Gaseous environment in LLAGN: modes of interaction with compact star nuclear population

Michal Zajaček[1,2], Vladimír Karas[2], Devaky Kunneriath[2], Andreas Eckart[3,4]

[1]Charles University in Prague, Faculty of Mathematics and Physics, V Holešovičkách 2, 18000 Prague, Czech Republic;
[2]Astronomical Institute, Academy of Sciences, Boční II 1401, 14100 Prague, Czech Republic;
[3]I. Physikalisches Institut der Universität zu Köln, Zülpicher Strasse 77, D-50937 Köln, Germany;
[4]Max-Planck-Institut für Radioastronomie (MPIfR), Auf dem Hügel 69, D-53121 Bonn, Germany.

We employ radio-interferometric data in the mm regime of the ionized medium near the centre of the Milky Way (Sgr A*). We use previously published results (Kunneriath et al., 2012) about physical conditions, the shape and the filling factor of the Mini-spiral feature to estimate the probability of passages of the putative population of neutron stars of the Nuclear star cluster (NSC) through the regions of enhanced density, and to assess different modes of the mutual interaction. Streams of the Mini-spiral gas are ionized by ultraviolet radiation of massive OB stars present in the NSC. Based on the inferred dynamic mass in the central parsec ($\sim 10^6\,M_\odot$), it is estimated that at least $\sim 10^4$ neutron stars should move in the sphere of influence of the Sgr A* SMBH. According to our simulations, a fraction of this unexplored population propagates through denser ionized medium concentrated along three arms of the Mini-spiral. Based on the density and the temperature of the gaseous environment inferred from observations, we analyse interaction regimes of neutron stars passing through this medium. Spectral features are expected to develop within the Mini-spiral due to non-thermal emission from bow shocks of strongly magnetized stars, and these could be revealed with the improved resolution of ALMA in the future. The results and the procedure may be applied to other galactic nuclei hosting NSC and the resulting distribution of interaction regimes is expected to be different across various galaxy types. Results for Sgr A* presented here may serve as a paradigm for low-luminosity AGN (LLAGN).

Introduction

Based on the enclosed dynamical mass of $\sim 10^6\,M_\odot$ in the innermost parsec, the NSC of the Milky Way is expected to host a large number of neutron stars of the order of $\sim 10^4$–10^5. These are expected to interact with the streams of ionized gas – the Mini-spiral, see Figure 1.

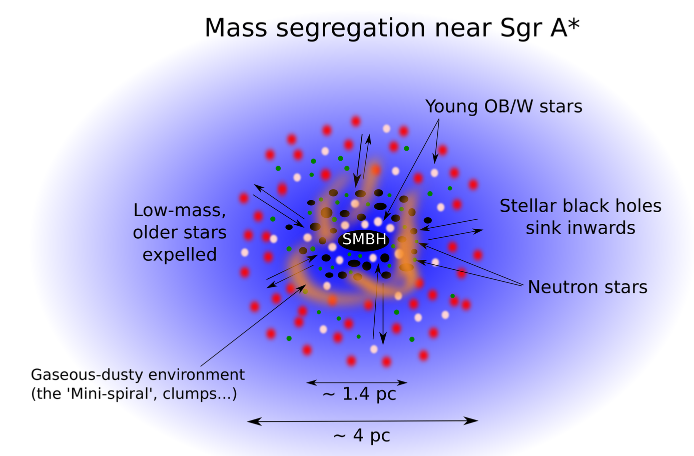

Figure 1: A schematic picture of compact remnants in the Nuclear Star Cluster near the Galactic centre. Neutron stars interact with the streams of ionized gas concentrated along the Mini-spiral arms.

The Mini-spiral properties

The Mini-spiral, the brightest part of the thermal radio source Sgr A West, consists of four main components: the Northern Arm, the Western Arc, the Eastern Arm and the Bar (see Figure 2, Zhao et al. 2009, 2010; Kunneriath et al. 2012). The Mini-spiral consists of a mixture of ionised and neutral gas and dust, with temperature ranging from a few 100s of K dust to up to $\sim 10^4$ K radio bremsstrahlung plasma. The inferred electron densities are $\sim 10^4$–$10^5\,\mathrm{cm^{-3}}$ (Zhao et al 2009, 2010).

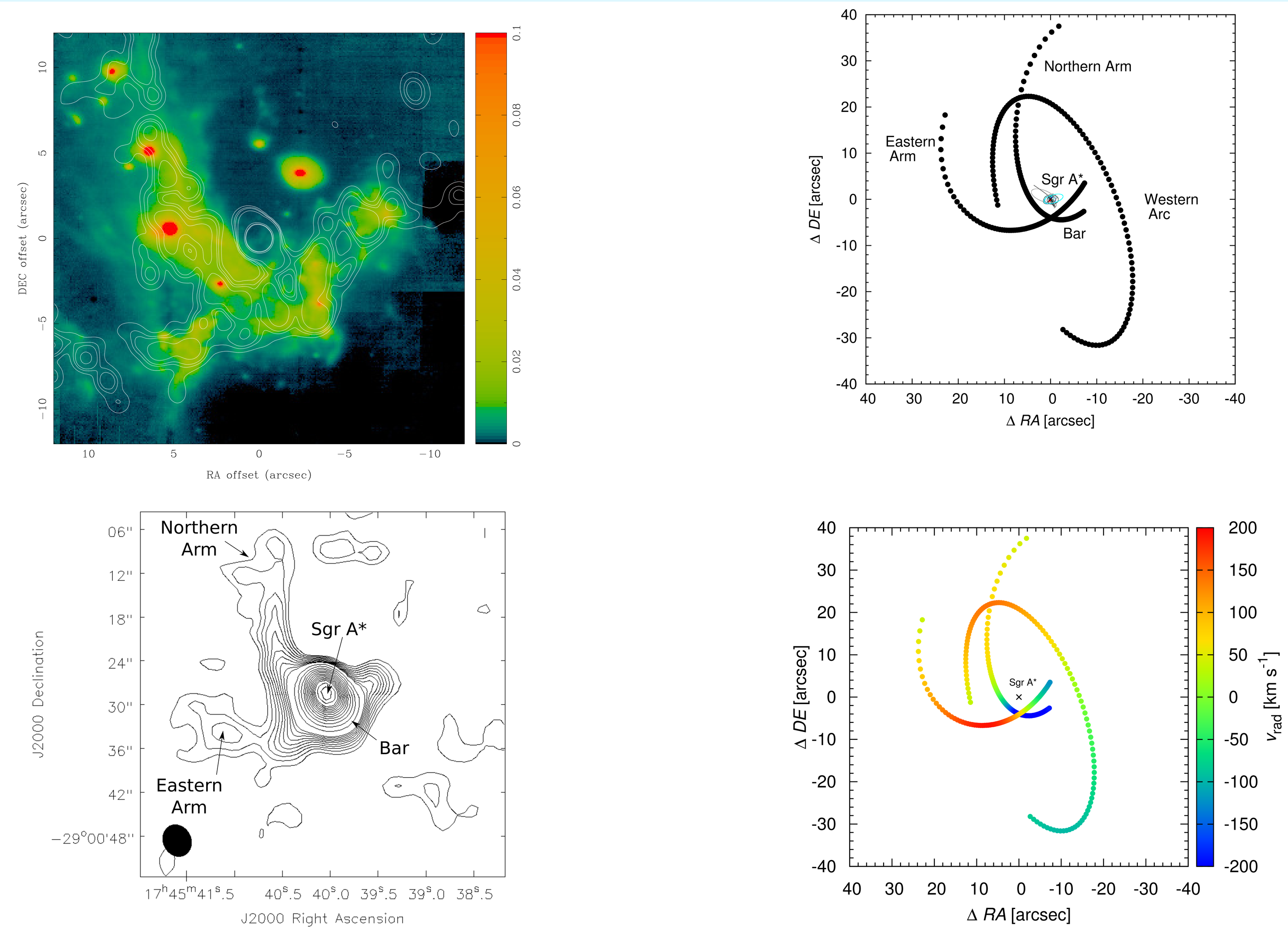

Figure 2: **Left:** Images of the Mini-spiral, (*Top*) 8.6 μm ESO's VLT/VISIR map of the central 40″ region overlaid with a 3 mm CARMA C array contour map of synthesised circular beam size 1″. Contour levels are at 0.0090, 0.015, 0.02, 0.035, 0.3, 0.4, 0.45 Jy/beam (Kunneriath et al. 2012); (*Bottom*) The main components of the Mini-spiral in a 3 mm CARMA image. **Right:** Keplerian model of the Mini-spiral according to Zhao et al. (2009, 2010), (*Top*) Main components; (*Bottom*) Radial velocities (km/s).

Results – Predictions for different interaction modes of neutron stars

The Mini-spiral arms seem to be a more promising target concerning both the number of encounters as well as observable effects than an isolated gaseous clump (such as the dusty S-cluster object G2, see Zajaček et al. 2014, de la Fuente Marcos and de la Fuente Marcos 2013). We use a Monte Carlo approach to study the encounters between neutron star population and the Mini-spiral. The fraction of interacting neutron stars is $\sim 1-10\%$ depending on the size of clumps constituting the Mini-spiral arms; based on observations we set the length-scale of each clump equal to $1'' - 2''$.

The established mode of interaction depends on the intrinsic properties of a neutron star (rotational period, magnetic dipole moment) and external conditions (density, temperature). We study the distribution of three main interaction modes of neutron stars: ejector (E), propeller (P), and accretor (A); see Lipunov (1992). We find that the distribution of these interaction modes is strongly dependent on the plasma density (see Figure 3, left panel), whereas only weakly dependent on the temperature in the range $\sim (10^3, 10^4)$ K. The decrease of rotational frequency, $\dot{\Omega} \propto -\Omega^3$, does not change the initial distribution on the time-scale of $\sim 10^4$ yr unless the magnetic field is considerably decayed. The distribution of interaction modes depends on the intrinsic distribution of periods and the magnetic dipole moments. However, for four considered distributions (see Table 1) and typical densities of the Mini-spiral, the following sequence is valid in terms of the abundance of individual regimes: $E > P \gtrsim A$ (Figure 3, right panel).

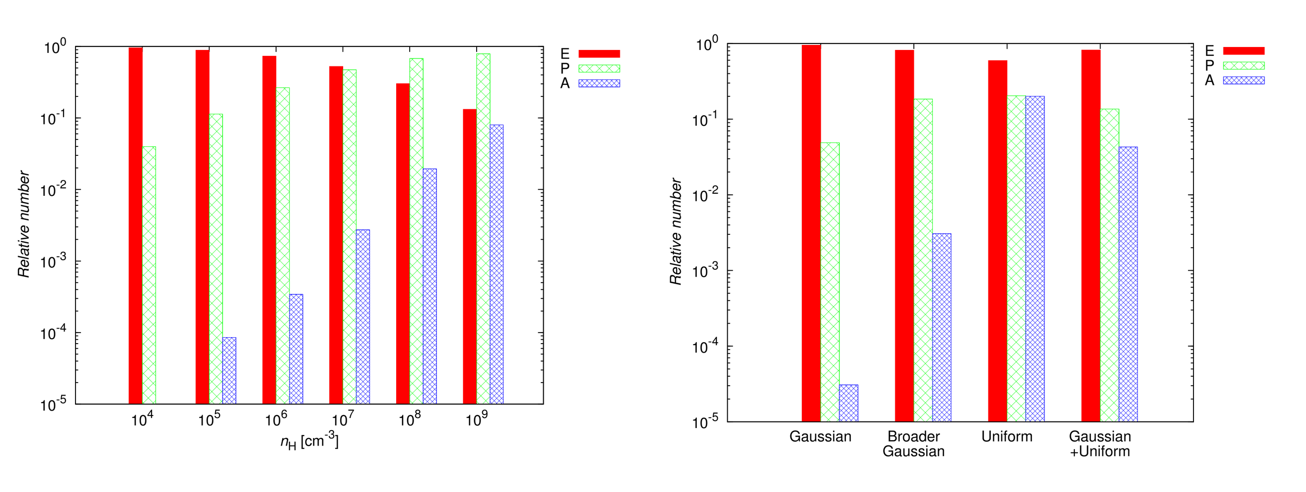

Figure 3: **Left:** Distribution of interaction modes for different plasma densities. **Right:** Abundance of interaction regimes for different distributions of periods and dipole moments of neutron stars.

Distribution number	Type	Parameters
1	Gaussian	$\mu_{\rm P} = -0.2188 \pm 0.0003$, $\sigma_{\rm P} = 0.3488 \pm 0.0004$ $\mu_{\rm B} = 12.0900 \pm 0.0005$, $\sigma_{\rm B} = 0.4711 \pm 0.0005$
2	Gaussian	$\mu_{\rm P} = -0.2178 \pm 0.0004$, $\sigma_{\rm P} = 0.7019 \pm 0.0005$ $\mu_{\rm B} = 12.0888 \pm 0.0006$, $\sigma_{B} = 0.85098 \pm 0.0008$
3	Uniform	$\log P_{\rm min} = -3$, $\log P_{\rm max} = 2$ $\log B_{\rm min} = 7$, $\log B_{\rm max} = 15$
4	Combined	$\mu_{\rm P} = -0.2189$, $\sigma_{\rm P} = 0.3478$ $\mu_{\rm B} = 12.09$, $\sigma_{\rm B} = 0.47$ $\log P_{\rm min} = -3$, $\log P_{\rm max} = 2$ $\log B_{\rm min} = 7$, $\log B_{\rm max} = 15$

Table 1: Distributions of the period and the magnetic field of neutron stars whose interaction regimes are plotted in Figure 3.

Send offprint requests to: M. Zajaček (michal.zajacek31@gmail.com).

Three interaction modes (E, P, A) may manifest themselves in different ways. Accreting old ($\tau \gtrsim 100$ Myr) isolated neutron stars can be detected as weak X-ray sources (bolometric luminosities $\sim 10^{30} - 10^{32}\,\mathrm{erg\,s^{-1}}$; Figure 4, left panel). Ejecting neutron stars are generally observed as radiopulsars, but severe scattering screen near the Galactic centre makes it difficult. Alternatively, they could be detected indirectly through bow-shock structures whose characteristic sizes depend on the density of the surrounding medium and intrinsic properties of neutron stars (period, magnetic dipole moment), see Figure 4 (right panel). About ~ 10 of them could be large enough ($\sim 100 - 1000$ mas). See the comparison of their sizes in $20'' \times 20''$ synthetic image of the Mini-spiral (Figure 5, left panel) to the spectral index map inferred from the observations (Figure 5, right panel).

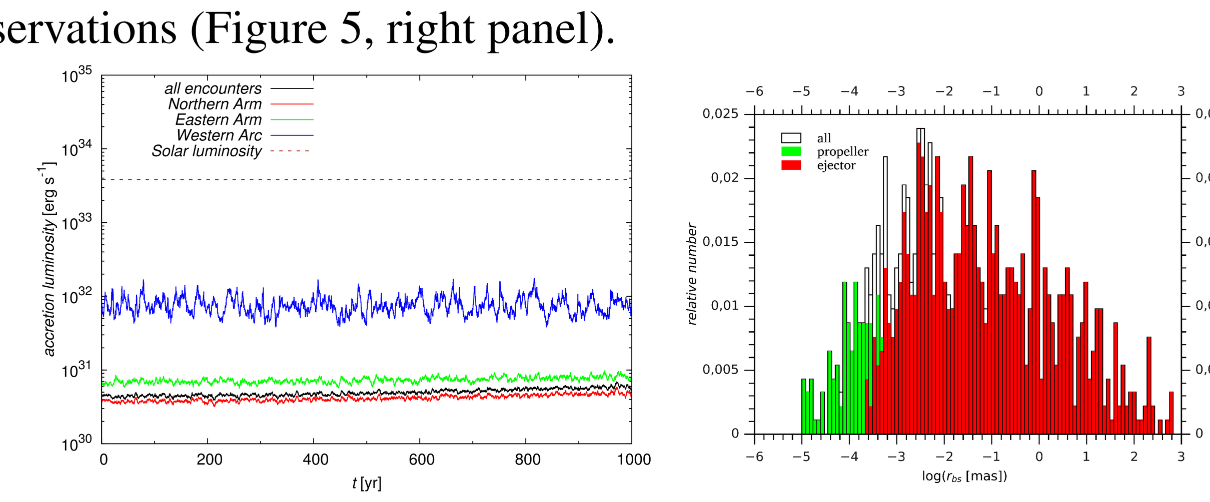

Figure 4: **Left:** Averaged bolometric accretion luminosities computed for different Mini-spiral arms. **Right:** Distribution of the sizes of bow-shock structures for propellers (green) as well as ejectors (red).

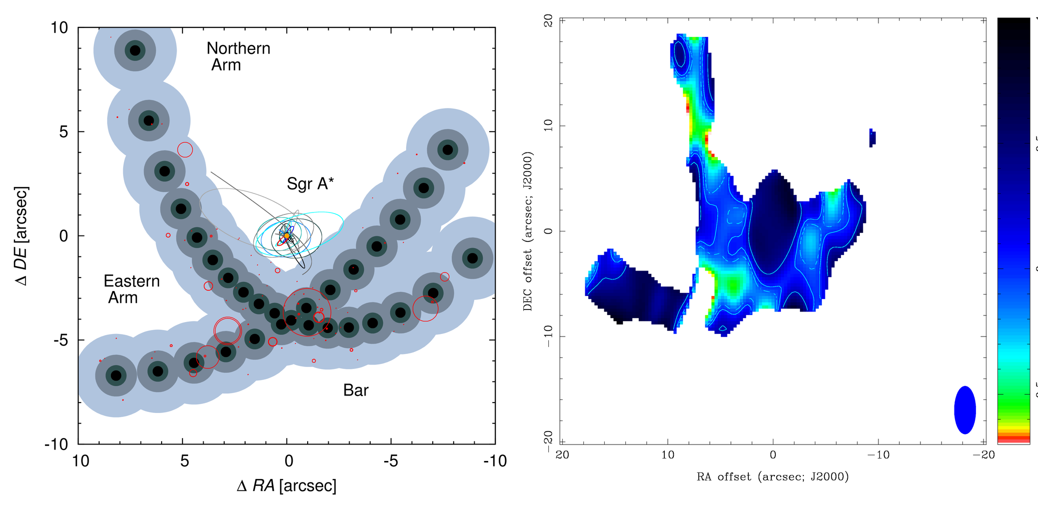

Figure 5: **Left:** Exemplary bow-shock sizes and positions (red circles) of ejectors in the Mini-spiral as a result of a Monte Carlo simulation run. **Right:** Spectral index map produced from the 3 and 1.3 mm maps at a resolution of $4'' \times 2''$ (P.A.=0°). Non-thermal spectral index could indicate the presence of a larger bow shock (given a sufficient resolution).

Acknowledgements: Supported by the Grant Agency of the Charles University in Prague (GAUK 879113).

References

[1] de la Fuente Marcos, R.; de la Fuente Marcos, C. 2013, MNRAS, 435, L19-L23
[2] Kunneriath, D.; Eckart, A.; Vogel, S. N.; Teuben, P.; Mužić, K. et al. 2012, A&A, 538, A127
[3] Lipunov, V. M. Astrophysics of Neutron Stars 1992, (Berlin/Heidelberg: Springer-Verlag)
[4] Zajaček, M.; Karas, V.; Eckart, A. 2014, A&A, 565, A17
[5] Zhao, J-H.; Morris, M R.; Goss, W. M.; An, T. 2009, ApJ, 699, 186-214
[6] Zhao, J-H.; Blundell, R.; Moran, J. M.; Downes, D.; Schuster, K. F.; Marrone, D. P. 2010, ApJ, 723, 1097-1109