Variable accretion of stellar winds onto Sgr A*

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Abstract.

We report a 3-dimensional numerical study of the accretion of stellar winds onto Sgr A*, the super-massive black hole at the centre of our Galaxy. 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 first show the strong influence of the stellar dynamics on the accretion onto the central black hole. We then present more realistic simulations of Sgr A* accretion and 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 in this case is highly variable on time-scales of tens to hundreds of years. Such variability can in principle lead to a strongly non-linear response through accretion flow physics not resolved here, making Sgr A* an important energy source for the Galactic centre.

1. Introduction

Sgr A* is identified with the \(M_{\text{BH}} \approx 3.5 \times 10^6 \, M_\odot\) super-massive black hole (SMBH) at the centre of our Galaxy [1, 2]. By virtue of its proximity, Sgr A* may play a key role in the understanding of Active Galactic Nuclei (AGN). Indeed, this is the only SMBH where observations detail 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* puzzles is its low luminosity with respect to estimates of the accretion rate. Young massive stars in the inner parsec of the Galaxy emit in total \(\sim 10^{-3} \, M_\odot \, \text{yr}^{-1}\), filling this region with hot gas. From Chandra observations, one can measure the gas density and temperature around the inner arcsecond\(^1\) and then estimate the Bondi accretion rate [3]. The expected luminosity is a few orders of magnitude higher than the measured \(\sim 10^{36} \, \text{erg s}^{-1}\).

The hot gas, however, is continuously created in shocked winds expelled by tens of young massive stars near Sgr A*, and the stars themselves are distributed in two discs [4]. The situation then is far more complex than in the idealised, spherically symmetric and steady state, Bondi model. An alternative approach is to model the gas dynamics of stellar winds, assuming that the properties of the wind sources are known [5, 6, 7]. Unfortunately, in the calculations just cited the stars were kept fixed in space and radiative cooling was not included. Here we present our numerical modelling of wind accretion onto Sgr A*, the first to include optically thin radiative cooling and allow the wind-producing stars to be on Keplerian orbits.

\(^1\) One arcsecond (1") corresponds to \(\sim 0.04 \, \text{pc}, \sim 10^{17} \, \text{cm} \) or \(\sim 10^5 R_\odot\) for Sgr A*. 

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2. Numerical approach and first results

We use the smooth particle hydrodynamics (SPH) code GADGET-2 [8] to simulate the dynamics of stars and gas in the gravitational field of the SMBH. Because of the Lagrangian nature of SPH, we can easily set the stars on orbits around Sgr A*. To model the stellar winds, new gas particles are continuously created around the stars. The SMBH is modelled as a ‘sink’ particle [9, 10], with all the gas passing within a given distance from it (0.05″ in the present simulations) disappearing from the computational domain. In addition, since we are not interested in following the evolution of the gas that leaves the inner region, we eliminate all the gas that goes beyond a 20″ outer boundary. More details of the numerical method along with validation tests have been presented elsewhere [11, 12].

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 [12]. This result highlights the necessity of using realistic orbits to model the accretion onto Sgr A*.

We then introduced in the simulations the luminous blue variable candidates (LBVs), mass-losing stars with outflow velocities of only $v_{w} \approx 300 \text{ km s}^{-1}$, low enough to be susceptible to radiative cooling. When including this process in the calculations, we found that the winds emitted from these stars indeed cool and form clumps and filaments, creating a complex two-phase medium together with the hotter gas coming from Wolf–Rayet stars (WRs). In addition, the existence of clumps adds variability to the accretion rate. Every time a clump is captured by the black hole, a sharp peak is produced [11, 12].

3. Set-up of the new simulations

In our previous calculations (§ 2), we used an ensemble of stars in circular orbits with roughly the same properties as the observed population. For the new simulations presented here, we use the latest available data for individual stars, going a step forward on the creation of more realistic models.

3.1. Stellar wind data

As wind sources in our calculations, we use the 30 stars identified as WRs or LBVs [4]. We do not include the stars IRS 3E and 7SE2, because of the poor constraints on their orbits.

To set the initial conditions of the stellar winds, we use the wind velocities and mass loss rates calculated for the stars IRS 5SW, 7SE, 7W, 15NE, and 16SE2, and for AFNWNW, AF, and AFNW [13]. For the rest of the stars we use the wind velocities derived previously [14] when available, otherwise we set $v_{w} = 1000 \text{ km s}^{-1}$. The mass loss rate for the stars without data is set to a common value such that the total mass loss rate from all the stars is $10^{-3} \text{ M}_\odot \text{ yr}^{-1}$. However, as the slow wind stars ($v_{w} < 500 \text{ km s}^{-1}$) are very important for the resulting gas morphology, and their mass loss rates are not well constrained, we experiment in some of the runs changing their mass loss rate to a lower value, while the fast wind stars values are increased accordingly, to keep the total $\dot{M}$ fixed.

In addition to the WR stars, we include as a wind source the object IRS 13E3. This is supposed to be the core of a small stellar cluster harbouring a few mass-losing stars [15, 16]. We count IRS 13E3 as 2 stars in terms of mass loss rate. As we expect some of the kinetic energy from its winds to dissipate ‘inside’ the cluster, we set its wind velocity to only $v_{w} = 500 \text{ km s}^{-1}$. 
Figure 1. Left panel: Column density of gas in the inner 6″ of the computational domain, as it would be observed from Earth. Stars are shown with green symbols, with labels indicating their identity. Right panel: Averaged temperature of the same region. Notice the dense cold clumps forming around the IRS 16 and 13 groups, where slow winds from different stars collide. Additionally, the winds from the powerful WR star IRS 16E2 that have not collided yet with any other winds remain cold but diffuse.

3.2. Orbital data

We use the published positions and velocities for the mass-losing stars [4]. For the stars without a \( z \) coordinate, this is set putting the star in the corresponding disc. For some of the stars (IRS 16NW, 29N, AFNWNW) this would put them in orbits that take them too close to the black hole. To avoid numerical problems, we changed their velocities within the error bars, increasing the pericentre distance for their orbits. It should be noticed that this is a conservative approach when computing the accretion rate, both in terms of quantity and variability.

After setting the current 3d positions and velocities for the stars, we use NEMO’s [17] N-body code GYRFALCON [18] to evolve the orbits back in time for \( \sim 1200 \) yr. The positions and velocities at this time were used as initial conditions for the SPH simulations.

4. Two-phase gas

Figure 1 shows the resulting morphology of the gas at the end of one simulation. Cool dense regions in the gas distribution are mainly produced by winds from LBVs. When shocked, these slow winds attain a temperature of only around \( 10^6 \) K, and, given the high pressure environment of the inner parsec of the GC, quickly cool radiatively [11]. LBV winds form bound clouds of gas, often flattened into filaments due to the SMBH potential. On the other hand, the WRs by themselves do not produce much structure. The fast winds they emit have temperatures \( > 10^7 \) K after shocking, and do not cool fast enough to form clumps. This temperature is comparable to
that producing X-ray emission detected by Chandra. Gas cooler than that would be invisible in X-rays due to the finite energy window of Chandra and the huge obscuration in the Galactic plane.

We find that it is harder to form a disc-like structure like the one found in our previous studies [11, 12]. The main reason for this is that in the present simulations there is not as much cold gas. The LBVs – from whose winds the cold clumps are mostly formed – have mass loss rates in the range $5 \times 10^{-7} - 1.5 \times 10^{-5} \, M_\odot \, yr^{-1}$, smaller than the $5 \times 10^{-5} \, M_\odot \, yr^{-1}$ used before, while their number went down from 9 to 6. Moreover, while before we put most slow wind stars in the same plane, now we put only two out of the three innermost stars in one plane, so in this case the preference for one plane is lower.

Another reason that prevents the formation of a disc is the presence of the energetic star IRS 16SE2 – its winds blow away any forming disc. Actually, one test where $\dot{M}_{16SE2}$ was decreased by a factor 10 from its measured value appeared to be more favourable for the formation of a disc.

5. Accretion onto Sgr A*

From any of our simulations, we can extract 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.

In all the simulations the accretion rate is quite variable, changing by factors $\sim 10$ on timescales as short as the chosen resolution of 10 yr. The variability is mainly caused by the accretion of clumps originating from material produced by the few innermost slow wind stars in the IRS 16 group (see Fig. 2). But even if the mass loss rates from these stars are reduced by more than a factor 10, a large degree of variability remains (see Fig. 3).

In our previous work [12], we had found that the accretion onto the SMBH could be separated into a quasi-steady hot component and a variable cold one coming from the episodic accretion of clumps. In these new calculations, we find instead that most of the accreted material is actually hot ($T > 10^7 \, K$), regardless of which star it originates from. This is most likely the effect of eccentric orbits for the stars. Such orbits increase the total velocity of the wind near orbit’s pericenter. Hence even winds from narrow line stars become hot when shocked in the inner arcsecond.
While we cannot resolve the inner accretion flow to predict the actual accretion rate onto Sgr A*, we estimate that variability by a factor of a few should still reach the black hole. In the extremely sub-Eddington regime of Sgr A*, a small change in the accretion rate produces a non-linear response on the luminosity [19]. The results from our simulations, the observational evidence for higher luminosity in the recent past [20], and the idea of star formation in an AGN-like accretion disc a few million yr ago [21], all suggest that on long time-scales Sgr A* is an important energy source for the inner Galaxy.

6. Line emission
To compare better the outcome of our simulations with actual observations, we create emission maps of atomic lines that are expected from gas at $T \sim 10^4$ K. Here we concentrate mostly in the inner arcsecond, where the influence of the mini-spiral can be neglected.

In the simulations the minimum temperature is set to $T = 10^4$ K, otherwise the time-steps could become prohibitively short. It is then questionable whether in reality atomic line emission would arise from the gas in the GC. However, the powerful UV radiation from the stars ensures that most of the gas remains ionised.

From our simulations we create maps to compare with published images of Paα emission [22]. We calculate the luminosity per unit volume as $4\pi j_{\text{Pa}\alpha} = 6.41 \times 10^{-18} \text{erg cm}^{-3} \text{s}^{-1} T^{-0.87} n_{\text{H}}^2$. Examples of resulting images are plotted in Fig. 4. Since there is still uncertainty on the stellar orbits, it is not possible to make a direct comparison of these images with observations. However, from the examples it is clear that the total emitted luminosity depends on the winds properties. While the emission on the right panel of Fig. 4 can be easily hidden in the observed maps [22], this might be not the case with the left panel. With this approach, we can constrain the mass loss rate from slow wind stars in the GC in a way complementary to the stellar spectra analysis [13].

7. Conclusions
Here we presented our new numerical simulations of wind accretion onto Sgr A*. Compared with previous works, our methodology includes a treatment of stellar orbital motions and of

\[ Q = 10^{46} Q_{46} \text{ s}^{-1}, \]  

\[ 1.38 \text{ pc} Q_{46}^{1/3} n_2^{-2/3}. \]
optically thin radiative cooling. While the results depend on the assumptions about stellar mass loss rates, orbits, and wind velocities, some relatively robust conclusions can be made.

Unless mass loss rates of narrow line stars are strongly over-estimated, the gas at $r \sim 1''$ distances from Sgr A* has a two-phase structure, with cold filaments immersed into hot X-ray emitting gas. Both the fast and the slow phase of the winds contribute to the accretion flow onto Sgr A*. The accretion rates we obtain are of the order of a few times $10^{-6} \, M_\odot \, yr^{-1}$, consistent with the *Chandra* estimates, although very variable on time-scales as short as tens of years. This implies that the current very low luminosity state of Sgr A* may be the result of a relatively unusual quiescent state. It also means that the real time-averaged output of Sgr A* in terms of radiation and mechanical jet power may be orders of magnitude higher than what is currently observed. The role of Sgr A* for the energy balance of the inner region of the Galaxy may therefore be far more important than its current meager energy output would suggest.

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