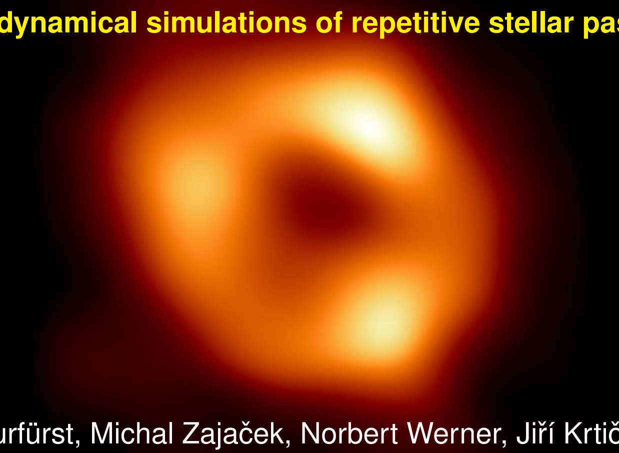

Modified red giants as smoking guns of relativistic nuclear jets

Hydrodynamical simulations of repetitive stellar passages

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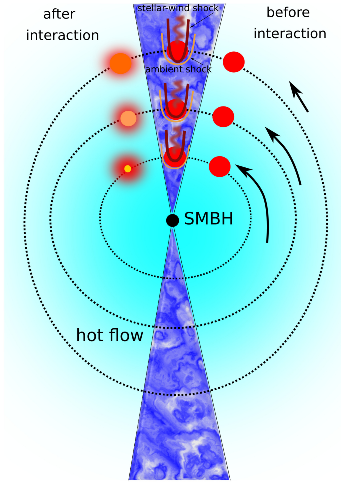
Galactic center - the inner ∼1 pc is a region of mutual interactions of stars, gas and dust within the gravitational potential of the SMBH

(see the analytical study in Zajaček+ 2020)



- illustration of the jet - red giant interaction
- at lower z this is expected to be stronger

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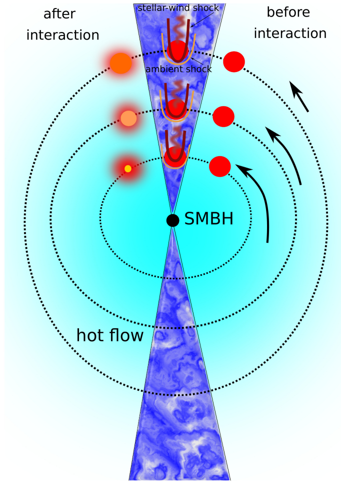

- illustration of the jet - red giant interaction
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Ambient medium:

The ρ and T profiles of the ambient plasma - power-law functions

$$n_{\mathrm{a}} \approx n_{\mathrm{B}} \left(\frac{r}{r_{\mathrm{B}}}\right)^{-1}, \qquad (1)$$

$$T_{\mathrm{a}} \approx T_{\mathrm{B}} \left(\frac{r}{r_{\mathrm{B}}}\right)^{-1}, \qquad (2)$$

where $n_{\mathrm{B}} = 26\,\mathrm{cm}^{-3}$, and $T_{\mathrm{B}} = 1.5 \times 10^7\,\mathrm{K}$ are the number density and the temperature at the Bondi radius

$$r_{\mathrm{B}} = \frac{2GM_{\bullet}}{c_{\mathrm{s}}^2} \sim 0.21 \left(\frac{T_{\mathrm{B}}}{10^7\,\mathrm{K}}\right)^{-1}\,\mathrm{pc}, \qquad (3)$$

where $M_{\bullet} = 4 \times 10^6\,M_{\odot}$

Galactic center - the inner ∼1 pc is a region of mutual interactions of stars, gas and dust within the gravitational potential of the SMBH

Jet structure:

We assume that the jet plasma is matter-dominated, consisting of electrons and protons. The jet exerts the pressure on the passing star mainly in the form of the bulk motion of the jet plasma at the velocity of $v_{\rm j}$, which results in the ram pressure of $P_{\rm j} = \Gamma \rho_{\rm j} v_{\rm j}^2$, where Γ is the Lorentz factor and $\rho_{\rm j}$ is the mass density inside the jet. The number density inside the hadronic jet can then be estimated as (Zajaček et al., 2020),

$$\begin{aligned} n_{\rm j} &= \frac{L_{\rm j}}{\mu m_{\rm H} (\Gamma - 1) c^2 v_{\rm j} \pi z^2 \tan^2 \theta} \\ &\simeq 53 \left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right) \left(\frac{z}{0.01\,{\rm pc}}\right)^{-2} {\rm cm^{-3}}\,, \end{aligned} \tag{4}$$

which gives the mass density $\approx 10^{-18}\,{\rm g\,cm^{-3}}$ at 10^{-3} pc.

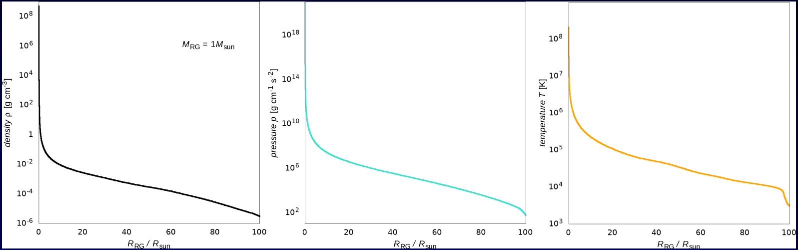
The jet temperature is assumed to be $T_{\rm j} = 10^{10}\,{\rm K}$ (Bosch-Ramon et al., 2012)

We assume the jet luminosity $L_{\rm j} = 10^{42}\,{\rm erg\,s^{-1}}$, the jet velocity $v_{\rm j} = 0.3\,c$, and the jet opening half-angle 10°

Galactic center - the inner 1 pc is a region of mutual interactions of stars, gas and dust within the gravitational potential of the SMBH (Kurfürst, Zajaček, et al. - in prep.)

Red giant model:

We model the red-giant as a star with mass $M_{\rm RG} = 1\,M_{\odot}$, and the radius $R_{\rm RG} = 100\,R_{\odot}$. The initial profiles of density, pressure, and temperature are calculated using the stellar evolution code MESA (e.g., Paxton et al., 2010).



We select sufficiently higher initial mass of the star to obtain 1 $M_{\odot}$ and 100 $R_{\odot}$ RGB star before the He-flash

We remap the MESA density, pressure, and temperature profiles to our computational grid, using its refined structure towards the stellar center

Global structure of the own hydrodynamic (MHD) code

(cf. Kurfürst & Krtička 2014, 2018; Kurfürst et al., 2017, 2019, 2020)

Conservative equations of ideal MHD:

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{v}) = 0, \tag{5}$$

$$\partial_t (\rho \vec{v}) + \vec{\nabla} \cdot (\rho \vec{v} \vec{v} + \mathcal{P}) = (8\pi)^{-1} \left[2(\vec{B} \cdot \vec{\nabla}) \vec{B} - \vec{\nabla} B^2 \right] + \rho \vec{g}, \tag{6}$$

$$\partial_t E + \vec{\nabla} \cdot [(E + \mathcal{P}) \cdot \vec{v}] = (8\pi)^{-1} \left\{ \vec{\nabla} \cdot \left[2 \left(\vec{B} \cdot \vec{v} \right) \vec{B} - B^2 \vec{v} \right] \right\} + \rho \vec{g} \cdot \vec{v}, \tag{7}$$

$$\partial_t \vec{B} + \vec{B} \vec{\nabla} \cdot \vec{v} + (\vec{v} \cdot \vec{\nabla}) \vec{B} - (\vec{B} \cdot \vec{\nabla}) \vec{v} = \vec{0}, \tag{8}$$

- where $\mathcal{P}$ is the pressure tensor (including shear terms), $\vec{g} = \vec{g}_{\rm grav} + \vec{g}_{\rm rot} + \vec{g}_{\rm rad}$, and $E = E_{\rm int} + E_{\rm kin} + E_{\rm mag}$
- The scalar thermal pressure p follows the ideal MHD EOS:

$$p = (\gamma - 1) \left[E - \rho v^2/2 - B^2/(8\pi) \right] \tag{9}$$

- All the equations are complemented with the divergence-free constraint:

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{10}$$

(We currently involve only the hydrodynamic part for the simulations!)

Global structure of the own hydrodynamic (MHD) code

(cf. Kurfürst & Krtička 2014, 2018; Kurfürst et al., 2017, 2019, 2020)

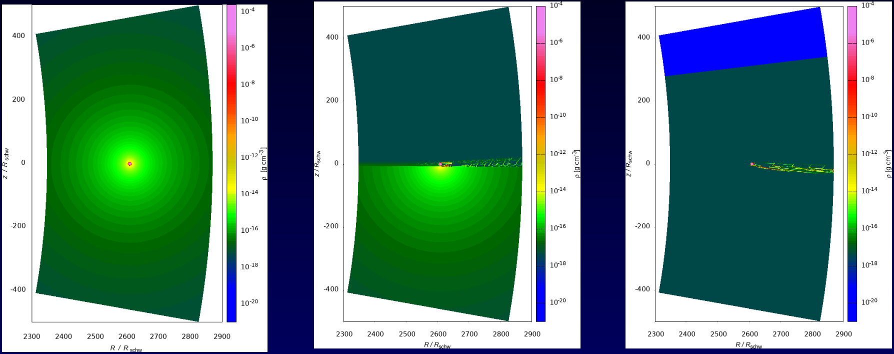
Two types of hydro-solvers:

- operator-split (**HLLE**) finite volume Eulerian algorithm on staggered mesh (Stone & Norman 1992)
- unsplit Eulerian **Roe solver** (Roe 1981; Toro 1999) for strong shocks
- **MHD solver** for both types; for the Roe solver only in Cartesian form
- **all basic geometries** (Cartesian, cylindrical, spherical 3D) plus one non-orthogonal for “flaring” disks (Kurfürst & Krtička 2018)
- **Navier-Stokes viscosity** solver in all the geometries
- **static mesh refinement** (in this simulation 2700 / 3600 grid cells)
- full implementation of **MPI** for parallelization

Currently is being upgraded (among other purposes) for the 2D analogy of the SN explosion code SNEC

Snapshots of the density

- orbital radius is 0.001 pc
- initial ambient stellar wind corresponds to $\dot{M}_{\rm RG} \approx 10^{-9}\, M_{\odot}\, \rm yr^{-1}$
- wind expansion velocity is $15\,\rm km\,s^{-1}$
- BCs are inflow at left and top, outflow at right at bottom



- **Left pane:** start of the simulation at $t = 0$
- **Central panel:** first entry to the jet at $t \approx 15\,\rm d$
- **Right panel:** evolution within the jet at $t \approx 35\,\rm d$

Snapshots of the density

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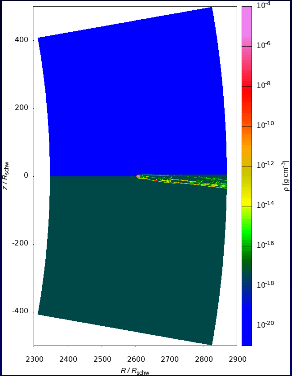
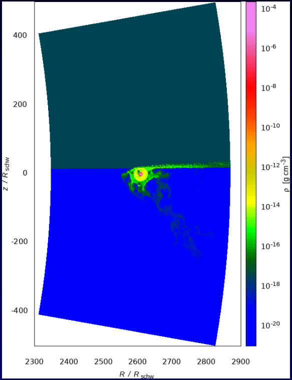
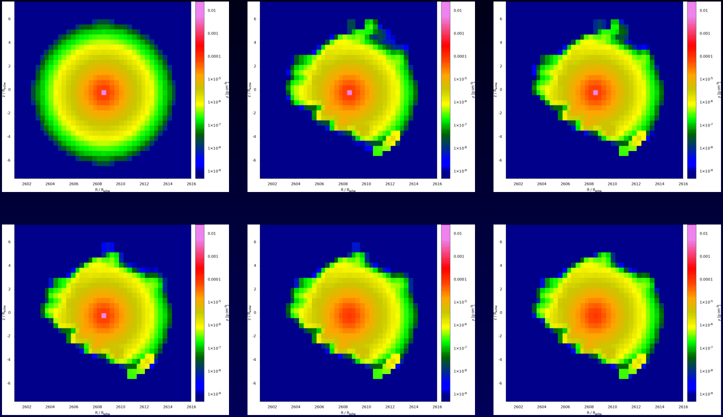


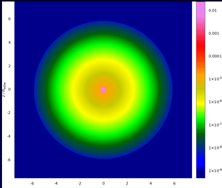


- **Left panel:** first exit of the jet at $t \approx 45\,\mathrm{d}$
- **Right panel:** second entry to the jet at $t \approx 285\,\mathrm{d}$

Snapshot of the density

- orbital radius is 0.001 pc

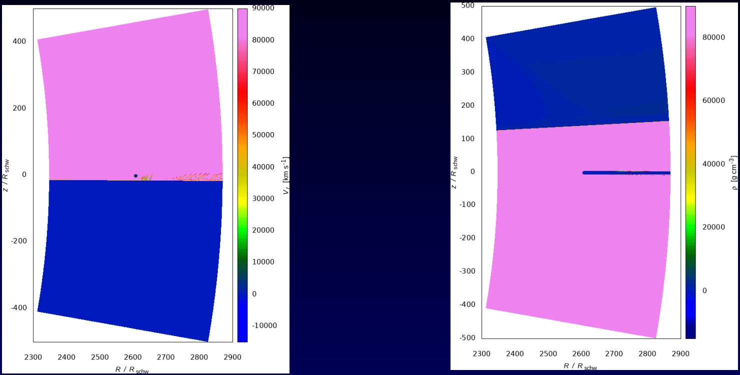




- **Top left to bottom right panels:** snapshot of the stellar region density after first five jet entries - 0 d, 15 d, 285 d, 555 d, 825 d, and 1095 d

Snapshot of the radial velocity

- orbital radius is 0.001 pc



- **Left panel:** snapshot of the velocity at first jet entry (a bit boring)
- **Right panel:** snapshot of the velocity before the first jet exit

Conclusions

- We develop the idea of ablation or “shaving off” of red giants’ envelopes in the jet-star interactions near Galactic center, following the analytical study of Zajaček+ 2020
- We simulate numerically the crosses of red giant stars through the typical jet of Galactic SMBH, using our own HD Eulerian code
- We calculate the realistic initial internal density, pressure, and temperature structure of RGB using the MESA code, the parameters of SMBH jet are set as analytical functions ($\rho_{\rm jet} \sim z^{-2}$, $v_{\rm jet} = 0.3c$)
- For $r_{\rm orb} = 10^{-3}\,$pc, density integrations after first 10 jet crosses reveal the stellar mass ablation $\sim 0.0465\,M_\star$; this will be further verified by long-term simulation including several hundreds or thousands passages
- The similar applies also for $r_{\rm orb} = 10^{-2}\,$pc and $10^{-1}\,$pc, where the calculations indicate the ablation $\sim 0.0207\,M_\star$ and $\sim 0.0083\,M_\star$ per first 10 jet crosses, respectively

Thank you!