AGN feedback on small scales: Depletion of bright red giants in the vicinity of Sgr A*

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Discovery of missing red giants

- discovery paper of **Kristen Sellgren** (now Emerita Professor, Ohio State University) from 1990

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VELOCITY DISPERSION AND THE STELLAR POPULATION IN THE CENTRAL 1.2 PARSECS OF THE GALAXY

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ABSTRACT

We have obtained spectra of the 2.3 μm CO band head in integrated starlight at several positions in the central 1.2 pc of the Galaxy. We find that the strength of the absorption feature declines with projected distance for projected distances less than 15″ (0.6 pc). We confirm that there is an increase in the velocity dispersion σ of the faint stars toward the Galactic center. However, within a 15″ radius of IRS 16, we find that there is no dependence of σ on projected distance. We find that $\langle\sigma\rangle = 125$ km s^{-1} and that systematic rotation of the stellar cluster is negligible in the central region. The observations are consistent with there being no CO absorption feature in the diffuse starlight within a true radius of 0.6 pc, with the observed CO feature at projected distances less than 0.6 pc arising in material at larger true radii along the line of sight. We discuss several possible explanations for the lack of CO absorption in the central 1.2 pc, including destruction of the atmospheres of late-type stars by stellar collisions, dissociation of the CO molecule in the atmospheres of the late-type stars by a central luminosity source, and a core radius for the old stellar population of 0.6 pc combined with an additional cluster of sources without CO absorption in the central parsec. Given the new information on the dependence of the strength of the CO band head on projected distance, we have reanalyzed the kinematic data presented in a previous paper (McGinn *et al.* 1989) to derive the mass distribution for radii between ~4 and ~0.6 pc. We confirm the conclusions of that paper that there is evidence for an increase in the mass–to–2 μm radiation ratio M/F_K toward the center of the Galaxy. If there is no change in M/F_K of the stellar cluster, then an unseen mass of $(5.5 \pm 1.5) \times 10^6\ M_\odot$ must be concentrated within a 0.6 pc radius of the Galactic center in order to explain the observed kinematics.

Subject headings: galaxies: internal motions — galaxies: The Galaxy — galaxies: nuclei — infrared: spectra

Discovery of missing red giants

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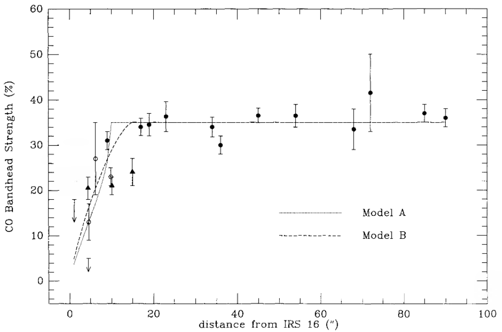
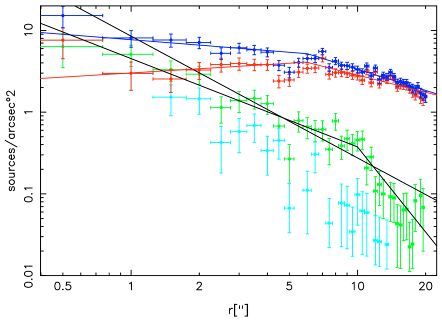


FIG. 5.—Observations of Fig. 3, compared with model calculations. The curves are model predictions for the CO absorption strength integrated along the line of sight, assuming that the density of CO absorption sources depends on true radius r as $r^{-1.8}$ outside a radius r_{CO} but changes for $r < r_{CO}$. These models assume that the density of all 2 μm sources is proportional to $r^{-1.8}$ for $r > r_{2\,\mu m}$, and is constant for $r < r_{2\,\mu m}$, where $r_{2\,\mu m}$ is the core radius for the 2 μm light. Model A (*dotted curve*): no CO absorption sources for $r < r_{CO} = 10''$; $r_{2\,\mu m} = 1''$. Model B (*dashed curve*): constant density of CO absorption sources for $r < r_{CO} = 15''$; $r_{2\,\mu m} = 1''$.

Motivation

- **flattening of the surface-brightness profile** of brighter late-type stars
- fainter late-type stars as well as young OB stars have **cusp-like** profiles

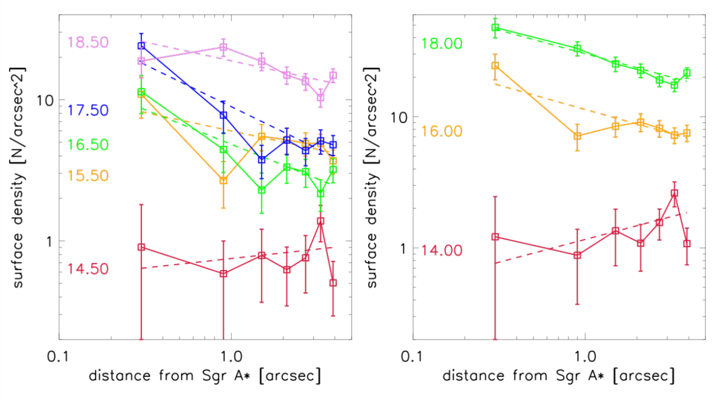
Surface density profiles of early- (green) and late-type (red) stars by Buchholz+09:



Observational results: surface-brightness profiles

- **fainter gaints** show a **cusp-like profile** (Habibi+19, Schoedel+20)
- **brighter late-type stars** of $K_s = 14.5 - 14.0$ mag have a **flat to a decreasing surface density profile**

Results from Schoedel+2020: $\alpha_{14.5} = 0.13 \pm 0.32$, $\alpha_{15.5} = -0.26 \pm 0.15$, $\alpha_{16.5} = -0.49 \pm 0.14$, $\alpha_{17.5} = -0.59 \pm 0.14$, $\alpha_{18.5} = -0.27 \pm 0.11$



Motivation

- Key question: **What mechanism is responsible for a stellar cusp of fainter late-type stars and a flat, core-like profile of brighter red giants?**
- Schoedel+2020 found that 80% of the stellar mass formed > 10 Gyr ago
- two-body (non-resonant) relaxation time (in the inner parsec):

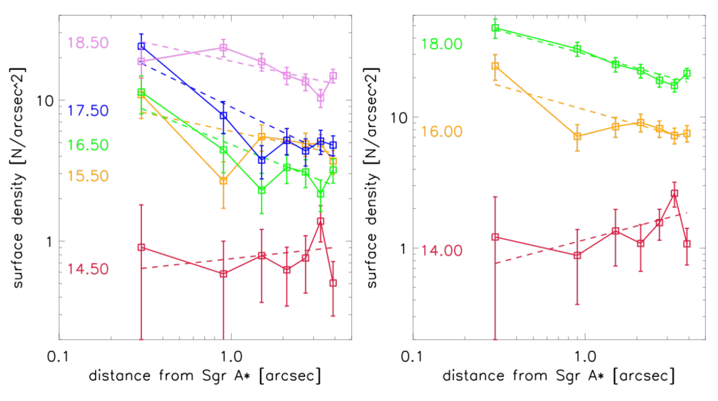
$$\tau_{\rm relax} = \frac{0.34\sigma^3}{G^2 m_\star \rho_\star \log \Lambda} \sim 1.3 \times 10^9 \, \mathrm{yr} \quad (1)$$

- most ($\sim 80\%$) of the late-type stars are expected to be relaxed $\rightarrow$ **Bahcall-Wolf-like** cusp should be present with the **3D** slope of $\rho(r) \propto r^{-1.5}$ (Solar-mass stars) and $\gamma \approx -2$ for stellar black holes (Alexander 2017)

Observational results: surface-brightness profiles

- apart from the brightest late-type stars with $K_\mathrm{s} = 14.5 - 14.0$ mag, fainter gaints show a cusp-like profile (Habibi+19, Schoedel+20)

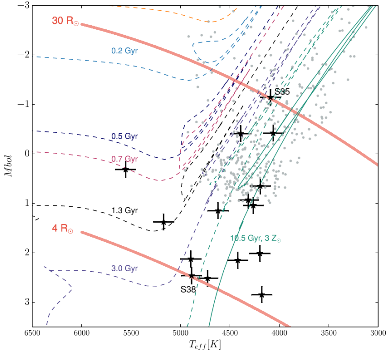
Results from Schoedel+2020: $\alpha_{14.5} = 0.13 \pm 0.32$, $\alpha_{15.5} = -0.26 \pm 0.15$, $\alpha_{16.5} = -0.49 \pm 0.14$, $\alpha_{17.5} = -0.59 \pm 0.14$, $\alpha_{18.5} = -0.27 \pm 0.11$



Observational results: surface-brightness profiles

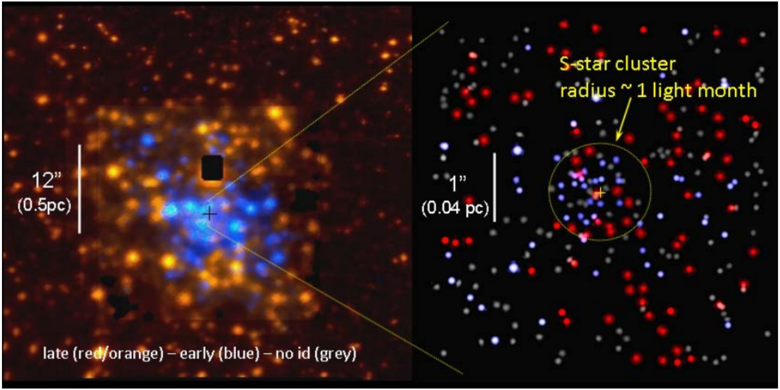
- Habibi+19 found that $\sim 4-5$ bright giants ($K_s < 15.5$) could be missing within $\sim 0.04\,\mathrm{pc}$
- Gallego-Cano+18 estimate ~ 100 missing bright giants within the inner $\sim 0.3\,\mathrm{pc}$

Habibi+19 infer that atmosphere radii of late-type stars $\lesssim 30R_\odot$ at $\lesssim 0.2\,\mathrm{pc}$:



Explanations of the missing bright giants

- a process that **preferantially** acts upon extended, large giants and leaves smaller, fainter giants as well as young OB stars intact $\rightarrow$ alternation of spatial, temperature, and/or luminosity distribution



Late-type stars (orange, red) vs. early-type stars (blue) (SINFONI, NACO; Genzel et al. 2010)

Explanations of the missing bright giants

Several scenarios proposed within the last 30 years:

(a) **tidal disruption of red giants** by the SMBH (Hills 1975; Bogdanovic+2014; King 2020),

(b) **red giant–accretion disc (clumps) collisions** (Armitage+1996; Amaro-Seoane & Chen 2014; Kieffer & Bogdanovic 2016),

(c) **collisions of red giants with field stars and compact remnants** (Phinney 1989; Morris 1993; Genzel+1996),

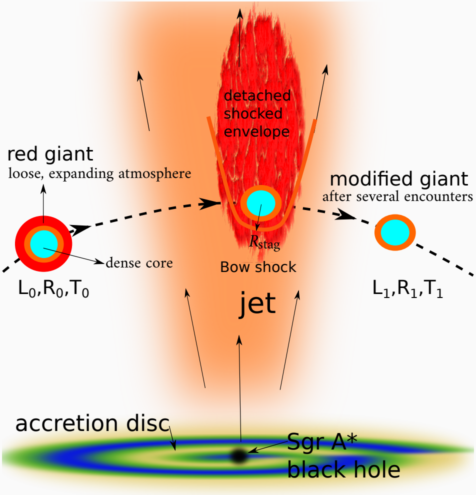
(d) **mass segregation effects:** the infall of a secondary massive black hole (Baumgardt+2006; Merritt & Szell 2006) or the infall of a massive cluster (Kim & Morris 2003; Ernst+2009, Antonini+2012) or the dynamical segregation of stellar black holes (Morris 1993).

(e) **stellar evolution of hard binary systems** $\rightarrow$ relevant also for globular cluster cores (Beer & Davies, 2003)

(f) **dark-matter collisions with red-giant cores** (Dessert & Johnson, 2021)

Novel scenario

We propose a **novel scenario**: **ablation or "shaving off" of red giants (their envelopes) in the jet–star interactions**



Novel scenario

- We propose a **novel scenario**: **ablation or "shaving off" of red giants (their envelopes) in the jet–star interactions**
- originally studied in the context of the production of high-energy non-thermal radiation in jetted AGN (gamma-ray flares; Bosch-Ramon, Perucho & Barkov, 2012)

Clouds and red giants interacting with the base of AGN jets

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ABSTRACT

Context. Extragalactic jets are formed close to supermassive black-holes in the center of galaxies. Large amounts of gas, dust, and stars cluster in the galaxy nucleus, and interactions between this ambient material and the jet base should be frequent, having dynamical as well as radiative consequences.
Aims. This work studies the dynamical interaction of an obstacle, a clump of matter or the atmosphere of an evolved star, with the innermost region of an extragalactic jet. Jet mass-loading and the high-energy outcome of this interaction are briefly discussed.
Methods. Relativistic hydrodynamical simulations with axial symmetry have been carried out for homogeneous and inhomogeneous obstacles inside a relativistic jet. These obstacles may represent a medium inhomogeneity or the disrupted atmosphere of a red giant star.
Results. Once inside the jet, an homogeneous obstacle expands and gets disrupted after few dynamical timescales, whereas in the inhomogeneous case, a solid core can smoothen the process, with the obstacle mass-loss dominated by a dense and narrow tail pointing in the direction of the jet. In either case, matter is expected to accelerate and eventually get incorporated to the jet. Particles can be accelerated in the interaction region, and produce variable gamma-rays in the ambient matter, magnetic and photon fields.
Conclusions. The presence of matter clumps or red giants into the base of an extragalactic jet likely implies significant jet mass-loading and slowing down. Fast flare-like gamma-ray events, and some level of persistent emission, are expected due to these interactions.

Novel scenario

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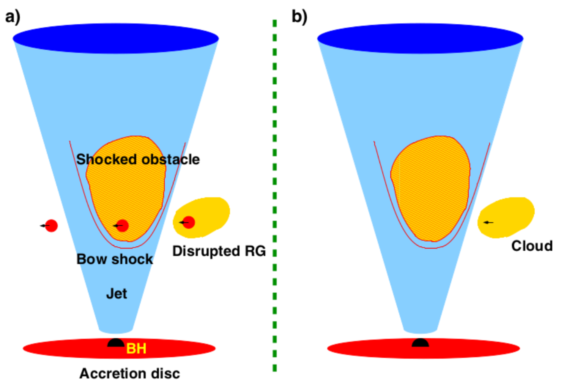

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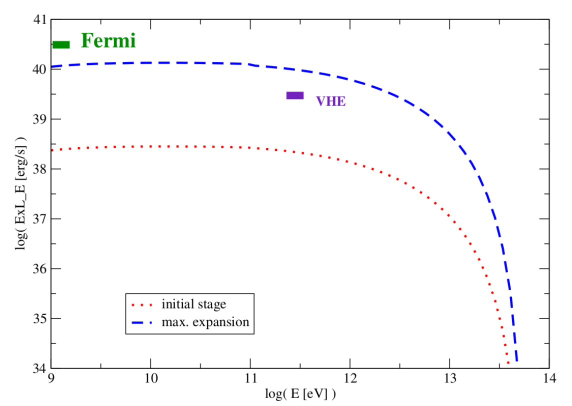

Novel scenario

- We propose a **novel scenario**: **ablation or "shaving off" of red giants (their envelopes) in the jet–star interactions**
- originally studied in the context of the production of high-energy non-thermal radiation in jetted AGN (gamma-ray emission via IC and synchrotron in elliptical blazars; Torres-Alba & Bosch-Ramon, 2019)

Gamma rays from red giant wind bubbles entering the jets of elliptical host blazars

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ABSTRACT

Context. Blazars in elliptical hosts have a population of red giants surrounding their jet. These stars can carry large wind-blown bubbles into the jets, leading to gamma-ray emission through bubble-jet interactions.
Aims. We study the interaction dynamics and the gamma-ray emission produced when the bubbles formed by red giant winds penetrate the jet of a blazar in an elliptical galaxy.
Methods. First, we characterized the masses and penetration rates of the red giant wind bubbles that enter the jet. Then, the dynamical evolution of these bubbles under the jet impact was analysed analytically and numerically, and the radiation losses of the particles accelerated in the interaction were characterised. Finally, the synchrotron and the inverse Compton contributions above $\sim$100 MeV were estimated under different jet magnetic fields, powers, and Lorentz factors.
Results. We find that an analytical dynamical model is a reasonable approximation for the red giant wind bubble-jet interaction. The radiation produced by these wind bubbles interacting with a jet can have a duty cycle of up to $\sim$1. For realistic magnetic fields, gamma rays could be detectable from sources within the local universe, preferentially from those with high Lorentz factors ($\sim$10), and this could be a relatively common phenomenon for these sources. For magnetic fields in equipartition with the jet power, and high acceleration rates, synchrotron gamma rays may be detectable even for modest Lorentz factors ($\sim$3), but with a much lower duty cycle.
Conclusions. Blazars in elliptical galaxies within the local universe can produce detectable transient or persistent gamma-ray emission from red giant wind bubbles entering their jets.

Model set-up

- jet kinetic luminosity and duration based on γ-**ray Fermi bubbles/bipolar radio bubbles/X-ray chimneys** (Su+2010; Heywood+2019; Ponti+2019)
- overall energy content of $10^{56} - 10^{57}\,\mathrm{erg}$ (Bland-Hawthorn+2019)
- Guo & Mathews(2012) can reproduce the γ-ray Fermi bubbles 50° north and south of the Galactic plane by an AGN jet duration of 0.1–0.5 Myr $\rightarrow L_{\mathrm{j}} \approx 10^{56-57}\,\mathrm{erg}/(0.1 - 0.5\,\mathrm{Myr}) = 6.3 \times 10^{42} - 3.2 \times 10^{44}\,\mathrm{erg\,s^{-1}} \lesssim L_{\mathrm{Edd}} \sim 5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$
- jet active 4 ± 1 Myr due to the higher accretion activity: infall of gas cloud at least 10 000 $M_\odot$ (Su & Finkbeiner 2012), potentially related to the observed stellar disks!? (Ali+2020)

Model set-up

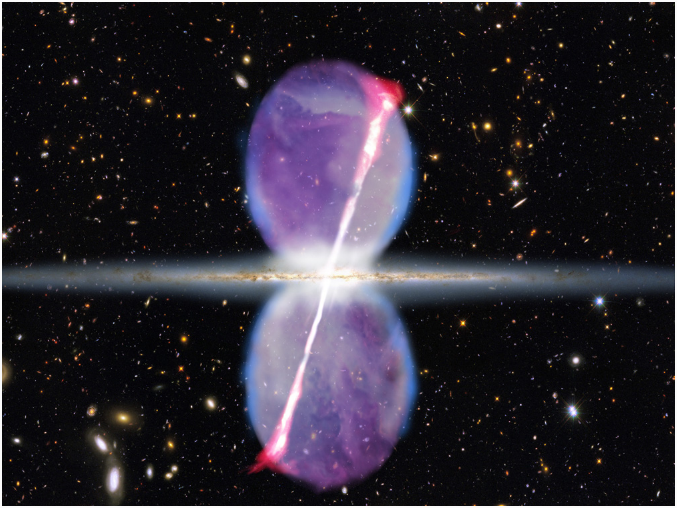
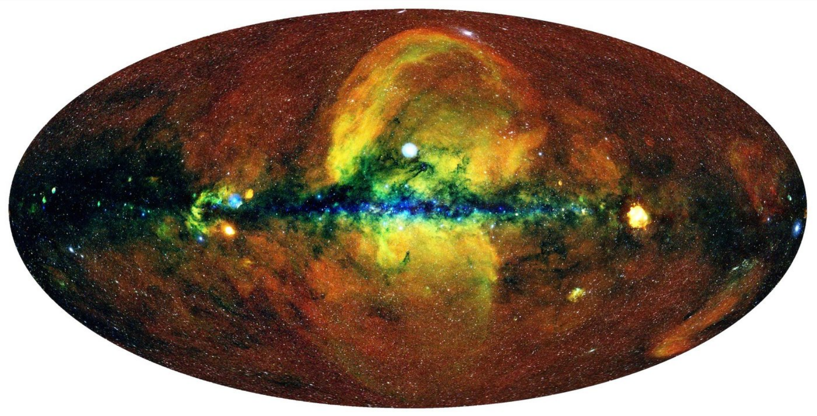


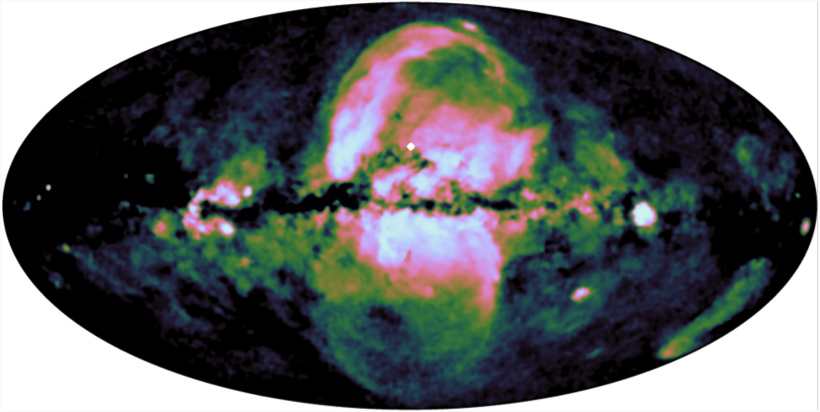
Image credit: David A. Aguilar (Harvard-Smithsonian Center for Astrophysics)

eROSITA bubbles



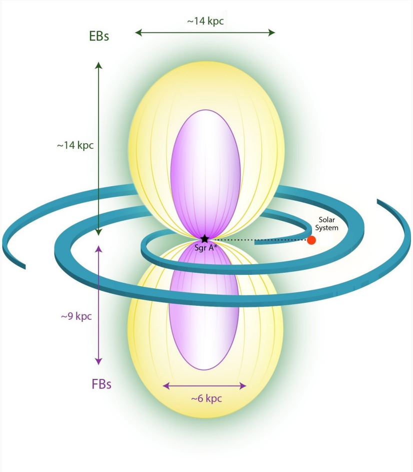
The SRG/eROSITA all-sky X-ray map (0.3-2.3 keV)/MPE/IKI
P. Predehl et al. and the eROSITA collaboration, Nature, 2020

eROSITA bubbles



The SRG/eROSITA all-sky X-ray map (0.6-1.0 keV)/MPE/IKI
P. Predehl et al. and the eROSITA collaboration, Nature, 2020

eROSITA and Fermi bubbles: comparison



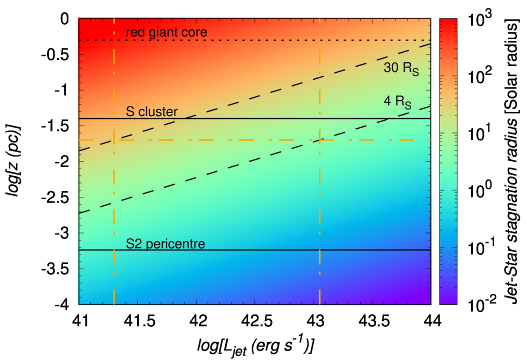
The eROSITA/Fermi bubbles: schematic view
Credit: MPE

Results

- stagnation radius profile as a function of distance and jet luminosity

$$P_{\mathrm{j}} = P_{\mathrm{sw}} \rightarrow R_{\mathrm{stag}} = z \tan\theta \sqrt{\frac{\dot{m}_{\mathrm{w}} v_{\mathrm{w}} c}{4 L_{\mathrm{j}}}}$$

$$R_{\mathrm{stag}} = 27 \left(\frac{z}{0.04\,\mathrm{pc}}\right) \left(\frac{\dot{m}_{\mathrm{w}}}{10^{-8}\, M_{\odot}\mathrm{yr}^{-1}}\right)^{\frac{1}{2}} \left(\frac{v_{\mathrm{w}}}{10\,\mathrm{km\,s^{-1}}}\right)^{\frac{1}{2}} \left(\frac{L_{\mathrm{j}}}{10^{42}\,\mathrm{erg\,s^{-1}}}\right)^{-\frac{1}{2}} R_{\odot}$$

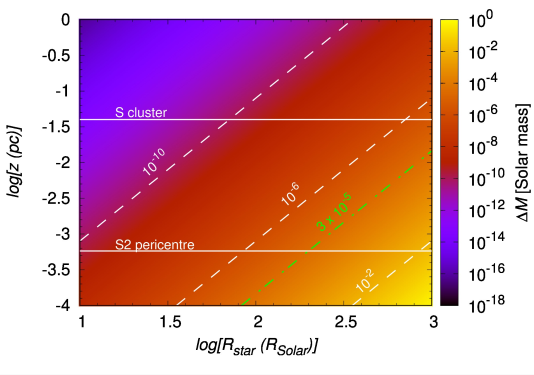


Results

- jet-induced envelope removal (single passage)

$$n_{\rm cross} = 2\frac{t_{\rm jet}}{P_{\rm orb}} \sim 2\times 10^4 \left(\frac{t_{\rm jet}}{0.5\,{\rm Myr}}\right)\left(\frac{M_\bullet}{4\times 10^6\,M_\odot}\right)^{\frac{1}{2}}\left(\frac{z}{0.01\,{\rm pc}}\right)^{-\frac{3}{2}}$$

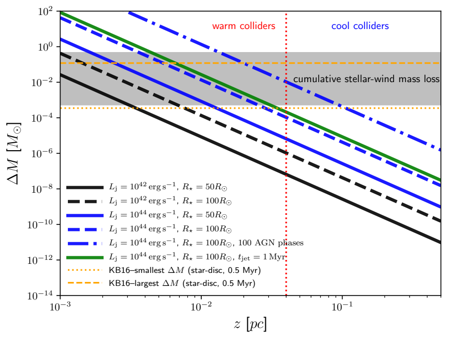
$$\frac{\Delta M_1^{\rm max}}{M_\odot} \approx 4\times 10^{-10}\left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right)\left(\frac{R_\star}{100\,R_\odot}\right)^4\left(\frac{z}{0.04\,{\rm pc}}\right)^{-2}\left(\frac{\theta}{0.22}\right)^{-2}\left(\frac{m_\star}{M_\odot}\right)^{-1}$$



Results

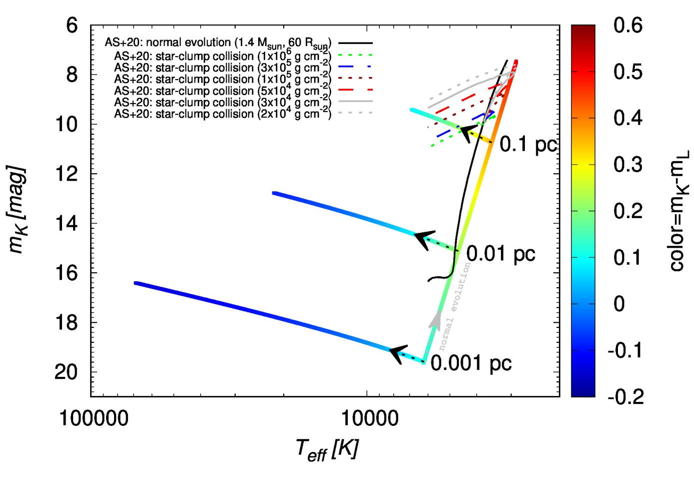
- jet-induced envelope removal – effect of multiple passages
- cumulative mass loss comparable to star–disc collisions as well as stellar-wind losses

$$\Delta M \sim n_{\rm cross}\Delta M_1$$
$$\approx 10^{-4}\left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right)\left(\frac{R_\star}{100\,R_\odot}\right)^4\left(\frac{z}{0.01\,{\rm pc}}\right)^{-\frac{7}{2}}\times$$
$$\left(\frac{\theta}{0.22}\right)^{-2}\left(\frac{m_\star}{M_\odot}\right)^{-1}\left(\frac{t_{\rm jet}}{0.5\,{\rm Myr}}\right)\left(\frac{M_\bullet}{4\times10^6\,M_\odot}\right)^{\frac{1}{2}}\,M_\odot$$



Results

- ablated red giants become warmer/“bluer” $T_{\rm abl} = T_0 (R_0/R_{\rm abl})^{1/2}$
- ablated red giants become fainter in the NIR domain $L_{\rm abl} \approx L_0 (R_{\rm abl}/R_0)^{3/2}$



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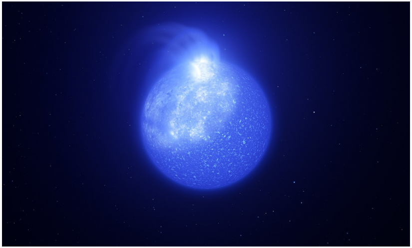
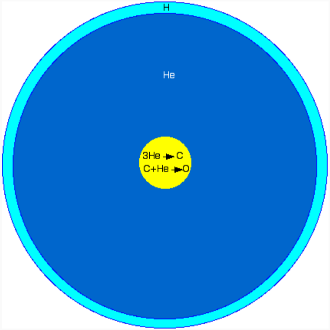
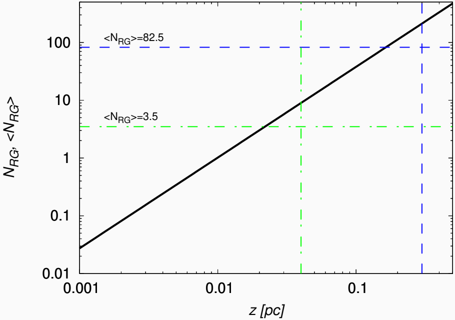
- alternated giants and supergiants could appear as **Subdwarf B**-type stars (sdB) (new formation channel?)
- 1% hydrogen, mostly helium, small ($0.15 - 0.25\,R_\odot$) and hot (20 000-40 000 K) $\rightarrow$ visible in the UV domain





Results

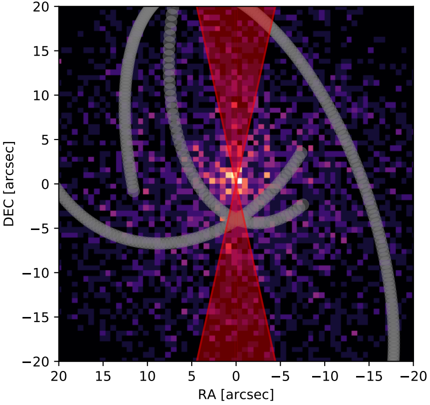
- a number of red giants crossing the jet per orbital period consistent with the inferred number of missing bright red giants at 0.04 and 0.3 pc: 4-5 (Habibi+2019) and 100 (Gallego-Cano+2018), respectively



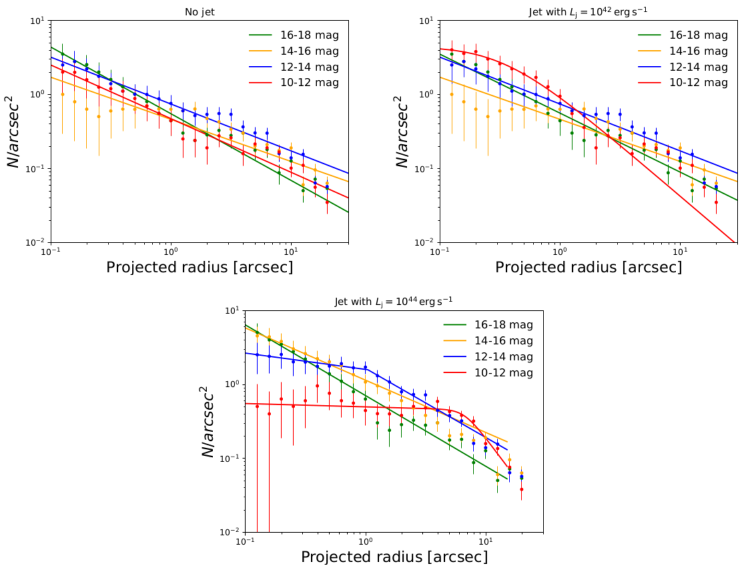
Distance	$L_j = 10^{42}\,\mathrm{erg\,s^{-1}}$	$L_j = 10^{44}\,\mathrm{erg\,s^{-1}}$
$0.04\,\mathrm{pc}$	$R_\star = 27\,R_\odot,\ m_{\rm abl} = 11.7,\ \eta = 1.27\%$	$R_\star = 2.7\,R_\odot,\ m_{\rm abl} = 16.1,\ \eta = 26.5\%$
$0.5\,\mathrm{pc}$	$R_\star = 338\,R_\odot,\ m_{\rm abl} = 6.95,\ \eta = 0.05\%$	$R_\star = 33.8\,R_\odot,\ m_{\rm abl} = 11.3,\ \eta = 0.95\%$

Results - Demonstration on the surface stellar profiles

- we generated a mock nuclear stellar cluster with the initial $n_{\mathrm{RG}} = n_0(z/z_0)^{-\gamma}$ with $\gamma \sim 1.43$ according to Gallego-Cano+2018 (4000 late-type stars in total)

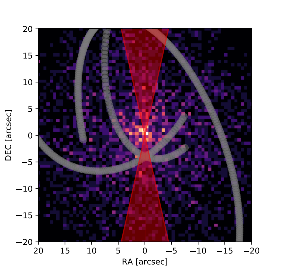


Results - Demonstration on the surface stellar profiles



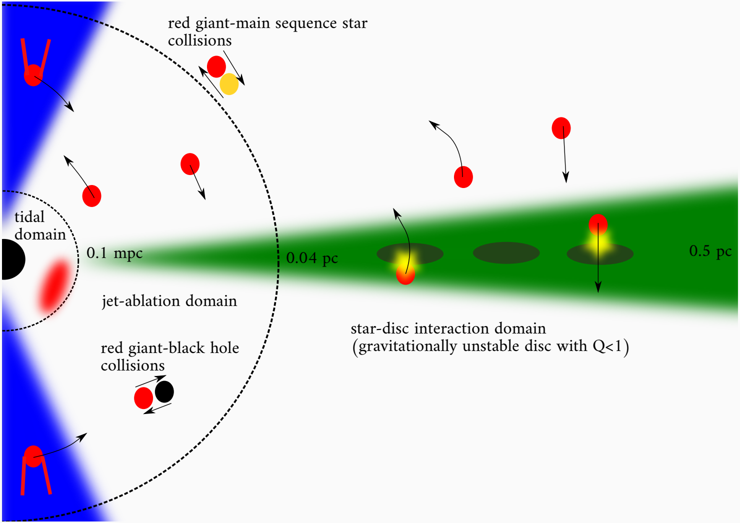
Results - Main conclusions

- in comparison with the **no-jet scenario**, the **active** Seyfert-like **jet flattens the surface profile of the brightest red giants** (10-12 mag, intrinsic), starting within the inner arcsecond (0.04 pc)
- for the most luminous jet ($10^{44}\,\mathrm{erg\,s^{-1}}$), the core-like profile extends up to 0.4 pc for the brightest gianst
- fainter giants ($>$ 14 mag, intrinsic) keep the cuspy profile within the S cluster for all jet luminosities
- young OB stars are left intact because of their powerful winds



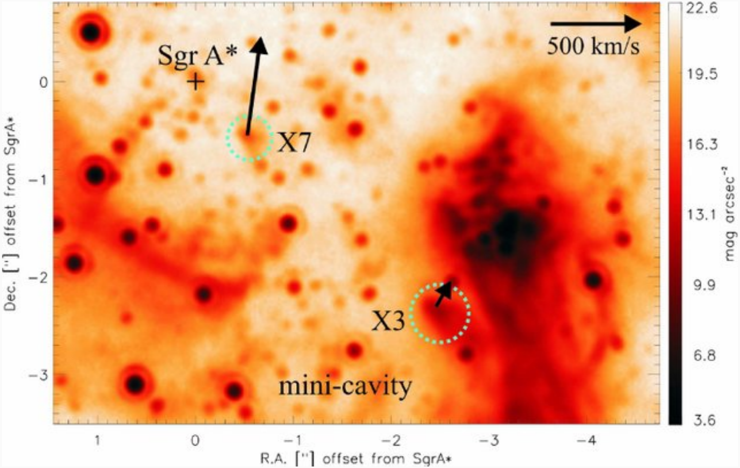
Results - Unification scheme

- tidal disruption of red giants, jet-ablation, and star-disc collisions **coexisted likely simultaneously** but on different spatial scales



Results - Implications for the current state of Sgr A*

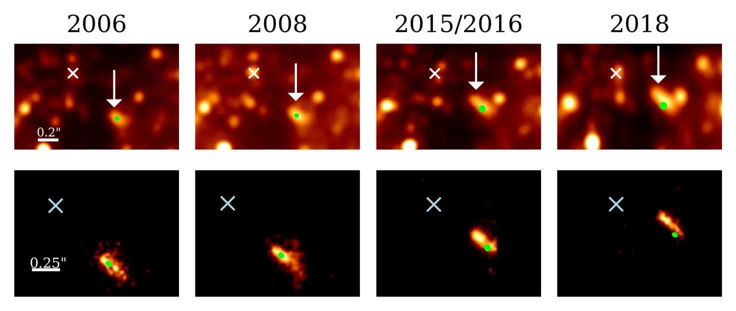
Two comet-shaped sources **–X3 and X7–**at 0.8" and 3.4" from Sgr A*



Interaction with the fast collimated nuclear outflow, **Muzic et al., 2010**

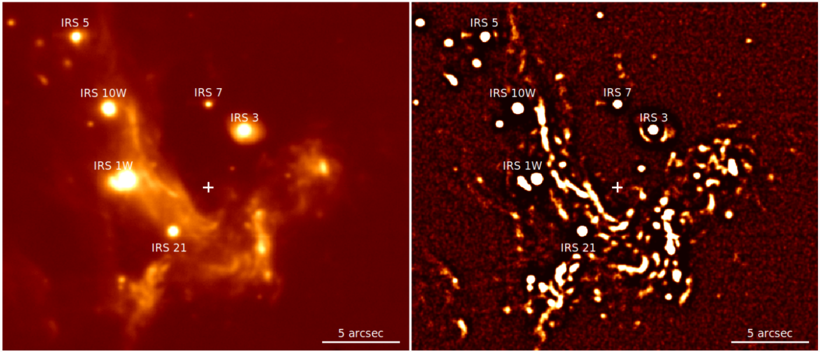
Results - Implications for the current state of Sgr A*

- the closest bow-shock source X7 exhibits morphological changes as it moves around Sgr A*
- gets progressively elongated and shows signs of envelope disintegration; see **Peissker, Ali, Zajaček et al. (2021)** for details
- **ablation by the low surface-brightness jet?!**



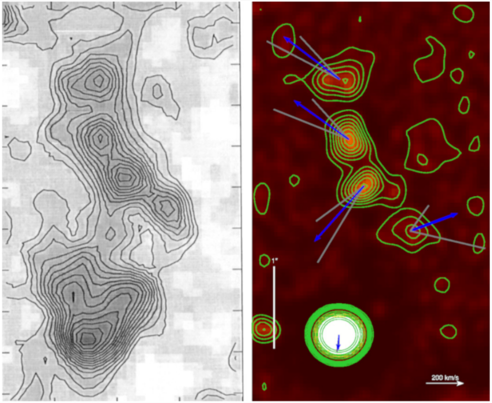
Other candidate sources in the Nuclear Star Cluster

Central 24" $\times$24" of the NSC in PAH1 filter (8.59 μm) (VISIR@VLT); Bhat et al. 2022 (submitted).



Other candidate sources in the Nuclear Star Cluster

IRS7: pulsating red supergiant (M1/M2), 5.5" north of Sgr A*
Prominent tail with a substructure



Left: 2cm radio image (Yusef-Zadeh & Melia, 1992); **Right:** MIR PAH1 smooth-subtracted image with proper-motion directions.

Other candidate sources in the Nuclear Star Cluster

IRS7: pulsating red supergiant (M1/M2), 5.5" north of Sgr A*
Prominent tail with a substracture → **Kelvin-Helmholtz instability**

$$\tau_{\mathrm{KH}} \sim \frac{\lambda_{\mathrm{tail}}}{v_{\mathrm{shear}}} \frac{1+r}{\sqrt{r}} \sim 111\,\mathrm{yr}\,. \tag{2}$$

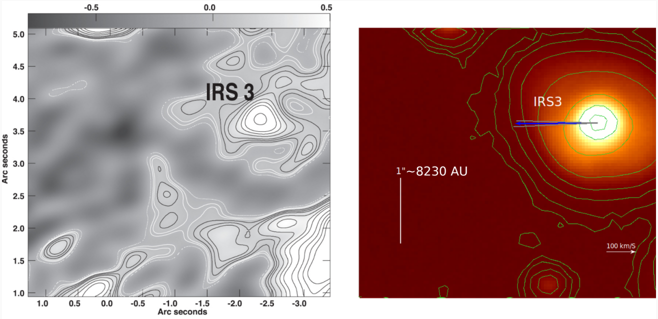
$$\begin{aligned} \tau_{\mathrm{evap}} &= \frac{25 k_{\mathrm{B}}\, n_{\mathrm{tail}}\, R_{\mathrm{tail}}^2}{8\kappa_{\mathrm{H}}} \\ &\simeq 4067 \left(\frac{n_{\mathrm{tail}}}{6\times 10^4\,\mathrm{cm}^{-3}}\right)\left(\frac{R_{\mathrm{tail}}}{0.02\,\mathrm{pc}}\right)^2 \mathrm{yr}\,, \end{aligned} \tag{3}$$

KH clumps can survive long enough: $\tau_{\mathrm{KH}} < \tau_{\mathrm{cross}} < \tau_{\mathrm{evap}}$

Other candidate sources in the Nuclear Star Cluster

IRS3: red giant/supergiant; brigtest and the largest stellar source in the NSC

Big fat, puffed-up red giant: $R_{\mathrm{IRS3}} \sim 1'' \sim 0.04\,\mathrm{pc} \sim 2 \times 10^6\,R_\odot$



Left: 226 GHz radio image (Yusef-Zadeh et al., 2017); **Right:** MIR PAH1 untreated image with a proper-motion direction.

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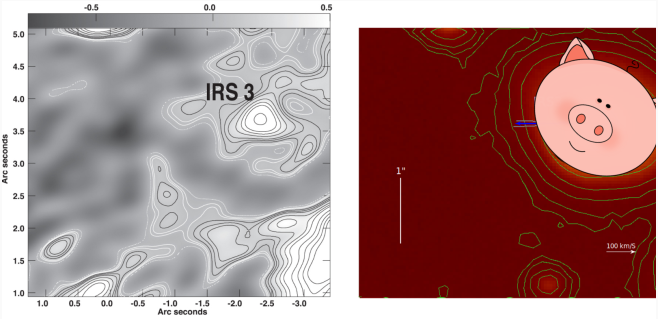

Left: 226 GHz radio image (Yusef-Zadeh et al., 2017); **Right:** MIR PAH1 untreated image with a proper-motion direction.

arXiv:**2009.14364; Michal Zajaček et al 2020 ApJ 903 140**

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CrossMark

Depletion of Bright Red Giants in the Galactic Center during Its Active Phases

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Abstract

Observations in the near-infrared domain showed the presence of the flat core of bright late-type stars inside $\sim$0.5 pc from the Galactic center supermassive black hole (Sgr A*), while young massive OB/Wolf–Rayet stars form a cusp. Several dynamical processes were proposed to explain this apparent paradox of the distribution of the Galactic center stellar populations. Given the mounting evidence on the significantly increased activity of Sgr A* during the past million years, we propose a scenario based on the interaction between the late-type giants and a nuclear jet, whose past existence and energetics can be inferred from the presence of γ-ray Fermi bubbles and bipolar radio bubbles. Extended, loose envelopes of red giant stars can be ablated by the jet with kinetic luminosity in the range of $L_{\rm j} \approx 10^{41}$–$10^{44}$ erg s^{-1} within the inner $\sim$0.04 pc of Sgr A* (S-cluster region), which would lead to their infrared luminosity decrease after several thousand jet–star interactions. The ablation of the atmospheres of red giants is complemented by the process of tidal stripping that operates at distances of $\lesssim$1 mpc, and by the direct mechanical interaction of stars with a clumpy disk at $\gtrsim$0.04 pc, which can explain the flat density profile of bright late-type stars inside the inner half parsec from Sgr A*.

Unified Astronomy Thesaurus concepts: Galactic center (565); Red giant stars (1372); Red supergiant stars (1375); Relativistic jets (1390); Stellar dynamics (1596)