Relativistic Non-Ideal Flows

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The Schwarzschild metric

Flat metric:

$$\mathrm{d}s^2 = -\,\mathrm{d}t^2 + \mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\varphi\right).$$

Schwarzschild metric:

$$\mathrm{d}s^2 = -\left(1 - \frac{2M}{r}\right)\mathrm{d}t^2 + \frac{1}{1 - \frac{2M}{r}}\,\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\varphi\right),$$

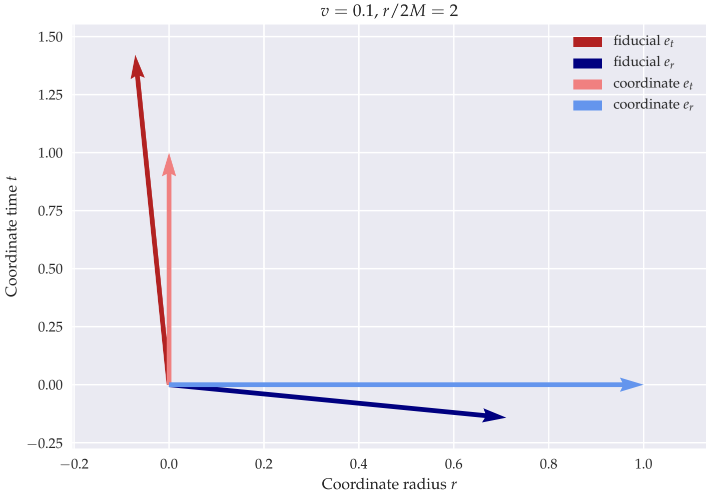
where $c = G = 1$.

Tetrads: the Local Rest Frame

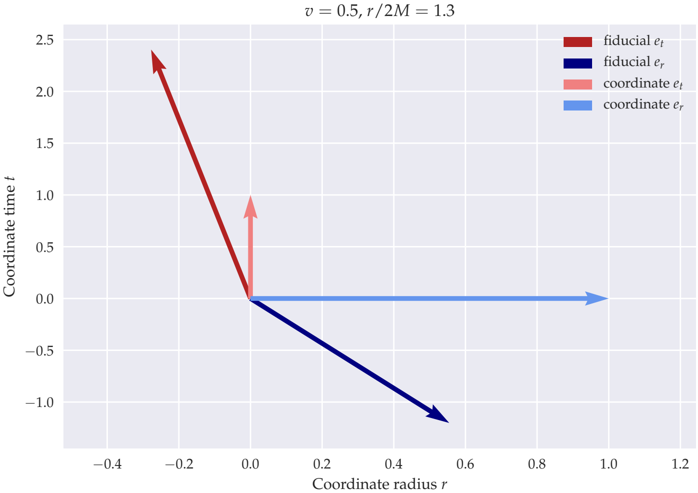
$$\hat{e}_t = u^\mu$$
$$\hat{e}_r = a^\mu / \sqrt{a^\nu a_\nu}$$
$$\hat{e}_\theta = \left(0, 0, 1/r, 0\right)$$
$$\hat{e}_t = \left(0, 0, 0, 1/\left(r \sin\theta\right)\right)$$

$$g_{\mu\nu} \hat{e}^\mu_{(\alpha)} \hat{e}^\nu_{(\beta)} = \eta_{(\alpha)(\beta)} .$$

The Local Rest Frame



The Local Rest Frame



The stress-energy tensor

The component $T^{\mu\nu}$ is the flux of μ-th component of the four-momentum p^{μ} through a surface of constant coordinate x^{ν}.
For an ideal fluid ($\eta = \xi = \kappa = 0$) in the Local Rest Frame:

$$T^{\mu\nu}_{\text{ideal fluid}} = \begin{bmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{bmatrix}_{\text{fid}} ,$$

where $\rho = \rho_0(1+\varepsilon)$.

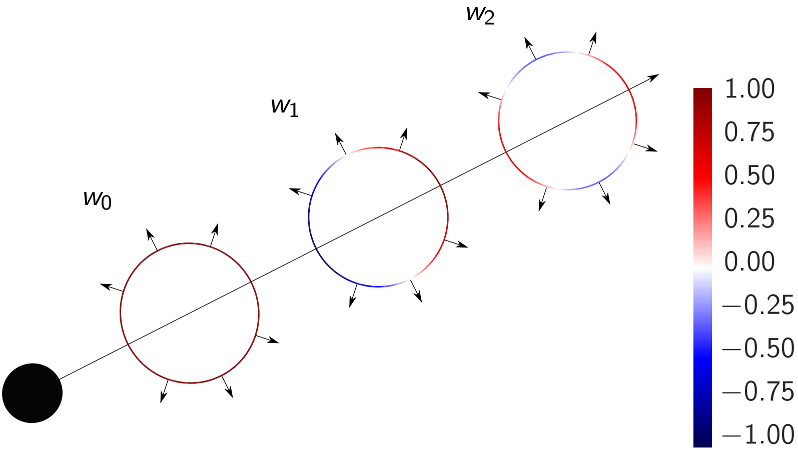
The radiation moments

$$w_0 = \int I \, \mathrm{d}\Omega \qquad \text{radiation energy density}$$

$$w_1 = \int I \cos\theta \, \mathrm{d}\Omega \qquad \text{radiation energy flux}$$

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

The radiation moments



The full stress-energy tensor

$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal fluid}} + \begin{bmatrix} w_0 & w_1 & 0 & 0 \\ w_1 & \frac{1}{3}w_0 + w_2 & 0 & 0 \\ 0 & 0 & \frac{1}{3}w_0 - \frac{1}{2}w_2 & 0 \\ 0 & 0 & 0 & \frac{1}{3}w_0 - \frac{1}{2}w_2 \end{bmatrix}_{\text{fid}}$$

The equations to solve are:

$$\begin{aligned} \nabla_\mu T^{\mu\nu} &= 0 && \text{2 equations} \\ \nabla_\mu(\rho_0 u^\mu) &= 0 && \text{1 equation} \\ \text{conservation of photon number} & && \text{2 equations.} \end{aligned}$$

Singularities

There is a singularity in the Euler equation at $v = v_s$:

$$(v^2 - v_s^2)\frac{(yv)'}{yv} - 2v_s^2 + \frac{M}{y^2 r} = -\frac{r}{yv(p+\rho)}\left((\Gamma - 1)s_0 + vs_1\right).$$

Also, since we assume $w_2 = f(\tau)w_1$, there is another singularity at the zeros of:

$$v^2 - vf(\tau) - \frac{1}{3}$$

Accretion efficiency

The Eddington luminosity is attained when the radiation pressure on a test electron-proton pair equals the gravitational pull on it.
We have approximately:

$$\frac{L_{\mathrm{Edd}}}{M} = \frac{4\pi c G m_p}{\sigma_T} \approx 3.27 \times 10^4 \frac{L_\odot}{M_\odot}\,.$$

From the numerical simulation, fixing the accretion rate $\dot{M}$, we get $L = 4\pi r^2 w_1$.
We can adimensionalize these with the Eddington luminosity and the Eddington accretion rate $\dot{M}_{\mathrm{Edd}} = L_{\mathrm{Edd}}/c^2$: we define $l = L/L_{\mathrm{Edd}}$ and $\dot{m} = \dot{M}/\dot{M}_{\mathrm{Edd}}$.

Accretion efficiency

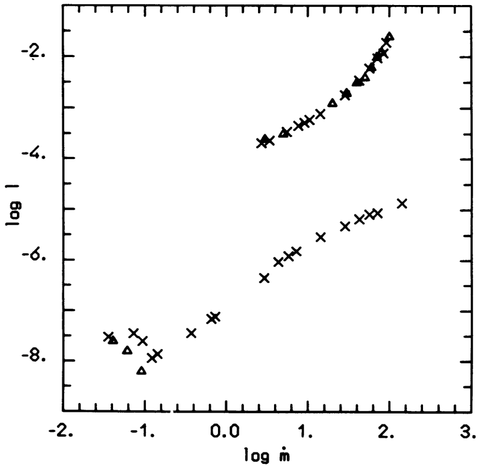


Image credit: L. Nobili, R. Turolla, L. Zampieri. In: *ApJ* 383 (Dec. 1991).