Appendix A

Mathematical Notation Used in this Book

This appendix gives a brief description of the mathematical notation used in this book, especially in Chapters 5 to 9. In all cases scalar quantities are presented in simple math mode. Examples are mass $m$ or $M$; fundamental constants $c, G, \text{etc.}$; and Greek letters $\gamma, \delta, \phi, \text{etc.}$. This does not include components of vectors and tensors, which are discussed below.

A.1 Vector and Tensor Notation for Two- and Three-Dimensional Spaces

Two and three-dimensional space notation is the same, as neither contains a time coordinate.

A.1.1 Two- and Three-Dimensional Vector and 1-Form Notation

Vectors in two and three dimensions are written as bold capital letters in math mode. Examples are momentum and velocity $P$ and $V$; electric and magnetic field $E$ and $B$; etc. Components of vectors are written in the same font as the geometrical quantity, but not in boldface and with a upper index indicating which component it represents. Examples: $P^x$, $V^r$, $E^y$, and $B^z$.

Roman subscripts are sometimes added to vectors or their components to distinguish which object or type of physics problem is being discussed. Examples are the velocity of object #2 $V_2$ or orbital velocity in Schwarzschild geometry $V_{\text{orb,SH}}^\phi$.

1-Forms for the above quantities are written in bold lower-case letters, also in math mode. Examples are the momentum and velocity 1-forms $p$ and $\nu$; electric and magnetic 1-forms $e$ and $b$; etc. Components are of these written in the same
font as the 1-form geometrical quantity, but not in boldface and with a lower index. Examples: \(p_z, v_x, e_r, \) and \(b_y\).

In flat two- and three-dimensional space, even when the coordinates are curvilinear, there usually is no distinction between vector and 1-form components. This is because they usually are written in a local orthonormal frame rather than a coordinate frame and because the metric in the that frame is simply the identity matrix. For example, in polar coordinates, the velocity \(V^\theta\) is actually the linear velocity \(V^\theta = r \, d\theta / dt\), not the speed of the angular coordinate \(\theta\) (\(V^\theta = \frac{d\theta}{dt}\)). Therefore, \(v_\theta = V^\theta\), so there is no distinction between vectors and 1-forms.

### A.1.2 Tensor Notation

Contravariant tensors in two and three dimensions are written as bold, sans serif capital letters. An example is the three-dimensional stress tensor \(T\). Components are written in non-bold sans serif capital letters, with upper indices: \(T^{xx}\).

Covariant tensors in two and three dimensions also are bold, sans serif letters, but lower-case is used. The covariant version of the stress tensor is \(t\), and its components are written \(t_{xx}, t_{xy}, \) etc. The metric tensor \(g\) follows this form, but its contravariant version does not, because it is the inverse of the metric \(G = g^{-1}\).

In order to limit confusion, mixed tensors are avoided in this book.

### A.2 Vector and Tensor Notation for Four-Dimensional Spacetime

In order to emphasize the fundamental difference between three-vectors and four-vectors (and between three- and four-dimensional tensors), we use a different notation for spacetime quantities.

#### A.2.1 Vector and 1-Form Notation in Four-Dimensional Spacetime

As above, four-vector geometric quantities are written as bold capital letters. However, the font is a roman one, not math mode. Examples are four-momentum and four-velocity \(P\) and \(U\); four-current \(J\) and four-potential \(A\). Components also are non-bold characters of the same font and again with upper indices: \(P^x, U^r, J^y, \) and \(A^z\).

Similarly, 1-form quantities in four dimensions are written as bold lower-case roman letters, with their components in non-bold roman font and having lower indices: \(p_z, u_x, j_r, \) and \(a_y\).
A.2.2 Tensor Notation in Four-Dimensional Spacetime

Contravariant tensors in four dimensions are written as bold, calligraphic capital letters. Examples are the stress-energy tensor $\mathcal{T}$ and the Faraday and Maxwell tensors $\mathcal{F}$ and $\mathcal{M}$. The components are written as upper indices: $T^{ww}$, $F^{xy}$, $M^{wz}$.

Because calligraphic letters are available only in upper-case, for covariant four-dimensional tensors we re-use the regular math mode letters. (There should be no ambiguity, as this notation is rarely used for three-dimensional 1-forms in this book. See above.) Examples are the metric $g$ with components $g_{xx}$, etc or the Faraday 2-form $f$. As in three-space, the covariant forms are written with the same letter, but in lower-case. The exception again is the metric, because its contravariant form is also its inverse $g^{-1}$.

In the rare case when we need to express a tensor with more than two indices (e.g., the Riemann tensor), we use the Fraktur font: $\mathfrak{R}$ or $\mathfrak{R}_{\alpha\beta\gamma\delta}$.

A.3 Miscellaneous Notation

Dipole and quadrupole moments often use similar letters to other physical quantities, so here we distinguish them by writing them in a Fraktur font. The same is true of other rare quantities used herein, including three-force per unit volume $\mathfrak{F}$ in a Fraktur font (as opposed to a simple force $F$) and four-force per unit volume $\mathcal{F}$ in a script font.

Occasionally a vector or tensor of the same spatial dimensions and rank will be needed to indicate the time and spatially-independent coefficients of a sinusoidal wave function. In that case we use the same letter (lower or upper-case) with a slightly different, but related, font. Examples are the Euler font $\mathcal{A}$ for the coefficient of the three-vector potential $A$ or the blackboard font $\mathbb{A}$ for the four-vector potential $A$. 
Appendix B

Derivatives of Vectors and Tensors: Differential Geometry

Physics, and therefore astrophysics, is described by equations that involve the spatial and time derivatives of vectors and tensors. In order to properly describe physics in a curved spacetime (and even in flat spacetime that is spanned by curvilinear coordinates) we will need to understand how gradients and divergences of these quantities are calculated when the coordinates are not Euclidean or Minkowskian. This requires the mathematics of differential geometry, which is a broad subject. Here we provide only a very brief introduction.

Gradients and divergences will depend, of course, on how the metric changes with those coordinates. The derivatives of $g$ are best embodied by a single function, called the “Christoffel symbol” or “connection coefficient”, and it takes into account all possible derivatives:

$$\Gamma_{\lambda\mu\nu} \equiv \frac{1}{2} \left( \frac{\partial g_{\lambda\mu}}{\partial x^\nu} + \frac{\partial g_{\lambda\nu}}{\partial x^\mu} - \frac{\partial g_{\mu\nu}}{\partial x^\lambda} \right)$$

The indices $\lambda$, $\mu$, and $\nu$ range over the dimension of the space (e.g., 0–3 for spacetime).

While the connection coefficients appear rather ugly, and the reader may be inclined to ignore them, they are of enormous importance in physics and even our daily lives. They give rise to:

- Formulae for the gradient, divergence, and curl in curvilinear coordinates that are routinely used in fluid dynamics, plasma physics, mechanics, etc.
- Pseudo-forces like centrifugal and Coriolis forces, which arise because our frame of reference is accelerated.
- The force of gravity, which in Einstein’s view is also a pseudo-force, arising because of the curvature of space and time.

1 There are a few places in this book where matrix notation is not adequate, so we shall revert to component notation. This is the case here, and in a few other places, where we must deal with quantities with more than two indices.
B.1 Covariant Gradients in Curved Spacetime

The gradient of a geometric quantity (scalar, vector, tensor) increases the number of indices on that quantity by 1: a scalar becomes a vector; a vector becomes a 2-tensor, etc. Using connection coefficients, the gradient can be written as follows:

\[
(\nabla \Phi)_\gamma = \frac{\partial \Phi}{\partial x^\gamma} \\
(\nabla V^\beta)_\gamma = \frac{\partial V^\beta}{\partial x^\gamma} + \sum_{\lambda, \mu} g^{\beta\lambda} \Gamma^\gamma_{\lambda\mu} V^\mu \\
\left(\nabla T^{\alpha\beta}\right)_\gamma = \frac{\partial T^{\alpha\beta}}{\partial x^\gamma} + \sum_{\lambda, \mu} \left[ g^{\alpha\lambda} \Gamma^\gamma_{\lambda\mu} T^{\mu\beta} + g^{\lambda\beta} \Gamma^\gamma_{\lambda\mu} T^{\alpha\mu} \right] \quad (B.2)
\]

The sums in the above formulae are performed over the number of dimensions in the space or spacetime.

Similar formulae also exist for 1-forms, 2-forms, etc.

\[
(\nabla v^\beta)_\gamma = \frac{\partial v^\beta}{\partial x^\gamma} - \sum_\mu \Gamma^\gamma_{\beta\mu} v^\mu \\
(\nabla t_{\alpha\beta})_\gamma = \frac{\partial t_{\alpha\beta}}{\partial x^\gamma} - \sum_{\lambda, \mu} \left[ g^{\mu\lambda} \Gamma^\gamma_{\alpha\mu} t_{\lambda\beta} + g^{\mu\lambda} \Gamma^\gamma_{\beta\mu} t_{\alpha\lambda} \right] \quad (B.3)
\]

These are called “covariant” gradients, because they can be used in physical laws that are invariant under any coordinate transformation. Furthermore, the formulae are true for any metric and so are quite amazing, if rather messy.

We can simplify the look of them, using the matrix notation we used in Chapters 6 and 7 if we define a simple derivative \( \partial_\gamma \) to be the operator

\[ \partial_\gamma \equiv \frac{\partial}{\partial x^\gamma} \]

\( \partial_\gamma \) is similar to \( \nabla_\gamma \), but it takes the derivative of only the components of the geometric quantities, not of their unit vectors as well. We then can write equations (B.2) as

\[
\nabla \Phi = \partial \Phi \\
\nabla V = \partial V + \left[ g^{-1} \cdot \Gamma \right] \cdot V \\
\nabla T = \partial T + \left[ g^{-1} \cdot \Gamma \right] \cdot T + T \cdot \left[ g^{-1} \cdot \Gamma \right] \quad (B.4)
\]

While these are much more intuitive than equations (B.3), they have much less computational power, because it is not clear over which indices the dot products occur.
B.2 Divergences in Curved Spacetime

The divergence of a geometrical quantity is simply the “contraction” of the gradient. This means that we set one upper index equal to the lower differentiating one and sum. Because it requires an upper index, the divergence applies only to vectors and tensors, not forms. Setting $\gamma = \beta$ in equations (B.2) and summing over $\beta$ we have

$$\nabla \cdot \mathbf{V} = \sum_{\beta} \left\{ \frac{\partial V^\beta}{\partial x^\beta} + \sum_{\lambda, \mu} g^{\beta \lambda} \Gamma_{\lambda \mu \beta} V^\mu \right\}$$

$$(\nabla \cdot \mathbf{T}^\alpha) = \sum_{\beta} \left\{ \frac{\partial T^\alpha\beta}{\partial x^\beta} + \sum_{\lambda, \mu} \left[ g^{\alpha \lambda} \Gamma_{\lambda \mu \beta} T^\mu \beta + g^{\lambda \beta} \Gamma_{\lambda \mu \beta} T^\alpha \mu \right] \right\}$$ \hspace{1cm} (B.5)

However, these can be simplified considerably by introducing the determinant of the metric

$$g \equiv |g|$$ \hspace{1cm} (B.6)

Equations (B.5) then become

$$\nabla \cdot \mathbf{V} = \frac{1}{\sqrt{|g|}} \sum_{\beta} \frac{\partial \left( \sqrt{|g|} V^\beta \right)}{\partial x^\beta}$$

$$(\nabla \cdot \mathbf{T}^\alpha) = \sum_{\beta} \left\{ \frac{1}{\sqrt{|g|}} \frac{\partial \left( \sqrt{|g|} T^\alpha\beta \right)}{\partial x^\beta} + \sum_{\lambda, \mu} \left[ g^{\alpha \lambda} \Gamma_{\lambda \mu \beta} T^\mu \beta + g^{\lambda \beta} \Gamma_{\lambda \mu \beta} T^\alpha \mu \right] \right\}$$ \hspace{1cm} (B.7)

Again, we can write these in our matrix notation as

$$\nabla \cdot \mathbf{V} = \frac{1}{\sqrt{|g|}} \partial \cdot \left( \sqrt{|g|} \mathbf{V} \right)$$

$$\nabla \cdot \mathbf{T} = \frac{1}{\sqrt{|g|}} \partial \cdot \left( \sqrt{|g|} \mathbf{T} \right) + [g^{-1} \cdot \mathbf{T} : \mathbf{T}]$$ \hspace{1cm} (B.8)

In three-dimensional curvilinear coordinates, the metric is often diagonal, with elements $g_{ii} = h_i^2$. The vector divergence in equations (B.7) then gives us the familiar form for the divergence in curvilinear coordinates

$$\nabla \cdot \mathbf{V} = \frac{1}{h_1 h_2 h_3} \sum_{i=1}^{3} \frac{\partial \left( h_1 h_2 h_3 V^i \right)}{\partial x^i}$$

This equation is useful only for diagonal three-metrics; however, equations (B.7) work for any metric and so are much more powerful.
B.3 The Metric Has No Gradient or Divergence

If we plug the metric tensor $g^{-1}$ into the tensor form of equations (B.2), (B.3), and (B.5), and use the definition of $\Gamma$ (equation (B.1)), we find that

$$\nabla g^{-1} = 0$$
$$\nabla g = 0$$

and, therefore, $\nabla \cdot g = 0$. The metric, therefore, has no covariant derivative or divergence, even though its components do change, in general, as we move through spacetime. The covariant derivative $\nabla$, therefore, picks up only those changes in a vector or tensor that are independent of the coordinates, not those that are generated by motion or curvature. This is why $\nabla$ is used to cast the equations of physics in a coordinate-invariant (covariant) form.

In fact, we can now return to equation (B.1) and see how it was derived in the first place. We begin by simply imposing the requirement that the metric have no gradient or divergence. The formula for $\Gamma^{\lambda\mu\nu}$, therefore, must involve a linear combination of all possible derivatives of the symmetric metric tensor $g$

$$\Gamma^{\lambda\mu\nu} \equiv a \frac{\partial g_{\lambda\mu}}{\partial x^\nu} + b \frac{\partial g_{\lambda\nu}}{\partial x^\mu} + c \frac{\partial g_{\mu\nu}}{\partial x^\lambda} \quad (B.9)$$

If we now express $\nabla g$ in the general form (B.3), require it to be zero, require $\Gamma^{\lambda\mu\nu}$ to be symmetric in $\mu$ and $\nu$, and solve for the coefficients $a$, $b$, and $c$, we recover the formula for $\Gamma$ in equation (B.1).
Appendix C

Derivation of the Adiabatic Relativistic Stellar Structure Equations

This appendix derives the equations for the structure and evolution of a relativistic star in spherical symmetry. Because of this assumption, there will be no time-dependent quadrupole moment of the star’s mass and, therefore, no gravitational radiation emitted. This derivation, while fairly basic in relativistic physics is a little beyond the scope of the main part of the book. Nevertheless, it is an important demonstration of the use of the Einstein field equations (7.21) in solving for the time evolution of a relativistic gravitational field and an excellent example of black hole formation. The equations presented here were first derived by Charles Misner (University of Maryland) and David Sharp (Princeton University) [638], and independently by Michael May and Richard White of the Lawrence Radiation Laboratory (now known as Lawrence Livermore National Laboratory or LLNL) [639]. We will follow May and White’s work most closely.

C.1 The Spherical Metric in Mass Coordinates

We begin with the spherically symmetric metric written in a manner similar to the Schwarzschild metric

\[ ds^2 = -\tilde{a}^2 c^2 \, d\tilde{t}^2 + \tilde{b}^2 \, dr^2 + r^2 \, d\Omega^2 \]  

(C.1)

where \( d\Omega^2 = d\theta^2 + \sin^2 \theta \, d\phi^2 \). Indeed, outside the star we do have Schwarzschild geometry, with \( \tilde{a} = b^{-1} = (1 - r_S/r)^{1/2} \). However, inside the star \( \tilde{a} \) and \( \tilde{b} \) will be functions of time as well as of the radius \( r \).

For many reasons, detailed in Section 5.2.2, it is more convenient to use a coordinate system in which the independent radial coordinate is the integral of rest mass from the center of the star to some fixed specific value

\[ m \equiv \int_V \rho \, dV \]  

(C.2)
where $dV$ is the Proper volume (including the curvature of space) and $\rho$ is the rest mass density only (no internal or kinetic energy included). The amount of rest mass $m$ inside this point will remain fixed during the evolution, but the radius of that shell $r(m, t)$ will change with time. It is helpful in this gauge to think of the star as composed of concentric shells, each with a mass $dm = \rho dV$, which can (1) collapse under their own gravitational weight if there are no other forces, (2) press against one another to keep the star in equilibrium if there are restoring pressure forces, or (3) even explode outward if the pressure can overcome gravity. A given value of $m$ sits at the outer edge of a given mass shell and follows that shell’s motion as the star evolves.

Switching from $r$ to the mass coordinate $m$, then, gives us a new metric

$$ds^2 = -a^2 c^2 dt^2 + b^2 dm^2 + r^2 d\Omega^2$$

where $a$, $b$, and $r$ are functions of $m$ and the new time variable $t$ only (the spherically symmetric assumption). In particular, $r$ will be the outer radius of the spherical mass shell at position $m$ and radial mass width $dm$. (To be precise, $r$ will be equal to $1/2\pi$ times the circumference of the $m$th spherical shell.)

Now, the proper three-dimensional volume element of each spherical shell in this metric is

$$dV = b dm r d\theta r \sin \theta d\phi$$

So equation (C.2) becomes

$$m = \int_0^{2\pi} d\phi \int_0^{\pi} \sin \theta d\theta \int_0^m \rho r^2 b dm$$

$$= \int_0^m 4\pi r^2 \rho b dm$$

(C.4)

Because the differential of both sides of equation (C.4) must be equal (i.e., $dm = 4\pi r^2 \rho b dm$) we immediately can write down the metric coefficient of $dm$

$$b = \frac{1}{4\pi r^2 \rho}$$

(C.5)

As with Newtonian stellar structure, the choice of mass coordinates automatically enforces the conservation of mass.

### C.2 The Field Equations and Conservation Laws

The remainder of the metric coefficients ($a$ and $r$) and the state variables ($\rho$ and internal energy $\varepsilon$) are determined by two Einstein field equations and two conservation laws. We will use the stress-energy-momentum tensor written in the rest frame
of each mass shell (i.e., in the moving \([m, t]\) coordinate system) (equation (6.69)). The \(G^{tt} = 8\pi G T^{tt}/c^4\) Einstein field equation is, then

\[
\frac{c^2}{2} \frac{\partial}{\partial m} \left\{ r \left[ 1 + \frac{1}{a^2 c^2} \left( \frac{\partial r}{\partial t} \right)^2 - \frac{1}{b^2} \left( \frac{\partial r}{\partial m} \right)^2 \right] \right\} = 4\pi G \left( \rho + \frac{\varepsilon}{c^2} \right) r \frac{\partial r}{\partial m}
\]

(C.6)

and the \(G^{tm}\) component has no source

\[
\frac{\partial^2 r}{\partial m \partial t} - \frac{1}{a} \frac{\partial a}{\partial m} \frac{\partial r}{\partial t} - \frac{1}{b} \frac{\partial b}{\partial t} \frac{\partial r}{\partial m}
\]

(C.7)

Finally, the \(t\) and \(m\) components of \(\nabla \cdot \mathbf{T} = 0\) are

\[
\frac{\partial}{\partial t} \left( \rho + \frac{\varepsilon}{c^2} \right) = -\xi \rho \left( \frac{1}{b} \frac{\partial b}{\partial t} + \frac{2}{r} \frac{\partial r}{\partial t} \right) \quad \text{(C.8)}
\]

\[
\frac{\xi \rho c^2}{a} \frac{\partial a}{\partial m} = -\frac{\partial p}{\partial m} \quad \text{(C.9)}
\]

where we have defined the inertia per unit rest mass to be

\[
\xi \equiv 1 + \frac{(\varepsilon + p)}{\rho c^2} \quad \text{(C.10)}
\]

It is helpful, both mathematically and physically, to define the gravitational mass

\[
\mathcal{M} \equiv \int_0^m 4\pi r^2 \left( \rho + \frac{\varepsilon}{c^2} \right) \frac{\partial r}{\partial m} \, dm \quad \text{(C.11)}
\]

which \(does\) include both the internal energy and the kinetic energy, as well as rest mass, inside the shell at coordinate \(m\). It also is useful to to define two quantities

\[
u \equiv \frac{1}{a} \frac{\partial r}{\partial t} \quad \text{(C.12)}
\]

\[
W \equiv \frac{1}{b} \frac{\partial r}{\partial m} \quad \text{(C.13)}
\]

These will turn out to be the \(m\)-component of the four-velocity of the mass shell and a geometric factor \(W\) telling us how \(dm\) and \(4\pi r^2 \rho \, dr\) are related. The coordinate derivatives of the gravitational mass \(\mathcal{M}\) have simple expressions

\[
\frac{\partial \mathcal{M}}{\partial m} = 4\pi r^2 \left( \rho + \frac{\varepsilon}{c^2} \right) \frac{\partial r}{\partial m} = \left[ 1 + \frac{\varepsilon}{\rho c^2} \right] W \quad \text{(C.14)}
\]

\[
\frac{\partial \mathcal{M}}{\partial t} = 4\pi r^2 \frac{p}{c^2} u \frac{\partial r}{\partial t} = -4\pi r^2 \frac{a p}{c^2} u \quad \text{(C.15)}
\]
The first of these follows directly from the mass derivative of equation (C.11). The second can be derived by taking the time derivative of that equation, folding in equations (C.7) to (C.10), and integrating over $dm$. (It also can be derived by computing the [redundant] $G^{rr} = 8\pi G T^{rr}/c^4$ Einstein field equation, which is an equivalent amount of work.)

## C.3 The Adiabatic, Relativistic Stellar Evolution Equations

We now are in a position to solve for some of the variables and put the equations in simple, familiar forms.

### C.3.1 The Mass Shell Geometric Factor

Using equation (C.14) we can replace the right-hand side of equation (C.6) with $G \partial M/\partial m$ and integrate over $dm$. Applying definition (C.13), this gives

$$W^2 = 1 + \frac{u^2}{c^2} - \frac{2G M}{c^2 r} \quad \text{(C.16)}$$

If there were no gravity ($G = 0$), the geometric factor $W$ would be simply the Lorentz factor. On the other hand, if we had gravity but no motion ($u = 0$), then $W$ would have the Schwarzschild form $\left(1 - \frac{2G M}{c^2 r}\right)^{1/2}$.

### C.3.2 The Density Equation

Equations (C.5) and (C.12) can be differentiated with respect to $t$ and $m$, respectively, and plugged into equation (C.7) to yield an equation analogous to the Newtonian density equation (5.58)

$$\frac{1}{\rho r^2} \frac{1}{a} \frac{\partial (\rho r^2)}{\partial t} = - \frac{\partial u/\partial m}{\partial r/\partial m}$$

This looks exactly like the Newtonian version if we identify

$$\frac{1}{a} \frac{\partial}{\partial t} = \frac{\partial}{\partial \tau} \quad \text{(C.18)}$$

as the time derivative in the rest frame of each mass shell (cf., equation (C.12)).
C.3.3 Conservation of Energy Equation

If we substitute the mass metric coefficient (equation (C.5)) and its time derivative into the conservation of energy equation (equation (C.8)), we obtain

$$\frac{\partial \varepsilon}{\partial t} = \frac{(\varepsilon + p)}{\rho} \frac{\partial \rho}{\partial t}$$  \hspace{1cm} (C.19)

which is the first law of thermodynamics (equation (5.50)) with no heating or cooling (adiabatic flow). The lack of any heat flow terms ($T_{tm}$) in the stress-energy tensor is where the adiabatic assumption was made. This ensures that the gas remains isentropic.

C.3.4 Equation of Motion in Mass Coordinates

Because the mass shell coordinate system is a moving (Lagrangian) one, it should come as no surprise that the conservation of momentum equation comes mainly from the Einstein field equation (the $rr$ one) with only some help from equation (C.9), rather than the other way around. To derive it, we differentiate the equation for the geometric factor $W$ with respect to time

$$W \frac{\partial W}{\partial t} = \frac{u}{c^2} \frac{\partial u}{\partial t} - \frac{G}{c^2 r} \frac{\partial M}{\partial t} + \frac{G M}{c^2 r^2} \frac{\partial r}{\partial t}$$  \hspace{1cm} (C.20)

We then substitute into the above equation an expression for $\partial W/\partial t$ derived from equations (C.5), (C.7), (C.9), and (C.13)

$$\frac{\partial W}{\partial t} = -\frac{4\pi r^2}{\xi c^2} \frac{\partial p}{\partial m} \frac{\partial r}{\partial t}$$  \hspace{1cm} (C.21)

plus the expressions for $\partial M/\partial t$, and $\partial r/\partial t$. The result, after multiplying by $c^2/\nu$, is

$$\frac{1}{a} \frac{\partial u}{\partial t} = -4\pi r^2 \frac{W}{\xi} \frac{\partial p}{\partial m} - \frac{G (M + 4\pi r^3 p/c^2)}{r^2}$$  \hspace{1cm} (C.22)

This is the relativistic version of the Newtonian conservation of momentum in mass coordinates (equation (5.61)). In the non-relativistic Newtonian limit, the mass contributed by pressure and internal energy in equation (C.22) will be negligible ($\xi \to 1$ and $4\pi r^3 p/M c^2 \to 0$). Also, because of equation (C.9), the lapse function $a$ will become be unity throughout the star, so $\partial \tau = \partial t$, and we will have $W \to 1$ as well. So the equation of motion does indeed reduce to the Newtonian one derived in Chapter 5.
C.3.5 Equation of Motion in Schwarzschild–Hilbert-like Coordinates

We also can write the relativistic equation of motion in terms the radial pressure gradient. It still will be in the Lagrangian frame of reference, but will appear more familiar.

Because $r$ is a monotonic function of $m$ at any time $t$, we can write

$$\frac{\partial p}{\partial m} = \frac{\partial p}{\partial r} \frac{\partial r}{\partial m} = \frac{\partial p}{\partial r} W b = \frac{W}{4\pi r^2 \rho} \frac{\partial p}{\partial r}$$  \hspace{1cm} (C.23)

So we now can convert equation (C.22) into one involving derivatives in proper time $\tau$ and the shell radius $r$

$$\frac{\partial u}{\partial \tau} = - \left( 1 + \frac{u^2}{c^2} - \frac{r_S}{r} \right) \frac{\partial p}{\partial r} - \left( 1 + \frac{4\pi r^3 \rho}{G M c^2} \right) \xi \frac{G M \rho}{r^2}$$ \hspace{1cm} (C.24)

The relativistic corrections in equation (C.23) have the following interpretations: acceleration term (inertia due to internal energy and pressure must be included); pressure term (one factor of $W$ comes from the $\partial / \partial r$ gradient and one comes from a Lorentz-like boost of the pressure itself); gravitational force (as pressure increases, its gravitational mass must be included, both in the enthalpy inertia and in the inertia of the mechanical force itself).
Appendix D

Derivation of the General Relativistic MHD Equations from Kinetic Theory

The equations of general relativistic magnetohydrodynamics, which play a central role in this book, can be derived from the general relativistic Boltzmann equation in a two-step process. First, we take velocity moments of that equation to generate the multi-fluid GRMHD equations. Then we perform weighted sums of those equations, over mass and over charge, to produce conservation laws for mass, charge, four-momentum, and four-current. The derivation presented here follows an article by D. Meier [346] on the generalized Ohm’s law (conservation of current).

D.1 The Multi-Fluid Equations of General Relativistic Magnetohydrodynamics

D.1.1 The Zeroth Moment: Conservation of Particle Number

We begin by re-writing the general relativistic Boltzmann equation (9.2) as

\[ \mathbf{U}_i \cdot \nabla N_i + \mathbf{F}_i \cdot \nabla P N_i = \dot{N}_i,_{\text{coll}} \]  

(D.1)

where \( \mathbf{U}_i = P/m_i \) is a function (like \( \mathbf{F}_i \)), not a coordinate.\(^1\) It can be shown [346] that the momentum integral of the second term on the left and of the collision term on the right vanish. And, because \( X \) and \( P \) are independent phase space coordinates, \( \nabla \cdot \mathbf{U}_i \propto \nabla \cdot P = 0 \), so the zeroth velocity moment of the Boltzmann equation becomes simply

\[ \nabla \cdot \iiint \mathbf{U}_i \, \dot{N}_i \, d^4 P = 0 \]  

(D.2)

\(^1\) As in Chapter 9, we use the blackboard font to indicate quantities pertaining to a given volume in eight-dimensional phase space (\( X, P, U, F \)) and the script font in six-dimensional phase space (\( X, P, V, F \)), while regular bold characters are used for average quantities in four- or three-dimensional physical space. See Appendix A.
This can be written in a more familiar form if we decompose \( U_i \) into an average center-of-mass velocity

\[
U \equiv \frac{\sum_i m_i \int \int \int \int U_i \mathcal{N}_i \, d^4P}{\sum_i m_i \int \int \int \mathcal{N}_i \, d^4P}
\]  

(D.3)

and the drift velocity \( \mathbb{V}_i \), which is always orthogonal to \( U \), giving us

\[
U_i = \gamma_i (U + \mathbb{V}_i)
\]  

(D.4)

where the Lorentz factor for each volume of phase space is defined as

\[
\gamma_i \equiv -\frac{1}{c^2} (U \cdot U_i) = (1 - \mathbb{V}_i \cdot \mathbb{V}_i)^{-1/2}
\]  

(D.5)

The second half of equation (D.5) is true if we measure the components of \( \mathbb{V}_i \) in the rest frame of the fluid. Note that, while \( \mathbb{V}_i \) is formally a four-vector, because \( U \cdot \mathbb{V}_i = 0 \), \( \mathbb{V}_i \) has only three non-zero (spatial) components in the rest frame of the fluid. The \( w \) (time) component of \( \mathbb{V}_i \) is zero and can be ignored.

Equation (D.2) now can be written as the conservation of particle species \( i \)

\[
\nabla \cdot n_i (U + \mathbb{V}_i) = 0
\]  

(D.6)

where the particle density of species \( i \) is

\[
n_i = \int \int \int \gamma_i \mathcal{N}_i \, d^4P = \int \int \int f_i \, d^3P
\]  

(D.7)

and the average drift velocity for that species is

\[
\mathbb{V}_i = \frac{1}{n_i} \int \int \int \gamma_i \mathbb{V}_i \mathcal{N}_i \, d^4P = \frac{1}{n_i} \int \int \int \mathbb{V}_i f_i \, d^3P
\]  

(D.8)

(Here we have used the relation between \( \mathcal{N}_i \) and \( f_i \) (equation (9.4)) and have performed the integral over the mass shell, as discussed in Section 9.1.) With these definitions we see that equation (D.3) implies that the mass weighted drift velocity vanishes.

\[
\sum_i n_i m_i \mathbb{V}_i = 0
\]  

(D.9)

**D.1.2 The First Moment: Conservation of Particle Four-Momentum**

The first velocity moment of the general relativistic Boltzmann equation can be obtained by first multiplying equation (D.1) by \( U_i \). This produces a vector Boltzmann
\[ \nabla \cdot (\mathbf{R}_i \mathbf{U}_i \mathbf{U}_i) + \mathbf{U}_i \left[ \frac{q_i}{m_i c} (\mathbf{U}_i \cdot \mathbf{F}_i) \cdot \nabla P \right] = \mathbf{U}_i \dot{\mathbf{R}}_i, \text{coll} \]

With \( \mathbf{F}_i \) given by equation (9.3), the integral of this equation over momentum four-space yields the conservation of four-momentum for particles of species \( i \)

\[
\nabla \cdot \left[ n'_i \mathbf{U}_i \mathbf{U}_i + n_i \mathbf{U} \mathbf{V}_i + n_i \mathbf{V}_i \mathbf{U} + \Pi_i \right] = \frac{1}{m_i c} \mathbf{J}_i \cdot \mathbf{F} - \nu n_i (\mathbf{U} + \mathbf{V}_i)
\]

where we now see two new averaged quantities: the relativistic particle density

\[
n'_i \equiv \int \int \int \gamma_i^2 \mathbf{R}_i \, d^4P = \int \int \int \gamma_i f_i \, d^3P
\]

and the beamed drift velocity

\[
\mathbf{V}'_i \equiv \frac{1}{n_i} \int \int \int \gamma_i^2 \mathbf{V}_i \mathbf{R}_i \, d^4P = \frac{1}{n_i} \int \int \int \gamma_i \mathbf{V}_i f_i \, d^3P
\]

We also now have a definition of the partial electric current contributed by each particle species

\[
\mathbf{J}_i \equiv q_i n_i (\mathbf{U} + \mathbf{V}_i)
\]

and the partial pressure tensor

\[
\Pi_i \equiv \int \int \int \gamma_i^2 (\mathbf{V}_i \mathbf{V}_i \mathbf{R}_i) \, d^4P = \int \int \int \gamma_i (\mathbf{V}_i \mathbf{V}_i f_i) \, d^3P
\]

Equations (D.6) and (D.10) are the general relativistic multi-fluid MHD equations for each particle species density \( n_i \) and velocity \( \mathbf{U} + \mathbf{V}_i \). These equations do not close (i.e., have the same number of equations as unknowns), because \( \Pi_i \) involves the second velocity moment, which we have not computed yet. There are only two ways to continue with the calculation and compute \( \Pi_i \); (1) compute the second velocity moment of equation (D.1) (which will only perpetuate the problem by producing an equation that needs the third velocity moment) or (2) assume a known equilibrium form for \( f_i(P) \), which allows us to explicitly calculate \( \Pi_i \) (and also \( n'_i \)). We choose the second method and further assume that \( f_i(P) \) is isotropic over the solid angle in momentum three-space

\[
\int \int f_i \, d^3P = f_i \frac{4 \pi P^2 \, dP}{P} \equiv \frac{dn_i}{dP} \, dP
\]

The partial pressure tensor then becomes diagonal.
\[ \Pi_i = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & p_i & 0 & 0 \\ 0 & 0 & p_i & 0 \\ 0 & 0 & 0 & p_i \end{pmatrix} \]

where the partial pressure is given by

\[
p_i = \frac{1}{3} \int \mathcal{P} v_i \frac{dn_i}{d\mathcal{P}} d\mathcal{P}
\]

(D.11)

since \( \mathcal{P} = \gamma_i m_i v_i \).

### D.2 The One-Fluid Equations of General Relativistic Magnetohydrodynamics

The most popular form of the MHD equations eliminates all reference to individual particle species \( i \) and considers the system to be composed of a single neutral fluid in which currents are generated by the collective drift of charge.

#### D.2.1 Conservation of Rest Mass and Four-Momentum

If we multiply equations (D.6) and (D.10) by the particle mass \( m_i \) and then sum over all species \( i \), we reduce these equations to the familiar forms

\[
\nabla \cdot (\rho U) = 0 \\
\nabla \cdot T_{\text{GAS}} = \frac{1}{c} J \cdot \mathbf{F}
\]

(D.12)

(D.13)

The gas stress-energy tensor obtained from this sum is given by

\[
T_{\text{GAS}} = \left( \rho + \frac{\varepsilon}{c^2} \right) U U + \frac{1}{c^2} [Q U + U Q] + p \mathcal{P}
\]

(D.14)

where the projection tensor is given by

\[
\mathcal{P} = \frac{1}{c^2} U U + g
\]

the rest mass density is given by
the total internal energy and total pressure are given by the sum over all particle species

\[ \varepsilon = \sum_i \varepsilon_i \quad p = \sum_i p_i \]

and the heat flux four-vector is given by

\[ Q = \sum_i n_i m_i c^2 V'_i = \sum_i n_i m_i c^2 (V'_i - V_i) \]

(The second equality is valid because of equation (D.9).) In addition to the partial pressure \( p_i \), we now have an integral expression for the internal (kinetic) energy of a relativistic gas

\[ \varepsilon_i = (n'_i - n_i) m_i c^2 = m_i c^2 \int \int \int (\gamma_i - 1) f_i d^3P \]

or

\[ \varepsilon_i = \int \varepsilon_{iK} \frac{dn_i}{dP} dP \tag{D.15} \]

where \( \varepsilon_{iK} \equiv (\gamma_i - 1) m_i c^2 \) is defined as the particle kinetic energy. Since the right-hand side of equation (D.13) can be written as the divergence of a tensor

\[ \frac{1}{c} J \cdot F = - \nabla \cdot T_{EM} \]

where \( T_{EM} \) is given by equation (6.119). Equation (D.13) then becomes, simply,

\[ \nabla \cdot T = 0 \]

where \( T = T_{GAS} + T_{EM} \). This exercise, therefore, shows us specifically how to calculate the stress-energy tensor for a conducting fluid in an electromagnetic field. It is this \( T \) that must be inserted into Einstein’s field equations (7.21) in order to generate the evolution equations for the gravitational field.

### D.2.2 Conservation of Charge and Four-Current

Another summation over all particle species can be done if we instead multiply equations (D.6) and (D.10) by the particle charge \( q_i \) before summing. We then obtain the conservation of charge and of four-current
\[ \nabla \cdot \mathbf{J} = 0 \]  
(D.16)

\[ \nabla \cdot \mathbf{C} = \frac{\omega_p^2}{4\pi} \left[ \frac{1}{c} (\mathbf{U} + h \mathbf{3}) \cdot \mathbf{F} - \eta_q (\rho_q \mathbf{U} + \mathbf{3}) \right] \]  
(D.17)

where the spatial current four-vector is given by
\[ \mathbf{3} \equiv \mathbf{J} - \rho_q \mathbf{U} \]
and is orthogonal to the four-velocity
\[ \mathbf{U} \cdot \mathbf{3} = 0 \]

The *total* four-current density and charge density are defined as
\[ \mathbf{J} \equiv \sum_i \mathbf{J}_i \]
\[ \rho_q \equiv \sum_i q_i n_i \]

The charge-current tensor looks similar to the stress-energy tensor
\[ \mathbf{C} = \left( \rho_q + \frac{\varepsilon_q}{c^2} \right) \mathbf{U} \mathbf{U} + \mathbf{U} \mathbf{3}' + \mathbf{3}' \mathbf{U} + p_q \mathbf{P} \]  
(D.18)

and the *beamed* spatial current is defined as
\[ \mathbf{3}' \equiv \sum_i q_i n_i \mathbf{V}_i' \]

In addition to \( \rho_q \), some other new charge-weighted thermodynamic quantities appear, like the charge-weighted internal energy
\[ \varepsilon_q \equiv \sum_i q_i c^2 \int \int \int (\gamma_i - 1) f_i \, d^3P \]
\[ = \sum_i q_i c_2 \int (\gamma_i - 1) \frac{dn_i}{dP} \, dP \]
\[ = \sum_i \frac{q_i}{m_i} \varepsilon_i \]

and the charge-weighted pressure
Finally, we see new plasma state variables, like the plasma frequency

$$\omega_p = \left[ 4\pi \sum_i q_i^2 n_i m_i \right]^{1/2}$$

the electrical resistivity

$$\eta_q \equiv 4\pi \frac{\nu}{\omega_p^2}$$

and the coefficient of the Hall-effect term

$$h \equiv \frac{4\pi}{\omega_p^2 |\mathbf{3}|} \sum_i q_i m_i |\mathbf{3}|$$

which is related to the classical Hall coefficient $R_H$ as

$$R_H = \frac{h}{\eta_q c} |\mathbf{B}|$$

($|\mathbf{B}|$ being the strength of the magnetic field).

Equation (D.17) is often referred to as the generalized Ohm’s law. When the left-hand side is small compared to the terms on the right (i.e., when $\omega_p^{-1}$ is much smaller than other time scales in the system), we obtain the classical Ohm’s law, with the Hall term

$$\frac{1}{c} (\mathbf{U} + h \mathbf{3}) \cdot \mathbf{F} = \eta_q \mathbf{J}$$

(which eventually reduces to the well-known $V = IR$ Ohm’s law taught in freshman physics and electrical engineering classes). If the time-dependent terms on the left-hand side (in the four-divergence of $\mathbf{C}$) are not negligible, the generalized Ohm’s law shows how the current evolves toward its equilibrium value given above.
Appendix E

Derivation of the General Relativistic Grad–Schlüter–Shafranov Equation

The Grad–Schlüter–Shafranov equation is a general statement of force-free degenerate electrodynamics (FFDE) under the assumptions of a steady state and axisymmetry. The non-relativistic version is used to study the structure of Tokamak and other terrestrial and solar system fields, while the relativistic version is used to study the electrodynamics of pulsars and black holes. Here I re-derive the GSS equation in the Kerr metric using the general relativistic notation employed in this book, with the electrodynamic definitions of $B$, $D$, $E$, and $H$ given in Section 9.5.1 (adopted from Komissarov [322]), to arrive at the version published by Uzdensky [486] (but with $c \neq G \neq 1$; see also [640] for the Schwarzschild case). Equation (E.11) below is useful for analyzing the magnetospheres of black holes in Kerr spacetime, as well as those of pulsars in a flat metric.

E.1 The Magnetic Induction Equation

In the Kerr metric in Boyer–Lindquist coordinates, under the assumption of axisymmetry ($\partial / \partial \phi = 0$) Maxwell’s solenoidal condition ($\nabla \cdot B = 0$) gives the following poloidal magnetic induction

$$B_p = \frac{1}{R} \nabla \Psi \times \hat{e}_\phi$$  \hspace{1cm} (E.1)

where $B_p = B_p(B_r, B_\theta, 0)$ and the cylindrical radius is given by

$$R \equiv \frac{\Sigma \sin \theta}{\rho}$$

and $\Sigma$ and $\rho$ are the usual Kerr area and radius parameters. The magnetic flux is a function of the poloidal coordinates.
\[ \Psi(r, \theta) = \frac{1}{2\pi} \int B \cdot dS = RA_\phi \]  

(E.2)

integrated over a disk surface with radius \( R \) that is centered on, and normal to, the rotation axis. \( A_\phi \) is the azimuthal component of the three-vector potential \( A \). The goal of this derivation is to find a single partial differential equation for the magnetic flux function \( \Psi \). Then, using secondary equations we will be able to derive all other electromagnetic quantities (\( B, H, D, \) and \( E \)) from \( \Psi \).

The azimuthal component of the magnetic induction comes from Ampère’s law (with \( \partial/\partial t = 0 \)), integrated over the same surface \( dS \)

\[ B_\phi = \frac{H_\phi}{\alpha} = -\frac{I}{\alpha Rc} \]  

(E.3)

where \( H_\phi \) is the \( \phi \) component of the magnetic field, \( \alpha \) is the Kerr lapse function, and the current distribution function is

\[ I = -\frac{1}{2} \int J \cdot dS \]  

(E.4)

Because \( I \) and \( \Psi \) are integrals over the same surface, \( I \) is a function of \( \Psi \), or

\[ I = I(\Psi) \]

Together, equations (E.1) and (E.3) give the complete magnetic induction three-vector for steady-state, axisymmetric FFDE

\[ B = \frac{1}{R} \nabla \Psi \times e_\phi - \frac{I}{\alpha Rc} e_\phi \]  

(E.5)

### E.2 The Electric and Magnetic Field Equations

The degeneracy condition of FFDE (\( B \cdot D = 0 \); see Section 9.5.2) implies that the electric displacement three-vector must be (equation (9.126))

\[ D = -\frac{1}{\alpha c} (V_f - \alpha \beta c) \times B \]

where \( \beta \) is the Kerr drift vector. (This is also the ideal form of Ohm’s law.) Furthermore, in order for \( B \) and \( D \) to be perpendicular, the field velocity \( V_f \) must be in the \( \phi \) direction only. So we now can define a field angular velocity to be

\[ \Omega_f = \frac{|V_f|}{R} \]

Plugging in \( B \) from equation (E.5) we obtain \( D \) in terms of \( \Psi \)
\[ D = -\frac{(\Omega_f - \omega)}{\alpha c} \nabla \Psi \]  
(E.6)

where \( \omega \) is the angular velocity in the Kerr metric. We also get \( E \) in terms of \( \Psi \)

\[ E = -\frac{\Omega_f}{c} \nabla \Psi \]  
(E.7)

Note that, as implied by equations (7.67) \( D \) and \( E \) are the electric field measured in
the rotating and fixed frames, respectively. As they both depend on \( \nabla \Psi \) only, they
are both poloidal functions only.

Finally, now that we know \( D \), we can calculate the magnetic field from the right-hand part of equation (9.124) as

\[ H = \frac{\alpha}{R} \left[ 1 + \frac{R^2}{\alpha^2 c^2} \omega (\Omega_f - \omega) \right] \nabla \Psi \times e_\phi - \frac{I}{R c} e_\phi \]  
(E.8)

E.3 The Charge and Current Densities

From Gauss’s law, we can immediately determine the charge density

\[ \rho_q = -\frac{1}{4\pi c} \nabla \cdot \left[ \frac{(\Omega_f - \omega)}{\alpha} \nabla \Psi \right] \]  
(E.9)

Calculation of the current density is a little more tricky: it is best done by computing the poloidal \( (J_p) \) and toroidal \( (J_\phi e_\phi) \) components separately and then combining the results.

Because \( I = I(\Psi) \), and therefore

\[ \nabla I = \frac{dI}{d\Psi} \nabla \Psi \]

then the poloidal current \( J_p \) must be parallel to the poloidal magnetic field \( B_p \). From equations (E.2) and (E.4), this proportionality must be

\[ J_p = -\frac{1}{4\pi} \frac{dI}{d\Psi} B_p \]

which gives us the poloidal component of the current density.

The toroidal component is found by dotting \( e_\phi \) into a version of equation (9.122),
also with \( \partial / \partial t = 0 \), to obtain

\[ J_\phi = \frac{c}{B^2} \rho_q (E \times B)_\phi + \frac{1}{B^2} (B \cdot J) B_\phi \]
The total current density, then, is the vector sum of both components

$$\mathbf{J} = \rho q \Omega_f R e_{\phi} - \frac{1}{4\pi} \frac{dI}{d\Psi} \mathbf{B}$$  \hspace{1cm} (E.10)

That is, the current is the sum of that flowing along the twisted magnetic field (second term) plus those charges that are dragged around as the magnetic field rotates (first term).

### E.4 The GSS Equation

The only independent equation that we have not yet incorporated into this discussion is the $\phi$ component of Ampère’s law (right-hand equation (9.123)). (The $r$ and $\theta$ components of Ampère’s law are redundant with the definition of the current $I$.) Because the spatial part of the Kerr metric in Boyer–Lindquist coordinates is diagonal, equation (E.8) gives

$$\nabla \times \mathbf{H} = -R \nabla \cdot \left( \frac{c}{R} \nabla \Psi \right)$$

Inserting this and $4\pi J_{\phi}/c$ into the $\phi$ component of Ampère’s law, and noting that $\mathbf{D}$ has no $\phi$ component and $\partial/\partial t = 0$, and combining some terms, gives us the general relativistic version of the GSS equation

$$\nabla \cdot \left\{ \alpha R^2 \left[ 1 - \frac{R^2}{\alpha^2 c^2} (\Omega_f - \omega)^2 \right] \nabla \Psi \right\} + \frac{(\Omega_f - \omega)}{\alpha c^2} \frac{d\Omega_f}{d\Psi} (\nabla \Psi)^2 + \frac{1}{2} \frac{dI^2}{d\Psi} = 0$$  \hspace{1cm} (E.11)

where we have used the relation

$$\nabla \Omega_f(\Psi) = \frac{d\Omega_f}{d\Psi} \nabla \Psi$$

The GSS equation, plus appropriate boundary conditions, gives us an equation for the scalar potential $\Psi$, under the assumptions of time independence and axisymmetry, in the stationary and axisymmetric Kerr metric.
Appendix F

Derivation of the Equations for Stationary, Axisymmetric Ideal SRMHD in Newtonian Gravity

Ideal, stationary, axisymmetric magnetohydrodynamics is the main method for treating the acceleration and collimation of jets in black hole systems. This appendix begins with the standard ideal MHD vector equations, given in Section 9.5.1, and shows how the assumptions of stationarity and axisymmetry simplify these to the ones used in Section 9.5.6. The discussion generally will follow that in Mestel’s 1961 paper on the subject [641], but we will do the derivations using the relativistic equations. While we will retain the possibility of flow near the speed of light, we will assume a Newtonian gravitational field only (i.e., \( GM/(Re^2) \ll 1 \)), with no appreciable frame dragging (Kerr drift vector \( \beta = 0 \)). The actual use of the resulting equations to study jet acceleration and collimation is in Section 15.1.

The MHD derivations here are the counterpart to the force-free electrodynamic ones given in Appendix E, except there we retained the possibility of a Kerr black hole metric.

F.1 The Axisymmetric, Stationary Equation(s) Parallel to the Magnetic Field

Under the assumptions of stationarity and axisymmetry magnetohydrodynamics generates two main differential equations, one perpendicular to the magnetic field (as in force-free electrodynamics) and a new one parallel to the field. The new equation describes the flow of plasma along the magnetic field lines, and was not needed in FFDE (where we ignored the matter entirely). We will derive the pieces of this equation below from Maxwell’s laws of electromagnetism and from conservation laws for fluid flow. Then we will discuss the cross-field equation in the MHD case.
F.1.1 Faraday’s and Ohm’s Laws and Conservation of Mass: The Frozen-in Magnetic Field

The time-independent form of Faraday’s law (9.103) states that
\[ \nabla \times E = 0 \]
or \[ E = \nabla \Phi + E_0, \] where \( \Phi \) is the scalar electric potential and \( E_0 \) is a vector uniform in space and constant in time. With the ideal Ohm’s law (9.105), Faraday’s law becomes
\[ \nabla \times (V \times B) = 0 \] (F.1)

Now, let us decompose \( V \) and \( B \) into poloidal and toroidal components
\[ V = V_p + V_t \quad B = B_p + B_t \]
where, for example, in cylindrical coordinates in flat space we have
\[ V_p = V_R e_R + V_Z e_Z \quad V_t = V_\phi e_\phi \]
Equation (F.1) then can be written as two equations, one in the poloidal plane and one in the toroidal direction
\[ 0 = [\nabla \times (V \times B)]_p = \nabla \times (V_p \times B_p) = -c \nabla \times (E_\phi e_\phi) \] (F.2)
\[ 0 = [\nabla \times (V \times B)]_t = \nabla \times [(V_p \times B_t) + (V_t \times B_p)] \] (F.3)
Note that equation (F.2) has only one term because \( V_t \times B_t = V_\phi B_\phi (e_\phi \times e_\phi) = 0 \).

F.1.1.1 The Poloidal Velocity – Magnetic Field Relation

First, we will examine the \textit{poloidal} equation (F.2). It has the solution
\[ E_\phi = [\nabla \Phi]_\phi = \frac{1}{R} \frac{\partial \Phi}{\partial \phi} \]
But the axisymmetric assumption means that \( \partial / \partial \phi = 0 \) for any function, so \( E_\phi = 0 \). That is, \( V_p \) is parallel to \( B_p \)
\[ V_p = K B_p \] (F.4)
where \( K \) is a scalar function of \( (R, Z) \).
F.1.1.2 The Toroidal Velocity – Magnetic Field Relation and the Field Angular Velocity

Next, we will examine the toroidal component (F.3). In cylindrical coordinates this can be written as

\[
\frac{\partial}{\partial R} \left[ B_R (V_\phi - \mathcal{K} B_\phi) \right] + \frac{\partial}{\partial Z} \left[ B_\phi (V_\phi - \mathcal{K} B_\phi) \right] = 0 \tag{F.5}
\]

We now can combine this equation with the axisymmetric version of the solenoidal condition

\[
\nabla \cdot B_p = \frac{1}{R} \left[ \frac{\partial (RB_R)}{\partial R} + \frac{\partial (RB_\phi)}{\partial Z} \right] = 0 \tag{F.6}
\]

to produce simply

\[
B_p \cdot \nabla \left( \frac{V_\phi - \mathcal{K} B_\phi}{R} \right) = B \cdot \nabla \left( \frac{V_\phi - \mathcal{K} B_\phi}{R} \right) = 0
\]

This means that the gradient of the quantity above in the parentheses is zero along a given magnetic field line. That is, the following is constant along each field line

\[
\frac{V_\phi - \mathcal{K} B_\phi}{R} = \text{constant} \equiv \Omega_f \tag{F.7}
\]

which we identify as the angular velocity of the magnetic field line \( \Omega_f \).

Why is \( V_\phi \) not equal to \( R \Omega_f \)? The reason is that, if the magnetic field has a toroidal component (\( B_\phi \)), then no matter what the field rotation rate plasma can flow freely in the \( e_\phi \) direction at the velocity \( \mathcal{K} B_\phi \), i.e., with the same proportionality as in the poloidal direction. So the total toroidal velocity of the plasma is, therefore,

\[
V_t = V_\phi e_\phi = (\mathcal{K} B_\phi + R \Omega_f) e_\phi \tag{F.8}
\]

If there were no field rotation (\( \Omega_f = 0 \)), then plasma would flow along the field line with the same proportionality in all dimensions. On the other hand, if there were no matter (as in FFDE), then \( \mathcal{K} = 0 \) and \( V_\phi \) simply would be equal to \( R \Omega_f \).

Combining equations (F.4) and (F.8), we find that the total three-velocity and total magnetic field are related as

\[
V = \mathcal{K} B + R \Omega_f e_\phi
\]

F.1.1.3 Determining the Proportionality Constant

We now can determine the value of \( \mathcal{K} \) by considering the conservation of mass equation (9.100)
\[ 0 = \nabla \cdot (\gamma \rho \mathbf{V}) = \nabla \cdot (\gamma \rho \mathbf{KB}) + \frac{1}{R} \frac{\partial (R \Omega_f)}{\partial \phi} \]

If we again apply both the axisymmetry and solenoidal conditions, the conservation of mass reduces to the conservation of another scalar along a field line \( \mathbf{B} \cdot \nabla (\gamma \mathcal{K} \rho) = 0 \). For mathematical purposes we define this scalar to be another constant \( k \) divided by \( 4\pi \)

\[ \gamma \mathcal{K} \rho = \text{constant} \equiv \frac{k}{4\pi} \quad \text{(F.9)} \]

Note that \( k \) is not unitless; it is the ratio of the constant local poloidal mass flux \((4\pi \gamma \rho \mathbf{V} \cdot dS_p)\) to the constant local poloidal magnetic flux \((\mathbf{B} \cdot dS_p)\), where \( dS_p \) is a small poloidal area vector. The final combination of the laws of Faraday, Ohm, and mass conservation yields the axisymmetric, stationary frozen-in condition

\[ \mathbf{V} = \frac{k}{4\pi \gamma \rho} \mathbf{B} + R \Omega_f \mathbf{e}_\phi \quad \text{(F.10)} \]

**F.1.2 Conservation of Specific Angular Momentum**

We now will use the toroidal component of the momentum equation (9.101), which also makes use of Gauss’s (9.117) and Ampère’s (9.116) laws, to derive a third scalar constant along a magnetic field line – the angular momentum per unit mass or specific angular momentum. The full axisymmetric, stationary vector equation of motion in a Newtonian gravitational potential \( \psi \) is

\[ \nabla \cdot \mathbf{T} = - \left( \gamma \rho + \frac{E}{c^2} \right) \nabla \psi \quad \text{(F.11)} \]

The component of this along \( \mathbf{e}_\theta \) has no gravitational force

\[ \frac{1}{R} \frac{\partial}{\partial R} \left[ R (RT_{\theta \hat{R}}) \right] + \frac{\partial (RT_{\theta \hat{Z}})}{\partial Z} = 0 \quad \text{(F.12)} \]

where the two components of the stress tensor are determined from equation (9.113)

\[ RT_{\theta \hat{i}} = \frac{k}{4\pi} \left[ \gamma \left( 1 + \frac{h}{c^2} \right) RV_{\theta} - \frac{RB_{\theta}}{k} \right] B_i \]

\( h \equiv h/\rho \) is the enthalpy per unit mass, and \( i = (Z, R) \). (Recall that \( E_{\phi} = 0 \) because of axisymmetry.) The momentum equation can be combined with the solenoidal condition again to obtain the conservation of another scalar quantity along a magnetic field line
\[ γ \left(1 + \frac{\hbar}{c^2}\right) RV_\phi - \frac{RB_\phi}{k} = \text{constant} \equiv \ell \]  

which we identify as the angular momentum per unit mass of the plasma \( \ell \).

### F.1.3 Conservation of Specific Entropy

The assumption of an adiabatic equation of state in equation (9.112) leads to a fourth quantity that is conserved along a field line: the entropy per unit mass

\[ \frac{S}{\rho} \propto \frac{p}{\rho^\Gamma} \Rightarrow K_\Gamma \text{ constant} \]  

While entropy must remain constant along a given field line, different field lines can have different values for \( K_\Gamma \).

### F.1.4 Conservation of Specific Energy

The final equation along each magnetic field line is the conservation of energy per unit mass. The master energy equation (9.102) in Newtonian gravity is

\[ \nabla \cdot \left[c^2 (\Psi - \gamma \rho V)\right] = -\Psi \cdot \nabla \psi \]  

with the axisymmetric, poloidal momentum given by

\[ \Psi = \frac{k}{4\pi} \left[ γ \left(1 + \frac{\hbar}{c^2}\right) - \frac{RB_\phi}{k\Omega_f} \right] B_p \]

Dropping one term in equation (F.15) that is proportional to \( \psi^2/c^4 \) and using the solenoidal condition, we obtain a fourth conserved quantity: the Bernoulli constant (specific total energy)

\[ (\epsilon - 1)c^2 + \epsilon \psi = \text{constant} \equiv Be \]  

where \( \epsilon c^2 \) is the total specific internal energy of the plasma, including rest mass

\[ \epsilon = γ \left(1 + \frac{\hbar}{c^2}\right) - \frac{RB_\phi}{k\Omega_f} \]

When (F.16) is combined with (F.10), (F.13), and (F.14), we can eliminate \( \rho, V_\phi, B_\phi, \) and \( p \), producing a single equation that relates poloidal velocity to poloidal
magnetic field. This energy equation is essentially the equation of motion along each magnetic field line and is governed by the five free parameters of the problem:

- \( \Omega_f \): field line angular velocity;
- \( k \): plasma mass loading of the field line;
- \( \ell, K_f, Bc \): specific angular momentum, entropy, and total energy of the plasma.

### F.2 The Axisymmetric, Stationary Equation(s) Normal to the Magnetic Field

We have only two remaining equations in the set (9.100) to (9.117) to consider: the \( R \) and \( Z \) components of the equation of motion (F.11). The projection of these vector components parallel to the poloidal magnetic field is essentially the equation along the field described above. The projection normal to the field is the cross-field equation that is analogous to the GSS equation derived in Appendix E for force-free electrodynamics. Formally, the component normal to \( B \) and in the poloidal plane is

\[
(e_\phi \times b) \cdot \left[ \nabla \cdot T + \left( \gamma \rho + \frac{\xi}{c^2} \right) \nabla \psi \right] = 0
\]

where \( b \equiv B_p/|B_p| \). In cylindrical coordinates this equation becomes

\[
\begin{align*}
\frac{b_\dot{Z}}{R} \frac{\partial (RT R\dot{R})}{\partial R} - \frac{b_\dot{R}}{R} \frac{\partial (RT \dot{Z})}{\partial R} + b_\ddot{Z} \frac{\partial T \ddot{Z}}{\partial Z} - b_\ddot{R} \frac{\partial T \ddot{R}}{\partial Z} \\
- b_\dot{Z} \frac{T \dot{\phi}}{R} + \left( \gamma \rho + \frac{\xi}{c^2} \right) \left( b_\dot{Z} \frac{\partial \psi}{\partial R} - b_\dot{R} \frac{\partial \psi}{\partial Z} \right) = 0
\end{align*}
\]  

where

\[
egin{align*}
T_{\dot{R}\dot{R}} &= \left[ p + \frac{1}{8\pi} (B^2 + E^2) \right] + \gamma^2 \left( \rho + \frac{h}{c^2} \right) V_R^2 - \frac{1}{4\pi} (B_R^2 + E_R^2) \\
T_{\dot{R}\dot{Z}} &= \gamma^2 \left( \rho + \frac{h}{c^2} \right) V_R V_Z - \frac{1}{4\pi} (B_R B_Z + E_R E_Z) \\
T_{\dot{Z}\dot{Z}} &= \left[ p + \frac{1}{8\pi} (B^2 + E^2) \right] + \gamma^2 \left( \rho + \frac{h}{c^2} \right) V_Z^2 - \frac{1}{4\pi} (B_Z^2 + E_Z^2) \\
T_{\dot{\phi}\dot{\phi}} &= \left[ p + \frac{1}{8\pi} (B^2 + E^2) \right] + \gamma^2 \left( \rho + \frac{h}{c^2} \right) V_\phi^2 - \frac{1}{4\pi} B_\phi^2
\end{align*}
\]

The cross-field equation (F.18) becomes quite complex as we substitute in the expressions for \( T_{ij} \), so we will not do that here. Specific cases of the cross-field equation, and their implications for jet production in black hole engines, are discussed in Chapter 15.
Appendix G

Physical and Astrophysical Constants
Used in this Book

Table G.1: Physical constants used in this book

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value in cgs/Gaussian units</th>
<th>Value in SI units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avogadro’s number</td>
<td>$N_A$</td>
<td>$6.02214 \times 10^{23}$ mol$^{-1}$</td>
<td>$6.02214 \times 10^{23}$ mol$^{-1}$</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>$k$</td>
<td>$1.38065 \times 10^{-16}$ erg K$^{-1}$</td>
<td>$1.38065 \times 10^{-23}$ K$^{-1}$</td>
</tr>
<tr>
<td>Charge on electron</td>
<td>$e$</td>
<td>$4.80321 \times 10^{-10}$ esu $^b$</td>
<td>$1.60218 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>Electronvolt</td>
<td>$e$</td>
<td>$1.60218 \times 10^{-12}$ erg</td>
<td>$1.60218 \times 10^{-19}$ J</td>
</tr>
<tr>
<td>Gas constant</td>
<td>$\mathcal{R}$</td>
<td>$8.31446 \times 10^7$ erg mol$^{-1}$ K$^{-1}$</td>
<td>$8.31446$ J mol$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>Gravitation constant</td>
<td>$G$</td>
<td>$6.6738 \times 10^{-8}$ erg cm g$^{-2}$</td>
<td>$6.6738 \times 10^{-11}$ J m kg$^{-2}$</td>
</tr>
<tr>
<td>Mass of electron</td>
<td>$m_e$</td>
<td>$9.1094 \times 10^{-28}$ g</td>
<td>$9.1094 \times 10^{-31}$ kg</td>
</tr>
<tr>
<td>Mass of proton</td>
<td>$m_p$</td>
<td>$1.6726 \times 10^{-24}$ g</td>
<td>$1.6726 \times 10^{-27}$ kg</td>
</tr>
<tr>
<td>Planck’s constant (/2π)</td>
<td>$h$</td>
<td>$6.62607 \times 10^{-27}$ erg s</td>
<td>$6.62607 \times 10^{-34}$ Js</td>
</tr>
<tr>
<td>Planck’s constant</td>
<td>$\hbar$</td>
<td>$1.05457 \times 10^{-27}$ erg s</td>
<td>$1.05457 \times 10^{-34}$ Js</td>
</tr>
<tr>
<td>Radiation constant</td>
<td>$a$</td>
<td>$7.5658 \times 10^{-15}$ erg cm$^{-3}$ K$^{-4}$</td>
<td>$7.5658 \times 10^{-16}$ J m$^{-3}$ K$^{-4}$</td>
</tr>
<tr>
<td>Speed of light</td>
<td>$c$</td>
<td>$2.997925 \times 10^{10}$ cm s$^{-1}$</td>
<td>$2.997925 \times 10^8$ m s$^{-1}$</td>
</tr>
<tr>
<td>Stefan–Boltzmann constant</td>
<td>$\sigma$</td>
<td>$5.6704 \times 10^{-5}$ erg s$^{-1}$ cm$^{-2}$ K$^{-4}$</td>
<td>$5.6704 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$</td>
</tr>
<tr>
<td>Thomson cross-section</td>
<td>$\sigma_T$</td>
<td>$6.65246 \times 10^{-25}$ cm$^2$</td>
<td>$6.65246 \times 10^{-29}$ m$^2$</td>
</tr>
</tbody>
</table>

$^a$ Source: National Institute of Standards and Technology (http://physics.nist.gov/cuu/Constants/).

$^b$ Note: 1 esu = 2997924580 $\sqrt{\pi \varepsilon_0}$ C.

Table G.2: Astrophysical constants used in this book

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value in cgs/Gaussian units</th>
<th>Value in SI units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronomical unit</td>
<td>AU</td>
<td>$1.496 \times 10^{13}$ cm</td>
<td>$1.496 \times 10^{11}$ m</td>
</tr>
<tr>
<td>Light year</td>
<td>ly</td>
<td>$9.461 \times 10^{17}$ cm</td>
<td>$9.461 \times 10^{15}$ m</td>
</tr>
<tr>
<td>Parsec</td>
<td>pc</td>
<td>$3.086 \times 10^{18}$ cm</td>
<td>$3.086 \times 10^{16}$ m</td>
</tr>
<tr>
<td>Solar mass</td>
<td>$M_\odot$</td>
<td>$1.989 \times 10^{33}$ g</td>
<td>$1.989 \times 10^{30}$ kg</td>
</tr>
<tr>
<td>Solar luminosity</td>
<td>$L_\odot$</td>
<td>$3.839 \times 10^{33}$ erg s$^{-1}$</td>
<td>$3.839 \times 10^{26}$ W</td>
</tr>
<tr>
<td>Solar radius (average)</td>
<td>$R_\odot$</td>
<td>$6.955 \times 10^{10}$ cm</td>
<td>$6.955 \times 10^{8}$ m</td>
</tr>
<tr>
<td>Jansky (unit of radiative flux)</td>
<td>Jy</td>
<td>$10^{-15}$ erg s$^{-1}$ Hz$^{-1}$</td>
<td>$10^{-26}$ W Hz$^{-1}$</td>
</tr>
</tbody>
</table>

$^a$ Source: International Astronomical Union (http://www.iau.org/science/publications/proceedings_rules/units/).
References


**Chapter 1**


**Chapter 2**

68. URL: http://heasarc.nasa.gov/docs/cgro/images/epo/gallery/agns/agn_spectra.gif

143. URL: http://heasarc.nasa.gov/docs/cgro/images/epo/gallery/agns/agn_up_model.gif

Chapter 3

References

References


Chapter 4

References

Chapter 5


Chapter 6


Chapter 7


References


Chapter 8


Chapter 9


**Chapter 10**
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Chapter 12

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Chapter 13


Chapter 14

References


Chapter 15

References


Chapter 16

References

Appendix C

Appendix E

Appendix F
<table>
<thead>
<tr>
<th>Glossary Item</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C</td>
<td>Third Cambridge catalog (of radio sources)</td>
</tr>
<tr>
<td>3CR</td>
<td>Third Cambridge catalog (Revised)</td>
</tr>
<tr>
<td>3CRR</td>
<td>Third Cambridge catalog (Revised a second time)</td>
</tr>
<tr>
<td>AAAS</td>
<td>American Association for the Advancement of Science</td>
</tr>
<tr>
<td>AAS</td>
<td>American Astronomical Society</td>
</tr>
<tr>
<td>ADAF</td>
<td>Advection-Dominated Accretion Flow</td>
</tr>
<tr>
<td>ADIOS</td>
<td>Advection-Dominated Inflow–Outflow Solutions (for accretion disk winds)</td>
</tr>
<tr>
<td>ADM formalism</td>
<td>Arnowitt–Deser–Misner formalism for expressing Einstein’s equations</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nucleus</td>
</tr>
<tr>
<td>AIGRMHD</td>
<td>Adiabatic Ideal General Relativistic MagnetohydroDynamics</td>
</tr>
<tr>
<td>AP</td>
<td>Alfvén Point (on the MHD Alfvén surface)</td>
</tr>
<tr>
<td>APS</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>AS</td>
<td>Alfvén Surface</td>
</tr>
<tr>
<td>ASCA</td>
<td>Advanced Satellite for Cosmology and Astrophysics</td>
</tr>
<tr>
<td>ASIAA</td>
<td>Astronomica Sinica Institute of Astronomy and Astrophysics (Taiwan)</td>
</tr>
<tr>
<td>ASJ</td>
<td>Astronomical Society of Japan</td>
</tr>
<tr>
<td>ASP</td>
<td>Astronomical Society of the Pacific</td>
</tr>
<tr>
<td>ATNF</td>
<td>Australia Telescope National Facility</td>
</tr>
<tr>
<td>AU</td>
<td>Astronomical Unit</td>
</tr>
<tr>
<td>AUI</td>
<td>Associated Universities, Inc.</td>
</tr>
<tr>
<td>AXP</td>
<td>Anomalous X-ray Pulsar</td>
</tr>
<tr>
<td>BAL</td>
<td>Broad Absorption Line (QSO)</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>BATSE</td>
<td>Burst And Transient Source Experiment, on the Compton Gamma-Ray Observatory</td>
</tr>
<tr>
<td>BEL</td>
<td>Broad Emission Line (QSO)</td>
</tr>
<tr>
<td>BH</td>
<td>Black Hole</td>
</tr>
<tr>
<td>BL</td>
<td>Boyer–Lindquist (coordinate system)</td>
</tr>
<tr>
<td>blazar</td>
<td>Generic name for highly variable AGN (BL Lacteal objects, OVV quasars, etc.)</td>
</tr>
<tr>
<td>BLR</td>
<td>Broad-Line Region (of AGN)</td>
</tr>
<tr>
<td>BLRG</td>
<td>Broad-Line Radio Galaxy</td>
</tr>
<tr>
<td>blue blazar</td>
<td>see HBL</td>
</tr>
<tr>
<td>BP</td>
<td>Blandford and Payne 1982 paper on non-relativistic MHD winds from accretion disk [507]</td>
</tr>
<tr>
<td>BSO</td>
<td>Blue Stellar Object (early name for QSO)</td>
</tr>
<tr>
<td>BSSN method</td>
<td>Baumgarte–Shapiro–Shibata–Nakamura method for solving Einstein’s equations</td>
</tr>
<tr>
<td>BZ</td>
<td>Blandford and Znajek 1977 paper on model for black hole magnetospheres [484]</td>
</tr>
<tr>
<td>CD</td>
<td>Current-Driven</td>
</tr>
<tr>
<td>CDI</td>
<td>Current-Driven Instability</td>
</tr>
<tr>
<td>CfA</td>
<td>Center for Astrophysics (Harvard University)</td>
</tr>
<tr>
<td>CGRO</td>
<td>Compton Gamma-Ray Observatory</td>
</tr>
<tr>
<td>CGS</td>
<td>Centimeter–Gram–Second (system of units)</td>
</tr>
<tr>
<td>Chandra</td>
<td>Chandra X-ray mission</td>
</tr>
<tr>
<td>CITA</td>
<td>Canadian Institute for Theoretical Astrophysics</td>
</tr>
<tr>
<td>CND</td>
<td>Circum-Nuclear Disk</td>
</tr>
<tr>
<td>CNO</td>
<td>Carbon–Nitrogen–Oxygen (nuclear burning cycle)</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>Compton depth ($y$)</td>
<td>measure of photon optical depth and energy transfer by Compton electron scattering</td>
</tr>
<tr>
<td>CR</td>
<td>Co-Rotation (disk radius)</td>
</tr>
<tr>
<td>CS</td>
<td>Cusp Surface</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation, Australia</td>
</tr>
<tr>
<td>CUP</td>
<td>Cambridge University Press</td>
</tr>
<tr>
<td>CV</td>
<td>Cataclysmic Variable (binary star)</td>
</tr>
<tr>
<td>DD</td>
<td>Doubly-Degenerate (binary star)</td>
</tr>
<tr>
<td>EBBH</td>
<td>Equal-mass Binary Black Hole</td>
</tr>
<tr>
<td>ED</td>
<td>ElectroDynamics</td>
</tr>
<tr>
<td>Eddington ratio</td>
<td>ratio of a source’s total radiative luminosity to the Eddington luminosity for its mass</td>
</tr>
<tr>
<td>EGRET</td>
<td>Energetic Gamma-Ray Experiment Telescope, on the Compton Gamma-Ray Observatory</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Term</td>
</tr>
<tr>
<td>--------------</td>
<td>------</td>
</tr>
<tr>
<td>EM</td>
<td>ElectroMagnetic</td>
</tr>
<tr>
<td>EMRIBH</td>
<td>Extreme Mass-Ratio Inspiral Black Hole</td>
</tr>
<tr>
<td>ESAC</td>
<td>European Space Astronomy Centre</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>EUV</td>
<td>Extreme UltraViolet (radiation)</td>
</tr>
<tr>
<td>FB</td>
<td>Flaring Branch (of neutron star Z sources)</td>
</tr>
<tr>
<td>FBG diagram</td>
<td>Fender–Belloni–Gallo diagram; see HID</td>
</tr>
<tr>
<td>FFDE</td>
<td>Force-Free Degenerate Electrodynamics</td>
</tr>
<tr>
<td>FIDO</td>
<td>FiDucial Observer (coordinate system)</td>
</tr>
<tr>
<td>FIX</td>
<td>FIXed (FIDO) coordinate system</td>
</tr>
<tr>
<td>FMS</td>
<td>Fast Magnetosonic Surface; classical fast surface</td>
</tr>
<tr>
<td>FMSS</td>
<td>Fast Magnetosonic Separatrix Surface</td>
</tr>
<tr>
<td>FR</td>
<td>Fanaroff &amp; Riley radio source morphological classification, 1974 paper [38]</td>
</tr>
<tr>
<td>FSRQ</td>
<td>Flat Spectrum Radio Quasar</td>
</tr>
<tr>
<td>GHz</td>
<td>Giga-Hertz (billion cycles per second)</td>
</tr>
<tr>
<td>GJ</td>
<td>Goldreich–Julian (pulsar magnetosphere model)</td>
</tr>
<tr>
<td>GLAST</td>
<td>Gamma-ray Large Area Space Telescope; a.k.a. Fermi gamma-ray telescope</td>
</tr>
<tr>
<td>GRB</td>
<td>Gamma-Ray Burst</td>
</tr>
<tr>
<td>GRHD</td>
<td>General Relativistic HydroDynamics</td>
</tr>
<tr>
<td>GRMHD</td>
<td>General Relativistic MagnetoHydroDynamics</td>
</tr>
<tr>
<td>GRO</td>
<td>Gamma-Ray Observatory; see CGRO</td>
</tr>
<tr>
<td>GRS</td>
<td>GRanat Source</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>GSS</td>
<td>Grad–Schlüter–Shafranov (general relativistic magnetosphere equation)</td>
</tr>
<tr>
<td>GW</td>
<td>Gravitational Wave</td>
</tr>
<tr>
<td>Gyr</td>
<td>Giga-year (billion years)</td>
</tr>
<tr>
<td>H I</td>
<td>atomic Hydrogen</td>
</tr>
<tr>
<td>H II</td>
<td>ionized Hydrogen</td>
</tr>
<tr>
<td>HartRAO</td>
<td>Hartebeesthoek Radio Astronomy Observatory</td>
</tr>
<tr>
<td>HB</td>
<td>Horizontal Branch (of neutron star Z sources)</td>
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<tr>
<td>HBL</td>
<td>High-frequency BL Lacertae object</td>
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<tr>
<td>HD</td>
<td>HydroDynamics</td>
</tr>
<tr>
<td>HF QPO</td>
<td>High Frequency Quasi-Periodic Oscillation</td>
</tr>
<tr>
<td>HiBAL</td>
<td>High-ionization Broad Absorption Line QSOs</td>
</tr>
<tr>
<td>HID</td>
<td>Hardness–Intensity Diagram</td>
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<tr>
<td>HLX</td>
<td>Hyper-Luminous X-ray source</td>
</tr>
<tr>
<td>HMXB</td>
<td>High-Mass X-ray Binary</td>
</tr>
<tr>
<td>Glossary</td>
<td>Definition</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
</tr>
<tr>
<td>horizon, (magneto)soniclocus</td>
<td>locus of points in space beyond which component of flow characteristics along streamlines all have the same sign</td>
</tr>
<tr>
<td>horizon, black hole</td>
<td>Surface surrounding the collapsed star interior to which events cannot affect the outside universe</td>
</tr>
<tr>
<td>HP</td>
<td>Horizon-Penetrating (coordinate system)</td>
</tr>
<tr>
<td>HR diagram</td>
<td>Hertzsprung–Russell (color–magnitude) diagram</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>HyLIRG</td>
<td>Hyper-Luminous InfraRed Galaxy</td>
</tr>
<tr>
<td>HYMOR</td>
<td>HYbrid MORphology (FR I/II) radio source</td>
</tr>
<tr>
<td>ICC</td>
<td>Interstellar Cloud Core</td>
</tr>
<tr>
<td>IDV</td>
<td>Intra-Day Variable blazar</td>
</tr>
<tr>
<td>IGM</td>
<td>InterGalactic Medium</td>
</tr>
<tr>
<td>IKI</td>
<td>Institut Kosmicheskix Issledovanii (Space Research Institute, Moscow)</td>
</tr>
<tr>
<td>IMBH</td>
<td>Intermediate Mass Black Hole</td>
</tr>
<tr>
<td>IMF</td>
<td>Initial Mass Function (for newborn stars)</td>
</tr>
<tr>
<td>INTEGRAL</td>
<td>INTErnational Gamma-Ray Astrophysics Laboratory</td>
</tr>
<tr>
<td>IR</td>
<td>InfraRed (radiation)</td>
</tr>
<tr>
<td>IRAS</td>
<td>Infrared Astronomy Satellite</td>
</tr>
<tr>
<td>IRS</td>
<td>InfraRed Source</td>
</tr>
<tr>
<td>IS</td>
<td>Island State (of neutron star atoll sources)</td>
</tr>
<tr>
<td>ISCO</td>
<td>Innermost Stable Circular Orbit (of a black hole)</td>
</tr>
<tr>
<td>ISM</td>
<td>InterStellar Medium</td>
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<tr>
<td>IXO</td>
<td>Intermediate X-ray luminosity Object; ULX</td>
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<tr>
<td>JCMT</td>
<td>James Clerk Maxwell Telescope</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>JWST</td>
<td>James Webb Space Telescope</td>
</tr>
<tr>
<td>KACST</td>
<td>King Abdulaziz City for Science and Technology</td>
</tr>
<tr>
<td>KER</td>
<td>KERr (metric)</td>
</tr>
<tr>
<td>KER–NEW</td>
<td>KERr–NEWman (metric)</td>
</tr>
<tr>
<td>KFD</td>
<td>Kinetic- (energy) Flux-Dominated</td>
</tr>
<tr>
<td>KH</td>
<td>Kelvin–Helmholtz</td>
</tr>
<tr>
<td>KHI</td>
<td>Kelvin–Helmholtz Instability</td>
</tr>
<tr>
<td>KITP</td>
<td>Kavli Institute for Theoretical Physics</td>
</tr>
<tr>
<td>LB</td>
<td>Lower Banana state (of neutron star atoll sources)</td>
</tr>
<tr>
<td>LBL</td>
<td>Low-frequency BL Lacertae object</td>
</tr>
<tr>
<td>LBV</td>
<td>Luminous Blue Variable (star)</td>
</tr>
<tr>
<td>LCB</td>
<td>Li, Chiueh, and Begelman 1992 paper on cold, relativistic MHD winds [537]</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>LF QPO</td>
<td>Low Frequency Quasi-Periodic Oscillation</td>
</tr>
<tr>
<td>LGRB</td>
<td>Long-duration Gamma-Ray Burst</td>
</tr>
<tr>
<td>LIGO</td>
<td>Laser Interferometer Gravitational wave Observatory</td>
</tr>
<tr>
<td>LINER</td>
<td>Low-Ionization Nuclear Emission-line Region</td>
</tr>
<tr>
<td>LIRG</td>
<td>Luminous InfraRed Galaxy</td>
</tr>
<tr>
<td>LISA</td>
<td>Laser Interferometer Space Antenna</td>
</tr>
<tr>
<td>LLAGN</td>
<td>Low-Luminosity AGN</td>
</tr>
<tr>
<td>LLNL</td>
<td>Lawrence Livermore National Laboratory (formerly Lawrence Radiation Labo-</td>
</tr>
<tr>
<td></td>
<td>ratory)</td>
</tr>
<tr>
<td>LMC</td>
<td>Large Magellanic Cloud</td>
</tr>
<tr>
<td>LMXB</td>
<td>Low-Mass X-ray Binary</td>
</tr>
<tr>
<td>LNRF</td>
<td>Local Non-rotating Reference Frame (FIDO coordinate system)</td>
</tr>
<tr>
<td>LoBAL</td>
<td>Low-ionization Broad Absorption Line QSOs</td>
</tr>
<tr>
<td>LSU</td>
<td>Louisiana State University</td>
</tr>
<tr>
<td>MACHO</td>
<td>MAssive Compact Halo Object</td>
</tr>
<tr>
<td>MBH</td>
<td>Massive Black Hole</td>
</tr>
<tr>
<td>MCG</td>
<td>Morphological Galaxy Catalog</td>
</tr>
<tr>
<td>MDAF</td>
<td>Magnetically-Dominated Accretion Flow</td>
</tr>
<tr>
<td>MERLIN</td>
<td>Multi-Element Radio Linked Interferometry Network</td>
</tr>
<tr>
<td>MFP</td>
<td>Modified Fast Point (on the MHD modified fast surface)</td>
</tr>
<tr>
<td>MFS</td>
<td>Modified Fast Surface; FMSS</td>
</tr>
<tr>
<td>MHD</td>
<td>MagnetoHydroDynamics</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega-Hertz (million cycles per second)</td>
</tr>
<tr>
<td>microqua-</td>
<td>Binary black hole system, usually with a jet; μQSR</td>
</tr>
<tr>
<td>sar</td>
<td></td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MK</td>
<td>Mega-Kelvin; million kelvins</td>
</tr>
<tr>
<td>MOV</td>
<td>MOVing-body (coordinate system)</td>
</tr>
<tr>
<td>MPG</td>
<td>Max-Planck-institute for Gravitational physics</td>
</tr>
<tr>
<td>MRI</td>
<td>Magneto-Rotational shearing Instability</td>
</tr>
<tr>
<td>MSFC</td>
<td>Manned Space Flight Center</td>
</tr>
<tr>
<td>MSP</td>
<td>Modified Slow Point (on the MHD modified slow surface)</td>
</tr>
<tr>
<td>MSS</td>
<td>Modified Slow Surface; SMSS</td>
</tr>
<tr>
<td>MSSSO</td>
<td>Mount Stromlo &amp; Siding Springs Observatories</td>
</tr>
<tr>
<td>Myr</td>
<td>Mega-year (million years)</td>
</tr>
<tr>
<td>N-galaxy</td>
<td>Galaxy (generally elliptical) with a bright Nucleus; NLRG, BLRG</td>
</tr>
<tr>
<td>NAOJ</td>
<td>National Astronomical Observatory of Japan</td>
</tr>
<tr>
<td>NB</td>
<td>Normal Branch (of neutron star Z sources)</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
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<tr>
<td>neutrinosphere</td>
<td>the surface of last neutrino absorption in a source</td>
</tr>
<tr>
<td>NGC</td>
<td>New General Catalog (of Nebulae and Clusters of Stars)</td>
</tr>
<tr>
<td>NLR</td>
<td>Narrow-Line Region (of AGN)</td>
</tr>
<tr>
<td>NLRG</td>
<td>Narrow-Line Radio Galaxy</td>
</tr>
<tr>
<td>NLSy1</td>
<td>Narrow-Line Seyfert (Type 1) galaxy</td>
</tr>
<tr>
<td>NOAO</td>
<td>National Optical Astronomy Observatory</td>
</tr>
<tr>
<td>NRAF</td>
<td>Non-Radiative Accretion Flow (computational approximation to RIAF/ADAF)</td>
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<tr>
<td>NRAO</td>
<td>National Radio Astronomy Observatory</td>
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<tr>
<td>NRHD</td>
<td>Non-Relativistic HydroDynamics</td>
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<tr>
<td>NRMHD</td>
<td>Non-Relativistic MagnetoHydroDynamics</td>
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<tr>
<td>NS</td>
<td>Neutron Star</td>
</tr>
<tr>
<td>NSF</td>
<td>National Science Foundation, USA</td>
</tr>
<tr>
<td>NuSTAR</td>
<td>Nuclear Spectroscopic Telescope ARray</td>
</tr>
<tr>
<td>OGLE</td>
<td>Optical Gravitational Lensing Experiment</td>
</tr>
<tr>
<td>OIS</td>
<td>Observer-at-Infinity/Synchronous (coordinate system)</td>
</tr>
<tr>
<td>ONeMg</td>
<td>Oxygen–Neon–Magnesium (stellar core)</td>
</tr>
<tr>
<td>peribarathron</td>
<td>minimum distance of star orbiting a BH</td>
</tr>
<tr>
<td>PFD</td>
<td>Poynting- (energy) Flux-Dominated</td>
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<tr>
<td>photosphere</td>
<td>the surface of last photon absorption in a source</td>
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<tr>
<td>PNS</td>
<td>Proto-Neutron Star</td>
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<tr>
<td>PP</td>
<td>Papaloizou–Pringle (instability)</td>
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<tr>
<td>PWN</td>
<td>pulsar wind nebula</td>
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<tr>
<td>QPO</td>
<td>Quasi-Periodic Oscillation</td>
</tr>
<tr>
<td>QSO</td>
<td>Quasi-Stellar Object; optically-identified quasar (usually RQQ)</td>
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<tr>
<td>QSR</td>
<td>Quasi-Stellar Radio source; quasar</td>
</tr>
<tr>
<td>quasar</td>
<td>QUAsi-StellAr Radio source</td>
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<tr>
<td>red blazar</td>
<td>see LBL</td>
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<tr>
<td>RIAF</td>
<td>Radiatively-Inefficient Accretion Flow; ADAF</td>
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<tr>
<td>RIKEN</td>
<td>RIKEN science institute (Japan)</td>
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<tr>
<td>RLQ</td>
<td>Radio Loud Quasar; classical quasar</td>
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<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>ROSAT</td>
<td>ROentgen SATellite</td>
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<tr>
<td>RQQ</td>
<td>Radio Quiet Quasar</td>
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<tr>
<td>RRAT</td>
<td>Rotating RAdio Transient</td>
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<td>RSG</td>
<td>Red SuperGiant star</td>
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<tr>
<td>RXTE</td>
<td>Rossi X-ray Timing Explorer</td>
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<td>Definition</td>
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<tr>
<td>SAS-1</td>
<td>First Small Astronomy Satellite (Uhuru)</td>
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<tr>
<td>SAS-2</td>
<td>Second Small Astronomy Satellite</td>
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<tr>
<td>SASI</td>
<td>Standing Accretion Shock Instability</td>
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<tr>
<td>SBH</td>
<td>Stellar-mass Black Hole</td>
</tr>
<tr>
<td>SCattersphere</td>
<td>the surface of last photon scattering in a source</td>
</tr>
<tr>
<td>SCH</td>
<td>SCHwarzchild (metric)</td>
</tr>
<tr>
<td>SCUBA</td>
<td>Submillimeter Common-User Bolometer Array</td>
</tr>
<tr>
<td>SDSS</td>
<td>Sloan Digital Sky Survey</td>
</tr>
<tr>
<td>SEW</td>
<td>Super-Eddington Wind</td>
</tr>
<tr>
<td>Seyfert</td>
<td>Galaxy (generally spiral) with a bright nucleus, originally discovered by Carl Seyfert; AGN</td>
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<tr>
<td>SGR</td>
<td>Soft Gamma-ray Repeater</td>
</tr>
<tr>
<td>SGRB</td>
<td>Short-duration Gamma-Ray Burst</td>
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<tr>
<td>SH</td>
<td>Schwarzschild–Hilbert (coordinate system)</td>
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<tr>
<td>SHB</td>
<td>Short Hard Burst; SGRB</td>
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<tr>
<td>SIM</td>
<td>Space Interferometer Mission</td>
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<tr>
<td>SIS</td>
<td>Singular Isothermal Sphere (distribution of stars)</td>
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<td>SISSA</td>
<td>Scuola Internazionale Superiore di Studi Avanzati</td>
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<tr>
<td>SLE</td>
<td>Shapiro–Lightman–Eardley (accretion disk solution)</td>
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<tr>
<td>SMBH</td>
<td>SuperMassive Black Hole</td>
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<tr>
<td>SMC</td>
<td>Small Magellanic Cloud</td>
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<tr>
<td>SMG</td>
<td>SubMillimeter Galaxy</td>
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<tr>
<td>SMS</td>
<td>Slow Magnetosonic Surface</td>
</tr>
<tr>
<td>SMSS</td>
<td>Slow Magnetosonic Separatrix Surface</td>
</tr>
<tr>
<td>SN</td>
<td>SuperNova</td>
</tr>
<tr>
<td>SNR</td>
<td>SuperNova Remnant</td>
</tr>
<tr>
<td>SPH</td>
<td>Smooth Particle Hydrodynamics</td>
</tr>
<tr>
<td>SPL</td>
<td>Steep Power-Law (X-ray binary accretion state)</td>
</tr>
<tr>
<td>SRMHD</td>
<td>Special Relativistic MagnetoHydroDynamics</td>
</tr>
<tr>
<td>SS</td>
<td>Shakura–Sunyaev (accretion disk solutions)</td>
</tr>
<tr>
<td>STScI</td>
<td>Space Telescope Science Institute</td>
</tr>
<tr>
<td>surface, critical</td>
<td>locus of points in space where flow characteristics appear or disappear</td>
</tr>
<tr>
<td>surface, separatrix</td>
<td>locus of points in space where component of flow characteristics along a streamline changes sign</td>
</tr>
<tr>
<td>surface, singular</td>
<td>locus of points in space where denominator of a mathematical accretion/wind equation vanishes</td>
</tr>
<tr>
<td>SXT</td>
<td>Soft X-ray Transient source</td>
</tr>
<tr>
<td>TOV equation</td>
<td>Tolman–Oppenheimer–Volkoff relativistic stellar structure equation</td>
</tr>
<tr>
<td>traceless-Lorenz gauge</td>
<td>see TT gauge</td>
</tr>
<tr>
<td>TT gauge</td>
<td>Transverse–Traceless gauge for the Einstein equations</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
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<tr>
<td>UB</td>
<td>Upper Banana state (of neutron star atoll sources)</td>
</tr>
<tr>
<td>UC</td>
<td>University of California</td>
</tr>
<tr>
<td>UCLA</td>
<td>University of California Los Angeles</td>
</tr>
<tr>
<td>UCSB</td>
<td>University of California Santa Barbara</td>
</tr>
<tr>
<td>UCSC</td>
<td>University of California Santa Cruz</td>
</tr>
<tr>
<td>UFO</td>
<td>Ultra-Fast Outflow (from AGN central engines)</td>
</tr>
<tr>
<td>ULIRG</td>
<td>Ultra-Luminous InfraRed Galaxy</td>
</tr>
<tr>
<td>ULX</td>
<td>Ultra-Luminous X-ray source</td>
</tr>
<tr>
<td>UNAM</td>
<td>Universidad Nacional Autónoma de México</td>
</tr>
<tr>
<td>UT</td>
<td>University of Texas</td>
</tr>
<tr>
<td>UV</td>
<td>UltraViolet (radiation)</td>
</tr>
<tr>
<td>UVOIR</td>
<td>UltraViolet–Optical–InfraRed (radiation)</td>
</tr>
<tr>
<td>VH</td>
<td>Very High (X-ray binary accretion state)</td>
</tr>
<tr>
<td>VHS</td>
<td>Very High State (for X-ray binaries)</td>
</tr>
<tr>
<td>VK</td>
<td>Vlahakis and Königl 2003 paper on warm, relativistic MHD winds</td>
</tr>
<tr>
<td>VLA</td>
<td>Very Large Array</td>
</tr>
<tr>
<td>VLBA</td>
<td>Very Long Baseline Array</td>
</tr>
<tr>
<td>VLBI</td>
<td>Very Long Baseline Interferometry</td>
</tr>
<tr>
<td>VMS</td>
<td>Very Massive Star</td>
</tr>
<tr>
<td>VTST</td>
<td>Vlahakis, Tsinganos, Sauty, and Trussoni 2000 paper on warm, non-relativistic MHD winds [549]</td>
</tr>
<tr>
<td>WC</td>
<td>Wolf–Rayet star with strong Carbon emission lines</td>
</tr>
<tr>
<td>WD</td>
<td>White Dwarf</td>
</tr>
<tr>
<td>WLRG</td>
<td>Weak-Lined Radio Galaxy</td>
</tr>
<tr>
<td>WN</td>
<td>Wolf–Rayet star with strong Nitrogen emission lines</td>
</tr>
<tr>
<td>WNE</td>
<td>see WN</td>
</tr>
<tr>
<td>WO</td>
<td>Wolf–Rayet star with strong Oxygen emission lines</td>
</tr>
<tr>
<td>WPVS</td>
<td>Wamsteker, Prieto, Vitores, Schuster et al. $H\alpha$ galaxy survey</td>
</tr>
<tr>
<td>XDIN</td>
<td>X-ray Dim Isolated Neutron star</td>
</tr>
<tr>
<td>XMM</td>
<td>X-ray Multi-mirror Mission; a.k.a., XMM Newton</td>
</tr>
<tr>
<td>XRB</td>
<td>X-ray binary</td>
</tr>
<tr>
<td>XTE</td>
<td>X-ray Timing Explorer; see RXTE</td>
</tr>
<tr>
<td>ZAMO</td>
<td>Zero-Angular-Momentum Observer (FIDO coordinate system)</td>
</tr>
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<td>ZAMS</td>
<td>Zero-Age Main Sequence (main locus of stars in HR diagram)</td>
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