RG stars’ deficiency near the Galactic center as a consequence of the enhanced galactic jet activity in the past

Petr Kurfürst, Michal Zajaček, Norbert Werner, Jiří Krtička

Dpt of Theoretical Physics and Astrophysics (ÚTFA), Masaryk University (MU)

Galactic Nuclei in the Cosmological Context,

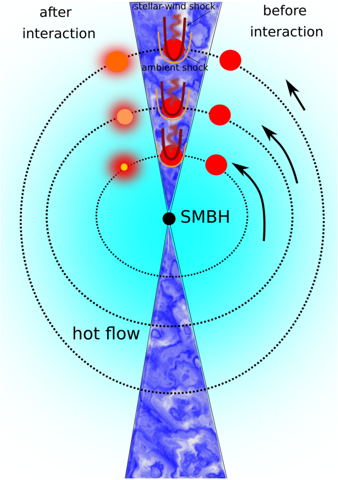
2024 June 3-6 * Szczecin, Poland

Motivation:

- The scientific community has studied the phenomenon of RGs **lacking near the center of Galaxy** for more than 30 years
- **Several explanations** have been proposed and published, such as the deformation or destruction of the outer layers of red giant stars due to tidal interaction with the central black hole, their abrasion when passing through the accretion disk, and others
- **New analytical theory** was (relatively) recently presented - based on a **long-term ablation** of the upper layers of these stars due to multiple passes **by a high-energy Galactic jet**
- We follow up on this work with detailed numerical modeling of this phenomenon, we model the rate of ablation of the surface layers of red giants

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

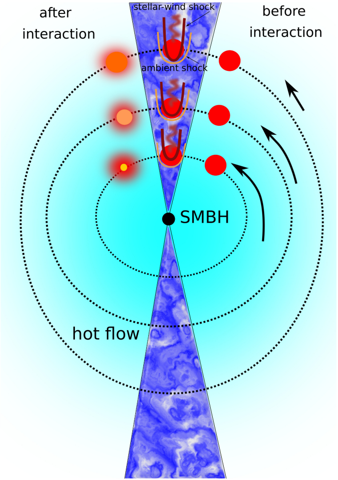
(see the analytical study Zajaček+ 2020)



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

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 Zajaček+ 2020)



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

Ambient medium:

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

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

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

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

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

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

Galactic center - the inner $\sim$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 e^- and p^+. 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 $v_j \rightarrow$ the ram pressure of $P_j = \Gamma \rho_j v_j^2$, where Γ is the Lorentz factor and ρ_j is the mass density inside the jet. The **number density** inside the hadronic jet can then be estimated as (Zajaček et al., 2020),

$$n_j = \frac{L_j}{\mu m_H (\Gamma - 1) c^2 v_j \pi x^2 \tan^2 \theta} \simeq 53 \left(\frac{L_j}{10^{42}\,\mathrm{erg\,s^{-1}}} \right) \left(\frac{x}{0.01\,\mathrm{pc}} \right)^{-2} \mathrm{cm}^{-3}, \quad (1)$$

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

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

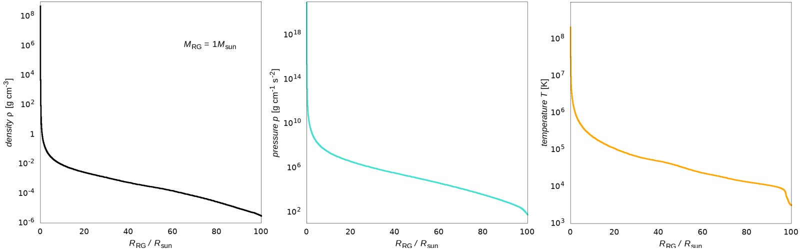
We assume the **jet luminosities** $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, $10^{44}\,\mathrm{erg\,s^{-1}}$ ($10^{48}\,\mathrm{erg\,s^{-1}}$), the jet velocity $v_j = 0.33\,c$, $0.66\,c$, and the jet opening half-angle 10°

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 $R_{\rm RG} = 100\,R_{\odot}$. We calculated originaly the initial profiles of density, pressure, and temperature using the **code MESA** (e.g., Paxton et al., 2010).



We later adopted the (most similar) **polytropic models** with $n = 2.7$ which correspond to the adiabatic equation of state incorporated in hydro-codes

We remap the stellar internal **density, pressure, and temperature** profiles to the hydro-code grid, with extra dense but small stellar center (cf. later)

Numerical setup (Much more difficult than it seemed at the beginning!)

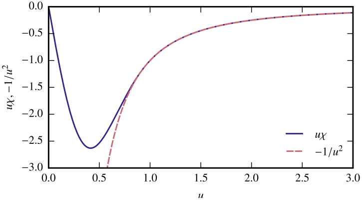
- **We successively used two hydrodynamic codes**
- **1. Our own hydro code:** (cf. Kurfürst et al. 2014, 2017, 2018, 2019, 2020)
  - operator-split (**HLLE**) finite volume Eulerian algorithm on staggered mesh (Stone & Norman 1992) + unsplit Eulerian **Roe solver** (Roe 1981; Toro 1999) for strong shocks
  - **all basic geometries** (Cartesian, cylindrical, spherical 3D) plus one non-orthogonal for disks (Kurfürst & Krtička 2018)
  - **Navier-Stokes viscosity** solver in all the geometries
- **2. We finally used the hydro code CASTRO** (Almgren, Zingale et al., 2010)
  - Solves the multi-component compressible hydrodynamic equations for astrophysical flows. Additional physics includes MHD, self-gravity, nuclear reactions, and radiation.
  - **Advantages:** CASTRO includes AMR that provides simultaneous refinement of the grids in both space and time. Castro employs the CT-Strang solver - extremely accurate for stong discontinuities and high Mach numbers. Many interpolation algorithms for implementing numerical 1D inputs.

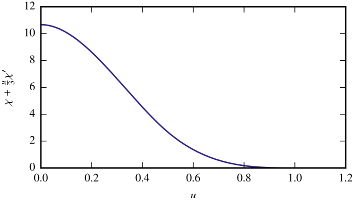
Numerical setup: **Absolutely essential difficulty - to keep the stellar hydrostatic balance but without artificial stabilization which would alter the physics of the outer stellar layers**

- We used the approach outlined in Ohlmann, Springel et al. 2017:

$$g_c(r) = -Gm_c \frac{h}{r^3} \begin{cases} -\frac{32}{3} + u^2\left(\frac{192}{5} - 32u\right) & \text{for } 0 \le u < 1/2 \\ \frac{1}{15u^3} - \frac{64}{3} + 48u - \frac{192}{5}u^2 + \frac{32}{3}u^3 & \text{for } 1/2 \le u < 1 \\ -\frac{1}{u^3} & \text{for } u \ge 1, \end{cases}$$

where $u = r/h$, h is the softening length of the interaction, and m_c is the mass of the "particle" representing the core. The **spurious velocity fluctuations** are damped by $\dot{v} = -v/\tau$.

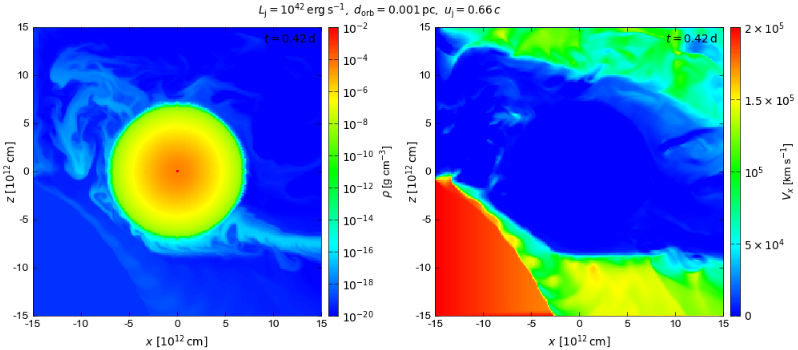




- Additionally - the very inner part of the star below $0.05R_\star$ is stabilized by the "sponge term" $v \to v \times 0.5(1 - \cos(\pi(r - 0.01R_\star)/0.04R_\star))(1 - e^{3r/R_\star})^2$.

Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{42}$ erg s^{-1}

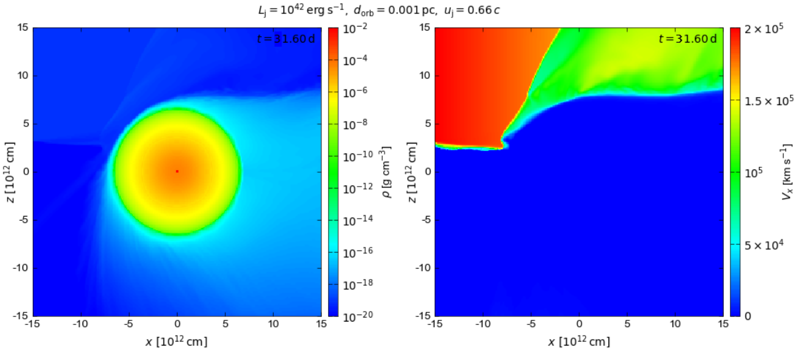
- Jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_j = 0.66\,c$
- 3D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Star enters the jet** at $t \approx 0.4$ d (simulation time)



- *Left panel:* density snapshot, *right panel:* x-velocity snapshot

Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{42}$ erg s^{-1}

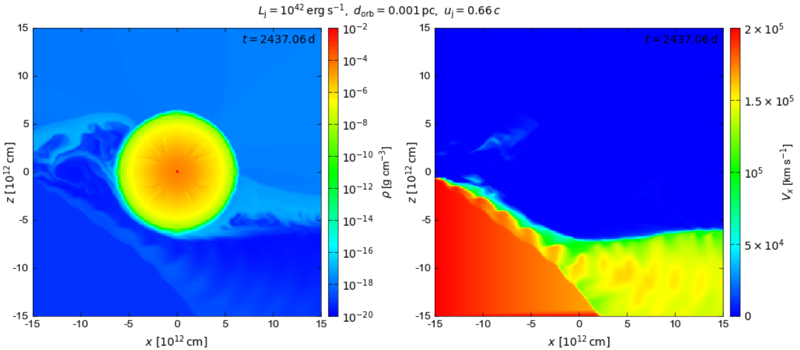
- Jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_j = 0.66\,c$
- 3D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Star exits the jet** for the first time at $t \approx 31.5$ d (simulation time)



- *Left panel:* density snapshot, *right panel:* x-velocity snapshot

Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$

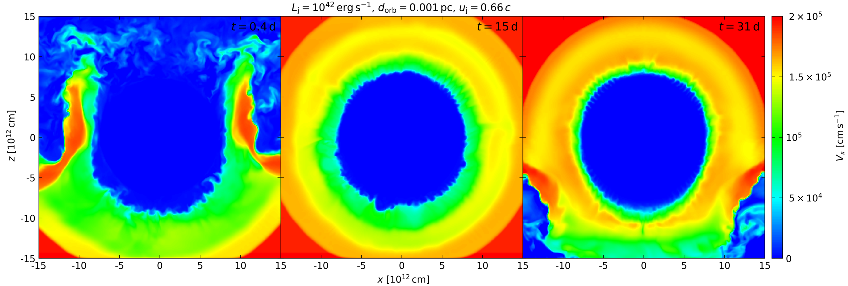
- Jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_j = 0.66\,c$
- 3D simulations in the "box" $2 \times 2 \times 2$ AU, in the star's comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Star enters the jet** for the tenth time at $t \approx 2400$ d (simulation time)



- *Left panel:* density snapshot, *right panel:* x-velocity snapshot
- **Video** of 10 stellar passages: star-jet_10passages_0.001pc_Lj_42.mp4

Star-jet interactions at the orbital distance 10^{-3} pc, $L_{\rm j} = 10^{42}$ erg s^{-1}

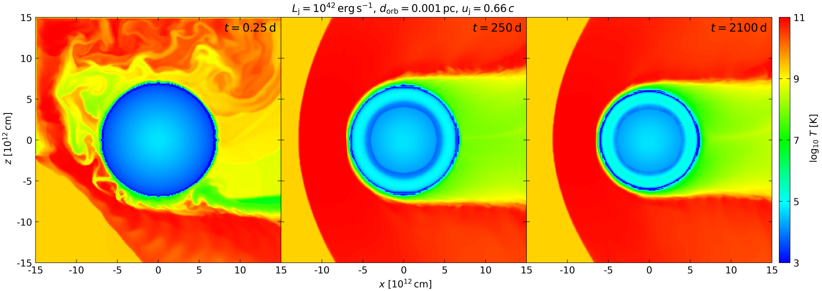
- Jet luminosity $L_{\rm j} = 10^{42}\,{\rm erg\,s^{-1}}$, jet velocity $v_{\rm j} = 0.66\,c$
- 3D simulations in the "box" $2 \times 2 \times 2$ AU, in the star's comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **"Head-on" views** at different times of the star-jet passage



- *Left-to-right panels:* x-velocity snapshots at times $\approx 1, 15,$ and 31 d
- **Video** of extended domain (1 passage): extended_0.001pc_Lj_42.mp4

Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$

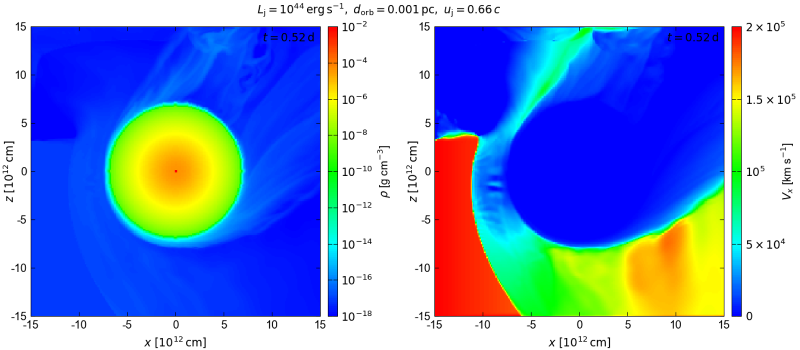
- Jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_j = 0.66\,c$
- 3D simulations in the "box" $2 \times 2 \times 2$ AU, in the star's comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Temperature structure** at different times within the 10 star-jet passages



- *Left-to-right panels:* temperature snapshots at times $\approx$ 1, 250, and 2100 d
- Involving radiation cooling would likely alter this profiles **but**:
- extremely computationally costly

Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{44}$ erg s^{-1}

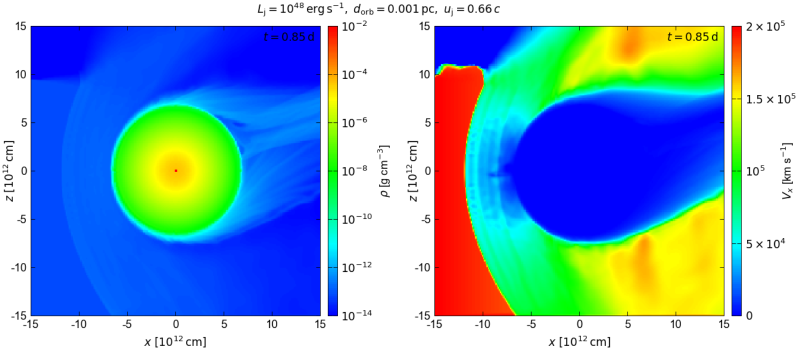
- Jet luminosity $L_j = 10^{44}$ erg s^{-1}, jet velocity $v_j = 0.66\,c$
- 3D simulations in the "box" $2 \times 2 \times 2$ AU, in the star's comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Star enters the jet** for the first time at $t \approx 0.5$ d (simulation time)



- *Left panel:* density snapshot, *right panel:* x-velocity snapshot
- **Video** of 10 stellar passages: star-jet_10passages_0.001pc_Lj_44.mp4

Star-jet interactions at the orbital distance 10^{-3} pc, $L_\mathrm{j} = 10^{48}$ erg s^{-1}

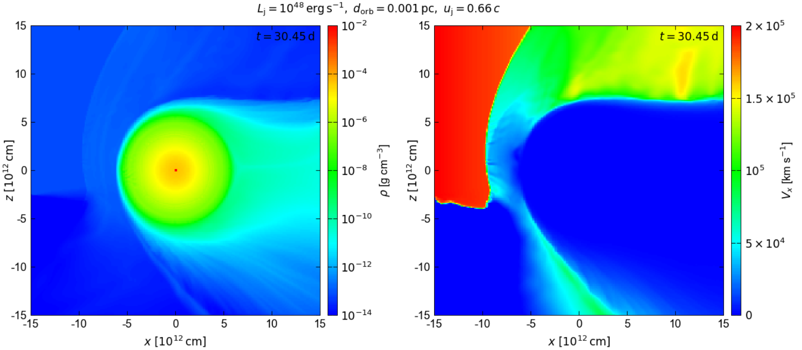
- Jet luminosity $L_\mathrm{j} = 10^{48}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_\mathrm{j} = 0.66\,c$
- 3D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Star enters the jet** for the first time at $t \approx 0.8$ d (simulation time)



• *Left panel:* density snapshot, *right panel:* x-velocity snapshot

Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{48}$ erg s^{-1}

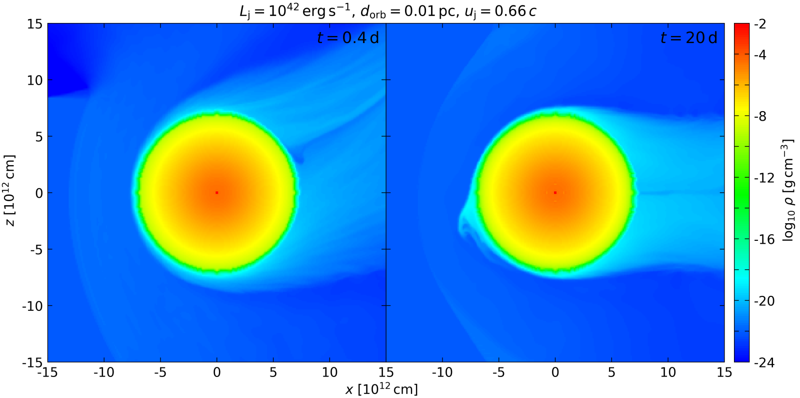
- Jet luminosity $L_j = 10^{48}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_j = 0.66\,c$
- 3D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Star exits the jet** for the first time at $t \approx 31$ d (simulation time)



- *Left panel:* density snapshot, *right panel:* x-velocity snapshot
- **Video** of 10 stellar passages: star-jet_10passages_0.001pc_Lj _48.mp4

Star-jet interactions at the orbital distance 10^{-2} pc, $L_j = 10^{42}$ erg s^{-1}

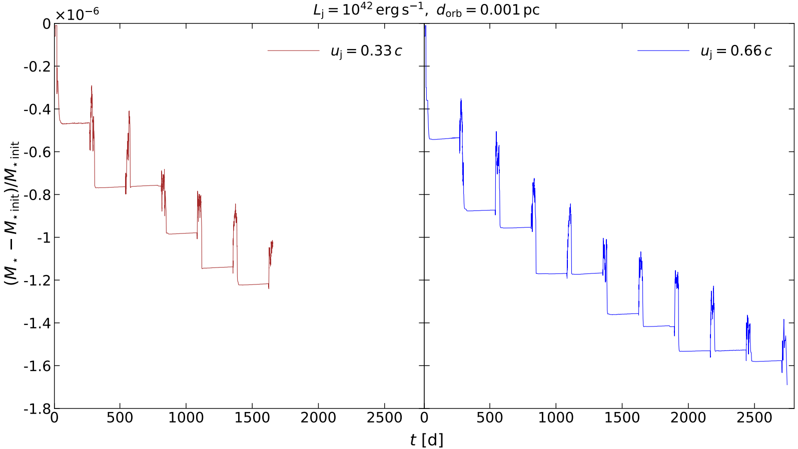
- Jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocity $v_j = 0.66\,c$
- 2D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- BCs are inflow at left and bottom, outflow at right at top
- **Early phase of the star-jet interaction**, at $t \approx 0.4$ d and $t \approx 20$ d



- *Left panel:* density snapshot at $t \approx 0.4$ d, *right panel:* same at $t \approx 20$ d

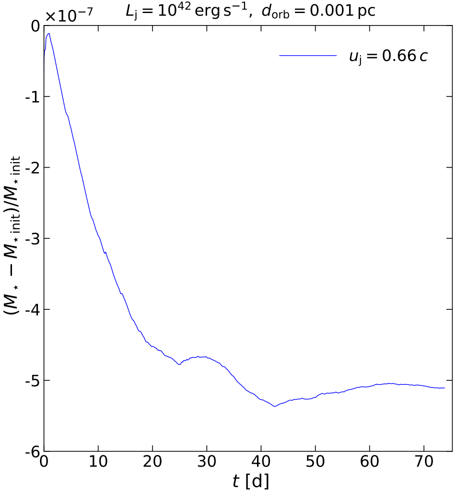
Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$

- Jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocities $v_j = 0.33\,c,\ 0.66\,c$
- 3D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- **Graph of the relative mass ablated**, up to 10 passages



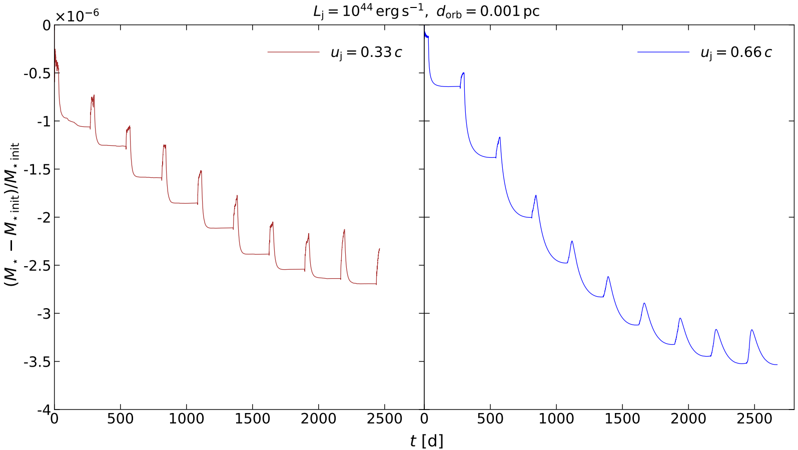
Star-jet interactions at the orbital distance 10^{-3} pc, $L_{\rm j} = 10^{42}\,{\rm erg\,s^{-1}}$

- Jet luminosity $L_{\rm j} = 10^{42}\,{\rm erg\,s^{-1}}$, jet velocities $v_{\rm j} = 0.33\,c,\ 0.66\,c$
- 3D simulations in the "box" $2 \times 2 \times 2$ AU, in the star's comoving frame
- **Detailed graph of the relative mass ablated** within 1 passage



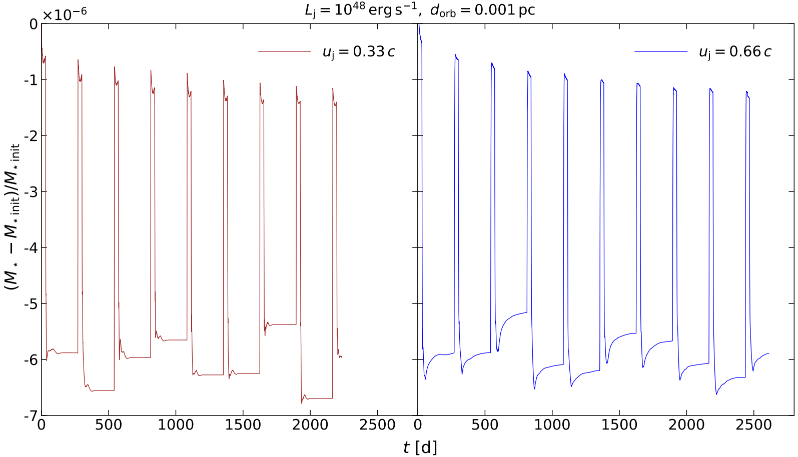
Star-jet interactions at the orbital distance 10^{-3} pc, $L_\mathrm{j} = 10^{44}\,\mathrm{erg\,s^{-1}}$

- Jet luminosity $L_\mathrm{j} = 10^{44}\,\mathrm{erg\,s^{-1}}$, jet velocities $v_\mathrm{j} = 0.33\,c,\ 0.66\,c$
- 3D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- **Graph of the relative mass ablated**, up to 10 passages



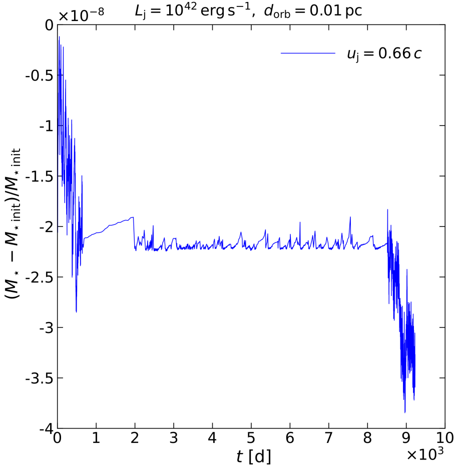
Star-jet interactions at the orbital distance 10^{-3} pc, $L_j = 10^{48}\,\mathrm{erg\,s^{-1}}$

- Jet luminosity $L_j = 10^{48}\,\mathrm{erg\,s^{-1}}$, jet velocities $v_j = 0.33\,c,\ 0.66\,c$
- 3D simulations in the "box" $2 \times 2 \times 2$ AU, in the star's comoving frame
- **Graph of the relative mass ablated**, up to 10 passages



Star-jet interactions at the orbital distance 10^{-2} pc, $L_\mathrm{j} = 10^{42}\,\mathrm{erg\,s^{-1}}$

- Jet luminosity $L_\mathrm{j} = 10^{42}\,\mathrm{erg\,s^{-1}}$, jet velocities $v_\mathrm{j} = 0.66\,c$
- 2D simulations in the “box” $2 \times 2 \times 2$ AU, in the star’s comoving frame
- **Graph of the relative mass ablated**, 2D sim, 2 passages only



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 passages of red giant stars through the typical jet of Galactic SMBH.
- For $r_{\rm orb} = 10^{-3}\,$pc, density integrations after first 10 jet crosses reveal the stellar mass ablation of the order of $\sim 10^{-6}\,M_\star$; this can be extrapolated as the ablation of $0.5\,M_\star$ after $\sim 100\,000$ crosses; this will be further verified by long-term simulations (computationally extremely costly).
- The similar applies also for $r_{\rm orb} = 10^{-2}\,$pc where the calculations indicate the ablation of the order of $\sim 10^{-8} - 10^{-7}\,M_\star$ per first 2 jet crosses which will likely lead to a similar extrapolation.