Close stars and an inactive accretion disk in Sgr A*: Eclipses and flares

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ABSTRACT

A cold neutral and extremely dim accretion disk may be present as a remnant of a past vigorous activity around the black hole in our Galactic Center (GC). Here we discuss ways to detect such a disk through its interaction with numerous stars present in the central 0.1 parsec of the Galaxy. The first major effect expected is X-ray and near infrared (NIR) flares arising when stars pass through the disk. The second is eclipses of the stars by the disk. We point out conditions under which the properties of the expected X-ray flares are similar to those recently discovered by Chandra. Since orbits of bright stars are now being precisely measured (e.g., Schödel et al. 2002), the combination of the expected flares and eclipses offers an invaluable tool for constraining the disk density, size, plane and even direction of rotation. The winds of the O-type stars are optically thick to free-free absorption in radio frequencies. If present near Sgr A* core, such powerful stellar winds can modulate and even occult the radio source.

1 INTRODUCTION

The center of our Galaxy appears to host a very massive black hole (e.g., Genzel 2000, Ghez et al. 2000) identified with the compact radio source Sgr A* (e.g., Reid et al. 1999), with $M_{BH} \sim 3 \times 10^6 M_\odot$. One mystery of Sgr A* is the fact that its bolometric (mostly radio) luminosity is very low, i.e. $\sim 10^{-9}$ of the corresponding Eddington luminosity $L_{Edd} = 1.3 \times 10^{44} \text{erg/} \text{sec} (M_{BH}/10^6 M_\odot)$ whereas its quiescent X-ray emission is even dimmer than radio: $L_x \sim 10^{-11} L_{Edd}$ (Baganoff et al. 2001b; for a review of Sgr A* see Melia & Falcke 2001 and Markoff et al. 2001 on the role of the jet). This is puzzling because there is enough hot gas observed at $\sim 0.04$ parsec from Sgr A* core to let the black hole radiate some $\sim 4$ orders of magnitude more (Baganoff et al. 2002a).

The current favorite explanation of this aspect of Sgr A* are accretion flow solutions (Narayan & Yi 1994; Narayan 2002) that radiate extremely little compared to the standard disks (Shakura & Sunyaev 1973).

However for “our” black hole to grow so massive there should have been a much more vigorous accretion activity in the past. Such an activity is usually assumed to proceed via the thin standard disk and cease when the supply of matter ends. Note that practically independently of the exact value of the specific angular momentum of the accreting material, $a$, above the threshold value of $\sqrt{3} R_g c$, an accretion disk will develop over a broad range of radii because matter in the disk flows in and out (Kolykhalov & Sunyaev 1980). $R_g$ here is the gravitational radius, i.e., $R_g = 2GM_{BH}/c^2 \sim 9 \times 10^{11}$ cm. A “light” and very cold ($T \sim 10^3 - 10^5$ K) inactive disk may remain there essentially indefinitely because its viscosity is extremely low. Nayakshin (2002) recently suggested that there is such a disk in Sgr A* and that it is draining the heat from the hot gas by thermal conduction. Instead of flowing into the black hole the hot gas in this model settles down (condensates) onto the inactive disk at large distances.

The accretion of the hot gas is thus delayed in this picture which then would explain the low luminosity of Sgr A*.

Sgr A* is believed to be closely related to the Low Luminosity AGN (LLAGN; e.g. Ho 1999). Most if not all of these sources seem to have cold disks that often can be seen only through water maser emission (e.g. Miyoshi et al. 1995) arising in a range of radii where gas temperature is $200 - 1000$ K (Neufeld & Maloney 1995). These disks also seem to miss their innermost parts (Quataert et al. 1999). Unfortunately our GC is an extremely “low luminosity” LLAGN and an inactive disk can be very hard to detect. In particular, a thermally emitting inactive accretion disk with $T_d \lesssim 100$ K and $R_d \lesssim 10^{17}$ cm is dim enough not to violate the quiescent bolometric luminosity constraints. In addition, disks of such low temperature are razor-thin, i.e. $H/R \sim 10^{-3}$. If the disk happened to be oriented nearly edge-on to us, it would be very difficult to spot it via its quiescent emission.

However there seems to be as many as $\sim 10^4$ stars in the central arcsecond ($1'' \approx 0.039$ pc $\approx 1.2 \times 10^{17}$ cm) of the Galaxy. The orbits of brightest of these stars (B and possibly O type; Gezari et al. 2002) are now being precisely mapped (e.g., Schödel et al. 2002). These stars may be eclipsed by the disk if it is optically thick. In addition, even much smaller and much less luminous solar-type stars will produce X-ray and near infra-red flares when passing through the disk. In this Letter we hope to present a concise but clear overview of our ongoing work on the star-disk interactions near GC (Nayakshin, Cuadra & Sunyaev 2003, in preparation).
2 STAR-DISK ECLIPSES AND CROSSINGS

A star can be eclipsed when it moves into the area shadowed by the disk as seen from our line of sight. If the star moves “far” behind the disk then this type of eclipses is completely analogous to the eclipses of Sun by the Moon and can be referred to as a “blocking eclipse”. As such it happens because both the blocked and the blocking objects have finite sizes. The star may instead strike the disk, pass through it, and become eclipsed because it moved from the front/visible side of the disk to its back/invisible side. This type of eclipses may be referred to as an “impact eclipse”.

In Figure 1 we show two star trajectories interesting in terms of eclipses and flares. The star moving along the ABCD path is eclipsed by the disk twice per orbit. In point B the star does not physically intercepts the disk but only its shadow, and hence this is the beginning of a blocking eclipse. Due to the star’s finite size and (most likely) a gradual rather than an abrupt nature of the disk edge on both the inner and the outer boundaries, partial eclipses could be observed for hours to months (see Fig. 4). The eclipse ends at point C when the star goes through the disk, from its back to its front side. NIR infra-red and an X-ray flare will be emitted (see Figure 3). If the disk is optically thick to X-rays, then NIR flare will precede the X-ray flare. The former is thermal in nature and is strongest when the star is in the disk midplane, whereas the latter can only reach the observer when the star is in the disk photosphere (see §3). The CD part of the trajectory is an “unremarkable” quiescent star emission, which terminates when the star hits the disk for the second time. This time the X-ray flare should be emitted first. The eclipsed part DA ends when the star emerges from the disk shadow without a flare.

To date, there is only one star whose orbit is nearly completely known, i.e. the star S2 (Schödel et al. 2002). The orbit is highly elliptical (eccentricity $e = 0.87$), inclined at $i = 46^\circ$ (we picked the + sign here), and the period is 15.2 years. We plot (Figure 3) the orbit of S2 and a disk that does not eclipse any of the measured positions (Fig. 1 in Schödel et al. 2002). Note that the disk can in principle still exist beyond $R_1$ or $R_d$ but it cannot be optically thick there. Figure 4 shows the expected lightcurve of the star.
(the passage of the periblackhole radius for S2 occurred at 2002.3). The eclipse $ab$ ($t \sim 2002.0$) is of the blocking type and therefore there is no flare associated with it, whereas the second eclipse (point $c$) begins with a flare. Figures 4 & 4 are only examples. We find that a disk with no inner hole or a disk with a larger inner hole, $R_i \gtrsim 0.05''$ and an arbitrarily large outer radius are also possible for the present data (Cuadra et al. 2003, in preparation).

A brief summary of what one can learn from observations of star eclipses and flares:

(i) Coordinates of star’s trajectories are three-dimensional; therefore, star-disk crossing points (e.g. D or C) yield 3D coordinate of a point in the disk. Together with the known coordinates of Sgr A* itself, any such crossing yields a line in the disk plane. Therefore, knowledge of 3D coordinates of points D & F, for example, (and Sgr A*) is sufficient to determine the plane of the disk rotation.

(ii) If the plane of the disk is known, then the projected coordinates of two blocking points (A & B) uniquely determine the outer disk radius (unless the disk is strongly warped).

(iii) Appearance or disappearance of stars (in blocking points) will be gradual and this should yield information on how the disk is terminated on both boundaries.

(iv) The maximum luminosity of a flare is a strong function of the angle between the star and the disk velocity at the point of impact (3, $\theta_r$). Hence one can tell whether the disk is rotating clockwise or counter-clockwise in Fig. 1.

The best constraints here are offered by a star whose orbital plane is close to the disk plane.

(v) In general, a star that is on an elliptical orbit and that strikes the disk twice per orbit, will do so at different radii from the black hole (e.g. F is farther from the center than E in Fig 1), so the flare durations, amplitudes and spectra will be different. Such events will offer better constraints on the variation of the disk density and temperature with $R$ than will flares from separate stars.

(vi) Currently orbits of only the bright stars can be followed in Sgr A* star cluster. These stars have radii $R_i \sim 5 - 10 R_\odot$ and hence should yield very large X-ray and NIR flares (see §3). Of course such flares are much less frequent than the typical flares from stars with $R_\star \sim R_\odot$.

3 PHYSICS OF STAR-DISK FLARES

Reader not interested in physical or mathematical detail of our model for the star-disk flares may proceed directly to §3.1 and Figure 5 where star-disk flare properties are summarized.

At a distance $R$ from the black hole, let a star with mass $M_\star = m_\star M_\odot$ and radius $R_\star = r_\star R_\odot$ move with velocity $v_\star$ that makes angle $\theta_\star$ with the disk circular Keplerian velocity, $v_K$. We also define for convenience $v_\text{rel} = R/10^4 R_g$. The relative velocity of the disk and the star, $v_\text{rel}$, is essential to the problem. In general $v_\text{rel} = v_K^2 + v_\star^2 - 2v_\star v_K \cos \theta_\star$, and one needs to carry out calculations for arbitrary $v_\star$ and $\theta_\star$ and then integrate over the star’s 3D velocity distribution. In what follows we simply assume that $v_\star \sim v_K$. Under the assumption of an isotropic star cluster the “average” angle $\theta_\star$ is equal to $\pi/2$, so $v_\text{rel} = \sqrt{2} v_K$. However we shall keep in mind the importance of the actual $v_\star$ and $\theta_\star$ for exact results (cf. point iv above).

The star’s internal density is very much larger than that of the disk and we can consider the star to be a rigid solid body (see Syer et al. 1991). We neglect tidal effects and accretion of gas onto the stellar surface because the corresponding Bondi radius is much smaller than $R_\star$ ($R_{\text{Bond}} = GM_\star/v_\text{esc}^2 = 1.5 \times 10^8 m_\star T_4 \ll 7 \times 10^{10} t_4 R_\odot$). The Mach number of the star in the disk is about $v_\text{rel}/\sqrt{(kT_4/m_\star)} \sim 10^{-3}$. Thus the star drags a narrow hole in the disk (Syer et al. 1991) Note also that $R_\star \ll H$. The star is essentially a piston moving into the gas and the rate at which the star makes work on the gas in the disk is approximately $L_w \sim \pi R^2_\star m_\star n_\star v_\text{rel}^2$, where $n_\star$ is the midplane density of hydrogen nuclei.

X-ray spectrum. The characteristic temperature to which the gas is heated in the shock wave is

$$T_{\text{char}} = \frac{2 \mu v_\text{rel}^4}{3k} = 1.8 \times 10^{8} t_4^{-1} \text{K},$$

where we set $\mu \simeq m_\star/2$. For $T_{\text{char}}$ as high as $10^8 \text{K}$, optically thin X-ray spectra are dominated by bremsstrahlung emission. The photon spectral index in the $2 \lesssim E \lesssim 8 \text{keV}$ energy range is $\Gamma \gtrsim 1.5$ and is in agreement with the observed values of $\Gamma \simeq 1 \pm 0.7$ (Baganoff et al. 2001, Goldwurm et al. 2002). Fe Kα line emission is weak as observed. Absorption of soft X-rays in the disk photosphere could be significant. However we find that X-rays from bright flares photo-ionize the disk material enough to hide this absorption on the background of the existing neutral absorber in the line of sight.

X-ray luminosity. Consider first an optically thin case. If the cooling time of the shocked gas, $t_c$, is shorter than $R_\star/v_\star$, then the X-ray luminosity, $L_{\text{xco}}$, should be about $L_w$. On the other hand, if adiabatic losses dominate cooling of the hot gas, then $L_{\text{xco}} \sim L_w(R_\star/v_\star t_c) \ll L_w$. We find that the latter case is more appropriate for Sgr A* flares, for which we obtain

$$L_{\text{xco}} \sim 4.1 \times 10^{33} n_\text{d}^2 r_\star^3 r_4^{-1/2} \text{erg/sec},$$

where $n_\text{d} = n_d/10^{11} \text{cm}^{-3}$.

If the disk is optically thick to photo-absorption, then X-ray emission becomes observable only when the star reaches the disk photosphere, i.e. when $\tau = (\cos i)^{-1} \sigma_{\text{eff}} H n_\text{p} \simeq 1$, where $i$ is the disk inclination angle, $H$ is disk half-thickness, $\sigma_{\text{eff}} = b \tau T$ is the effective X-ray total cross section ($b \sim$ few), and $n_\text{p}$ is local density. This moment defines the maximum in the X-ray light curve; inside the disk X-rays cannot escape to the observer; in the disk photosphere, on the other hand, the gas density is much smaller than it is in the midplane.

Using the $\tau = 1$ condition we then obtain the density $n_{\text{max}} \sim \cos i/(b \tau_7 T) H$ at which the maximum X-ray luminosity, $L_{\text{max}}$, is emitted. $L_{\text{max}}$ is clearly given by the optically thin luminosity (eq. 2), calculated with $n_{\text{max}}$ instead of $n_d$, times $\exp[-1]$:}

$$L_{\text{max}} \sim 2 \times 10^{34} \left(\frac{\cos i}{b} \right)^2 T_7^{-2} r_3^{-1} r_4^{-7/2} \text{erg/sec}.$$  

Flare duration. The disk half thickness, $H$, is


\[ H = \sqrt{\frac{kT_d R^2}{GM_{BH} m_p}} = 3.9 \times 10^{12} T_2^{1/2} r_4^{3/2} \text{ cm}, \]

where \( T_2 = T/100 \text{ K} \) and we assumed that the gas is mainly molecular hydrogen. The flare duration for an optically thick disk is \( t_{\text{dur}} \sim (H + 2R_*)/c_v: \)

\[ t_{\text{dur}} \simeq 2.5 \times 10^{4} T_2^{1/2} r_4^2 + 670 \ r_4 T_2^{1/2} \text{ sec}, \]

which is in accord with observations if \( R \sim 10^{-3} - 10^{-2} R_g. \)

**Mass of the disk.** The disk surface density \( \Sigma \simeq 2H n_d m_p = 12.8 \ n_{12} r_4^{1/2} T_2^{1/2} \ g \ cm^{-2}. \) The mass of the accretion disk, calculated for density and temperature independent of radius, is \( M_d \sim M_\odot n_{12} r_4^{7/2} T_2^{1/2}. \) Such a “light” disk is neither globally nor locally self-gravitating (e.g. Kolykov & Sunyaev 1980; Gammie 2001).

**NIR Luminosity.** Consider optically thick case, \( \Sigma \gtrsim 1 \ g/cm^2. \) Deep inside the disk X-rays are absorbed and re-emitted as a black body emission in the near infrared. Assuming \( L_x \sim \sigma_B T_4^4 \pi^2 (2H)^2, \) we get \( T_{x} \sim 2.7 \times 10^5 \ K \ n_{12} r_4^{2} T_2^{1/4} r_4^{9/8}. \) The predicted NIR luminosity is then \( \nu L_\nu = 4H^2 \cos i \nu \dot{B}_\nu (T_{\nu}): \)

\[ \nu L_\nu = 4.5 \times 10^{35} \cos i \ T_2 r_4^4 \frac{\tilde{\nu}^4}{c_\nu^2 - 1} \text{ erg/sec}, \]

where \( \tilde{\nu} \equiv \nu/1.5 \times 10^{14}, \) and \( x = h \nu/kT_{\nu}; \) we assumed the distance to the GC \( D = 8 \) kpc. While the luminosity in the optically thin case will be different from that given in eq. (4), we continue to use the latter as a rough guide in both cases.

**Number of star-disk flares per year.** A cusp with stellar density \( n_e(R) = n_o (R/R_\odot)^{-p}, \) with \( p = 7/4 \) is predicted by Bahcall & Wolf (1976) for \( R_t < R < R_c, \) where \( R_t \simeq 20 R_\odot m_\odot^{1/3} \) is the tidal radius and \( R_c \) is the cusp radius. Alexander (1999) finds that \( n_e(R) \) with \( p \) ranging from \( 3/2 \) to \( 7/4 \) is slightly favored over a constant density one (i.e. \( p = 0 \)). Eckart et al. (2003) finds that the mass of a putative cusp is \( M_{\text{cusp}} \sim 5 \times 10^3 M_\odot \) and \( R_c \sim 0.14'' \sim 1.7 \times 10^{16} \) cm. Thus \( n_o \sim 3.8 \times 10^9 m_\odot^{-1} \text{ pc}^{-3}. \) As an example, we give the number of star-disk crossings per year for \( p = 3/2: \)

\[ \dot{N}(R) \sim 6.7 \times 10^3 m_\odot^{-1} \frac{\ln(R_d/R_c)}{\ln(500)} \text{ year}^{-1}, \]

where we assumed \( R_t > R_c. \) This is the rate of star-disk crossings, and not all of these will produce flares strong enough to be detected. Within current uncertainties the expected rate of flares compares quite well with the observed \( \sim 1 \) flare per day (Baganoff et al. 2002b) for power-law indices \( p \) ranging from \( 1 \) to \( 2, \) but would be too low if \( p \sim 0 \) unless \( M_{\text{cusp}} \) is greatly underestimated.

**Inner hole in the disk.** The star-disk interactions can remove the disk angular momentum and yield some accretion. The time to remove all disk angular momentum (found as in Ostriker 1983) is shorter than \( 10^6 \) years for radii less than \( \sim 2 \times 10^3 R_g \) where we assumed \( p = 3/2. \) The disk viscous time at \( r_3 = R/10^3 R_g \) is \( \nu_{\text{visc}} \sim 5 \times 10^7 \alpha^{-1} T_2^{-1} r_4^{1/2} \) years, where \( \alpha < 1 \) is viscosity parameter (Shakura & Sunyaev 1973). Clearly the disk inner hole cannot be refilled by accretion of material from larger radii for \( R \lesssim 10^3 R_\odot. \) In addition, any “minor” accretion events in the past would heat up the inner disk and destroy it.

### 3.1 Summary of flare properties

We plot flare properties in Figure (5) for two values of the star’s radius, \( R_\odot = R_\odot \) (thin curves) and \( R_\odot = 5 R_\odot \) (thick).

**Conclusions from Figure (5):**

(i) Flare X-ray luminosity is a strong function of radius \( R. \) Flares even from large stars are too dim to be detected for \( R > 7 \times 10^3 R_\odot \) and are optically thick. Two values for the star radius, \( r_\star \sim R_\odot \) (thick) are considered. \( b = 2 \) for all the curves.

(ii) To date no flares from Sgr A* much in excess of \( L_x \sim 10^{35} \text{ erg/sec} \) were observed by Chandra or XMM. This requires the disk midplane density be \( n_d \lesssim 10^{11} \text{ cm}^{-3}. \) The infrared opacity of dust is \( k_{\text{mir}} \sim \text{ few cm}^2/\text{gm} \) (Fig 3b in Pollack et al. 1994). The disk is optically thin in NIR for \( R \lesssim \text{ few } \times 10^3 R_\odot \).
(iii) The disk cannot be exactly edge-on to us or else X-ray flares would be too weak (see eq. 3).

(iv) The maximum NIR 2 μm luminosity for solar-type stars is \( \sim \text{few} \times 10^{34} \text{ erg/sec} \). Such flares cannot be detected because the current limit on NIR flares (Hornstein et al. 2002) is about 20 mJy or 2 \times 10^{35} \text{ erg/sec}. Further, the flares are actually offset from Sgr A* location by \( \sim 0.1'' \). If detected they would probably appear as “noise” not associated with Sgr A*

(v) Similar X-ray and NIR flares from star-disk interactions in more distant LLAGN with \( M_{\text{BH}} \gg 3 \times 10^6 M_\odot \) have smaller luminosities (typically \( n_d \propto 1/M_{\text{BH}} \)). In accord with this, no such X-ray flares have yet been observed in other LLAGN.

(vi) Radio emission from the shocked gas is very weak (compared to the NIR or X-ray luminosities) since it is completely self-absorbed. This explains why there is no radio flares correlated with X-ray outbursts in Sgr A*

(vii) The bolometric luminosities of the O-type stars can be as high as \( 10^{39} \text{ erg/sec} \). Passing through the disk their radiation will form a strong ionization front and will be reprocessed into a cooler thermal emission. The emission will be coming from a larger surface area than \( \pi R^2 \). The flare NIR K-band luminosity should be much larger than the star quiescent emission (in the same band).

5 DISCUSSION

We have shown that eclipses of close stars by the disk may be a very effective tool with which to constrain the disk’s plane and direction of rotation, inner and outer radii, and the optical depth variation with radius. The predicted X-ray and NIR flares may yield additional constraints on the properties of the disk. The disk density is the only parameter of the model that is completely free; all the others – the star’s radii, number density, disk size, temperature and inclination angle have certain limitations from observations of either stellar orbits near Sgr A* or its quiescent emission. It is thus remarkable that a disk with midplane density \( n_d \sim \text{few} 10^{11} \text{ cm}^{-3} \) produces X-ray flares with “right” duration, X-ray luminosity, spectrum, and low enough NIR and radio emission to pass all of the observational constraints on Sgr A* flares. If the inactive disk indeed exists, it is necessary to understand how it interacts with the hot (ADAF-type) flow.

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