Accretion of Stellar Winds in the Galactic Centre

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Abstract
We report a 3-dimensional numerical study of the gas dynamics around Sgr A*, the super-massive black hole at the centre of our Galaxy. We follow the gas from its origin as stellar winds, until its capture by the black hole. Compared with previous investigations, we allow the stars to be on realistic orbits, include the recently discovered slow wind sources, and allow for optically thin radiative cooling. We find that the slow winds shock and rapidly cool, forming cold gas clumps and filaments that coexist with the hot X-ray emitting gas. The accretion rate is on average consistent with the Bondi estimate, but highly variable on time-scales of tens to hundreds of years. Such variability could lead to a strongly non-linear response through accretion flow physics not resolved in our simulations, and it could even make Sgr A*'s X-ray luminosity reach the high values implied by the observation of nearby X-ray reflection nebulae.

Key words: Galaxy: centre – accretion: accretion discs – galaxies: active – stars: winds, outflows

1. Introduction
Sgr A* is identified with the $M_{\text{BH}} \sim 3.5 \times 10^6 M_\odot$ supermassive black hole (SMBH) at the centre of our Galaxy (e.g., Schödel et al. 2002). By virtue of its proximity, Sgr A* plays a key role in the understanding of Active Galactic Nuclei (AGN). Indeed, this is the only SMBH for which observations reveal the origin of the gas in its vicinity. This information is absolutely necessary for the accretion problem to be modelled self-consistently.

One of Sgr A*'s puzzles is its low luminosity with respect to estimates of the accretion rate. Young massive stars in the inner parsec of the Galaxy fill this region with hot gas. From Chandra observations, one can measure the gas properties around the inner arcsecond\footnote{One arcsecond (1") corresponds to $\sim 0.04$ pc, $\sim 10^{17}$ cm, or $\sim 10^5 R_{\text{Sch}}$ for Sgr A*.} and then estimate the Bondi accretion rate (Baganoff et al. 2003). The expected luminosity is orders of magnitude higher than the measured $\sim 10^{36}$ erg s$^{-1}$.

The hot gas, however, is continuously created in shocked winds expelled by the stars near Sgr A*, and the stars themselves are distributed in discs (e.g., Paumard et al. 2006). The situation then is far more complex than in the idealised Bondi model. An alternative approach to study the accretion is to model the gas dynamics of stellar winds, using the measured properties of the wind sources (e.g., Coker & Melia 1997). Here we present our numerical modelling of wind accretion onto Sgr A*, the first to allow the wind-producing stars to be on realistic orbits.

2. Numerical approach and initial conditions
We use the SPH code GADGET-2 (Springel 2005) to simulate the dynamics of stars and gas in the gravitational field of the SMBH (Cuadra et al. 2005, 2006, 2008). To model the emission of stellar winds, new gas particles are continuously created around the stars. The SMBH is modelled as a ‘sink’ particle, with all the gas passing within 0.05" from it disappearing from the computational domain. As this ‘sink radius’ is $\sim 20$ times smaller than the Bondi radius, we can study the accretion onto Sgr A*.

To test the importance of the stellar dynamics, we first performed several simulations with different configurations for the stellar orbits. We found that the angular momentum of the gas has a strong dependence on the orbital motions. Moreover, only the fraction of the gas with the ‘right’ low angular momentum goes to the inner region and can be accreted. Therefore, when the stars are rotating in a disc, the gas has more angular momentum and the accretion rate is lower than in the case where stars orbit the central black hole isotropically (Cuadra et al. 2006). This result highlights the necessity of using realistic orbits to model the accretion onto Sgr A*.

For our latest simulations (Cuadra et al. 2008), we include in our calculations the 30 stars identified as Wolf-Rayet, with their measured positions and velocities (Paumard et al. 2006). For the initial conditions of the stellar winds, we use the wind velocities and mass loss rates calculated from the analysis of individual stellar spectra.
(Martins et al. 2007).

3. Two-phase gas

Figure 1 shows the resulting morphology of the gas at the end of a simulation. Cool dense regions in the gas distribution are mainly produced by winds from stars with relatively slow winds, \( \sim 500 \text{ km s}^{-1} \). When shocked, these slow winds attain a temperature of only around \( 10^6 \text{ K} \), and, given the high pressure environment of the inner parsec of the Galactic Centre, quickly cool radiatively (Cuadra et al. 2005). The cooled gas forms bound clouds, often flattened into filaments due to the SMBH potential. On the other hand, stars with faster winds do not produce much structure. The winds they emit have temperatures \( > 10^7 \text{ K} \) after shocking, and do not cool fast enough to form clumps. This temperature is comparable to that producing the X-ray emission detected by Chandra.

4. Accretion onto Sgr A*

From the simulations we can obtain the accretion history onto Sgr A*. Accretion is here defined by the quantity of gas entering the inner boundary (0.05") of our computational domain.

The accretion rate is of the order of a few \( \times 10^{-6} \text{ M}_\odot \text{yr}^{-1} \) and very variable, changing by factors of a few on time-scales as short as the chosen time resolution of 30 yr. The variability is caused by the eccentricity of the stellar orbits and the stochastic infall of cold clumps (Fig. 2, left). We attempt to model the emission of the accretion flow inside our inner boundary with a crude approximation in which the X-ray luminosity efficiency is a power of the accretion rate. The obtained luminosity is quite variable and can reach very high values (Fig. 2, top right). This seems to be a promising way of explaining the higher luminosity of Sgr A* in the recent past, as implied by the X-ray reflection nebulae detected by Suzaku and other satellites (e.g., Revnivtsev et al. 2004, Koyama et al. 2008, Nobukawa et al. 2008, Nakajima et al. 2009).²

Despite the low resolution of our calculations in this region, we try to quantify the angular momentum of the accretion flow close to our inner boundary. We find that the angular momentum profile is quite flat (Fig. 2, bottom right), and interpret this as a signature that the flow is well mixed and simply advects to the inner boundary. We expect the flow to circularise at \( R \sim 5000 R_{\text{Sch}} \).

5. Discussion

We studied numerically the present day dynamics of the stellar winds around Sgr A*. We found that they create a complicated two-phase medium, with cold clumps immersed in the hot X-ray gas. The resulting accretion rate is variable on time-scales of tens to hundreds of years. This variability implies that Sgr A*'s luminosity could have been much higher just a few hundred years ago, as implied by the X-ray echoes observed in molecular clouds.

Despite the complexity, the average accretion rate is of the order of the Bondi estimate. The reason for Sgr A* dimness lies then inside our inner boundary. Future studies should focus in this region and include the magnetic processes that are likely important at this distance from the black hole. As a first step, we are running hydrodynamical simulations of the inner accretion flow, using as boundary condition the physical properties of the gas at the inner boundary of the larger scale simulations presented here (M.C. Wu et al., in prep.).

Acknowledgements

This paper is based on work done in collaboration with S. Nayakshin, V. Springel, T. Di Matteo, and F. Martins. JC is supported by the CAS Research Fellowship for International Young Researchers, by NSFC (10533030, 10821302), and by the 973 Programme (No. 2007CB815402).

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² See also the contributions of Koyama, Nobukawa, and Nakajima in these proceedings.
Fig. 1. Gas morphology at the present time (\(t = 0\)) from a stellar wind simulation. *Left:* Column density of gas in the inner 6" of the computational domain. Stars are shown with green symbols, with labels indicating their names. *Right:* Averaged temperature of the same region. Notice the dense cold clumps forming around the slow-wind-emitting star 33E. Clumps also form in the region around the 13E group, where the slow winds from 13E2 collide with the faster ones coming from its neighbour 13E4. On the other hand, winds from the powerful WR star 9W have not collided yet with any other winds and remain cold but diffuse. Figures from Cuadra et al. (2008).
Fig. 2. Characteristic of the accretion from one of our simulations. Top left: Accretion rate as a function of time. Different lines show the contribution from different stars. Bottom left: Distance from the close stars to the black hole as a function of time. Notice how the contribution to the accretion rate from some stars correlates with their proximity to the black hole. Top right: Expected X-ray luminosity of the accretion flow calculated with two different efficiency assumptions. Bottom right: Angular momentum profile of the gas in the inner region. Figures from Cuadra et al. (2008).