Does the lack of red giants around the Galactic centre reveal past Galactic jet activity?

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Abstract

The cause of the missing red giants near the centre of our Galaxy has long been debated. In the last few decades, many explanatory theories have been published regarding this phenomenon. Relatively recently, a new analytical theory has been proposed based on the idea of long-term ablation of the upper layers of red giant envelopes during repeated passages through the relativistic Galactic jet. We are currently engaged in detailed numerical modelling of this phenomenon. Using both our own advanced multidimensional hydrodynamical code and the 3D code CASTRO, we calculate the rate of red giant ablation as they pass through differently parameterized jets, potentially at different distances from the galactic centre. The initial state of the star, i.e. its density, pressure, and temperature profiles, is determined using the MESA evolution code. We determine the initial stellar state, i.e., its density, pressure, and temperature profiles, using the MESA evolutionary code. Subsequently, we also compute the hydrodynamical behaviour of the star after exiting such a jet since exposing the deeper subsurface layers of the star can result in a temporary or even permanent change in its luminosity and spectral characteristics. These changes, especially if we consider the larger number of stars in the dense Nuclear Cluster undergoing similar evolution, may contribute to visible changes in the observable characteristics in this region. We aim to examine the implications for galactic nuclei in general and AGN in particular because multiple and recurrent interactions of stars with the jet also affect the variability and density profile of the inner nuclei.

Introduction

The internal processes in the Galactic nuclear star cluster (NSC) preferentially depleted the large red giants, leading to their apparent nuclear distribution, and were less effective for both early-type and fainter late-type stars. Such mechanisms might have altered the spatial, luminosity, and probably temperature distribution of bright red giants so that they became undetectable or instead mimicked younger, "bluer" stars.

Zajaček et al. (2020) proposed a new mechanism that could affect the current population of bright late-type stars in the Galactic centre based on the idea of removing the outer layers of the star during many repeated passages through the relativistic SMBH jet. They used analytical and semi-analytical calculations to assess whether the proposed potential star-jet interactions in the past could have affected the evolution of the stellar populations within the radius of influence of Sgr A*. Following these considerations, we present an elaborate 3D hydrodynamical numerical model of the passage of a star through a galactic SMBH jet, which aims to simulate and evaluate as realistically as possible the rate of red giants' ablation due to such interactions.

Model set-up

Figure 1 shows a sketch of the situation within the Galactic nuclear stellar cluster (including SMBH disk and jets) and a more detailed case of star-jet passage. We assume a jet plasma is dominated by electrons and protons. The jet exerts mainly the ram pressure on the passing star, $P_j = \Gamma \rho_j v_j^2$, where $\Gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor, the jet velocity $v_j = 0.3\,c$, and ρ_j is the mass density inside the jet, see Zajaček et al. (2020) for the analysis of this process.

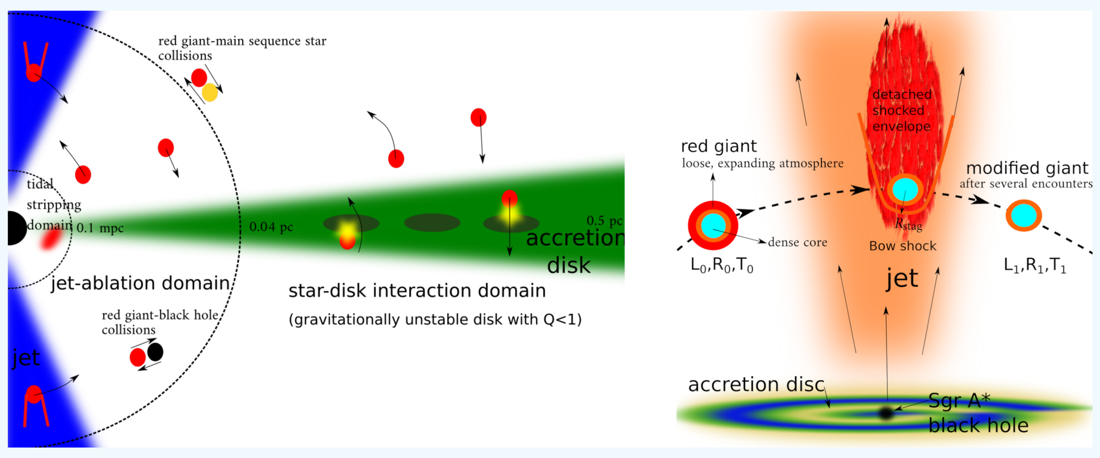

Figure 1. **Interactions of red giants within the NSC.** Left: Illustration of collisions of stars and/or their transits through the disk/jet system around the central SMBH. Right: The red giant's passage through the galactic jet, during which the stellar outer layers are partially ablated. From Zajaček et al. (2020).

For the star orbiting outside the jet, the density and temperature of the ambient plasma typically behave as decreasing power-law functions [Różańska et al. 2015], parameterised by the number density $n_B = 26\,\mathrm{cm}^{-3}$ and the temperature $T_B = 1.5 \times 10^7\,\mathrm{K}$ at the Bondi radius $r_B = 2GM_\bullet/c_s^2 \sim 0.21\,(T_B/10^7\,\mathrm{K})^{-1}\,\mathrm{pc}$ [Baganoff et al. 2003], where c_s is the local speed of sound and $M_\bullet = 4 \times 10^6\,M_\odot$ is the mass of the Galactic SMBH. The number density inside the hadronic jet in the distance z from SMBH can then be estimated as

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

The jet temperature is assumed to be $T_j = 10^{10}$ K, the jet luminosity $L_j = 10^{42}$ - $10^{44}\,\mathrm{erg\,s^{-1}}$, and its opening half-angle 10°. We model the red giant as a star with mass $M_\star = 1\,M_\odot$ and the initial radius $R_\star = 100\,R_\odot$, using the stellar evolution code MESA.

Methods

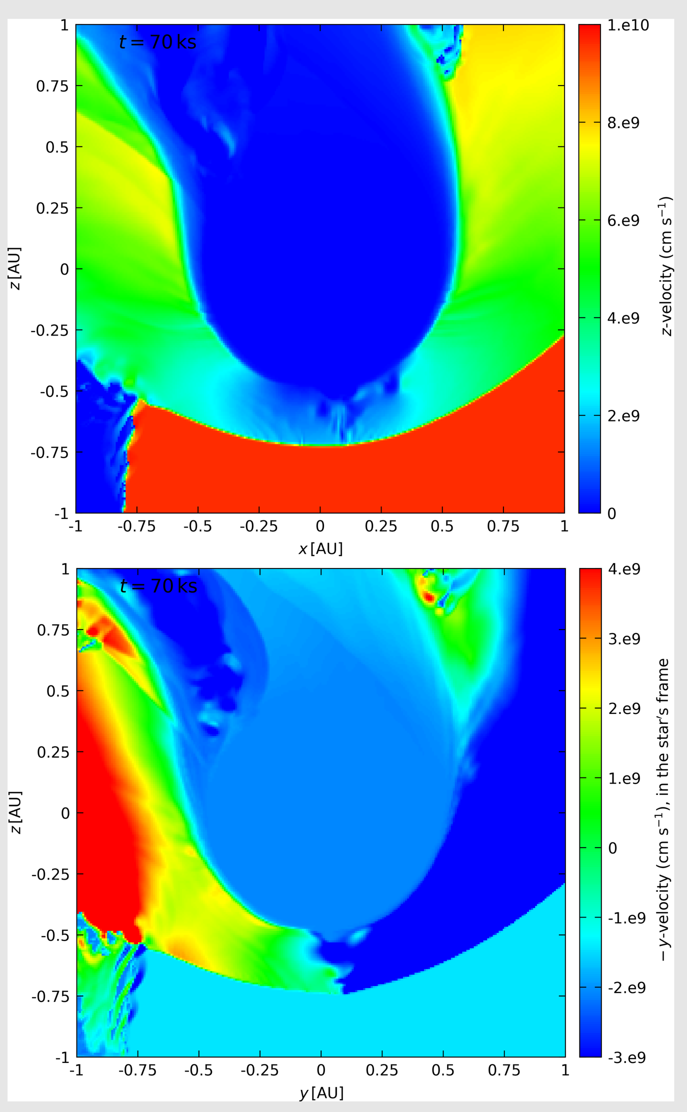

Figure 2. **Map of the z and y-velocity.** at the time ≈ 0.8 d. The bottom turquoise region in the lower panel corresponds to the star's orbital velocity magnitude $v_{orb} \approx 4.16 \times 10^8\,\mathrm{cm\,s^{-1}}$.

We performed the current simulation using the widely used and well-tested 3D hydrodynamic code CASTRO, which is capable of combining specific physical and geometric requirements for this type of calculation. We use the Cartesian grid centred on the star, while all the spherical quantities, including gravity and hydrostatic equilibrium, are re-calculated onto the rectangular grid with 275^3 cells via the multipole expansion. We implemented the initial state profiles described in the previous section. The boundary conditions (see Fig. 2 and Figs. 3 - 5 for the geometric context) are inflow at the bottom and right edges, accounting for jet inflow from the bottom and the orbital velocity motion from the right, and outflow at the left and top edges. To achieve numerical feasibility, we model the whole process in a frame associated with the star, where the jet material orbits rightwards. The current simulation is performed purely as a hydrodynamic one, we do not implement the magnetic fields or radiation. These could affect the process, but we currently estimate these effects as secondary.

Results

The following images demonstrate the current progress in the 3D numerical modelling of the red giant star's passage through a galactic jet with the parameters described in previous sections:

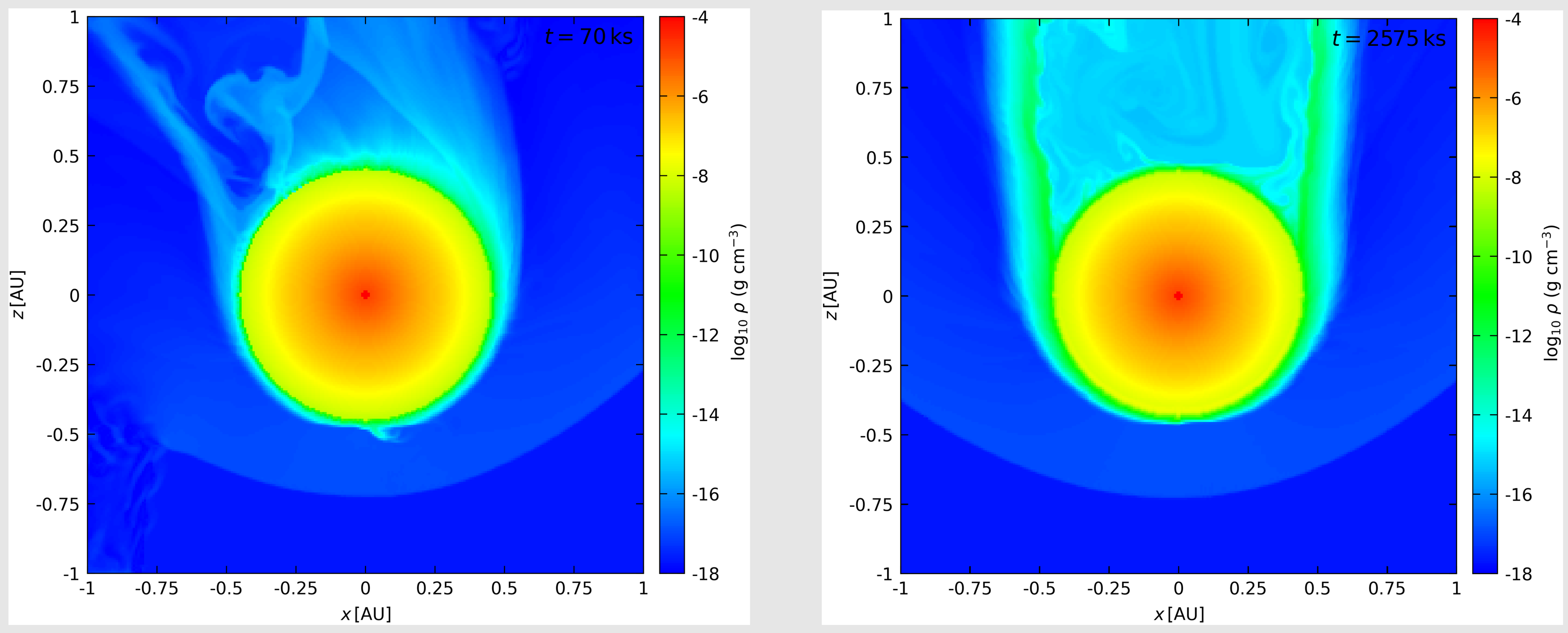

Figure 3. **2D slices of the red giant star-jet 3D interaction model along the galactic jet plane.** The density snapshots show the entering of the jet by the star (left panel) and roughly the end (right panel) of the first crossing through the jet with the jet luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$.

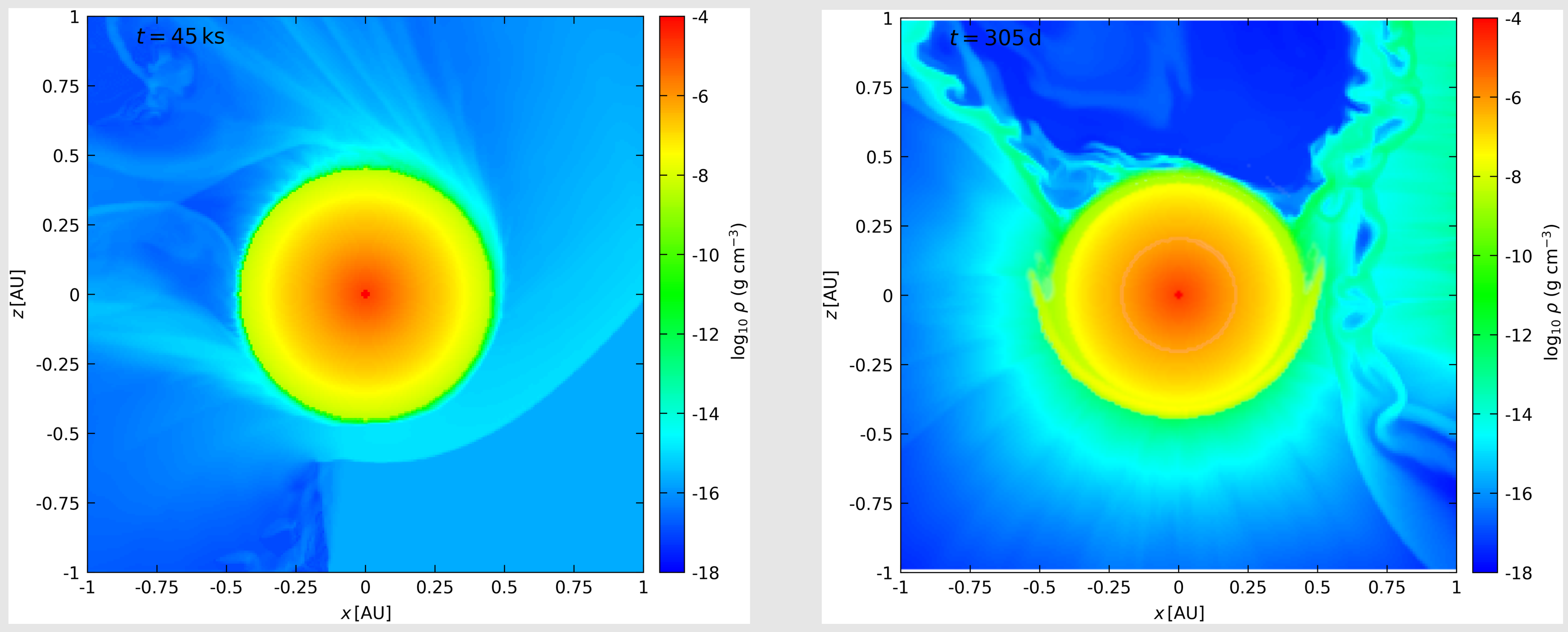

Figure 4. **Similar process of the density evolutio as in Fig. 3**, now with the jet luminosity $L_j = 10^{44}\,\mathrm{erg\,s^{-1}}$. Left: The star enters the jet. Right: The star is shortly after exiting the jet for the second time. Both with the same colour scaling as in Fig. 3.

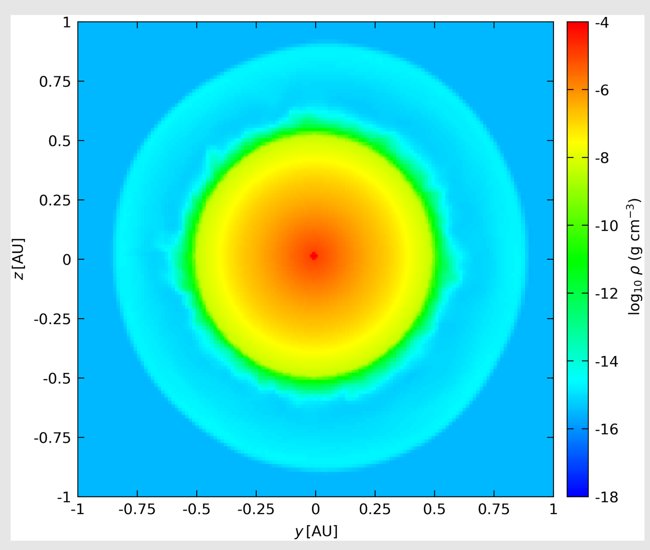

Figure 5. **Front** "downstream" **view** of the star-jet interaction; the "weaker" jet with luminosity $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$.

We currently calculate one period of the stars' orbit around SMBH, i.e., two star-jet passages. The snapshots at time ≈ 0.8 d correspond to the moment of the first entering of the star, orbiting at a distance of 0.001 pc from the Galactic SMBH, in the jet. We recognize two shocked zones manifested by the dramatic change in the jet velocity. Integrations of the density reveal the removal of the following fractions of stellar matter: $\Delta M_1 \approx 5 \times 10^{-5}\,M_\odot$ for the $L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$ case and $\Delta M_2 \approx 2 \times 10^{-4}\,M_\odot$ for the $L_j = 10^{44}\,\mathrm{erg\,s^{-1}}$ case, after the first passage. We expect we will obtain statistically more relevant values after completing at least several hundred star-jet passages.

Conclusions

We present the first part of numerical models of an analytical scenario introduced in Zajaček et al. (2020) that newly explains the deficiency of bright red giants in the inner regions of the Galactic centre in the sphere of influence of the currently quiescent but previously active radio source Sgr A*. Although this process likely operated in parallel with other previously proposed mechanisms, such as the star - disc interactions, star - star collisions, and tidal disruption events, we suppose such interactions could substantially contribute to the observed lack of bright red giants in the central parts of the Galactic nuclear star cluster. The ongoing detailed numerical computations of red giant - jet interactions in combination with a modified stellar evolution will help to verify our previously introduced analytical estimates.

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