Accretion of cool stellar winds on to Sgr A*: another puzzle of the Galactic Centre?

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ABSTRACT
Sgr A* is currently being fed by winds from a cluster of gravitationally bound young mass-losing stars. Using observational constraints on the orbits, mass-loss rates and wind velocities of these stars, we numerically model the distribution of gas in the ~ 0.1–10 arcsec region around Sgr A*. We find that radiative cooling of recently discovered slow winds leads to the formation of many cool filaments and blobs, and to a thin and rather light accretion disc on a scale of about an arcsecond. The disc, however, does not extend all the way to our inner boundary. Instead, hot X-ray-emitting gas dominates the inner arcsecond. In our simulations, cool streams of gas frequently enter this region on low angular momentum orbits, and are then disrupted and heated up to the ambient hot gas temperature. The accreting gas around Sgr A* is thus two-phase, with a hot component, observable at X-ray wavelengths, and a cool component, which may be responsible for the majority of the time variability of Sgr A* emission on time-scales of 100–1000 yr. We obtain an accretion rate of a few × 10⁻⁶ M⊙ yr⁻¹, consistent with Chandra estimates, but variable on time-scales even shorter than 100 yr. These results strongly depend on the chosen stellar orbits and wind parameters. Further observational input is thus key to a better modelling of the Sgr A* wind accretion.

Keywords: accretion, accretion discs – methods: numerical – stars: winds, outflows – Galaxy: centre – galaxies: active.

1 INTRODUCTION
Sgr A* is identified with the M BH ~ 3 × 10⁶ M⊙ supermassive black hole (SMBH) in the centre of our Galaxy (e.g. Schödel et al. 2002; Ghez et al. 2003). By virtue of its location, Sgr A* may play a key role in the understanding of active galactic nuclei (AGN). Indeed, this is the only AGN where recent observations detail the origin of the gas in the immediate vicinity of the SMBH capture radius (e.g. Najarro et al. 1997; Paumard et al. 2001; Baganoff et al. 2003; Genzel et al. 2003b). This information, missing for all other AGN because of the great distance to them, their large luminosity, or both, is absolutely necessary if the accretion problem is to be modelled self-consistently.

Arguably the most famous puzzle of Sgr A* is its low luminosity with respect to estimates of the accretion rate at around the capture radius, i.e. at distances of the order of 1 arcsec ~ 10⁵ R S ~ 0.04 pc, where R S is the Schwarzschild radius of Sgr A*. Two methods have been deployed to obtain these estimates. From Chandra observations of the Galactic Centre region, one can measure the gas density and temperature around the inner arcsecond and then infer an estimate of the Bondi accretion rate of M ~ 10⁻⁶ M⊙ yr⁻¹ (Baganoff et al. 2003). However, unlike in the classical textbook problem (Bondi 1952), hot gas is continuously created in shocked winds expelled by tens of young massive stars near Sgr A*, and there is neither a well-defined concept of gas density and temperature at infinity, nor one for the gas capture radius.

The other method addresses this problem by direct modelling of the gas dynamics of stellar winds, assuming that the properties of the wind sources are known. Three-dimensional simulations of wind accretion around Sgr A* were performed by Coker & Melia (1997), who randomly positioned 10 mass-losing stars a few arcseconds away from Sgr A*. They presented two different runs in which the stars were distributed in either a spherically isotropic or a flattened system. Rockefeller et al. (2004) used a particle-based code with more detailed information on stellar coordinates and wind properties. However, in both cases the stars were at fixed locations, whereas in reality they follow Keplerian orbits around the SMBH. The accretion rate on to Sgr A* predicted by both studies was estimated at ~ a few × 10⁻⁶ M⊙ yr⁻¹. Finally, Quataert (2004) studied the problem in the approximation that there are an infinite number of wind sources distributed isotropically around Sgr A*, in a range of radii. His model yields an accretion rate estimate of ~ a few × 10⁻⁵ M⊙ yr⁻¹.

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Owing to recent impressive progress in observations of Sgr A*, we now know much more about the origin of the gas feeding the SMBH. Stellar wind sources are locked into two rings that are roughly perpendicular to each other (Paumard et al. 2001; Genzel et al. 2003b). In addition, the wind velocities of several important close stars have been revised downward from \( \sim 600 \) km s\(^{-1}\) (Najarro et al. 1997) to only \( \sim 200 \) km s\(^{-1}\) (Paumard et al. 2001), making the Keplerian orbital motion much more important.

Motivated by these points, we performed numerical simulations of wind accretion on to Sgr A* including optically thin radiative cooling and allowing the wind-producing stars to be on Keplerian orbits. In this Letter we report our most important findings: (i) the cooling and allowing the wind-producing stars to be on Keplerian

\[ v^* = \frac{\mu_a}{\mu_c} v_k, \]

\[ \tau_{cool} = \frac{3kT}{\Delta n} \approx 10^4 \mu_0^{1/2} v_k^{1/2} p_{-1} \text{ yr}, \]

\[ 1.2 \times 10^{5} \mu_0 v_k^2 \text{ K}, \]

where \( \mu_0 \) is the mean molecular weight in units of half the proton mass. This temperature is to a large degree compatible with the \( T_6 \) \( \approx 1.2 \) keV measured by Chandra at slightly larger radii. The optically thin cooling function, dominated by metal line emission, is \( \Lambda \approx 6.0 \times 10^{-23} T_6^{0.7} (Z/3), \) where \( T_6 \) \( = T/10^4 \) K, and \( Z \) is the metal abundance relative to solar (Sutherland & Dopita 1993). The cooling time is thus

\( T_6 \approx 3 \times 10^{5} \mu_0 v_k^2 \text{ K}, \]

which \( p_0 = n_0 T_6 \approx 3 \times 10^6 \text{ K cm}^{-3}. \) The temperature resulting from collisions of stellar winds with wind velocity \( v_w = 10^5 v_k \text{ cm s}^{-1} \) is

\[ T = 1.2 \times 10^7 \mu_0 v_k^2, \]

\[ (1) \]

the high-pressure environment of Sgr A*.

\[ T \approx 8 \text{ K} \]

is the sum of the wind velocity and the stellar orbital motion. At a

\[ v_k \approx 3 \times 10^6 \text{ cm s}^{-1}. \]

distance of 2 arcsec, for example, the Keplerian circular velocity is

\[ v_k = \frac{R}{\mu_0} \approx 60 (R^*)^{1/2} \text{ yr}, \]

where \( R^* \) is the radial distance to Sgr A* in arcseconds and \( v_k \) is the Keplerian velocity at that distance. This shows that cooling is of no importance for the gas originating in the winds with outflow velocity \( v_\infty \sim 1. \) However, if the wind velocity is, say, \( v_\infty = 300 \text{ km s}^{-1}, \) then \( t_{cool} \) is only roughly 15 yr, which is shorter than the dynamical time. Therefore one could expect slower winds may be susceptible to radiative cooling in the high-pressure environment of Sgr A*. In reality the gas velocity is the sum of the wind velocity and the stellar orbital motion. At a distance of 2 arcsec, for example, the Keplerian circular velocity is about 440 km s\(^{-1}\). With respect to the ambient medium, the leading wind hemisphere will move with velocity \( v_k \sim 1, \) whereas the opposite one will move even more slowly than \( v_\infty. \) This shows that even for winds with velocities \( v_w \gtrsim 500 \text{ km s}^{-1}, \) lagging regions of the wind may still be affected by cooling.

### 2 ANALYTICAL ESTIMATES

The density of hot gas 1.5 arcsec away from Sgr A* is about \( n_e = 130 \text{ cm}^{-3} \) (Baganoff et al. 2003), and the gas temperature is \( T_6 \approx 2 \text{ keV}. \) The pressure of the hot gas is thus \( p_0 = n_0 T_6 \approx 3 \times 10^6 \text{ K cm}^{-3}. \) The temperature resulting from collisions of stellar winds with wind velocity \( v_w = 10^5 v_k \text{ cm s}^{-1} \) is

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where \( \mu_0 \) is the mean molecular weight in units of half the proton mass. This temperature is to a large degree compatible with the \( T_6 \) \( \approx 1.2 \) keV measured by Chandra at slightly larger radii. The optically thin cooling function, dominated by metal line emission, is \( \Lambda \approx 6.0 \times 10^{-23} T_6^{0.7} (Z/3), \) where \( T_6 \) \( = T/10^4 \) K, and \( Z \) is the metal abundance relative to solar (Sutherland & Dopita 1993). The cooling time is thus

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### 3 METHOD AND INITIAL CONDITIONS

A full account of our numerical method, along with validation tests, will appear in Cuadra et al. (in preparation). Here we only briefly describe the method. We use the smoothed particle hydrodynamics (SPH)/N-body code gadget-2 (Springel, Yoshida & White 2001; Springel & Hernquist 2002) to simulate the dynamics of stars and gas in the gravitational field of the SMBH. This code, developed for cosmological simulations, takes into account the (Newtonian) \( N \)-body gravitational interactions of all particles and also follows the hydrodynamics of the gas. We use the cooling function cited in Section 2 with \( Z = 3, \) and set the minimum gas temperature to \( 10^4 \text{ K}. \)

We model the SMBH as a heavy ‘sink’ particle (Springel, Di Matteo & Hernquist 2004; Di Matteo, Springel & Hernquist 2005), with its mass set to \( 3.5 \times 10^6 \text{ M}_\odot. \) For scales of interest, the black hole gravity completely dominates over that of the surrounding stars and gas. The inner boundary condition is specified by requiring the gas passing within the radius \( R_{\text{in}} \) from the SMBH to disappear in the black hole. In addition, particles at distances larger than the ‘outer radius’ \( R_{\text{out}} \) are of little interest for our problem and are simply eliminated.

Stars are modelled as collisionless particles moving in the potential of Sgr A*. The stars emit new gas particles that are initialized with the minimum temperature and a mass \( m_{\text{sp}} = 5 \times 10^{-7} \text{ M}_\odot. \)

The initial particle velocity is the sum of the orbital motion of the star, and a random component. The latter is equal in magnitude to the wind velocity and its direction is chosen randomly to simulate isotropic winds in the frame moving with the star.

Following results of Paumard et al. (2001), we assume that ‘narrow-line stars’ produce winds with velocity \( v_w = 300 \text{ km s}^{-1}, \) whereas the ‘broad-line stars’ produce winds with \( v_w = 1000 \text{ km s}^{-1}. \) We refer to the former as LBV stars, and to the latter as WR stars. The radial extent of the inner stellar ring is from 2 to 5 arcsec, and the inner and outer radii of the outer ring are 4 and 8 arcsec, respectively. The rings are perpendicular to each other for simplicity (Genzel et al. 2003b) concluded that the rings are inclined at \( i \approx 74^\circ \) to each other. We argue that the total number of wind sources is likely to be higher than those that have been resolved so far. On average they would clearly have to be less powerful than estimated by Najarro et al. (1997). We therefore use 20 wind sources in total, with each star losing mass at the rate of \( m_{\text{sp}} = 4 \times 10^{-3} \text{ M}_\odot \text{yr}^{-1}. \)

Note that this is still a factor of \( \sim 2-3 \) below the observationally estimated total mass-loss rate from the Sgr A* star cluster, but some of the wind sources are likely to be outside \( R_{\text{out}} \) and thus should not be included here. Typically, the time-step of the calculation is \( \sim 0.18 \text{ yr}, \) so the mass-loss rate above implies that \( \sim 20 \text{ SPH particles are created around each star per time-step}. \) The stars are distributed in rings uniformly in radius but randomly along the azimuthal angle. Stars in the same ring rotate in the same direction, of course, as they follow circular Keplerian orbits. We populate the inner ring with six LBVs and two WRs, and the outer one with three LBVs and nine WRs.

To increase the resolution in the inner region, we split the SPH particles that get closer than \( 10 \text{ R}_\odot \) to the SMBH. To avoid numerical problems, the splitting is performed at a randomly chosen time – of the order of the dynamical time at that radius – after the particle entered the inner \( 10 \text{ R}_\odot. \) Then the particle is divided into \( N_{\text{split}} = 5 \) new ones that are placed randomly within the smoothing length of the original one. The mass of the old particle is equally divided between the new ones, while the temperature and velocity are kept constant. The rest of the SPH properties are updated.
As fast stellar winds fill the available space, the slower ones are shocked and cool radiatively. Dense shells are formed around the shocks. These shells are torn into filaments and blobs. Different parts of the shells have different velocities and thus angular momenta, creating many cool gas blobs with different velocities. Some are directed to outer radii and have velocities large enough to escape from the computational domain. Others receive velocities directing them inward. At smaller radii the density of blobs is higher, thus they collide, and settle in the plane established by the inner LBVs. The blobs are also sheared by the differential Keplerian rotation, and a gas disc is born at radii somewhat smaller than that of the stellar orbits. The blobs typically consist of a few hundred SPH particles, many more than the minimum 40 neighbours used in the SPH kernel averaging for these simulations.

We find that the disc does not extend all the way inwards, as the inner arcsecond or so is dominated by the hot X-ray-emitting gas. Surprisingly, the hot component originates from both fast and slow winds. Cool filaments that enter the inner region appear to be torn by differential rotation and then shock-heated to the ambient temperature as they interact with the hot gas. Since the disc mass is miniscule by AGN standards, the disc is constantly violently affected by the stars from the other ring. Streams and blobs of cool gas are kicked high up above the disc mid-plane because of interactions with winds from stars crossing the disc. These blobs rain down on to the disc, and some are brought into the subarcsecond region of the flow.

4.2 Accretion on to Sgr A* 

The ‘accretion rate’, $\dot{M}_{\text{BH, onto Sgr A*}}$ is defined in our simulations as the rate at which SPH particles enter the sphere with radius $R_{\text{in}}$, and is plotted versus time in Fig. 2. Solid and dotted lines correspond to time bins of 10 and 200 yr, respectively. The latter seems to be a reasonable estimate for the viscous time-scale of the hot accretion flow at around $R_{\text{in}}$. The average rate we obtain, a few $\times 10^{-6} \, M_\odot \, \text{yr}^{-1}$, is in good agreement with the Bondi estimate

\[ \frac{\dot{M}_{\text{Bondi}}}{\dot{M}_{\text{onto Sgr A*}}} = \frac{\frac{4}{3} \pi \rho_{\text{in}} \times 10^{-4}}{\frac{4}{3} \pi \rho_{\text{in}} \times 10^{-4}} = 1 \]

\[ \dot{M}_{\text{Bondi}} = \frac{4}{3} \pi \rho_{\text{in}} \times 10^{-4} \times 10^{-6} \, M_\odot \, \text{yr}^{-1} \]

4 RESULTS

4.1 Gas morphology

Fig. 1 shows the column density of gas and the stellar wind sources in the inner 6 arcsec of the computational domain. The inner and outer rings are viewed at inclination angles of 40° and 50° in the figure, respectively. The inner ring rotates clockwise in this projection, while the outer one rotates in the opposite sense.1

1 An animated movie of this simulation is available at http://www.mpa-garching.mpg.de/~jcuadra/Winds.
and is one to two orders of magnitude lower than what previous studies found (cf. Section 1). However, factors of a few variability in the accretion rate are immediately obvious. This variability can be tracked down to the arrival of individual cool gas blobs or filaments in the innermost region. Since the density of the hot gas in the vicinity of Sgr A∗ is never zero, the accretion rate never decreases to zero.

It must be stressed that the real $M_{\text{crit}}$ further depends on intricate physical details of the inner accretion flow that we cannot resolve here. Some of the gas entering $R \lesssim R_{\text{in}}$ is unbound and some may become unbound later on as a result of viscous heating in the flow (Blandford & Begelman 1999). Therefore the accretion rate measured in our simulations is best understood to yield the outer boundary conditions for the inner accretion flow, and as such should be a more physically complete estimate of that than the commonly used Bondi accretion rate based on Chandra observations of hot X-ray-emitting gas only.

The number of particles in the inner 1 arcsec (comparable to the Bondi radius estimate for this problem) is about 70,000. This ensures that we have enough resolution at the inner boundary. On average, $\sim 4$ SPH particles are accreted at each time-step.

4.3 Existence of a cold disc in subarcsecond region of Sgr A∗

The cold ‘disc’ found in our simulations is constantly being created, but it is also likely to be destroyed from time to time. Its mass can be estimated as $M_{\text{disc}} = M_{\text{web}} - 10 M_{\odot} (M_{\text{we}}/10^{-3} M_{\odot} \text{yr}^{-1}) t_4$, where $t_4 = t/10^4$ yr and $M_{\text{we}}$ is the mass outflow rate of cool stellar winds. A supernova occurring within the inner 0.5 pc of the Galaxy would easily destroy such a disc. The number of young early-type stars in the Sgr A∗ cluster is likely to be in the hundreds, and some have already reached the WR stage (e.g. Paumard et al. 2001; Genzel et al. 2003b). Assuming that the most recent star formation event occurred a few million years ago, one would then estimate the supernova rate in the inner star cluster of Sgr A∗ to be at least $\sim 10^{-4}$ yr$^{-1}$. For comparison, the viscous time at a radius of 1 arcsec is $10^{4} - 10^{5}$ yr at best (e.g. fig. 2 in Nayakshin & Cuadra (2005)). Furthermore, there is much more cool material on scales of several arcseconds and beyond that may be plunging on to Sgr A∗ (Paumard, Maillard & Morris 2004). Arrival of this mass in the inner accretion disc could also destroy the disc.

Therefore it is likely that the cool disc of $\sim$ arcsecond scales does not smoothly extend inside the subarcsecond region of Sgr A∗. However, occasionally we observe cool gas blobs to directly fall into the capture ‘sphere’ in the simulation. It is also conceivable that events started by a supernova shell passage, or by an infall of additional cool material, could also leave a remnant in the form of a cold disc. Thermal conduction between the two phases could lead to evaporation of a cold accretion disc via the Meyer & Meyer-Hofmeister (1994) mechanism, which is unfortunately model-dependent because of our poor knowledge of the magnetic field geometry and strength.

Nayakshin & Sunyaev (2003) suggested, mainly based on the presence of X-ray flares in Sgr A∗, that there is a cool disc at $\sim 0.01 - 0.1$ arcsec scales and beyond. The required mass of the disc was estimated to be smaller than a solar mass. However, observations of near-infrared flares (Genzel et al. 2003a) put the flares at no more than a few milliarcseconds away from the radio position of Sgr A∗, which is somewhat problematic for this model. Also, the near-infrared flare spectra appear strongly to favour a synchrotron (i.e. SMBH jet) origin. Further, no eclipses or star ‘brightenings’ expected when bright stars approach the disc (Cuadra, Nayakshin & Sunyaev 2003) have been observed so far. Summarizing, there is currently no observational motivation to favour the existence of such a disc in Sgr A∗, although it is also difficult to rule out its presence [unless the disc extends to the SMBH horizon (Falcke & Melia 1997)].

Concluding, we suggest that there cannot be a smooth transition of the larger scale cool disc into the inner subarcsecond regions of Sgr A∗. Nevertheless, the issue of the current existence of a cool disc or its periodic appearance and disappearance is an open subject for future work.

4.4 Note on the importance of initial conditions

While this work appears to be the most detailed (to date) numerical attempt to model the accretion of stellar winds on to Sgr A∗, observational uncertainties in the stellar orbits and wind mass-loss rates and velocities still leave a lot of room for uncertainties in the final results. The latest observations (Genzel & Paumard, private communication) reveal that the narrow-emission-line stars might be more equally divided between the two discs than what we have assumed here. In this case, the disc-like structure would form at a larger scale and be probably not as conspicuous. Similarly, if the mass-loss rate of the ‘LBV’ stars is smaller, the cool disc becomes obviously less massive. In addition, mass-loss rates of LBV stars have been observed to vary by more than an order of magnitude within a few years (e.g. Leitherer 1997). This effect would bring further variability and uncertainty to the results.

Another important ingredient, still missing in our approach, is the inclusion of cooler gas filaments observed to be (possibly) infalling on to Sgr A∗ on scales of several to tens of arcseconds from Sgr A∗. These structures, referred to as the ‘mini-spiral’ (Scoville et al. 2003; Paumard et al. 2004), would undoubtedly change some of our results.

Finally, like all previous numerical investigations (Coker & Melia 1997; Rockefeller et al. 2004; Quataert 2004), we have entirely neglected the contribution of the wind-producing stars on orbits inside the central 2 arcsec. While the most important wind sources are all located outside this region (Najarro et al. 1997; Paumard et al. 2001), the weaker OB stellar winds inside the inner region may still contribute. For example, if their wind loss rates are about the inferred accretion rate, these stars [which appear to be on more randomly oriented orbits: Eisenhauer et al. (2005)] could potentially destroy the disc in the inner arcsecond.$^2$

Future observations of the wind properties and stellar orbits near Sgr A∗ are key to producing an increasingly more realistic model of the accretion flow on to Sgr A∗.

5 DISCUSSION AND CONCLUSIONS

AGN accretion discs are less well understood than discs in X-ray binaries on comparable relative scales, because we do not have good observational constraints on the origin of gas accreting on to the SMBH. Sgr A∗ is becoming the only exception to this as observations improve. In this Letter we have made an attempt to simulate

$^2$ Note that an extreme case of this has already been studied analytically, assuming a ballistic trajectory approximation, by Loeb (2004). He showed that if the inner ‘S’-stars (e.g. Ghez et al. 2005; Eisenhauer et al. 2005) produce wind outflow rates as strong as $\sim 10^{-6} M_{\odot} \text{yr}^{-1}$, then their winds alone could provide enough fuel for the emission of Sgr A∗. However, most of the ‘S’-stars now appear to be of intermediate to later B-type, suggesting that their winds could be orders of magnitude weaker than assumed by Loeb (2004).
realistically the outer ∼ 0.1–10 arcsec region of the gas flow on to Sgr A*. The resulting gas flow is far more complex than thought earlier based on studies that included non-radiative fast stellar winds from stars either fixed in space or distributed in a spherically symmetric fashion. The presence of cool gas in the subarcsecond region, as found here, may considerably complicate the interpretation of observational constraints on the accretion of Sgr A*, although, as discussed above, this does depend on still somewhat poorly known details of stellar orbits and wind parameters.

The average accretion rate in our simulation, a few ×10^{-6} M_⊙ yr^{-1}, is consistent with the estimates of Baganoff et al. (2003) and 1–2 orders of magnitude lower than what previous models found (Coker & Melia 1997; Rockefeller et al. 2004; Quataert 2004). However, this accretion rate changes by factors of a few on time-scales shorter than 100 yr. Then how representative is the current low-luminosity state of Sgr A*, if the feeding of the inner region is indeed as turbulent and time-variable as our simulation suggests? After all, observations of X-ray/γ-ray echoes from nearby molecular clouds indicate that Sgr A* might have been much more luminous some ∼ 300 yr ago (Sunyaev, Markevitch & Pavlinsky 1993; Koyama et al. 1996; Revnivtsev et al. 2004). Another aspect of the same issue is that ‘accretion’ of a cool blob in our simulations is not yet a true accretion event. If the blob manages to survive in the hot gas and settles to a disc or a ring at say ∼ 10^3 R_s, it may circle Sgr A* for a long time without being noticed. Further uncertainty in these results is the interaction between the hot and the cold gas via thermal conduction. If a cold blob enters the inner region of the hot flow, and is evaporated there, how will this affect the flow there? These and other related questions need to be resolved in future work if we want to reach a full understanding of the accretion process on to Sgr A*.

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