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Relativistic non-ideal flows

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Abstract

The problem of stationary, spherically symmetric accretion onto a Schwarzschild black hole is discussed here with the use of a formalism which is completely consistent with Einstein's General theory of Relativity.

The transfer of heat is a significant part of this process, however treating it without approximations has proven difficult. Here I explore the adiabatic case first; then I consider a more general case by assuming that all the heat transfer happens through electromagnetic radiation. For the latter I apply the PSTF formalism which, roughly speaking, while still being relativistic allows for the decomposition of the radiation into its first moments: energy density and flux.

The numerical analysis of the differential equations the problem can be reduced to shows a bimodal behaviour: a branch of solutions has a much higher efficiency (ratio of luminosity to accretion rate) than another.

In order to treat this problem, first I briefly recall the formalism of general relativity; then I treat the basics of the relativistic formulation of the fluid dynamical equations, including the relativistic version of the Second Principle of thermodynamics.

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1 Introduction

The proper study of the problem of accretion onto a black hole requires the use of a relativistic formalism, since the gravitational effect of such an object can only be properly described as the curvature of space-time, and the speed of matter from radial infinity to the horizon spans the whole interval $[0, c]$: neither the non-relativistic nor the ultra-relativistic approximations are justified if the whole accretion problem is to be considered.

To this end, in section 3 I will briefly recall the basics of special relativity, differential geometry and general relativity in order to introduce the Schwarzschild metric, which is the geometrical background on which the spherical accretion problem is studied.

In classical mechanics the equations of fluid dynamics are the conservation equations of mass (the continuity equation), of momentum (the Navier-Stokes equations) and of energy. In section 4

I will compare the equations of motion of a non-relativistic fluid to those of a relativistic fluid: the classical equations have direct relativistic analogues; however an important difference is the fact that the energy conservation equation cannot be decoupled from the momentum conservation equations since they are the components of the same tensorial equation: the conservation of the stress-energy tensor.

I will use the formalism first introduced by Eckart [Eck40] for the decomposition the stress energy-tensor, and following Taub [Tau78] analyze the spatial projection of the conservation equations, distinguishing the relativistic forces acting on the fluid due to viscosity and to heat transfer.

I will then give a proof of the relativistic Second Principle of thermodynamics, which will justify the definition of an ideal fluid: ideality implies the isentropicity of flow lines.

The relativistic equations of fluid dynamics are very complicated in the general case: in order to be able to analyze the solutions one has to make several simplifying assumptions. I will derive the equations which govern accretion in the spherically symmetric, adiabatic case. These already give an interesting result: they show a critical point corresponding to the adiabatic speed of sound: to avoid a divergence of the velocity gradient, one must impose the condition that the speed of sound be reached exactly at a certain critical radius.

In order to describe the heat transfer one assumes that the stress-energy tensor of matter is simply the ideal-fluid one, and that all of the transfer of heat happens through radiation. The description of the radiation stress-energy tensor is, however, difficult in general. In section 5 I will introduce and apply the PSTF moments formalism by Thorne [Tho81]: it is a relativistic generalization of a technique from classical mechanics which allows, in the spherically symmetric case, for a simple description of the stress-energy tensor in terms of few scalar *moments*; these are tied to each other by differential equations which are derived as a harmonic expansion of the transfer equation for photons.

With these tools, the equations of motion can be reduced to a system of six ODEs, which still show the adiabatic speed of sound critical point but also have another one. Also, they can be integrated numerically [NTZ91]: the solutions, when characterized by their efficiency, cluster in two regions.

2 Notational preface

I will use Greek indices (μ, ν, ρ, \dots) to denote 4-dimensional indices ranging from 0 to 3, and Latin indices (i, j, k, \dots) to denote 3-dimensional indices ranging from 1 to 3.

I will use the “mostly plus” metric for flat Minkowski space-time, $\eta_{\mu\nu} = \text{diag}(-, +, +, +)$: therefore four-velocities will have square norm $u^\mu u_\mu = -1$. I will use Einstein summation convention: if an index appears multiple times in the same monomial, it is meant to be summed over.

I will adopt the abuse of notation by which a vector is denoted by its components, and a free index means we consider all of the possible values it can take, such as x^μ denoting a point in spacetime.

Take a diffeomorphism $x \rightarrow y$, with Jacobian matrix $\partial y^\mu / \partial x^\nu$. The indices of contravariant vectors, transforming as

$$V^\mu \rightarrow \left(\frac{\partial y^\mu}{\partial x^\nu} \right) V^\nu \quad (2.1)$$

will be denoted as upper indices, while the indices of covariant vectors, transforming as

$$V_\mu \rightarrow \left(\frac{\partial x^\nu}{\partial y^\mu} \right) V_\nu \quad (2.2)$$

will be denoted as lower indices; the same applies to higher rank tensors.

Unless otherwise specified, I will work in geometrized units, where $c = G = 1$.

In section 5 I will use the notation from Thorne [Tho81]: A_k will represent a sequence of k indices labelled as α_i , for i between 1 and k . The same will hold for $B_k \rightarrow \{\beta_i\}$ etc.

Take a tensor with many indices, $T_{A_k B_j}$. These indices can be symmetrized and antisymmetrized, and I will use the following conventions:

$$T_{(A_k)B_j} = \frac{1}{k!} \sum_{\sigma \in S_k} T_{\sigma(A_k)B_j} \quad (2.3)$$

$$T_{[A_k]B_j} = \frac{1}{k!} \sum_{\sigma \in S_k} \text{sign } \sigma T_{\sigma(A_k)B_j} \quad (2.4)$$

where $S_k \ni \sigma$ is the group of permutations of k elements, and $\text{sign } \sigma$ is 1 if σ is an even permutation (it can be obtained with an even number of pair swaps) and -1 otherwise.

3 Relativity

3.1 Special relativity

Special Relativity is a theory which satisfies the following axioms [Lec14]:

1. space and time are homogeneous (i. e. shift-invariant), space is isotropic (i. e. rotation-invariant);
2. the speed of light is the same in every inertial reference frame;
3. all the laws of physics are written in the same way in every inertial reference frame.

In special relativity, instead of having vectors in 3D space and a time scalar coordinate, we denote events as points in 4D spacetime, which is an intrinsically flat semi-Riemannian manifold with metric signature $(-, +, +, +)$, with coordinates such as $x^\mu = (t, x, y, z)$. This is called Minkowski flat spacetime.

This difference is not just semantic: the spacetime formalism is needed because the axioms are equivalent to the conservation of the spacetime interval $ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$, and the only transformations between inertial reference frames which leave it invariant often *mix* time and space: they are represented in 4D spacetime as $x^\mu \rightarrow \Lambda^\mu_\alpha x^\alpha + a^\mu$, with the Λ^μ_α being $(1,1)$ tensors which satisfy $\Lambda^\mu_\alpha \Lambda^\nu_\beta \eta_{\mu\nu} = \eta_{\alpha\beta}$, and a^μ being a generic constant 4-vector.

The flat metric allows us to compute the lengths of vectors, and since it is indefinite there are nonzero vectors of positive, negative and zero spacetime length. These are respectively called spacelike, timelike and null-like.

We define the proper time τ by $d\tau \stackrel{\text{def}}{=} \sqrt{-ds^2}$. Unlike coordinate time $x^0 = t$ this has the advantage of being Lorentz-invariant.

We can define a tensorial velocity by differentiating the position with respect to proper time: $u^\mu \stackrel{\text{def}}{=} dx^\mu / d\tau$. Defined this way, the so-called 4-velocity transforms like a tensor. If \vec{v} is the regular three-velocity and v is its magnitude, we define $\gamma = 1/\sqrt{1-v^2}$ and then: $u^\mu = (\gamma, \gamma\vec{v})$.

Now, differentiating any function of position looks like $dT^{A_k}(x^\mu)/d\tau = (\nabla_\mu T^{A_k}) dx^\mu / d\tau = u^\mu \nabla_\mu T^{A_k}$.

Once we have this, we can define the 4-acceleration:

$$a^\nu = \frac{du^\mu}{d\tau} = u^\mu \nabla_\mu u^\nu. \quad (3.1)$$

The 4-velocity is a unit vector: $u^\mu u_\mu = -1$, and by differentiating this relation we get the often used identity $u^\mu a_\mu = 0$.

We also define the 4-momentum $p^\mu = mu^\mu$, where m is the rest mass of the body at hand.

The 0-th component of the 4-momentum vector is the energy of the body, while the i -th components define a new relativistic 3-momentum $p^i = \gamma m v^i$: we then have $p^\mu p_\mu = m^2 = E^2 - |\mathbf{p}|^2$.

3.2 Differential geometry and tensor calculus

3.2.1 Metric

The metric tensor $g_{\mu\nu}$ is a symmetric $(0,2)$ tensor which defines a scalar product at every point in our manifold: $x \cdot y = g_{\mu\nu} x^\mu y^\nu$. It is not intrinsic to the manifold. By integrating the velocity vector we can find the lengths of curves $x^\mu(\lambda)$:

$$L = \int \sqrt{g_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda}} d\lambda . \quad (3.2)$$

For a flat spacetime we use the Minkowski metric $\eta_{\mu\nu}$. In general, in the presence of matter the manifold will be intrinsically curved (the meaning of this will be discussed in section 3.3.2), so there will not be a coordinate transformation to cast $g_{\mu\nu}$ in the form $\eta_{\mu\nu}$. If we choose a certain point P , however, it is possible to find a transformation so that $g_{\mu\nu}(P) = \eta_{\mu\nu}(P)$, $\partial_\rho g_{\mu\nu}(P) = 0$ [Car97, pages 49–50].

The spacetime interval ds^2 , defined with $g_{\mu\nu}$ instead of $\eta_{\mu\nu}$, is still an invariant scalar.

3.2.2 Tensor calculus

An object such as $\partial_\mu A^\nu$ (the matrix of the partial derivatives with respect to the coordinates of some vector A^ν) does not in general transform as a tensor.

Because of this, we wish to define a new kind of derivative, which is *covariant*, that is, which transforms as a tensor. There is not an intrinsic way to do this, but for any choice of covariant derivative one makes it can be written as

$$\nabla_\mu A^\nu = \partial_\mu A^\nu + \Gamma_{\alpha\mu}^\nu A^\alpha . \quad (3.3)$$

where the rank-3 objects Γ are called Christoffel symbols. They are not tensors: they depend on the choice of basis e_α .

A specific covariant derivative can be chosen by imposing the condition of it being torsion-free: $\Gamma_{\alpha\mu}^\nu = \Gamma_{\mu\alpha}^\nu$ and compatible with the metric: $\nabla_\sigma g_{\mu\nu} = 0$. This allows us to have a well-defined unique covariant derivative. If we make this assumption, the Christoffel symbols can be calculated as:

$$\Gamma_{\nu\rho}^\mu = \frac{1}{2} g^{\mu\alpha} (\partial_\rho g_{\alpha\nu} + \partial_\nu g_{\alpha\rho} - \partial_\alpha g_{\nu\rho}) . \quad (3.4)$$

The covariant derivative is the same as the coordinate derivative for scalars.

We can define the covariant derivative of higher order tensor analogously; adding a Christoffel symbol for every new index. The symbols corresponding to lower indices have a minus sign: this can be seen by differentiating a scalar such as $\nabla_\nu (A_\mu B^\mu) \stackrel{!}{=} \partial_\nu (A_\mu B^\mu)$ and matching the Christoffel terms.

The divergence of a vector field A^μ can be calculated as:

$$\nabla_\mu A^\mu = \frac{1}{\sqrt{-g}} \partial_\mu (\sqrt{-g} A^\mu) \quad (3.5)$$

where g is the determinant of the metric.

3.2.3 Stokes' theorem

If we have a manifold of dimension n , and an n -dimensional region V of this manifold equipped with coordinates x^μ a metric $g_{\mu\nu}$, with a submanifold boundary ∂V equipped with coordinates y^μ and the induced metric $h_{\alpha\beta} = \left(\partial x^\mu / \partial y^\alpha\right) \left(\partial x^\nu / \partial y^\beta\right) g_{\mu\nu}$, and for which we have a properly oriented normal vector $n^\mu(y)$; then for any vector f^μ we have [Ung16]:

$$\int_V \nabla_\mu f^\mu \sqrt{|\det g|} d^n x = \int_{\partial V} f^\mu n_\mu \sqrt{|\det h|} d^{n-1} y . \quad (3.6)$$

3.2.4 Geodesics

A path $x^\mu(\lambda)$ is called a *geodesic* if it is stationary with respect to path length. To check whether a given path is a geodesic we can stationarize the action corresponding to the Lagrangian $\mathcal{L}(x, \dot{x}) = g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu$ (where we use the notation $\dot{x} = dx/d\lambda$). The Lagrange equations then are:

$$\ddot{x}^\mu + \Gamma_{\nu\rho}^\mu \dot{x}^\nu \dot{x}^\rho = 0 \quad (3.7)$$

where $\Gamma_{\nu\rho}^\mu$ are the Christoffel symbols, which can be calculated by differentiating the metric, as shown in (3.4). \mathcal{L} is an integral of these Lagrange equations.

If the parameter λ is taken to be the proper time s , then the equation is

$$\frac{du^\mu}{ds} + \Gamma_{\nu\rho}^\mu u^\nu u^\rho = 0 . \quad (3.8)$$

Notice that this is equivalent to the covariant acceleration (3.1) being zero.

3.2.5 Fermi-Walker transport

Take a general vector field $V^\mu(s)$ defined along a curve, with the curve's tangent vector u^μ whose covariant acceleration is a^μ . Then we say that V^μ is transported according to Fermi-Walker if it satisfies

$$\dot{V}^\mu = u^\nu \nabla_\nu V^\mu = 2V_\rho u^{[\mu} a^{\rho]} . \quad (3.9)$$

This condition is always satisfied by $V^\mu = u^\mu$, since $a^\mu u_\mu = 0$, whether or not the curve is a geodesic: the tangent vector is always *Fermi-Walker* transported, but it is *parallel* transported only for geodesics.

The justification of this definition is the fact that we want the transformations of our reference frame to be infinitesimal Lorentz boosts, which are generated by antisymmetric tensors, and we want to forbid any rotations in the plane orthogonal to a^μ and u^μ .

3.2.6 Tetrads and projectors

We want to work in a reference in which the velocity u^μ is purely timelike. This can always be found by the equivalence principle. Such a reference can be completed into what is called a tetrad, for which the metric becomes the Minkowski metric in a neighbourhood of the point we consider.

We call the velocity $u^\mu = V_{(0)}^\mu$ and complement it with three other vectors $V_{(i)}^\mu$ such that

$$g_{\mu\nu} V_{(\alpha)}^\mu V_{(\beta)}^\nu = \eta_{(\alpha)(\beta)} \quad (3.10)$$

where the brackets around the indices denote the fact that they label four vectors, not the components of a tensor.

We can choose the vectors $V_{(i)}^\mu$ so that they are Fermi-Walker transported along the worldline defined by u^μ : this allows us to find the relativistic equivalent of a non-rotating frame of reference.

It is useful to project tensors onto the space-like and time-like subspaces defined by our tetrad (and we wish to do so in a coordinate-independent manner, so just taking the 0th and i -th components in the tetrad will not suffice). We therefore define the projectors:

$$h_{\mu\nu} = u_\mu u_\nu + g_{\mu\nu} \quad \pi_{\mu\nu} = -u_\mu u_\nu \quad (3.11)$$

respectively onto the space- and time-like subspaces defined by the four-velocity.

3.2.7 Killing vector fields

Suppose there is a certain direction (which, for simplicity, we assume to be along one of our coordinate axes) along which the metric is preserved: an $\tilde{\alpha}$ such that $\partial_{\tilde{\alpha}} g_{\mu\nu} = 0$.

Then the metric properties of curves along the manifold are unchanged if we shift their coordinate representation by a constant along the $\tilde{\alpha}$ coordinate axis.

Let us call the direction of this translation $\xi^\mu = \delta_{\tilde{\alpha}}^\mu$ if we use this coordinate system. It can be shown by direct computation that

$$\nabla_\nu \xi_\mu = \frac{1}{2} \left(\partial_{\tilde{\alpha}} g_{\mu\nu} + \partial_\nu g_{\mu\tilde{\alpha}} - \partial_\mu g_{\nu\tilde{\alpha}} \right) \quad (3.12)$$

but by hypothesis the first term on the RHS of (3.12) is zero, therefore we have shown that $\nabla_\nu \xi_\mu = \nabla_{[\nu} \xi_{\mu]}$ in this coordinate frame, but since this is a covariant equation it extends to every other one.

This can equivalently be stated by writing $\nabla_{(\nu} \xi_{\mu)} = 0$: this is called *Killing's equation* [MTW73, section 25.2, page 650]. This is useful since: given a geodesic $x^\mu(\lambda)$, for which we define $u^\mu = dx^\mu/d\lambda$, it must be the case that $u^\nu \nabla_\nu u^\mu = 0$. Then, the component of u^μ along ξ^μ ($u^{\tilde{\alpha}} = u^\mu \xi_\mu$) is conserved:

$$\frac{d}{d\lambda} (u^\mu \xi_\mu) = u^\nu \nabla_\nu (u^\mu \xi_\mu) = \cancel{\xi^\mu u^\nu \nabla_\nu u_\mu} + \cancel{u^\nu u^\mu \nabla_\nu \xi_\mu} \equiv 0. \quad (3.13)$$

3.2.8 Surfaces in space-time and acceleration decomposition

We consider 3D space-like surfaces in 4D space-time: if a fluid is moving with velocity u^μ , we denote the solutions of the differential equation associated with the vector field as $x^\mu(\xi^i, s)$, where ξ^i are the 3D coordinates of the starting position and s is the time at which we look at the solution. Then the “starting” hypersurface is $\Sigma = \{x^\mu(\xi^i, 0)\}$.

Suppose we have a curve $\xi^i(\tau)$ in Σ . Then we can define the two-dimensional surface defined by the evolution of $\xi^i(\tau)$: $x^\mu(\xi^i(\tau), s) \stackrel{\text{def}}{=} x^\mu(\tau, s)$. If we also define the “spatial” tangent vector $\lambda^\mu = dx^\mu/d\tau$, it follows from Schwarz's theorem that:

$$\frac{\partial^2 x^\mu}{\partial \tau \partial s} = \frac{\partial^2 x^\mu}{\partial s \partial \tau} \implies \frac{\partial u^\mu}{\partial \tau} = \frac{\partial \lambda^\mu}{\partial s}. \quad (3.14)$$

Now let us take the spatial vectors of an orthonormal Fermi-Walker transported tetrad $V_{(a)}^\mu$ as described in section 3.2.6, and express λ^μ in this frame: its covariant components will be

$$X_{(a)} = V_{(a)\mu} \lambda^\mu. \quad (3.15)$$

If we differentiate (3.15) with respect to s , and use (3.14) with the fact that $\frac{d}{ds} = \lambda^\mu \nabla_\mu$, we get:

$$\frac{dX_{(a)}}{ds} = \frac{dV_{(a)\mu}}{ds} \lambda^\mu + V_{(a)\mu} \frac{d\lambda^\mu}{ds} \quad (3.16a)$$

$$= V_{(a)}^\rho \lambda^\mu \cancel{u_\mu a_\rho}^0 - \cancel{V_{(a)}^\rho u_\rho \lambda^\mu a_\mu}^0 + V_{(a)}^\nu \nabla_\mu u_\nu \quad (3.16b)$$

$$= V_{(a)}^\rho \lambda^\mu \nabla_\mu u_\rho \quad (3.16c)$$

$$= \left(\nabla_\mu u_\rho \right) V_{(a)}^\rho V_{(b)}^\mu X^{(b)} \quad (3.16d)$$

where in the last step we expressed everything with respect to the tetrad coordinate system. Therefore, in those coordinates, the evolution of the components $X^{(a)}$ is linear, and defined by the tetrad components of the two-form $\nabla_\mu u_\nu$ [Tau78, section 4]. So, we want to decompose this tensor:

$$\nabla_\sigma u_\tau = \underbrace{\omega_{\sigma\tau}}_{\text{spatial rotation}} + \underbrace{\sigma_{\sigma\tau}}_{\text{spatial shear}} + \underbrace{\frac{1}{3}\theta h_{\sigma\tau}}_{\text{spatial compression}} - \underbrace{a_\tau u_\sigma}_{\text{acceleration}} \quad (3.17)$$

1. $\theta = \nabla_\mu u^\mu$ is the bare trace of the tensor, corresponding to the expansion velocity;
2. $a_\mu = u^\nu \nabla_\nu u^\mu$ is the covariant acceleration;
3. $\sigma_{\sigma\tau} = \left(\nabla_{(\mu} u_{\nu)} \right) h_\sigma^\mu h_\tau^\nu - 1/3 \theta h_{\sigma\tau} = \nabla_{(\sigma} u_{\tau)} + a_{(\sigma} u_{\tau)} - 1/3 \theta h_{\sigma\tau}$ is the spatial symmetric trace-free part of the tensor, which corresponds to the shear stress;
4. $\omega_{\sigma\tau} = h_\sigma^\nu h_\tau^\mu \nabla_{[\nu} u_{\mu]} = \partial_{[\tau} u_{\sigma]} + a_{[\tau} u_{\sigma]}$ is the spatial (antisymmetric, trace-free) rotation tensor.

To verify the formulas given for $\sigma_{\sigma\tau}$ and $\omega_{\sigma\tau}$ it is enough to expand the definitions, simplifying the terms which contain products of the 4-acceleration and the 4-velocity; also, the terms such as $u^\mu u_\tau \nabla_\sigma u_\mu$ vanish since $0 = u_\tau \nabla_\sigma (u^\mu u_\mu) = 2u^\mu u_\tau \nabla_\sigma u_\mu$.

3.3 General Relativity

3.3.1 The Equivalence Principle

In the General theory of Relativity we make a stronger claim than that of the axioms of SR, which are only formulated for inertial reference frames.

The *Einstein Equivalence Principle* states [Car97, p. 100] that in small enough regions of space-time the laws of physics are those of special relativity, and we cannot detect gravitational effects locally. The frame of reference in which we must write the laws for them to appear in their special-relativistic form is called the Locally Inertial Reference Frame or Local Rest Frame (LRF).

Unlike special relativity, the transformation laws between different reference frames are not linear, but can be in general be represented as diffeomorphisms.

We model spacetime as a manifold which has intrinsic (basis-independent) curvature; an object which is modelled in newtonian mechanics as being in free fall, accelerated by a gravitational force, is modelled in general relativity as following a geodesic in the manifold.

3.3.2 Curvature

The intrinsic curvature of spacetime is fully described by the Riemann curvature tensor, which is a fourth rank tensor: for any generic vector V^μ ,

$$R^\mu_{\nu\rho\sigma} V^\nu \stackrel{\text{def}}{=} [\nabla_\rho, \nabla_\sigma] V^\mu. \quad (3.18)$$

It can be calculated using the Christoffel symbols, and while they are not tensors $R^\mu_{\nu\rho\sigma}$ is one. This result follows by expanding all the covariant derivatives in formula (3.18):

$$R^\mu_{\nu\rho\sigma} = \partial_\rho \Gamma^\mu_{\nu\sigma} - \partial_\sigma \Gamma^\mu_{\nu\rho} + \Gamma^\mu_{\rho\lambda} \Gamma^\lambda_{\sigma\nu} - \Gamma^\mu_{\sigma\lambda} \Gamma^\lambda_{\rho\nu} \quad (3.19)$$

The Christoffel symbols can be nonzero if we choose certain coordinates even for flat spacetime, but the Riemann tensor is zero if and only if the spacetime is flat.

The Riemann tensor satisfies the following identities [MTW73, eqs. 8.45 and 8.76]:

$$\nabla_{[\lambda} R_{\mu\nu]\rho\sigma} = 0 \quad (3.20a)$$

$$R_{\mu\nu\rho\sigma} = R_{[\mu\nu][\rho\sigma]} = R_{[\rho\sigma][\mu\nu]} \quad (3.20b)$$

$$R_{[\mu\nu\rho\sigma]} = 0 = R_{\mu[\nu\rho\sigma]}. \quad (3.20c)$$

If we define the Ricci tensor $R_{\mu\nu} = R^\rho_{\mu\rho\nu}$ and the curvature scalar $R = R_{\mu\nu} g^{\mu\nu}$, we can derive from (3.20a) the *contracted Bianchi identity* $\nabla_\mu R = 2\nabla_\nu R^\nu_\mu$, which means that $\nabla_\mu (R^{\mu\nu} - 1/2 R g^{\mu\nu}) = 0$.

3.3.3 The Einstein Field Equations

They describe the way the presence of matter changes the geometry of spacetime. They involve the *stress-energy tensor* $T^{\mu\nu}$ which is defined in section 4.2.1 and the Einstein tensor $G^{\mu\nu} = R^{\mu\nu} - 1/2 R g^{\mu\nu}$, which is the only independent tensor satisfying the following properties: it can be constructed from only the Riemann tensor and the metric, it vanishes for flat spacetime and it identically satisfies the conservation laws $\nabla_\mu G^{\mu\nu} = 0$.

The field equations (EFE) are:

$$G^{\mu\nu} = 8\pi T^{\mu\nu}. \quad (3.21)$$

The constant comes by imposing continuity with the newtonian limit, in which we know the gravitational field Φ is determined by the matter density ρ_0 according to the Poisson equation $\partial_i \partial^i \Phi = 4\pi \rho_0$.

The matter density ρ_0 is replaced in the relativistic formulation by T_{00} ; as for the gravitational field Φ , in order to see how it appears in the relativistic formulation we must calculate the weak-field limit of the Einstein tensor: this is done by assuming the metric is in the form $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll |\eta_{\mu\nu}|$.

By comparing the geodesic equation we get with this perturbed metric with the equations of motion of a particle in a newtonian gravitational field we can identify $\Phi = -1/2 h_{00}$ [Car97, eq. 4.20]. The expression for the Ricci tensor contains exactly the derivatives needed to get the Laplacian operator which appears in the newtonian Poisson equation: this is what allows us to find the constant of proportionality by continuity.

The EFE can be written in a more general way by removing the condition that the LHS vanish for flat spacetime, and thus including there a *cosmological constant* term $\Lambda g^{\mu\nu}$ with constant Λ . It is unclear whether this term should appear, and what the value of Λ should be.

3.3.4 The Schwarzschild solution

The EFE are generally very difficult to solve, but they admit analytical solutions in certain special cases. One of the simplest is that of a central mass M described with spherical coordinates (t, r, θ, φ) and in the presence of spherical symmetry. Here I present a sketch of the procedure used to derive the metric, following what is done in Carroll [Car97, section 7].

We impose the condition that the stress energy tensor be identically zero for radii greater than a certain (arbitrarily small) radius, $r > r_c$.

Then, we can write down the most general possible spherically symmetric metric, which turns out to be [Car97, eq. 7.13]:

$$ds^2 = -e^{2\alpha(r,t)} dt^2 + e^{2\beta(r,t)} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\varphi^2) \quad (3.22)$$

and plug this into the equations $G_{\mu\nu} = 0 \implies R_{\mu\nu} = 0$ for all $r > r_c$. We get the result that the metric possesses a timelike Killing vector field which is orthogonal to a family of hypersurfaces $t = \text{const}$: therefore it is *static*, unchanging with time. α and β only depend on r , and we can show that

$$e^{2\alpha(r)} = e^{-2\beta(r)} = \left(1 + \frac{C}{r}\right) \quad (3.23)$$

for some C . By continuity with the weak-field limit, for which we have the newtonian gravitational field $\Phi = -M/r$ and $g_{00} = -(1 + 2\Phi)$, one sets $C = -2M$. Keeping the notation $\Phi = -M/r$ we have:

$$ds^2 = -(1 + 2\Phi) dt^2 + \frac{1}{1 + 2\Phi} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\varphi^2) \quad (3.24)$$

or, equivalently,

$$g_{\mu\nu} = \text{diag} \left(-(1 + 2\Phi), \frac{1}{1 + 2\Phi}, r^2, r^2 \sin^2 \theta \right). \quad (3.25)$$

We can see that it approaches the spherical-coordinates flat metric $\eta'_{\mu\nu} = \text{diag}(-1, 1, r^2, r^2 \sin^2 \theta)$ both in the limit $M \rightarrow 0$ and the limit $r \rightarrow \infty$. Its determinant is $g = -r^4 \sin^2 \theta$, so $\sqrt{-g} = r^2 \sin \theta$.

4 Fluid dynamics

4.1 Nonrelativistic fluid mechanics

Nonrelativistic (compressible) fluid mechanics is described by the equations:

$$\partial_t \rho_0 + \partial_i (\rho_0 v^i) = 0 \quad \text{conservation of mass} \quad (4.1a)$$

$$\rho_0 (\partial_t v^i + v^j \partial_j v^i) = \partial_j \sigma^{ij} \quad \text{conservation of momentum} \quad (4.1b)$$

$$\rho_0 \partial_t E + v^i \partial_i E = \partial_i (\sigma^{ij} v_j + \kappa \partial^i T) \quad \text{conservation of energy} \quad (4.1c)$$

where ρ_0 is the density of the fluid, v^i are the components of the velocity vector field, σ^{ij} is the classical stress tensor. E is the energy density of the fluid, κ is the thermal conductivity, T is the temperature field of the fluid.

We use the compressible formulation in order for these to be closer to their relativistic counterpart, for which compressive effects cannot be ignored.

The nonrelativistic stress tensor can be written as:

$$\sigma_{ij} = -(p - \zeta \partial_k v^k) \delta_{ij} + 2\eta \partial_{(i} v_{j)} \quad (4.2)$$

where p is the (isotropic) pressure, η the viscosity, ζ is the bulk viscosity.¹ We are assuming that the normal stresses are only those exerted by pressure, so the diagonal terms σ_{ii} (not summed) must just be $-p$, and the term $-\zeta \partial_k v^k$ must equal $\eta \partial_{(i} v_{i)} = 2\eta \partial_i v_i$ (not summed). Therefore, by isotropy, $\zeta = -2\eta/3$.

Note that we are working in Euclidean 3D space, so the metric is the identity and upper and lower indices are equivalent.

The energy density is the sum of kinetic and internal energies:

$$E = v^i v_i / 2 + \varepsilon \quad (4.3)$$

where ε is the specific internal energy.

4.2 The relativistic fluid

We want to develop a formalism to treat a fluid dynamical problem in the presence of relativistic speeds and strong gravitational fields, such as in spherical accretion onto a black hole. It will have to be fully relativistic: the conservation laws will have to be written as tensorial equations.

We treat the fluid as a continuous medium which will have a certain density of particles per unit volume n : that is, what we consider “infinitesimal” is not actually arbitrarily small but should be considered much smaller than the characteristic lengths of the problem, while still containing many particles.

The 4-current of particles is $N^\mu = n u^\mu$, where u^μ is the 4-velocity field of the fluid. If these particles have a certain rest mass m_0 , we can then define the rest-mass-flow vector $\rho_0 u^\mu = m_0 N^\mu$, which is conserved: $\nabla_\mu (\rho_0 u^\mu) = 0$, since particles do not spontaneously appear or disappear nor change their rest mass. The presence of particles with different rest masses can be easily accounted for by adding the mass flow vectors.

Particles in a fluid can have three kinds of energy we concern ourselves with: rest mass, kinetic energy and other forms of energy (thermal, chemical, nuclear. . .). We can always perform a change of coordinates to bring us to the Local Rest Frame, in which the kinetic energy is zero.

Do note that, since our volume element is not actually arbitrarily small, being in the LRF only means that, locally, the average velocity of the fluid is purely timelike: the temperature can be nonzero, so in the LRF the particles in the volume element will still have isotropically distributed nonzero velocities.

We write the sum of mass-energy and internal energy as $\rho = \rho_0(1 + \epsilon)$, the *energy* density of the fluid in its Local Rest Frame, while ρ_0 is the *mass* density in the LRF. So, ϵ is the ratio of the internal non-mass energy to the mass.

4.2.1 Stress-energy tensor

The stress-energy tensor $T^{\mu\nu}$ is a symmetric $(2,0)$ tensor whose μ, ν components are defined as the flux of μ -th component of the four-momentum p^μ through a surface of constant coordinate x^ν .

Because of our choice of the metric signature, the spatial part of the tensor corresponds to the *negative* of the classical continuum-mechanics stress tensor: $T^{ij} = -\sigma^{ij}$, since that tensor describes the stresses *on* the “box” of fluid [Mor16].

¹For consistency with the later sections, here we define ζ with the opposite sign to what appears in [Tau78, page 301].

To give an example: for a gas of non-interacting particles, the stress-energy tensor is very simple: the momentum density is ρu^μ , and then to obtain the flow through a surface of constant x^ν we just need to multiply by u^ν , so in the Local Rest Frame we have:

$$T^{\mu\nu} = \rho u^\mu u^\nu = \begin{bmatrix} \rho & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \quad (4.4)$$

The fact that momentum is conserved (which follows from Noether's theorem applied to the translational invariance of spacetime) can be expressed as the statement that the stress-energy tensor is conserved: $\nabla_\mu T^{\mu\nu} = 0$.

In our example, this can be written as

$$\rho(a^\nu + u^\nu(\nabla_\mu u^\mu)) + u^\nu \frac{d\rho}{d\tau} = 0. \quad (4.5)$$

4.2.2 Relativistic non-ideal fluid dynamics

The evolution of the fluid is described by the conservation of the stress-energy tensor $\nabla_\mu T^{\mu\nu} = 0$ and the conservation of mass $\nabla_\mu(\rho_0 u^\mu) = 0$.

If we wanted to analyze our fluids without *any* approximation we would need to consider the stress-energy tensor of the fluid when solving the Einstein Field Equations: this can be done but it makes the geometry of the system significantly harder to work with, and since we wish to consider other effects such as heat transfer and viscosity throughout the fluid we assume the fluid is not self-gravitating, that is, we solve the conservation equations in a fixed Schwarzschild metric background. This assumption is reasonable in our case: the components of the stress-energy tensor of the infalling gas are much smaller than those of the black hole.

Any stress-energy tensor can be decomposed into its space and time-like parts in the local rest frame of the fluid:

$$T_{\mu\nu} = w u_\mu u_\nu + 2w_{(\mu} u_{\nu)} + w_{\mu\nu} \quad (4.6)$$

where [Tau48, eqs. 8.2, 8.3, 8.5]:

$$w = T_{\mu\nu} u^\mu u^\nu = \rho_0(1 + \varepsilon) = \rho \quad \text{rest energy} \quad (4.7a)$$

$$w_\mu = T_{\nu\sigma} h_\mu^\sigma u^\nu = -\kappa h_\mu^\sigma (\partial_\sigma T + T a_\sigma) \quad \text{heat conduction} \quad (4.7b)$$

$$w_{\mu\nu} = T_{\rho\sigma} h_\mu^\rho h_\nu^\sigma = (p - \xi\theta) h_{\mu\nu} - 2\eta\sigma_{\mu\nu} \quad \text{pressure and viscous stresses.} \quad (4.7c)$$

Do note that by definition the tensors w^μ and $w^{\mu\nu}$ are purely spatial: $u^\mu w_\mu = u^\mu w_{\mu\nu} = 0$.

For the definition of the acceleration, vorticity etc. see equation (3.17).

As in section 4.1 η is the viscosity, ξ is the bulk viscosity, κ is the thermal conductivity, T is the temperature field, p is the pressure field, ρ_0 is the rest mass density while $\rho = \rho_0(1 + \varepsilon)$ is the rest energy density.

Equivalently, we can write

$$T_{\mu\nu} = T_{\mu\nu}^p \quad - \quad T_{\mu\nu}^V \quad + \quad T_{\mu\nu}^h \quad (4.8a)$$

$$= w u_\mu u_\nu + p h_{\mu\nu} \quad - \quad \xi\theta h_{\mu\nu} - 2\eta\sigma_{\mu\nu} \quad + \quad 2w_{(\mu} u_{\nu)} \quad (4.8b)$$

perfect fluid \quad viscous stresses \quad heat conduction.

In the nonrelativistic limit the velocity is approximately $u^\mu = (1, v^i)$, so the conservation of mass becomes (4.1a), while we can obtain both the conservation of energy (4.1c) and the conservation of momentum (4.1b) from the four equations of conservation of the stress-energy tensor, projected respectively onto the 4-velocity and the subspace orthogonal to it.

4.2.3 Viscous and heat-flow relativistic forces

If we consider the spatial components of the conservation equations by applying $h_\mu^\sigma \nabla_\nu$ to the formulation of the stress-energy tensor given in (4.8) we get:

$$h_\mu^\sigma \nabla_\nu ((p + \rho) u^\mu u^\nu + p g^{\mu\nu}) = h_\mu^\sigma \nabla_\nu (T_V^{\mu\nu} - T_h^{\mu\nu}) \quad (4.9a)$$

$$(\rho + p) a^\sigma + h_\nu^\sigma \partial^\nu p = h_\mu^\sigma \nabla_\nu \left(+\xi \theta h^{\mu\nu} + 2\eta \sigma^{\mu\nu} - 2w^{(\mu} u^{\nu)} \right) \quad (4.9b)$$

$$= \underbrace{\nabla_\nu T_V^{\sigma\nu} - u^\sigma \left(\frac{\xi \theta^2}{3} + 2\eta \sigma_{\mu\nu} \sigma^{\mu\nu} \right)}_{\mathcal{F}_V^\sigma} - \underbrace{\nabla_\nu (w^\sigma u^\nu) - w^\nu \nabla_\nu u^\sigma + a_\mu w^\mu u^\sigma}_{\mathcal{F}_h^\sigma}. \quad (4.9c)$$

The vectors $\mathcal{F}_{V,h}^\sigma$ are relativistic forces on the fluid due respectively to viscosity and heat flow. The equations in (4.9c) are four, but they were projected into a three-dimensional subspace so their component along the velocity is trivial, therefore we say that, practically speaking, they are three independent equations: the relativistic generalization of the Navier-Stokes equations.

4.2.4 The Second Principle in General Relativity

Because of the conservation of the stress-energy tensor, we have:

$$\nabla_\nu (u_\mu T^{\mu\nu}) = T^{\mu\nu} \nabla_\nu u_\mu. \quad (4.10)$$

Let us also consider the *fundamental thermodynamic relation*, which follows from the first and second principles in classical thermodynamics, as a definition for the scalar entropy per unit rest mass S :

$$T dS = d\varepsilon + p d\frac{1}{\rho_0}. \quad (4.11)$$

Claim 4.1. We can mold equation (4.10) into a version of the second principle of thermodynamics

$$T \nabla_\mu S^\mu = \xi \theta^2 + 2\eta \sigma_{\mu\nu} \sigma^{\mu\nu} + \frac{w^\mu w_\mu}{\kappa T} \geq 0 \quad (4.12)$$

where we define $S^\mu = \rho_0 S u^\mu + w^\mu / T$.

Proof. We will need the decompositions of the derivative of velocity (3.17), of the stress-energy tensor (4.6), (4.7), the expression of differential entropy (4.11) and the conservation of mass $\nabla_\mu (\rho_0 u^\mu) = 0$.

First of all, the LHS of (4.10) can be greatly simplified by noticing that $u^\mu w_\mu = u^\mu w_{\mu\nu} = 0$, so it becomes

$$\nabla_\nu (u_\mu T^{\mu\nu}) = \nabla_\nu \left(\underbrace{w u_\mu u^\mu}_{-1} u^\nu + \underbrace{u_\mu w^\mu}_{0} u^\nu + \underbrace{u_\mu u^\mu}_{-1} w^\nu + \underbrace{u_\mu w^{\mu\nu}}_{0} \right) \quad (4.13a)$$

$$= \nabla_\nu (-u^\nu \rho_0 (1 + \varepsilon) - w^\nu) \quad (4.13b)$$

$$= -\rho_0 u^\nu \partial_\nu \varepsilon - \nabla_\nu w^\nu. \quad (4.13c)$$

In the RHS of (4.10) many terms cancel as well because they contain contractions of space and timelike indices: we get

$$(\nabla_\nu u_\mu) T^{\mu\nu} = \left(\omega_{\nu\mu} + \sigma_{\nu\mu} + \frac{1}{3} \theta h_{\nu\mu} - a_\mu u_\nu \right) (w u^\mu u^\nu + w^\mu u^\nu + u^\mu w^\nu + w^{\mu\nu}) \quad (4.14a)$$

$$= w^{\mu\nu} \left(\omega_{\mu\nu} + \sigma_{\mu\nu} + \frac{\theta h_{\mu\nu}}{3} \right) + a_\mu w^\mu \quad (4.14b)$$

$$= \left((p - \xi\theta) h^{\mu\nu} - 2\eta\sigma^{\mu\nu} \right) \left(\omega_{\mu\nu} + \sigma_{\mu\nu} + \frac{\theta h_{\mu\nu}}{3} \right) + a_\mu \left(-\kappa h_\sigma^\mu (\partial^\sigma T + T a^\sigma) \right) \quad (4.14c)$$

$$= (p - \xi\theta)\theta - 2\eta\sigma_{\mu\nu}\sigma^{\mu\nu} - \kappa a_\mu \partial^\mu T - \kappa T a_\mu a^\mu. \quad (4.14d)$$

So far, we have:

$$-\rho_0 u^\nu \partial_\nu \varepsilon - \nabla_\nu w^\nu = (p - \xi\theta)\theta - 2\eta\sigma_{\mu\nu}\sigma^{\mu\nu} - \kappa a_\mu \partial^\mu T - \kappa T a_\mu a^\mu. \quad (4.15)$$

Let us rearrange (4.15) in a convenient way:

$$+\rho_0 u^\nu \partial_\nu \varepsilon + p\theta = -\nabla_\nu w^\nu + \xi\theta^2 + 2\eta\sigma_{\mu\nu}\sigma^{\mu\nu} + \kappa a_\mu \partial^\mu T + \kappa T a_\mu a^\mu. \quad (4.16)$$

Now let us consider a quantity we wish to obtain from these manipulations: $T\nabla_\mu S^\mu$. It can be expanded using the continuity equation into:

$$T\nabla_\mu S^\mu = T\nabla_\mu \left(\rho_0 S u^\mu + \frac{1}{T} w^\mu \right) = T\rho_0 u^\mu \partial_\mu S + \nabla_\mu w^\mu - w^\mu \frac{\nabla_\mu T}{T}. \quad (4.17)$$

We can turn the differentials in (4.11) into proper-time derivatives: $d \rightarrow d/d\tau = u^\mu \partial_\mu$. Also, we can use the continuity equation to see that $u^\mu \partial_\mu \rho_0 = -\rho_0 \theta$. Then (4.11) becomes:

$$T \frac{dS}{d\tau} = \frac{d\varepsilon}{d\tau} - \frac{p}{\rho_0^2} \frac{d\rho_0}{d\tau} = \frac{d\varepsilon}{d\tau} + \frac{p\theta}{\rho_0}. \quad (4.18)$$

So we can write the LHS of (4.16), using the identities in equation (4.17) and (4.18):

$$\rho_0 \left(u^\nu \partial_\nu \varepsilon + \frac{p\theta}{\rho_0} \right) = \rho_0 T u^\nu \partial_\nu S = T\nabla_\mu S^\mu - \nabla_\mu w^\mu + \frac{1}{T} w^\mu \nabla_\mu T. \quad (4.19)$$

Let us substitute (4.19) into (4.16), and then subtract the desired result (4.12) from the equation: this way, if we get an identity the proof will be complete (this may seem circular, but it is done just for convenience in the algebraic manipulations: to get a more rigorous argument one may just reverse the steps, using the identity (4.20b) in equation (4.20a) to get equation (4.12)).

$$T\nabla_\mu S^\mu - \nabla_\mu w^\mu + \frac{1}{T} w^\mu \nabla_\mu T = -\nabla_\nu w^\nu + \xi\theta^2 + 2\eta\sigma_{\mu\nu}\sigma^{\mu\nu} + \kappa a_\mu \partial^\mu T + \kappa T a_\mu a^\mu \quad (4.20a)$$

$$-\nabla_\mu w^\mu + \frac{1}{T} w^\mu \nabla_\mu T = -\nabla_\nu w^\nu + \kappa a_\mu \partial^\mu T + \kappa T a_\mu a^\mu - \frac{w^\mu w_\mu}{\kappa T} \quad (4.20b)$$

$$+ \frac{1}{T} w^\mu \nabla_\mu T = +\kappa a_\mu \partial^\mu T + \kappa T a_\mu a^\mu - \frac{w^\mu w_\mu}{\kappa T}. \quad (4.20c)$$

The last term in (4.20c) looks like:

$$\frac{w^\mu w_\mu}{\kappa T} = \frac{1}{\kappa T} \kappa^2 h_\mu^\sigma h^{\mu\nu} (\partial_\sigma T + T a_\sigma) (\partial_\nu T + T a_\nu) = \kappa \left(\frac{h^{\mu\nu}}{T} \partial_\mu T \partial_\nu T + 2a^\mu \partial_\mu T + T a_\mu a^\mu \right). \quad (4.21)$$

Inserting the identity in (4.21) and making the last w^μ explicit in (4.20c) we get:

$$-\frac{1}{T}\kappa h_\sigma^\mu(\partial^\sigma T + Ta^\sigma)\partial_\mu T = +\kappa a_\mu\partial^\mu T + \kappa Ta_\mu a^\mu - \kappa\left(\frac{h^{\mu\nu}}{T}\partial_\mu T\partial_\nu T + 2a^\mu\partial_\mu T + Ta_\mu a^\mu\right) \quad (4.22a)$$

$$+\frac{1}{T}h^{\mu\nu}\partial_\nu T\partial_\mu T + h^{\mu\nu}a_\nu\partial_\mu T = -a_\mu\partial^\mu T - Ta_\mu a^\mu + \left(\frac{h^{\mu\nu}}{T}\partial_\mu T\partial_\nu T + 2a^\mu\partial_\mu T + Ta_\mu a^\mu\right) \quad (4.22b)$$

$$0 = -a_\mu\partial^\mu T - Ta_\mu a^\mu + \left(a^\mu\partial_\mu T + Ta_\mu a^\mu\right) \quad (4.22c)$$

Thus we have proved the equation in (4.12); the inequality follows directly from the fact that we are considering square moduli of spacelike vectors, and the coefficients such as ξ are assumed to be positive. \square

If we assume that the fluid is in equilibrium ($\nabla_\mu S^\mu = 0$) then we must have $\theta = 0$ (no compression), $\sigma_{\mu\nu} = 0$ (no shear stresses), $w_\mu = 0$: the interpretation of this last equation is slightly harder, but it is equivalent to the statement that, in the LRF, the log-temperature gradient is purely spatial and it defines the acceleration, by $a_\sigma = -\partial_\sigma \log T$.

4.2.5 Ideal fluids

They are fluids with $\eta = \xi = \kappa = 0$, that is, without viscosity (neither bulk nor shear) nor heat transmission. They are described by the following stress-energy tensor:

$$T^{\mu\nu} = \rho u^\mu u^\nu + p h^{\mu\nu} = \rho_0 h u^\mu u^\nu + p g^{\mu\nu} \quad (4.23)$$

where $h = (p + \rho)/\rho_0$ is the specific enthalpy. If our fluid is ideal then the RHS of (4.12) is zero and so is w^μ , therefore $T\nabla_\mu S^\mu = T\nabla_\mu(\rho_0 S u^\mu) = T\rho_0 u^\mu\partial_\mu S$ by the continuity equation. So, S is conserved along the world-lines of the fluid.

Also, the RHS of (4.9c) is zero, therefore we get the Euler equation:

$$(p + \rho)a^\mu + h^{\mu\nu}\partial_\nu p = 0. \quad (4.24)$$

4.2.6 Speed of sound

The definition of the adiabatic speed of sound is $v_s^2 = (\partial p/\partial \rho)_s$: here we give a justification for it, following an exposition by Yoshida [Yos11].

We work in Minkowski spacetime, where $g_{\mu\nu} = \eta_{\mu\nu}$, and with an ideal fluid, for which $T_{\mu\nu} = (p + \rho)u_\mu u_\nu + p\eta_{\mu\nu}$. Then, the equations of conservation of mass and momentum read:

$$\rho_0\partial_\mu u^\mu + u^\mu\partial_\mu\rho_0 = 0 \quad \text{mass} \quad (4.25a)$$

$$u^\mu(\partial_\mu\rho - h\partial_\mu\rho_0) = 0 \quad \text{momentum along } u^\mu \quad (4.25b)$$

$$(p + \rho)a^\mu + h^{\mu\rho}\partial_\rho p = 0 \quad \text{momentum normal to } u^\mu \quad (4.25c)$$

where h is the specific enthalpy. If we consider small perturbations $p \rightarrow p + \delta p$, $\rho_0 \rightarrow \rho_0 + \delta\rho_0$, $\rho \rightarrow \rho + \delta\rho$, $u^\mu \rightarrow (1, \delta u^x, 0, 0)$ (the normalization condition is satisfied to first order in δu^x) we get the following simplification of our three equations, up to first order in the perturbations:

$$\partial_x(\delta u^x) = -\frac{\partial_t(\delta\rho_0)}{\rho_0} \quad (4.26a)$$

$$\partial_t(\delta\rho) - h\partial_t(\delta\rho_0) = 0 \quad (4.26b)$$

$$-(p + \rho)\partial_t(\delta u^x) = \partial_x p. \quad (4.26c)$$

We manipulate these by differentiating and substituting, in order to eliminate the dependence on δu^x and ρ_0 , and get:

$$\partial_t \delta \rho + (p + \rho) \partial_x (\partial u^x) = 0 \quad (4.27a)$$

$$\partial_x \delta p + (p + \rho) \partial_t (\partial u^x) = 0 \quad (4.27b)$$

which simplifies to $\partial_{tt}^2 \delta \rho - \partial_{xx}^2 \delta p = 0$.

We can write this as the wave equation $(v_s^{-2} \partial_{tt}^2 - \partial_{xx}^2) \delta p = 0$, where we define $v_s^2 = \partial p / \partial \rho$, the square of the characteristic velocity of propagation v_s .

4.3 Bondi accretion: the adiabatic case

We now apply the formalism developed in this section to the problem of spherical accretion into a black hole the *adiabatic* case, where we model the gas as an ideal fluid.

We assume the geometry of the spacetime is described by the Schwarzschild metric (3.24) and make the following assumptions:

1. spherical symmetry: $\partial_\theta = \partial_\varphi = 0$;
2. stationarity: $\partial_t = 0$.

4.3.1 Fiducial congruence

The comoving tetrad defined by the fluid's motion is called the *fiducial congruence reference*.

Claim 4.2. *When written with respect to the usual spherical coordinates (t, r, θ, φ) the fiducial congruence looks like:*

$$\hat{t} = e_t = u^\mu = (\gamma^2 / y, -y v, 0, 0) \quad (4.28a)$$

$$\hat{r} = e_r = a^\mu / \sqrt{a^\rho a_\rho} = (-v \gamma^2 / y, y, 0, 0) \quad (4.28b)$$

$$\hat{\theta} = e_\theta = (0, 0, 1/r, 0) \quad (4.28c)$$

$$\hat{\varphi} = e_\varphi = (0, 0, 0, 1/(r \sin(\theta))) \quad (4.28d)$$

where γ is the Lorentz factor ($\gamma = 1/\sqrt{1-v^2}$), and $y = \gamma\sqrt{1+2\Phi} = \gamma\sqrt{1-2M/r}$ is the “energy-at-infinity per unit rest mass” (see [TFŽ81, equation 3]).

Proof. First of all, we prove that we can form a comoving tetrad by rescaling the vectors $(u^\mu, a^\mu, e_\theta, e_\varphi)$. They are clearly orthogonal, let us show that they are Fermi-Walker transported (see equation (3.9)); notice that the condition of being FW-transported is 1-homogeneous, so proving it before or after normalization makes no difference. For the velocity $u^\mu \propto \hat{t}$ we have

$$u^\nu \nabla_\nu u^\mu = a^\mu = u_\rho (u^\mu a^\rho - u^\rho a^\mu) = -(u_\rho u^\rho) a^\mu. \quad (4.29)$$

For the acceleration $a^\mu \propto \hat{r}$ we need the following identity: $0 = d(u^\mu a_\mu) / d\tau = a^\mu a_\mu + u^\mu da_\mu / d\tau$. We multiply this by u^μ to get: $u^\mu (a^\rho a_\rho) = da^\mu / d\tau$.

Then, we can prove:

$$u^\nu \nabla_\nu a^\mu = a_\rho (u^\mu a^\rho) = a_\rho (u^\mu a^\rho - u^\rho a^\mu). \quad (4.30)$$

In the proof for the $\hat{\theta}$ and $\hat{\phi}$ vectors, the RHS vanishes immediately since the time-radial surface to which the velocity and acceleration belong is orthogonal to the sphere's surface; the LHS instead vanishes since it is a derivative with respect to proper time, therefore along the fluid's flow lines, which all lie in the time-radial surface.

Now, we need to show that the velocity and the acceleration actually have the form shown in (4.28): for the velocity, it is enough to impose the normalization $u^\mu u_\mu = -1$, and to consider an observer with velocity k^μ who is stationary with respect to the spherical coordinates: by normalization their 4-velocity will be $k^\mu = (1/\sqrt{g_{00}}, 0, 0, 0)$, and the local transformation between the frames will be a Lorentz transformation with factor γ defined by the fluid's velocity, therefore it must hold that $\gamma = -k^\mu u_\mu$.

Since $g_{00} = -y^2/\gamma^2$ we have:

$$\gamma = -k^\mu u^\nu g_{\mu\nu} = -u^0 \frac{g_{00}}{\sqrt{-g_{00}}} = u^0 \sqrt{-g_{00}} = u^0 \frac{y}{\gamma} \quad (4.31)$$

which gives us $u^0 = \gamma^2/y$, while for u^1 we must impose (already knowing that $u^2 = u^3 = 0$):

$$-1 = (u^0)^2 g_{00} + (u^1)^2 g_{11} \quad (4.32a)$$

$$= -\left(\frac{\gamma^2}{y}\right)^2 \left(\frac{y}{\gamma}\right)^2 + (u^1)^2 \frac{\gamma^2}{y^2} \quad (4.32b)$$

$$-1 + \gamma^2 = (u^1)^2 \frac{\gamma^2}{y^2} \quad (4.32c)$$

$$y^2 \left(-\frac{1}{\gamma^2} + 1\right) = (u^1)^2 \quad (4.32d)$$

$$y^2 v^2 = (u^1)^2. \quad (4.32e)$$

We now have a choice for the sign of the radial component of the velocity: since we are modelling accretion, we choose $u^1 < 0$ (with $v > 0$).

As for a^μ , we do not need to compute the covariant derivative since the two components of the normalized vector we want are determined by $u^\mu a_\mu = 0 = u^\mu \hat{r}^\nu g_{\mu\nu}$ and the normalization condition $\hat{r} \cdot \hat{r} = 1$. The first one translates to $\hat{r}^0 y^2 + \hat{r}^1 v \gamma^2 = 0$ and the second one to $(\hat{r}^0)^2 (-y^2/\gamma^2) + (\hat{r}^1)^2 (\gamma^2/y^2) = 1$, since we know the other two components of the acceleration are zero. Solving this system for the two unknown components yields precisely the desired expression.

The $\hat{\theta}$ and $\hat{\phi}$ vectors just need to be rescaled, and they will need to become $1/\sqrt{g_{22}}$ and $1/\sqrt{g_{33}}$ respectively. \square

4.3.2 The equations of motion

The first equation we consider is the conservation of mass: if ρ_0 is the rest mass density of the fluid, we must have $\nabla_\mu (\rho_0 u^\mu) = 0$. This, using the formula for covariant divergence (3.5), yields:

$$\frac{d}{dr} (\rho_0 y v r^2) = 0. \quad (4.33)$$

In the newtonian limit both γ and y approach 1; also, the infalling mass rate \dot{M} at a certain radius is $\rho_0(r) v(r) 4\pi r^2$. Then, by continuity to the newtonian limit, the quantity which is constant with respect to the radius must be $\dot{M}/(4\pi)$: therefore

$$\dot{M} = 4\pi \rho_0 y v r^2. \quad (4.34)$$

The second equation we consider is the Euler equation (4.24), which follows from the spatial projection of the conservation of the stress-energy tensor: because of spherical symmetry, the only nontrivial component of this is the radial one, so we need to calculate $a^1 = u^\mu \nabla_\mu u^1 = du^1/d\tau + \Gamma_{\mu\nu}^1 u^\mu u^\nu$. To do this we will need the radial Schwarzschild Christoffel coefficients:

$$\Gamma_{\mu\nu}^1 = \begin{bmatrix} \frac{M(-2M+r)}{r^3} & 0 & 0 & 0 \\ 0 & \frac{M}{r(2M-r)} & 0 & 0 \\ 0 & 0 & 2M-r & 0 \\ 0 & 0 & 0 & (2M-r)\sin^2(\theta) \end{bmatrix} \quad (4.35)$$

while the proper-time derivative is $d/d\tau = u^\mu \partial_\mu = yv\partial_1$. Plugging in the expression for the only relevant component of $h^{\mu\nu}$, $h^{11} = g^{11} + u^1 u^1 = (1+2\Phi)(1+v^2\gamma^2) = y^2$ we get, after a lengthy computation,

$$a^1 = y^2 \left(\gamma^2 v \frac{dv}{dr} + \frac{M}{(1+2\Phi)r^2} \right). \quad (4.36)$$

Substituting this into the (radial component of the) Euler equation (4.24) we get

$$(p+\rho)y^2 \left(\gamma^2 v \frac{dv}{dr} + \frac{M}{(1+2\Phi)r^2} \right) = -h^{11}\partial_1 p = -y^2\partial_1 p \quad (4.37a)$$

$$\gamma^2 v \frac{dv}{dr} + \frac{M}{(1+2\Phi)r^2} + \frac{1}{p+\rho} \frac{dp}{dr} = 0. \quad (4.37b)$$

The third equation we consider is the projection of the conservation of the ideal fluid stress energy tensor onto the 4-velocity, $-u_\mu \nabla_\nu T^{\mu\nu} = 0$, which can be written as $d\rho/d\tau + (p+\rho)\theta = 0$; using the conservation of mass, it can be cast into $d\rho_0/d\tau + \rho_0\theta = 0$ or $\theta = -\rho_0^{-1} d\rho_0/d\tau$.

Therefore we get an equation for the variation of the total internal energy, which holds for ideal fluids at constant entropy:

$$\frac{d\rho}{d\tau} = \frac{p+\rho}{\rho_0} \frac{d\rho_0}{d\tau} \quad \text{or} \quad \left(\frac{\partial \rho}{\partial \rho_0} \right)_s = \frac{p+\rho}{\rho_0} \stackrel{\text{def}}{=} h \quad (4.38)$$

where h is the specific enthalpy.

4.3.3 The Bernoulli equation

From these we can show that

Claim 4.3. *The quantity $\gamma h \sqrt{1+2\Phi} = yh$, is a constant of motion.*

Proof. First of all, by direct computation it can be shown from the definition of y that

$$\gamma^2 v \frac{dv}{dr} + \frac{M}{(1+2\Phi)r^2} = \frac{d \log y}{dr}. \quad (4.39)$$

Then, following Gourgoulhon [Gou06, section 6.3] we find that $dp = \rho_0 dh$ in the isentropic case, therefore

$$\frac{1}{\rho+p} \frac{dp}{dr} = \frac{d \log h}{dr} \quad (4.40)$$

so we can substitute the results in (4.39) and (4.40) into (4.37b):

$$\frac{d \log h}{dr} + \frac{d \log y}{dr} = \frac{d \log(hy)}{dr} = 0. \quad (4.41)$$

□

In the nonrelativistic, weak-field limit this becomes the classical conservation of energy density: Bernoulli's theorem,

$$\gamma h \sqrt{1 + 2\Phi} \approx \frac{p}{\rho_0} + \frac{v^2}{2} - \frac{M}{r} + \epsilon = \text{const}. \quad (4.42)$$

4.3.4 Simplifying the equations of motion

We want to write the equations of motion with the formalism of logarithmic derivatives: we replace all the derivatives which were with respect to r , d/dr , with derivatives with respect to $\log r$, which properly speaking would be ill-defined but we understand to mean $d/d \log r \stackrel{\text{def}}{=} r d/dr$; a more formal approach to this definition would be to use an adimensional radial coordinate $r/(2M)$ as is done in [NTZ91], but for consistency with [Nob00] I will not use that notation.

We can recast the mass conservation equation (4.33) using logarithmic derivatives, since when a quantity has zero derivative its logarithm also does:

$$\frac{d \log \rho_0}{d \log r} + \frac{d \log yv}{d \log r} + 2 = 0. \quad (4.43)$$

With the same approach we can recast all the equations we found as the following system, in which we introduce the notation of primes denoting derivatives with respect to $\log r$:

$$\frac{y'}{y} + \frac{p'}{p + \rho} = 0 \quad \text{Euler equation} \quad (4.44a)$$

$$\rho' - h\rho'_0 = 0 \quad \text{energy equation} \quad (4.44b)$$

$$\frac{(yv)'}{yv} + \frac{\rho'_0}{\rho_0} + 2 = 0 \quad \text{mass conservation.} \quad (4.44c)$$

We can express the gradients of ρ and P in terms of ρ_0 and T as follows:

$$\frac{\rho'}{p + \rho} = A \frac{\rho'_0}{\rho_0} + B \frac{T'}{T} \quad (4.45a)$$

$$\frac{p'}{p + \rho} = a \frac{\rho'_0}{\rho_0} + b \frac{T'}{T} \quad (4.45b)$$

where the parameters A , B , a and b are defined by:

$$A = \frac{\rho_0}{p + \rho} \left(\frac{\partial \rho}{\partial \rho_0} \right)_T \quad B = \frac{T}{p + \rho} \left(\frac{\partial \rho}{\partial T} \right)_{\rho_0} \quad (4.46a)$$

$$a = \frac{\rho_0}{p + \rho} \left(\frac{\partial p}{\partial \rho_0} \right)_T \quad b = \frac{T}{p + \rho} \left(\frac{\partial p}{\partial T} \right)_{\rho_0}; \quad (4.46b)$$

the subscripts T and ρ_0 on the derivatives mean that the denoted quantity should be held constant when differentiating.

These are related by the reciprocity relation [Fla82, eq. B3]: $A + b = 1$.

When inserting these relations into equation (4.44b) we get:

$$0 = \left(A \frac{\rho'_0}{\rho_0} + B \frac{T'}{T} - \frac{\rho'_0}{\rho_0} \right) (p + \rho) \quad (4.47a)$$

$$= \frac{T'}{T} + \frac{A-1}{B} \frac{\rho'_0}{\rho_0} \quad (4.47b)$$

$$= \frac{T'}{T} - \frac{b}{B} \frac{\rho'_0}{\rho_0} \quad (4.47c)$$

$$= \frac{T'}{T} - (\Gamma - 1) \frac{\rho'_0}{\rho_0} \quad (4.47d)$$

where we define the *local adiabatic exponent* $\Gamma = 1 + b/B$.

When we insert the relations into equation (4.44a) we get:

$$0 = \frac{y'}{y} + a \frac{\rho'_0}{\rho_0} + b \frac{T'}{T} \quad (4.48a)$$

$$= \frac{y'}{y} + a \frac{\rho'_0}{\rho_0} + \frac{b^2}{B} \frac{\rho'_0}{\rho_0} \quad (4.48b)$$

$$= \frac{y'}{y} + v_s^2 \left(-2 - \frac{(yv)'}{yv} \right) \quad (4.48c)$$

$$= \left(\frac{(yv)'}{yv} - \frac{v'}{v} \right) + -v_s^2 \left(2 + \frac{(yv)'}{yv} \right) \quad (4.48d)$$

$$= (v^2 - v_s^2) \frac{(yv)'}{yv} - 2v_s^2 + \frac{M}{y^2 r} \quad (4.48e)$$

where we used: the fact that $v_s^2 = \left(\partial p / \partial \rho \right)_s = a + b^2/B = a + b(\Gamma - 1)$ [Fla82, eq. B12], the energy equation (4.47d), the conservation of mass equation (4.43), and the identity we now derive, starting from the expression for the logarithmic derivative of y (4.39):

$$\frac{y'}{y} = \gamma^2 v^2 \frac{v'}{v} + \frac{M \gamma^2}{y^2 r} \quad (4.49a)$$

$$= (\gamma^2 - 1) \frac{v'}{v} + \frac{M \gamma^2}{y^2 r} \quad (4.49b)$$

$$= \gamma^2 \left(\frac{v'}{v} + \frac{M}{y^2 r} \right) - \frac{v'}{v} \quad (4.49c)$$

$$(1 - v^2) \frac{(yv)'}{yv} = \frac{v'}{v} + \frac{M}{y^2 r} \quad (4.49d)$$

$$\frac{(yv)'}{yv} - \frac{v'}{v} = v^2 \frac{(yv)'}{yv} + \frac{M}{y^2 r} \quad (4.49e)$$

$$\frac{y'}{y} = v^2 \frac{(yv)'}{yv} + \frac{M}{y^2 r} \quad (4.49f)$$

The system which describes the motion is then given by equations (4.47d), (4.48e) and by (4.44c), which remains unchanged. This is a system of three first-order differential equations in the variables T , yv and ρ_0 (y and v can be recovered since we have an explicit definition in the form $y = y(v)$), which would ordinarily need three boundary conditions, but actually we only need two.

When $v = v_s$, the logarithmic derivative of yv term in (4.48e) vanishes: then, either $r = 2v_s y^2 / M$ or the logarithmic derivative diverges. Since the latter condition is unphysical, we must consider the former, which defines a radius r_s , and impose $v(r_s) = v_s$.

This constrains the acceptable solutions, and allows the solution to be fully determined by just imposing two conditions, such as $\rho_0(r \rightarrow \infty) = \rho_\infty$ and $T(r \rightarrow \infty) = T_\infty$.

5 Radiative effects in spherical accretion

5.1 Thorne's PSTF moment formalism

The PSTF moment formalism was developed by Thorne [Tho81] in order to treat radiation energy transfer to an arbitrarily high degree of accuracy: it is fully relativistic, and — in the presence of certain symmetries, such that it is possible to use its scalar-moments version, which will be developed in section 5.2.3 — it gives rise to an infinite number of ordinary linear first-order differential equations for the various scalar moments, which can be truncated at a certain order.

In the presence of those symmetries the scalar moments fully describe the radiation; truncating the sequence of differential equations at order $6 \div 8$ probably gives a reasonably high degree of accuracy in all cases [TN88, p. 1285].

5.1.1 Mathematical introduction

We start by introducing the mathematical operations which will need to be applied to the moment tensors.

Given any tensor $A^{\mu_1 \dots \mu_k} = A^{M_k}$ we can use the tensor $h^{\mu\nu}$ to project it into the space-like subspace defined by the velocity u^μ :

$$A^{M_k} \rightarrow \left(A^{M_k} \right)^P = \left(\prod_{i=1}^k h_{\nu_i}^{\mu_i} \right) A^{M_k}. \quad (5.1)$$

Then, we can take the symmetric part of any tensor as outlined in section 2:

$$A^{M_k} \rightarrow \left(A^{M_k} \right)^S = A^{(M_k)}. \quad (5.2)$$

We can select the trace-free part of a projected, symmetric tensor by

$$A^{\mu_1 \dots \mu_k} \rightarrow \left(A^{\mu_1 \dots \mu_k} \right)^{TF} = \sum_{i=0}^{\lfloor k/2 \rfloor} (-1)^i \frac{k!(2k-2i-1)!!}{(k-2i)!(2k-1)!!(2i)!!} h^{(\alpha_1 \alpha_2} \dots h^{\alpha_{2i-1} \alpha_{2i}} A^{\alpha_{2i+1} \dots \alpha_k) \beta_1 \dots \beta_i}_{\beta_1 \dots \beta_i}. \quad (5.3)$$

To see what this produces, let us consider its action on a rank-two projected tensor: it is just the subtraction of its trace,

$$A^{\mu\nu} \rightarrow A^{\mu\nu} - \frac{1}{3} h^{\mu\nu} A^\rho_\rho. \quad (5.4)$$

Now, let us consider all the unit vectors n^μ in the space normal to the velocity, which have $n_\mu u^\mu = 0$ and $n^\mu n_\mu = 1$. They span the sphere S^2 .

If we have a function $F: S^2 \rightarrow \mathbb{R}$, we can decompose it into harmonics as:

$$F(n) = \sum_{k=0}^{\infty} \mathcal{F}_{\alpha_1 \dots \alpha_k} \prod_{i=1}^k n^{\alpha_i} \quad (5.5)$$

where the PSTF moments $\mathcal{F}_{\alpha_1 \dots \alpha_k}$ can be computed as

$$\mathcal{F}_{\alpha_1 \dots \alpha_k} = \frac{(2k+1)!!}{4\pi k!} \left(\int F \prod_{i=1}^k n^{\alpha_i} d\Omega \right)^{TF}. \quad (5.6)$$

In particular, the function we will apply this to is the distribution of electromagnetic radiation around the black hole. So, we consider a photon, whose trajectory in spacetime is parameterized as $\gamma(\xi)$, with a choice of ξ such that the photon's momentum is $p = d/d\xi$.

Now, our observer has a timelike velocity u^μ . We can find a spacelike vector n^μ corresponding to the space-like part of the movement of the photon, or

$$p^\mu = (-u^\nu p_\nu)(u^\mu + n^\mu). \quad (5.7)$$

It must hold that $u^\mu u_\mu = -1$ while $n^\mu n_\mu = +1$ in order for p^μ to be null-like. Now, we define a parameter l which corresponds to the space distance the photon moved through in this frame (l is *not* covariant!)

$$l = \int (-u^\nu p_\nu) d\xi \quad (5.8)$$

now, d/dl is parallel to p but it has different length, in fact since $dl/d\xi = (-u^\nu p_\nu)$ it is $d/dl = (n^\mu + u^\mu)\partial_\mu$.

It holds ([Tho81, eq. 2.17], with the notation from (3.17)), that

$$\frac{d\nu}{dl} = (u^\mu + n^\mu)\nabla_\mu(-p^\nu u_\nu) = -\nu \left(n_\mu a^\mu + \frac{\theta}{3} + n_\mu n_\nu \sigma^{\mu\nu} \right). \quad (5.9)$$

We want to quantify the number density of photons in relation to their momentum. We assume the radiation is unpolarized, therefore for each unit h^3 cell in phase space there can be 2 photons: so we denote the distribution function of the photons as $2N(x^\mu, p^\mu)$.

It is known that the volume element $dV_p = d^3p/p^0$ is Lorentz invariant (see [MTW73, box 22.5]). We can write this using the photons' frequency $\nu = -p^\mu u_\mu/h$ as $dV_p = \nu d\Omega d\nu$.

Let us define the *specific radiative intensity* as

$$I_\nu = \frac{\delta E}{\delta A \delta t \delta \nu \delta \Omega} = \frac{h\nu \delta N}{\delta A \delta t \delta \nu \delta \Omega} \quad (5.10)$$

where δA denotes an infinitesimal area the photons are coming through, δt an infinitesimal time, $\delta \nu$ an infinitesimal photon frequency, $\delta \Omega$ an infinitesimal solid angle.

Then, the number density of photons in phase space is [MTW73, figure 22.2]

$$\frac{2N(x^\mu, p^\mu)}{h^3} = \frac{\delta N}{V_x V_p} = \frac{\delta N}{h^3 \nu^2 \delta A \delta t \delta \nu \delta \Omega} = \frac{1}{h^4 \nu^3} I_\nu \quad (5.11)$$

therefore $I_\nu = 2N\nu^3 h$.

Now, we want to describe the variation of the occupation number N with respect to the photons' trajectories' parameter l . We encapsulate all possible effects into a source term \mathfrak{S} :

$$\mathfrak{S} \stackrel{\text{def}}{=} \frac{d}{dl} 2N(x^\mu, p^\mu) = 2 \left(\frac{\partial N}{\partial x^\mu} \frac{dx^\mu}{dl} + \frac{\partial N}{\partial p^\mu} \frac{dp^\mu}{dl} \right) \quad (5.12)$$

since the occupation number can be thought of as just a function of the spatial components of the momentum.

Since $d/dl = (n^\mu + u^\mu)\partial_\mu$ and the covariant derivative of p^γ is zero (since the photon's trajectory is a geodesic), we can compute

$$\frac{dp^\gamma}{dl} = (n^\mu + u^\mu)\nabla_\mu p^\gamma - \Gamma_{\alpha\beta}^\gamma p^\alpha (u^\beta + n^\beta) = -\Gamma_{\alpha\beta}^\gamma p^\alpha (u^\beta + n^\beta). \quad (5.13)$$

5.1.2 Moments' definitions

In this subsection I will follow Thorne [Tho81] in his usage of units where $c = h = 1$.

We define the (unprojected) k -th moments of radiative transfer:

$$M_\nu^{A_k} \stackrel{\text{def}}{=} \int 2N \frac{\delta(\nu - (-p^\nu u_\nu))}{\nu^{k-2}} \prod_i^k p^{\alpha_i} dV_p \quad (5.14a)$$

$$= \int (2N\nu^3) \frac{1}{\nu} \delta(\nu + p^\nu u_\nu) \prod_i^k \left(\frac{p^{\alpha_i}}{\nu} \right) (\nu d\Omega d\nu) \quad (5.14b)$$

$$= \int I_\nu \prod_i^k (n^{\alpha_i} + u^{\alpha_i}) d\Omega . \quad (5.14c)$$

In general, we can compute the k -th moments of any function just as here we computed those of $2N = I_\nu/\nu^3$: if we apply this procedure to the the source term \mathfrak{S} we get the following moments:

$$S_\nu^{A_k} = \nu^3 \int \mathfrak{S} \prod_i^k (n^{\alpha_i} + u^{\alpha_i}) d\Omega . \quad (5.15)$$

5.1.3 Redshift-adapted version

Thorne [Tho81] also defines a redshift-adapted version of the moments' definition: if R is a universal redshift functions, such that $R(p^\nu u_\nu)$ is conserved along every photon geodesic $p^\mu \nabla_\mu p^\nu = 0$, that is, R allows us to calculate the redshift between any two points A, B which are connected by a geodesic as $\nu_A/\nu_B = R_B/R_A$.

Then, we define $M_f^{A_k} = M_\nu^{A_k}/R$.

5.1.4 Frequency-integrated version

We may not wish to consider the frequency dependence of the radiation, but instead to treat all radiative transfer "in bulk": to this end, we define the frequency-integrated moments:

$$M^{A_k} = \int M_\nu^{A_k} d\nu \quad (5.16)$$

and the same is applied to the source moments $S_\nu^{A_k} \rightarrow S^{A_k}$.

Since this includes the radiation intensity from all frequencies, we have direct interpretations for the first moments:

$$M = \int I_\nu d\Omega d\nu \quad \text{energy density of radiation} \quad (5.17a)$$

$$M^\alpha = \int I_\nu (n^\alpha + u^\alpha) d\Omega d\nu \quad (M^0, M^i) = (\text{energy density of radiation, energy flux}) \quad (5.17b)$$

$$M^{\alpha\beta} = \int I_\nu (n^\alpha + u^\alpha)(n^\beta + u^\beta) d\Omega d\nu \quad \text{stress-energy tensor of radiation.} \quad (5.17c)$$

5.1.5 The moment equations

These can be derived from the transport equation, see Thorne [Tho81, eq. 3.14]. I present them only in the grey (frequency-integrated) case:

$$\nabla_\beta M^{A_k\beta} - (k-1)M^{A_k\beta\gamma}(\nabla_\gamma u_\beta) = S^{A_k}. \quad (5.18)$$

The moments (the frequency-integrated M^{A_k} , but also the full moments $M_\nu^{A_k}$ and the redshift-adapted ones $M_f^{A_k}$) satisfy the following:

$$M^{A_k\beta}{}_\beta = 0 \quad (5.19a)$$

$$u_\beta M^{A_k\beta} = -M^{A_k} \quad (5.19b)$$

$$h_{\beta\gamma} M^{A_k\beta\gamma} = M^{A_k}. \quad (5.19c)$$

So, the k -th moment contains all the information about the l -th moments with $l \leq k$; also, to get lower-order moments we take partial traces onto space- and time-like subspaces: therefore the unique information to the k -th moment, which is not redundantly expressed in lower-order moments, is in its PSTF part:

$$\mathcal{M}^{A_k} = \left(M^{A_k} \right)^{PSTF}. \quad (5.20)$$

The same can be applied to $M_\nu^{A_k}$ and $M_f^{A_k}$, to the moment equations (5.18) and to the source moments $S^{A_k} \rightarrow \mathcal{S}^{A_k}$. Since we are taking the projection onto the space-like subspaces, we can simplify the expression of the PSTF moments: all the terms which contain at least a four-velocity vanish, therefore:

$$\mathcal{M}^{A_k} = \left(\int I \prod_i n^{\alpha_i} d\Omega \right)^{TF} \quad (5.21)$$

where $I = \int I_\nu d\nu$. The first PSTF moments also have physical interpretations:

$$\mathcal{M} = \int I d\Omega \quad \text{energy density of radiation} \quad (5.22a)$$

$$\mathcal{M}^\alpha = \int I n^\alpha d\Omega \quad \text{energy flux of radiation} \quad (5.22b)$$

$$\mathcal{M}^{\alpha\beta} = \int I n^\alpha n^\beta d\Omega \quad \text{shears in the stress-energy tensor of radiation.} \quad (5.22c)$$

We can write the stress-energy tensor $T^{\mu\nu} = M^{\mu\nu}$ with the PSTF moments (see [Tho81, eq. 4.9]):

$$T^{\mu\nu} = \mathcal{M} u^\mu u^\nu + 2\mathcal{M}^{(\mu} u^{\nu)} + \mathcal{M}^{\mu\nu} + \frac{1}{3}\mathcal{M} h^{\mu\nu} \quad (5.23)$$

and compare these to the expression of the components of the stress-energy tensor (4.7) to get the following identifications:

$$\mathcal{M} = w = \rho \quad (5.24a)$$

$$\mathcal{M}^\mu = w^\mu = -\kappa h^\mu_\sigma (\partial^\sigma T + T a^\sigma) \quad (5.24b)$$

$$\mathcal{M}^{\mu\nu} + \frac{1}{3}\mathcal{M} h^{\mu\nu} = (p - \xi\theta)h^{\mu\nu} - 2\eta\sigma^{\mu\nu} \quad (5.24c)$$

and since the photons' paths are geodesics in this case $\theta = 0$, for the components proportional to $h^{\mu\nu}$ of equation (5.24c) we just get $\rho = 1/3p$, which is what we expect for a photon gas. For the traceless part of the equation, we get $\mathcal{M}^{\mu\nu} = -2\eta\sigma^{\mu\nu}$.

5.1.6 The PSTF moment equations

We want to express the grey moment equations (5.18) in terms of the PSTF moments. This can be done as follows: an expression can be found for the full moments in terms of the PSTF moments in [Tho81, eq. 4.10c]:

$$M^{A_k} = \sum_{l=0}^k \sum_{j=0}^{\lfloor \frac{k-l}{2} \rfloor} \frac{1}{(2j)!!(k-l-2j)!} \frac{k!}{l!} \frac{(2l+1)!!}{(2l+1+2j)!!} \mathcal{M}^{(A_l)} \prod_{i=l+1}^{l+2j-1} h^{\alpha_i \alpha_{i+1}} \prod_{x=l+2j+1}^k u^{\alpha_x} \quad (5.25)$$

where all the indices of the \mathcal{M} , h and u are meant to be symmetrized.

We insert this into the moment equations and expand, making use of the decomposition of the covariant derivative of the 4-velocity (3.17).

Then, we should take the PSTF part of the equations. This yields a very complicated expression, so here I record only the implicit formula given in Thorne [Tho81, eq. 4.11c]:

$$\left(\nabla_\beta \mathcal{M}^{A_k \beta} + u^\beta \nabla_\beta \mathcal{M}^{A_k} + \frac{k}{2k+1} \nabla_{\alpha_k} \mathcal{M}^{A_{k-1}} - (k-1) \mathcal{M}^{A_k \beta \gamma} \sigma_{\beta \gamma} - (k-1) \mathcal{M}^{A_k \beta} a_\beta + \frac{4}{3} \mathcal{M}^{A_k} \theta + \right. \\ \left. + \frac{5k}{2k+3} \mathcal{M}^{A_{k-1} \beta} \sigma_\beta^{\alpha_k} - k \mathcal{M}^{A_{k-1} \beta} \omega_\beta^{\alpha_k} + \frac{k(k+3)}{2k+1} \mathcal{M}^{A_{k-1}} a^{\alpha_k} + \frac{(k-1)k(k+2)}{(2k-1)(2k+1)} \mathcal{M}^{A_{k-2}} \sigma^{\alpha_{k-1} \alpha_k} \right)^{PSTF} = \mathcal{S}^{A_k}. \quad (5.26)$$

5.1.7 How to recover the intensity

Once we solve the PSTF grey moment equations, can compute the intensity from the moments by comparing (5.6) and (5.21):

$$I = \sum_{k=0}^{\infty} \frac{(2k+1)!!}{4\pi k!} \mathcal{M}^{A_k} \prod_{i=1}^k n_{\alpha_i}. \quad (5.27)$$

5.2 Generalized Bondi accretion

5.2.1 Simplifications under assumptions of symmetry

Instead of treating the general case as it is done by Thorne [Tho81], we describe the specific choices made under the assumption of spherical symmetry, following Thorne, Flammang, and Żytkow [TFŻ81].

The fiducial frame defined in (4.28) can still be used here: we denote with a subscript “fid” the tensors expressed in that basis. We get the following expressions:

$$a^\mu = (0, dy/dr, 0, 0)_{\text{fid}} \quad (5.28a)$$

$$\theta = -\frac{1}{r^2} \frac{d}{dr} (r^2 v y) \quad (5.28b)$$

$$\sigma_{\mu\nu} = -\frac{d}{dr} \left(\frac{vy}{r} \right) \frac{2r}{3} \begin{bmatrix} 0 & & & \\ & 1 & & \\ & & -1/2 & \\ & & & -1/2 \end{bmatrix}_{\text{fid}} = \sigma \begin{bmatrix} 0 & & & \\ & 1 & & \\ & & -1/2 & \\ & & & -1/2 \end{bmatrix}_{\text{fid}} \quad (5.28c)$$

$$\Gamma_{\theta r \theta} = \Gamma_{\varphi r \varphi} = \frac{y}{r}. \quad (5.28d)$$

We can see that the shear has been heavily simplified. This is a specific case of a general statement about the PSTF moments: in the spherically symmetric case, the k -th PSTF moment only has one independent component. This is because it satisfies the following identities:

$$\mathcal{M}^{A_k} = 0 \text{ if } A_k \text{ contains an odd number of } \theta\text{s or } \varphi\text{s} \quad (5.29a)$$

$$\mathcal{M}^{A_k \theta \theta} = \mathcal{M}^{A_k \varphi \varphi} = -\frac{1}{2} \mathcal{M}^{A_k r r}. \quad (5.29b)$$

Equation (5.29a) comes from the fact that an odd number of θ or φ indices corresponds to an odd number of unit vectors which are integrated on the sphere (see the definition (5.21)): therefore the integrand is odd.

Equation (5.29b) comes from two observations: first of all, the moments corresponding to indices θ and φ respectively must be equal because of spherical symmetry; secondly the moments must be traceless, therefore the sum of the $\theta\theta$, $\varphi\varphi$ and rr moments must be zero (for any pair of indices).

So, with these every k -th moment is fully determined by the component $\mathcal{M}^{r \dots r}$ (k rs), which we denote by w_k . This fact is analogous to the statement that the only spherically symmetrical one of the spherical harmonics Y_{lm} is Y_{l0} , therefore as in that case we have only one independent component for every l .

5.2.2 Legendre polynomials complement

The l -th Legendre polynomial is:

$$P_l(x) = \frac{1}{2^l} \sum_{k=0}^{\lfloor l/2 \rfloor} \frac{(-1)^k (2l-2k)!}{k!(l-k)!(l-2k)!} x^{l-2k}. \quad (5.30)$$

We can see that the coefficient of x^l is $(2l)!/(2^l(l!)^2)$. We can rewrite this making use of the identities $(2n)! = (2n-1)!!(2n)!!$ and $(2n)!! = 2^n n!$, as:

$$\frac{(2l)!}{2^l(l!)^2} = \frac{1}{l!} \frac{(2l)!}{(2l)!!} = \frac{(2l-1)!!}{l!} = \frac{(2l+1)!!}{l!(2l+1)} \quad (5.31)$$

which is equation [Tho81, eq. 5.7d].

In Thorne [Tho81, eqs. 5.6] we find the statement that:

$$\int_{-1}^1 I(\mu) P_k(\mu) \left(\frac{(2k-1)!!}{l!} \right)^{-1} d\mu = \left(\int_{-1}^1 I(\mu) \prod_{i=1}^k n^r d\mu \right)^{TF} \quad (5.32)$$

where n^r denotes the radial component of a normal vector in spherical coordinates, P_k is the k -th Legendre polynomial and $\mu = \cos \theta$ where θ is the azimuthal coordinate of n . $I(\mu)$ is a generic function.

5.2.3 The scalar moments

It can be shown, using the identity (5.32) that the definition of w_k we gave is equivalent to

$$w_k = \int_{-1}^1 I(\cos \theta) P_k(\cos \theta) \left(\frac{(2k-1)!!}{l!} \right)^{-1} 2\pi d \cos \theta \quad (5.33)$$

where P_k is the k -th Legendre polynomial (5.30). Then the first moments are:

$$w_0 = \int I d\Omega \quad \text{radiation energy density} \quad (5.34a)$$

$$w_1 = \int I \cos \theta \, d\Omega \quad \text{radiation energy flux} \quad (5.34b)$$

$$w_2 = \int I \left(\cos^2 \theta - \frac{1}{3} \right) d\Omega \quad \text{radiation shear stress.} \quad (5.34c)$$

We can explicitly write the radiation stress-energy tensor in terms of the w_k using (5.23):

$$T_{\text{radiation}}^{\mu\nu} = \begin{bmatrix} w_0 & w_1 & 0 & 0 \\ w_1 & \frac{1}{3}w_0 + w_2 & 0 & 0 \\ 0 & 0 & \frac{1}{3}w_0 - \frac{1}{2}w_2 & 0 \\ 0 & 0 & 0 & \frac{1}{3}w_0 - \frac{1}{2}w_2 \end{bmatrix}_{\text{fid}}. \quad (5.35)$$

5.2.4 The source moments

We can get an explicit formula for the source moments $s_k = \mathcal{S}^{r\dots r} (k \text{ rs})$ with the same procedure which was used in section 5.2.3: we get

$$s_k = \int_{-1}^1 \frac{dI}{dl} (\cos \theta) P_k(\cos \theta) \left(\frac{(2k-1)!!}{l!} \right)^{-1} 2\pi \, d\cos \theta \quad (5.36)$$

where $dI/dl = \int \mathfrak{S} \nu^3 \, d\nu$ is the frequency-integrated source term in the transfer equation.

5.2.5 The simplified moment equations

It is possible to write equations (5.26) explicitly in terms of the w_k and of derivatives wrt the fiducial basis: one gets [Tho81, eq. 5.10c]

$$\begin{aligned} \frac{\partial w_{k+1}}{\partial \hat{r}} + [(2-k)a + (k+2)b]w_{k+1} + \frac{\partial w_k}{\partial \hat{t}} + \left[\frac{4}{3}\theta + \frac{5k(k+1)}{2(2k-1)(2k+3)}\sigma \right] w_k + \\ + \frac{k^2}{(2k-1)(2k+1)} \frac{\partial w_{k-1}}{\partial \hat{r}} + \frac{k^2[(k+3)a + (1-k)b]}{(2k-1)(2k+1)} w_{k-1} + \\ - \frac{3}{2}(k-1)\sigma w_{k+2} + \frac{3(k-1)^2 k^2 (k+2)}{2(2k-3)(2k-1)^2 (2k+1)} \sigma w_{k-2} = s_k \end{aligned} \quad (5.37)$$

where $a = dy/dr = \sqrt{a^\mu a_\mu}$ is the magnitude of the 4-acceleration, $b = y/r$ is the extrinsic curvature, θ is the expansion velocity, σ is the scalar shear — the largest eigenvalue of the shear matrix. Explicit expressions for these are found in (5.28).

Nobili, Turolla, and Zampieri [NTZ91] only used the first two of the moment equations, so here is how the expression is simplified for $k = 0, 1$: for $k = 0$ we get:

$$\frac{\partial w_1}{\partial \hat{r}} + 2(a+b)w_1 + \frac{\partial w_0}{\partial \hat{t}} + \frac{4}{3}\theta w_0 + \frac{3}{2}\sigma w_2 = s_0. \quad (5.38)$$

For $k = 1$ we get:

$$\frac{\partial w_2}{\partial \hat{r}} + (a+3b)w_2 + \frac{\partial w_1}{\partial \hat{t}} + \left[\frac{4}{3}\theta + \sigma \right] w_1 + \frac{1}{3} \frac{\partial w_0}{\partial \hat{r}} + \frac{4a}{3} w_0 = s_1. \quad (5.39)$$

These have to be simplified further to be used: specifically, they can be expressed with respect to r, v, y .

5.2.6 Simplifying the moment equations further

Because of the hypothesis of stationarity, we can express the derivatives in (5.37) as:

$$\frac{\partial}{\partial \hat{t}} = \frac{\gamma^2}{y} \frac{\partial}{\partial t} - yv \frac{\partial}{\partial r} = -yv \frac{\partial}{\partial r} \quad (5.40a)$$

$$\frac{\partial}{\partial \hat{r}} = -v \frac{\gamma^2}{y} \frac{\partial}{\partial t} + y \frac{\partial}{\partial r} = y \frac{\partial}{\partial r}. \quad (5.40b)$$

Now, we can make the scalar PSTF moment equations (5.37) fully explicit: denoting derivation with respect to r with a prime, we have

$$y \frac{dw_1}{dr} + 2 \left(\frac{dy}{dr} + \frac{y}{r} \right) w_1 - yv \frac{dw_0}{dr} - \frac{4}{3} \frac{w_0}{r^2} \frac{d}{dr} (r^2 vy) - w_2 r \frac{d}{dr} \left(\frac{vy}{r} \right) = s_0 \quad (5.41a)$$

$$y \frac{dw_2}{dr} + \left(\frac{dy}{dr} + \frac{3y}{r} \right) w_2 - yv \frac{dw_1}{dr} - \frac{4}{3r^2} \frac{d}{dr} (r^2 vy) w_1 - \frac{2r}{3} \frac{d}{dr} \left(\frac{vy}{r} \right) w_1 + \frac{y}{3} \frac{dw_0}{dr} + \frac{4}{3} \frac{dy}{dr} w_0 = s_1. \quad (5.41b)$$

We can simplify these by expanding the derivatives of products $d(vyr^2)/dr$ and $d(vy/r)/dr$:

$$y \frac{dw_1}{dr} + 2 \left(\frac{dy}{dr} + \frac{y}{r} \right) w_1 - yv \frac{dw_0}{dr} - \frac{4}{3} w_0 \left(\frac{d(vy)}{dr} + \frac{2vy}{r} \right) - w_2 \left(\frac{d(vy)}{dr} - \frac{vy}{r} \right) = s_0 \quad (5.42a)$$

$$y \frac{dw_2}{dr} + \left(\frac{dy}{dr} + \frac{3y}{r} \right) w_2 - yv \frac{dw_1}{dr} - 2w_1 \left(\frac{d(vy)}{dr} + \frac{vy}{r} \right) + \frac{y}{3} \frac{dw_0}{dr} + \frac{4}{3} \frac{dy}{dr} w_0 = s_1. \quad (5.42b)$$

Equations (5.42) are the ones which appear in Nobili, Turolla, and Zampieri [NTZ91, eq. 4] and which are reported in equation (5.43), with the notation of primes denoting differentiation with respect to $\log r$.¹

$$w'_1 - vw'_0 - vw_2 \left[\frac{(vy)'}{vy} - 1 \right] + 2w_1 \left(1 + \frac{y'}{y} \right) - \frac{4}{3} vw_0 \left[\frac{(vy)'}{vy} + 2 \right] = \frac{rs_0}{y} \quad (5.43a)$$

$$w'_2 - vw'_1 + \frac{1}{3} w'_0 + w_2 \left(3 + \frac{y'}{y} \right) - 2vw_1 \left[\frac{(vy)'}{vy} + 1 \right] + \frac{4}{3} \frac{y'}{y} w_0 = \frac{rs_1}{y}. \quad (5.43b)$$

5.2.7 Some properties of the accretion variables

From equation (4.34) we can find an expression [TFZ81, eq. 18a] for y which only depends on r and constants:

$$y = \sqrt{y^2(1 - v^2 + v^2)} = \sqrt{\left(\frac{y^2}{\gamma^2} \right) + y^2 v^2} = \sqrt{\left(1 - \frac{2M}{r} \right) + \left(\frac{\dot{M}}{4\pi r^2 \rho_0} \right)^2} \quad (5.44)$$

therefore by the continuity equation v can also be expressed in terms of r and constants:

$$v = \frac{\dot{M}}{4\pi r^2 \rho_0 y(r)}. \quad (5.45)$$

¹Do note that in the paper [NTZ91] the letter r is used to denote the adimensional radial coordinate $r/(2M)$.

5.2.8 The source term

The source term can be written [TFZ81, eq. 15] as

$$s_k = \frac{l!(2l+1)}{(2l+1)!!} \int_{-1}^1 \frac{dI}{dl} P_k(\mu) 2\pi d\mu. \quad (5.46)$$

The general relation for the change in intensity is

$$\frac{dI_\nu}{dl} = \rho_0(\varepsilon_\nu - \kappa_\nu I_\nu) \quad (5.47)$$

where ρ_0 is the rest mass density, while ε_ν and κ_ν are the specific coefficients of emission and absorption. If we integrate this relation over all frequencies and take its k -th moment, we get

$$s_k = \rho_0(\varepsilon_k - \kappa_k w_k) \quad (5.48)$$

where w_k are the PSTF scalar moments, ε_k is the k -th moment of the emissivity and κ_k is the k -th moment of the opacity of the gas.

Equation (5.48) can be taken to be a practical definition of ε_k and κ_k ; we do the integral in (5.46) and get constant terms and terms proportional to w_k , which we split into the two terms in the RHS of (5.48).

We will only consider the $k = 0$ and $k = 1$ moments. If the emission is isotropic, then the emissivity moment ε_1 is 0 since its definition contains an integral of the product of an even and odd function.

Because of this, we just call the one emissivity moment we need $\varepsilon = \varepsilon_0$.

The source moments given in [NTZ91, eq. 6] are:

$$s_0 = \rho_0 \left(\varepsilon - w_0 \left(\kappa_0 - \kappa_{\text{es}} \frac{4k_B}{m_e} (T - T_\gamma) \right) \right) \quad (5.49a)$$

$$s_1 = -\rho_0 w_1 \kappa_1 \quad (5.49b)$$

with

$$T_\gamma = \frac{1}{4k_B} \frac{\int_0^\infty h\nu w_0(r, \nu) d\nu}{\int_0^\infty w_0(r, \nu) d\nu}. \quad (5.50)$$

Do note that the determination of the radiation temperature T_γ with the definition given here is impossible if only the frequency-integrated transfer problem is solved: a reasonable approximation has to be made in order to compute it in this case.

Nobili, Turolla, and Zampieri [NTZ91, eq. 17], following the works of Park and Ostriker, propose the following differential equation for the determination of the logarithmic derivative of T_γ when the temperature profile is known:

$$\frac{T'_\gamma}{T_\gamma} = \frac{4k_B T \max(\tau, \tau^2)}{m_e} \frac{T - T_\gamma}{T}. \quad (5.51)$$

where τ is the adimensional optical depth, which will be defined in 5.2.13. This differential equation has to be solved simultaneously with the ones which will be found later.

Furthermore, we use the facts that $\varepsilon/\kappa_0 = aT^4$ if there is thermodynamic equilibrium and that we have the following expression for the emissivity ε in terms of the cooling function $\Lambda(T)$ (given in (5.58)):

$$\varepsilon = \frac{\rho_0 \Lambda(T)}{m_p^2} \quad (5.52)$$

to write the source term s_0 as

$$s_0 = \frac{\rho_0^2 \Lambda(T)}{m_p^2} \left(1 - \frac{w_0}{aT^4} \right) + \rho_0 \kappa_{\text{es}} w_0 \frac{4k_B}{m_e} (T - T_\gamma). \quad (5.53)$$

As for the s_1 term, we model κ_1 as

$$\kappa_1 = \kappa_{\text{es}} + \langle \kappa_{\text{ff}} \rangle = \kappa_{\text{es}} + 6.4 \times 10^{22} \text{ cm g}^{-2} \rho_0 T^{-7/2} \quad (5.54)$$

where the second term is the conventional approximation of the *Rosseland mean opacity* computed taking into account only free-free transitions: the definition of the RMO is a harmonic mean of the opacities at every frequency, weighted by the derivatives with respect to temperature of the Planck function¹ at specific frequencies [RL04, eq. 1.110].

$$\frac{1}{\langle \kappa_{\text{ff}} \rangle} = \frac{\int_0^\infty \frac{dB_\nu}{dT} \frac{1}{\kappa_\nu^{\text{ff}}} d\nu}{\int_0^\infty \frac{dB_\nu}{dT} d\nu} \quad (5.55)$$

The expression we get for s_1 is:

$$s_1 = -\rho_0 w_1 \left(\kappa_{\text{es}} + 6.4 \times 10^{22} \text{ cm g}^{-2} \rho_0 T^{-7/2} \right). \quad (5.56)$$

5.2.9 Cooling function

The cooling function $\Lambda(T)$ is defined by the following relation, which describes the variation in the energy density by radiative processes:

$$\frac{d\rho}{d\tau} = n_b^2 (\Gamma(T) - \Lambda(T)) \quad (5.57)$$

where ρ is the energy density (measured in erg cm^{-3}), n_b is the baryon density (measured in cm^{-3}), while Γ and Λ are the heating and cooling functions, both measured in $\text{erg cm}^3 \text{ s}^{-1}$, see [GH12, equation 1].

The cooling function of the infalling gas is plotted in figure 1 and given in equation (5.58):

$$\begin{aligned} \Lambda(T) = & \left(\left(1.42 \times 10^{-27} T^{1/2} \left(1 + 4.4 \times 10^{-10} T \right) + 6.0 \times 10^{-22} T^{-1/2} \right)^{-1} \right. \\ & \left. + 10^{25} \left(\frac{T}{1.5849 \times 10^4 \text{ K}} \right)^{-12} \right)^{-1} \text{ erg cm}^3 \text{ s}^{-1}. \end{aligned} \quad (5.58)$$

¹The Planck function [RL04, eq. 1.51], here given reintroducing c explicitly,

$$B_\nu = \frac{2h\nu^3 c^{-2}}{\exp(h\nu/k_B T) - 1}$$

quantifies the spectral radiance emitted by a blackbody.

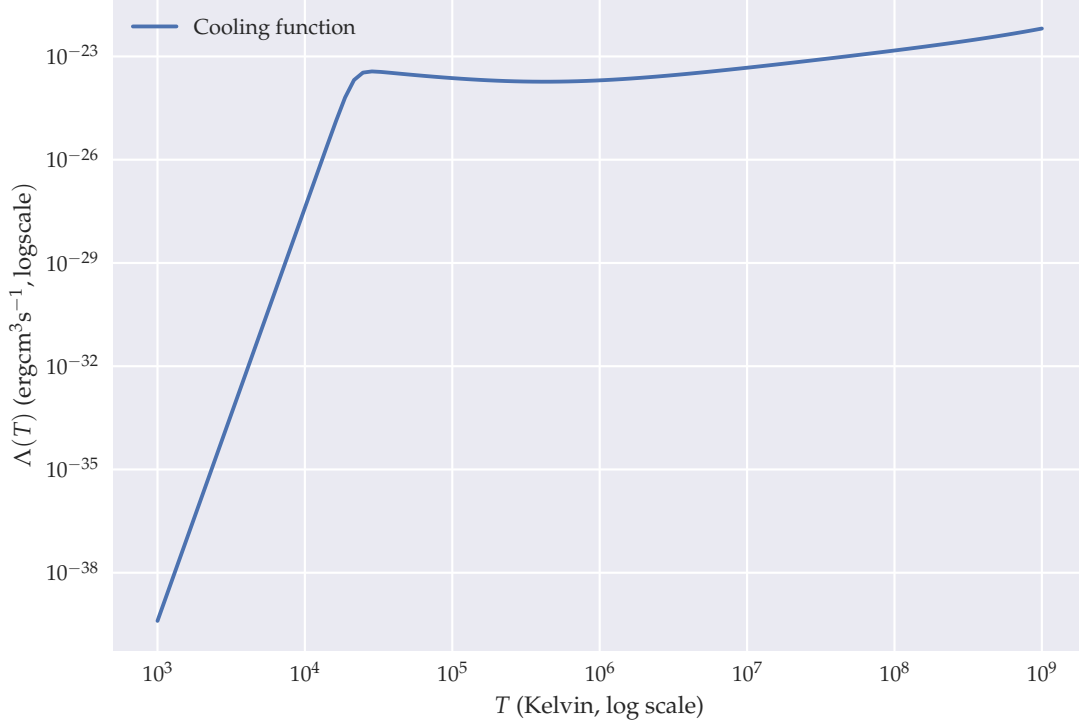


Figure 1: Cooling function graph.

5.2.10 How the conservation equations change using the moment equations

The way we use the grey moment equations (5.43) to study the accretion problem is by using them to simplify the conservation equations $\nabla_\mu T^{\mu\nu}$.

The full energy momentum tensor of the problem is given, in the fiducial reference frame, by combining an ideal-fluid stress-energy tensor (with pressure p and rest energy density ρ) with the one given in (5.35):

$$T^{\mu\nu} = T_{\text{radiation}}^{\mu\nu} + T_{\text{matter}}^{\mu\nu} = \begin{bmatrix} \rho + w_0 & w_1 & 0 & 0 \\ w_1 & p + \frac{w_0}{3} + w_2 & 0 & 0 \\ 0 & 0 & p + \frac{w_0}{3} - \frac{w_2}{2} & 0 \\ 0 & 0 & 0 & p + \frac{w_0}{3} - \frac{w_2}{2} \end{bmatrix}_{\text{fid}}. \quad (5.59)$$

The t, r by t, r components of the stress-energy tensor with contravariant indices in spherical coordinates are:

$$\begin{bmatrix} \frac{\gamma^4 \left(\rho - v w_1 + \frac{v(3p + w_0 + 3w_2) - 3w_1}{3} + w_0 \right)}{y^2} & \gamma^2 \left(-\frac{v(3p + w_0 + 3w_2)}{3} + v(-\rho + v w_1 - w_0) + w_1 \right) \\ \gamma^2 \left(-v(\rho + w_0) + \frac{v(-3p + 3v w_1 - w_0 - 3w_2)}{3} + w_1 \right) & y^2 \left(p - v w_1 + v(v(\rho + w_0) - w_1) + \frac{w_0}{3} + w_2 \right) \end{bmatrix}. \quad (5.60)$$

5.2.11 The total luminosity \dot{E}

We can project the conservation of the stress energy tensor along the unit vector in the temporal direction in the spherical reference frame, $(e_t)_v$: we get $(e_t)_v \nabla_\mu T^{\nu\mu} = \nabla_\mu T_t^\mu = 0$.

Then, applying (3.5) and our symmetry assumptions:

$$0 = \nabla_\mu T_t^\mu = \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial r} (r^2 \sin \theta T_t^r) = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 T_t^r) \implies r^2 T_t^r = \text{const} . \quad (5.61)$$

In [TFZ81, before eq. 18c] this appears with an additional immaterial factor of 4π .

The quantity which is conserved is $r^2 g_{tt} T^{tr}$, where T^{tr} is the $(0,1)$ matrix element which appears in (5.60). We can simplify it by expressing it in terms of the radiation luminosity L which is $L = 4\pi r^2 w_1$: we get

$$4\pi r^2 g_{tt} \left(\gamma^2 (1 + v^2) \frac{L}{4\pi r^2} - v \gamma^2 \left(p + \rho + w_2 + \frac{4}{3} w_0 \right) \right) = \text{const} . \quad (5.62)$$

We can also substitute in the expression for $v = \dot{M} / (4\pi r^2 \rho_0 y)$, and recognize the expression for the specific enthalpy h and for $y^2 = -g_{tt} \gamma^2$:

$$-y^2 (1 + v^2) L + y \dot{M} \left(h + \frac{4w_0/3 + w_2}{\rho_0} \right) \stackrel{\text{def}}{=} -\dot{E} = \text{const} . \quad (5.63)$$

This is the total luminosity of the accretion process (while L is only the *radiation* luminosity).

5.2.12 The full equations of motion

The conservation of the stress-energy tensor can be projected onto \hat{t} and \hat{r} and cast into [NTZ91, eq. A7]:

$$(p + \rho) \frac{dy}{dr} + y \frac{dp}{dr} + \frac{4}{3} w_0 \frac{dy}{dr} + \frac{1}{3} y \frac{dw_0}{dr} + \underbrace{\frac{1}{yvr^2} \frac{d}{dr} (y^2 v^2 r^2 w_1) + \frac{1}{r^3} \frac{d}{dr} (r^3 y w_2)}_{s_1} = 0 \quad (5.64a)$$

$$\frac{d\rho}{dr} - \frac{p + \rho}{\rho_0} \frac{d\rho_0}{dr} + \frac{dw_0}{dr} + \underbrace{\frac{4}{3} \frac{w_0}{yvr^2} \frac{d}{dr} (yvr^2) + \frac{1}{y^2 vr^2} \frac{d}{dr} (y^2 r^2 w_1) + w_2 \frac{r}{yv} \frac{d}{dr} \left(\frac{yv}{r} \right)}_{s_0/(yv)} = 0 \quad (5.64b)$$

where the identifications come from a reframing of the moment equations (5.43) (see [NTZ91, eq. A8]).

By adding the continuity equation (4.43) to the equations (5.64) — which are reworked slightly to get the expressions of logarithmic derivatives — we get the full system of the simplified conservation equations we will work with. Here, as in [NTZ91] and as in section 4.3.4, primes denote differentiation with respect to $\log r$.

$$(p + \rho) \frac{y'}{y} + p' + \frac{rs_1}{y} = 0 \quad (5.65a)$$

$$\rho' - (p + \rho) \frac{\rho'_0}{\rho_0} + \frac{rs_0}{vy} = 0 \quad (5.65b)$$

$$\frac{(vy)'}{vy} + \frac{\rho'_0}{\rho_0} + 2 = 0 \quad (5.65c)$$

We can express these in terms of the variables $(yv)(r)$, $\rho_0(r)$ and $T(r)$. To this end, we apply the same manipulations used in section 4.3.4 and thus get [NTZ91, eqs. 15]:

$$(v^2 - v_s^2) \frac{(yv)'}{yv} - 2v_s^2 + \frac{M}{y^2 r} + \frac{r}{yv(p + \rho)} ((\Gamma - 1)s_0 + vs_1) = 0 \quad (5.66a)$$

$$\frac{T'}{T} - (\Gamma - 1) \frac{\rho'_0}{\rho_0} - \frac{rs_0}{Bvy(p + \rho)} = 0 \quad (5.66b)$$

$$\frac{(yv)'}{yv} + \frac{\rho'_0}{\rho_0} + 2 = 0 \quad (5.66c)$$

where Γ , B , and v_s^2 are those defined in section 4.3.4.

Their expressions will in general be unknown: they are however defined in terms of derivatives of ρ and p , so if we can write an equation for those variables in terms of T and ρ_0 we can compute all the desired thermodynamic variables. The desired equations of state, which need to account both for slow-moving and fully relativistic regimes, are [NTZ91, eqs. 16]:

$$p = \left(1 + \frac{F}{1 + F}\right) \frac{\rho_0 k_B T}{m_p} \quad (5.67a)$$

$$\rho = \rho_0 + \left(\frac{3}{2} \frac{F}{(1 + F)} + \left(\frac{\eta - 1}{\theta} - 1\right)\right) \frac{\rho_0 k_B T}{m_p} + \left(1 - \frac{F}{1 + F}\right) \frac{\rho_0 E_H}{m_p} \quad (5.67b)$$

where $F = 2(T/1 \text{ K}) \exp(-1.58 \times 10^5 \text{ K}/T)$ and the quantity $F/(1 + F)$ is the approximate degree of collisional ionization, $\theta = k_B T/m_e$ while η is defined with the use of the modified Bessel functions of order n , K_n : $\eta = K_3(\theta^{-1})/K_2(\theta^{-1})$; m_p and m_e are the masses of the proton and of the electron, k_B is the Boltzmann gas constant, while E_H is the energy of first ionization of a hydrogen atom.

5.2.13 Closures and singularities

The full system of differential equations which has to be solved is composed of the two grey moment equations (5.43), the three equations of motion (5.66), plus the equation for the radiation temperature (5.51), to be solved in the six unknowns $w_0, w_1, \rho_0, yv, T, T_\gamma$.

The shear moment w_2 also appears in the grey moment equations (5.43), but it cannot be determined simultaneously. A *closure relation* is a reasonable approximation for the behaviour of w_2 : what is assumed is

$$w_2 = f(\tau) w_0 = \frac{2}{3} \frac{1}{1 + \tau^n} w_0 \quad (5.68)$$

where τ is the electron scattering optical depth, which is defined [RL04, eqs. 1.25, 1.26] as the function along photon paths such that the incoming intensity diminishes as $I = I_0 e^{-\tau}$; $f(\tau)$ is called the variable Eddington factor, while $n \in \mathbb{N}$ can be chosen to reproduce different behaviours. The error introduced by this approximation is typically of the order of 15% [TN88].

The flow is called optically thick when, along a typical photon path (which in our case will be radial) $\tau \gg 1$, and optically thin when $\tau \sim 0$. In these two cases $f(\tau)$ approaches 0 and $2/3$ respectively.

If we substitute the closure relation into the grey moment equations (5.43) and solve for w_l , where $l = 0, 1$, we get an equation of the form [NTZ91, eq. 18]:

$$\left(v^2 - vf(\tau) - \frac{1}{3}\right) w'_l = \text{a function of } r, w_0, w_1, v, v', l. \quad (5.69)$$

This adds a singularity to the system beyond the one at $v = v_s$ discussed in section 4.3.4. This singularity is located at the zeroes of the Legendre polynomial $P_2(v)$ (see (5.30), the order of the polynomial is $2 = 1 + l_{\max}$ where $l_{\max} = 1$ is the maximum order of moments considered) in the optically thick limit, and at $v \rightarrow 1$ in the optically thin limit.

5.2.14 Boundary conditions

To solve the differential equations boundary conditions must be provided, both at the horizon and at infinity. Here are the conditions used by Nobili, Turolla, and Zampieri [NTZ91].

At radial infinity we suppose there is radiative equilibrium ($s_0 = 0$) and the density gradient vanishes ($\rho'_0/\rho_0 = 0$), so by the energy equation:

$$\frac{T'}{T}(r \rightarrow \infty) = 0. \quad (5.70)$$

Also, we assume the energy density and energy flux decay as r^{-2} : $w_0, w_1 \propto r^{-2}$, or

$$\frac{w'_0}{w_0}(r \rightarrow \infty) = \frac{w'_1}{w_1}(r \rightarrow \infty) = -2. \quad (5.71)$$

At radial infinity the effects of Comptonization are negligible: this is expressed as

$$T(r \rightarrow \infty) = T_\gamma(r \rightarrow \infty). \quad (5.72)$$

All the previous conditions are fixed, and we have a residual degree of freedom: we can look at different accretion rates \dot{M} , which amounts to fixing the density ρ_0 at a certain radius,¹ we choose the horizon:

$$\rho_0(r = 2M) = \rho_{0,\text{hor}}. \quad (5.73)$$

Conditions must be assigned at the singularities of the Jacobian of the system: we shall not explore those here, but they can be found at the end of section 3 of [NTZ91].

Lastly, we must fix the constant mass of the black hole M : the results are generally not scale-independent, so this is actually an important choice. Nobili, Turolla, and Zampieri [NTZ91] chose a value of

$$M = 3M_\odot \quad (5.74)$$

where $M_\odot \approx 2 \times 10^{30}$ kg is the mass of the Sun.

5.2.15 Complement: Eddington luminosity

It is the characteristic luminosity at which the radiation pressure from the photons moving outward equals the gravitational specific force on the infalling matter.

The gravitational force, in the newtonian limit, is

$$F_{\text{grav}} = \frac{GMm}{r^2}. \quad (5.75)$$

The radiation pressure can be given in terms of the luminosity L (reinserting the units of c for this) as

$$P_{\text{rad}} = \frac{L}{c4\pi r^2}, \quad (5.76)$$

then, the radiative force on a test object of mass m is given by $F_{\text{rad}} = P_{\text{rad}}\kappa m$, where κ is the specific opacity: the per-unit-mass cross-section of the interaction. We usually assume $\kappa = \sigma_T/m_p$, that

¹This follows from the continuity equation (4.34): since the two variables are bound by an equation, fixing one also fixes the other.

is, that the interaction between radiation and matter is all due to Thompson scattering and the matter is only composed of hydrogen atoms.

Equating the forces, we get our result:

$$\frac{L_{\text{Edd}}}{M} = \frac{4\pi c G}{\kappa}. \quad (5.77)$$

In the $\kappa = \sigma_T/m_p \approx 0.04 \text{ m}^2/\text{kg}$ case, we get L_{Edd}/M to be around 6.32 W kg^{-1} (constants' values from [18]). If we express this in units of $L_\odot/M_\odot \approx 1.93 \times 10^{-4} \text{ W kg}^{-1}$ [Wil18] we get $L_{\text{Edd}}/M \approx 3.27 \times 10^4 L_\odot/M_\odot$: the amount of radiation emitted by the Sun is much less than the Eddington limit.

It is, of course, important to note that this is a limit found with many approximations: non-relativistic gravity, spherical symmetry, only Thompson scattering, only hydrogen.

5.2.16 Solutions

The solutions of the differential equation system, obtained numerically, include the profiles of all the variables at hand: a particularly interesting one is the variation of the luminosity $L = 4\pi r^2 w_1$ with respect to the accretion rate \dot{M} . To plot these, adimensional units are used: the luminosity is rescaled by the Eddington luminosity, defining $l = L/L_{\text{Edd}}$; the accretion rate can also be rescaled by the luminosity if we are working in natural units (otherwise we would need to use $\dot{M}_{\text{Edd}} c^2 = L_{\text{Edd}}$), defining $\dot{m} = \dot{M}/L_{\text{Edd}}$. The results are shown in figure 2.

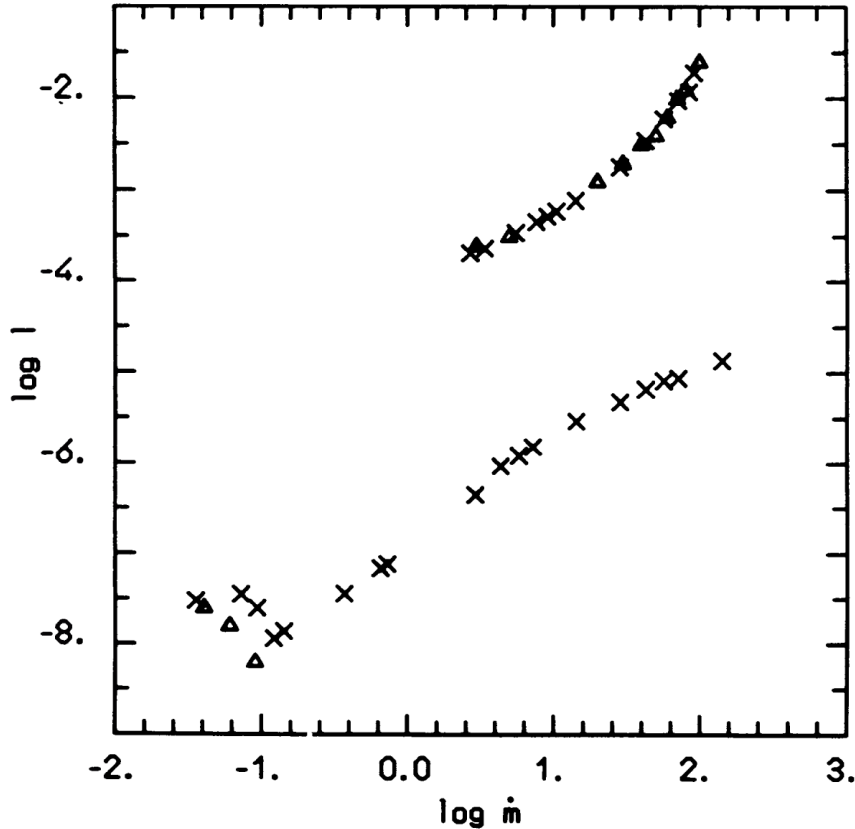


Figure 2: Log-log plot of the luminosity against the accretion rate. The crosses are the results of the simulations by Nobili, Turolla, and Zampieri [NTZ91], the triangles are the results of the simulations by Park (1990a). Image credit: [NTZ91, fig. 1].

The ratio between \dot{m} and \dot{E} is called the *efficiency* e , and it represents the fraction of the mass of the infalling gas which gets converted to energy in the accretion process.

The numerical solutions for spherical accretion show two branches: the high-luminosity one has $e \sim 5 \times 10^{-5} \div 9 \times 10^{-5}$, while the low-luminosity one has $e \sim 9 \times 10^{-8} \div 9 \times 10^{-7}$.

6 Conclusions

One important conclusion to draw from the models is that spherically symmetric accretion is generally a very *dim* process: in non-radial motion around a Schwarzschild black hole the efficiency can be as high as $e \sim 6 \times 10^{-2}$ [Nob00, eq. 2.8.5], which is almost three orders of magnitude more than $e \sim 9 \times 10^{-5}$, the maximum efficiency obtained in the models of spherical accretion considered here.

Further, the bimodal behaviour of the efficiency does not have an apparent theoretical justification.

The research explored in this thesis is pioneering in the numerical study of accretion using a fully relativistic formulation, but there are many aspects of this problem to be explored beyond what was treated here. The problem may be treated introducing viscosity (which is done in [TN89]), time dependence, frequency dependence, considering more of the moment equations, relaxing the assumption of spherical symmetry.

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