ZEUS-3D USER MANUAL

Version 3.6

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zeus3d.ca/zeus3d/version3.6

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Contents

Preface

Most, if not all of the astrophysical MHD codes used around the world bearing the name *ZEUS* can trace their roots to the original 2-D code developed by Michael Norman and myself in 1986. Of these, this manual describes a version of the code that I have been developing and maintaining ever since. The interested reader will find a complete history of this code from its inception to the present release in the "history deck" of the source code.

The pervasiveness of *ZEUS* throughout the world is in large part due to the generous spirit of Michael Norman whose vision included "astrophysical community codes" to serve theorists much like *AIPS* serves radio astronomers. *ZEUS-3D* was first developed at the National Center for Supercomputing Applications (NCSA) between 1988 and 1990, and in 1992 version 3.2 was made available to the public. A few years later, MLN released the MPI version of the code (*ZEUSMP*) and use of the code spread. Many versions of the code now exist and have been significantly modified by various users to perform simulations from comet-planet collisions to cosmology.

While the *ZEUS*-family of codes are not fully-upwinded (like a Godunov scheme, for example), they have proven to be flexible and robust. One can add almost any physical process to the code without worrying too much about its effects on the underlying MHD scheme. It has therefore found a niche amongst numerically literate, though perhaps not expert, astrophysicists who have a computational problem to investigate but neither the time nor the resources to develop their own code.

One of the roles of the Institute for Computational Astrophysics (ICA) at Saint Mary's University is to provide and, in some cases, support code to the astrophysical community. To this end, the website (`zeus3d.ca/zeus3d/version3.6`) places into the public domain this author's double-precision version of *ZEUS-3D* (version 3.6; `dzeus36`). This code is distinct from the NCSA/UCSD version of the code (*ZEUSMP*; `https://lca.ucsd.edu`) which has not enjoyed significant algorithm development in more than a decade. As evident in §1, version 3.6 has undergone significant code development and bears little resemblance algorithmically to version 3.2 released around 20 years ago and, for that matter, to *ZEUSMP*. This includes, for example, a "planar-split" MHD algorithm, fully conservative in 3-D, self-consistent boundary conditions, an "N–log N" Poisson solver, and a full suite of graphics. The code now runs under *OpenMP* with 98% parallelism [yielding a speed-up factor of 12.5 (20) with 16 (32) processors] and AZEuS[1], an *AMR* version of the code and still under development at the time of this writing, will become available from a parallel site (`zeus3d.ca/azeus`) in the near future.

Conditions for use of this code are on the next page. The proper citations for referencing the algorithms used in `dzeus36` are:

Clarke, D. A., *A Consistent Method of Characteristics for Multidimensional MHD*, 1996, ApJ, 457, 291.

Clarke, D. A., *On the Reliability of ZEUS-3D*, 2010, ApJS, 187, 119.

It is requested that any publication reporting results performed by `dzeus36` or any of its

[1] Adaptive Zone Eulerian Scheme

derivatives include the following acknowledgement:

> Use of *ZEUS-3D*, developed by D. A. Clarke at the Institute for Computational Astrophysics (www.smu.ca/centres-and-institutes/ica.html) with financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC), is hereby acknowledged.

If length is an issue, the following will also suffice:

> Use of *ZEUS-3D*, developed by D. A. Clarke at the Institute for Computational Astrophysics with support from NSERC, is acknowledged.

Inquiries about this software, constructive criticism, bug reports, *etc.*, should be directed to the author at dclarke@zeus3d.ca.

Implicit user agreement

In what follows, *this software* refers to "*ZEUS-3D*, version 3.6" (`dzeus36`), and *the author* refers to David A. Clarke, ICA, Halifax. It is assumed that anyone using this code has read, understood, and agreed to the following conditions of use:

1. Distribution of this software shall remain the purview of the author. A user is free to share this software with students and co-workers, but requests from those not working directly with the user should be directed to zeus3d.ca/zeus3d/version3.6.

2. This software shall be used exclusively for education, research, non-profit, and non-military purposes. Specific written permission from the author must be obtained before any commercial use of this software is undertaken.

3. The banner and history decks (first two modules of the source code) shall remain with this software and any descendent developed from and still based substantially upon this software.

4. The name(s) of the institution(s) with which the author is or has been affiliated shall not be used to publicise any data and/or results generated by this software. All findings and their interpretations are the opinions of the user and do not necessarily reflect those of the author nor the institution(s) with which the author is or has been affiliated.

The author makes no representations about the suitability of this software for any purpose. Subject to the above conditions, this software and accompanying manual are provided "as is" without expressed or implied warranty.

Acknowledgements

The author wishes to express his gratitude to students, research associates, collaborators, and mentors past and present, for their valuable contributions toward the development of `dzeus36`, and in particular in debugging, providing and/or developing subroutines and algorithms, giving advice, and development of this user manual. In alphabetical order, these include Jack Burns, Stephen Campbell, Mike Casey, Jean Pierre DeVilliers, Kevin Douglas, Logan Francis, Phil Hardee, John Hawley, Chris Howard, Tom Jones, Byung-Il Jun, Chris Loken, Pierre-Yves Longaretti, Nick MacDonald, Chris MacMackin, Mordecai-Mark Mac Low, Alexander Men'shchikov, Michael Norman, Rachid Ouyed, Michael Power, Jon Ramsey, Mark Richardson, Alex Rosen, Jim Stone, Martin Sulkanen, and Joel Tanner.

Acknowledgement is made of the use and incorporation of routines from *Numerical Recipes* by William Press, Saul Teukolsky, William Vetterling, and Brian Flannery. This is an epic tomb of enormous benefit to the computational science community, and the *ZEUS-3D* project has benefited from this classic text on numerous occasions.

The author thanks the late Kevin Kohler, formerly of the Oceanographic Center at Nova Southeastern University, for allowing the source code for *PSPLOT* to be distributed with `dzeus36`. *PSPLOT* has improved and broadened in-line graphics—which had traditionally been accomplished with NCAR graphics—as well as simplify their installation.

The author also wishes to thank Professor Tom Jones of the Department of Astronomy at the University of Minnesota for his permission to include his Riemann solver into this release. These modules provide the "analytical" comparator for the suite of 1-D Riemann problems that comprise a significant portion of the test suite used to confirm *ZEUS-3D*.

Over the years, financial and technical support for the *ZEUS* development project(s) has been provided by many sources, including the NCSA and the University of Illinois, the American National Science Foundation and NASA, the Harvard-Smithsonian Center for Astrophysics, Saint Mary's University, and NSERC.

Finally, and most profoundly, the author wishes to thank his former advisor and mentor, Michael Norman, for his vision of a community astrophysics code which came to be known as *ZEUS*. Some of the coding in `dzeus36` still bears Mike's signature, and certainly the fundamental structure of the program follows the Jim Wilson and Mike Norman school of thought.

ZEUS-3D USER MANUAL

Version 3.6, David A. Clarke, ICA, March 2015

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1 Introduction

1.1 VERSION 3.0

ZEUS-3D is a 3-D magnetohydrodynamics (MHD) solver, and although it was designed with astrophysical applications in mind, fluid dynamic problems in the other physical sciences can be addressed with this code too. The code is now about 35,000 lines of *FORTRAN* and growing, and represents many years of work by many people. During the past two years, I have been the primary developer of the code, although algorithms and structures developed by many others over the past 20 years have been freely used. These include Philip Colella, Chuck Evans, John Hawley, Michael Norman, Larry Smarr, Jim Stone, Bram van Leer, Jim Wilson, Karl-Heinz Winkler, Paul Woodward, and others.

ZEUS-3D was created as part of the *ZEUS* development project, begun and headed by Dr. Michael Norman at the NCSA (National Center for Supercomputing Applications). It has been Mike's continuing efforts to support this project, both financially and intellectually, that have made the development of *ZEUS-3D* possible. Dr. Jim Stone, also a member of the *ZEUS* development project, was the principle creator of *ZEUS-2D*, the predecessor to *ZEUS-3D*. Although the two codes now differ substantially, the efforts that Jim and Mike made to develop the magnetic field algorithm and the modularity of the code are still very evident in *ZEUS-3D*.

In its present incarnation, *ZEUS-3D* is a three-dimensional ideal (non-resistive, non-viscous, adiabatic) non-relativistic magnetohydrodynamical (MHD) fluid solver which solves the following coupled partial differential equations as a function of time and space:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0; \tag{1}$$

$$\frac{\partial \vec{s}}{\partial t} + \nabla \cdot (\vec{s}\vec{v}) = -\nabla p - \rho \nabla \Phi + \vec{J} \times \vec{B}; \tag{2}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\vec{v}) = -p \nabla \cdot \vec{v}; \tag{3}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}). \tag{4}$$

where:

ρ = matter density
$\vec{v}$ = velocity flow field
$\vec{s}$ = $\rho\vec{v}$ = momentum density vector field
p = thermal pressure

Φ = gravitational potential
$\vec{B}$ = magnetic induction
$\vec{J}$ = current density ($\nabla \times \vec{B}$)
e = internal energy density (per unit volume)

The code possesses the following numerical attributes:

1. finite differencing on an Eulerian mesh (but possibly moving in an average sense with the fluid);
2. fully explicit in time and therefore subject to the CFL limit;
3. operator and directional splitting of the MHD equations;
4. can be used efficiently for 1-D and 2-D simulations with any of the coordinates reduced to symmetry axes;
5. Cartesian geometry for 3-D simulations, Cartesian and cylindrical coordinates for 2-D simulations, Cartesian, cylindrical, and spherical coordinates for 1-D simulations;
6. written in a "covariant" fashion to minimise the effects of the different coordinate systems on the structure of the code;
7. fully staggered grid, with scalars (density and internal energy) zone-centred and vector components (velocity and magnetic field) face-centred [derived vector components (current density and emfs) are edge-centred];
8. von-Neumann Richtmyer artificial viscosity to smear shocks;
9. upwinded, monotonic interpolation using one of donor cell (first order), van Leer (second order), or piecewise parabolic interpolation—PPI (third order) algorithms;
10. Consistent Advection used to evolve internal energy and momenta; and
11. Constrained Transport modified with the Method of Characteristics used to evolve the magnetic fields.

This code is strictly Newtonian. Relativistic astrophysics cannot be simulated in any way with this version. No explicit account for relativistic particles is incorporated either. The code assumes strict charge neutrality at all times—it is not a plasma code. It is assumed that the fluid is thermal, and is coupled to the magnetic fields via collisions with an ionised component which never undergoes charge separation. Pressure is assumed to be isotropic and gravitation is limited to the specification of a point mass. A fully three-dimensional Poisson-solver is planned for the next version (3.1) which will account for the self-gravity of the fluid.

The purpose of this manual is not to educate the potential user on numerical techniques, physical justification of the assumptions inherent to the code, or even what the potential problems to be solved are. Instead, it is assumed that the user is intimately familiar with the

fundamentals of MHD and has come up with a complex problem to solve which is completely described by equations 1 through 4. It is also assumed that the user has a working knowledge of *UNIX*. In this spirit, this manual is designed to instruct the user on the mechanics of using *ZEUS-3D* to solve the equations that pen and paper cannot attempt.

D. Clarke, February 1991

1.2 VERSION 3.2

The code has undergone numerous changes since the release of version 3.0 and has grown to nearly 45,000 lines of *FORTRAN* and more than 160 subroutines. Version 3.1 was never actually released as such, and so there is no corresponding manual. This, then, is the first revision of the user manual. The major differences between versions 3.0 and 3.2 include:

1. Line-of-sight integrations through the data volume for a variety of variables, including the Stokes parameters (see §3.9) are possible in both `XYZ` and `ZRP` coordinates. The *EDITOR* definition `RADIO` (§2.2.1) must be set to invoke this display option.

2. An option has been added to generate time slice plots. The *EDITOR* definition `TIMESL` has been added which now must be set in order to get time slice output.

3. Subroutines peculiar for generating polar pixel dumps (written by Carol Song) have been expunged. *ZEUS-3D* now converts polar slices to Cartesian slices "on the fly" before generating pixel dumps.

4. 2-D *NCAR* graphics have been enhanced with better annotation. Polar contours and vector plots now work properly.

5. An *EDITOR* alias `FINISH` has been added which represents a subroutine called after the main loop of the main program `zeus3d`. This gives the user a slot in which to perform various tasks at the end of the run.

6. The code can be micro-tasked for the Crays. Tests indicate that for typical runs, a real-time speed-up of 3.9 can be achieved with 4 dedicated processors.

7. The code will now run efficiently (*i.e.*, it vectorises) as a uni-tasked process on the Convex. This is done by defining the *EDITOR* definition `CONVEXOS`. Multi-tasking on a Convex using the `-O3` option can be done, but yields a real-time speed-up of only about 2.5 on a four processor machine. For runs on the Crays, `UNICOS` must now be defined.

8. More combinations of dimension and geometry are now known to work. The list now includes Cartesian (`XYZ`) with any two, any one, or no symmetry flag(s) set, cylindrical (`ZRP`) with either `JSYM+KSYM` or `KSYM` set, spherical polar (`RTP`) with either `JSYM+KSYM` or `KSYM` set. Other combinations will be debugged as needed.

9. One can now select an isothermal equation of state. A new *EDITOR* definition `ISO` has been added to take advantage of the reduction in memory and computation requirements for isothermal systems.

10. Yu Zhang (NCSA) has implemented a 3-D self-gravity module using the so-called DADI (Dynamical Alternating Direction Implicit) scheme. The *EDITOR* definition `GRAV` must be set if self-gravity is to be invoked.

11. One now has the choice of solving either the total energy equation or the internal energy equation (the only choice in previous versions). The toggle `itote` has been introduced to the namelist `hycon` to specify which of these formalisms is to be used (Byung-Il Jun, NCSA).

12. Pixel, Voxel and *RADIO* dumps may now be made in *HDF* format. This avoids the cumbersome process of "bracketing" the images, but at the cost of more than four times the disc space requirements.

13. The common blocks have been radically restructured, and the way restart dumps are generated has been overhauled entirely. It is now possible to read a restart dump, for example, that was generated by a compiled version of the code with different *EDITOR* macro settings and different values for the array parameters.

14. Ragged boundaries are no longer available. This feature has been expunged from the code for lack of use and because of the increasing effort necessary to incorporate it into new features. Boundaries must now be regular.

Users of version 3.0 will be happy to note that there are no major changes in the way *ZEUS-3D* is compiled or executed, and the namelist parameters have remained more or less fixed. Still, there are enough subtle changes that it might do the experienced user some good to review these notes before attempting to run a job with this new version. Also note that version 3.2 cannot read restart dumps created by version 3.0, and vice versa.

D. Clarke, August, 1992

1.3 VERSION 3.3

The NCSA, under the auspices of the Laboratory for Computational Astrophysics and the leadership of Dr. Michael Norman, has developed `zeus32` into an MHD-cosmology code and continues to make their code available to the community. Independent of the NCSA effort, I and my co-workers have developed `zeus32` into an CR-MHD (CR $\equiv$ cosmic rays) code (`zeus33`). This manual, therefore, describes the first non-NCSA version of the code and was developed at the Harvard-Smithsonian Center for Astrophysics. This version contains more than 52,000 lines of source code and is the most extensive re-write of the code since version 3.0 was first generated from the 2-D template. Most of the routines in the `PHYSICS` group—including the hydrodynamics—have been rewritten in order to implement the new Consistent Method of Characteristics (CMoC). The CMoC was developed to solve the chronic problem of magnetic field explosions in previous MHD algorithms. While substantive to the code, these changes are mostly transparent to the user. Changes of significance to the user include:

1. The *EDITOR* alias `MOC` has been removed, since the MoC algorithm has been replaced with the CMoC algorithm. The option to use the original CT scheme has also been

eliminated since, unlike MoC, CMoC reduces to the original CT scheme in the weak field limit. The *EDITOR* alias `FASTCMOC` has been added to activate the more efficient version of CMoC for cases where the ratio of the flow and Alfvén velocities is not expected to exceed 10^8 for 64-bit words, and 10^4 for 32-bit words.

2. A two-fluid approximation for a relativistic fluid has been installed (Byung-Il Jun, NCSA). It is turned on by specifying the *EDITOR* macro `TWOFLUID`. The two-fluid approximation takes after Jones & Kaing (1991, ApJ, 363, 499) and can reproduce all of their results. The diffusion coefficient is determined by a subroutine linked with the *EDITOR* alias `DIFFUSION`. The diffusion operator is performed using a time-centred, sub-cycling algorithm which allows the CFL limit to be specified independently of the diffusion time scale.

3. A time-centred subcycling option for the artificial viscosity has been installed and is activated by setting `iscyqq=1` in namelist `hycon`. This renders the CFL limit independent of the viscous time scale. For applications with strong shocks, this can reducing computational time by a factor of 2 or more.

4. An additional option for `ARTIFICIALVISC` has been introduced (`gasdiff`) by Byung-Il Jun. This routine uses ordinary gas diffusion to stabilise shocks. It does so without any excess heating often associated with viscosity, but tends to render the solution very smooth since it is applied everywhere.

5. The variables `iordd`, `iorde`, *etc.* and `istpd`, `istpe`, *etc.* have been expunged. In this release, `iord` and `istp` specify respectively the order of the interpolation algorithm and whether the steepener is to be applied in the third order *PPI* algorithm for all variables.

6. The I/O has been updated with the two-fluid variables. In addition, the conventions used in the various I/O routines have been standardised. In particular, with the exception of *RADIO* variables, virtually all variables available for output in any one I/O routine are available in all. By necessity, the *RADIO* variables remain limited.

7. A "pseudogravity" option has been added. The pseudogravity "holds onto" artificial pressure gradients (*e.g.*, a King atmosphere) much like ordinary gravity was used in `ZEUS04` (the predecessor to *ZEUS-2D*). The pseudogravity is activated by setting the *EDITOR* macro `PSGRAV` which is mutually exclusive with `GRAV`. The pseudo-gravitational potential has the same units as pressure (*i.e.*, ρv^2) rather than the usual units of gravitational potential (*i.e.*, v^2). The pseudo-gravitational acceleration is given by $dv/dt = -(\nabla\phi)/\rho$ and is treated exactly as a pressure in the source term routines. Thus, to "hold onto" an artificial atmosphere in a problem initialisation routine, simply define `PSGRAV` and set `gp(i,j,k) = p(i,j,k)`.

8. Bremsstrahlung emission has been added to the *RADIO* dumps.

9. The code has been generalised to run on SUN SPARCstations. The `EDITOR` macro `SUNOS` must be specified for either *SUNOS* or *SOLARIS* operating systems.

D. Clarke, December 1993

1.4 VERSION 3.4

It has been more than a decade since version 3.3 was completed. Except for one bug found in the CMoC algorithm (to do with density, and described below), it has proven to be an extremely robust algorithm. The main problem with the code is its boundary conditions, and this version has seen numerous rewrites and experimentation with its boundary condition routines, none satisfactory.

The main problem is that as released, version 3.3 could not do something as simple as launch an Alfvén wave from an inflow boundary. As released, version 3.4 can, but at the cost of introducing monopoles at an inflow boundary in some circumstances (such as Ouyed-type jets from problem generator `CORONA`), and numerous patches have been installed to prevent or at least limit these. In particular, inflow/outflow boundary conditions should be used with great caution. On the plus side, with help form Pierre-Yves Longaretti, periodic boundary conditions are now *exact*, with both sides of a periodic grid committing identical machine round-off errors.

Other changes to the code include:

1. The code has been upgraded to double precision, and is now called `dzeus34`. Creating the executable `xdzeus34` now requires linking the double precision libraries: `dnamelist.a` and `dsci01.a`.

2. The problem generator for launching jets from accretion discs (à la Ouyed and Pudritz) has been added (corona). A new *EDITOR* definition `POLYTROPE` has been added if the results of solving the internal energy equation are to be set aside in favour of a strict polytrope ($p = \kappa\rho^\gamma$). This feature should be used with extreme caution as a polytrope is not physically equivalent to an adiabatic equation of state (the former forbidding irreversible processes).

3. The problem generator for Couette type flows (Longaretti) has been added.

4. PSGRAV and GRAV may now be set simultaneously, if needed. A new 3-D array, `psgp`, has been added to keep the pseudo-gravity separate from the physical gravitational potential, `gp`.

5. Yu Zhang's DADI gravity routines, which never worked properly, have all been expunged and two new Poisson solvers have been installed by A. Men'shchikov: SOR (Successive Over-Relaxation), and FMG (Full Multi-Grid). The algorithm is chosen by setting `gravalg` to 1 or 2 for SOR or FMG. Only SOR is fully debugged.

6. The code is now portable to *AIX* (IBM) and *LINUX*.

7. A bug in the CMoC algorithm was fixed. The original scheme used four-point averages of the density to the location of the *emf* when estimating the characteristic velocities. However, it was found that at steep density gradients, this proved disastrous. A degree of freedom overlooked in the original CMoC implementation was exploited to allow the density to be upwinded too, thus preventing steep gradients from over- or underestimating *emf*s.

8. Kinematic viscosity has been added to the code (constant viscosity only), and is triggered by specifying a non-zero value for "`nu`", a global variable, in namelist `HYCON`. "`nu`" is the kinematic viscosity defined by $\nu = VL/\mathcal{R}$, where $\mathcal{R}$ is the Reynolds number of the flow and L and V are length and velocity scales of the problem.

9. A. Men'shchikov has introduced *PSPLOT*[2] to the plotting library `grfx03.a`. Three namelist parameters (`norppl1`, `norppl2`, `norptsl`) will allow for publication-quality graphics with colour without linking any *NCAR* libraries. Two additional user-creatable libraries `psplot.a` and `noncar.a` must be linked instead for this option to work.

10. The subroutines `CURRENT*` have been replaced with `CURL*`, which compute components of the curl. It is a generalisation that may be used to compute the vorticity as well.

11. Vector potentials are now available in all graphics options (*e.g.*, §B.19, §B.20, §B.21, *etc.*). To allow this, "inverse curl" routines have been added (following Arfken, ed. 5, pp. 73–74) that compute a vector potential from a given magnetic field.

D. Clarke, September, 2005

1.5 VERSION 3.5

Modifications to the code from version 3.4 are numerous and invasive, and needed to correct long-standing problems with boundary conditions and to complete the installation of the total energy equation. The code now has more that 90,000 lines of *FORTRAN* and 350 subroutines.

A self-consistent framework for setting magnetic boundary conditions has been developed and installed in this release. In particular, inflow and outflow boundary conditions, while still not perfect, are now much cleaner than in `dzeus34`, and can be used with some confidence. For the user, the visible consequences are four-fold:

1. A distinction is now made between the *skin* values (*e.g.*, variables on the `i=is` face at the inner-i boundary) and proper *boundary* values (*e.g.*, variables, face-centred or zone-centred, at `i=ism1` and `i=ism2` at the inner-i boundary). For inflow conditions, the user must now set the *skin* values of the transverse (to the boundary normal) components of the *emf* (thus, ε_2 and ε_3 at the inner-i boundary), and the *boundary* values of the transverse magnetic field components (thus, B_2 and B_3 at the inner-i boundary). Note that there are no skin values for the transverse magnetic field and the boundary values of the transverse *emf*s are set directly by a new routine `BVALEMFS` called at the top of `CT`.

2. Arrays containing desired inflow values for the normal (to the boundary) magnetic field components (*e.g.*, `b1iib1`, `b2ijb1`, *etc.*) are no longer available. Instead, the normal magnetic field component is now set by the solenoidal condition and therefore "floats".

[2] with kind permission from its author, Kevin Kohler. Please see *Acknowledgements* for the full citation.

3. Routines `BVALB1`, `BVALB2`, and `BVALB3` used to set magnetic boundary values in previous versions are no longer available. Instead, the user must initialise every element of the magnetic field arrays (`b1`, `b2`, and `b3`) in their problem generator including boundary zones making sure that $\nabla \cdot \vec{B} = 0$ at $t = 0$ everywhere.

4. Boundary type 8, a *selective inflow* boundary condition, can now be set and is suitable for sub-magnetosonic inflow conditions. At a given inflow boundary, as many boundary conditions may be set as there are characteristics pointing into the grid (*e.g.*, see Bogovalov, 1997, A&A, 323, 634). For supermagnetosonic flow, this means all seven variables, namely ρ, p (or e), all three components of the velocity, and the two transverse components of the magnetic field (the normal component being determined by the solenoidal condition). On the other hand, for sub-slowmagnetosonic inflow, only four characteristics point into the grid, and three of the inflow variables must be allowed to "float". A variable floats if one sets the boundary type [*e.g.*, `niib(j,k)`] to 8, and if the inflow array for that variable [*e.g.*, `diib1(j,k)` for density, *etc.*] is set to "`huge`" (a global parameter; see §C.6).

Complete details are given in §B.8. Other changes made to this release include:

1. A new parameter, `iords` (§B.7), now lets one specify the order of interpolation for the scalars (*e.g.*, ρ, e, *etc.*) separately from the vector components, which are still controlled by `iord`. The default value for `iords` is `iord`, whose default is still 2 (van Leer). Note that with the scalars interpolated with PPI (`iords=3`) and the contact steepener activated (`istp=2`), contacts in most 1-D Riemann problems are as steep as fast shocks—two or three zones.

2. Additional interpolation schemes have been partially added (*i.e.*, available for scalars only), most notably a velocity-corrected second-order van Leer scheme (`iord=-2`). See §B.7 for details.

3. The new boundary conditions fix many problems, including a long standing one with 3-D toroidal fields in propagating jets. Previously, it was noted that such a field introduced a strong axial field from the `i=is` skin, and tapering the magnetic profile to zero before the jet radius was necessary to avoid this. 3-D toroidal fields now leave the `i=is` skin perfectly cleanly, with zero (to machine round off errors) B_1 left on the skin itself.

4. Stone's *MOC* and the Hawley-Stone variation, *HSMOC*, have been installed to allow for comparisons among the various algorithms. New *EDITOR* aliases `MOC` and `HSMOC` are used to engage these algorithms (§2.2.1).

5. Parameter `ijkn` is now `ijkx` (`x` ⇒ maximum) and a new parameter `ijkn` (`n` ⇒ minimum) has been added. Confusion between the old and new uses of `ijkn` is minimised as these are now set automatically and no longer need to be set by the user in the script file, `dzeus35.s` (§2.3).

6. Installation of the total energy equation is complete, and is now the default (`itote=1`). This has mitigated numerous changes throughout the code, including removal of consistent advection from the energy equations, and the introduction of a new global variable, `et`, that always contains the total energy density, regardless of which energy equation is being solved. The old energy variable, `e`, and its related inflow variables, *e.g.*, `eiib1`, *etc.*, have been changed to `e1` and `e1iib1`, *etc.*, and always contains the internal energy density, regardless of which energy equation is being solved. See §B.7 for further details.

7. Tom Jones' "Reimann solver" has been included, and is compiled when the *EDITOR* macro `RIEMANN` is defined. Its purpose is strictly to provide the "analytical" solution for the suite of 1-D Riemann test problems, and is controlled via namelist `pl1con` (§3.2).

8. *EDITOR* macro `VECPOT` has been added to allow the vector potential to be used as the primary magnetic variables instead of the magnetic field. In principle, this should cause differences only at the machine round-off level, and other than setting the macro, requires no changes by the user. For example, the user would still initialise the magnetic field components everywhere. With `VECPOT` set, the code would then use the "anticurl" routines, `ACURL*`, `*=1,2,3`, to compute the initial vector potential from the initial magnetic field.

9. Toru Okuda's flux-limited diffusion algorithm for radiation HD has been included, though in an incomplete and untested form. It is activated by setting the *EDITOR* macro `RADIATION`.

10. The code has been tuned for *OpenMP*, and its directives can be inserted automatically by setting `iutask=2` in *EDITOR*'s input deck `inedit` (part of `dzeus35.s`; see §2.3).

D. Clarke, September, 2007

1.6 VERSION 3.6

The most significant change to the code is a new "finely interleaved transport" (FIT) algorithm which retains most of the algorithmic details of CMoC (planar split, fully Eulerian transport, *etc.*), but rearranged into finer modules, with more frequent updates to v and B. As such, the code is now largely impervious to a "striping instability" (affecting 2-D shear Alfvén waves and 2-D advection) to which the code has been vulnerable since `zeus04`.

The code is now over 130,000 lines of *FORTRAN* with nearly 500 subroutines and functions.

1. `GRFX03` has been overhauled. All 1-D plotting routines have been merged to a new `GRFX1D` which now does single and multiple plots using lines or one of a variety of symbols. For 2-D plots, the user may now select as many as two scalars and three vector fields (along with "corks"; see change 3 below) for each plot in this "buffet-style" of plotting. (See §B.20.)

Also for 2-D plots, one may now rebin the 2-D data-slices to a lower resolution grid before plotting. *e.g.*, for high-resolution runs, one doesn't always need contour plots of the full-resolution data which, for *PSPLOT*, can require significant cpu, memory, and disc resources to generate.

2. Nick MacDonald's "aging" module has been added to track the synchrotron age of a zone, thereby allowing spectral indices to be calculated. This should still be considered experimental.

3. Nick MacDonald's and Mark Richardson's Lagrangian particle ("corks") routine has been added. These tracer particles can be initialised by the problem generator and/or injected during the simulation, and carry with them a whole host of measurables. To engage, *EDITOR* macro `CORKS` must be set. See namelist `crkcon`.

4. From the outset (`zeus30`), differences among compilers were inaccurately attributed to the operating system (OS) rather than the compiler. As such, a longish list of *EDITOR* macros for OSs (e.g., `SUNOS`, `CTSS`, *etc.*) had accumulated which couldn't cleanly accommodate different compilers running under the same OS. In this release (and in version 2.2 of *EDITOR*), all *EDITOR* OS macros have been replaced with compiler macros. The user now specifies in the `dzeus36.s` file (rather than the `zeus36.mac` file where the OS used to be set) a supported compiler with the compiler option (`coption`) "debug", "optimise" or "openmp", and *EDITOR* creates the appropriate `makezeus` file. Supported compilers include: `cf77` (Cray), `f90` (Sun), `g95` (`g95.org`), `gfortran` (Gnu), `ifort` (Intel), `pgf77`, `pgfortran` (Portland Group), and `xlf` (IBM).

   The compilers `g95` and `gfortran` can give numerous inscrutable warning messages from the loader which seem to be entirely innocuous:

   ```
   ld:  warning for symbol _g01wdt_ tentative definition of size 16 from ...
   ```

   There is some discussion of these on various web forums, none of which reveals the origin or cause. Further, the `g95` compiler does not seem to be ANSI-standard, as some test problems (*e.g.*, Fig. 3b from Ryu & Jones, 1995) exhibits noise in v_2 at the 10^{-17} level which is entirely absent with all other compilers.

   In the 1-D tests with optimisation turned on, `ifort` is 75% faster than `gfortran` which is 67% faster than `g95`.

5. Slip periodic boundary conditions have been added (see `*gp boundary`).

6. The old voxel dumps have been purged out of complete disuse.

7. Stephen Campbell (B.Sc. 2014) has introduced a new animation-making option in the pixel dump routine (`morppix=1`). All images are stored as `real*4` (instead of `character*1`) and assembled at the end of the run into mpeg files. The original `real*4` frames are gathered in a tarball to allow the user to remake the animation with different palette, bracketing, *etc.*, without having to rerun the simulation. See `PIXDMP` for further details.

   A similar feature is available for the radio dumps (`RADDMP`).

8. Logan Francis (B.Sc. 2014) has added an FFT/FST gravity solver (`grvalg=3`) which can handle all types of boundary conditions (periodic by using a Fourier transform, Dirichlet conditions by using a sine transform). As with the full multi-grid algorithm (`grvalg=2`), active grid dimensions must be powers of 2. See GRAVFFT for further details.

9. The long-standing problem of 2-D shear Alfven wave "wings" has been resolved, resulting in a nearly complete overhaul of the transport step. *ZEUS* can now perform 2-D shear Alfvén wave propagation, 2-D advection, and vortex ring transport totally free from what I call the "striping instability" using "Finely Interleaved Transport" (FIT; `trnvrsn=1`). The traditional transport algorithm ("legacy transport") is still available by setting `trnvrsn.le.0`.

   FIT represents the most significant overhaul of the transport step since the introduction of CMoC in 1993. There are no new algorithms *per sé*, rather the granularity of existing algorithms has been reduced and the order in which quantities are updated altered. Thus, and for example, for various values of `ix1x2x3`, `v2` is updated from 3-transport of `s2` before 2-transport of `s1` (using `v2`). Likewise, `b2` and `b3` are updated from `emf1` before `emf2` is computed from `b1` and `b3`, *etc.* With these changes, `dzeus36` is not vulnerable to the "striping instability" (which it has been since `zeus04`), and 2-D transport is now CFL-limited for the first time.

10. The one-fluid ambipolar diffusion algorithm described by Duffin & Pudritz (2008, MNRAS, 391, 1659) has been implemented by Chris MacMackin (B.Sc 2015). It should still be considered experimental and be used only in the limit of *low* ionisation. For a highly ionised fluid, one needs a two-fluid approach. Chris has also implemented the super-stepping (Runga-Kutta) method of Meyer, Balsara, & Aslam (2012, MNRAS, 422, 2102) to address the exceedingly short time step ambipolar diffusion otherwise requires. This allows an AD problem to be evolved on the CFL-limited MHD time scale.

D. Clarke, December, 2015

2 Running *ZEUS-3D*

2.1 Overview

At the time of this writing, *ZEUS-3D* may be compiled with any one of `cf77` (Cray), `ifort` (Intel), `f90` (Sun), `g95` (`g95.org`), `gfortran` (Gnu), `pgf77`, `pgfortran` (Portland Group), and `xlf` (IBM). Other compilers can be used with only minor changes required to the code, and the user is referred to the installation instructions in the document `install_dz36.txt`[3] for details.

This manual is written assuming the use of Gnu's `gfortran`[4], the most recent and still-supported version of this most-commonly used publicly available *FORTRAN* compiler, though differences with other compilers are mostly minor and transparent. For those familiar with versions 3.5 of *ZEUS-3D* and earlier, the OS-specific *EDITOR* macros `AIX`, `CONVEXOS`, `LINUX`, `SUNOS`, and `UNICOS` have been replaced with the compiler-specific macros listed above. This long-overdue change was made to correct an early and incorrect notion that *FORTRAN* differences were necessary to accommodate differences in the operating system rather than the compiler. The move to compiler-specific macros affects primarily the installation instructions and introduces minor changes to the `zeus36.mac` and `dzeus36.s` files; all other aspects of using *ZEUS-3D* remain unchanged.

With the code installed, the user controls what simulation is performed by editing the two files `zeus36.mac` and `dzeus36.s`. These are relatively short and painless to edit, and their complete descriptions are included in the next two subsections. Once edited to the user's satisfaction, the *ZEUS-3D* executable is created by running the `dzeus36.s` script file which is done by typing:

```
csh -v dzeus36.s
```

Running this file performs sequentially the following tasks:

1. sets the *FORTRAN* compiler;
2. retrieves all necessary files from user-specified home directories;
3. creates a directory called `dzeus3.6` within the user's present working directory (*pwd*) to store all the source and object files created during compilation;
4. creates a change deck for `dzeus36` containing preprocessor macros and aliases (`zeus36.mac`, next subsection), and changes to the source code (if any) required for the application (the most common and often the only changes necessary to the source code are to the parameter statements which set the size of the arrays needed for the run.);
5. fires up the *EDITOR* preprocessor;
6. creates the input deck for the `dzeus36` run; and finally

[3] Available from zeus3d.ca/zeus3d/version3.6
[4] gcc.gnu.org/fortran

7. makes the executable `xdzeus36` (using the *UNIX* facility *MAKE*).

A description of the file naming convention is required at this point. *ZEUS-3D* refers in a general way to the package and its capabilities while `dzeus36` is more specific, and is a mnemonic for "double precision *ZEUS-3D*, version 3.6". `zeus36` is the common denominator for the names of the principle files required to create the executable. Thus, the source code itself is `dzeus36`, the script file is `dzeus36.s`, the macro file is `zeus36.mac` (there is no leading "`d`" since no changes were needed in this file during migration to double precision), and the executable is `xdzeus36`. However, to confuse matters, the minor files don't follow this convention. The input deck is `inzeus` and the change deck is `chgzeus`—no "`36`" suffix—and the libraries don't even have ZEUS as part of their names. And so it goes. The bottom line, though, is that if the only changes to be made to the source code are the values of the parameters which set the array dimensions, then there are only two files to be concerned with: `dzeus36.s` and `zeus36.mac`. The rest is automatic.

2.2 The macro file `zeus36.mac`

Below is an example of a `zeus36.mac` file. A similar file can be downloaded from the *ZEUS-3D* web site. It is suggested that this file be copied and used as a general template since all the macros used by `dzeus36` are listed in this example.

```
**--+----1----+----2----+----3----+--+----3----+----2----+----1----+----
**                                                                    **
******************  CONDITIONAL COMPILATION SWITCHES  ******************
**                                                                    **
**  1) symmetry axes:  ISYM, JSYM, KSYM
**
*define   JSYM, KSYM
**
**  2) geometry:  XYZ, or ZRP, or RTP
**
*define   XYZ
**
**  3) physics:  AGING, AMBIDIFF, GRAV, ISO, MHD, POLYTROPE, PSGRAV,
**               RADIATION, TWOFLUID
**
*define   MHD
**
**  4) data output modes:  CORKS, DISP, HDF, PIX, PLT1D, PLT2D, RADIO,
**                         TIMESL
**
*define   PLT1D, TIMESL
**
**  5) other:  DEBUG, FASTCMOC, HSMOC, MOC, NOMOC, RIEMANN, VECTORISE
**
*define   FASTCMOC, RIEMANN
**                                                                    **
************************  MODULE NAME ALIASES  ************************
**                                                                    **
**  The modules "BNDYUPDATE", "SPECIAL", "SPECIALSRC", "SPECIALTRN",
**  "FINISH", "PROBLEM", PROBLEMRESTART", "USERSOURCE", and "USERDUMP"
**  are slots available for user-developed subroutines.
**
```

```
*alias    BNDYUPDATE       empty
*alias    EXTENDGRID       empty
*alias    GRAVITY          empty
*alias    SPECIAL          empty
*alias    SOURCE           srcstep
*alias    SPECIALSRC       empty
*alias    TRANSPORT        trnsprt
*alias    SPECIALTRN       empty
*alias    NEWTIMESTEP      newdt
*alias    NEWGRID          empty
*alias    FINISH           empty
**
*alias    PROBLEM          shkset
*alias    ATMOSPHERE       empty
*alias    PROBLEMRESTART   empty
*alias    USERSOURCE       empty
*alias    ARTIFICIALVISC   viscous
*alias    DIFFUSION        empty
*alias    USERDUMP         empty
**                                                              **
************************  ERROR CRITERIA ALIASES  ***********************
**                                                              **
*alias    GRAVITYERROR     1.0e-6
*alias    GRIDERROR        1.0e-6
*alias    PDVCOOLERROR     1.0e-6
*alias    NEWVGERROR       1.0e-10
*alias    RADIATIONERROR   1.0e-6
**                                                              **
************************  ITERATION LIMITS ALIASES  ***********************
**                                                              **
*alias    GRAVITYITER      600
*alias    GRIDITER         20
*alias    PDVCOOLITER      20
*alias    NEWVGITER        20
*alias    RADIATIONITER    20
```

These are all preprocessor commands (the preprocessor used here is called *EDITOR*—also developed by the author—and for those familiar with the old Cray OS *CTSS*, it has the "look and feel" of *HISTORIAN*), and become part of the "change deck" `chgzeus` created by the script file `dzeus36.s`, described in the next subsection. A change deck is a file which is merged with the source code during the preprocessing step of `dzeus36.s`. Both the source code and the change deck can contain preprocessor commands which are interpreted, carried out, and then expunged from the code by *EDITOR* before the code is compiled by the *FORTRAN* compiler. All preprocessor commands have an asterisk (`*`) in column 1; two asterisks (`**`) in columns 1 and 2 indicate a comment. When the preprocessor has finished, the result is a pure *FORTRAN* source code tailored specifically for the problem to be solved. Therefore, in order to customise the code, it is necessary to set the *EDITOR* "definitions" and "aliases" (generically referred to as "macros") found in `zeus36.mac`.

The combined effect of the macros is two-fold. First, they determine what parts of the code are activated and what parts are ignored. Thus, it is possible to eliminate the computations and the memory requirements necessary to evolve the magnetic fields, for example, by not defining the `MHD` macro [this can be done by "commenting out" (double asterisk) the `*define MHD` statement in the example above]. The preprocessor will then remove all coding

peculiar to the magnetic field including the declarations of the magnetic field arrays during the preprocessing step. The compiler never sees the magnetic stuff, and the executable is streamlined for the hydrodynamical problem. Of course, the original source code is not altered by preprocessing it. Rather, the preprocessor creates a precompiled version of the code and stores each subroutine into its own file (to facilitate *MAKE* and debuggers such as *DBX*) in the directory `dzeus3.6` which is created by the script file `dzeus36.s`. Second, the alias macros can be used to substitute any character string in the code during the preprocessing step.

This manual discusses only those aspects of the *EDITOR* preprocessor necessary for the user to make changes to the code, compile it, and then execute it. A full account of *EDITOR* is given in the manual, `edit22_man.ps`, found in the `manuals` directory of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6.

2.2.1 The *EDITOR* definitions

A description of the definition macros (called "Conditional Compilation Switches" at the top of the given example of `zeus36.mac` above) follows:

1. The code can be streamlined (optimised) for 1-D and 2-D problems by setting the appropriate symmetry macros. If symmetry along any of the i (x_1), j (x_2), or k (x_3) axes is desired, then set the `ISYM`, `JSYM`, or `KSYM` macros. If the macros are not set and a 1-D or 2-D calculation is initialised by the input deck, *ZEUS-3D* will still carry out the sub 3-D computation correctly, but will do so less efficiently.

2. The geometry is set by setting *one* of the `XYZ` (Cartesian), `ZRP` (cylindrical), or `RTP` (spherical polar) macros. Obviously, these macros are mutually exclusive.

3. `AGING` activates the subroutines and define an additional scalar array necessary to track the "age" of high-energy electrons required for calculations of synchrotron emissivity. `AMBIDIFF` turns on the single-fluid approximation for ambipolar diffusion described by Duffin & Pudritz (2008, MNRAS, 391, 1659). Defining `GRAV` *and* setting the *EDITOR* alias `GRAVITY` to `gravity` will turn on the Poisson solver and one of three algorithms (SOR, FMG, FFT) will be used to solve the self-gravitational potential. The `ISO` macro should be set if an isothermal equation of state is desired. With `ISO` defined, an isothermal equation of state is presumed and the energy variables are not declared saving both computational time and memory. By setting the `MHD` macro, the algorithm for evolving the magnetic fields is activated. With `MHD` on, additional field arrays are declared and the code peculiar to updating the magnetic field is compiled. `POLYTROPE` forces a strict polytropic equation of state. `PSGRAV` (no longer mutually exclusive with `GRAV`) activates the pseudo-gravity feature used to hold onto artificial atmospheres. The macro `RADIATION` enables the (incomplete) flux-limited diffusion algorithm for RMHD. Defining `TWOFLUID` will activate the arrays and coding necessary to solve the energy equation for the second thermal fluid. Note that partial densities and momenta are not tracked for the second fluid; only partial internal energies (and thus partial pressures). The second fluid may be subjected to diffusion, if desired.

4. The graphics enabled during a run are set by the graphics macros. Set `CORKS` to activate Lagrangian tracer particles and their output dumps, set `DISP` for display dumps, set `HDF` for *HDF* dump files, set `PIX` to enable 2-D pixel dumps, set `PLT1D` for 1-D line plots, set `PLT2D` for 2-D contour and/or vector plots, set `RADIO` for *RADIO* dump files, and set `TIMESL` for time slice dumps. As many as these may be set simultaneously as necessary. See §3 for a discussion of the various *ZEUS-3D* dump files.

5. The `DEBUG` macro turns on portions of the code designed for development and debugging, and will send all sorts of messages to the terminal and may even cause the code to crash. It should be invoked only by developers of the code. The faster CMoC algorithm may be invoked by setting the macro `FASTCMOC`. This macro should be set only if the accuracy of the smallest of the flow and Alfvén speeds is unimportant when it falls below 10^{-8} (10^{-4}) times the largest of the speeds for 64-bit (32-bit) words. Otherwise, the general CMoC algorithm (activated by *not* setting the `FASTCMOC` macro) can handle arbitrarily small Alfvén and/or flow speeds accurately, but at the cost of 25% more computational time. The macros `HSMOC`, `MOC`, and `NOMOC` invoke other MHD algorithms which are available for comparison, but are not recommended for general use. The macro `RIEMANN` is needed if 1-D analytical solutions are to be overlaid with the results of 1-D shock-tube tests, and `VECTORISE` invokes special "vectorised" versions of the CMoC routines generally used only in debugging.

2.2.2 The *EDITOR* aliases

The alias macros allow phrases in the code to be substituted for other phrases during the precompiling step. Thus, "Module Name Aliases" (in the middle of the given example of `zeus36.mac` above) give the user control over what subroutines are called during execution. As an example, in the main program of the source code, there is a statement: `call SOURCE` which becomes `call srcstep` after preprocessing using the given example of `zeus36.mac`. Note that there is no subroutine called `SOURCE` but there is a subroutine in the source code called `srcstep`. Thus, the user is free, in principle, to create their own subroutine to manage the source terms instead of `srcstep`, and this new routine can be linked into the code by altering the alias setting for `SOURCE` from `srcstep` to the name of the new routine. Note that by setting any of the Module Name Aliases to `empty` (a subroutine in `dzeus36` which does nothing but return to the calling routine), a Module Name Alias can be effectively "turned off".

Aliases can also be used to set parameters in various parameter statements scattered throughout the source code. These are the "Error Criteria Aliases" and "Iteration Limits Aliases" at the bottom of the given example of `zeus36.mac` above. Thus the *EDITOR* statement:

```
alias GRAVITYERROR     1.0e-6
```

sets the maximum convergence error in the self-gravity module to 10^{-6}. Somewhere in the code is the statement `parameter ( errmax = GRAVITYERROR )` and the preprocessor makes the substitution. However, the majority of the parameters (array dimensions, for example) are set directly in `dzeus36.s` which is described in the next subsection.

To understand better the descriptions of the "Module Name Aliases" which follow, the reader should examine the flow charts in App. A (*ZEUS-3D* Skeleton) which indicate the order in which the Module Name Aliases are called. Some subroutines are charged with reading the input data from the input deck `inzeus`. A description of all the input namelist parameters is given in App. B.

1. `BNDYUPDATE`: This module is called at the beginning of each loop and allows inflow boundary conditions to be evolved in time should this be necessary for the simulation. Examples of evolving inflow boundary conditions include helically perturbing the inflow at a jet orifice to break the symmetry (`wiggle`), generating magnetic field at the boundary (`bgen`), or `empty` if no inflow boundary update is desired. The user can, of course, supply a subroutine for this alias. See §5.1 for discussion on how to add a subroutine to the code.

2. `EXTENDGRID`: This module will allow the grid to be extended as a disturbance (shock) propagates into initially quiescent zones. Currently, the only options are `extend` and `empty`. The subroutine `extend` will prevent quiescent zones from being updated until the disturbance comes within five zones, potentially saving significant amounts of computational time. Care should be exercised in its use, however. If the subroutine is unsuccessful in determining when the disturbance gets close to an edge of the current computational domain, the results can be disastrous.

3. `GRAVITY`: This module updates the self-gravitational potential. Currently, the only choices are `empty` and `gravity`. If `gravity` is selected, the user will have to choose a Poisson solver (`grvalg` in namelist `grvcon`), as well as a method to determine boundary values (`giib`, *etc.* in namelist `iib`, *etc.*).

4. `SPECIAL`: This is a simplistic solution to the potentially complex problem of the user desiring to add a whole new type of physics to the code. It assumes that changes do not need to be intertwined into existing modules, which in practise, often will be necessary. The three accompanying "plugs" `SPECIALSRC` (for "special" source terms to be added after the artificial viscous step), `USERSOURCE` (for source terms to be added before the artificial viscous step), and `SPECIALTRN` (for "special" transport terms) allow for some flexibility in installing new physics within the current structure, but this still may not be enough for any type of sophisticated addition. Currently, all four macros are set to `empty`.

5. `SOURCE`: This is the module in which source terms are incorporated. For full dynamics, this should be set to `srcstep` (or the user's module if need be) while for problems of pure advection, this should be set to `empty`.

6. `SPECIALSRC`: See `SPECIAL`.

7. `TRANSPORT`: This is the module for the transport of variables across zone boundaries and should be set to `trnsprt` or to the user's equivalent module. It is unlikely that `empty` should ever be used here.

8. `SPECIALTRN`: See `SPECIAL`.

9. `NEWTIMESTEP`: This module determines how the next time step is computed. Since *ZEUS-3D* is an explicit code, all algorithms should incorporate the CFL limit. Current choices are `newdt` for full (M)HD problems, and `advectdt` for pure advection problems.

10. `NEWGRID`: This module adjusts the grid should grid velocities be set to follow the flow, at least partially. Current choices are `newgrid` and `empty`. In practise, the user will have to provide their own prescription for evaluating the grid velocities, as most of the available methods are untested. This will require replacing or adding to the subroutine `newvg`. See §5 for discussion on how to add or modify a subroutine in the code.

11. `FINISH`: This is a "plug" available to the user to have any user-supplied subroutine called once at the end of execution. This could, for example, be a routine to generate diagnostics and/or graphics for data the user may have been accumulating in `USERDUMP`.

12. `PROBLEM`: This macro is used to link the user-supplied "problem generating" subroutine that initialises all flow variables and boundary values. It is called by the subroutine `setup`, which is called by `mstart`. Alternately, a number of problem generators for a variety of applications already exist in the source code. In the present example, `PROBLEM` is set to `shkset`, an existing problem generator which initialises the variables for a 1-D Riemann problem ("shock tube"); in this case, the so-called *Brio and Wu problem*.

13. `PROBLEMRESTART`: This macro allows the specifications of the problem to be altered should the job be restarted from a restart dump. Set the macro to `empty` if no alteration of the problem is desired (as, for example, to simply extend the evolution time).

14. `USERSOURCE`: See `SPECIAL`.

15. `ARTIFICIALVISC`: This macro specifies which artificial viscosity algorithm should be used. Current options are `viscous`, which uses the von-Neumann Richtmyer artificial viscosity algorithm, and `gasdiff` which invokes ordinary gas diffusion.

16. `DIFFUSION`: This macro specifies the subroutine to use to compute the diffusion coefficient for the two-fluid model. Currently, the only options are `empty` and `diffco`.

17. `USERDUMP`: This macro allows the user to link their own I/O routine if additional I/O capacity is needed other than what is currently available in `dataio` (1-D and 2-D plot files, pixel dumps, *HDF* files, time slice dumps, cork dumps, display files, *RADIO* dumps, and full-precision restart dumps, all created at user-set time intervals; §3).

It is unlikely that the "Error Criteria Aliases" or the "Iteration Limits Aliases" should ever have to be changed.

Finally, in addition to the aliases listed above is module name alias `ATMOSPHERE` called by problem generator `jetinit` which allows a user to specify their own routine to initialise an atmosphere through which a jet is launched. Existing atmosphere routines include `cloud` (to set up a jet-cloud collision) and `king`, which sets up a King atmosphere.

2.3 The script file `dzeus36.s`

Below is a copy of the script file `dzeus36.s` found in the `zeus` directory of the file `dzeus36.tar` downloaded from zeus3d.ca/zeus3d/version3.6. It can be run by typing: `csh -v dzeus36.s`.

```
#---+----1----+----2----+----3----+--+----3----+----2----+----1----+---#
#============== SCRIPT FILE TO CREATE THE ZEUS EXECUTABLE =============#
#                                                                      #
#                          B R I O W U . X 1                           #
#                                                                      #
#-----------------------------------------> Select FORTRAN compiler.
#  Supported compilers include:
#     cf77 (Cray), f90 (Sun), g95 (g95.org), gfortran (Gnu), ifort
#     (Intel), pgf77 (Portland Group), xlf (IBM)
#
setenv FCOMP gfortran
#======================================> Get files from home directory.
if(! -e ./xedit22) cp ../editor/xedit22 .
if(! -e ./dnamelist.a) cp ../nmlst/dnamelist.a .
if(! -e ./dsci01.a) cp ../sci/dsci01.a .
if(! -e ./grfx03.a) cp ../grfx/grfx03.a .
if(! -e ./psplot.a) cp ../grfx/psplot.a .
if(! -e ./noncar.a) cp ../grfx/noncar.a .
#======================> If necessary, create the directory "dzeus3.6".
if(! -e ./dzeus3.6) mkdir ./dzeus3.6
#-------------------------------------------> Create the change deck.
rm -f ./chgzeus
cat << EOF > ./chgzeus
*read zeus36.mac
*define $FCOMP
*d par.44,45
       parameter     (   in = 555,   jn =   1,   kn =   1 )
       parameter     ( nxpx =   1, nypx =   1, nxrd =   1, nyrd =   1 )
**read chguser
EOF
#======================> Create the input deck for EDITOR, and execute.
rm -f ./inedit
cat << EOF > ./inedit
 \$editpar   inname='dzeus36', chgdk='chgzeus', idump=1, job=3
          , ipre=1, inmlst=1, iupdate=1, iutask=0, safety=0.20
          , branch='dzeus3.6', xeq='xdzeus36', makename='makezeus'
          , compiler='$FCOMP'
c         , coptions='debug'
          , coptions='optimise'
c         , speccopt='-O0', specdk='corona','phistv','nmlsts','plot1d'
          , libs='checkin.o dnamelist.a dsci01.a grfx03.a psplot.a
  noncar.a'                                                          \$
c         , libs='checkin.o dnamelist.a dsci01.a grfx03.a psplot.a
c  noncar.a -L/usr/local/gcc-fortran/lib -ldf -ljpeg -lz -lsz'       \$
c         , libs='checkin.o dnamelist.a dsci01.a grfx03.a psplot.a
c -L/usr/local/gcc-fortran/lib -ldf -ljpeg -lz -lsz -L/opt/local/lib
c -lncarg -lncarg_gks -lncarg_c -lX11 -lcairo -lfreetype'           \$
EOF
chmod 755 ./xedit22
./xedit22
#-------------------------------------> Create the input deck for ZEUS.
rm -f ./inzeus
cat << EOF > ./inzeus
```

```
 \$iocon    iotty=6, iolog=2                                                \$
 \$rescon   dtdmp=0.0, idtag='xa', resfile='zr000xa'                        \$
 \$ggen1    nbl=550, x1min=0. ,x1max=550., igrid=1, x1rat=1.0, lgrid=.t.\$
 \$ggen2                                                                    \$
 \$ggen3                                                                    \$
 \$pcon     nlim= 999999, tlim=-80.0, ttotal=900.0, tsave=10.0              \$
 \$hycon    qcon=1.0, qlin=0.2, courno=0.75, iord=2, iords=3, istp=2
         , trnvrsn=1, itote=1                                             \$
 \$iib      niib(1,1)=9                                                     \$
 \$oib      noib(1,1)=9                                                     \$
 \$ijb                                                                      \$
 \$ojb                                                                      \$
 \$ikb                                                                      \$
 \$okb                                                                      \$
 \$grvcon                                                                   \$
 \$ambcon                                                                   \$
 \$eqos     gamma=2.0                                                       \$
 \$gcon                                                                     \$
 \$extcon                                                                   \$
 \$pl1con   dtpl1=80.0, pl1dir=1, corl=1, aspect=1.0, npl1h=2, npl1v=2
         , norppl1=2, pl1soln=12*1, xdiscpl1=200.0
         , pl1var= 'd ', 'se', 'p ', 'et', 'v1', 'v2', 'v3', 'mA'
                 , 'b1', 'b2', 'b3', 'bd'                                 \$
 \$pl2con                                                                   \$
 \$pixcon                                                                   \$
 \$usrcon                                                                   \$
 \$hdfcon                                                                   \$
 \$tslcon                                                                   \$
 \$crkcon                                                                   \$
 \$discon                                                                   \$
 \$radcon                                                                   \$
 \$pgen     idirect=1, n0=200, d0=1.000, e10=1.0, v10=0.0, b10=0.75
         , b20=0.6, b30=0.8                                               \$
 \$pgen     idirect=1, n0=350, d0=0.125, e10=0.1, v10=0.0, b10=0.75
         , b20=-0.6, b30=-0.8                                             \$
EOF
#============================================> MAKE the ZEUS executable.
make -f ./makezeus
#=================================================> Tidy up directory.
rm -f ./editlp ./inedit ./output ./xedit22 ./*.a
```

Note that a # in column 1 indicates a comment in a script file. In this example, two flavours of comment lines are used. Comments led with a double dashed line (=======>) indicate portions of the script file which rarely, if ever, need to be changed by the user. Comments with a single dashed line (-------->) indicate portions of the script file that will probably need to be changed with every simulation. Below are descriptions of the eight segments found in the script file `dzeus36.s`.

2.3.1 Select *FORTRAN* compiler

The first segment sets the environment variable `FCOMP` to the desired *FORTRAN* compiler (*e.g.*, `gfortran`). This may be one of the compilers already supported within `dzeus36` (`cf77`, `f90`, `g95`, `gfortran`, `ifort`, `pgf77`, `pgfortran`, or `xlf`), or to a compiler the user has introduced into `dzeus36`, as per the installation instructions `install_dz36.txt`.

2.3.2 Get files from home directory

The second segment retrieves the files necessary to create the *ZEUS-3D* executable and are retrieved only if they do not already exist on disc [`if (! -e` *filename*`)`]. This example assumes that the script file is launched from the directory `zeus` created when `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6 is unpacked. Files already in this directory and thus not retrieved include:

`dzeus36`	the nearly 130,000 lines of source code divided up into more than 450 subroutines
`zeus36.mac`	file containing all the *EDITOR* macros (§2.2)
`checkin.o`	the object file of the *C*-routine `checkin.c` (the only *C*-routine used by *ZEUS-3D*) which allows interrupt messages to be read from the terminal during interactive runs (§4)

while those retrieved from other directories include:

`xedit22`	the preprocessor executable
`dnamelist.a`	the double precision library of subroutines which emulate the *namelist* feature (§2.3.6)
`dsci01.a`	the double precision library of four specialised max-min subroutines
`grfx03.a`	library of subroutines calling routines in external graphics libraries (*NCAR* and *PSPLOT*)
`psplot.a`	library of routines for *PSPLOT* graphics
`noncar.a`	library of dummy *NCAR* routines used when *NCAR* graphics are not installed at the site

2.3.3 If necessary, create the directory `dzeus3.6`

The third segment creates the directory `dzeus3.6` provided it doesn't already exist. The precompiled source files (one subroutine per file) and the compiled object files are put here.

2.3.4 Create the change deck

The fourth segment creates the change deck `chgzeus` which is merged with the source code `dzeus36` during the preprocessing step. The first line in `chgzeus` reads the *EDITOR* macros in `zeus36.mac` using the *EDITOR* command `*read`. This command replaces the statement with the contents of the named file. Thus, the macros in `zeus36.mac` become part of the change deck `chgzeus`, and get merged with the source code.

The second line uses the environment variable set in the first segment to set the appropriate *EDITOR FORTRAN* macro.

The third line is the *EDITOR* `*delete` (or `*d`) command used to replace lines 44 and 45 in the common deck `par` in the main source code `dzeus36` with the two following parameter statements which set the parameters to the desired values for the simulation. This is where the user should indicate the size of the arrays required for the simulation to be performed. These include `in`, `jn`, and `kn`, which set the dimensions of the 3-D "field variables" (density, velocity, *etc.*; §C.2), and `nxpx`, `nypx`, `nxrd`, and `nyrd`, which set the dimensions of arrays

used by the two types of output to create animations (`pixel` and `radio` dumps; §3.4 and §3.9). These and other parameters used by the code are described in §C.6.

And while we're on the subject of array parameters, as the dimensions for the primary arrays used by *ZEUS-3D*, `in`, `jn`, and `kn` are the principle determinators of memory requirement of a particular run. For a 3-D, single-fluid, non-isothermal MHD run with no self-gravity, radiative transport, *etc.*, the memory occupancy of a run is about $21 \times \texttt{in} \times \texttt{jn} \times \texttt{kn} \times 8$ bytes. This includes all field variables, scratch arrays, and the assortment of 2-D boundary arrays required by the run. For an HD run (`MHD` not defined), replace the 21 with a 17. Obviously, defining `GRAV` or any other feature that adds or subtracts a 3-D array to the mix would have the commensurate affect on memory occupancy.

Finally, should the user have their own changes to the code, these can be most conveniently put into a file called `chguser`, for example, and the statement `**read chguser` would then be "de-commented" by deleting one of the asterisks. This will ensure that the user's changes will be incorporated just like those in `zeus36.mac` and the two parameter statements discussed above. Changes should be specified using the language of *EDITOR* (code prepared for the old CTSS precompiler *HISTORIAN* can be processed by *EDITOR*), and would include additional subroutines such as the problem generator which need to be compiled with the rest of the source code. Full description of how to do this is found in §5.

2.3.5 Create the input deck for *EDITOR*, and execute

The fifth segment creates the input deck for the preprocessor *EDITOR* and then fires it up. Changes to this segment should be needed rarely. If it becomes necessary to change the name of the main source file from `dzeus36`, or to change the name of the change deck from `chgzeus`, or to change the name of the directory created for the precompiled and compiled subroutine files from `dzeus3.6`, or to change the name of the makefile from `makezeus`, or to change the name of the *ZEUS-3D* executable from `xdzeus36`, or to specify compiler options other than the default "debug" or "optimise" settings, these changes should be made in the *EDITOR* input deck `inedit`.

On the latter, by setting `coptions='optimise'`, *EDITOR* will insert the appropriate compiler options for the selected compiler (`FCOMP`) so long as the selected compiler is one of the eight compilers supported by *EDITOR*[5]. Similarly if `coptions='debug'`, the appropriate debugging compiler options are set including array size and over-flow checking. For any other compiler, the user will have to set `coptions` explicitly. Similarly, loader options can be specified in `loptions`.

On occasion and depending on the compiler, a few subroutines can cause a run to generate significantly different results when compiled with full optimisation than with little or no optimisation [often traceable to exponentiation (`**`)]. For example, Sun's old `f77` compiler generated errant object code when compiling the routines `corona`, `phistv`, and `couette` with full optimisation. Other routines, such as `plot1d`, `plot2d`, and `nmlsts` compiled correctly, but took forever to optimise. For such occasions, *EDITOR* allows one to specify troublesome routines in `specdk` (a 1-D character*8 array) and the special compiler options to be used for these routines in `speccopt`. Thus, "de-commenting" the line:

[5] At the time of the writing, this list is the same as those supported by `dzeus36`, namely `cf77`, `f90`, `g95`, `gfortran`, `ifort`, `pgf77`, `pgfortran`, and `xlf`.

```
c         , speccopt='-O0', specdk='corona','phistv','nmlsts','plot1d'
```

in the sample file `dzeus36.s` above would apply no optimistation (`-O0`) to the four routines listed, and full optimisation (`-O2`) to the rest. For additional details, the reader is referred to the `EDITOR` user manual: `edit22_man.ps`.

For parallel processing at the do-loop level, set `iutask` (second line of the namelist `editpar`) to 1 for Cray *microtasking*, or 2 for *OpenMP*. This will cause *EDITOR* to insert the appropriate *scoping* commands at the beginning of the major do-loops in the code. One then has to set the appropriate compiler options for your compiler to compile the code for multiple processors. If the user is using *OpenMP* and one of the eight supported compilers, one can set `coptions='openmp'` to let *EDITOR* set the appropriate compiler options.

Libraries are specified by setting `libs`, of which three examples are given in the sample file `dzeus36.s` above. The first and uncommented setting of `libs` requires only libraries included in `dzeus36.tar` (from zeus3d.ca/zeus3d/version3.6); no systems or third-party libraries such as *NCAR* (for graphics, *e.g.*, §3.2, §3.3) or *HDF* (§3.5) are required. By virtue of the *PSPLOT* library, publication-quality and full-colour graphics are possible without *NCAR* (originally, the only graphics capability *ZEUS* possessed). The second `libs` command (commented out) is the variation used at the ICA for *HDF* libraries, while the third (also commented out) is when both *HDF* and *NCAR* are linked. Additional libraries may be linked by appending them to whatever `libs` list is used. Note that lines "commented out" in a namelist are echoed on the CRT as the input deck is read, which is a feature of the *EDITOR* `namelist`. (See §2.3.6 and App. B for a discussion of the *EDITOR* `namelist` feature.)

With this input deck, the preprocessor will merge the change deck `chgzeus` with `dzeus36`, carry out the precompiler commands according to the aliases and definitions in the macro file `zeus36.mac`, split up the precompiled source code (now containing nothing but *FORTRAN* syntax) into separate files for each subroutine, search the directory `dzeus3.6` and write to disc only those files which do not already exist or have been changed, and finally create the makefile `makezeus`, described in §2.3.7.

2.3.6 Create the input deck for *ZEUS*

The sixth segment is where the input deck for the *ZEUS-3D* executable is created (`inzeus`) and so the user should set all input parameters here (described fully in App. B). In this example, `inzeus` is set up for the 1-D MHD Brio and Wu shock tube problem. *ZEUS-3D* uses namelists to specify input parameters but does not use the standard `namelist` utility. Historically, the first versions of `namelist` available under *UNICOS* were horrid (character variables could not be set, vectors could only be set one element at a time, error messages were unreadable), and so a more useful `namelist` utility was incorporated into the preprocessor *EDITOR*. Thus, as one of its duties, *EDITOR* can be instructed (`inmlst=1`) to replace all references to namelists with calls to subroutines found in the library `dnamelist.a` which is linked to the executable during the *MAKE* process. This step is entirely transparent to the user. Namelists can be used as always, with the usual (more or less) syntax, bearing in mind that once defined, a namelist must be read before the next namelist is defined. Since this time, `namelist` has become a standard feature of Fortran90 and has been significantly

improved. Should the user prefer to use the `namelist` utility of the local OS, then the input parameter `inmlst` in the *EDITOR* input deck `inedit` should be set to 0 (§2.3.5). Be warned that doing this may make some of the namelists in the `dzeus36.s` (`inzeus`) file unreadable and generate run-time error messages. Syntactic errors may even arise during compilation.

One major difference between the Fortran90 `namelist` and the *EDITOR* `namelist` is the latter allows for rank 2 arrays to be specified in an extremely intuitive fashion. For example, to set `((diib1(i,j),i=20,30),j=70,80)` to 1.0, while setting the rest of the 100 by 100 array to 0.1, one merely needs to type:

```
diib1(1:100,1:100)=0.1, diib1(20:30,70:80)=1.0
```

where the order is important. This capacity is not supported by Fortran90, and so some of the `namelist` syntax will have to be changed in the input decks `inzeus` and `inedit` should the user wish to use the standard `namelist`. If using the `EDITOR namelist` feature, remember not to allow any of the namelist lines to extend beyond the 72nd column. The first column in each line can be a blank or a 'c' (to comment out the line) and nothing else. The second column may contain a blank or a '$' and nothing else. (Note that because `dzeus36.s` is a script file, the $ must be "protected" by a \. Otherwise, the script file will try to interpret the $ as a control character rather than treating it as a character to be written to a disc file. The user will note that a \ does not precede the $ in the input deck `inzeus` once it is written to disc by `dzeus36.s`.) Text specifying the input parameters may start in column 3. If a character string is too long to fit in the 72 column format, one simply types as much as one can in the first line (*i.e.*, up to and including the 72nd column), then resumes typing the character string on the next line, beginning in column 3. A single quote must appear before the first character in the first line of the character string and after the last character in the last line of the character string only.

A detailed description of all the namelist parameters is contained in App. B.

2.3.7 Make the *ZEUS* executable

The seventh segment fires up the makefile `makezeus` created by the preprocessor *EDITOR*. The makefile will compile only those *FORTRAN* files in the directory `dzeus3.6` which have been written since the last time they were compiled, then link all the object files together with the specified libraries to create the executable `xdzeus36`.

2.3.8 Tidy up directory

The eighth and final segment deletes the temporary files no longer needed.

2.4 Executing *ZEUS-3D*

Once the script file has completed successfully, simply type `xdzeus36` followed by a carriage return, and *ZEUS-3D* will begin running. In general, one can move the two files `xdzeus36` and `inzeus` to any other directory and the executable can be launched from that directory simply by typing `xdzeus36`, followed by a carriage return (enter).

Alternatively, one can run *ZEUS-3D* in batch mode, and for this the user should consult their systems administrator as batch facilities are highly system and installation dependent.

3 Output from *ZEUS-3D*

A variety of methods for dumping data to disc during execution are available in *ZEUS-3D*. Each of these methods has their specific use, and at times all types are used simultaneously. In this section, a brief description of each method is given, along with a list of the most vital statistics. These include: the *EDITOR* definition (if any) which enables the data dump, the logical unit to which the dumps are attached during execution, the namelist which controls the data dump (App. B), the convention used for naming the disc file for this type of data dump, and the format of the data in the disc file created.

3.1 Restart dumps

These are full precision dumps of all flow variables at specified time intervals suitable for resuming a simulation. Execution can be instructed to overwrite the previous even (odd) numbered dump with the new even (odd) numbered dump should disc space be limited. Thus, only two restart dumps would exist at any one time. For MHD runs, the size of a restart dump is about $10 \times$ `in` $\times$ `jn` $\times$ `kn` words, while for HD runs, $6.5 \times$ `in` $\times$ `jn` $\times$ `kn` words.

The first data written to a restart dump are the array dimensions and parameters that indicate which *EDITOR* macros are defined. Values of *EDITOR* aliases are not stored. These, then, are the first data read from a restart dump and are used to allow a restart dump to be read regardless of the differences between the array dimensions and *EDITOR* definition settings in the new executable (that which is reading the restart dump) and the old executable (that which created the restart dump). Thus, it is possible to resume an MHD run without the `MHD` definition set (and thus resume the calculation hydrodynamically), to read the inner eighth of a 64^3 data volume into any part of a new 128^3 grid, *etc.*

EDITOR definition:	none
logical unit:	`iodmp`
namelist:	`rescon`
filename:	`zr`*nnn*`id`, where `zr` is the common prefix to all restart dumps, *nnn* is a three digit integer distinguishing the multiple dumps created during a run, and `id` is a two character, user-specified problem tag.
format:	binary, one word (8 bytes) per datum

3.2 1-D plot files

These are metacode (*NCAR*) or postscript (*PSPLOT*) files containing publication-quality 1-D plots for every variable selected. A separate file is created for each slice specified.

EDITOR definition:	`PLT1D`
logical unit:	`iopl1`
namelist:	`pl1con`
filename:	`zp`*nnn*`id`.*mm*, where `zp` is the common prefix to all 1-D plot files, *nnn* and `id` are as defined for restart dumps, and *mm* is an extension indicating the slice number. For *PSPLOT*, the suffix `.ps` is added to the filename.

format:	metacode—use `idt` to read *NCAR*-generated metafiles postscript—use `mgv`/`gv` to read *PSPLOT*-generated postscript files

If, after the run is complete, the user needs 1-D plots of variables that were not selected before execution, these can be created after the run using the stand-alone ancillary program *PLOTZ*, provided the user has created a total HDF dump at or near the desired problem time. See the *User Manual for ZEUS Ancillaries* found in the `manuals` directory of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6 for details.

3.3 2-D plot files

These are metacode (*NCAR*) or postscript (*PSPLOT*) files containing publication-quality 2-D plots of a user-specified combination of variables (colour contours, line contours, and/or vectors) using the so-called *buffet-style plotting* introduced in this version (§B.20). A separate file is created for each slice specified.

EDITOR definition:	`PLT2D`
logical unit:	`iopl2`
namelist:	`pl2con`
filename:	`zq`*nnn*`id`.*mm*, where `zq` is the common prefix to all 2-D plot files, *nnn* and `id` are as defined for restart dumps, and *mm* is an extension indicating the slice number. For *PSPLOT*, the suffix `.ps` is added to the filename.
format:	metacode—use `idt` to read *NCAR*-generated metafiles postscript—use `mgv`/`gv` to read *PSPLOT*-generated postscript files

See the note at the end of §3.2 if, after the run is complete, the user needs 2-D plots of variables that were not selected before execution.

3.4 Pixel dumps/movie frames

These are "binned" 2-D slices through the data volume of a single variable designed for animation. Files are written in one, two, or all three of three formats: `real*4` "movie" (**new to version 3.6**); Mike Norman's `char*1` "pixel dumps"; and *HDF4*.

Movie frames (`pixfmt=1`, default) are 4-byte unformatted files written with a header that includes grid dimensions, grid, and data extrema. If this format is selected then, at the end of the run, they are automatically converted to PPM format then assembled into an `mpeg` file assuming `FFmpeg` (`ffmpeg.org`) is available on the user's platform. The PPM files may then be deleted, and the original `real*4` movie frames are assembled into a compressed tarball which can be used by the stand-alone ancillary program *ANIM8Z* to re-render the animation if the bracketing was not chosen to the user's satisfaction.

Pixel dumps (`pixfmt=2`) are unformatted files just *one* byte deep (one ascii character per datum) and include no header whatever, not even array dimensions. These were designed for use with Carol Song's `IMAGETOOL`, long since abandoned by the NCSA. To render these into an animation, one has to convert each to a PPM file (*e.g.*, Dave Lane's `RAW2PPM`) and then assemble the PPM files into an `mpeg` using `FFmpeg`.

In either movie or pixel format, polar plots are rebinned to a Cartesian plane, then dumped as a regular movie frame or pixel plot. Both formats are designed to create animations, though with the passage of `IMAGETOOL`, the movie frames are more straight-forward to use. Multiple slices per variable may be requested so that the number of animations per run can be substantial (*e.g.*, four slices of six variable means 24 animations).

Finally, *HDF4* files are written for `pixfmt=3`.

EDITOR definition:	`PIX`
logical unit:	`iopix`
namelist:	`pixcon`
filename	`zi**`*nnn*`id.`*mm*`{.f}`, where `zi` is the common prefix to all *image* frames, `**` is a two-character representation of the variable (see Table 3.1 in §3.12), *nnn* and `id` are as defined for restart dumps, *mm* is an extension indicating the slice number, and `f` is one of `m` for movie format (`pixfmt=1`), blank for pixel format (`pixfmt=2`), or `h` for *HDF4* (`pixfmt=3`). On exit, movie files (`pixfmt=1`) are converted to PPM, used to create an mpeg file `zi**id.`*mm*`.mpg`, and assembled in a tarball `zi**id.`*mm*`.tar.gz`.
format:	`pixfmt=1`: unformatted, four bytes per datum plus header `pixfmt=2`: unformatted, one byte per datum, no header `pixfmt=3`: *HDF4*

3.5 *HDF4* files

HDF4 (Hierarchical Data Format; version 4) files contain 3-D data of one or more variables in the *HDF* format developed at the NCSA. The data are written in four byte words which is adequate for quantitative graphical study but not for checkpointing (see §3.1). All graphical software packages from the NCSA use this format for data dumps, as do many other commercially available products (*e.g.*, IDL). *HDF* files contain header information which include array dimensions, data extrema, and grid coordinates. The size of an *HDF* file containing a single variable is a little more than the number of active zones (*e.g.*, `n1xz`, `n2xz`, `n3xz`, and not `in`, `jn`, `kn`; see §C.1), times 4 bytes. For a "total" dump (all primary variables to the same *HDF* file) with none of `GRAV`, `PSGRAV`, or `TWOFLUID` defined, the size is the number of active zones times 32 bytes for MHD runs, or times 20 bytes for HD runs.

EDITOR definition:	`HDF`
logical unit:	none
namelist:	`hdfcon`
filename:	`zh**`*nnn*`id`, where `zh` is the common prefix to all *HDF* files, `**`, *nnn*, and `id` are as defined for pixel dumps.
format:	*HDF4*, four bytes per datum

If, after the run is complete, the user needs 1-D, 2-D, or *RADIO* dumps that were not created during the simulation, these can be created after the run using the stand-alone ancillary programs *PLOTZ* and *RADIO*, which use HDF "total dumps" as input (see §B.23). For this reason, it is recommended that HDF total dumps be created at least as often as 1-D

and 2-D plots and, if disc space is not a problem, as often as *RADIO* dumps. See the *User Manual for ZEUS Ancillaries* found in the `manuals` directory of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6 for details on how to install and use *PLOTZ* and *RADIO*.

3.6 Time slice dumpfiles

There are two types of time slice dumps, and either, both, or neither may be selected. The first is a single ascii file which contains values of various scalars at specified time intervals such as the total mass, angular momenta, magnetic monopoles, energy, *etc.*, as well as extrema of quantities such as density, pressure, divergence of magnetic field, *etc.* The second is a plot file (metacode or postscript) containing 1-D plots of these scalars as a function of time. The user selects the time interval for the ascii and plot dumps independently.

EDITOR definition:	`TIMESL`
logical units:	`iotsl` and `iotsp`
namelist:	`tslcon`
filenames:	`zt`*nnn*`id` (ascii file), where `zt` is the common prefix to all time slice ascii files, *nnn* and `id` are as defined for restart dumps. `ztp`*nnn*`id` (plot file), where `ztp` is the common prefix to all time slice plots.
formats:	ascii and metacode/postscript

3.7 Cork dumpfiles

New to version 3.6, one can specify a set of Lagrangian (tracer) particles scattered throughout the grid at $t = 0$ as well request others to be injected onto the grid at specified time intervals. These particles (*a.k.a.* "corks") are completely passive in nature, and gather user-specified information about their local conditions as the simulation progresses. At each time step where cork information is dumped, a single line of data for each cork is appended to an accumulating ascii file which can be used by the user for post-processing to display the data as desired. In addition, the location of the corks (but not their accumulated data) may be added to the 2-D *NCAR*/*PSPLOT* files.

EDITOR definition:	`CORKS`
logical unit:	`iocrk`
namelist:	`crkcon`
filename:	`zc`*nnn*`id`, where `zc` is the common prefix to all cork files, *nnn* and `id` are as defined for restart dumps.
format:	ascii

3.8 Display dumpfiles

Display dumps are single ascii files (maximum of 80 characters per line) which contains a quantitative display (matrix format) of a specified portion of various 2-D slices through any of many variables at evenly spaced time slices during a simulation. The data are scaled and converted to integers before being written to the ascii file. The dynamic range of the scaled

data depends on the specified "width" of the field of view (no more than 38), and ranges from 10^2 to 10^6. For very small widths (≤ 8), the data are not scaled and written as real numbers, with three or four significant figures. This utility is much like `PRTIM` in *AIPS*, for those familiar with the Astronomical Image Processing System. Its primary use is in debugging, or when one needs to view a small portion of data quantitatively and simultaneously.

EDITOR definition:	`DISP`
logical unit:	`iodis`
namelist:	`discon`
filename:	`zd`*nnn*`id`, where `zd` is the common prefix to all display files, *nnn* and `id` are as defined for restart dumps.
format:	ascii

3.9 *RADIO* dumps

RADIO[6] dumps are similar to the pixel dumps/movie frames (§3.4), but contain line-of-sight integrations of various quantities rather than 2-D slices through the data volume. In this release, *RADIO* dumps are possible in both Cartesian (`XYZ`) and cylindrical (`ZRP`) coordinates, though the latter are not fully tested. The integrands include all three Stokes parameters and numerous other scalars (*e.g.*, density, Mach numbers, bremsstrahlung, *etc.*) and are integrated using a very fast binning algorithm that is as much as 50 times faster than traditional direct ray-tracing algorithms.

As with pixel/movie files, `RADIO` files may be written in one, two, or all three of three formats: `real*4` "movie frame" (`radfmt=1`, **new to version 3.6**); Mike Norman's `char*1` "pixel dumps" (`radfmt=2`); and *HDF4* (`radfmt=3`), with the latter suitable for graphical analysis if desired.

EDITOR definition:	`RADIO`
logical unit:	`iorad`
namelist:	`radcon`
filename:	`zR**`*nnn*`id{.f}`, where `zR` is the common prefix to all *RADIO* dumps, and where `**`, *nnn*, `id`, and `f` are as defined for pixel dumps (§3.4). On exit, movie files (`radfmt=1`) are converted to PPM, used to create a movie file `zR**id`.*mm*`.mpg`, and assembled in a tarball `zR**id`.*mm*`.tar.gz`.
format:	`radfmt=1`: unformatted, four bytes per datum plus header `radfmt=2`: unformatted, one byte per datum, no header `radfmt=3`: *HDF4*

If, after the run is complete, the user needs *RADIO* dumps at different vantage points than selected before execution and/or animations of certain stills rotating about an axis, these can be created after the run using the stand-alone ancillary program *RADIO*, provided

[6]The original post-processing program, *RADIO*, was designed to take line-of-sight integrations through an MHD datacube to compute the Stokes parameters, and thus mimic *radio* observations from telescopes such as the VLA, whence the name.

the user has created a total HDF dump at or near the desired problem time. See the *User Manual for ZEUS Ancillaries* found in the `manuals` directory of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6 for details.

3.10 Message log files

The message log file contains all the messages that are written to the terminal by the code during execution. In addition, the grid and all the values of the namelist parameters specified in the file `inzeus` are dumped here. It serves as the log for the execution.

EDITOR definition:	none
logical unit:	`iolog`
namelist:	`none`
filename:	`zl`*nnn*`id`, where `zl` is the common prefix to all log files, *nnn* and `id` are as defined for restart dumps.
format:	ascii

3.11 Userdump

`USERDUMP` is an *EDITOR* alias available for the user to include their own special type of I/O which may be desired in addition to those currently available. See §5 for details on how to add subroutines to the code.

EDITOR definition:	none
logical unit:	`iousr`
namelist:	`usrcon`
filename:	`zu`*nnn*`id`, where `zu` is the common prefix to all user dump files, *nnn* and `id` are as defined for restart dumps.
format:	

3.12 Recognised plotting variables

Table 3.1 below and continued on the following page lists the two-character variable representations [corresponding to the double asterisks (`**`) used in §3.4, §3.5, and §3.9 above] used for generating the filenames for pixel (P), *HDF* (H), and *RADIO* (R) dumps. These two-character representations are identical to those used to specify the variables to be dumped (see `pixvar` in namelist `pixcon`, `hdfvar` in namelist `hdfcon`, and `radvar` in namelist `radcon`, App. B) with the exception that variables specified by a single character (*e.g.*, `d`) appear with a trailing underscore (*e.g.*, `d_`) in the dump file name. The third column indicates the I/O types in which the variable may be dumped.

Table 3.1 Two Character Variable Representations

**	Variable	Dumps	**	Variable	Dumps
a_	vector potential norm	PH	p2	magnetic pressure	PH
a1	1-vector potential	PH	p3	1st thermal + mag. pres.	PH
a2	2-vector potential	PH	p4	2nd thermal pressure	PH
a3	3-vector potential	PH	p5	1st + 2nd thermal pres.	PH
ag	synchrotron age	PH	p6	2nd thermal + mag. pres.	PH
an	normal vector pot.	P	p7	1st + 2nd + mag. pres.	PH
ap	poloidal vector pot.	P	pa	pitch angle; $\tan^{-1}(B_1/B_\phi)$	P
b_	magnetic field norm	PH	pg	pseudo-grav. potential	PH
b1	1-magnetic field	PH	s1	1-momentum	PH
b2	2-magnetic field	PH	s2	2-momentum	PH
b3	3-magnetic field	PH	s3	3-momentum	PH
bP	ϕ-magnetic field	P	sd	skew-density	P
bR	radial magnetic field	P	sn	normal momentum	P
bn	normal magnetic field	P	sp	poloidal momentum	P
bp	poloidal magnetic field	P	sy	synchrotron emissivity	P
bt	plasma beta = $2p/B^2$	PH	to	all field arrays	H
cs	sound speed	P	u1	1st specific int. energy	PH
d_	density	PH	u2	2nd specific int. energy	PH
da	synchrotron density-age	PH	v_	velocity norm (speed)	PH
e1	first internal energy	PH	v1	1-velocity	PH
e2	second internal energy	PH	v2	2-velocity	PH
er	radiation energy density	PH	v3	3-velocity	PH
et	total energy density	PH	vA	Alfvén speed	P
fn	normal flux function	P	vf	fast magnetosonic speed	P
gp	gravitational potential	PH	vn	normal velocity	P
j_	current density norm	PH	vp	poloidal velocity	P
j1	1-current density	PH	vs	slow magnetosonic speed	P
j2	2-current density	PH	vv	$\nabla \cdot \vec{v}$	PH
j3	3-current density	PH	w_	vorticity norm	PH
jn	normal current density	P	w1	1-vorticity	PH
jp	poloidal current density	P	w2	2-vorticity	PH
k1	first specific entropy	PH	w3	3-vorticity	PH
k2	second specific entropy	PH	wn	normal vorticity	P
ka	averaged specific entropy	PH	wp	poloidal vorticity	P
lu	radiative luminosity	PH	A_	pol'n position angle	R
m_	Mach number	PH	AV	A with pol'n vectors	R
ma	Alfvénic Mach number	PH	B_	magnetic field strength	R
mf	fast magnetosonic number	PH	BR	bremsstrahlung	R
ms	slow magnetosonic number	PH	D_	density	R
nb	break frequency	P	E1	1st internal energy	R
p1	1st thermal pressure	PH	F_	fractional pol'n	R

Table 3.1, continued. Two Character Variable Representations

**	Variable	Dumps	**	Variable	Dumps
FV	F with pol'n vectors	R	P_	polarised intensity	R
I_	total intensity	R	PV	P with pol'n vectors	R
IV	I with pol'n vectors	R	SH	scalar velocity shear	R
M_	Mach number	R	U1	1st specific int. energy	R
MA	Alfvénic Mach number	R	V_	pol'n vectors (black)	R
MF	fast magnetosonic num.	R	VR	pol'n vectors (white)	R
MS	slow magnetosonic num.	R	VV	$\nabla \cdot \vec{v}$	R

4 Interacting with *ZEUS-3D*

During an interactive execution (as opposed to batch), the user may probe *ZEUS-3D* for its status, change select input parameters, and submit instructions to create a dump, stop, pause, resume, *etc.* This is done by typing a recognised three-character "interrupt message" followed by a carriage return. Once every "time step", *ZEUS-3D* "glances" at the terminal buffer (by virtue of the lone *C* routine `checkin.c` introduced in §2.3.2). If an interrupt message has been entered, *ZEUS-3D* will carry out the instruction. If no interrupt message is found, execution proceeds without pause. Below is a list of the interrupt messages recognised by *ZEUS-3D*, along with a brief description of their function. Only the first three characters of each command (those in `typewriter` font) need be entered. Note that there are several synonyms for a number of the commands, which are separated by commas.

On some batch systems, having the code checking the terminal buffer can interfere with execution. In this icase, one can turn this feature off by setting `intractv=0` in namelist `iocon` (App. B).

Controlling execution:

- `tim`e, `cycle`, `status`, `t`, `n`, `?`
  prints a time and cycle report, then resumes execution
- `quit`, `abort`, `cra`sh, `bre`ak
  immediate emergency termination, no final dumps are made
- `stop`, `end`, `exit`, `fin`ish, `ter`minate
  clean stop—all final dumps are made
- `halt`, `pause`, `wait`, `int`errupt
  halt execution and wait for a message from the crt or controller.
- `res`tart, `go`
  restarts execution after a halt
- `tlimit`, `tfinish` (followed by a real number)
  resets the physical (problem) time limit (when computation will stop)
- `nlimit`, `nfinish` (followed by an integer)
  resets the cycle limit
- `ttot`al, `tcpu` (followed by an integer number of seconds)
  resets maximum cpu time to consume.
- `tsa`ve, `tre`serve (followed by an integer number of seconds)
  resets the save time reserved for cleanup and termination

Controlling data output:

- `dump`
  creates a restart dump at current time

- `dtdmp` (followed by a real time interval)
  resets the problem time interval between restart dumps
- `pl1`
  creates a 1-D plot at current time
- `dt1` (followed by a real time interval)
  resets the problem time interval between 1-D plots
- `pl2`
  creates a 2-D plot at current time
- `dt2` (followed by a real time interval)
  resets the problem time interval between 2-D plots
- `pixel`
  creates a pixel dump at current time
- `dtpix` (followed by a real time interval)
  resets the problem time between pixel dumps
- `usr`
  creates a user dump (calls `USERDUMP`) at current time
- `dtusr` (followed by a real time interval)
  resets the problem time between user dumps
- `hdf`
  creates an *HDF* dump at current time
- `dth` (followed by a real time interval)
  resets the problem time between *HDF* dumps
- `tslice`
  adds a time slice dump at current time to time slice file
- `dttslice` (followed by a real time interval)
  > 0 $\Rightarrow$ resets the problem time between time slice ascii dumps
  < 0 $\Rightarrow$ resets the problem time between time slice plot dumps
- `display`
  adds a display dump at current time to display dump file
- `dty` (followed by a real time interval)
  resets the problem time between display dumps
- `radio`
  creates a radio dump at current time
- `dtradio` (followed by a real time interval)
  resets the problem time between radio dumps
- `corks`
  creates a cork dump at current time

- `dtc`orks (followed by a real time interval)
  resets the problem time between cork dumps
- `1dd`iagnostics
  creates a 1-D diagnostic dump at current time (for programmers only)
- `1dt` (followed by a real time interval)
  resets the problem time between 1-D diagnostic dumps
- `2dd`iagnostics
  creates a 2-D diagnostic dump at current time (for programmers only)
- `2dt` (followed by a real time interval)
  resets the problem time between 2-D diagnostic dumps

5 Adding source code to *ZEUS-3D*

5.1 Adding an entire subroutine

Adding source code to the *ZEUS-3D* package is not as difficult as one might think, especially if all one wants to do is add new subroutines or replace existing ones. Below is the subroutine `myprob` which can be used as a template to create a problem generator. A soft copy of `myprob` may be found in the `zeus` directory of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6. The style is that which is used for all subroutines currently in `dzeus36`.

```
*insert zeus3d.9999
*deck myprob
c=======================================================================
c
c    \\\\\\\\\\      B E G I N   S U B R O U T I N E      //////////
c    //////////                M Y P R O B                \\\\\\\\\\
c
c=======================================================================
c
       subroutine myprob
c
c    abcd:zeus3d.myprob <----------------------- initialises my problem
c                                                      september, 1990
c
c    written by: A Busy Code Developer
c    modified 1: July, 2006 by ABCD; updated for dzeus35
c    modified 2: October, 2010 by ABCD; updated for dzeus36
c    modified 3: November, 2014 by ABCD; added div(B) check.
c
c  PURPOSE:  Initialises all the flow variables for my problem.  More
c  description of my problem can go here.  Boundary values are set in
c  the calling routine immediately after MYPROB is called.
c
c  INPUT VARIABLES:
c
c  OUTPUT VARIABLES:
c
c  LOCAL VARIABLES:
c
c  EXTERNALS:
c    DIVERG
c
c-----------------------------------------------------------------------
*call comvar
c
       integer       i       , j       , k
       real*8        da      , db      , e1a     , e1b     , e2a
     1             , e2b     , v1a     , v1b     , v2a     , v2b
     2             , v3a     , b1a     , b1b     , b2a     , v3b
     3             , b2b     , b3a     , b3b     , sumdivb
*if def,MHD
     4             , q11     , q12     , q2      , q3
*endif MHD
c
c      The 1-D and 2-D arrays "array1d" and "array2d" are never used and
c  are included only to show how arrays can be declared and equivalenced
c  to "global worker arrays".  The 3-D array "divb" is used at the end
```

```
c  of the template to check on whether the magnetic field as set up
c  satisfies the solenoidal condition.
c
       real*8        array1d (ijkx)
       real*8        array2d (idim,jdim)
       real*8        divb    (  in,  jn,  kn)
c
       equivalence   ( array1d , wa1d     )
       equivalence   ( array2d , wa2d     )
       equivalence   ( divb    , wa3d     )
c
       external      diverg
c
c-----------------------------------------------------------------------
c
c  Input parameters:
c
c    da , db    array and boundary values for density
c    e1a, e1b   array and boundary values for first  internal energy
c    e2a, e2b   array and boundary values for second internal energy
c    v1a, v1b   array and boundary values for 1-velocity
c    v2a, v2b   array and boundary values for 2-velocity
c    v3a, v3b   array and boundary values for 3-velocity
c    b1a, b1b   array and boundary values for 1-magnetic field
c    b2a, b2b   array and boundary values for 2-magnetic field
c    b3a, b3b   array and boundary values for 3-magnetic field
c
       namelist / pgen     /
     1               da      , db      , e1a     , e1b     , e2a
     2             , e2b     , v1a     , v1b     , v2a     , v2b
     3             , v3a     , b1a     , b1b     , b2a     , b2b
     4             , b3a     , b3b
c
c      Default values
c
       da  = 1.0d0
       db  = 0.1d0
       e1a = 0.9d0
       e1b = 0.9d0
       e2a = 0.0d0
       e2b = 0.0d0
       v1a = 0.0d0
       v1b = 0.0d0
       v2a = 0.0d0
       v2b = 0.0d0
       v3a = 0.0d0
       v3b = 0.0d0
       b1a = 0.0d0
       b1b = 0.0d0
       b2a = 0.0d0
       b2b = 0.0d0
       b3a = 0.0d0
       b3b = 0.0d0
c
c      Read namelist pgen, and store contents to log file.
c
       read  (ioin , pgen)
       write (iolog, pgen)
c
```

```
c      Set field arrays.  Metric factors in the magnetic field settings
c  are necessary to preserve the solenoidal condition.
c
       do 30 k=ksm2,kep3
         do 20 j=jsm2,jep3
           do 10 i=ism2,iep3
             d (i,j,k) = da
             v1(i,j,k) = v1a
             v2(i,j,k) = v2a
             v3(i,j,k) = v3a
*if -def,ISO
             e1(i,j,k) = e1a
*endif -ISO
*if def,TWOFLUID
             e2(i,j,k) = e2a
*endif TWOFLUID
*if def,MHD
             b1(i,j,k) = b1a
             b2(i,j,k) = b2a
             b3(i,j,k) = b3a
*endif MHD
10         continue
20       continue
30     continue
*if -def,ISYM
c
c      Set inflow boundary arrays.  Setting niib=10 imposes inflow
c  boundary conditions, for which quantities such as diib1, etc., set
c  the desired inflow variable values.
c
*if def,MHD
       q11 = ( v2b * b3b - v3b * b2b ) * dx1a(ism1)
       q12 = ( v2b * b3b - v3b * b2b ) * dx1a(ism2)
       q2  = ( v3b * b1b - v1b * b3b ) * h2a (is  )
       q3  = ( v1b * b2b - v2b * b1b ) * h31a(is  )
*endif MHD
       do 50 k=ksm2,kep3
         do 40 j=jsm2,jep3
           niib    (j,k) = 10
           diib1   (j,k) = db
           diib2   (j,k) = db
           v1iib1  (j,k) = v1b
           v1iib2  (j,k) = v1b
           v1iib3  (j,k) = v1b
           v2iib1  (j,k) = v2b
           v2iib2  (j,k) = v2b
           v3iib1  (j,k) = v2b
           v3iib2  (j,k) = v2b
*if -def,ISO
           e1iib1  (j,k) = e1b
           e1iib2  (j,k) = e1b
*endif -ISO
*if def,TWOFLUID
           e2iib1  (j,k) = e2b
           e2iib2  (j,k) = e2b
*endif TWOFLUID
*if def,MHD
           b2iib1  (j,k) = b2b
           b2iib2  (j,k) = b2b
```

```
           b3iib1  (j,k) = b3b
           b3iib2  (j,k) = b3b
           emf1iib1(j,k) = q11
           emf1iib2(j,k) = q12
           emf2iib1(j,k) = q2 * dx2a(j)
           emf3iib1(j,k) = q3 * dx3a(k) * h32a(j)
*endif MHD
40       continue
50     continue
*endif -ISYM
*if def,MHD
c
c      As a check, compute div(B), and integrate it over the grid
c  ("sumdivb").  The fourth parameter in the calling list for DIVERG is
c  set to 1 and thus the returned values "divb" and "sumdivb" will be
c  normalised by the specified magnetic field configuration and the
c  grid.  Therefore, "sumdivb" should be of order 10**-12 or less (e.g.,
c  machine round off) for the field to be divergence-free.
c
       call diverg ( b1, b2, b3, 1, 1, divb, sumdivb )
*else MHD
       sumdivb = 0.0d0
*endif MHD
c
       if (iotty .gt. 0) write (iotty, 2010) sumdivb
       if (iolog .gt. 0) write (iolog, 2010) sumdivb
c
c-----------------------------------------------------------------------
c----------------------- Write format statements ------------------------
c-----------------------------------------------------------------------
c
2010   format('MYPROB  : Initialisation complete; normalised div(B) = '
     1       ,1pg12.5,'.')
c
       return
       end
c
c=======================================================================
c
c    \\\\\\\\\\        E N D   S U B R O U T I N E       //////////
c    //////////                M Y P R O B               \\\\\\\\\\
c
c=======================================================================
c
c
```

There are many ingredients to this template which warrant discussion. In order of appearance, these are:

1. Ignoring for the moment the *EDITOR* statement `*insert zeus3d.9999`, the first line of each subroutine must be an *EDITOR* `*deck` (`*dk` for short) statement. Without this statement, the precompiler won't put the subroutine into a separate file, inhibiting the debugger should it be necessary. It is easiest, although not necessary, to give the deck the same name as the subroutine.

2. Note that there is no parameter list in the subroutine statement. A parameter list is unnecessary since all variables that need to be used and/or set are accessible via

the common blocks. In fact, using a parameter list would inhibit the inclusion of a user-supplied subroutine using the present structure of the code.

3. All of the important variables declared in `dzeus36` are in common blocks, and can be included into a subroutine simply by inserting the *EDITOR* statement `*call comvar` just before the local declarations are made. The *EDITOR* `*call` (`*ca` for short) statement is much like `INCLUDE` whereby a section of code known as a "common deck" (called `comvar` in this case) is inserted at the location of the `*call` statement. Every variable of any possible interest is declared in `comvar`, including many that the user would never need. (A description of the most widely used variables is given in App. C.) At the beginning of `comvar` is an "`implicit none`" statement, which requires that the attributes (`real*8`, `integer`, *etc.*) of all variables used in the subroutine be declared. Note that should the user inadvertently try to use a variable name already declared in `comvar`, the compiler will flag the repetition and abort compilation. While the "`implicit none`" does not require that all externals called by the program unit be declared in an `external` statement, it is still good practise to do so. In fact, if undeclared externals appear inside a nested do-loop construct, this may inhibit *EDITOR*'s auto-tasking feature (parameter `iutask`; see §2.3).

4. Should local 1-D arrays be needed to store data at grid points along an axis, it is best to declare them with dimension `(ijkx)`, such as `array1d` in the template. The parameter `ijkx` is declared and defined in `comvar` as the largest of `in`, `jn`, and `kn` (the dimensions of the 3-D arrays), also declared in `comvar`. So that no additional memory is occupied by this local array, it can be equivalenced to one of the 26 1-D scratch arrays declared in `comvar`, as done in the template. Similarly, local 2-D arrays (*e.g.*, `array2d`) should be dimensioned `(idim,jdim)` (where `idim` and `jdim` are set by `comvar` to one of `in`, `jn`, and/or `kn`, depending on the defined symmetries) and equivalenced to one of the 2-D worker arrays. Finally, local 3-D arrays can be declared and equivalenced as exemplified by `divb` in the template. The names of all the scratch arrays (1-D, 2-D, and 3-D) are given in §C.4 and their dimensions are defined in §C.6.

5. The namelist `pgen` is reserved for the namelist in the Problem `GEN`erator. Of course, any name other than `pgen` could be used, so long as it is not already used in the input deck `inzeus` and the new name for the namelist is substituted for `pgen` in `inzeus`. Note how default values for the input parameters can be assigned before the namelist is read.

6. Loop 30 is a typical way the 3-D field variables (`d` = density, `e1` = first internal energy per unit volume, *etc.*) are assigned values. In this very simple case, the variables are assigned to the scalars read from the namelist `pgen`. Note that all energy variables (*e.g.*, `e1`, `e1iib1`, *etc.*) should be considered "pressure-like" (energy per unit *volume*) and not "temperature-like" (energy per unit *mass*). Appendix C has a list of all the variable names and their dimensions. The do-loop indices declared in `comvar` are all assigned values in the subroutine `nmlsts` which is called immediately before the user's problem generator (`PROBLEM`) is called (see App. A) and so they can be used explicitly in any user-supplied subroutine called thereafter. Thus, the index for loop 30 (`k`)

ranges from `ksmnm2` (k-start minimum minus 2) to `kemxp3` (k-end maximum plus 3), which includes all boundary zones. This is particularly important for the magnetic field variables. Similarly for the indices of loops 20 (`j`) and 10 (`i`). Note the use of the *EDITOR* `*if define`, `*endif` (`*if def`, `*ei` for short) structure which conditionally includes or excludes a segment of coding depending on whether, in this case, `MHD` was defined during precompilation. Similar conditionals can be based on the "truth" of any *EDITOR* definition, and on how aliases are set. For example, one could place an *EDITOR* `*if alias PROBLEM.eq.myprob` just after the `subroutine` statement, and the matching `*endif` just before the `return` statement. In this way, the subroutine would be empty (nothing between the `subroutine` and `return` statements) unless the *EDITOR* alias `PROBLEM` were set to `myprob`. This would prevent it from being compiled when it is not needed.

7. Loop 50 illustrates how inflow boundary values (to be applied only to those boundary zones where matter is flowing into the grid in a known fashion) can be set for super-magnetosonic flow. (See §§1.5 and B.8 for variations required for submagnetosonic inflow conditions.) In this case, the "inner-i-boundary" (`iib`) values of the flow variables are being initialised. Alternatively, one could set the in-flow boundary values as input parameters using the namelists `iib`, `oib`, *etc.* (§B.8, §B.9, *etc.*). Note the use of the *EDITOR* `*if define`, `*endif` construct to prevent this loop from being compiled in the event that `ISYM` is defined. If `ISYM` has been defined, the variables `niib`, *etc.* are *not* declared in `comvar`. Variables that are conditionally declared (depending on which *EDITOR* definitions are set) are noted in App. C.

8. Note the use of the *ZEUS*-subroutine `DIVERG` which, in this case, computes the normalised average magnetic field divergence as initialised by the user. This quantity (`sumdivb`) should be of the order 10^{-12} if the initialised magnetic field is to be declared solenoidal. Note carefully that the MHD algorithm in *ZEUS-3D* is designed to *conserve* $\nabla \cdot \vec{B}$ to machine round-off error, not to ensure that $\nabla \cdot \vec{B}$ is specifically zero.. Thus, if the user initialises $\vec{B}$ with a non-zero divergence, the MHD algorithm will diligently conserve that divergence to machine round-off error throughout the simulation. Therefore, if the user wants a divergence-free field, it must be initialised that way.

9. Finally, if desired, the user can write various messages to the terminal (logical unit `iotty`) or to the message log file (logical unit `iolog`). Both `iotty` and `iolog` are declared in `comvar` and set by the subroutine `mstart`, and thus available in `PROBLEM` so long as this subroutine starts off with `*ca comvar` as exemplified in `myprob`.

Once the subroutine is written, it should be placed in its entirety into a change deck called, for example, `chguser` and the line `**read chguser` in the script file `dzeus36.s` should be "de-commented" by deleting one of the asterisks (§2.3). Upon its first pass (the merge step), the preprocessor will, in this case, insert the user's subroutine into `dzeus36` immediately after line 9,999 of the main program `zeus3d` (by virtue of the *EDITOR* statement `*insert zeus3d.9999` appearing at the top of the subroutine template). Since `zeus3d` doesn't have 9,999 lines, *EDITOR* will simply stick the subroutine after the last line of the main program. It doesn't matter where in `dzeus36` the subroutine gets inserted so long as it

isn't in the middle of an existing subroutine (deck). Immediately after the main program is as good a place as any. Upon the second pass, the precompiler will find the user's subroutines and treat them as it would any other it encounters. Thus, if there are any *EDITOR* commands in the user's routines (such as `*call comvar`, `*if define,MHD`), they will be carried out and then expunged from the working copy of the source code. The user's subroutine will then be placed in its own file in the directory `dzeus3.6`, and the name of the subroutine will be included in the makefile `makezeus` which will then compile the subroutine and link it with the rest of the object files and libraries. Provided the *EDITOR* alias `PROBLEM` has been set to `myprob` (or whatever it's called) in the macro file `zeus36.mac`, the user's problem generator will be called at the appropriate time during execution. Similarly, if the subroutine should be called at the location of any of the other available "plugs" in the code, set the appropriate alias (*i.e.* `SPECIAL`, `SPECIALSRC`, `USERSOURCE`, `SPECIALTRN`, `USERDUMP`, `PROBLEM`, `PROBLEMRESTART`, or `FINISH`; see §2.2.2 and the *ZEUS-3D* skeleton in App. A) in `zeus36.mac` to the subroutine name.

5.2 Microsurgery using *EDITOR*

For the truly adventurous, it is possible to alter individual lines of code in `dzeus36` without actually changing the original source code. In this way, the changes made can be kept separate from the code, and thus not lost in the abyss of `dzeus36`. In addition, the user's changes could, in principle, be incorporated into the master code at a later date and become part of the next release. To do this, there are two things required: an *EDITOR* listing of the code and a short tutorial on how to use *EDITOR*. For those who have worked with *HISTORIAN*, all this should seem very familiar. For those who haven't, take heart—the structure is very intuitive. The real problem will be ensuring that the changes made don't break something else in the code. This is where the headaches will lie, and those who really want to change the code do so at their own peril!

To get an *EDITOR* listing of the code, copy the script file `number.s` (a soft-copy of which may be found in the `editor` directory of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6):

```
#---+----1----+----2----+----3----+--+----3----+----2----+----1----+---#
#============== SCRIPT FILE TO CREATE A NUMBERED LISTING ==============#
#                                                                       #
#=======================================> Get files from home directory.
if(! -e ./xedit22) cp ../editor/xedit22 .
#----------------------> Create the input deck for EDITOR, and execute.
rm -f ./inedit
cat << EOF > ./inedit
 \$editpar   inname='SOURCECODE'
          , ibanner=1, job=1, inumber=3, itable=1, ixclude=1          \$
EOF
chmod 755 ./xedit22
./xedit22
#=====================================================> Tidy up directory.
rm -f ./editlp ./inedit ./output ./xedit22
```

to the directory in which `dzeus36` lives, replace `'SOURCECODE'` with `'dzeus36'`, and run it by typing:

```
csh -v number.s
```

This script file will fire up *EDITOR* in its numbering mode (`job=1`), and produce a listing with a table of contents, and various labels on each line. The numbered file will be called `dzeus36.n`, and can be viewed in a wide (132 character) window. Printed copy is not recommended; at 60 lines per page, there will be more than 1,800 pages of output! The third column to the right of the source listing is the number of lines since the most recent *EDITOR* `*deck` or `*cdeck` statement. This is the column needed to perform microsurgery on the master file.

During preprocessing, *EDITOR* makes two major passes over the code. The first pass does the merging of the change deck `chgzeus` (which contains `zeus36.mac` and possibly `chguser`) into the main code. *EDITOR* commands performed during this pass include:

1. `*insert` *deckname.n*—inserts text immediately following the `*insert` command into the source code directly after line n in deck (or cdeck: common deck) *deckname*. The value of n is determined from the third column to the right of the source code in the numbered listing, `dzeus36.n`.

2. `*delete` *deckname.n,m*—deletes lines n through m in deck (or cdeck) *deckname*, and replaces it with the text immediately following the `*delete` command, if any. Note that m must be greater than n. If m is missing altogether, then $m = n$ will be assumed.

That's it. An example:

```
*delete zeus3d.10,20
       a = b
       b = c
*insert mstart.100
       d(i,j,k) = 1.0
*i zeus3d.100
       c = d
*d zeus3d.120
```

Note that `*d` and `*i` are short forms for `*delete` and `*insert` respectively. In addition, `*replace` (`*rp` for short) is a synonym for `*delete`. In the example, lines 10 through 20 in the main program `zeus3d` are replaced with the two lines which set `a` and `b`, a single line setting `d(i,j,k)` is inserted after line 100 in subroutine `mstart`, a single line setting `c` is inserted after line 100 in `zeus3d`, and line 120 in `zeus3d` is simply deleted.

To aid the user in deciding what changes to make and where to make them, a flow chart showing the sequence of the major subroutine calls in *ZEUS-3D* is given in App. A. This will be particularly useful once faced with the task of comprehending the source code listing, `dzeus36.n`.

If *EDITOR* detects any merge syntax errors or conflicts during the merge, it will write the merged file [as best as could be done given the error(s) detected] into a file named `dzeus36.m` and insert an error message immediately after each offending line. A merge error will prevent the second pass of preprocessing (*i.e.*, precompilation) from being executed and the user will be told what character pattern to search for in the file `dzeus36.m` in order to find the generated error messages.

Should the merge step be successful, *EDITOR* goes through a second pass and performs all the precompilation commands. These include:

1. `*if define,`*macro*—the following source code is kept provided the macro is defined by a `*define` statement somewhere in the file.

2. `*if -define,`*macro*—the following source code is kept provided the macro is *not* defined by a `*define` statement somewhere in the file.

3. `*if def,.not.`*macro*—same as 2. Note that `def` is an acceptable short form for `define`.

4. `*if def,`*macro1*`.and.`*macro2*—the following source code is kept provided both macros are defined by a `*def` statement somewhere in the file.

5. `*if def,`*macro1*`.or.`*macro2*—the following source code is kept provided either macro is defined by a `*def` statement somewhere in the file.

6. `*if alias` *macro*`.eq.`*phrase*—the following source code is kept provided the alias *macro* has been set to the character string *phrase* by an `*alias` statement somewhere in the file.

7. `*if alias` *macro*`.ne.`*phrase*—the following source code is kept provided the alias *macro* has *not* been set to the character string *phrase* by an `*alias` statement somewhere in the file.

8. `*else`—the following source code is kept if the truth value of the previous `*if` is false.

9. `*endif`—closes the previous `*if`, `*else` structure. All source code following the `*endif` statement is not affected by the previous `*if` or `*else` statements. For every `*if` statement, there must be an `*endif` statement which follows.

10. `*call` *deckname*—includes the contents of the common deck *deckname* at the location of the `*call` statement.

These precompiler commands can be used as part of the changes to be inserted into `dzeus36` using the *EDITOR* `*delete` and `*insert` commands. All changes should be placed in the user's change deck which, in our example, has been called `chguser`. These changes are then incorporated into the code by "de-commenting" the line `**read chguser` in the script file `dzeus36.s` by deleting one of the asterisks (§2.3).

Note that during both passes, the `*deck` and `*cdeck` statements are used as reference points, and are then expunged from the source code during the second pass. If any precompilation syntax errors are detected, *EDITOR* will write the precompiled file [as best as could be done given the error(s) detected] into a file named `dzeus36.f` and insert an error message immediately after each offending line. *EDITOR* will abort further processing and the user will be told what character pattern to search for in the file `dzeus36.f` in order to find the generated error messages. On the other hand, if the precompilation pass is successful, *EDITOR* will make yet another pass through the code to substitute `namelist` statements with subroutine calls, perform auto-tasking, update the files in the directory `dzeus3.6`, and create the makefile, `makezeus`. This makefile compiles only those subroutines affected by the

changes made, links all the subroutines and libraries together, and creates the new executable `xdzeus36`.

A complete discussion of *EDITOR*'s `merge` and `precom`pilation features can be found in the *EDITOR* user manual `edit22_man.ps` found in the directory `manuals` of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6.

5.3 Debugging in *ZEUS-3D*

It is the author's experience that virtually no change of significance can be introduced into the code without tripping up some problems requiring a debugger. And while the vast majority of these bugs will eventually be traced back to the user's initialisation routine or other change made by the user, it will often necessitate probing other parts of the code to find these problems. To someone not knowing their way around *ZEUS-3D*, this will come as a daunting task indeed. Therefore, this section attempts to offer—in a generic way—some guidance in starting a debugging session.

The debugger `DBX`, originally a Cray then Sun Microsystems product, can be used with code compiled with `f90 -g` (which may be available on non Cray and non-Sun platforms; check with your sysadmin). The debugger `GDB` may be used with code compiled with `g95 -g` or `gfortran -g`. Other debuggers are required for other compilers. In any case, to prepare `xdzeus36` for a debugger, it should be compiled with `coptions='debug'`; see §2.3. One then enters the debugging environment by typing:

```
dbx xdzeus36
```

(or whatever debugger is being used) at the *UNIX* prompt. From there the user can set "breakpoints", reassign variable values, and navigate pretty well anywhere within the code probing variable values as one moves along. For the uninitiated, a very short three-page primer on using `dbx`, `dbxprimer.ps`, may be found in the directory `manuals` of `dzeus36.tar` from zeus3d.ca/zeus3d/version3.6. For `GDB` and other debuggers, the user is directed to on-line resources.

While not specific to this package, the following discussion assumes `dbx` to be the default debugging environment.

1. Stop in your initialisation routine (`PROBLEM`)

The first task is to make sure all variables are set as you think they should be. Stop at the `return` statement of your initialisation routine, and probe all variable values, particularly those around the periphery of the grid where users often forget to initialise the flow variables. 90% of all bugs a user introduces into the code can be traced to flow variables (density, velocity, *etc.*) not being assigned properly or fully. Make sure, for example, that each array is set from `1:in`, `1:jn`, and `1:kn` and not, for example, simply from `is:ie`, `js:je`, and `ks:ke` (see App. C for a review of the variable and parameter names and definitions). In addition, if any boundaries are set to "inflow" (`nflo=10`), the user will need to set the inflow boundary arrays such as `diib1`, `diib2`, `v1iib1`, *etc.* (see the template routine `myprob.f` in §5.1).

2. Stop in `srcstep`

Stopping at the top of routine `srcstep` (where the source terms are updated; see the `dzeus36` "skeleton" in App. A for guidance on how to navigate through the code) will allow you to make certain that once set in the initialisation routine, all variables have been passed to the beginning of the first MHD cycle correctly. If execution dies before reaching `srcstep`, it is possible there has been a problem in one of the graphics routines, and you should probe the variable values there.

If execution makes it correctly to the top of `srcstep`, one can advance through `srcstep` one call after the other, making sure that each of `stv1`, `stv2`, `stv3`, `viscous`, *etc.*, is executing correctly.

3. Stop in ***`trnsprt`***

If `srcstep` reveals no anomalies, one next ventures into `trnsprt`, which takes care of the transport terms (fluxes), the induction equation, and the transverse Lorentz forces. Navigating through this routine is complicated by the fact that the order in which the constituent routines (`ctran1`, `ctran1`, `ctran3`, `ttran1`, `ttran2`, and `ttran2` for FIT; `tranx1`, `tranx2`, `tranx3`, `cmoc1`, `cmoc2`, and `cmoc3` for legacy transport) are executed depends on how many MHD cycles have been run through. This is an attempt to reduce any favouritism among the directions in the directional- and planar-split algorithms, but it can make debugging more challenging.

The variable controlling the order in which the constituent routines are called is the integer `ix1x2x3` which can take on any integral value between and including 1 and 6. Knowing the value of `ix1x2x3` will tell you to which segment of `trnsprt` you have to go.

With any luck, you will not have to venture into the `cmoc*` routines, as these are long with many local variables, most of which are scalars which can make debugging all the more painful.

4. Double-debug sessions

For the really stubborn bugs, often I have to do a "double debug session" in which I have `dzeus36` without the changes compiled and open in a debug session in one window on the left side of my screen, and the code with the changes opened up in a debug session in another window on the right side of my screen. From there, I undertake the tedious task of advancing through the code routine by routine, line by line until I find where the two versions diverge, and go from there.

5. "Gotchas"

Depending on your installation, `dbx` is capable of a number of very annoying "gotchas" which can slow progress markedly. I mention a few below.

While any variable declared either globally or local to the subroutine should, in principle, be accessible (*i.e.*, their values probed) from within the subroutine, this is not always the case. In some installations, only variables actually set or modified by the subroutine may be probed and, if you really need to see these variable values, one either has to go to a routine where these values are modified or, if that is insufficient, put a "dummy" assignment statement in the routine (*e.g.*, `var = var + 0.0d0`), recompile, and restart the debug session.

In my own installation of `dbx`, local variables that are equivalenced in the subroutine

to a globally declared variable are often inaccessible by the local variable name—one has to use the global variable name to probe values. This, like the first "gotcha", is a completely stupid design "feature", but you may be stuck with it. Sometimes using the global variable name is no big deal. However, in some situations such as in the `cmoc*` routines where the local variable is not dimensioned the same as the global array [*e.g.*, in `cmoc1`, local variable `v2t(kn,jn)` is equivalenced to `wi2d(ijkx,ijkx)` in 3-D], it isn't always so simple to determine the indices needed for the global array to retrieve the desired element of the local array. In these situations, it may be necessary to comment out the equivalence statements and recompile, hoping that this doesn't somehow affect the nature of the problems you are trying to uncover.

Finally, `dbx` will only report the first 15 decimal places of the variable (for double precision), and sometimes problems start to occur in the 16th decimal place or beyond. Even though values beyond the 15th or 16th significant figure are normally considered "noise", unlike real noise computer noise is always repeatable and thus can serve as a useful indicator of when deviation from the correct answer begins. In `dbx`, for example, one can probe these additional digits by subtracting the reported result from the variable itself. Thus, if `v1(i,j,k)` is reported as `3.14159265358979`, you could type :

```
print v1(i,j,k)-3.14159265358979
```

which may, for example, then report:

```
v1(i,j,k)-3.14159265358979 = 2.5430056384790e-16
```

which can be compared to another session to make sure differences aren't creeping in at this extremely low but sometimes significant level. It is my experience that if `dbx` reports two number to be equal to 15 decimal places, they aren't always equal. However, if the noises are also equal then the variable values can safely be taken as identical.

These are only a few general guidelines to debugging within `dzeus36`, and may cover 95% of the situations a typical user may encounter. If bugs or "undesired features" are found or strongly suspected in the code itself that are unrelated to changes introduced by the user, the user is encouraged to report these to the author at `david.clarke@smu.ca` or at the address given in the *Preface*.

6 Quick summary

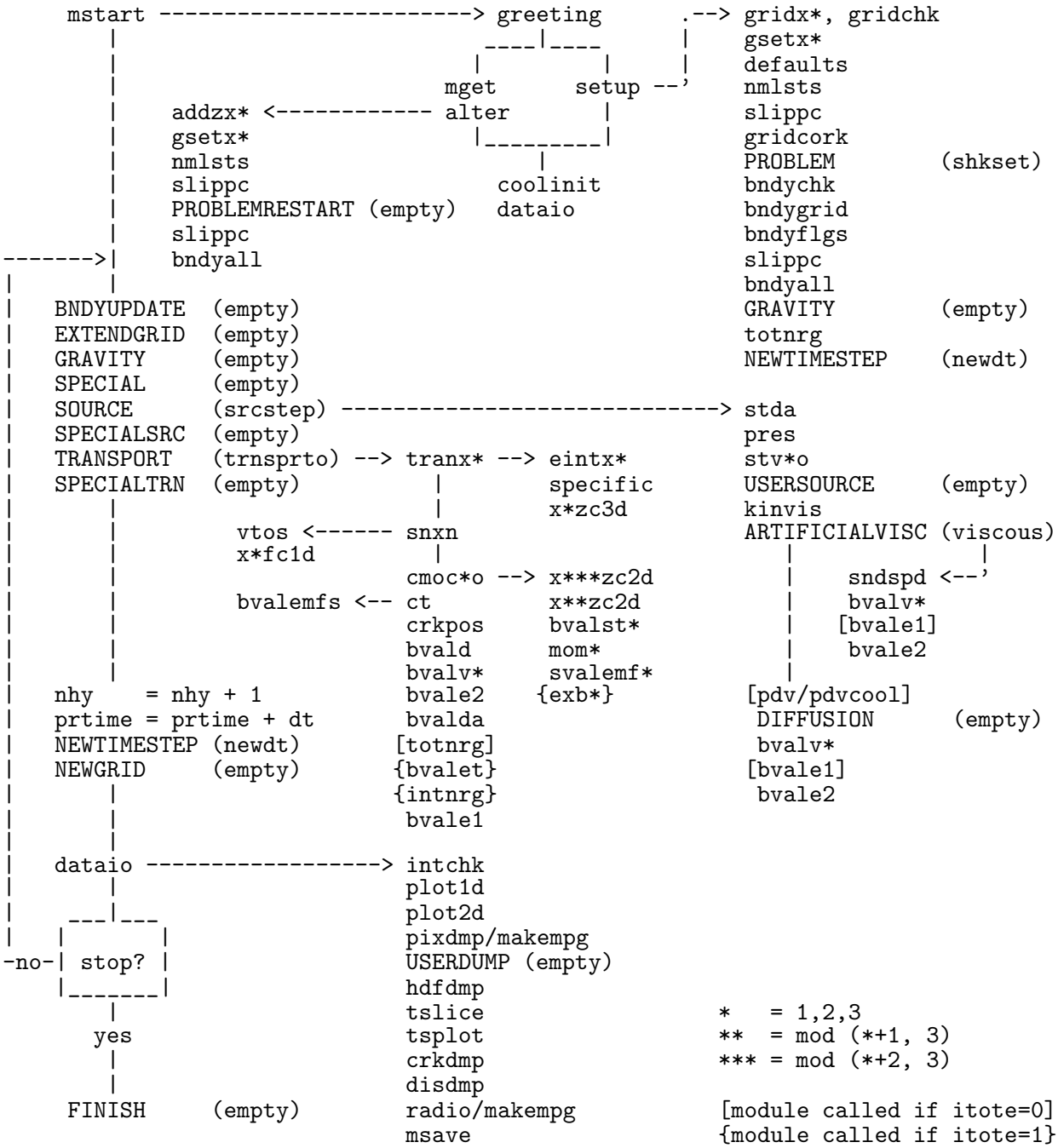
This final section is intended to serve as a quick reference sheet for those who are already familiar with running *ZEUS-3D*.

1. Set the macros in the file `zeus36.mac` (§2.2 and App. A).
2. Make the necessary changes to the `dzeus36.s` script file, including the parameters in the change deck `chgzeus` (§2.3.4) and the input parameters in the input deck `inzeus` (§2.3.6 and App. B).
3. Put the desired source code changes, if any, into the file `chguser` (§5), and "de-comment" the line `**read chguser` in the script file `dzeus36.s` by deleting one of the asterisks (§2.3).
4. Run the script file to create the *ZEUS-3D* executable by typing `csh -v dzeus36.s`
5. Fire up the executable by either typing `xdzeus36`, or by submitting the job to the appropriate batch queue.

A The *ZEUS-3D* skeleton

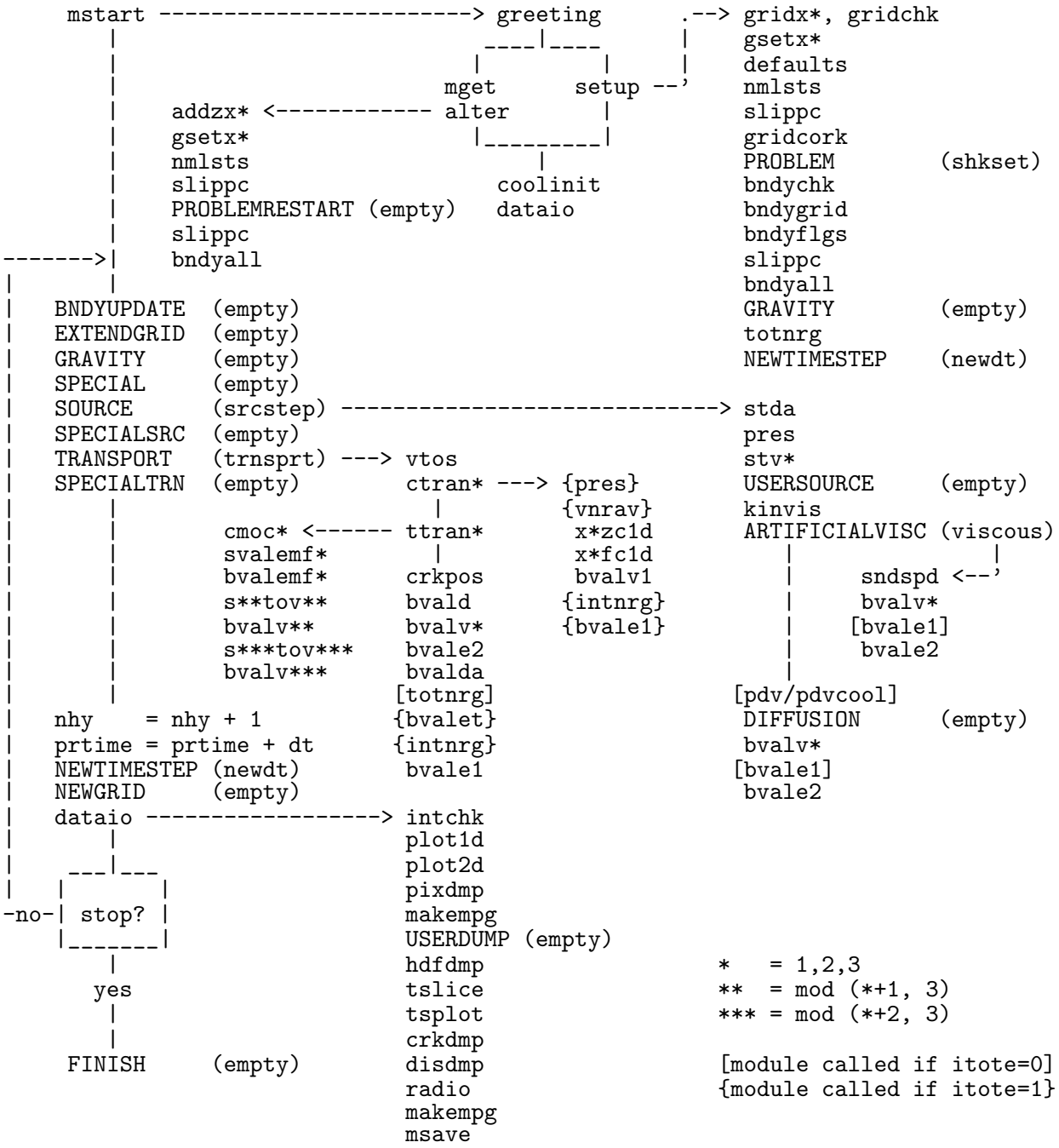
A.1 Legacy transport

The following flowchart depicts "legacy transport" (`hycon` namelist parameter `trnvrsn=0`; `MHD`, `GRAV` on, `RADIATION` off) as of November, 2013 with no further modifications anticipated. Modules in upper case are *EDITOR* aliases set in `zeus36.mac`, with exemplary choices (appropriate for the 1-D Brio & Wu problem; §2.2, 2.3) given parenthetically. Modules in lower case are actual subroutine names in the source code.



A.2 Finely Interleaved Transport

New to version 3.6: The following flowchart depicts the FIT algorithm (`hycon` namelist parameter `trnvrsn=1`; `MHD`, `GRAV` on, `RADIATION` off; `trnvrsn=2` engages the fully conservative variant of FIT) as of November, 2013, representing the most significant change to *ZEUS* transport since the introduction of CMoC in 1993, and designed to address the "striping instability". Modules in upper case are *EDITOR* aliases set in `zeus36.mac`, with exemplary choices (appropriate for the 1-D Brio & Wu problem; §2.2, 2.3) given parenthetically. Modules in lower case are actual subroutine names in the source code.



A.3 *EDITOR* aliases

The "empty" routine `empty` (returns immediately to calling routine) is a option for just about any *EDITOR* alias macros (other than `TRANSPORT`, `NEWTIMESTEP`, and `PROBLEM`) that effectively "turns them off". This subsection lists most of the other more substantive subroutines within *ZEUS-3D* that can be aliased to each macro, along with their intended purpose.

`BNDYUPDATE`	`breset`	resets flow-in boundary values for some test problems
	`jetbndy`	generates magnetic field and wiggles at jet boundary
	`jetcork`	injects corks at jet inlet
	`krasdisc`	maintains "Krasnopolsky boundary conditions" (`corona`)
	...	user-defined module to maintain boundaries
`EXTENDGRID`	`extend`	to extend computational domain
`GRAVITY`	`gravity`	one of three Poisson solver algorithms may be chosen
`SPECIAL`	...	user-defined module for additional physics
`SOURCE`	`empty`	for advection tests
	`srcstep`	standard source term module
`SPECIALSRC`	`twinjet`	sustains two outflowing jets from "fertile zones"
	`resetalf`	for launching Alfvén waves from the boundary (`ALFVTST`)
	...	user-defined module for additional source terms
`TRANSPORT`	`trnsprt`	standard transport module
`SPECIALTRN`	`minden`	resets density to floor value
	...	user-defined module for additional transport terms
`NEWTIMESTEP`	`newdt`	full dynamics
	`advectdt`	for advection tests
`FINISH`	`spectra`	generates Fourier spectra from gathered data
	`pertest`	reports deviations from periodicity
	...	user-defined module called once at the end of execution
`USERSOURCE`	`phistv`	non-conservative point mass gravity (see `corona`)
	...	user-defined module for additional source terms
`ARTIFICIALVISC`	`viscous`	von Neumann-Richtmyer artificial viscosity
	`gasdiff`	heat and mass diffusion
`DIFFUSION`	`diffuse`	second fluid diffusion
`USERDUMP`	...	user-defined I/O module
`PROBLEM`	`shkset`	for shock tube tests
	`corona`	sets up jet-disc problem
	`jetinit`	sets up propagating jet problem
	...	user-defined module to initialise flow variables
`PROBLEMRESTART`	...	user-defined module to alter variables for restarted job

B The namelists

There are well over 500 `namelist` parameters to specify a unique initialisation. Take heart—most defaults can be used for most applications. As a start, use the input deck given in the `dzeus36.s` template (§2.3), and then alter as needed.

On the next page begins a complete catalogue of all the input parameters in `dzeus36`. The parameters are grouped together in "namelists" and discussion for each namelist is contained within a segment headed by the name of the namelist and the subroutine in which the namelist is called. For example, the first namelist is `iocon` (input/output control) and is called by the subroutine `mstart`. After each heading is a discussion of what the namelist controls, a list of all the parameters which are elements of the namelist, and finally the syntax used in `dzeus36` to declare the namelist.

For the uninitiated, `namelist` is a non-standard feature of most *FORTRAN77* compilers and a standard feature of Fortran90 which provides a convenient way to specify input data. Before Fortran90 was released in 1994, each platform had its own `namelist` with its own syntax, and this made it difficult to port *ZEUS-3D* even among different flavours of *UNIX*. Thus, a `namelist` emulator was built into *EDITOR* which, during one of its many passes through the code, replaces all namelist references (including `read`s and `write`s) with calls to subroutines in the `dnamelist.a` library. The following discussion, therefore, reflects the syntax for the *EDITOR* `namelist`, which differs somewhat from the Fortran90 version. If desired, *EDITOR* can be instructed not to replace the `namelist` syntax (`inmlst=0`), in which case your compiler's `namelist` would be invoked. This may cause syntax errors to be issued since standard *FORTRAN* `namelist`s don't allow variables passed via a subroutine to be used as a namelist parameter, whereas the *EDITOR* `namelist` does.

In order to specify an input parameter, one merely needs to set it to the desired value as done in the input deck `inzeus` found in the sample script file `dzeus36.s` (§2.3). The order in which the variables appear in the namelist declaration need not be adhered to in the input deck nor must all the variables be set. So long as the variable specified in the input deck is a member of the namelist, then `namelist` will set the variable as specified.

There are a few rules to bear in mind. The namelists (but not necessarily the variables within a namelist) in the input deck must be in the same order as they are encountered during execution. If no parameters are to be set, an empty namelist (one with the namelist name between two $ sentinels) must appear in the correct sequence. There is no problem with namelists appearing that are never read, but a read to a non-existent namelist will generate a `namelist` error message. In this catalogue, the order of the namelists is the same as the order in which they appear in `inzeus` and in which they are encountered in `dzeus36`.

The syntactic rules of setting the variables can be gleaned from the input deck `inzeus` (§2.3). Column 1 is reserved for a '`c`' to "comment out" a namelist line which is then echoed on the CRT when encountered in the input deck. Column 2 is reserved for the leading $ sentinel. The specification of the namelist may start in column 3 and must terminate with a second $ sentinel. Until the second $ sentinel is found, all lines will be interpreted as part of the same namelist. All characters appearing after the 72nd column will be ignored, including the closing $ sentinel, should it inadvertently be placed there.

B.1 IOCON—I/O CONtrol (subroutine MSTART)

This namelist sets the logical units to be used during execution. Typically, these parameters will not need to be set to anything other than their default values. These parameters are *not* written to the restart dump. Therefore, all non-default values for any of the parameters in this namelist must be set each time the job is resumed.

```
parameter                    description                          default

iotty      logical unit for terminal (standard output)              6
iopl1      logical unit for 1-D plots using NCAR/PSPLOT graphics   99
iopl2      logical unit for 2-D plots using NCAR/PSPLOT graphics   99
iolog      logical unit for message log dump                       30
iodmp      logical unit for restart dumps                          31
iopix      logical unit for pixel dumps                            32
iousr      logical unit for user dumps                             33
iotsl      logical unit for time slice (history) ascii dumps       34
iotsp      logical unit for time slice (history) plot  dumps       99
iodis      logical unit for display dumps                          36
iorad      logical unit for RADIO dumps                            37
iocrk      logical unit for cork dumps                             38
iotmp      logical unit for temporary files; unit should always    39
           be closed after using so that other routines can
           expect them to be available when needed.
intractv   = 1 => interactive mode on (see INTCHK)                  1
           = 0 => interactive mode off; to prevent batch jobs
                  from calling CHECKIN at every time step.

WARNING: AVOID LOGICAL UNIT 3. APPARENT CONFLICT WITH NCAR.

NOTE   : IOTTY MAY BE SET TO 6 (TO GET CRT OUTPUT) OR 0 (NO OUTPUT).

      namelist / iocon    /
     1               iotty   , iopl1   , iopl2   , iolog   , iodmp
     2             , iopix   , iousr   , iotsl   , iotsp   , iodis
     3             , iorad   , iocrk   , iotmp   , intractv
```

B.2 RESCON—RESstart dump CONtrol (subroutine MSTART)

This namelist determines if the job is to be started from initial conditions, or if it is to be restarted from a previous run. These parameters are *not* written to the restart dump. Therefore, all non-default values for any of the parameters in this namelist must be set each time the job is resumed.

The default values are set for starting from initial conditions, which occurs when the third to fifth characters in `resfile` are `000`. To restart a job, one can usually use the same input deck as was used for the original run with `resfile` set to the desired restart dump name. In addition, parameters in the namelist `pcon` may have to be changed.

The parameters `*getm?`; `*=i,j,k`, `?=n,x` are designed so that only a portion of the restart dump may be read, and/or so that the data may be read into a larger grid. That is, it is not necessary for the field arrays in a restarted job to be dimensioned the same as those in the run which generated the restart dump.

Example 1: For a straight restart without altering the grid or the *EDITOR* macros, leave

the values of `igetmn`, *etc.* to their defaults and make sure that the parameters `in`, *etc.* are set to the same values as in the run which generated the restart dump.

Example 2: If the first run was on a 64^3 grid and the user wishes to read the inner eighth of the data and position them at the centre of a 100^3 grid, and if the new portion of the grid is to be determined from the existing grid, then the following settings are necessary:

```
igetmn = 17, jgetmn = 17, kgetmn = 17, iaddz = 1
igetmx = 48, jgetmx = 48, kgetmx = 48, jaddz = 1
iputmn = 35, jputmn = 35, kputmn = 35, kaddz = 1
```

The desired portion of the restart dump will be read and loaded into the 100^3 grid between `i=35,66`, `j=35,66`, `k=35,66`. In addition, the 1-grid `x1a(35:66)` (see §C.1 for a discussion of the naming convention for the grid variables) will be filled by the values of `x1a(17:48)` in the restart dump. The code will detect that the grids `x1a`, `x2a`, `x3a` are now incomplete, and will call the appropriate modules to add zones to the `x1`-, `x2`-, and `x3`-grids. If the user wishes, (`*addz=1`, `*=i,j,k`), the new portion of the grid may be determined automatically from the existing grid. In this example, `x1a(1:34)` would be determined (*i.e.*, `dx1min`, `x1rat`, *etc.*, see namelist `ggen1`) from `x1a(35:37)`. Similarly, `x1a(67:100)` would be determined from `x1a(64:66)`. Alternatively, the user may opt to set the new portion of the grid manually. In this case, one should set `*addz=0` and proceed with setting the namelists `ggen1`, `ggen2`, `ggen3`. (See discussion in `ggen1`.) Note that if the user selects the manual option, it is imperative that the portion of the new grid that overlaps the old grid be, in fact, identical to the old grid. Next, all arrays will be padded with values at the edges of the portion read. Thus `d(1:34,j,k)=d(35,j,k)`, `d(67:100,j,k)=d(66,j,k)` (where `d` is the density array—see §C.2), *etc.* Of course, the user is free to set the values of the padded portion of the arrays to whatever values they want by linking a user-supplied subroutine to the *EDITOR* macro `PROBLEMRESTART` (§2.2.2).

Finally, a job may be resumed from a restart dump with different *EDITOR* macros defined or not. Thus, if a job that began with magnetic fields is to be resumed without them, the user may recompile `dzeus36` *without* magnetic fields (`MHD` not defined) and then blindly read the restart dump which contains magnetic field arrays. There is enough information in the restart dump that the code can selectively read the non-magnetic part of the dump and resume the calculation as though there were never any magnetic fields. Of course, whether suddenly disappearing the magnetic fields is physically realistic is another matter!

```
parameter                      description                              default

dtdmp       problem time interval between restart dumps                   0.0
            = 0 => no restart dumps (probably a bad idea)
            > 0 => write each dump to a new file
            < 0 => overwrite old even (odd) numbered dump with
                   new even (odd) numbered dump at time interval
                   abs(dtdump)
nresdmp     the sequential number for the next restart dump              -1
            < 0 => nresdmp = iresdmp
nlogdmp     the sequential number for the next log file                  -1
            < 0 => nlogdmp = ilogdmp
```

```
idtag      character*2 problem tag appended to filenames              'aa'
resfile    restart dump filename                                  'zr000aa'
igetmn     minimum x1-index (i) to be read from restart dump          1
igetmx     maximum x1-index (i) to be read from restart dump          in
iputmn     i-index at which x1a(igetmn) is stored                     1
iaddz      < 0 => no new zones are generated                          0
           = 0 => call GRIDX1 to redo entire grid
           > 0 => new zone spacing determined from existing grid
```

The variables (jgetmn, jgetmx, jputmn, jaddz) and (kgetmn, kgetmx, kputmn, kaddz) are analogous to (igetmn, igetmx, iputmn, iaddz) for the 2- and 3-directions respectively.

```
      namelist / rescon   /
     1               dtdmp   , nresdmp , nlogdmp , idtag   , resfile
     2             , igetmn  , igetmx  , jgetmn  , jgetmx  , kgetmn
     3             , kgetmx  , iputmn  , jputmn  , kputmn  , iaddz
     4             , jaddz   , kaddz
```

B.3 GGEN1—Grid GENerator for x1 (subroutine GRIDX1)

This namelist controls how the grid is determined in the 1-direction. All the parameters in this namelist, as well as those in namelists ggen2, ggen3, and those read by subroutine nmlsts are written to the restart dump. The stored values, therefore, will become the "default" values of the parameters for any run resumed from the restart dump.

The grid can be created all at once or in several blocks. Each block requires a separate read of this namelist specifying how that portion of the grid is to be computed. The parameter lgrid should be set to .true. (or equivalently .t. for the *EDITOR* namelist) only for the last block. (Note that the *EDITOR* namelist also allows .f. as a short form for .false..)

There are two types of gridding. The first is "ratioed gridding" where the distance across a zone is a fixed multiple of the distance across the previous zone. If this multiple is 1, then the zones are uniform. If the multiple is 1.1, then each zone is 10% larger than the previous one. If the multiple is 0.9, then each zone is 10% smaller than the previous one. To determine a block of ratioed zones uniquely, one must specify the number of zones in the block (nbl), the minimum and maximum extent of the block in coordinate units (x1min, x1max), and *either* the smallest zone size in the block (dx1min) *or* the ratio to use between zones (x1rat). Specifying either dx1min or x1rat will allow the other to be computed.

The second type of gridding is "scaled gridding" where the coordinate value is some fixed multiple of the previous coordinate value. For ratioed grids, dx(n)=mult*dx(n-1). For scaled grids, x(n)=mult*x(n-1). For example, scaled gridding would be appropriate for the r-direction in spherical polar coordinates if the zones were all to have the same *shape*. To determine a block of scaled zones uniquely, one must specify the number of zones in the block (nbl) and the minimum and maximum extent of the block in coordinate units (x1min, x1max). Neither dx1min nor x1rat are needed.

The grid can be scaled to physical units most conveniently by setting the multiplicative factor x1scale to the desired scaling value.

For restarted jobs, there is a third gridding option. Setting igrid to zero will cause the grid generator to skip over the nbl zones specified for this block. Thus, in the second

example in the discussion for namelist `rescon`, one could set the new zones for the x1-direction manually with three `ggen1` namelist "cards". The first card would set zones (1:34) in whatever manner desired with the condition that the last zone of the new grid ends where the first zone of the old grid begins. The second card would set `igrid=0` and `nbl=32`. This would leave zones (35:66) alone since they were set when the restart dump was read. Finally, the third card would set zones (67:100) in whatever manner desired with the condition that the first zone of the new grid begins where the last zone of the old grid ends.

Other than remaining within the memory limits of the machine (and see discussion in §2.3.4 on how to estimate memory occupancy for a particular run), there are two practical considerations when choosing the number of zones for each of the three dimensions. First, if at all possible, the greatest number of zones should be along the 1-direction so that the vector length of the vectorised loop is as long as possible[7]. Second, if the code is to be multi-tasked, the number of zones (including the five boundary zones) in each direction should be an integral multiple of the number of parallel processors available on the machine. This will yield the best overall degree of parallelism.

```
parameter                    description                          default

nbl         number of active zones in block being generated          1
x1min       x1a(imin); bottom position of block                      0.0
x1max       x1a(imax); top    position of block                      0.0
x1scale     arbitrary scaling factor for "x1min" and "x1max"         1.0
igrid       method of computing zones.                               1
            = 0  => block has already been set (restarted runs only)
            =+1  => (ratioed) use input "x1rat" to compute "dx1min".
                    "dx1min" = size of first zone in block
            =-1  => (ratioed) use input "x1rat" to compute "dx1min".
                    "dx1min" = size of last  zone in block
            =+2  => (ratioed) use input "dx1min" to compute "x1rat".
                    "dx1min" = size of first zone in block
            =-2  => (ratioed) use input "dx1min" to compute "x1rat".
                    "dx1min" = size of last  zone in block
            = 3  => (scaled) compute "x1rat" and "dx1min" from "nbl".
x1rat       desired ratio dx1a(i+1) / dx1a(i)                        1.0
dx1min      size of first (igrid>0) or last (igrid<0) zone in block  0.0
lgrid       = .false. => read another block (namelist card).      .false.
            = .true.  => all blocks are read in.  Do not look for
                         another "ggen1" namelist card.

       namelist / ggen1    /
     1               nbl     , x1min   , x1max   , x1scale , igrid
     2             , x1rat   , dx1min  , lgrid
```

B.4 GGEN2—Grid GENerator for x2 (subroutine GRIDX2)

See comments for `GGEN1`.

```
parameter                    description                          default

nbl         number of active zones in block being generated          1
x2min       x2a(jmin); bottom position of block                      0.0
```

[7] This is an issue only if one is using a vector machine.

```
x2max      x2a(jmax); top    position of block                        0.0
x2scale    arbitrary scaling factor for "x2min" and "x2max"           1.0
igrid      method of computing zones.                                 1
           = 0  => block has already been set (restarted runs only)
           =+1  => (ratioed) use input "x2rat" to compute "dx2min",
                   "dx2min" = size of first zone in block
           =-1  => (ratioed) use input "x2rat" to compute "dx2min",
                   "dx2min" = size of last  zone in block
           =+2  => (ratioed) use input "dx2min" to compute "x2rat",
                   "dx2min" = size of first zone in block
           =-2  => (ratioed) use input "dx2min" to compute "x2rat",
                   "dx2min" = size of last  zone in block
           = 3  => (scaled) compute "x2rat" and "dx2min" from "nbl".
x2rat      desired ratio dx2a(j+1) / dx2a(j)                          1.0
dx2min     size of first (igrid>0) or last (igrid<0) zone in block    0.0
units      sets the angular units (character*2, RTP only)             'rd'
           'rd' => radians, 'pi' => pi radians, 'dg' => degrees
lgrid      = .false. => read another block (namelist card).        .false.
           = .true.  => all blocks are read in.  Do not look for
                        another "ggen2" namelist card.

      namelist / ggen2    /
    1               nbl     , x2min   , x2max   , x2scale , igrid
    2             , x2rat   , dx2min  , units   , lgrid
```

B.5 GGEN3—Grid GENerator for x3 (subroutine GRIDX3)

See comments for GGEN1.

```
parameter                      description                          default

nbl        number of active zones in block being generated            1
x3min      x3a(kmin); bottom position of block                        0.0
x3max      x3a(kmax); top    position of block                        0.0
x3scale    arbitrary scaling factor for "x3min" and "x3max"           1.0
igrid      method of computing zones.                                 1
           = 0  => block has already been set (restarted runs only)
           =+1  => (ratioed) use input "x3rat" to compute "dx3min",
                   "dx3min" = size of first zone in block
           =-1  => (ratioed) use input "x3rat" to compute "dx3min",
                   "dx3min" = size of last  zone in block
           =+2  => (ratioed) use input "dx3min" to compute "x3rat",
                   "dx3min" = size of first zone in block
           =-2  => (ratioed) use input "dx3min" to compute "x3rat",
                   "dx3min" = size of last  zone in block
           = 3  => (scaled) compute "x3rat" and "dx3min" from "nbl".
x3rat      desired ratio dx3a(k+1) / dx3a(k)                          1.0
dx3min     size of first (igrid>0) or last (igrid<0) zone in block    0.0
units      sets the angular units (character*2, ZRP and RTP only)     'rd'
           'rd' => radians, 'pi' => pi radians, 'dg' => degrees
lgrid      = .false. => read another block (namelist card).        .false.
           = .true.  => all blocks are read in.  Do not look for
                        another "ggen3" namelist card.

      namelist / ggen3    /
    1               nbl     , x3min   , x3max   , x3scale , igrid
    2             , x3rat   , dx3min  , units   , lgrid
```

B.6 PCON—Problem CONtrol (subroutine NMLSTS)

Determines the criteria for terminating the job.

```
parameter                    description                              default

nlim       cycles to run                                                0
tlim       physical (problem) time to stop calculation                  0.0
           if tlim < 0, problem is stopped at exactly abs(tlim)
ttotal     total seconds of execution time permitted for job            0.0
tsave      seconds of execution (cpu) time reserved for cleanup         0.0

WARNING: should a job be restarted from a job with tlim<0, the sum of the
first and restarted job will not be identical to machine round-off to a
job that did the simulation in one run.  This is because the single-run
job would not have the abbreviated time step in the middle as needed by
the first partial job to finish exactly on "prtime".

      namelist / pcon     /
     1               nlim    , tlim    , ttotal  , tsave
```

B.7 HYCON—HYdro CONtrol (subroutine NMLSTS)

Sets the parameters which control the hydrodynamics. One of the most important selectors in this namelist, `itote`, chooses between the internal (`itote=0`) and total (`itote=1`; default) energy equations, with the latter *often* but not *always* giving superior results. *Pros* and *cons* for choosing between the two energy equations include: Execution time is generally faster for the internal energy equation (by about 20%), and pressures are guaranteed positive definite for `courno<0.5`. However, the algorithm is not strictly conservative which, among other things, causes it to converge on incorrect values (by as much as 20%) in some 1-D shock-tube tests and lead to qualitatively different results in some multi-dimensional problems. The total energy equation is conservative and somewhat more stable allowing a slightly larger Courant number (*e.g.*, `courno=0.75`) than the internal energy equation in some applications. However, internal energies are not positive definite and where they become negative, are reset to `e1floor`. In the opinion of this author, the requirement that a code be strictly conservative has been somewhat overblown in the literature. It is true that only conservative codes will converge correctly on 1-D shock tube problems but, in the messy universe where the sum of mechanical and thermal energies is known not to be conserved, a strictly conservative code may be less important than the assurance of positive-definite pressures. This version of the code gives the user both options.

All energy variables should be interpreted as *energy per unit volume*. In setting up a problem, the user should always initialise the internal energy density (variable `e1` and boundary values `e1iib1`, *etc.*; see §C.2 and §C.3) and not the total energy density, (`et`), regardless of (`itote`). Being a primitive variable, boundary conditions are always applied to the internal energy density. Note that if `ISO` is defined, `itote` is set to 0.

The steepest discontinuities this code can sustain are obtained with `iord=2`, `iords=3`, and `istp=2`, where the latter assures only *contact* discontinuities are steepened. `istp=1` will cause *any* discontinuity to be steepened and is intended for advection tests only. These settings maintain contacts in 2 or 3 zones and most shocks in `qcon+1` zones (although some

slow shocks may be smeared out over as many as ten zones), but can also can cause the bases of discontinuities or rarefactions to undershoot slightly and even "ring" in some 1-D shock tube tests. More conservative settings are the defaults, for which the code runs 20% faster and maintains contacts in 5 to 7 zones, and most shocks to `qcon+2` zones.

A note on Consistent Advection: CA is a modification of how fluxes are computed to keep them consistent with mass flux. Thus, "numerical drift" between angular momentum and mass, such as that which caused early simulations of mass accretion to form rings rather than discs, is significantly reduced (see Norman, Barton, and Wilson, 1980, ApJ).

Since its earliest inception, *ZEUS* has used CA on all flow variables, including all momentum components and energy, although its original purpose was for angular momentum transport. In 2006, I discovered that CA applied to energy transport causes significant ringing in Figures 1b and 2b of Ryu & Jones (1995, ApJ) and subsequently introduced a parameter into *ZEUS-3D* (`cadvs`) to turn off CA for all scalar transport, including energy density. At the same time, I introduced `cadvc` and `cadvt` to turn off CA for compressive and transverse transport of momenta. I have found no test problem nor application in which disengaging CA from energy transport has any deleterious consequence and, accordingly, the default setting for `cadvs` is 0 (off). Conversely and not surprisingly, numerous tests show that CA should remain engaged with momentum transport. Accordingly, the default settings for `cadvc` and `cadvt` is 1 (on). Indeed, in a private communication, Mike Norman recalled there to be no compelling reason at the time to include energy in the CA algorithm, other than "what's good for the goose is good for the gander", and the failure of CA in energy transport in the two R&J tests was the first evidence he saw of any problems introduced by the algorithm.

```
parameter                    description                          default

qcon       quadratic artificial viscosity (q) constant              2.0
qlin       linear    artificial viscosity (q) constant              0.0
courno     The CFL-determined time step is multiplied by the        0.5
           "Courant number", a "safety factor".
dtrat      ratio of "dtmin" to initial value of "dt"                0.001
           Set to 0.2 for no ramp-up of time step.
dtmax      maximum time step to use                                 huge
dtset      constant value of "dt" to be set throughout simulation,  0.0
           used only for testing; 0 => use computed "dt".
iord       order of interpolation                                   2
           = 1 => first order (donor cell) interpolation
           =-1 => first order implicit interpolation
           = 2 => second order (van Leer) interpolation
           =-2 => second order implicit interpolation
           = 3 => piecewise parabolic interpolation (PPI)
           = 4 => second order velocity-corrected interpolation
           = 5 => second order non-harmonic interpolation
           = 6 => second order interpolation for non-uniform grid

Implicit interpolations (iord=-1,-2) affect compressive s* transport only;
interpolations for all other transport steps use abs(iord).

iords      order of interpolation for scalars to override "iord"    iord
istp       contact discontinuity steepener (third order only)       0
           = 0 => always off, 1 => always on,  2 => on only at
```

```
           contact discontinuity
**floor    smallest value desired for variable **          scalars  tiny
                                                           vectors  0.0
icool      = 0 => use PDV in SRCSTEP                                 0
           = 1 => use PDVCOOL in SRCSTEP for pdv work with
                  arbitrary cooling function
itote      = 0 => solve the internal energy equation (positive       1
                  definite pressures but energy not conserved).
           = 1 => solve the total energy equation (energy
                  conserved but pressure not positive definite)
iscydf     = 0 => no subcycling on diffusion                         0
           = 1 => subcycle on diffusion
iscyqq     = 0 => no subcycling on artificial viscosity              0
           = 1 => subcycle on artificial viscosity (itote=0 only)
ix1x2x3    seed for directional splitting sequence                   1
mind       minimum value subroutine MINDEN will allow for density  dfloor
nu         kinematic viscosity (in units of LV)                      0.0
isetemf    affects flow-in skin values for emf(perp) and flow-in     0
           boundary values for emf(par)
           = 0 => SVALEMF* and BVALEMFS don't overwrite (C)MOC*-
                  computed flow-in emfs with pre-set flow-in
                  arrays.
           = 1 => SVALEMF* overwrite (C)MOC*-computed flow-in
                  emfs with preset flow-in arrays, but BVALEMFS
                  doesn't.
           = 2 => Both SVALEMF* and BVALEMFS overwrite (C)MOC*-
                  computed flow-in emfs with preset flow-in
                  arrays.
tspinup    time to add all the desired angular velocity (SPINUP).    1.0
           1.0 is characteristic time scale of the Bondi problem.
delta      amplitude of imparted angular velocity (SPINUP)      sqrt(2.0)
           Default puts centrifugal barrier at critical point
           (r=1) for perturbed Bondi flow.
orbchk     = 0 => BNDYCHK will abort at a non-physical boundary.     0
           = 1 => BNDYCHK issues a warning at a non-physical
                 boundary, but execution continues (dangerous!).
pjump     minimum pressure jump that defines a "strong shock";       2.0
           sets the limit for diffusive shock acceleration
cadvs      = 1 => consistent advection (CA) used with scalar         0
                  (energy) transport
           = 0 => CA not used with scalar transport
cadvc      = 1 => CA     used with compressive momentum transport    1
           = 0 => CA not used with compressive momentum transport
cadvt      = 1 => CA     used with transverse  momentum transport    1
           = 0 => CA not used with transverse  momentum transport
trnvrsn    = 0 => use legacy CMoC algorithm (MoC, HSMOC, CT)         1
           = 1 => use the FIT algorithm
           = 2 => same as 1, but with transverse Lorentz terms
                  rendered in conservative form.
           =-2 => same as 2 but for legacy transport
           = 3 => same as 2, but with new source terms in CTRAN*
                  expressed as a true flux triggering "magnetic
                  centrifugal" terms in STV*
           =-3 => same as 3 but for legacy transport

Toggles for highly experimental "downwinding" algorithm:

uordq      = 1 =>   upwinded interpolations of qq (art. visc.)       1
           = 2 => downwinded interpolations of qq
```

```
avordw    = 1 => use 2-point averages for v* for et <-> e1          2
          = 2 => use downwinded v* for et <-> e1
voutbc    = 1 => outflow BC, v1(is) set to min(0,v1(isp1)),         1
                 original Wilson scheme (same @ other boundaries)
          = 2 => outflow BC, v1(is) set to min(0,v1(is)) to
                 reduce negative pressures at boundaries

The routine SPINUP and the associated namelist variables "tspinup" and "delta"
were designed to perturb Bondi flow to form discs, but can be used in other
applications in which a gradual spin-up of the grid is desired.

      namelist / hycon    /
     1               qcon    , qlin    , courno  , dtrat   , dtmax
     2             , dtset   , iord    , iords   , istp    , dfloor
     3             , e1floor , e2floor , v1floor , v2floor , v3floor
     4             , b1floor , b2floor , b3floor , dafloor , icool
     5             , itote   , iscydf  , iscyqq  , ix1x2x3 , mind
     6             , nu      , isetemf , tspinup , delta   , orbchk
     7             , pjump   , cadvs   , cadvc   , cadvt   , trnvrsn
     8             , uordq   , avordw  , voutbc
```

B.8 IIB—Inner I Boundary control (subroutine NMLSTS)

This namelist specifies both the boundary type and the inflow values for the variables that can be set at the inner-i boundary. These variables are *not* declared if the *EDITOR* macro `ISYM` is set. Any one of ten MHD boundary conditions may be specified independently at every boundary zone by setting `niib(j,k)` to the desired value of `btype`, as follows:

```
btype =  1 (-1) =>  reflecting; grid singularity or symmetry axis
      =  2  (1) =>  reflecting; non-conducting boundary (b_par=0 on bdy)
      =  3  (5) =>  reflecting; conducting boundary (b_perp=0 on bdy)
      =  4  (6) =>  reflecting; no B components change sign across boundary
      =  5  (4) =>  periodic
      =  6      =>  self-computing (for AMR)
      =  7      =>  outflow (not yet functional)
      =  8      =>  selective inflow
      =  9  (2) =>  non-characteristic outflow
      = 10  (3) =>  non-characteristic inflow
```

where the values of `btype` used in versions of *ZEUS-3D* previous to 3.5 are given parenthetically.

The boundary values for the variables are used only in the event that a zone along the boundary is inflow (`btype=8,10`). Otherwise, the boundary value is determined from the flow variables on the active portion of the computational grid. The flow variables are `d` (density), `e1` (first internal energy density), `e2` (second internal energy density), `er` (radiation energy density), `v1` (1-velocity), `v2` (2-velocity), and `v3` (3-velocity). In addition, skin values for the transverse *emf* components and boundary values for the transverse magnetic field components can be set (see extensive discussion below). Note that boundary values for the *total* energy (`et`) are not set directly. These are computed (in `BVALET`) from the boundary values of the primitive variables

The boundary type for the gravitational potential (`gtype`) is treated independently of the MHD boundaries, since the nature of the Poisson equation (elliptical) is different from

that of the MHD equations (hyperbolic). Gravitational boundary type is specified by setting `giib` to the desired value of `gtype`, as follows:

```
gtype = 5  (4) =>  periodic
      = 9  (2) =>  six-term multipole expansion
      = 10 (3) =>  analytical (or preset) boundary values stored in gpiib.  Time-
                   varying boundaries can be updated by a routine aliased to
                   BNDYUPDATE
```

where the values of `gtype` used in versions of *ZEUS-3D* previous to 3.5 are given parenthetically. Any other value for `gtype` means the boundaries of ϕ are never updated, which would be appropriate for constant boundary values set as part of the initial conditions.

New to version 3.5: Magnetic boundary conditions have been completely revamped, and a new, stable algorithm has been implemented. To start, a distinction is now made between the *skin* (which can receive characteristic information directly from the boundary region and/or the active grid) and the *boundary*, which can only receive characteristic information from the boundary region within a given CFL-limited timestep. For example, at the inner-i boundary, the `i=is` face constitutes the "skin", while all zones—face- or zone-centred—at `i=ism1, ism2` are *in* the boundary. Because of this distinction, magnetic "skin" values and "boundary" values are now treated differently in *ZEUS-3D*. Skin values are set in routines `SVALEMF*` which are called by the `(C)MOC*` routines where the distinction between the two "terms" in the *emf*s is needed to set some skin conditions. Boundary values are set by `BVALEMFS` called at the top of `CT` where all components of the *emf*s are needed to set the boundary conditions for each.

The main problem with the algorithm used in version 3.4 was that skin values of the magnetic field were set directly when setting boundary conditions. This is folly, since resetting the magnetic flux through the face of a zone lying along the skin changes the net magnetic flux into the adjacent grid zone, introducing a magnetic monopole. This problem was particularly acute when setting inflow boundaries, and thus all inflow arrays such as `b1iib1` which allowed the normal (to the boundary) magnetic field to be set directly both on the skin and inside the boundary have been purged from the code.

In this version, the user must now completely initialise all magnetic field arrays (`b1`, `b2`, and `b3`) in their problem generator, including all boundaries. For inflow boundaries, *skin* values of the parallel field (*e.g.*, B_1 at the i-skins) are maintained by user-set arrays `emf2iib1` and `emf3iib1` which lie along the inner i-skin. Typically, these components of the *emf* are set by physical boundary conditions on the skin (*e.g.*, $v_2 = v_3 = 0$; $B_2 = B_3 = 0 \Rightarrow \varepsilon_2 \propto v_3 B_1 - v_1 B_3 = 0$; $\varepsilon_3 \propto v_1 B_2 - v_2 B_1 = 0$). Meanwhile, *boundary* values for the parallel field [*e.g.*, `b1(ism2:ism1)`] are determined by the solenoidal condition and thus are allowed to "float", regardless of boundary conditions. Accordingly, there are no arrays `emf2iib2`, `emf3iib2`, *etc.*

As in previous versions of the code, inflow conditions on the *transverse* magnetic field components (*e.g.*, B_2 and B_3 at the i-boundaries) are controlled by the user-set arrays `b2iib1`, `b2iib2`, `b3iib1`, and `b3iib2` at the inner-i boundary. Note that there are no *skin* values for the transverse components, only boundary values. Should constant boundary values be desired, these are most conveniently set to the corresponding initial values of `b2` and `b3`. Should these components need to vary in time, the user must supply updated values

of b2iib1, b2iib2, b3iib1, and b3iib2 at the current time and proper location at the beginning of each MHD cycle. For this, the *EDITOR* alias BNDYUPDATE can be aliased to a user-supplied routine that sets the boundary arrays as needed (§2.2.2).

Further, the concept of *selectively* setting inflow conditions depending on whether various characteristics arrive at the skin from the boundary or grid has been introduced. For the *emf*s, selective inflow conditions is controlled by the parameter isetemf, set in namelist hycon. In general, if one expects the skin to receive information only from the boundary region (as in *super-fast* inflow), isetemf should be set to 1 and the user should supply values for the transverse *emf*s based on boundary conditions alone. If flow across the boundary is *sub-fast*, *sub-Alfvén*, or even *sub-slow*, isetemf *probably* should be set to 0 (in which case, the skin *emf*s will remain as computed by the (C)MOC* routines), though there are circumstances where it still may be best to set isetemf differently (*e.g.*, CORONA). Regardless, care must be taken not to over-specify the boundary.

Selective inflow conditions are enabled using the new boundary type 8. This behaves just like boundary type 10 (inflow), except it allows designated variables to "float" at the boundary (take on the nearest grid value) rather than being set to the pre-determined boundary arrays (*e.g.*, diib1 for density). To specify that a variable float, its boundary array should be set to the global parameter huge (§C.6), a nonsensical value that triggers logic in the boundary routines to set the variable according to its value in the nearest active grid zone (very similar to reflecting boundary type 2, except v1 is not set to zero at i=is). An example of the use of selective inflow conditions may be found in the problem generator CORONA for the case where local parameter oork=2. This establishes the so-called *Krasnopolsky conditions*, first introduced into an NCSA version of *ZEUS-3D* by Krasnopolsky, *et al.* (1999, ApJ, 526, 631) to launch sub-Alfvénic (initially) astrophysical jets from an accretion disc maintained as a boundary condition.

Additional discussion may be found in §1.5.

```
parameter                       description                          default

niib  (j,k)      "btype" of inner i boundary on sweep j,k              9
giib             "gtype" of entire inner i boundary                    2
**iib1(j,k)      first  inner i boundary value of variable **       **floor
                 for sweep j,k (flow in only)
**iib2(j,k)      second inner i boundary value of variable **       **floor
                 for sweep j,k (flow in only)
**iib3(j,k)      third  inner i boundary value of variable **       **floor
                 for sweep j,k (flow in only)
gpiib*(j,k)      analytical or preset values for gp on iib             0.0
                 for sweep j,k (giib=3 only)
jsli             number of zones in j-direction to slip periodic       0
                 i-boundaries >0 => oib is ahead of the iib.
ksli             number of zones in k-direction to slip periodic       0
                 i-boundaries >0 => oib is ahead of the iib.

       namelist / iib      /
     1               niib    , giib    , diib1   , diib2   , v1iib1
     2             , v1iib2  , v1iib3  , v2iib1  , v2iib2  , v3iib1
     3             , v3iib2  , jsli    , ksli
*if -def,ISO
```

```
     4             , e1iib1  , e1iib2
*endif -ISO
*if def,TWOFLUID
     5             , e2iib1  , e2iib2
*endif TWOFLUID
*if def,RADIATION
     6             , eriib1  , eriib2
*endif RADIATION
*if def,GRAV
     7             , gpiib1  , gpiib2
*endif GRAV
*if def,MHD
     8             , emf1iib1, emf1iib2, emf2iib1, emf3iib1, b3iib1
     9             , b3iib2  , b2iib1  , b2iib2
*endif MHD
*if def,AGING
     1             , daiib1  , daiib2
*endif AGING
```

Only `v1` has three boundary values that can be set (at `i=is,ism1,ism2`). Since just the skin values of `emf2` and `emf3` can be set, there is no second or third boundary variable available. All remaining variables are zone-centred in the i-direction, and thus have two boundary values to set (at `i=ism1,ism2`).

B.9 OIB—Outer I Boundary control (subroutine NMLSTS)

This namelist specifies both the boundary type and the in-flow values of all the flow variables for the outer-i boundary. These variables are *not* declared if the *EDITOR* macro `ISYM` is set. See comments for `IIB`.

```
parameter                    description                          default

noib  (j,k)     "btype" of outer i boundary on sweep j,k             2
goib            "gtype" of entire outer i boundary                   2
**oib1(j,k)     first  outer i boundary value of variable **      **floor
                for sweep j,k (flow in only)
**oib2(j,k)     second outer i boundary value of variable **      **floor
                for sweep j,k (flow in only)
**oib3(j,k)     third  outer i boundary value of variable **      **floor
                for sweep j,k (flow in only)
gpoib*(j,k)     analytical or preset values for gp on oib            0.0
                for sweep j,k (goib=3 only)
```

```
       namelist / oib      /
     1               noib    , goib    , doib1   , doib2   , v1oib1
     2             , v1oib2  , v1oib3  , v2oib1  , v2oib2  , v3oib1
     3             , v3oib2
*if -def,ISO
     4             , e1oib1  , e1oib2
*endif -ISO
*if def,TWOFLUID
     5             , e2oib1  , e2oib2
*endif TWOFLUID
*if def,RADIATION
     6             , eroib1  , eroib2
*endif RADIATION
```

```
*if def,GRAV
     7             , gpoib1  , gpoib2
*endif GRAV
*if def,MHD
     8             , emf1oib1, emf1oib2, emf2oib1, emf3oib1, b3oib1
     9             , b3oib2  , b2oib1  , b2oib2
*endif MHD
*if def,AGING
     1             , daoib1  , daoib2
*endif AGING
```

B.10 IJB—Inner J Boundary control (subroutine NMLSTS)

This namelist specifies both the boundary type and the in-flow values of all the flow variables for the inner-j boundary. These variables are *not* declared if the *EDITOR* macro JSYM is set. See comments for IIB.

parameter	description	default
nijb (k,i)	"btype" of inner j boundary on sweep k,i	2
gijb	"gtype" of entire inner j boundary	2
**ijb1(k,i)	first inner j boundary value of variable ** for sweep k,i (flow in only)	**floor
**ijb2(k,i)	second inner j boundary value of variable ** for sweep k,i (flow in only)	**floor
**ijb3(k,i)	third inner j boundary value of variable ** for sweep k,i (flow in only)	**floor
gpijb*(k,i)	analytical or preset values for gp on ijb	0.0
kslj	number of zones in k-direction to slip periodic j-boundaries >0 => ojb is ahead of the ijb.	0
islj	number of zones in i-direction to slip periodic j-boundaries >0 => ojb is ahead of the ijb.	0

```
       namelist / ijb      /
     1               nijb    , gijb    , dijb1   , dijb2   , v1ijb1
     2             , v1ijb2  , v2ijb1  , v2ijb2  , v2ijb3  , v3ijb1
     3             , v3ijb2  , kslj    , islj
*if -def,ISO
     4             , e1ijb1  , e1ijb2
*endif -ISO
*if def,TWOFLUID
     5             , e2ijb1  , e2ijb2
*endif TWOFLUID
*if def,RADIATION
     6             , erijb1  , erijb2
*endif RADIATION
*if def,GRAV
     7             , gpijb1  , gpijb2
*endif GRAV
*if def,MHD
     8             , emf2ijb1, emf2ijb2, emf3ijb1, emf1ijb1, b1ijb1
     9             , b1ijb2  , b3ijb1  , b3ijb2
*endif MHD
*if def,AGING
     1             , daijb1  , daijb2
*endif AGING
```

B.11 OJB—Outer J Boundary control (subroutine NMLSTS)

This namelist specifies both the boundary type and the in-flow values of all the flow variables for the outer-j boundary. These variables are *not* declared if the *EDITOR* macro JSYM is set. See comments for IIB.

```
parameter                    description                          default

nojb  (k,i)     "btype" of outer j boundary on sweep k,i             2
gojb            "gtype" of entire outer j boundary                   2
**ojb1(k,i)     first  outer j boundary value of variable **      **floor
                for sweep k,i (flow in only)
**ojb2(k,i)     second outer j boundary value of variable **      **floor
                for sweep k,i (flow in only)
**ojb3(k,i)     third  outer j boundary value of variable **      **floor
                for sweep k,i (flow in only)
gpojb*(k,i)     analytical or preset values for gp on ojb            0.0
```

```
       namelist / ojb      /
     1               nojb    , gojb    , dojb1   , dojb2   , v1ojb1
     2             , v1ojb2  , v2ojb1  , v2ojb2  , v2ojb3  , v3ojb1
     3             , v3ojb2
*if -def,ISO
     4             , e1ojb1  , e1ojb2
*endif -ISO
*if def,TWOFLUID
     5             , e2ojb1  , e2ojb2
*endif TWOFLUID
*if def,RADIATION
     6             , erojb1  , erojb2
*endif RADIATION
*if def,GRAV
     7             , gpojb1  , gpojb2
*endif GRAV
*if def,MHD
     8             , emf2ojb1, emf2ojb2, emf3ojb1, emf1ojb1, b1ojb1
     9             , b1ojb2  , b3ojb1  , b3ojb2
*endif MHD
*if def,AGING
     1             , daojb1  , daojb2
*endif AGING
```

B.12 IKB—Inner K Boundary control (subroutine NMLSTS)

This namelist specifies both the boundary type and the in-flow values of all the flow variables for the inner-k boundary. These variables are *not* declared if the *EDITOR* macro KSYM is set. See comments for IIB.

```
parameter                    description                          default

nikb  (i,j)     "btype" of inner k boundary on sweep i,j             2
gikb            "gtype" of entire inner k boundary                   2
**ikb1(i,j)     first  inner k boundary value of variable **      **floor
                for sweep i,j (flow in only)
**ikb2(i,j)     second inner k boundary value of variable **      **floor
                for sweep i,j (flow in only)
```

```
**ikb3(i,j)     third  inner k boundary value of variable **      **floor
                for sweep i,j (flow in only)
gpikb*(i,j)     analytical or preset values for gp on ikb            0.0
islk            number of zones in i-direction to slip periodic      0
                k-boundaries >0 => okb is ahead of the ikb.
jslk            number of zones in j-direction to slip periodic      0
                k-boundaries >0 => okb is ahead of the ikb.

      namelist / ikb      /
     1              nikb    , gikb    , dikb1   , dikb2   , v1ikb1
     2            , v1ikb2  , v2ikb1  , v2ikb2  , v3ikb1  , v3ikb2
     3            , v3ikb3  , islk    , jslk
*if -def,ISO
     4            , e1ikb1  , e1ikb2
*endif -ISO
*if def,TWOFLUID
     5            , e2ikb1  , e2ikb2
*endif TWOFLUID
*if def,RADIATION
     6            , erikb1  , erikb2
*endif RADIATION
*if def,GRAV
     7            , gpikb1  , gpikb2
*endif GRAV
*if def,MHD
     8            , emf3ikb1, emf3ikb2, emf1ikb1, emf2ikb1, b2ikb1
     9            , b2ikb2  , b1ikb1  , b1ikb2
*endif MHD
*if def,AGING
     1            , daikb1  , daikb2
*endif AGING
```

B.13 OKB—Outer K Boundary control (subroutine NMLSTS)

This namelist specifies both the boundary type and the in-flow values of all the flow variables for the outer-k boundary. These variables are *not* declared if the *EDITOR* macro KSYM is set. See comments for IIB.

```
parameter                    description                          default

nokb  (i,j)     "btype" of outer k boundary on sweep i,j             2
gokb            "gtype" of entire outer k boundary                   2
**okb1(i,j)     first  outer k boundary value of variable **      **floor
                for sweep i,j (flow in only)
**okb2(i,j)     second outer k boundary value of variable **      **floor
                for sweep i,j (flow in only)
**okb3(i,j)     third  outer k boundary value of variable **      **floor
                for sweep i,j (flow in only)
gpokb*(i,j)     analytical or preset values for gp on okb            0.0

      namelist / okb      /
     1              nokb    , gokb    , dokb1   , dokb2   , v1okb1
     2            , v1okb2  , v2okb1  , v2okb2  , v3okb1  , v3okb2
     3            , v3okb3
*if -def,ISO
     4            , e1okb1  , e1okb2
*endif -ISO
```

```
*if def,TWOFLUID
     5             , e2okb1  , e2okb2
*endif TWOFLUID
*if def,RADIATION
     6             , erokb1  , erokb2
*endif RADIATION
*if def,GRAV
     7             , gpokb1  , gpikb2
*endif GRAV
*if def,MHD
     8             , emf3okb1, emf3okb2, emf1okb1, emf2okb1, b2okb1
     9             , b2okb2  , b1okb1  , b1okb2
*endif MHD
*if def,AGING
     1             , daokb1  , daokb2
*endif AGING
```

B.14 GRVCON—GRaVity CONtrol, (subroutine NMLSTS)

Gravitational self-potential is switched on by defining GRAV and aliasing GRAVITY to the desired gravity routine. If GRAVITY is aliased to gravity, the user must select the desired Poisson-solver by specifying a value for grvalg.

A point mass potential can be included by specifying a positive value for ptmass. A point mass potential does not require defining GRAV, does not call the GRAVITY module, and is not included in the array gp which is strictly used for *self*-gravity. Its effect is explicitly added as velocity source terms in the routines stv1, stv2, and stv3. Thus, a point-mass potential may be used in conjunction with self-gravity or with self-gravity turned off. Note that ptmass should scale with d*x1**3.

Finally, a uniform background acceleration (as on the surface of the Earth) may be imposed along one of the grid directions by specifying a non-zero value for gacc (negative value ⇒ toward inner boundary) and gdir. As with ptmass, gacc is applied directly in STV* without requiring GRAV to be defined and independent of array gp. Note that gacc should scale with cs**2/dx1. Thus, on the surface of the Earth and with cs = 331.5 m/s = 1 (scaled) and dx1 = 1 m = 1 (scaled), g = 9.81 m/s^2 = 8.93 × 10^{-5} (scaled).

parameter	description	default
gcnst	gravitational constant = 0.25/pi for unitless calculations = 6.67428d-11 for mks (2006 CODATA value) = 6.67428d-08 for cgs	0.25/pi
ptmass	fixed central point mass object. If using scaled units, "ptmass" (scaled point mass M) will depend on "gcnst", the scaling for density, and grid size. For gcnst = 1/(4 pi), ptmass = (4 pi G M) / (ds rs**3), where "ds" is the density scale and "rs" the length scale. For M = 1 solar mass, ds = 3.0e5 H atoms per m**3, and rs = 1.0e3 AU, ptmass ~ 1.	0.0
iptmass	i index of point mass	ismn
jptmass	j index of point mass	jsmn
kptmass	k index of point mass	ksmn
gacc	uniform background acceleration field	0.0

```
                < 0 => toward inner boundary
                > 0 => toward outer boundary
gdir            direction of gacc                                    1
grvalg          self-gravitational algorithm to be used.             1
                = 1 => Successive Overrelaxation (SOR)
                = 2 => Full Multi-grid (FMG)
                = 3 => FFT/FST solvers
gcycle          maximum number of iterations for SOR          GRAVITYITER
                number of V-cycles for FMG
epsgrv          maximum tolerance for convergence of         GRAVITYERROR
                Poisson solvers

      namelist / grvcon   /
     1               gcnst   , ptmass  , iptmass , jptmass , kptmass
     2             , gacc    , gdir    , grvalg  , gcycle  , epsgrv
```

B.15 AMBCON—AMBipolar Diffusion CONtrol, (subroutine NMLSTS)

This namelist includes the parameters to control ambipolar diffusion (AD), and is included in the precompiled code if the `AMBIDIFF` macro is defined. Note that if `gammaad<0`, AD will not be applied.

Ambipolar diffusion is the physical process by which magnetic field is not fully coupled to the fluid. If only a portion of the fluid is ionised, the neutral particles are coupled to the magnetic field only via collisions with the ionised particles which *are* coupled to the field. Failure of such collisions to keep the ionised and neutral components together can cause some mass to "slip" relative to the magnetic field, a process known as ambipolar diffusion.

Done properly, one would track both the neutral and ionised components as two separate but co-spatial fluids. Given the current capability of *ZEUS-3D* to track a second fluid, this may not be terribly difficult to implement though, at the time of this writing, has not been tried. Instead, the one-fluid approach of Duffin & Pudritz (2008, MNRAS, 391, 1659) has been implemented which is computationally relatively inexpensive, but does limit its use to *low-ionisation* fluids.

As a parabolic term in an otherwise hyperbolic system of equations, the CFL-limited AD time step is typically much less (by a factor of $\sim$100) than the MHD time step. Running the simulation on the AD time step (`iscyad` = 0), while being the most accurate, can be prohibitively expensive computationally. Alternately, one can run on the MHD time step and sub-cycle on the AD time step (`iscyad` = 1), much like is currently possibly for a diffusive second fluid (`iscydf`) and the artificial viscosity (`iscyqq`). This speeds up the 1-D C-shock test by a factor of $\sim$ 5–6. Better still, one can "super-step" on the AD time step (Meyer *et al.*, 2012, MNRAS, 422, 2102) giving a further factor of $\sim$ 6 speed-up with little if any appreciable cost in accuracy over sub-cycling.

The default settings assume that the gas is a mix of 10% He and 90% H, by number of atoms. The ions are taken to be HCO^+ and Na^+, which both have masses of approximately 29.0 a.m.u., and hydrogen is assumed to be molecular. `gammaad` is given by:

$$\gamma_{\rm AD} = \frac{\langle\sigma\nu\rangle_{\rm ni}}{m_{\rm i}+m_{\rm n}},$$

where $\langle\sigma\nu\rangle_{\rm ni}$ is the collision rate between neutral and ionized particles ($1.7\times10^{-9}\,{\rm cm^3\,s^{-1}}$ for

H_2), m_i is the mass of an ion, and m_n is the mass of a neutral particle. For the gas described here, $\gamma_{AD} = 3.28 \times 10^{13}\,g^{-1}\,cm^3\,s^{-1}$.

For further details, the reader is referred to Duffin & Pudritz (2008, MNRAS, 391, 1659), or the Honours thesis by Chris MacMackin (2015, SMU).

```
parameter                    description                              default

iscyad          =0 => no subcycling for AD                              1
                =1 => subcycling for AD
                =2 => super time-stepping for AD
gammaad         drag coefficient representing coupling between        -1.0
                ions and neutrals. <0 => huge, turning off AD.
                Default masses => 3.28d13 g^-1 cm^3 s^-1.
betacoef        numerator in expression for AD beta. For 10% He,        1.4
                90% H, use 1.4. For 100% H, use 1.0.
ionconst        =0 => calculate ion density using parameterisation      0
                =1 => constant ion density (for C-shock tests)
dscale          scaling to convert ion density from ZEUS to cgs         2.0d-18
                units.
mion            mass of ions in cgs units                               4.81d-23
mneutral        mass of neutrals in cgs units                           3.82d-24

      namelist / ambcon   /
     1               iscyad  , gammaad , betacoef, ionconst, dscale
     2             , mion    , mneutral
```

B.16 EQOS—EQuation Of State control (subroutine NMLSTS)

This namelist specifies the parameters which control the equation of state. Using all the defaults is recommended, unless a different adiabatic constant (gamma) is required. Note that if an isothermal equation of state is desired, setting the *EDITOR* definition `ISO` in addition to setting `niso` = 1 will allow execution to take advantage of the reduced computations necessary for isothermal systems. Parameters dimensioned with `nmat` allow for values to be set for both fluids if `TWOFLUID` is set, with the first element reserved for the first fluid (that which exists when `TWOFLUID` is not set), and the second element for the second (possibly diffusive) fluid enabled when `TWOFLUID` is set.

```
parameter                    description                              default

gamma   (nmat)  ratio of specific heats                                 5/3
rgas    (nmat)  gas constant                                            1.0
niso    (nmat)  = 0 => adiabatic  eos                                   0
                = 1 => isothermal eos
ciso    (nmat)  isothermal sound speed                                  1.0
rmetal  (nmat)  metallicity => cooling strength  M-MML                  0.0
diffc1, diffc2  diffusion coefficient (for the second fluid) is         0.0
                set to diffc1 / B**diffc2

      namelist / eqos     /
     1               gamma   , rgas    , niso    , ciso    , rmetal
     2             , diffc1  , diffc2
```

B.17 GCON—Grid motion CONtrol (subroutine NMLSTS)

This namelist sets the parameters for grid motion, should a partial tracking of the flow be required. This feature has been dormant for years, and should this feature be desired, some code development may be required.

```
parameter                    description                          default

x1fac          x1 motion factor                                     0.0
               < 0 gives "Lagrangian" tracking in x1 lines
x2fac          x2 motion factor                                     0.0
               < 0 gives "Lagrangian" tracking in x2 lines
x3fac          x3 motion factor                                     0.0
               < 0 gives "Lagrangian" tracking in x3 lines
ia             i<ia => zone ratio is preserved in x1 lines       is=3
ja             j<ja => zone ratio is preserved in x2 lines       js=3
ka             k<ka => zone ratio is preserved in x3 lines       ks=3
igcon          selects grid treatment:                              0
               =0 => separate motion
               =1 => averaged motion
               =2 => tracking x1, x2, and x3 boundaries
               =3 => averaged boundary tracking
               =4 => input grid boundary speeds
                     vg1(ie) = x1fac * central sound speed
                     vg2(je) = x2fac * central sound speed
                     vg3(ke) = x3fac * central sound speed

      namelist / gcon     /
     1               x1fac   , x2fac   , x3fac   , ia      , ja
     2             , ka      , igcon
```

B.18 EXTCON—grid EXTension CONtrol (subroutine NMLSTS)

This namelist controls the grid extension feature of the code. This is useful only for problems in which a shock separates quiescent material (which does not require updating) from material requiring computations. As the shock propagates across the grid, more zones are added to the computational domain until the entire domain has been included. Because quiescent zones are not being updated, a substantial savings in computation time could be realised. Use this feature with caution; improper use can be disastrous.

```
parameter                    description                          default

istretch(1) .le.  0  => perform computations over entire i-domain    0
            .gt.  0  => i-index of first zone in initial i-domain
istretch(2)             i-index of last  zone in initial i-domain.   0
            .le. (1) => istretch(2)=istretch(1)+istretch(3)-1
istretch(3) .le.  0  => 10                                           0
istretch(4) .le.  0  => istretch(3)                                  0
jstretch(1,2,3,4)       same as "istretch", but for 2-direction.
kstretch(1,2,3,4)       same as "istretch", but for 3-direction.
extvar                  specifies variable used to detect dis-       'd'
                        turbance in the quiescent ambient medium
                        (character*2).  Legal values are: 'd ',
                        'e ' (pressure), 'se' (temperature).
```

Note that `ismn` and `iemx` are the user-imposed limits of the grid in the `i`-direction, while `is` and `ie` are the `i`-limits of the do-loops. With grid extension off, `is = ismn` and `ie = iemx`. With grid extension on, `is .ge. ismn` and `ie .le. iemx` (§C.1). `is` is decremented by `istretch(3)` and/or `ie` is incremented by `istretch(4)` whenever the quiescent value of the specified variable (`extvar`) changes by 3% within 5 zones of the current domain boundary. Note that `is` will not be permitted to fall below `ismn` and `ie` will not be permitted to rise above `iemx`. Grid extension in the `i`-direction is turned off by keeping `istretch(1) = 0` (its default value).

An entirely analogous discussion holds for the `j`- and `k`-directions.

```
      namelist / extcon   /
     1               istretch, jstretch, kstretch, extvar
```

B.19 PL1CON—PLot (1-D) CONtrol (subroutine NMLSTS)

This namelist controls the 1-D graphics. During a run, as many as `nios` 1-D slices may be specified for each variable plotted, where `nios` is a parameter set before compilation. For every slice chosen, a file (in either metacode or postscript) is created with a plot generated for each variable specified. These plots may be arranged in the same frame or separate frames, and can have any rectangular shape desired. All plots are of publication quality. Each 1-D slice (bounded by `x1pl1mn`, `x1pl1mx`, *etc.*) runs parallel to one of the axes of the computational grid. To specify the slice uniquely, two of `ipl1`, `jpl1`, and `kpl1` must be set. If `ipl1mn`, *etc.* is 0, `x1pl1mn`, *etc.* is used instead.

For 1-D runs such as shock-tube tests, the analytical solution may be overlaid by setting *EDITOR* macro `RIEMANN` and setting the namelist parameters `pl1soln` and `xdiscpl1`. The Riemann solver (courtesy of Tom Jones) takes the end points of the 1-D run as the left and right states, and thus the run should stop before the boundaries are reached.

N.B. For restarted runs in which the computation is resumed on a larger or smaller grid and where the default values for `x1pl1mn`, `x1pl1mx`, *etc.* were used in the initial run, it will be necessary to set `x1pl1mn`, `x1pl1mx`, *etc.* in the input deck for the restarted run to the extrema of the new grid if the plots are to extend to the bounds of the new grid. Otherwise, the plots will be bound by the old grid.

```
parameter                    description                              default

General

dtpl1           physical (problem) time interval between 1-D          0.0
                plot dumps.  0.0 => no plots.
npl1dmp         the sequential number for the next 1-D plot file     -1
                < 0 => npl1dmp = ipl1dmp (default)
units           sets the units of angular dimensions (character*2)    'rd'
                'dg' => degrees, 'rd' => radians
                'pi' => units of pi radians
aspect          < 1.0 => plots are wide and short                     1.0
                = 1.0 => square plots
                > 1.0 => plots are tall and narrow
pwtpl1          pen weight for 1-D plots                              1.0
norppl1         = 1 => use NCAR graphics library for 1-D plots        2
                = 2 => use PSPLOT graphics library for 1-D plots
```

```
corl            selector for lines and symbols for plots            1
                =-6 => open diamonds; one per plot element
                =-5 => open pentagrams
                =-4 => asterisk (*)
                =-3 => open squares
                =-2 => open triangles
                =-1 => plus signs (+)
                = 0 => crosses (x)
                = 1 => open circles (o)
                = 2 => smooth curve drawn through points
                any other value => no plot
npl1h           number of frames horizontally per page              1
npl1v           number of frames vertically   per page              1
allxl           = 2 => all x labels/annotations are drawn           2
                = 1 => only the x-label/annotations on the bottom
                       row of plots on the page are drawn.
                = 0 => labels aren't even drawn on the bottom row.
                allxl < 0 same as abs(allxl) except last annotation
                is not drawn if it falls at right edge of frame.
                If plots are assembled a posterori, this is useful
                to prevent right-most annotation of left plot from
                overwriting left-most annotation of right plot.
allyl           = 2 => all y labels/annotations are drawn           2
                = 1 => only the y-label/annotations on the left
                       column of plots on the page are drawn.
                = 0 => labels aren't even drawn on the left column.
pl1hdr          = 0 => suppresses header                            1
                = 1 => header is printed on top    of plot
pl1ftr          = 0 => suppresses footer                            1
                = 1 => footer is printed on bottom of plot

Slice control

pl1dir  (nios)  direction of 1-D plot: 1, 2, or 3 => 1-, 2-, or     0
                3-direction.  0 => no plots.
ipl1    (nios)  i index of 1-D plot in 2- or 3-direction       (is+ie)/2
jpl1    (nios)  j index of 1-D plot in 3- or 1-direction       (js+je)/2
kpl1    (nios)  k index of 1-D plot in 1- or 2-direction       (ks+ke)/2
x1pl1mn (nios)  minimum x1 of slice; or used by "pl1mean"      x1a(is)
x1pl1mx (nios)  maximum x1 of slice; or used by "pl1mean"      x1a(ie+1)
x2pl1mn (nios)  minimum x2 of slice; or used by "pl1mean"      x2a(js)
x2pl1mx (nios)  maximum x2 of slice; or used by "pl1mean"      x2a(je+1)
x3pl1mn (nios)  minimum x3 of slice; or used by "pl1mean"      x3a(ks)
x3pl1mx (nios)  maximum x3 of slice; or used by "pl1mean"      x3a(ke+1)
ipl1mn  (nios)  i-index of minimum x1 of slice                      0
ipl1mx  (nios)  i-index of maximum x1 of slice                      0
jpl1mn  (nios)  j-index of minimum x2 of slice                      0
jpl1mx  (nios)  j-index of maximum x2 of slice                      0
kpl1mn  (nios)  k-index of minimum x3 of slice                      0
kpl1mx  (nios)  k-index of maximum x3 of slice                      0
pl1xlab (nios)  character string containing NCAR mark-up language
                (see below) for the desired x-label.  Default is
                the generic coordinate label (x1, x2, x3).

NCAR markup syntax:

    Fonts: |F0|  = times-roman (default)
           |F10| = times-roman italic
           |F14| = times-roman italic bold
```

```
           |F5|  = greek italic: |F5|r => \rho; |F5|w => \omega
           |F18| = math characters: |F18|A = \perp; |F18|R => \parallel
                                    |F18|Q = | (vertical bar)
           |F34| = math characters: |F34|W = \cdot; |F34|Q => \nabla
                                    |F34|0 = \deg

    Position: |B| => subscript; |S| => superscript; |N| => normal

    One may combine one position designator with one font change in
    each "field" (bounded by ||), and then string as many fields
    together as one needs:
           "|F10|e|BF0|t|NF10|+e|BF0|r" = $e_{\rm t}+e_{\rm r}$

Variable control

pl1var  (niov)  names of variables to be plotted (character*2).      'zz'
                Valid names are: 'a ' (vector potential norm),
                'a1', 'a2', 'a3' (vector potential components),
                'ag' (synchrotron age), 'B3' (b3*b3), 'b ' (mag-
                netic field norm), 'b1', 'b2', 'b3', 'ba', 'bb',
                'bc' (magnetic field components), 'bd' (magnetic
                field norm/density), 'bP', 'bR' (phi- and radial
                magnetic field components), 'br' (bremsstrahlung
                emissivity), 'bt' (plasma beta), 'cs' (sound
                speed), 'd ' (density), 'da' (density-age), 'e1'
                (1st int. energy), 'e2' (2nd int. energy), 'er'
                (radiation energy), 'et' (total energy density),
                'gl' [d(r lt) / dr], 'gk' [d(r kt) / dr], 'gp'
                (gravitational potential), 'hy' [(1/rho) dp/dr -
                3/(2r**2)], 'j ' (current density norm), 'j1',
                'j2', 'j3' (current density components), 'k1'
                (entropy of 1st fluid), 'k2' (2nd entropy), 'ka'
                (avg. 1st + 2nd ent.), 'kt' (kinetic viscous
                radial trans.), 'lu' (radiative luminosity), 'l '
                (angular momentum), 'lt' (angular momentum radial
                transport), 'm ' (Mach number), 'mA' (Alfven Mach
                number), 'mf' (fast MS Mach number), 'ms' (slow
                MS Mach number), 'om' (angular velocity), 'p1'
                (1st thermal pressure), 'p2' (magnetic pressure),
                'p3' (1st ther. + mag. pres.), 'p4' (2nd thermal
                pressure), 'p5' (1st ther. + 2nd ther. pres.),
                'p6' (mag. + 2nd ther. pres.), 'p7' (1st ther. +
                mag. + 2nd ther. pres.), 'pa' [pitch angle;
                atan(b1/bP)], 'pg' (pseudo-gravitational poten-
                tial), 'ps' [atan(b3/b2)], 's1', 's2', 's3'
                (momentum components), 'sy' (synchrotron emissiv-
                ity), 'u1' (1st specific int. energy), 'u2' (2nd
                specific int. energy), 'v ' (speed), 'v1', 'v2',
                'v3', 'va', 'vb', 'vc' (velocity components),
                'vA' (Alfven speed), 'vf' (fast speed), 'vs'
                (slow speed), 'vv' [div(v)], 'w ' (vorticity
                norm), 'w1', 'w2', 'w3' (vorticity components).
nlpl1   (niov)  = 1 => linear-linear     plot                        1
                = 2 => log(y)-linear(x)  plot
                = 3 => linear(y)-log(x)  plot
                = 4 => log-log           plot
pl1min  (niov)  minimum value to be plotted.                         0.0
pl1max  (niov)  maximum value to be plotted.                         0.0
pl1mm           = 1 => "pl1min" and "pl1max" are set to extrema      1
```

```
                       of each variable.
                  = 0 => Use input values of "pl1min" & "pl1max" to
                       set range of plot.  If pl1max .le. pl1min,
                       they are set to extrema (as though pl1mm=1)
                 =-1 => same as 0, but extend plot range by one
                       minor tick mark in each direction
pl1mean (niov)   = 0 => ordinary 1-D slices; no means taken.          0
                  = 1 => 1-D slices are filled with means of
                       variable across plane (limited by x*pl1mn
                       and x*pl1mx) orthogonal to the slice.
thetapl1         meridonal rotational angle between 1-2-3 & a-b-c   0.0
                 coordinates (to compute va vb vc from v1 v2 v3)
phipl1           azimuthal rotational angle between 1-2-3 & a-b-c   0.0
                 coordinates (to compute va vb vc from v1 v2 v3)
pl1ylab (niov)   character string containing NCAR mark-up language
                 for the desired y-label.  Most defaults are fine,
                 unless, for e.g., v_\phi is desired over v_3.

Overlays

pl1grid          every (pl1grid)th a-grid line is drawn as a fine     0
                 vertical line (for both regular and diagn. plots)
                 = 0 => no grid lines are drawn
pl1ref  (niov)   dashed reference line drawn on plot                -huge
                 (< -1.0d30 => no line)
pl1soln (niov)   = 0 => no overlay                                   0
                  = 1 => Analytical solution to Riemann problem
                       using end points of slice as left- and
                       right-states overlaid.
                  = 2 => analytical solution plotted without
                       numerical solution
xdiscpl1(nios)   location of discontinuity (default: middle of
                 slice)

Diagnostic dumps

dtgr1d           physical (problem) time interval between diag-       0.0
                 nostic 1-D graph dumps (0.0 => no plots)
```

If you are using *NCAR* graphics (`norppl1=1`), you will need to link all *NCAR* graphics libraries to your executable (see your system administrator if you do not know what or where these libraries are) as well as two user-created libraries, `grfx03.a` and `psplot.a`. If you are using *PSPLOT* (`norppl1=2`) exclusively, you can dispense with all the *NCAR* libraries, and just link `grfx03.a`, `psplot.a`, and `noncar.a`, the last of which serves only to satisfy external calls to non-existing *NCAR* subroutines.

```
      namelist / pl1con   /
     1              dtpl1   , npl1dmp , units   , aspect  , pwtpl1
     2            , norppl1 , corl    , npl1h   , npl1v   , allxl
     3            , allyl   , pl1hdr  , pl1ftr  , pl1dir  , ipl1
     4            , jpl1    , kpl1    , x1pl1mn , x1pl1mx , x2pl1mn
     5            , x2pl1mx , x3pl1mn , x3pl1mx , ipl1mn  , ipl1mx
     6            , jpl1mn  , jpl1mx  , kpl1mn  , kpl1mx  , pl1xlab
     7            , pl1var  , nlpl1   , pl1min  , pl1max  , pl1mm
     8            , pl1mean , thetapl1, phipl1  , pl1ylab , pl1grid
     9            , pl1ref  , pl1soln , xdiscpl1, dtgr1d
```

B.20 PL2CON—PLot (2-D) CONtrol (subroutine NMLSTS)

This namelist controls the 2-D graphics. During a run, as many as `nios` 2-D slices may be specified for each variable plotted. For every slice chosen, a file (metacode or postscript) is created with a plot generated for each individual or combination of variables specified. The normal to each slice is parallel to one of the axes of the computational grid and is specified by `pl2dir`. The extent of the slice is limited by `x1pl2mn`, `x1pl2mx`, *etc.*, while the index at the base of the normal to the slice is given by `lpl2`. If `ipl2mn`, *etc.* is 0, `x1pl2mn`, *etc.* is used instead.

New to version 3.6 is *buffet-style plotting* in which the user may select for each plot as many as two scalars, three vector fields, and the positions of some or all of the "corks" (Lagrangian particles). This is accomplished by the addition of several new namelist parameters to allow more than one variable to be plotted per plot, and users used to previous versions of *ZEUS-3D* should pay special attention to these new namelist parameters described below. In previous versions of *ZEUS-3D*, only a select few combination plots were available (*e.g.*, density plus velocity vectors). With the introduction of buffet-style plotting, the combination of variables that may be plotted together is now virtually limitless.

For PSPLOT graphics, the first scalar may be plotted using colour, gray scale, or line contours while the second scalar may be plotted using line contours only. If colour or grey scale contours is selected for the first scalar (`pl2ccol=1,2`), a colour bar is included immediately to the right of the plot (to indicate what values of the scalar correspond to each colour); this may be suppressed by negating `pl2ccol`. Each vector field may be drawn with different colours and a legend indicating which variables are represented by which contours and vectors is drawn in the upper right corner. The introduction of a legend (controlled by `pl2leg`) has obviated the need for a title, and thus `pl2hdr` is no longer a valid namelist parameter.

For NCAR graphics, both scalars must be line contours, and only one vector field may be specified. A legend is also produced instead of a title.

PSPLOT 2-D graphics can generate *enormous* post-script files; a single file with several variables plotted in full colour from a high-resolution data-slice (*e.g.*, 1,000 zones on a side) can approach 1 Gbyte. Not only does this needlessly occupy disc space and cause commonly-available graphics-viewers such as `ghostview` to take forever opening each page, it can also soak up all the available memory on the machine while the plots are being generated, limiting the number of zones in the simulation. Such plots tend to be *hyper-resolved* often with multiple graphics instructions assigned to each screen pixel, and are rarely worth the computational effort.

New to version 3.6, one can now mitigate against this by specifying parameters `npl2i` and `npl2j` to be smaller than the actual grid dimensions (*e.g.*, of the order 250–500). These parameters set the dimensions of the *re-binning* grids into which the 2-D data-slices are rebinned (much like pixel plots) before plotting. This can decimate the size of the post-script file while still generating perfectly acceptable plots, qualitatively identical to the hyper-resolved ones. (*N.B.*, If the "hyper-resolved" plots are still wanted—*e.g.*, for a poster—one can always dump *HDF* files as often as or instead of 2-D plots, then use *PLOTZ* after the simulation is completed to generate the desired plots.)

All plots are of publication quality and come fully labelled, including a time stamp

for easy identification. Unlike the 1-D plots, only one plot may be written to each frame. However, the plot may be scaled down (`pl2scale`) if desired.

N.B. For restarted runs in which the computation is resumed on a larger or smaller grid, and where the default values for `x1pl2mn`, `x1pl2mx`, *etc.* were used in the initial run, it will be necessary to set `x1pl2mn`, `x1pl2mx`, *etc.* in the input deck for the restarted run to the extrema of the new grid if the plots are to extend to the bounds of the new grid. Otherwise, the plots will be bound by the old grid.

parameter	description	default
General		
dtpl2	physical (problem) time interval between 2-D plot dumps. 0.0 => no plots.	0.0
npl2dmp	the sequential number for the next 2-D plot file < 0 => npl2dmp = ipl2dmp	-1
units	sets units of angular dimensions (character*2). 'dg' => degrees, 'rd' => radians, 'pi' => units of pi radians	'zz'
pl2scale	.lt. 1.0d0 => scaling factor to reduce plot size .ge. 1.0d0 => full size	1.0
pwtpl2	pen weight for 2-D plots	1.0
norppl2	= 1 => use NCAR graphics library for 2-D plots = 2 => use PSPLOT graphics library for 2-D plots	2
pl2grid	= 0 => do not overlay grid lines onto plots > 0 => overlay a-grid < 0 => overlay b grid every mod(|pl2grid|,1000)th grid line drawn	0
Slice control		
pl2dir (nios)	direction of normal to image plane: 1, 2, or 3 => 1-, 2-, or 3-direction. 0 => no plots.	0
lpl2 (nios)	level of 2-D plot (value of 1-, 2-, or 3-index)	(is+ie)/2
pl2avg (nios)	= 1 => averages slice with lpl2-1 = 0 => no average taken (default)	
x1pl2mn (nios)	minimum x1 of plot window	x1a(ismn)
x1pl2mx (nios)	maximum x1 of plot window	x1a(iemxp1)
x2pl2mn (nios)	minimum x2 of plot window	x2a(jsmn)
x2pl2mx (nios)	maximum x2 of plot window	x2a(jemxp1)
x3pl2mn (nios)	minimum x3 of plot window	x3a(ksmn)
x3pl2mx (nios)	maximum x3 of plot window	x3a(kemxp1)
ipl2mn (nios)	i-index of minimum x1 of plot window	0
ipl2mx (nios)	i-index of maximum x1 of plot window	0
jpl2mn (nios)	j-index of minimum x2 of plot window	0
jpl2mx (nios)	j-index of maximum x2 of plot window	0
kpl2mn (nios)	k-index of minimum x3 of plot window	0
kpl2mx (nios)	k-index of maximum x3 of plot window	0
iflippl2(nios)	= 0 => no flipping of plots = 1 => plot flipped about x-axis before writing	0
jflippl2(nios)	= 0 => plot not flipped about x-axis = 1 => plot flipped about y-axis before writing	0
ireflpl2(nios)	= 0 => plot not reflected about x-axis = 1 => plot reflected about x-axis before writing rendering plot twice as tall	0
jreflpl2(nios)	= 0 => plot not reflected about y-axis = 1 => plot reflected about y-axis before writing	0

```
                        rendering plot twice as long
npl2i    (nios)  no. of horizontal zones in rebinned grid (<= idim)   0
                 = 0 => no rebinning in x- or y-direction
npl2j    (nios)  no. of vertical   zones in rebinned grid (<= jdim)   0
                 = 0 => no rebinning in x- or y-direction
pl2xlab (nios)   character string containing NCAR mark-up language
pl2ylab (nios)   for the desired x- and y-labels.  Default is the
                 generic coordinate label (x1, x2, x3).
pl2xl    (nios)  = 0 => suppresses xlabel (but not x-annotations)     1
                 = 1 => xlabel is put below horizontal axis
pl2yl    (nios)  = 0 => suppresses ylabel (but not y-annotations)     1
                 = 1 => ylabel is put beside vertical  axis
pl2ftr   (nios)  = 0 => suppresses footer                            1
                 = 1 => footer is printed on bottom of plot
pl2leg   (nios)  = 0 => suppresses legend                            2
                 = 1 => legend is printed above plot (as a header)
                 = 2 => legend is printed on inside top right
                        corner of plot

Contours; for contour variables, * = 1,2

pl2sca* (niov)   names of scalars to plot (character*2)              'zz'
                 Valid names are: 'a ', 'a1', 'a2', 'a3', 'ag',
                 'an' (normal vector potential), 'b ', 'b1', 'b2',
                 'b3', 'bn' (normal magnetic field), 'bP', 'bR',
                 'bt', 'cs', 'd ', 'da', 'e1', 'e2', 'er', 'et',
                 'fn' (normal magnetic flux function), 'gp', 'j ',
                 'j1', 'j2', 'j3', 'jn' (normal current density),
                 'k1', 'k2', 'ka', 'lu', 'm ', 'mA', 'mf', 'ms',
                 'nb' (break frequency), 'p1', 'p2', 'p3', 'p4',
                 'p5', 'p6', 'p7', 'pa', 'pg', 's1', 's2', 's3',
                 's ' (momentum norm), 'sn' (normal momentum),
                 'sy', 'u1', 'u2', 'v ', 'v1', 'v2', 'v3', 'vA',
                 'vf', 'vn' (normal velocity), 'vs', 'vv', 'w ',
                 'w1', 'w2', 'w3', 'wn' (normal vorticity).
                 See "pl1var" in pl1con for other definitions.
pl2ng*   (niov)  = 1 => contours are spaced evenly                   1
                 > 1 => contours are spaced geometrically such
                        that first two contours are spaced "pl2ng*"
                        times closer than evenly spaced contours.
                 <-1 => contours are spaced geometrically such
                        that last two contours are spaced "-pl2ng*"
                        times closer than evenly spaced contours.
pl2min* (niov)   minimum contour level to be plotted.                0.0
pl2max* (niov)   maximum contour level to be plotted.                0.0
pl2mm*           = 0 => use input "pl2min*" & "pl2max*" for plots    1
                 = 1 => compute "pl2min*" & "pl2max*" for plots
                 If both "pl2min*" and "pl2max*" are 0.0, compute
                 them as though "pl2mm*" were 1 for that variable.
thetapl2         meridonal rotation angle between 1-2-3 and a-b-c    0.0
                 coordinates (compute va, vb, vc from v1, v2, v3)
phipl2           azimuthal rotation angle between 1-2-3 and a-b-c    0.0
                 coordinates (compute va, vb, vc from v1, v2, v3)
numcl*   (niov)  = 0 => min(20,ncls) evenly spaced contours are      0
                       drawn between "pl2min*" and "pl2max*"
                 > 0 => number of evenly spaced contours to draw
                        between "pl2min*" and "pl2max*" (max ncls).
                 < 0 => abs(numcl*) contours drawn and are
                        specified by "pl2min*" and "levs*".
```

```
                if numcl*(2:niov) are not set by user, they are
                set to numcl*(1).
levs*   (ncls)  real array specifying multiples of "pl2min*" to
                use for contour levels (for numcl* < 0 only).  If
                levs2(1) not set by user, levs2 = levs1.
negcon          = 0 => negative contours are indistinguishable       0
                       from positive contours.
                = 1 => negative contours drawn with dotted lines
hilo            = 0 => highs and lows are not labelled               0
                = 1 => highs and lows are labelled H/L
                = 2 => highs and lows are labelled H/L with values
                       as subscripts (NCAR only).
pl2ccol (niov)  = 0 => do not use colour or grey-scale               0
                = 1 => use grey-scale to fill between contour
                = 2 => use colour     to fill between contour
                if pl2ccol(2:niov) are not set by user, they are
                set to pl2ccol(1).  Used for PSPLOT only.
                pl2ccol < 0 same as abs(pl2ccol) except colour
                bar not drawn (contour levels listed in footer
                instead)
pl2clin1(niov)  controls type of contour lines for first scalar
                = 0 => no     contours (default if pl2ccol .ne. 0)
                = 1 => solid  contours (default if pl2ccol=0 or NCAR)
                =-1 => dashed contours
pl2clin2(niov)  controls type of contour lines for second scalar
                = 0 => no     contours
                = 1 => solid  contours (default if pl2clin1 .ne. 1)
                =-1 => dashed contours (default if pl2clin1=1)
  abs(pl2clin*) = 2 => contour pen weight halved (recommended).
                If pl2clin*(2:niov) not set by user, they're set to
                pl2clin*(1).

Vectors; for vector variables, @ = 1,2,3

pl2vec@ (niov)  names of poloidal vectors to plot (character*2)     'zz'
                Valid names are: 'a ' (vector potential), 'b '
                (magnetic field), 'cf' (centrifugal force), 'gp'
                [grad(p)], 'gr' (gravitational force), 'j '
                (current density), 'lf' (Lorentz force), 's '
                (momentum), 'v ' (velocity), 'w ' (vorticity).
vnorm@  (niov)  >=1.0 => normalise vectors, draw all vectors with   0.0
                         original length > 1.0e-24 * vmax
                > 0.0 => do not normalise vectors, draw vectors
                < 1.0    .ge. vnorm@ * vmax only
                = 0.0 => do not normalise vectors, draw vectors
                         .ge. 0.04  * vmax only
                < 0.0 => normalise vectors, draw all vectors with
                         original length > 10**vnorm@ * vmax
vscale          scaling factor for vector                           0.8
nxvec   (nios)  |nxvec| = # of vectors in x-direction              20
                > 0 => different vector fields are staggered in x
                < 0 => different vector fields have same x-coord
                = 0 => same spacing (not #) as y-direction
nyvec   (nios)  |nyvec| = # of vectors in y-direction               0
                > 0 => different vector fields are staggered in y
                < 0 => different vector fields have same y-coord
                = 0 => same spacing (not #) as x-direction
pl2vcol@(niov)  colours to use for vector fields (PSPLOT only)
                = 0 => white;  = 1 => purple;  = 2 => blue;
```

```
                = 3 => green;  = 4 => orange;  = 5 => red;
                = 6 => black
                (Defaults: 6 for 1st field; 5 for 2nd, 2 for 3rd)
                if pl2vcol@(2:niov) are not set by user, they are
                set to pl2vcol@(1).

Corks

pl2crk  (niov)  = 0 => no corks overlaid on plots                    0
                > 0 => overlay every (pl2crk)th cork as a small
                       dot
                < 0 => same as >0 plus cork number to upper left
                In 3-D, corks within a half a zone of specified
                plane are plotted.

Diagnostic dumps

dtgr2d          physical (problem) time interval between             0.0
                diagnostic 2-D dumps; 0.0 => no dumps
```

See note at the end of §B.19 describing the namelist `pl1con` concerning libraries required with and without *NCAR* graphics.

```
      namelist / pl2con   /
     1              dtpl2   , npl2dmp , units   , pl2scale, pwtpl2
     2            , norppl2 , pl2grid , pl2dir  , lpl2    , pl2avg
     3            , x1pl2mn , x1pl2mx , x2pl2mn , x2pl2mx , x3pl2mn
     4            , x3pl2mx , ipl2mn  , ipl2mx  , jpl2mn  , jpl2mx
     5            , kpl2mn  , kpl2mx  , iflippl2, jflippl2, ireflpl2
     6            , jreflpl2, npl2i   , npl2j   , pl2xlab , pl2ylab
     7            , pl2xl   , pl2yl   , pl2ftr  , pl2leg  , pl2sca1
     8            , pl2sca2 , pl2ng1  , pl2ng2  , pl2min1 , pl2min2
     9            , pl2max1 , pl2max2 , pl2mm1  , pl2mm2  , thetapl2
     1            , phipl2  , numcl1  , numcl2  , levs1   , levs2
     2            , negcon  , hilo    , pl2ccol , pl2clin1, pl2clin2
     3            , pl2vec1 , pl2vec2 , pl2vec3 , vnorm1  , vnorm2
     4            , vnorm3  , vscale  , nxvec   , nyvec   , pl2vcol1
     5            , pl2vcol2, pl2vcol3, pl2crk  , dtgr2d
```

B.21 PIXCON—PIXel/movie graphics CONtrol (subroutine NMLSTS)

This namelist controls the pixel dumps, which are 2-D images of slices through the data volume rebinned to a uniform, square Cartesian grid. **New to version 3.6**, depending on the new parameter `pixfmt`, images may be dumped as movie frames (four bytes deep with grid and dimensions stored in a header) and/or traditional pixel dumps (one byte per datum, no header) and/or HDF files. As always, pixel dumps remain as separate files, to be dealt with manually by the user after the run. HDF files are a fossil from very early versions of the code, and are suitable for graphical analysis if desired. For movie frames, at the end of the run `makempg` gathers all files in a tarball (to be used at a later time by *ANIM8Z* to recreate the animation with a different palette or bracketing if desired), converts them to PPM format, and assembles them into an mpeg movie file according to user-set namelist parameters. Thus, the end product is an mpeg animation for each quantity selected along with an accompanying tarball of four-byte deep frames. For a smooth temporal animation, aim for about 400–600 dumps per animation.

During a run, as many as `nios` slices may be specified for each variable plotted, and a single movie frame/pixel dump is created for every variable and every slice specified. The number of files generated per run can therefore be enormous. The extent of the 2-D slice can be limited by setting `x1pixmn`, `x1pixmx`, *etc.* The normal to the slice is parallel to one of the axes of the computational grid and is specified by `pixdir`. The index at the base of the normal is given by `lpix`.

Pixel images (`pixfmt=2`) were introduced by Michael Norman in the late 1980s as a way to assemble animations with high temporal resolution without overrunning the limited disc space of the day. Each image is only 1 byte deep, and thus has a dynamic range of 256; sufficient for qualitative rendering only if the data are properly bracketed and scaled beforehand. To do this, two parameters were introduced.

First, by setting `pixmm=1` (automatic bracketing), each image is bracketed separately to its own extrema and differences from one image to the next are caused by both the evolution of the flow *and* the fluctuations of the extrema. By setting `pixmm=0` (manual bracketing), the same user-set values for `pixmin` and `pixmax` are applied to each image, and fluctuations from one image to the next are entirely because of evolution of the flow. A practical way of finding optimal values for `pixmin` and `pixmax` is to run a low resolution run with `pixmm` set to 1, then use the reported extrema (in the log file, `zl`*nnn*`id`) of the pixel dumps to set `pixmin` and `pixmax` for the high resolution run (with `pixmm` set to 0).

Second, the parameter `nlpix` sets the scaling ("transfer function"). Setting `nlpix=1` gives a linear scaling whereas `nlpix>1` gives an essentially logarithmic scaling, where the colour contours at the low end are `nlpix` times closer together than at the high end. For positive-definite scalars, `nlpix=100` usually works well; for vector components that can be either positive or negative, a linear transfer function is usually best. Note, however, that quantities need not be positive definite in order to have "logarithmic scaling" applied.

Pixel images were originally designed for use with Carol Song's `IMAGETOOL` which was great in its time but sadly discontinued by the NCSA in the late 90s. I know of no software now which can read separate `ZEUS`-style pixel dumps and render them as animations the way `IMAGETOOL` did. Thus, pixel dumps are now largely obsolete. In order to create an animation from them, one has to convert each to PPM format (tripling their size), then assemble the PPM files in an mpeg using software such as `FFmpeg`.

Instead, movie frames (`pixfmt=1`, default) are the recommended way to create animations. These files are 4-bytes deep with some header information, and are automatically converted to PPM files at the end of a run which are then assembled into an mpeg by the subroutine `makempg` (which relies on `FFmpeg` being available on the user's platform; see `ffmpeg.org` if it isn't). The movie files are compressed into a g-zipped tarball, and the user is left with two files per desired animation: the mpeg, and the tarball which can be used later to recreate the animation without rerunning the simulation should the bracketing or scaling of the animation need to be changed (using the standalone program *ANIM8Z*). Thus, while movie files still need to be bracketed and scaled as pixel dumps, choosing the right values for `pixmin`, `pixmax`, and `nlpix` before the simulation begins is not critical. Note also for movie files, `pixmm=2` sets `pixmin` (`pixmax`) to the minimum (maximum) of the minima (maxima) of all the frames in a single animation. This obviates the need to run a low-resolution simulation to determine the optimal values of `pixmin` and `pixmax`. Even if the absolute extrema of the extrema are not optimal, one can redo the animation from the tarball after

the simulation using *ANIM8Z*.

Polar slices are binned to a Cartesian grid before they are written to disc. If a polar grid includes very small zones near the origin, it may be best to request two animations for each slice visualised. One animation could include the entire grid and reflect the resolution near the mid-radial regions (*i.e.*, oversample the outer grid but under-sample the inner), while the second could include only the inner radial regions to reflect the resolution of the inner grid.

The parameters which set the dimensions of the arrays for the slices `(nxpix,nypix)` are independent of the parameters which set the dimensions of the flow variables `(in,jn,kn)`. Thus, in the case of a non-uniform grid, files may be written with enough pixels to preserve the highest resolution on the grid.

N.B. For restarted runs in which the computation is resumed on a larger or smaller grid, and where the default values for `x1pixmn`, `x1pixmx`, *etc.* were used in the initial run, it will be necessary to set `x1pixmn`, `x1pixmx`, *etc.* in the input deck for the restarted run to the extrema of the new grid if the dumps are to extend to the bounds of the new grid. Otherwise, the dumps will be bound by the old grid.

Also for a restarted run, the g-zipped movie tarballs from the previous run should be in the same directory as the executable so that the new movie frames can be added to the tarballs, and the mpegs can be made from all movie frames since the beginning of the first run, rather than just from those created from the beginning of the present run. To enable this feature, neither the problem tag nor the names of the movie tarballs should be changed from one run to the next.

parameter		description	default
General			
dtpix		problem time interval between pixel dumps/movie frames. If dtpix .le. 0, no files are generated.	0.0
npixdmp		sequential number for next pixel/movie file < 0 => npixdmp = ipixdmp	-1
units		sets units of angular dimensions (character*2). 'dg' => degrees, 'rd' => radians, 'pi' => units of pi radians	'rd'
pixfmt		= 1 => PIXDMP creates 4-byte movie frames. = 2 => PIXDMP creates 1-byte raw pixel dumps. = 3 => PIXDMP creates movie and raw files (1+2). = 4 => PIXDMP creates 4-byte HDF files. = 5 => PIXDMP creates movie and HDF files (1+4). = 6 => PIXDMP creates raw and HDF files (2+4). = 7 => PIXDMP creates files of each format (1+2+4).	1
Slice control			
pixdir	(nios)	direction of normal to image plane. 1, 2, or 3 => 1-, 2-, or 3-direction. If "pixdir" is not set, no pixel dumps will be generated.	0
lpix	(nios)	level of 2-D pixel dump (value of 1-, 2-, or 3-index)	(is+ie)/2
npixi	(nios)	number of x-pixels before any j-reflection	nxpx
npixj	(nios)	number of y-pixels before any i-reflection	nypx
x1pixmn	(nios)	minimum x1 for pixel image	x1a(is)

```
x1pixmx (nios)  maximum x1 for pixel image                      x1a(ie+1)
x2pixmn (nios)  minimum x2 for pixel image                      x2a(js)
x2pixmx (nios)  maximum x2 for pixel image                      x2a(je+1)
x3pixmn (nios)  minimum x3 for pixel image                      x3a(ks)
x3pixmx (nios)  maximum x3 for pixel image                      x3a(ke+1)
iflippix(nios)  = 0 => no flipping of images                        0
                = 1 => image flipped about x-axis before writing
                       (size of image not changed, just flipped)
jflippix(nios)  = 0 => no flipping of images                        0
                = 1 => image flipped about y-axis before writing
ireflpix(nios)  = 0 => no reflection about x-axis                   0
                = 1 => image reflected about x-axis on output =>
                       twice the number of y-pixels requested
jreflpix(nios)  = 0 => no reflection about y-axis                   0
                = 1 => image reflected about y-axis on output =>
                       twice the number of x-pixels requested

Variable control

pixvar  (niov)  names of variables to be plotted (character*2).     'zz'
                Valid names are:  'a ', 'a1', 'a2', 'a3', 'ag',
                'ap', 'an', 'b ', 'b1', 'b2', 'b3', 'bP', 'bR',
                'bn', 'bp', 'bt', 'cs', 'd ', 'da', 'e1', 'e2',
                'er', 'et', 'fn', 'gp', 'j ', 'j1', 'j2', 'j3',
                'jn', 'jp', 'k1', 'k2', 'ka', 'lu', 'm ', 'mA',
                'mf', 'ms', 'nb', 'p1', 'p2', 'p3', 'p4', 'p5',
                'p6', 'p7', 'pa', 'pg', 's ', 's1', 's2', 's3',
                'sd' (skew-density)   , 'sp', 'sn', 'sy', 'u1',
                'u2', 'v ', 'v1', 'v2', 'v3', 'vA', 'vf', 'vn',
                'vp', 'vs', 'vv', 'w ', 'w1', 'w2', 'w3', 'wn',
                'wp'.  See "pl1var" in pl1con and "pl2sca*" in
                pl2con for other definitions.
nlpix   (niov)  = 0 => store data                                   0
                > 0 => store log10(data), concentrating colours
                       at low end.  Dynamic range = nlpix,
                       1 => 100.
                < 0 => store log10(data), concentrating colours
                       at high end.  Dynamic range = -nlpix,
                       -1 => -100.
pixmin  (niov)  value to be assigned the minimum colour.            0.0
pixmax  (niov)  value to be assigned the maximum colour.            0.0
pixmm   (niov)  = 0 => use input "pixmin", "pixmax" for each image  1
                       If pixmin=pixmax=0, "pixmm" reset to 1
                = 1 => compute "pixmin", "pixmax" for each image
                       (default)
                = 2 => extreme of computed "pixmin", "pixmax" used
                       for all frames (movie format only; raw and
                       HDF formats, pixmm=1 and 2 are the same)
ncpix           number of colour contours in image              255

Animation control; note that a separate palette can be chosen for each variable

pixpal  (niov)  = 0 => use user palette 'pfilepix'                  2
                = 1 => greyscale palette.
                = 2 => ZEUS' spectral colour palette
                if pixpal(2:niov) not set by user, they're set to
                pixpal(1).
pfilepix(niov)  character*128 user's palette file (pixpal = 0). If
                file not found, pixpal reverts to default (2).
```

```
fratepix        FFmpeg's integer parameter.  Animation assembled    24
                to run at "fratepix" frames per second
mpgpix          = 1 => animations written in mpg format             4
                = 4 => animations written in mp4 format
                else=> neither mpegs nor PPM files created, movie
                       frames are bundled into a tarball for post-
                       processing (e.g., ANIM8Z)
ppmpix          = 0 => PPM files are discarded, staging directory   0
                       makempg.dir deleted after use
                = 1 => PPM files are retained in makempg.dir

      namelist / pixcon   /
     1              dtpix   , npixdmp , units   , pixdir  , lpix
     2            , npixi   , npixj   , x1pixmn , x1pixmx , x2pixmn
     3            , x2pixmx , x3pixmn , x3pixmx , iflippix, jflippix
     4            , ireflpix, jreflpix, pixvar  , nlpix   , pixmin
     5            , pixmax  , pixmm   , ncpix   , morppix , pixpal
     6            , pfilepix, fratepix, mpgpix  , ppmpix
```

B.22 USRCON—USeR dump CONtrol (subroutine NMLSTS)

This namelist is reserved for a user-supplied I/O subroutine aliased to USERDUMP (see App. A to see where USERDUMP is called). Additional namelist parameters may be added as needed.

```
parameter                    description                          default

dtusr     physical (problem) time interval between user dumps.     0.0
          0.0 => no user dumps
nusrdmp   the sequential number for the next user dump file       -1
          < 0 => nusrdmp = iusrdmp

      namelist / usrcon   /
     1              dtusr   , nusrdmp
```

B.23 HDFCON—HDF dump CONtrol (subroutine NMLSTS)

This namelist controls the *HDF* (Hierarchical Data Format, version 4) dumps. *HDF* is a format for data files developed at the NCSA. This format is fairly widely used, appearing in various commercial applications such as *IDL*. *HDF* dumps are 4 bytes deep, and contain the grid coordinates along with other useful information about the data. They are suitable for graphical and quantitative analysis, but not for resuming a simulation.

In order to use *HDF*, it is necessary to link all the *HDF4* libraries to your executable. If you don't know what or where these libraries are on your system, ask your system administrator who may have to download the (free) *HDF4* libraries from the NCSA website (www.ncsa.uiuc.edu).

```
parameter                    description                          default

dthdf           physical (problem) time interval between hdf       0.0
                dumps.  0.0 => no hdf dumps
nhdfdmp         the sequential number for the next HDF file        -1
                <0 => nhdfdmp = ihdfdmp
hdfvar(niov)    names of variables to be dumped (character*2).     'zz'
```

```
                Valid names are: 'to' ("total" dump => v1, v2,
                v3, b1, b2, b3, d, et, e1, e2, gp, pg, er, da
                in the same file)     , 'a1', 'a2', 'a3', 'a ',
                'ag', 'b1', 'b2', 'b3', 'b ', 'bt', 'd ', 'da',
                'e1', 'e2', 'er', 'et', 'gp', 'j1', 'j2', 'j3',
                'j ', 'k1', 'k2', 'ka', 'lu', 'm ', 'mA', 'ms',
                'mf', 'p1', 'p2', 'p3', 'p4', 'p5', 'p6', 'p7',
                'pg', 's1', 's2', 's3', 's ', 'u1', 'u2', 'v1',
                'v2', 'v3', 'v ', 'vv', 'w1', 'w2', 'w3', 'w '
                See "pl1var" in pl1con and "pl2sca*" in pl2con
                for definitions.

      namelist / hdfcon   /
    1               dthdf   , nhdfdmp , hdfvar
```

B.24 TSLCON—Time SLice (history) dump CONtrol (subroutine NMLSTS)

This namelist controls the time slice data dumps. Various scalars, such as total mass, angular momenta, energy, extrema of variables, *etc.* are periodically written to an ascii file and/or a plot (*NCAR* or *PSPLOT* graphics). See §B.19 for what libraries are needed for *NCAR* and *PSPLOT* graphics respectively.

```
parameter                       description                          default

General

dttsl           problem time interval between ascii dumps             0.0
                0.0 => no ascii timeslice dumps
ntsldmp         sequential number for next timeslice file            -1
                < 0 => ntsldmp = itsldmp
itslmn          minimum i-index of integration domain                 ismn
itslmx          maximum i-index of integration domain                 iemx
jtslmn          minimum j-index of integration domain                 jsmn
jtslmx          maximum j-index of integration domain                 jemx
ktslmn          minimum k-index of integration domain                 ksmn
ktslmx          maximum k-index of integration domain                 kemx

Plot control

dttsp           problem time interval between plot dumps              0.0
                0.0 => no timeslice plot dumps
ntspdmp         sequential number for next timeslice plot file       -1
                < 0 => ntspdmp = itspdmp
pwttsp          pen weight for timeslice plots                        1.0
norptsp         = 1 => use NCAR graphics for timeslice plots          2
                = 2 => use PSPLOT graphics for timeslice plots
ntsph           number of frames horizontally per page                1
ntspv           number of frames vertically   per page              1
tsphdr          = 1 => write headers to timeslice plot file           1
                = 0 => suppresses headers
tspftr          = 1 => write footers to timeslice plot file           1
                = 0 => suppresses footers
ttspmn          problem time for beginning of plot                    0.0
ttspmx          problem time for end of plot (0.0 => prtime)          0.0

      namelist / tslcon   /
    1               dttsl   , ntsldmp , itslmn  , itslmx  , jtslmn
```

```
     2            , jtslmx  , ktslmn  , ktslmx  , dttsp   , ntspdmp
     3            , pwttsp  , norptsp , ntsph   , ntspv   , tsphdr
     4            , tspftr  , ttspmn  , ttspmx
```

B.25 CRKCON—CoRK dump CONtrol (subroutine NMLSTS)

New to version 3.6: This namelist controls the cork dump, which consist of data (cork positions, values of flow variables, and functions of flow variables such as $\nabla \cdot \vec{v}$, Mach number, *etc.*) collected at user-specified time intervals at the locations of all Lagrangian particles (corks) populating the grid at $t = 0$ (those set by GRIDCORK), as well as those injected onto the grid by the user during the simulation (*e.g.*, JETCORK). These data are continually appended to an opened ascii file (zc*nnn*id) which tabulates the locations of each cork at each time interval, along with each of the specified tracked variables. User-provided post-processing routines can be used to display these data after the simulation is complete and/or the user could provide a routine aliased to FINISH to generate a plot file on termination (see routine SPECTRA for a template).

```
parameter                    description                              default

dtcrk           problem time interval between cork dumps                0.0
                0.0 => no cork dumps
ncrkdmp         the sequential number for the next cork file           -1
                < 0 => ncrkdmp = icrkdmp
gcrk*           GRIDCORK sets a lattice of gcrk1 x gcrk2 x gcrk3        0
                corks (default = 1 for *SYM).
iordcrk         = 1 => first order integration of cork positions        1
                = 2 => second order integration
crkvar  (niov)  names of variables to be tracked (character*2).        'zz'
                Valid names are:  'a1', 'a2', 'a3', 'a ', 'ag',
                'B3', 'b1', 'b2', 'b3', 'bP', 'bR', 'b ', 'bd',
                'br', 'bt', 'd ', 'da', 'e1', 'e2', 'er', 'et',
                'gl', 'gk', 'gp', 'hy', 'j1', 'j2', 'j3', 'j ',
                'k1', 'k2', 'ka', 'kt', 'l ', 'lt', 'lu', 'm ',
                'mA', 'mf', 'ms', 'om', 'p1', 'p2', 'p3', 'p4',
                'p5', 'p6', 'p7', 'pg', 's1', 's2', 's3', 's ',
                'sy', 'u1', 'u2', 'v1', 'v2', 'v3', 'v ', 'vv',
                'w1', 'w2', 'w3', 'w ', 'ze' (shock ratio).
                See "pl1var" in pl1con and "pl2sca*" in pl2con
                for definitions.

      namelist / crkcon   /
     1               dtcrk   , ncrkdmp , gcrk1   , gcrk2  , gcrk3
     2             , iordcrk , crkvar
```

B.26 DISCON—DISplay dump CONtrol (subroutine NMLSTS)

This namelist controls the display dumps of 2-D slices. During a run, as many as nios slices may be specified for each variable displayed. All display dumps generated during a run are dumped to the same ascii data file. The extent of the display slice can be limited by setting idismn, idismx, *etc.* The normal to the display slice is parallel to one of the axes of the computational grid and is specified by disdir. The index at the base of the normal is given by ldis.

The display format allows the user to view a small portion of the data quantitatively in a matrix format. The maximum amount of data that can be visualised at once from each specified variable and slice is 38 by 38. The data are scaled and converted to integers with a dynamic range anywhere from 100 to 10^6, depending on the amount of data being displayed. The data are arranged in a 2-D matrix and labelled with the grid indices and the scaling factor used to scale the data. (The functionality is similar to that of the task `PRTIM` in *AIPS*.)

N.B. For restarted runs in which the computation is resumed on a larger or smaller grid, and where the default values for `idismn`, `idismx`, *etc.* were used in the initial run, it will be necessary to set `idismn`, `idismx`, *etc.* in the input deck for the restarted run to the extrema of the new grid if the dumps are to extend to the bounds of the new grid. Otherwise, the dumps will be bound by the old grid.

parameter		description	default
dtdis		physical (problem) time interval between display dumps. 0.0 => no display dumps.	0.0
ndisdmp		the sequential number for the next display file < 0 => ndisdmp = idisdmp	-1
disdir	(nios)	direction of normal to display plane: 1, 2, or 3 => 1-, 2-, or 3-direction; 0 => no display dumps	0
ldis	(nios)	level of 2-D display (value of 1-, 2-, or 3-index)	(is+ie)/2
disvar	(niov)	names of variables to be displayed (character*2). Valid names are: 'a ', 'a1', 'a2', 'a3', 'b ', 'b1', 'b2', 'b3', 'bt', 'd ', 'e1', 'e2', 'er', 'et', 'gp', 'k1', 'k2', 'ka', 'j1', 'j2', 'j3', 'j ', 'lu', 'm ', 'mA', 'ms', 'mf', 'p1', 'p2', 'p3', 'p4', 'p5', 'p6', 'p7', 'pg', 's ', 's1', 's2', 's3', 'u1', 'u2', 'v ', 'v1', 'v2', 'v3', 'vv', 'w ', 'w1', 'w2', 'w3'. See "pl1var" in pl1con and "pl2sca*" in pl2con for definitions.	'zz'
idismn	(nios)	bottom i-index of display window	is
idismx	(nios)	top i-index of display window	ie
jdismn	(nios)	bottom j-index of display window	js
jdismx	(nios)	top j-index of display window	je
kdismn	(nios)	bottom k-index of display window	ks
kdismx	(nios)	top k-index of display window	ke

```
      namelist / discon   /
     1              dtdis   , ndisdmp , disdir  , ldis    , disvar
     2            , idismn  , idismx  , jdismn  , jdismx  , kdismn
     3            , kdismx
```

B.27 RADCON—RADio dump CONtrol (subroutine NMLSTS)

This namelist controls the *RADIO* dumps, which are 2-D images of lines-of-sight integrations through the data volume at arbitrary viewing angles (`theta` and `phi`) binned on a uniform, square Cartesian grid. **New to version 3.6**, depending on the new parameter `radfmt`, images may be dumped as movie frames (four bytes deep with grid, dimensions, and viewing angles stored in a header) and/or traditional pixel dumps (one byte per datum, no header) and/or HDF files. As always, pixel dumps remain as separate files, to be dealt with manually

by the user after the run. HDF files are a fossil from very early versions of the code, and are suitable for graphical analysis if desired. For movie frames, at the end of the run `makempg` gathers all files in a tarball (to be used at a later time by *ANIM8Z* to recreate the animation with a different palette or bracketing if desired), converts them to PPM format, and assembles them into an mpeg movie file according to user-set namelist parameters. Thus, the end product is an mpeg animation for each quantity selected along with an accompanying tarball of four-byte deep frames. For a smooth temporal animation, aim for about 400–600 dumps per animation.

The integration volume can be limited by setting `x1radmn`, `x1radmx`, *etc.* *RADIO* dumps are currently available for Cartesian (`XYZ`) and cylindrical (`ZRP`) geometries, with the latter not fully tested. See discussion in §B.21 regarding strategy of bracketing images, dumping images logarithmically, and making animations.

There are two types of integrated quantities: flow variables and emissivities. Many of the parameters listed below are for controlling the latter. For example, the Stokes parameters once integrated can be convolved with a beam, polarisation vectors may be plotted directly (rather than raster images), polarisation vectors may be superposed on total intensity raster images, and so on.

The "masks" (`*lower`, `*upper`, `dmask*`, and `bmask`) are useful in limiting which portion of the grid is included in the integration of the non-emissivity scalars. For example, if there is a contact discontinuity (CD) enclosing the region of interest, then there will be a jump in the density (`d`) along this interface. Thus, if `d` jumps, say, from about 0.1 to about 1.0 across the CD, setting `dmask*=1.0` and `dupper=0.5` would allow only the low density region (be it interior or exterior to the CD) to contribute to the line-of-sight integration of variable `*`. Alternatively, if the magnetic field is found only in the material of interest, setting `bmask*=1.0` would allow only material with magnetic field to be included in the integration of variable `*`. Finally, the variables `*lower` and `*upper` allow each variable to be masked by its own distribution. These can be set in addition to the density and/or magnetic field masks (`dmask*`, `bmask*`). For example, if only the compressive portions of the flow are to be integrated, then setting `xupper=0.0` will mean that only negative values of $\nabla \cdot \vec{v}$ will be included in the integration. All values excluded by the various masks will be given zero weight. In all cases, the default is no mask.

Reversing the palette (`nlrad<0`) is useful for images in which `radmin<0` and `radmax<0` (*e.g.*, negative velocity divergences). In these cases, it may be desirable to have the "maximum" colour correspond to the minimum pixel value (which has the greatest absolute value).

Note that the parameters which set the dimensions of the arrays for the *RADIO* dumps `(nxrd,nyrd)` are independent of the parameters which set the dimensions of the flow variables `(in,jn,kn)` and of the regular pixel slices `(nxpx,nypx)`.

N.B. For restarted runs in which the computation is resumed on a larger or smaller grid, and where the default values for `x1radmn`, `x1radmx`, *etc.* were used in the initial run, it will be necessary to set `x1radmn`, `x1radmx`, *etc.* in the input deck for the restarted run to the extrema of the new grid if the dumps are to extend to the bounds of the new grid. Otherwise, the dumps will be bound by the old grid.

Also for a restarted run, the g-zipped movie tarballs from the previous run should be in the same directory as the executable so that the new movie frames can be added to the tarballs, and the mpegs can be made from all movie frames since the beginning of the first

run, rather than just from those created from the beginning of the present run. To enable this feature, neither the problem tag nor the names of the movie tarballs should be changed from one run to the next.

parameter	description	default
General		
dtrad	problem time interval between RADIO dumps 0.0 => no RADIO dumps.	0.0
nraddmp	the sequential number for the next radio file <0 => nraddmp = iraddmp	-1
units	sets the angular units (character*2) 'rd' => radians, 'pi' => units of pi radians 'dg' => degrees	'rd'
thetamin	minimum angle between x1-axis and plane of sky	0.0
dtheta	desired increment in "theta" between successive dumps	0.0
phimin	minimum azimuthal angle for lines of sight.	0.0
dphi	desired increment in "phi" between successive dumps	0.0
x1radmn	minimum x1 for RADIO integration	x1a(is)
x1radmx	maximum x1 for RADIO integration	x1a(ie+1)
x2radmn	minimum x2 for RADIO integration	x2a(js)
x2radmx	maximum x2 for RADIO integration	x2a(je+1)
x3radmn	minimum x3 for RADIO integration	x3a(ks)
x3radmx	maximum x3 for RADIO integration	x3a(ke+1)
radfill	= 0 => diameter of image plane set to sqrt (x1radln**2 + x2radln**2 + x3radln**2) so that no matter the viewing angle, image fits entirely on image plane. = 1 => diameter of image plane set to x1radln so that viewed face-on, image fills entire plane, leaving no black space around image.	0
radbox	= 0 => no box drawn around integration region = 1 => all box lines drawn with highest colour =-1 => all box lines drawn with lowest colour = 2 => all lines except those to "hidden corner" drawn with highest colour (default) =-2 => all lines except those to "hidden corner" drawn with lowest colour	2
radfmt	= 1 => RADDMP creates 4-byte movie frames. = 2 => RADDMP creates 1-byte raw pixel dumps. = 3 => RADDMP creates movie and raw files (1+2). = 4 => RADDMP creates 4-byte HDF files. = 5 => RADDMP creates movie and HDF files (1+4). = 6 => RADDMP creates raw and HDF files (2+4). = 7 => RADDMP creates files of all 3 formats (1+2+4).	1
Emission control		
radtype	= 0 => emissivities are not computed = 1 => Smith et al emissivity (p**2) = 2 => CNB emissivity (function of d, p, B) = 3 => synchrotron emissivity with break freq.	2
pindex	power law index of relativistic electrons N(E) = kappa * E**(-pindex) (radtype = 2, 3)	2.0
freq	frequency of RADIO observation (Hz)	5.0d+9

```
nubrs           nubr(Hz)/nubr(zeus); scaling factor for break        0.5
                frequency (radtype=3 only)
                0.0 => value is computed in JETINIT
brn0            fiducial number density for bremsstrahlung           lrge
                emission (m**-3)
brt0            fiducial temp. for bremsstrahlung emission (K)       lrge
brnu1, brnu2    limits of frequency band for brem. (Hz)         1.000000e17
                                                               1.000001e17
betarel         relativistic beta = v/c for fastest zone (for        0.0
                Mike Casey's Doppler boosting)

Convolution control ("beam")

Only the Stokes parameters and the Q-SRA variables are convolved with the
specified elliptical "beam".

cnvlv           = 0 => do not apply convolution                      0
                = 1 => apply convolution to Stokes parameters
bmajor          major axis of convolving beam (distance units)       1.0
bminor          minor axis of convolving beam (distance units)       1.0
bpa             beam position angle (radians) measured counter-      0.0
                clockwise between major axis and +x axis
cpb             "cells" per beam                                     5.0

"cpb" is an accuracy parameter.  The default (5.0) should be fine in most cases.
Setting it lower will speed up the computation, but will yield a more ragged
image.

Masking control

In what follows,

* = d, p1, t , b, sh, vv, br, w, m, ma, ms, mf, db, eb, de
q = d, p, p/d, B, shear, divv, brem, curlv, M, MA, MS, MF, d*b, e1**2b, d/e1**2

*lower          q is integrated along los provided q > *lower      -huge
*upper          q is integrated along los provided q < *upper       huge
dmask*          density mask toggle for variable * (except "d")     -1.0
                = 1.0 => "dlower" and "dupper" set int. limits
                = 0.0 => not
                =-1.0 => use "dmask"
dmask           density mask toggle for all variables                0.0
                If "dmask*" .ne. -1.0, value of "dmask*" overrides
                "dmask" for variable * only
bmask*          B-field mask toggle for variable *                  -1.0
                = 1.0 => B-field extent sets int. limits
                = 0.0 => not
                =-1.0 => use "bmask"
bmask           B-field mask toggle for all variables                0.0
                If "bmask*" .ne. -1.0, value of "bmask*" overrides
                "bmask" for variable * only

Variable control

Controls which variables are to be "carried" with the line-of-sight
integrations, and how the pixel dumps are to be bracketed.  The bulk of CPU is
used up in setting up the lines-of-sight; the additional cpu required for each
variable is nominal.  The only real "cost" of selecting all variables is the
additional disc space required to store all the files.
```

```
radvar  (niov)  character*2 mnemonics for variables to be plotted    'zz'
                using pixel-plotting routines.  Legal mnemonics are:
                'A ' => pol. position angle [ 0.5 * atan (Q/U) ]
                'AV' => A with polarisation vectors superposed
                'F ' => fractional pol'n (fpol) rastor plot
                'FV' => fpol with polarisation vectors
                'I ' => total intensity (toti) rastor plot
                'IV' => toti with polarisation vectors
                'P ' => polarised intensity (poli) rastor plot
                'PV' => poli with polarisation vectors
                'V ' => pol'n vector rastor plot (black on white)
                'VR' => pol'n vector rastor plot (white on black)
                'D ' => column density
                'P1' => column pressure (internal energy density)
                'B ' => column magnetic field strength
                'T ' => column temperature (specific internal energy)
                'SH' => column velocity shear
                'VV' => column divergence of velocity
                'BR' => bremsstrahlung emission
                'W ' => vorticity
                'M ' => Sonic Mach number
                'MA' => Alfven Mach number
                'MS' => Fast magnetosonic Mach number
                'MF' => Fast magnetosonic Mach number
                'DB' => d * B     (K-S R A variable)
                'EB' => p1**2 * B (K-S R A variable)
                'DE' => d / p1**2 (K-S R A variable)
nlrad   (niov)  = 0 => store data                                   0
                > 0 => store log10(data) concentrating colours at
                       low end.  Dyn. range = nlrad, 1 => 100.
                < 0 => store log10(data) concentrating colours at
                       high end.  Dyn. range =-nlrad, -1 => -100.
radmin  (niov)  value of data to be assigned the minimum colour.    0.0
radmax  (niov)  value of data to be assigned the maximum colour.    0.0
radmm   (niov)  = 0 => use input "radmin", "radmax" for each image  1
                       If radmin=radmax=0, "radmm" reset to 1
                = 1 => compute "radmin", "radmax" for each image
                = 2 => extreme of computed "radmin", "radmax" used
                       for all frames (movie format only; raw and
                       HDF formats, radmm=1 and 2 are the same)
ncrad           number of colour contours in image                  255

Reversing the palette (nlrad<0) is useful for images in which radmin<0 and
radmax<0 (e.g., negative velocity divergences).  In these cases, it may be
desirable to have the "maximum" colour correspond to the minimum pixel value
(which has the greatest absolute value).

Vector control

eorb            = 1 => E-vectors                                    2
                = 2 => B-vectors
porf            = 1 => vector length proportional to poli           2
                = 2 => vector length proportional to fpol
bworb           = 1 => black and white pixel vectors                1
                = 2 => black pixel vectors only
vlmin           vectors with length < vlmin*(max vector) not        0.001
                plotted.
icut            vectors are not plotted if total intensity          0.001
```

```
                toti < icut*max(toti)
pcut            vectors are not plotted if polarised intensity       0.001
                poli < pcut*max(poli)
polsc           scaling factor for polarisation vectors              0.8
                = 1 => vectors lining up along image axis touch
                < 0 => vectors scaled by |polsc| and have uniform
                       length (useful to map polarisation angles)
incpx           plot every incpx(th) vector in x-direction           1
incpy           plot every incpy(th) vector in y-direction           1

Animation control; note that a separate palette can be chosen for each variable

radpal  (niov)  = 0 => use user palette 'pfilerad'                   2
                = 1 => greyscale palette.
                = 2 => spectral colour palette (default).
                if radpal(2:niov) not set by user, they're set to
                radpal(1).
pfilerad(niov)  character*128 user's palette file (radpal = 0).
                If file not found, radpal reverts to default.
fraterad        FFmpeg's integer parameter.  Animation assembled    24
                to run at "fraterad" frames per second
mpgrad          = 1 => animations written in mpg format              4
                = 4 => animations written in mp4 format
                else=> neither mpegs nor PPM files created, movie
                       frames are bundled into a tarball for post-
                       processing (e.g., ANIM8Z)
ppmrad          = 0 => PPM files are discarded, staging directory    0
                       makempg.dir deleted after use
                = 1 => PPM files are retained in makempg.dir
```

```
      namelist / radcon   /
     1              dtrad   , nraddmp , units   , thetamin, dtheta
     2            , phimin  , dphi    , x1radmn , x1radmx , x2radmn
     3            , x2radmx , x3radmn , x3radmx , radfill , radbox
     4            , radfmt  , radtype , pindex  , freq    , nubrs
     5            , brn0    , brt0    , brnu1   , brnu2   , betarel
     6            , cnvlv   , bmajor  , bminor  , bpa     , cpb
     7            , dlower  , p1lower , tlower  , blower  , shlower
     8            , vvlower , brlower , wlower  , mlower  , malower
     9            , mslower , mflower , dblower , eblower , delower
     1            , dupper  , p1upper , tupper  , bupper  , shupper
     2            , vvupper , brupper , wupper  , mupper  , maupper
     3            , msupper , mfupper , dbupper , ebupper , deupper
     4            , dmaskp1 , dmaskt  , dmaskb  , dmasksh , dmaskvv
     5            , dmaskbr , dmaskw  , dmaskm  , dmaskma , dmaskms
     6            , dmaskmf , dmaskdb , dmaskeb , dmaskde , dmask
     7            , bmaskd  , bmaskp1 , bmaskt  , bmasksh , bmaskvv
     8            , bmaskbr , bmaskw  , bmaskm  , bmaskma , bmaskms
     9            , bmaskmf , bmaskdb , bmaskeb , bmaskde , bmask
     1            , radvar  , nlrad   , radmin  , radmax  , radmm
     2            , ncrad   , eorb    , porf    , bworb   , vlmin
     3            , icut    , pcut    , polsc   , incpx   , incpy
     4            , radpal  , pfilerad, fraterad, mpgrad  , ppmrad
```

B.28 PGEN—Problem GENerator (subroutine aliased to PROBLEM)

This namelist is reserved for the problem generator, which sets the flow variables to the desired initial conditions. Thus the parameters which appear in this namelist depend on which problem is being studied. The desired problem is specified by setting the *EDITOR* alias `PROBLEM` in the file `zeus36.mac` to the name of the problem generating subroutine. This subroutine should initialise the active zones of all field variables as well as any inflow boundary arrays. The routines `bndyflgs` and `bndyall` are called after `PROBLEM`, and thus need not be called in the user's problem generator (§5.1).

Below is a description of the problem generator to `shkset`, which is used for the 1-D Brio and Wu problem and consistent with the sample of `dzeus36.s` given in §2.3. In general, the user will be writing their own problem generator and may, if they wish, call their namelist `pgen` as well. Note that it does not matter that more than one subroutine uses `pgen` as the name of its namelist, so long as only one problem generating subroutine is called in a run (as is typical). If the user wishes to use one of the problem generators already in `dzeus36`, each of their namelists are described in the comments of the problem generating routine in exactly the same format as that for `shkset` which follows.

```
parameter                    description                          default

idirect         = 1 => 1-direction                    ie biggest => 1
                = 2 => 2-direction                    je biggest => 2
                = 3 => 3-direction                    ke biggest => 3
isetib          = 1 => set inner boundary conditions based on        1
                       v(par)
                = 0 => inflow BC are already set by iib, etc.
isetob          same as isetib for outer boundary                    1
n0              Number of zones to be initialised.  Namelist is    max(nx*z)
                read from ioin until a total of ie-is+1 [je-js+1,
                ke-ks+1] zones are initialised.
d0              input density                                        tiny
e10             input first  internal energy density                 tiny
p10             input first  pressure ( = gamm1(1) * e10 )          -1.0
e20             input second internal energy density                 tiny
p20             input second pressure ( = gamm1(2) * e20 )          -1.0
v10             input velocity in 1 direction                        0.0
v20             input velocity in 2 direction                        0.0
v30             input velocity in 3 direction                        0.0
b10             input magnetic field in 1 direction                  0.0
b20             input magnetic field in 2 direction                  0.0
b30             input magnetic field in 3 direction                  0.0

Namelist variables idirect, isetib, and isetob must be set in the first
namelist card and may, though need not be, set in all.

Parameters n0-b30 must be set in each namelist card to override defaults.

p10 (p20) used if e10 (e20) not set.

      namelist / pgen     /
     1              idirect , isetib  , isetob  , n0      , d0
     2            , e10     , p10     , e20     , p20     , v10
     3            , v20     , v30     , b10     , b20     , b30
```

C The *ZEUS-3D* variables

This appendix contains a glossary of the variables used in `dzeus36`, and is meant to aid the user in writing subroutines and making changes to the source code itself. It is by no means complete, but should contain the variables needed for most purposes. All these variables are declared in the common deck `comvar`. Thus, adding the *EDITOR* command `*call comvar` before the local declarations makes all these variables accessible from within the subroutine.

The user should be aware of the index convention used. A 3-D array, such as the density, is denoted `d(i,j,k)`, where `i` is the index for the `x1` coordinate, `j` is the index for the `x2` coordinate, and `k` is the index for the `x3` coordinate. The coordinates `x1`, `x2`, and `x3` are intentionally generic, since an attempt has been made to write the code in a covariant fashion. In Cartesian, cylindrical, and spherical polar coordinates, `(x1,x2,x3)` corresponds to `(x,y,z)`, `(z,r,`ϕ`)` [not `(r,`ϕ`,z)`], and `(`ρ`,`θ`,`ϕ`)` respectively. In *FORTRAN*, the index which changes the fastest is the first one. Thus, in triple do-loops which manipulate the 3-D arrays, it is best to have the outer loop run on `k`, the middle loop run on `j`, and the inner loop run on `i`. If one of the directions is divided into more zones than the other two, then it is best that this direction be the 1-direction (with index `i`) since it is the inner loop which vectorises on vector machines. In Cartesian coordinates, this can always be arranged. The indices strictly follow a right-hand rule. Thus, the array `nijb(k,i)` is a 2-D array which has `k` as its first index and `i` as its second (and not `i` as the first index and `k` as the second which would follow a left-hand rule). In the tables in this appendix, arrays are given with their indexing to remind the user of the *ZEUS-3D* convention.

The user should also be aware of the gridding. The computational domain is divided into `in` by `jn` by `kn` zones. In each direction, five of these zones are "ghost" or "boundary" zones, while the remaining zones are "active" zones in which the equations of MHD are solved. In Cartesian geometry, these zones are rectangular boxes. In general, the gridding need not be uniform, so the ratio of the dimensions of each zone need not be constant across the grid. There are eight locations one can associate uniquely with each zone. Each of these locations can be tagged with the indices `(i,j,k)`. These locations are: the centre of each box, the centre of three of the six faces, the centre of three of the twelve edges, and one of the eight corners.

In *ZEUS-3D*, there are two grids which are referred to as the half-grid (or the a-grid) and the full grid (or the b-grid). By convention, the `(i,j,k)`th point on the a-grid is half a grid spacing closer in each dimension to the (left, bottom, back) corner of the grid than the `(i,j,k)`th point on the b-grid. As seen in the table below, zone centres have pure b-grid coordinates, zone corners have pure a-grid coordinates, while faces and edges of each zone have mixed coordinates.

location	coordinates	location	coordinates
zone centre	`(x1b(i), x2b(j), x3b(k))`	zone corner	`(x1a(i), x2a(j), x3a(k))`
1-face	`(x1a(i), x2b(j), x3b(k))`	1-edge	`(x1b(i), x2a(j), x3a(k))`
2-face	`(x1b(i), x2a(j), x3b(k))`	2-edge	`(x1a(i), x2b(j), x3a(k))`
3-face	`(x1b(i), x2b(j), x3a(k))`	3-edge	`(x1a(i), x2a(j), x3b(k))`

Part of the strength of *ZEUS-3D* is its use of a "staggered" grid. On such a grid, not all variables are located at the same place. Scalars (density and internal energy) are zone-

centred quantities while the components of the flow vectors (velocity and magnetic field) are face-centred quantities penetrating the face upon which they are centred. Vectors derived from vector quantities such as the current density ($\nabla \times \vec{B}$) and the induced electric field ($\vec{v} \times \vec{B}$) have edge-centred components parallel to the edges while scalars derived from vector quantities such as $\nabla \cdot \vec{v}$ are zone-centred. Thus, the two grids play equally important roles, and the user needs to be careful about which grid should be used and where the variables are located while making any changes to the code.

C.1 Grid variables

Limits for do-loops are tabulated below.

Variable	Description
`is, ie`	beginning and ending `i`-index for active zone-centres
`js, je`	beginning and ending `j`-index for active zone-centres
`ks, ke`	beginning and ending `k`-index for active zone-centres

Corresponding to each variable (`is`, `ie`, *etc.*) are the limiting variables (`ismn`, `iemx`, *etc.*) which indicate the extreme values possible for the do-loop indices should the grid extending option be used (§B.18). In addition, the variables `ism2`, `ism1`, `isp1`, `isp2`, and `isp3` exist which are set to `is-2`, `is-1`, `is+1`, `is+2`, and `is+3` respectively. If the computation is symmetric in the `i`-direction, `ism2`, `ism1`, `isp1`, `isp2`, and `isp3` are simply set to `is`. Similar variables exist for `ie`, `js`, `je`, `ks`, and `ke`. Finally, for convenience the total number of active zones in each direction is given by:

$$\texttt{nx1z} = \texttt{ie} - \texttt{is} + 1; \quad \texttt{nx2z} = \texttt{je} - \texttt{js} + 1; \quad \texttt{nx3z} = \texttt{ke} - \texttt{ks} + 1,$$

with corresponding limiting variables `nx1zmx`, `nx2zmx`, and `nx3zmx`.

In order to make the grid covariant, metric factors have been introduced which carry all the dependence of the geometry. In general, the metric appears in the expression for a differential in volume, $dV = h_1 dx_1\, h_2 dx_2\, h_3 dx_3$. In Cartesian coordinates, $h_1 = h_2 = h_3 = 1$. In cylindrical coordinates, $h_1 = h_2 = 1$, $h_3 = x_2$. In spherical polar coordinates, $h_1 = 1$, $h_2 = x_1$, $h_3 = x_1 \sin x_2$. Note that if one is limited to `XYZ`, `ZRP`, and `RTP` coordinates, there is no need for h_1 and h_3 can be split into two variables, one dependent just on x_1, the other just on x_2. In this way, h_3 can be represented by two 1-D arrays (h_{31} and h_{32}) rather than one 2-D array. Thus, three 1-D metric factors are used in *ZEUS-3D*.

The most commonly used a- and b-grid variables are listed in the two tables following.

a-variable	Location	Description
`x1a(i)`	zone-corner	`x1`-coordinate in grid units
`x2a(j)`	zone-corner	`x2`-coordinate in grid units
`x3a(k)`	zone-corner	`x3`-coordinate in grid units
`dx1a(i)`	1-edge	`x1a(i+1) - x1a(i)`
`dx2a(j)`	2-edge	`x2a(j+1) - x2a(j)`
`dx3a(k)`	3-edge	`x3a(k+1) - x3a(k)`
`h2a(i)`	zone-corner	`= 1` for Cartesian and cylindrical coordinates, `= x1a(i)` for spherical polar coordinates

h31a(i)	zone-corner	= h2a(i)
h32a(j)	zone-corner	= 1 for Cartesian coordinates, = x2a(j) for cylindrical coordinates, = sin(x2a(j)) for spherical polar coordinates

b-variable	Location	Description
x1b(i)	zone-centre	x1-coordinate in grid units
x2b(j)	zone-centre	x2-coordinate in grid units (radians in spherical polar coordinates)
x3b(k)	zone-centre	x3-coordinate in grid units (radians in both cylindrical and spherical polar coordinates)
dx1b(i)	1-face	x1b(i) - x1b(i-1)
dx2b(j)	2-face	x2b(j) - x2b(j-1)
dx3b(k)	3-face	x3b(k) - x3b(k-1)
h2b(i)	zone-centre	= 1 for Cartesian and cylindrical coordinates, = x1b(i) for spherical polar coordinates
h31b(i)	zone-centre	= h2b(i)
h32b(j)	zone-centre	= 1 for Cartesian coordinates, = x2b(j) for cylindrical coordinates, = sin(x2b(j)) for spherical polar coordinates

Every grid variable has a corresponding inverse variable, denoted with the suffix "i". Thus, dx1ai=1/dx1a, x2bi=1/x2b, *etc.* Evidently, there are numerous grid variables. However, only the a-grid variables x1a, x2a, and x3a are written to the restart dump. All others are re-computed when a job is resumed.

Note that x1a(i) < x1b(i). The exact relationship between the two grids is:

$$\texttt{x1b(i)} = \texttt{x1a(i)} + 0.5 * \texttt{dx1a(i)},$$

with similar expressions applying for the 2- and 3-directions.

C.2 Field variables (3-D arrays)

The most common field variables are listed below.

Variable	Location	Description
d (i,j,k)	zone centre	density
v1(i,j,k)	1-face	velocity in the 1-direction (grid units)
v2(i,j,k)	2-face	velocity in the 2-direction (grid units)
v3(i,j,k)	3-face	velocity in the 3-direction (grid units)
et(i,j,k)	zone centre	total energy density
e1(i,j,k)	zone centre	first internal energy density ($\propto$ pressure)
e2(i,j,k)	zone centre	second internal energy density
gp(i,j,k)	zone-centre	gravitational potential
b1(i,j,k)	1-face	magnetic field in the 1-direction ($\mu_0 = 1$)
b2(i,j,k)	2-face	magnetic field in the 2-direction ($\mu_0 = 1$)
b3(i,j,k)	3-face	magnetic field in the 3-direction ($\mu_0 = 1$)
da(i,j,k)	zone centre	product of density and synchrotron age

There is very little internal scaling of variables in *ZEUS-3D* that the user must consider. Density, energy, and velocity all may be scaled according to the user's needs simply by setting the initial conditions as appropriate. For example, the user may wish to set the density and the sound speed at infinity to 1. This, along with some canonical length scale will set the time scale for the calculation. The only scaling implicit to *ZEUS-3D* is the permeability of free space ($4\pi \times 10^{-7}$ in mks, 4π in cgs) is set to 1. Thus, the total pressure (thermal plus magnetic) is given by $p_{\rm tot} = p_{\rm th} + B^2/2$. Having set the scale of the hydrodynamical variables, the user should set the magnetic fields with this additional scaling in mind.

If the *EDITOR* macro `ISO` is defined, the total and first internal energy densities, `e1` and `et`, are not declared. The second internal energy (`e2`), the gravitational potential (`gp`), the magnetic field components (`b1`, `b2`, `b3`), and the synchrotron "density-age" (`da`) are declared only if the *EDITOR* macros `TWOFLUID`, `GRAV`, `MHD`, and `AGING` are defined respectively. If `PSGRAV` is defined, the "pseudo-gravitational potential" array (`psgp`) ($\neq$ `gp`) is declared.

C.3 Boundary variables (2-D arrays)

Variable		Location	Description
`niib`	`(j,k)`		boundary type for all variables except `gp`
`giib`			boundary type for gravitational potential
`diib1`	`(j,k)`	zone-centre at `i=is-1`	density
`v1iib1`	`(j,k)`	1-face at `i=is`	1-velocity (normal to the boundary)
`v2iib1`	`(j,k)`	2-face at `i=is-1`	2-velocity (tangential to the boundary)
`v3iib1`	`(j,k)`	3-face at `i=is-1`	3-velocity (tangential to the boundary)
`e1iib1`	`(j,k)`	zone-centre at `i=is-1`	first internal energy density ($\propto$ pressure)
`e2iib1`	`(j,k)`	zone-centre at `i=is-1`	second internal energy density
`gpiib1`	`(j,k)`	zone-centre at `i=is-1`	gravitational potential
`b2iib1`	`(j,k)`	2-face at `i=is-1`	2-magnetic field (tangential to the boundary)
`b3iib1`	`(j,k)`	3-face at `i=is-1`	3-magnetic field (tangential to the boundary)
`emf1iib1`	`(j,k)`	1-edge at `i=is-1`	1-*emf* (normal to the boundary)
`emf2iib1`	`(j,k)`	2-edge at `i=is`	2-*emf* (tangential to the boundary)
`emf3iib1`	`(j,k)`	3-edge at `i=is`	3-*emf* (tangential to the boundary)
`daiib1`	`(j,k)`	zone-centre at `i=is-1`	synchrotron density-age
`diib2`	`(j,k)`	zone-centre at `i=is-2`	density
`v1iib2`	`(j,k)`	1-face at `i=is-1`	1-velocity (normal to the boundary)
`v2iib2`	`(j,k)`	2-face at `i=is-2`	2-velocity (tangential to the boundary)
`v3iib2`	`(j,k)`	3-face at `i=is-2`	3-velocity (tangential to the boundary)
`e1iib2`	`(j,k)`	zone-centre at `i=is-2`	first internal energy density ($\propto$ pressure)
`e2iib2`	`(j,k)`	zone-centre at `i=is-2`	second internal energy density
`gpiib2`	`(j,k)`	zone-centre at `i=is-2`	gravitational potential
`b2iib2`	`(j,k)`	2-face at `i=is-2`	2-magnetic field (tangential to the boundary)
`b3iib2`	`(j,k)`	3-face at `i=is-2`	3-magnetic field (tangential to the boundary)
`emf1iib2`	`(j,k)`	1-edge at `i=is-2`	1-*emf* (normal to the boundary)
`daiib2`	`(j,k)`	zone-centre at `i=is-2`	synchrotron density-age
`v1iib3`	`(j,k)`	1-face at `i=is-2`	1-velocity (normal to the boundary)

The previous table lists the arrays for the first, second, and third inner-i boundaries. Note there are no boundary arrays for the total energy density; these values are computed directly from boundary values of the primitive variables where needed. Analogous boundary variables exist at the outer-`i` boundary (`oib`), inner-`j` boundary (`ijb`), outer-`j` boundary (`ojb`), inner-`k` boundary (`ikb`), and outer-`k` boundary (`okb`).

Note that the `i`-boundary variables use indices `(j,k)` and are declared so long as the *EDITOR* macro `ISYM` is *not* defined. Similarly, the `j`-boundary variables use indices `(k,i)` and are declared so long as `JSYM` is *not* defined while the `k`-boundary variables use indices `(i,j)` and are declared so long as `KSYM` is *not* defined. All internal energy boundary variables (`e1iib1`, *etc.*) are *not* declared if `ISO` is defined. The boundary variables for the second internal energy (`e2iib1`, *etc.*), gravity (`gpiib1`, *etc.*), the magnetic field components (`b2iib1`, *etc.*) and the synchrotron density-age (`daiib1`, *etc.*) are declared *only if* `TWOFLUID`, `GRAV`, `MHD`, and `AGING` are defined respectively.

Note that boundary variables are used only for regions of the boundary specified as inflow [`niib(j,k)=8,10` and/or `giib=10`]. For boundary type 8 (selective inflow), grid values are used where boundary variables are set to `huge`. For the gravitational potential, the boundary variable, `gpiib1`, is set to known analytical or asymptotic values. For all other boundary types, the boundary values of the flow variables are determined from the values in the neighbouring active zones (§B.8).

C.4 Scratch variables

There are a multitude of scratch arrays available which can be used to minimise the additional memory required by the user's subroutines. These should be used wherever possible, especially for 3-D arrays. There are 26 1-D arrays dimensioned (`ijkx`) and named `wa1d` through `wz1d`, 18 2-D arrays dimensioned (`idim,jdim`) and named `wa2d` through `wr2d` (see §C.6 for definition of parameters `idim` and `jdim`), and finally nine 3-D arrays dimensioned (`in,jn,kn`) and named `wa3d` through `wi3d`.

C.5 Sundry variables (an abbreviated list)

Variable	Description
`ioin`	logical unit attached to input deck
`iolog`	logical unit attached to message log file
`iotty`	logical unit attached to terminal (TTY or CRT)
`iodmp`	logical unit attached to restart dumps
`iopl1`	logical unit attached to 1-D plot files
`iopl2`	logical unit attached to 2-D plot files
`iopix`	logical unit attached to 2-D pixel dumps
`iousr`	logical unit attached to user dumps
`iotsl`	logical unit attached to time slice ascii dump
`iotsp`	logical unit attached to time slice plot dump
`iodis`	logical unit attached to display dump
`iorad`	logical unit attached to *RADIO* dump

Variable	Description
`iocrk`	logical unit attached to cork dump
`nhy`	number of cycles (time steps) completed in simulation
`nwarn`	running total of warnings issued
`prtime`	problem time elapsed in simulation
`dt`	increment of problem time that solution is being advanced

In addition, all of the namelist variables (except for namelist `pgen`) are declared in `comvar`.

C.6 Parameters

All global parameters are declared and set in common deck `par`. Primary parameters (those which the user can set) include:

Parameter	Description
`in`	number of zones in 1-direction plus 5 ghost zones
`jn`	number of zones in 2-direction plus 5 ghost zones
`kn`	number of zones in 3-direction plus 5 ghost zones
`nxpx`	maximum number of pixels in the x-direction for pixel dumps
`nypx`	maximum number of pixels in the y-direction for pixel dumps
`nxrd`	maximum number of pixels in the x-direction for *RADIO* dumps
`nyrd`	maximum number of pixels in the y-direction for *RADIO* dumps
`niov`	maximum number of variables plotted/dumped
`nios`	maximum number of slices for each variable plotted/dumped
`ncls`	maximum number of contour levels in 2-D *NCAR/PSPLOT* plots
`ntsl`	maximum number of time slices to be collected for plots
`ncrk`	maximum number of Lagrangian particles ("corks")
`nmat`	maximum number of materials. With `TWOFLUID` set, this should be 2
`isig`	number of significant figures to which some real*8 numbers are rounded.
`pi`	3.14159...
`tiny`	1.0×10^{-99}: smallest greater-than-zero number available on machine
`huge`	$1.0 \times 10^{+99}$: largest number available on machine
`smll`	1.0×10^{-6}: a convenient "small" number.
`lrge`	$1.0 \times 10^{+6}$: a convenient "large" number.

The parameter `nios` is used by 1-D and 2-D *NCAR/PSPLOT* plots, pixel dumps, and display dumps. The parameter `niov` is used by these plus *HDF* dumps and *RADIO* dumps.

Secondary parameters (those which are computed from the primary parameters and the user does not set but should still be aware of) include:

Parameter	Description
`ijkx`	the maximum of `in`, `jn`, and `kn`
`ijkn`	the minimum of `in`, `jn`, and `kn`
`idim`	= `jn` (`kn`, `in`) if `ISYM` (`JSYM`, `KSYM`) is set [1- (2-, 3-) symmetry flag] = `ijkx` if no symmetry is set
`jdim`	= `kn` (`in`, `jn`) if `ISYM` (`JSYM`, `KSYM`) is set [1- (2-, 3-) symmetry flag] = `ijkx` if no symmetry is set

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