Modelling the bow–shock evolution along the DSO/G2 orbit in the Galactic centre

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ABSTRACT
A radially directed flow of gaseous environment from a supermassive black hole affects the evolution of a bow–shock that develops along the orbit of an object passing through the pericentre. The bow–shock exhibits asymmetry between the approaching and receding phases, as can be seen in calculations of the bow-shock size, the velocity profile along the shocked layer, and the surface density of the bow–shock, and by emission-measure maps. We discuss these effects in the context of the recent pericentre transit of DSO/G2 near Sagittarius A*.

Keywords: Galactic center – Sagittarius A* – Astrophysical processes – Bow shocks – DSO – G2 – Interstellar medium

1 INTRODUCTION

A supermassive black hole (SMBH) resides in the centre of our Milky Way, at the distance of $\approx 8.19 \pm 0.11$ kpc (for a very recent exposition, see Parsa et al. 2017). The position of the Galactic center (GC) has been associated with the compact radio source, Sagittarius A* (Sgr A*). It is a highly variable radio, near–infrared, and X–ray source. It is believed that its mass is $M_{\bullet} \sim 4 \times 10^6 M_{\odot}$. Sgr A* is the nearest nucleus of an inactive galaxy to us – about two orders of magnitude closer to us than the next similar nucleus. Thanks to the rich morphology of different objects in mutual interaction, Sgr A* and its immediate neighbourhood are among the most interesting fields in the sky (Eckart et al., 2005; Sanders, 2014).

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The Milky Way does not qualify as an active galaxy because the Galactic Center exhibits a very low level of accretion activity and the emerging electromagnetic signal is very weak compared to typical examples of active galactic nuclei, such as Seyfert galaxies and quasars. We can detect relatively weak events of enhanced emission. Recent multi-wavelength studies show that the current level of activity is low, although this might have been much higher in the past and it could rise in future, once the supply of accretion gas and dust is restored. This can be particularly well seen in X-rays and in NIR/mm wavelengths (Kunneriath et al., 2010).

The Galactic center activity manifests itself not only by the emission at various wavelengths, but also by the presence of streamers of gas within the innermost region with the size of a fraction of parsec. Shocks develop within the violently interacting, multi-temperature environment of gas, dust, stars, and the supermassive black hole (Karas et al., 2007). Stars of the Nuclear Star Cluster serve as probes of the gravitational potential, while their motion can be traced by studying the properties of bow-shocks that develop due to their super-sonic motion (Chatterjee and Cordes, 2002).

The transient component of the signal likely arises very close to the central supermassive black hole. It may thus enable us to study the 'plunge region' (about which very little is known), between the event horizon and its immediate vicinity where the accreting material performs the final inspiral. With the greatly enhanced spectral resolution and throughput, need arises for realistic theoretical models of the accretion flow emission and computational tools that are powerful enough to deal with complex models and to allow actual fitting of theoretical models to observational data. However, the current models available for fitting X-ray data are subject to various restrictions. These limitations became particularly problematic during the recent campaign on the G2/DSO event for which several interpretations have been put forward.

The Galactic centre is a dense region of gas, dust, and stars; variety of structures emerge in the immediate vicinity of SMBH. We concentrate our interest mainly in the DSO/G2 – a Dusty S-Cluster Object, which approached its nearest point to the SMBH (peri-bothron) in 2014. It was suggested to be a core-less gas and dust cloud (Eckart et al., 2014). After the pericentre passage, DSO/G2 stayed rather compact, not loosing matter as expected. A likely interpretation has thus emerged that DSO/G2 could be a young accreting star (Valencia-S. et al., 2015). Based on the polarimetry maps from Shahzamanian et al. (2015, 2016) DSO/G2 could also be a dustenshrouded young star with bipolar outflows that form a bow shock on its way to Sgr A*. Especially the bow–shock scenario (neglecting hydrodynamical instabilities) has been studied in Zajaček et al. (2015, 2016), Štofanová (2016), and Zajaček et al. (2017). Moreover, the hydrodynamical models and maps for DSO/G2 were examined in several recent papers (e.g. Ballone et al., 2013; De Colle et al., 2014; Christie et al., 2016; Ballone et al., 2017, and further references cited therein).

In the present paper we summarise the main aspects of stellar (supersonic) fly-by through the gaseous medium surrounding the central black hole, where bow-shock structures must develop and their morphology can help us to trace the physical properties of the ambient medium.

2 MODEL OF BOW–SHOCKS

Bow shock is a shock wave that is generated by a wind–blowing star moving supersonically with respect to the ambient medium. We model DSO/G2 as a bow–shock structure around a star orbiting the SMBH. Momentum-conserving bow-shock is described by an analytical model Wilkin (1996), where several assumptions are adopted, such as as an effective cooling process and the thin–shell limit (see Fig. 1). The internal momentum within the shell is conserved. At the point of the head–on collision between stellar wind and ISM one can get a formula for so called stand-off distance R_0 as

$$R_0 = \sqrt{\frac{\dot{m}_{\rm w} V_{\rm w}}{4\pi\rho_{\rm A} V^{\star 2}}}\,, \tag{1}$$

where $\dot{m}_{\rm w}$ is the mass rate of the isotropic stellar wind in the distance R_0 from the star, $V_{\rm w}$ is the velocity of the stellar wind, $\rho_{\rm A}$ is the density of the ambient medium (ISM) and $V^\star$ is the velocity of the star with respect to the ambient medium. Stand-off distance can be understood as a parameter which scales the size of the bow shock (it sets the length scale of the shell).

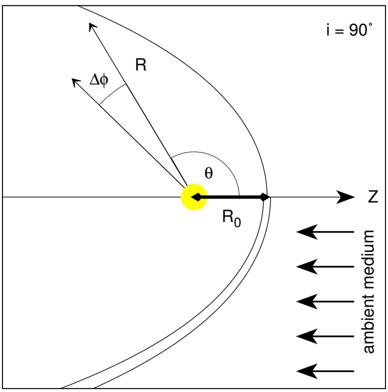

Figure 1. An illustration of the bow-shock shell given by eq. (2). In the star co-moving frame, the star (yellow dot) resides at the coordinate origin. The stellar wind blows in the radial direction, i.e., directed away from the star; z-axis is the symmetry axis of the shell. The ambient medium moves in the opposite direction of the axis z. Parameter R_0 stands for the stand-off distance given by eq. (1), $\Delta\phi$ is azimuthal angle about the symmetry axis, i is the inclination angle, R and θ are polar coordinates.

By assuming this very simple model (Wilkin, 1996) one can obtain an analytic solution for the shape of the bow–shock shell only as a function of polar coordinate

$$R(\theta) = R_0 \csc\theta \sqrt{3(1-\theta\cot\theta)}\,. \tag{2}$$

The surface density and tangential velocity of shocked gas at all points in the shell (eqs. (3) and (4), respectively) can be derived as only a function of θ

$$\sigma(\theta) = R_0\rho_{\rm A} \frac{\left[2\alpha(1-\cos\theta)+\varpi^2\right]^2}{2\varpi\sqrt{(\theta-\sin\theta\cos\theta)^2+\left(\varpi^2-\sin^2\theta\right)^2}}\,, \tag{3}$$

$$v_{\rm t}(\theta) = V^{\star} \frac{\sqrt{(\theta - \sin\theta\cos\theta)^2 + \left(\varpi^2 - \sin^2\theta\right)^2}}{2\alpha(1-\cos\theta) + \varpi^2} \,, \tag{4}$$

where $\alpha \equiv V^{\star}/V_{\rm w}$ is a non-dimensional parameter and $\varpi^2 = 3(1 - \theta\cot\theta)$ is a normalized cylindrical radius obtained from eq. (2).

From eq. (1) one can also obtain the ratio of stand-off distances in the apocentre and pericentre as a function of the eccentricity of the stellar orbit and γ,

$$n_{\rm A} = n_{\rm A0}\left(\frac{r_0}{r}\right)^{\gamma} \,, \tag{5}$$

where n stands for the number density and γ is a power-law index (Zajaček et al., 2016; Štofanová, 2016). Than the ratio of stand-off distances is

$$\frac{R_{\rm 0Apo}}{R_{\rm 0Per}} = \left(\frac{1+e}{1-e}\right)^{1+\gamma/2} \,. \tag{6}$$

Near the passage through the apocentre and pericentre, we should be able to estimate the behaviour of the number density of the ISM. If the ambient medium would be in the hydrostatical equilibrium, the number density should follow the profile Štofanová (2016)

$$n_{\rm a0} = \frac{n_{\rm A}(r)}{n_{\rm A}(r_{\rm s})} = \exp\left[-\frac{GM_{\bullet}m_{\rm H}\mu}{k_{\rm B}T_{\rm A}}\left(\frac{1}{r_{\rm s}} - \frac{1}{r}\right)\right] \,. \tag{7}$$

where $r_{\rm s} = 2GM_{\bullet}/c^2$; $M_{\bullet}$ is the mass of the SMBH, $n_{\rm A}$ stands for the number density of an ambient medium, G is a gravitational constant, c is the speed of light, $m_{\rm H}$ is the mass of hydrogen atom and μ is the relative molecular mass.

3 RESULTS

The results we present here are based on Štofanová (2016) and inspired by Zajaček et al. (2016) where the scenario assuming spherical outflow from the SMBH was taken into account. We give the detailed analysis of the shape of the bow–shock shell (in 2D), how it is changed along the orbit and how the profiles for the tangential velocity and mass surface density along the shell vary assuming four simple scenarios for the ISM movement: (a) without the presence of any gaseous medium emerging from or accreting onto the SMBH, (b) outflow from the SMBH, (c) the case of an inflow onto the SMBH, and finally (d) the combined model involving both an outflow and an inflow at the same time.

We neglected the relativistic effects mainly because, as seen in Fig. 2, the orbit of DSO/G2 object lies more than $10^3\ r_s$ away from the SMBH in our Galactic centre. At the same time we can see that it should be moving with the supersonic velocity for the most of its orbit if not the whole (which depends on the temperature of the ambient medium T_a). In the models we have also included different density profiles for ISM (constant value of 1.67×10^{-21} g/cm^3 or a decreasing function of r); a sequence of values for the stellar wind

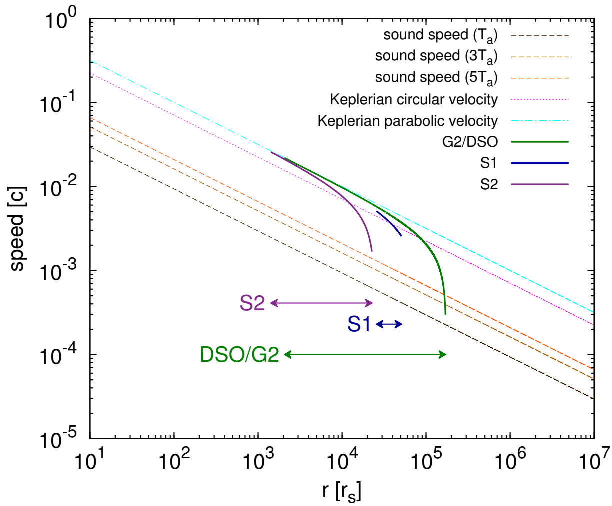

Figure 2. Comparison of Keplerian circular, parabolic and elliptic velocities of sources S1, S2 and DSO/G2 with speed of sound in central cavity (black, light brown and red dashed lines). All mentioned velocities are plotted as a function of distance r from the SMBH. Three lines for speed of sound vary through different temperatures of the ambient medium. All objects (S1, S2 and DSO/G2) are labelled with arrows (range of the arrows is between r_{apo} and r_{peri}).

velocity: 20, 200, and 2000 km/s, and the ISM velocity 100, 500, 1000 and 2000 km/s, respectively.

Here we present only a combined model assuming that the Bondi accretion is a dominant process for the falling material onto SMBH and we set up the Bondi radius to 8000 au (in fact, for the Galactic centre Bondi radius is believed to be at ≃ 33 000 a.u.; cf. Wang et al. 2013). Outside of this radius we assume that the material is moving in the direction away from SMBH. Exactly at the radius the ambient medium is at its rest. By following these assumptions one can get interesting results (see Sec. 4).

4 A COMBINED MODEL

Changes of orientation and the shape of the bow–shock shells due to different parameters can be seen in the Fig. 3 where is a graphical representation of its properties plotted in a cross-section with the orbital plane. One can see that with increasing velocity of the ambient medium the bow shocks are becoming smaller in size and they are being blown–off (outside Bondi radius) or dragged into the sphere of influence of SMBH.

Even more illustrative are the graphs plotted for the stand-off distance R_0 as a function of radius and time (see Fig. 4). The function is symmetric for zero velocity of ISM. As the ambient velocity increases, the function becomes distorted with respect to the pericentre passage (see the plot constructed for several viable scenarios that we had considered). We explored how these different schemes influence the tangential velocity and mass surface density profiles (for further details, see Štofanová 2016). Let us note that the asymmetrical bow-shock shapes are well-known from Pulsar Wind Nebulae (PWN; e.g. Romani et al., 2010; Bykov et al., 2017), where the angle between the magnetic moment and the rotation axis stands as the most decisive parameter. In our case, in addition to orientation of the intrinsic magnetic field, it is the enormous speed of translational motion of the star with

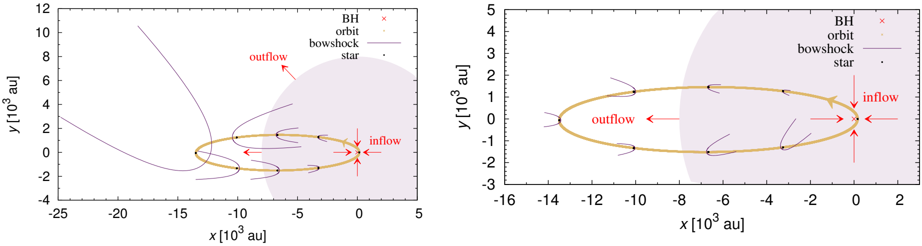

Figure 3. The geometrical shape and orientation of bow–shock shells that are plotted along the orbit for the combined model of an outflow from the SMBH and an inflow onto the SMBH. Graphs vary by the velocity of the outflow V_0, which was set to 100 km/s (left figure) and 2000 km/s (right figure). The parameter of the stellar wind $V_{\rm w}$ is fixed to 200 km/s. Light purple circle marks the area of Bondi radius (Štofanová, 2016).

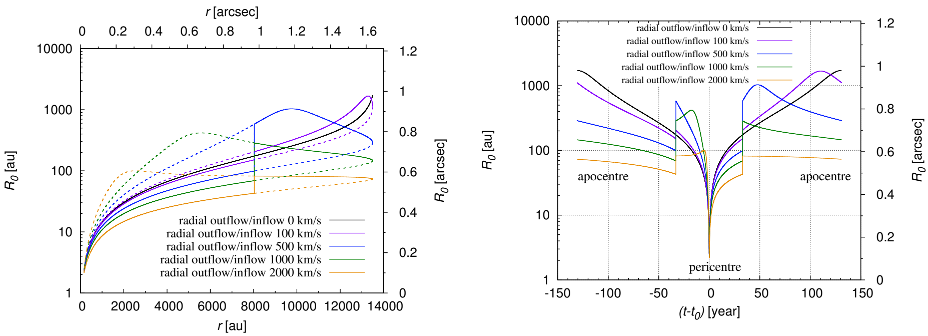

Figure 4. Dependence of the stand-off distance R_0 on the distance r from the SMBH (left panel) and on the time interval $(t - t_0)$ (right panel) for the ambient medium at rest (black line) and for different velocities of the outflow/inflow from/onto the SMBH (colour lines). The time t_0 of the apocentre passage is $\simeq$ 131 years. Solid lines represent post-pericentre phase and dashed lines correspond to pre-pericentre phase.

respect to the inflow/outflow transition of the SMBH accretion flow which have the main impact on the shock morphology. The above-mentioned combined model exhibits the most asymmetrical behaviour.

5 CONCLUSIONS

While DSO/G2 is a recently discovered object, numerous scenarios have been developed to point out its disputable origin. Here we assumed it was a star moving supersonically with respect to the ambient medium and as a consequence of this supersonic motion it creates a bow–shock structure. The aim was to find out how the bow–shock shell can change its properties along the orbit for different scenarios of the ambient medium surrounding the SMBH in our Galactic centre.

We found the combined model to be the most interesting case of all above-assumed scenarios as showing the most asymmetrical morphology in terms of the behaviour of the stand-off distance and star velocity as the functions of the distance and time. One can see that R_0 is the smallest in the pericentre for all considered velocities and with increasing velocity of an outflow/inflow the local maximum is decreasing after the pericentre passage. At the Bondi radius the solution exhibits a jump, which can be made smooth by employing a more realistic scheme for the density of ISM at the transition radius.

Here we presented only thin axisymmetric bow shocks in two dimensions. The bow shocks in three dimensions (with luminosity maps) could improve our models and make them more realistic by including a possibility of more general solutions for anisotropic stellar wind and non-axisymmetric bow-shock structure (Wilkin, 2000; Romani et al., 2010). The progress of a combined model could be formulated by employing self–consistent inflow/outflow accretion scheme, which can avoid somewhat artificial discontinuities at the Bondi radius, seen in our current plots.

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