Bow shocks as tracers of the environment and stellar outflows near the supermassive black hole

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INTRODUCTION

In the centre of the Milky Way, Sagittarius A* is a prototypical example of an underluminous galactic nucleus that harbours a supermassive compact dark object [Eckart+2017]. Its low luminosity has been attributed to an extremely small and inefficient level of accretion activity. Despite that various structures emerge within the sphere of the black hole influence. A dense nuclear cluster surrounds the nucleus and vigorous winds of massive OB/WR stars interact with the overall inward advection of rarefied gas, whereas further out an outflow occurs. We model the occurrence, morphology and geometrical properties of bow shocks that can develop near fast moving stars with emerging winds. We show how the shape and orientation of bow shocks change with the distance from the centre [Zajaček+2016] and in the region where the bulk motion of the flow changes from inflow to outflow [Štofanová 2016]. Under suitable circumstances, a large and dense bow shock structure can be detected in infrared domain and their properties can trace the environment of the Galactic Centre. If the density of the ambient medium (ISM) is determined from mm/radio observations [Kunneriath+2012; Moser+2017], bow shocks can constrain mass-loss rates of massive OB/WR stars.

BOW SHOCKS AND THEIR OCCURRENCE

These gaseous cometary structures occur when the wind-blowing stars move supersonically with respect to ISM. The analytic solution for thin axisymmetric bow shocks (BS) [Wilkin 1996] gives its geometry, so that the radius vector of the shell in polar coordinates can be fully described as a function of polar angle θ. One of the parameters describing BS is standoff distance R_0 which sets the length scale of the BS shell. All the details of the model can be found in Zajaček+2016. As an example we selected DSO/G2, which recently (2014) passed its pericentre at the distance of ~2000 r_s Schwarzschild radii [Gillessen+2012; Eckart+2014; Zajaček +2015, 2016, 2017 and more].

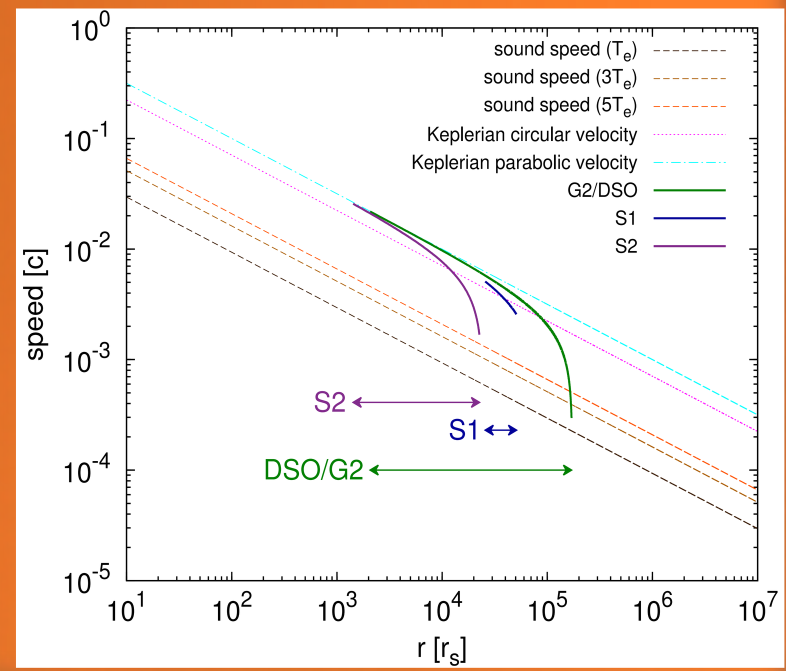
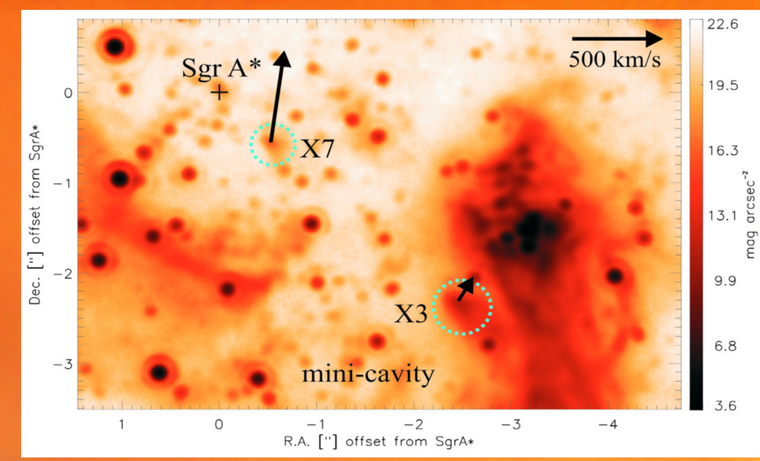


Figure 1. Comparison of Keplerian orbital velocities with speed of sound in the central cavity (for three different electron gas temperatures) [Štofanová 2016]. Stars S1 and S2 are a part of the S-cluster which is located in the close neighborhood of the SMBH in the region from ~(10-10^6) r_S [Psaltis 2012].

BACKGROUND PHOTO shows a bow shock created by LL Orionis young star, as its wind collides with the surrounding interstellar medium of the Orion Nebula central star cluster (Trapezium region in the lower-right corner). For a comparison, figure to the right shows bow shocks around stars X3 and X7 that can be observed near SMBH in our Galactic Centre (marked by +) [Mužić+2010], which is more distant than Orion Nebula.

Background photo credit: Hubble Heritage Team – AURA/STScI; C. R. O'Dell – Vanderbilt Univ; NASA



DIFFERENT SCENARIOS FOR THE MOVING AMBIENT MEDIUM NEAR THE GALACTIC CENTRE

As other astrophysical objects, also black holes have their sphere of influence (if we take a spherical symmetry of the problem into account) where its gravitational potential prevails over the potential of other stars. In the most simplified scenario we can assume that Bondi accretion is the dominant process for the accretion of the surrounding material falling onto Sgr A*. Based on the observations [Wang +2013], Bondi radius of our central SMBH is around 33 000 au. In this case, the whole orbit of DSO should lie inside Bondi radius so the BS orientation should be influenced by the ambient medium falling towards SMBH (Fig.2 left). We take into account also scenario where the Bondi radius is smaller, so that BS crosses the region where outflow of the material prevails over the inflow (Fig.2 right, so called combined model). At Bondi radius we suppose ISM is at rest. In the first approximation we take the temperature profile of the material as constant and the density profile ρ_A radial (more about outflow scenario and other free parameters can be found in Zajaček+2016 and Štofanová 2016).

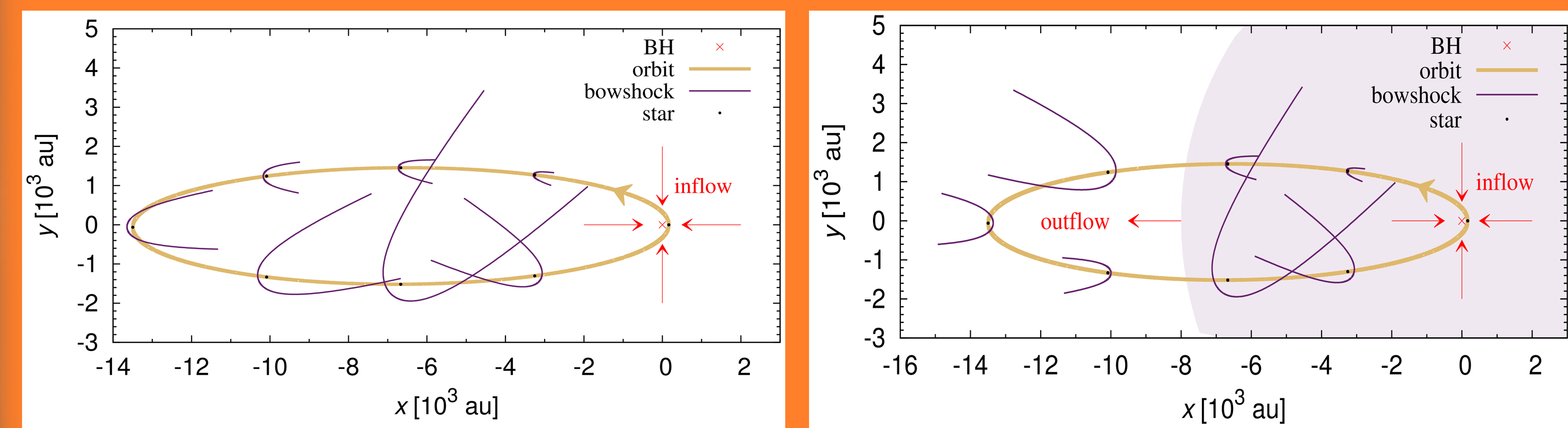


Figure 2. A graphical representation of the shape of bow shocks in a cross-section with the orbital plane (the inclination angle is 90°). The bow-shock shells are shown along the orbit for the inflow scenario (left) and combined model (right). We assume that the ambient medium has a radial movement of velocity 1 000 km/s. Bondi radius for the combined model is set to 8 000 au.

Based on calculations [Štofanová 2016], the size and orientation of the BS shells depend on velocity and density of ISM significantly. Behaviour of R_0 in the previously mentioned models is asymmetric with respect to the pericentre passage (Fig.3) while being symmetric for zero velocity of ISM. Of all mentioned models the combined model is the most asymmetric one. Star velocity profiles show similar asymmetrical behaviour.

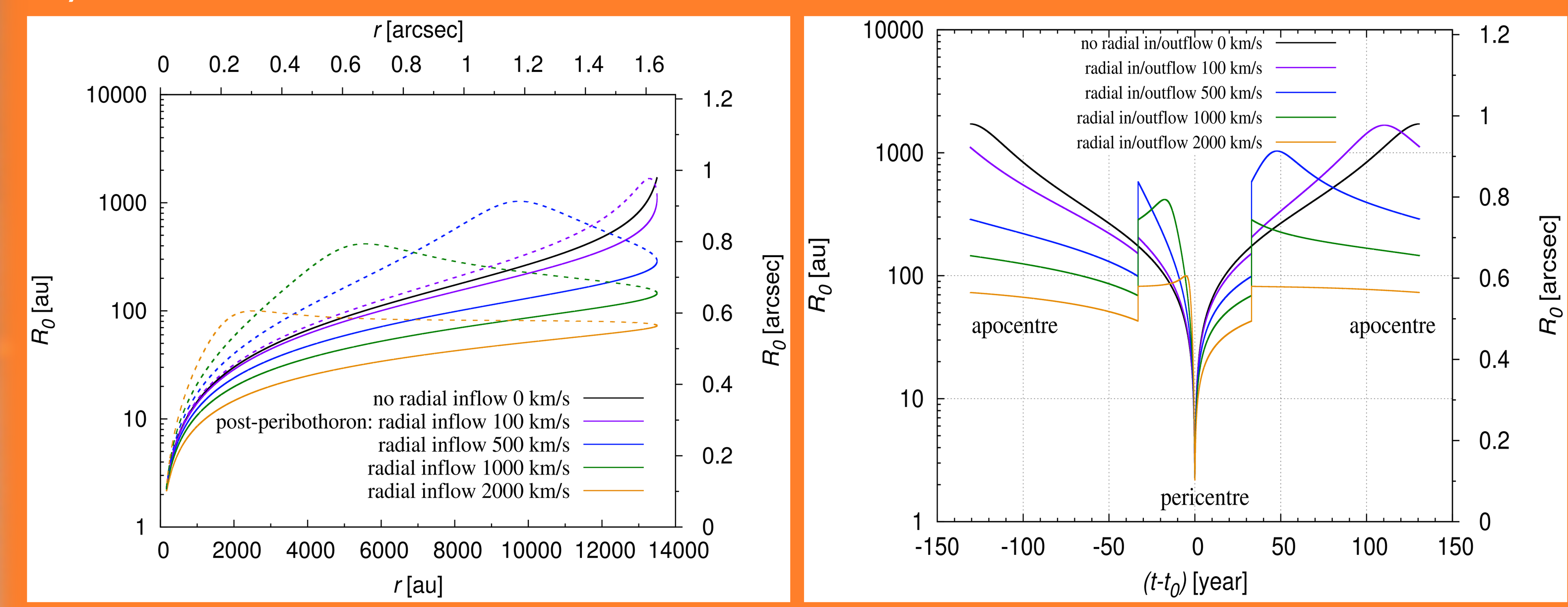


Figure 3. Dependence of the standoff distance R_0 on the distance r from the SMBH (left panel) and on time interval (t–t_0) (right panel) for the ambient medium at rest (black line) and for different velocities of the outflow from the SMBH (colour lines). Constant parameter of t_0 is set to 131 years and it stands for the moment when the star passes through the apocentre. Solid lines represent post-pericentre phase and dashed lines correspond to pre-pericentre phase.

Profiles for tangential velocity and the mass surface density of the shell as a function of θ [Wilkin 1996] show how the mass emanates along the shell of BS. The tangential velocity of the mass is zero at the apex of the shell and it increases towards its tails. The mass density profile has exactly opposite behaviour. Various scenarios and different velocities of ISM change these profiles significantly while being strongly dependent also on the ratio of the star velocity and its wind. We show how these profiles vary along the orbit of DSO in Štofanová 2016.

POLARISATION OF DSO

DSO can be primary tracked in L'-band and recombination line emission (e.g. Brγ) in K-band. It shows a near-infrared excess of Ks-L'>3 and remains compact while approaching its pericentre on the orbit around Sgr A* [Valencia-S.+2015]. Using near-infrared polarimetric imaging data obtained in different years (2008–2012) one can not only determine the nature and the geometry of the source but also get improved Ks-band identification of it in median polarimetry images [Shahzamanian +2016]. As DSO approaches its pericentre the polarisation degree remains approximately constant (~30%) within uncertainties and the polarisation angle varies (Fig.4) so it could possibly be a dust-enshrouded young star with bipolar outflows which forms a bow shock on its way to Sgr A* (for more details see Shahzamanian+2016, Zajaček+2015, 2016, 2017).

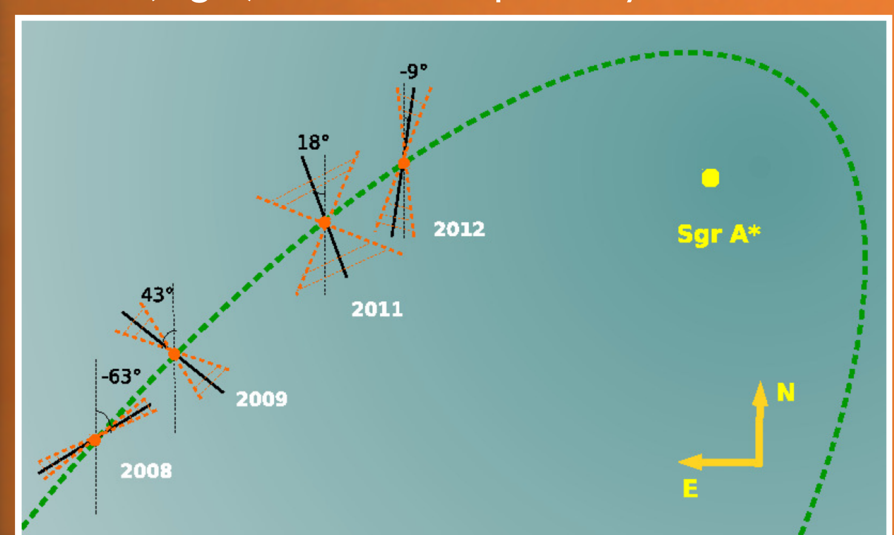


Figure 4. Sketch of the DSO polarisation angle variation when it moves around Sgr A. Orange shaded areas show the range of possible values of the polarisation angle for DSO based on the observation and the measurement uncertainties in Shahzamanian+2016.*

CONCLUSION

We took into account different scenarios of the movement of ISM and how this movement can affect the properties of the bow-shock source (specifically Dusty S-Object) in the nearby vicinity of SMBH in the centre of our Galaxy-Sgr A*. Velocity and density of an ambient medium causes asymmetries in different parameters (R_0, star velocity) with respect to the pericentre passage. While the nature of DSO is still disputable we give a possible theory (based on the polarimetric data) that it could be a dust-enshrouded young star with bipolar outflows (for more see references). One can possibly not only study the geometry and morphology of BS but could also use models and observations in addition to determining the stellar outflows along with the properties of the ambient medium surrounding the source. Based on a simple estimate and on our models for the geometry of BS (for our fiducial S-star), the changes of R_0 along the orbit after 10 years for the outflow model would be observable in both Ks- and L'-bands (see [Štofanová 2016]). The latest results from H.E.S.S collaboration claim that the observation of BS at shorter wavelenghts (e.g X-ray, gamma ray) have not been so far successful in the energy range ~(0.14–18) Tev [Abdalla+2017] though the previous paper [López-Santiago+2012] claims to detect very first X-ray emission at ~30'' to the northeast of the runaway star AE Aurigae (IC 405 nebula) in the energy interval (0.3–8) keV.

REFERENCES: Abdalla+2017, ArXiv: 1705.02263v1 ● Eckart+2014, 303 IAU Symposium ● Eckart+2017, 678 FoPh ● Gillessen+2012, 481 Nature ● Kunneriath+2012, 538 A&A ● López–Santiago+2012, 757 ApJL ● Moser+2017, 322 IAU Symposium ● Mužić+2010, 521 A&A ● Psaltis 2012, 759 ApJ ● Shahzamanian+2016, 678 A&A ● Štofanová 2016, BSc. Thesis ● Valencia-S.+2015, 800 ApJ ● Wang+2013, 341 Science ● Wilkin 1996, 459 ApJL ● Zajaček+2014, 565 A&A ● Zajaček+2015, WDS 2015 ● Zajaček+2016, 455 MNRAS ● Zajaček+2017, 602 A&A

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