Low angular momentum accretion-outflow model of flares from Sgr A*

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ABSTRACT
We employ a low angular momentum accretion-outflow scenario to model the flares emanating out from the central region of Sgr A*. The primary donor for matter accreting onto the central SMBH of Sgr A* is assumed to be the WR star ISR 13 E3. We analytically calculate the specific energy and angular momentum density of stellar wind originating from ISR 13 E3 and study the dynamics of that wind down to the very close vicinity of the central SMBH of Sgr A*. We show that on the way to the Galactic centre, such wind-fed accretion may encounter standing shocks and such shock drives outflow from the close vicinity of the SMBH. Matter content of such outflow is computed and it is argued that such outflow is responsible for production of the Galactic centre flares. We then self-consistently compute the luminosity $L_j$ and the duration time scale $\tau$ of such flares, as a function of fundamental accretion parameters. Our theoretical calculation of $L_j$ and $\tau$ are in good agreement with observational results.

Key words: Galaxy: center - accretion, accretion discs - black hole physics - hydrodynamics

1 INTRODUCTION
The center of our Galaxy harbors a massive black hole, and the surrounding region including the central SMBH is now customarily referred as Sgr A* as a whole, after the radio source first discovered at that location (for a review, see e.g. Melia & Falcke 2001). Sgr A* shows frequent flares originating from the direct vicinity of the central black hole. In the X-ray band, multiple flares are superimposed on a steady, extended emission at the level of $\sim 2.2 \times 10^{33}$ erg s$^{-1}$ cm$^{-2}$ (Baganoff et al. 2003). Two extremely bright flares have been reported so far (Baganoff et al., 2001, Porquet et al. 2003; maximum flux of $1.0 \pm 0.1 \times 10^{35}$ and $3.6^{+0.3}_{-0.4} \times 10^{35}$, respectively), along with many fainter flares observed in the Chandra data (e.g. Eckart et al. 2004). The duration of the flares ranges from half an hour to several hours, while the rise/decay time is found to be of the order of few hundred seconds (Baganoff 2003).

Variable emission was also detected in the NIR band. Quiescence emission takes place at the level of $\sim 1.9$ mJy (Eckart et al. 2004). Variable and quiescent emission was reported by Genzel et al. (2003) based on the VLT observations, and by Ghez et al. (2004) based on Keck data. In two of the events, a 17 min periodicity was found (Genzel et al. 2003). X-ray and NIR outbursts are directly related, as shown by the detection of a simultaneous NIR/X-ray event (Eckart et al. 2004). The 2-8 keV luminosity of the event was $\sim 6 \times 10^{33}$ erg s$^{-1}$ and 2.2 $\mu$m flux was 3.7 mJy. The duration of the X-ray event was 55 - 115 min, with the decay time of such flares measured to be of the order of several minutes. Detection of TeV emission from the Galactic Center (Aharonian et al. 2004) supports the view that emission comes from a jet.

These properties of the flare emission suggest that such flares originate in the innermost region of accretion flow onto the central black hole, and we need to introduce an appropriate theoretical model of accretion to understand the properties of these flares. Most of the works on accretion processes onto the SMBH of Sgr A* concentrate either on almost purely Bondi (1952) type accretion, or on high angular momentum ADAF type flow (Narayan, Yi & Mahadevan 1995; Yuan, Quataert & Narayan 2004), which is sometimes claimed to be coupled with jet-like outflows (e.g. Markoff et al. 2001, Yuan, Markoff & Falcke 2002).

In this letter, however, we employ a different kind of accretion model - a low angular momentum (highly sub-Keplerian) flow with standing shock, to explain the generation of flares from Sgr A* and to compute the luminosity of the flare $L_j$ along with its duration time scale $\tau$ in a self-consistent way. Sub-Keplerian advective accretion onto galactic and extra-galactic black holes is expected to produce multi-transonic behaviour (see e.g. Das 2004, Barai,
Fig. 1: The schematic picture of the wind flow from the star IRS 13E3 towards the Galactic center.

Wiita & Das 2004, and references therein) and standing shocks are an essential ingredient in an low angular momentum flow in general (Das 2002, hereafter D02, Das, Pendharkar & Mitra, 2003, hereafter DPM, and the references therein). Such shocks in turn play an important role in governing the overall dynamical and radiative processes taking place in accreting material and the hot, dense, entropic post-shock fluid is supposed to be responsible for launching jets/outflows from black hole accretion discs (Das & Chakrabarti 1999, hereafter DC, Das, Rao & Vadawale 2003, hereafter DRV, and references therein). Such a coupled accretion-outflow model may reproduce the characteristic behaviours of the Sgr A* flares in a natural way.

2 SOURCE OF THE ACCRETING MATERIAL

Stellar winds originating from the central cluster are plentiful sources of gas. Most of this material is likely to be expelled from the central region (e.g. Quataert 2003) but a remaining fraction may power the observed activity. Among various mass losing stars, particularly active one is the Wolf-Rayet star IRS 13 E3 (Paumard et al. 2001, Melia & Falcke 2001). We assume this star to be the dominant source of the matter accreting onto Sgr A*. We determine the angular momentum and the Bernoulli constant of the flow from IRS 13 E3 in the following way:

We consider the case where the wind velocity is much higher than the orbital velocity of a star. Therefore, the material ejected from a fractional region of the star surface located at $\phi_o$ (see Fig.1) can reach the gravity center with zero angular momentum (see, e.g. Loeb 2004). This angle is given by the condition:

$$\sin \phi_o = \frac{v_{\text{star}}}{v_{\text{wind}}}.$$  

The wind is not significantly accelerated as long as the gravity field is dominated by the stellar component. It is moderately supersonic, with the Bondi-Hoyle-Lyttleton accretion radius, $R_{\text{BHL}}$, given by the formula

$$R_{\text{BHL}} = \frac{2GM}{v_{\text{wind}}^2 + v_s^2},$$

where $v_{\text{wind}}$ is the flow velocity and $v_s$ is the sound speed. We further assume that the velocity $v_{\text{wind}}$ is unmodified down to a distance $R_{\text{BHL}}$. The value of the Bernoulli constant, $\mathcal{E}$,

$$\mathcal{E} = 0.5v_{\text{wind}}^2 + \frac{v_s^2 - \frac{GM}{R_{\text{BHL}} - r_g}}{\gamma_i - 1},$$

is effectively determined by the value of the polytropic index on the inflow, $\gamma_i$, and an assumed gas temperature, where $r_g = 2GM_/c^2$. Through out this work, we use the Paczyński and Wiita (1980) potential to describe the flow.

The spherically-symmetric wind blowing at $\phi \neq \phi_o$ or out of the orbital plane will possess certain amount of positive or negative specific angular momentum (angular momentum density), $\lambda$. In the second order approximation

$$\lambda \approx -v_{\text{wind}}D\delta\phi \cos(\phi_o)\left[1 - \frac{1}{2}\tan \phi_o \delta\phi \right],$$

where $\delta\phi = \phi - \phi_o$, $\phi$ is the azimuthal angle of the element at the star surface and $D$ is the distance between the star and the Galactic center.

A cylindrical fraction of this flow, with $\Delta\phi = R_{\text{BHL}}/D$, and $\Delta\theta \sim R_{\text{BHL}}/D$ will be intercepted by the central black hole, where the angle $\theta$ determines the deviation from the orbital plane.

Integrating the Eq. 4 with respect to $\delta\phi$ and $\delta\theta$ in the limits specified by $\Delta\phi$ and $\Delta\theta$, we obtain the net angular momentum of the flow as:

$$\lambda_{\text{eff}} = \frac{3}{2\pi} \frac{1}{\left(1 - \frac{v_{\text{star}}/v_{\text{wind}}}{\delta\theta}\right)^2} v_{\text{star}} D \left(\frac{R_{\text{BHL}}}{D}\right)^2.$$

The above relation is valid if the star velocity is significantly smaller than the wind velocity. Large value of the angular momentum density of the donor star, $v_{\text{star}}D$, is decreased by small quadratic term in the $R_{\text{BHL}}/D$ ratio.

The formula changes if the wind is not perfectly isotropic. If the departure of the mass flux, $\delta(\rho_{\text{wind}} v_{\text{wind}})/v_{\text{wind}} > 1$, happen at distances $\delta\phi R_{\text{star}}$, the net angular momentum density can be estimated by integrating the formula 4 as

$$\lambda_{\text{eff}} = \frac{1}{\pi} D v_{\text{star}} R_{\text{BHL}}^2 \frac{\delta(\rho_{\text{wind}} v_{\text{wind}})}{\delta\theta v_{\text{wind}}},$$

i.e. the net angular momentum density is a fraction of $R_{\text{BHL}} v_{\text{wind}}$. The flow, initially one-sided, becomes roughly spherical below $R_{\text{BHL}}$. We further express $\lambda$ in dimensionless units $2GM_/c$, and the radius in $r_g$.

3 LOW ANGULAR MOMENTUM FLOW CLOSE TO SGR A*

If the accreting material is assumed to be at rest far from black hole, the flow must exhibit transonic behaviour in order to satisfy the inner boundary conditions imposed by the event horizon. Low angular momentum flow may posses more than one sonic point, as first shown by Abramowicz & Zurek (1981). Typically the external sonic point, $r_{\text{out}}$, lies close to the corresponding Bondi radius. The internal sonic point $r_{\text{in}}$, and the middle sonic point $r_{\text{mid}}$ exist within and outside the marginally stable orbit, respectively, for general relativistic (Das 2004, Barai, Das & Wiita 2004) as well as for post-Newtonian (D02, DFM) model of accretion flow. The location of the sonic points can be calculated as a function of the specific flow energy $\mathcal{E}$ (the Bernoulli’s constant), angular momentum $\lambda$ and inflow polytropic index $\gamma_i$ (see, e.g. §3 of D02 for details of such calculations).

If $\lambda$ is almost zero, a shock does not form, and accretion remains supersonic down to the event horizon and it crosses $r_{\text{out}}$. For slightly larger $\lambda$ the centrifugal barrier becomes strong enough, inflowing matter starts pilling up close to the black hole due to the resistance offered by the barrier, and the depleted matter may break the incoming flow...
behind it and consequently a shock forms. Such shocks may become steady and standing so that they can be studied within the framework of stationary flow (D02, DPM and references therein).

Following D02, we consider here a stationary, non-self-gravitating, non-magnetized, inviscid accretion of polytropic fluid. We assume that the flow proceeds through a standing shock, so the discontinuity in the radial velocity allows to match the supersonic flow through \( r_{\text{out}} \) with the subsonic flow through \( r_{\text{in}} \). The exact location of the shock as a function of parameters \([E, \lambda, \gamma_i]\), is obtained by solving the generalized Rankine-Hugoniot conditions. We assume that the shock is non-radiating and infinitesimally thin.

Formation of the shock leads additionally to the generation of an outflow, and the shock location, \( r_{\text{sh}} \), may be assumed to be the radial length scale of the outflow launching zone. The exact amount of the outflowing material \( M_{\text{out}} \) can be calculated as a function of \([E, \lambda, \gamma_i, \gamma_0]\), where \( \gamma_0 \) is the outflow polytropic index and is always less that \( \gamma_i \) due to the radiation momentum deposition on slowly expanding outflowing matter at shock location. In our work, we assume \( \gamma_0 \) to be a free parameter (subjected to the constraint \( \gamma_0 < \gamma_i \)), although in reality \( \gamma_0 \) may be directly related to the heating and cooling processes taking place in post-shock matter; see DC and DRV for details.

Flares observed from Sgr A* can be due to the emission from this outflowing material. Jet emission seems to be the plausible origin of both the X-ray and the NIR radiation (e.g. Markoff et al. 2001), if the dissipation within the shock itself does not lead to a strong emission. In this case the luminosity of Sgr A* during the flare, \( L_{\text{f}} \), is related to the outflow rate, \( \dot{M}_{\text{out}} \), as \( L_{\text{f}} = 0.1 c^2 \dot{M}_{\text{out}} \). Here we assume the 10% efficiency of energy conversion, since studies of AGN jet indicate rather high efficiency of jets even if the radiative efficiency of the accretion flow is low (e.g. Maraschi & Tavecchio 2003). We basically model a stationary situation. However, the flow pattern with an outflow can fully develop under the condition that the accretion phase with a shock lasts long enough. Therefore, the minimum duration of the flare, \( \tau \), is associated with the infall time scale of post-shock accretion and can be defined as:

\[
\tau = \int_{r_{\text{in}}}^{r_{\text{sh}}} \frac{dr}{u(r)}
\]

where \( u(r) \) is the dynamical flow velocity and \( r_{\text{sh}} \) is the location of the event horizon.

It is to be noted that multi-transonic flow and standing shocks form for a specific region of parameter space spanned by \([E, \lambda, \gamma_i]\) (see, e.g. Figure 4. of D02 for a global classification of shock forming parameter space). For certain values of \([E, \lambda, \gamma_i]\), no multi-transonic or standard mono-transonic stationary solution exists. The corresponding flow pattern becomes inherently time-dependent. Such non-stationary flow might even better account for Sgr A* variability but we have no adequate description of such a flow.

4 RESULTS

We adopt \( 3.8 \times 10^6 M_\odot \) for the black hole mass in Sgr A* (Ghez et. al. 2003) and consider the accretion rate to be equal to \( 10^{-8} M_\odot \) yr\(^{-1}\). The distance to the donor star is 3.5 pc, and the wind velocity of the star, \( v_{\text{wind}} \), is of order of 1000 km/s (adopted after Rockefeller et al. 2004). We assume that the orbital star velocity, \( v_{\text{orb}} \), is 200 km/s, of order of radial velocities of other stars at similar distance from the center although the actual radial velocity of this star is lower (Eckart & Genzel 1997, Paumard et al. 2001). As the polytropic index of the inflow, we take the value \( \gamma_i = 1.426 \), representative for non-relativistic flow, and for the wind temperature we take 1.3 keV, the plasma temperature estimated at the basis of the analysis of the extended X-ray emission (Baganoff et al. 2003a). This means that the flow is moderately supersonic at the \( R_{\text{BHL}} \) (\( v_s = 600 \) km s\(^{-1}\), \( R_{\text{BHL}} = 7.4 \times 10^{16} \) cm or \( 6.6 \times 10^4 r_s \)). These values allow us to estimate the Bernoulli constant of the flow, \( E \), in Eq. 3 as \( 5.2 \times 10^{-6} \) in units of \( c^2 \). The effective angular momentum given by Eq. 5 is usually small, \( \lambda_{\text{eff}} = 0.14 \). This means that
typically the flow can proceed directly toward the black hole, without the need for angular momentum loss and without considerable dissipation. However, if the wind is occasionally non-uniform, $\delta(\rho_{\text{wind}}v_{\text{wind}}) < \rho_{\text{wind}}v_{\text{wind}}$ of order of 2 percent, changes the net angular momentum by a factor of 11. Such a large value of the angular momentum forms effective centrifugal barrier and the inflow may proceed through a shock, with accompanying outflow and a burst of radiation in the X-ray and NIR bands.

Fig. 2 represents a characteristic topology of shocked accretion flow. The values of $[E, \lambda, \gamma_1, \gamma_0]$ used are provided in the figure. Matter first passes through $r_{\text{out}}$ (3.2 $\times$ 10$^4 r_g$) and encounters a shock at $r_{\text{sh}}$ (10.03 $r_g$) close to the black hole. The dashed vertical line marked with a down-ward arrow represents the shock transition. $M_-$ and $M_+$ are the pre/post shock Mach numbers and the shock strength $S$ is defined as $S = M_+/M_-$, which comes out to be 16.64 for this case. Post-shock supersonic inflow becomes supersonic again after crossing $r_{\text{a}}$ (2.61 $r_g$) and finally dives through the event horizon $r_e$. Part of the shock compressed hot and dense matter with polytropic index $\gamma_a = 1.327$ emerges as outflow. The outflow rate $M_{\text{out}}$ in this case comes out to be $2.1 \times 10^{-10} M_\odot$ yr$^{-1}$. The corresponding values of $L_j$ and $\tau$ come out to be $1.1 \times 10^{36}$ erg s$^{-1}$ cm$^{-2}$ and $4 \times 10^3$ s respectively.

The position of the shock is quite sensitive to the choice of $\lambda$, if other parameters of the flow are kept fixed. One can have a range of $r_{\text{sh}}$ and $M_{\text{out}}$ by varying $[E, \lambda, \gamma_1, \gamma_0]$ as well as by varying $\lambda$ only by keeping $[E, \gamma_1, \gamma_0]$ constant. For a fixed set of $[E, \gamma_1, \gamma_0]$ shown in the figure, we represent the dependence of the outflow rate on the location of the outflow launching zone in Fig. 3 by varying the value of flow angular momentum. Similar figure can be drawn for other outflow launching zone in Fig. 3 by varying the value of flow Mach numbers and the shock strength $S$ used to draw the Fig. 3. We show the values $[E, \gamma_1, \gamma_0]$ as well. Note, however, that although very large values for $r_{\text{sh}}$ (outflow launching zone) can be obtained as a consistent mathematical solution, they may not correspond to the real physical situation. Smaller values of the outflow launching zone length scale could be obtained by further decreasing the value of $\gamma_1$.

Fig. 4 shows the relation between the luminosity of the flare $L_j$ (in CGS unit) and the flare duration time scale $\tau$ (in units of one thousand seconds). The figure is drawn for the same $[E, \gamma_1, \gamma_0]$ used to draw the Fig. 3. We show the values of $L_j$ and $\tau$ for the range of $r_{\text{sh}}$ as $r_{\text{sh}} = 8.69 r_g$ to $r_{\text{sh}} = 17.03 r_g$, the corresponding range for $\lambda$ is from 1.651 to 1.675. The low luminosity flares are of shorter duration and the length scale at which they are generated is also shorter, this is because the dynamical time is shorter as matter gets closer to the Black hole. One can have a further small (compared to the lowest value shown in the figure) value of $\tau$ by fine tuning the values of $[\lambda, \gamma_1, \gamma_0]$ for a fixed value of $E$. Note, however, that $\tau$ co-relates with the black hole mass. If one considers $M_{BH} = 2.6 \times 10^6 M_\odot$ (the lower limit of $M_{BH}$ for Sgr A*), all values of $\tau$ will be reduced. If $\tau_{2.6}$ and $\tau_{3.8}$ corresponds to $M_{BH} = 2.6 \times 10^6 M_\odot$ and $M_{BH} = 3.8 \times 10^6 M_\odot$ respectively, then $(\tau_{3.8} - \tau_{2.6})$ comes out to be about 1250 seconds for low luminosity flares and the difference increases for flares with higher value of luminosity, i.e., for larger value of $r_{\text{sh}}$. For example, for $r_{\text{sh}} = 17.03 r_g$, $\tau_{2.6}$ is only equal to $\sim$ 749 seconds whereas $\tau_{3.8}$ comes out to be equal to $\sim$ 10887 seconds.

5 DISCUSSION AND CONCLUSIONS

The type of weakly rotating flows presented in this letter, have not been theoretically explored much in the literature; although they are well exhibited in nature for various real physical situations like detached binary systems fed by accretion from OB stellar winds (Illarionov & Sunyaev 1975; Liang & Nolan 1984), semi-detached low-mass non-magnetic binaries (Bisikalo et al. 1998) and super-massive BHs fed by accretion from slowly rotating central stellar clusters (Illarionov 1988; Ho 1999 and references therein). Even for a standard Keplerian accretion disc, turbulence may produce such low angular momentum flow (e.g. Igumenshchev & Abramowicz 1999, and references therein).

We consider this type of flow as an attractive model of Sgr A* activity. We expect that accretion onto the central black hole proceeds roughly continuously but small (up to 2-3 %) fluctuations in the wind density or velocity lead to small variations in the angular momentum density which in turn results in temporary shock/jet formation and consequently an enhanced dissipation. The range of predicted shock positions $10r_g < r_{sh} < 300r_g$ give interesting range of expected burst timescales, and more luminous flares are expected to last rather longer than fainter flares.

The predicted exemplary flare luminosities are in the interesting range. The exact estimate of the flare bolometric luminosity is rather difficult, as nicely discussed by Aharonian & Neronov (2004). As on order of magnitude estimate we can assume that the bolometric luminosity of the flare is ten times higher than the measured X-ray flux so the predicted outburst would have the measured X-ray luminosity around $10^{35}$ erg s$^{-1}$ cm$^{-2}$.

The shown luminosity range is, however, rather narrow. The barionic load of the outflow (and hence, $L_j$) is controlled mainly by the post shock thermal pressure and post shock thermal energy generated is modulated by the total energy content of the flow as well as the thermal energy content of fluid. Hence broader luminosity range can be obtained if we allow for variation of $\gamma_1, \gamma_0$ and $E$ on the top of perturbations of the angular momentum density. We found that $L_j$ correlates with $[E, \gamma_1, \gamma_0]$. While the variation of $L_j$ is quite sensitive on $\gamma_0$, it is relatively less sensitive to the variation of $[E, \gamma_1]$. Hence the thermal properties of the outflow mainly contributes to the variation of $L_j$ as is expected.
Our approach to description of the low angular momentum flow is based on several assumptions.

First, in our work, viscous transport of the angular momentum is not explicitly taken into account. Even thirty years after the discovery of standard accretion disc theory (Shakura & Sunyaev 1973), exact modeling of viscous multi-transonic BH accretion, including proper heating and cooling mechanisms is still quite an arduous task. Nevertheless, extremely large radial velocity close to the BH implies $\tau_{\text{inj}} < \tau_{\text{visc}}$ ($\tau_{\text{inj}}$ and $\tau_{\text{visc}}$ are the fall and the viscous time scales respectively). Large radial velocities even at larger distances are due to the fact that the angular momentum content of the accreting fluid is relatively low (see, e.g., Beloborodov & Illarionov 1991, Igumenshchev & Beloborodov 1997, Proga & Begelman 2003). Hence, our assumption of inviscid flow is not unjustified.

On the other hand, the introduction of viscosity would further reduce the radial angular momentum of the accreting matter. As we have seen (Fig. 3), lower values of $\lambda$ produces the smaller values of the outflow launching zone ($r_{\text{sh}}$) and smaller amount of $\dot{M}_{\text{out}}$, which means (see Fig. 4 and related discussions) that viscous transonic flow would produce flares from Sgr A* with shorter duration time scale ($\tau$), compared to the values of $\tau$ obtained using our inviscid flow treatment.

Second, we apply here the stationary solution to deduce the properties of the time-dependent flow. However, explicit time-dependent considerations addressed so far only specific issues like time-dependent and oscillatory behaviours of the shock (see, e.g., Okuda, Teresi, Toscano & Molteni 2004, and references therein), which, for example, leads to the quasi-periodic oscillation of black hole candidates (Das 2003, and references therein). Several groups performed numerical hydrodynamical computations. For example, numerical simulations by Coker & Melia (1997) and Rockefeller et al. (2004) of winds from many stars lead to predictions of much higher average angular momentum than adopted in our paper ($\lambda \sim 60$) but also to much higher accretion rate than allowed by the Faraday rotation constraints (Baganoff et al. 2003a). The problem is that such computations cannot resolve the flow deeply inside $R_{\text{BHL}}$, where the flare formation occurs.

Our picture of accretion flow is qualitatively similar to the one developed by Loeb (2004). However, he considered accretion from stars very close to the black hole, well within appropriate Bondi-Hoyle-Lyttleton radius, with less efficient winds and star velocities being smaller than the wind velocity only at a fraction of an orbit. In this picture accretion from any of the considered stars is expected to occur once per orbit and to last only for a few months. IRS 13 E3 is expected to supply the mass continuously. Therefore, Loeb (2004) model would require significant correlation of the long time-scale activity with the motion of nearby stars while our picture would be in agreement with no such trends. Observational search for such correlations will help to determine the dominant source of the accreting material.

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