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Radio variability of Sagittarius A* due to an orbiting star

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Abstract. Recently, unprecedentedly accurate data on the orbital motion of stars in the vicinity of Sgr A* have become available. Such information can be used not only to constrain the mass of the supermassive black hole (SMBH) in the Galactic center but also to study the source of the radio emission. Two major competing explanations of the radio spectrum of Sgr A* are based on two different models, that is, hot accretion disk and jet. Hence, independent observational constraints are required to resolve related issues. It has been suggested that a star passing by a hot accretion disk may cool the hot accretion disk by Comptonization and consequently cause the radio flux variation. We explore the possibility of using the observational data of the star S2, currently closest to the Galactic center, to distinguish physical models for the radio emission of Sgr A*, by applying the stellar cooling model to Sgr A* with the orbital parameters derived from the observation. The relative difference in the electron temperature due to stellar cooling by S2 is a few parts of a thousand and the consequent relative radio luminosity difference is of the order of 10^{-4}. Therefore, one might expect to observe the radio flux variation with a periodic or quasi-periodic modulation in the frequency range $\nu \lesssim 100$ MHz if radiatively inefficient hot accretion flows are indeed responsible for the radio emission, contrary to the case of a jet. According to our findings, even though no periodic radio flux variations have been reported up to date a radiatively inefficient hot accretion disk model cannot be conclusively ruled out. This is because the current available sensitivity is insufficient and because the energy bands that have been studied are too high to observe the effect of the star S2 even if it indeed interacts with the hot disk.

Key words. accretion, accretion disks – Galaxy: center – galaxies: active – black hole physics

1. Introduction

The compact radio source in our Galactic center Sgr A* is widely believed to be associated with an accreting supermassive black hole (SMBH) whose mass is $\sim 10^6\ M_\odot$ (Eckart & Genzel 1997; Ghez et al. 1998; Melia & Falcke 2001; Eckart 2002). A number of models for the observed radio spectrum are essentially based on an accretion process, as quasars and active galactic nuclei are powered by accreting SMBHs (e.g., Rees 1984). Though the existence of the SMBH at the Galactic center and its role seem unanimously accepted, the details of the accretion process and/or the nature of the central inner part of the accretion flow remain unsettled. For instance, even the recent *Chandra* observation of X-ray flare by Baganoff et al. (2001) have been explained by physically quite different models of Sgr A* (Markoff et al. 2001; Liu & Melia 2002; Yuan et al. 2002).

Lower radio luminosities from Sgr A* can be reasonably well explained by the radiatively inefficient accretion flow, such as, advection-dominated accretion flows (Narayan et al. 1995). The radiative luminosity of advection-dominated accretion flows (ADAFs) is much less than that of the standard thin disk (Shakura & Sunyaev 1973). ADAFs have a low luminosity since most of the energy in the flows is stored in hot ions and advected into the central black hole due to the low efficiency of heat transfer from ions to electrons (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994). The electron temperature is very high, and thus the electrons are relativistic.

Several models have been further introduced to account for the detailed spectrum of the Sgr A*. Other versions of the radiatively inefficient accretion flow, for instance, are accretion flows with significant macroscopic convection (Narayan et al. 2000; Quataert & Gruzinov 2000a), so called convection-dominated accretion flows (CDAF), those with mass loss due to outflows from the accretion flow (Blandford & Begelman 1999; Turolla & Dullemond 2000), advection-dominated inflow-outflow solutions (ADIOS). A truncated disk with a radio jet has been also proposed (Falcke & Biermann 1999; Falcke & Markoff 2000; Beckert & Falcke 2002; Yuan et al. 2002). They all have both virtues and drawbacks in explaining the

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spectrum in details, implying that the spectral energy distribution alone is probably insufficient to sort out the models. Hence, independent observations resolving the central part are required to settle related issues. One example is the observation of polarization. Constraints by the linear/circular polarization measurements seem quite robust (Agol 2000; Quataert & Gruzinov 2000b; Melia et al. 2000; Aitken et al. 2000; Bower et al. 2003). The measured polarizations provide information on the emitting region, the mass accretion rate, the nature of the accretion flows, the physical process of the radio emission, and so on. Another item which has been of great interests for observers is flux variations (Baganoff et al. 2001; Duschl & Lesch 1994; Eckart 2002; Hornstein et al. 2002; Goldwurm et al. 2003; Zhao et al. 2001, 2003). The short timescale variation is of course important since it may provide information on the physical change in the inner part of the accretion disk (e.g., Mushotzky et al. 1993). On the other hand, the long timescale variation in the very low frequency band can also provide useful information on the central engine of a source like Sgr A*.

This paper is motivated by the recent observational report on the proper motion of stars close to Sgr A* (Schödel et al. 2002; Gezari et al. 2002; Ghez et al. 2003). Stellar proper motion data covered by an interval from 1992 to 2002 makes it possible to determine orbital accelerations for some of the stars nearest the Galactic center, thus the mass of Sgr A*. The observations covering both pericenter and apocenter passages show that the star S2, currently the closest star to Sgr A*, is on a bound, highly elliptical Keplerian orbit around the SMBH, with an orbital period of ~15 years, a pericenter distance of only 124 AU, or ~2000 Schwarzschild radii, and an eccentricity of 0.87. It might be possible to use this kind of observation to constrain the central source of Sgr A*, e.g. to distinguish physical models for its radio emission. Similar attempts have already been made in the sense that the same observational data have been used to test putative accretion disk theories (Nayakshin & Sunyaev 2003; Cuadra et al. 2003). Using the three dimensional orbit of the star S2 the latter authors concluded that there cannot exist an optically thick and geometrically thin disk near Sgr A* unless the cool disk has a large inner radius since otherwise it should have shown up in the course of the observation campaign. In this paper we apply the stellar cooling model suggested by Chang (2001) to the particular case of Sgr A* by recalculating with the orbital parameters derived from the observation.

2. Stellar interaction with ADAF

A hot accretion disk is believed to exist in low luminosity AGNs and dormant galaxies, such as our own Galaxy (Narayan et al. 1995; Narayan et al. 1998; Ho 1999). If there is an accretion disk around the SMBH, several processes may occur due to the interaction of a star flying by and the accretion disk around the SMBH (Syer et al. 1991; Hall et al. 1996), without mentioning the tidal disruption events (Cannizzo et al. 1990; Rees 1988, 1990; Menou & Quataert 2001; Komossa 2002; Choi et al. 2002). A more interesting phenomenon can be observed particularly when the accretion disk is relativistically hot. A star flying by may cool the hot accretion disk as a result of Comptonization (Chang 2001). One observable signature of a flying by star on the hot accretion disk, e.g., on the ADAF is the decrease of the electron temperature and subsequently the radio flux of the hot accretion disk. In the following we summarize briefly what happens when a bright star encounters a hot accretion disk.

Firstly, when the star passes through the accretion disk around the SMBH the dynamical friction causes viscous heating. The power is given by $P = F_{\rm df}\, v_{\rm rel}$, where $F_{\rm df}$ is the drag force and $v_{\rm rel}$ is the relative velocity of the star with respect to the background gas. The drag force $F_{\rm df}$ on a star with mass M_* moving through a uniform gas density ρ with relative velocity $v_{\rm rel}$ can be estimated as

$$F_{\rm df} = -4\pi I \left(\frac{GM_*}{v_{\rm rel}}\right)^2 \rho, \tag{1}$$

where the negative sign indicates that the force acts in the opposite direction from the star, G is the gravitational constant (Ostriker 1999; Narayan 2000). The coefficient I depends on the Mach number, $\mathcal{M} \equiv v_{\rm rel}/c_{\rm s}$, where $c_{\rm s}$ is the sound speed of the medium. In the limit of a slow moving $\mathcal{M} \ll 1$, $I_{\rm subsonic} \rightarrow \mathcal{M}^3/3$, so that the resulting $F_{\rm df}$ is proportional to the relative speed of the star. In the limit of a fast moving $\mathcal{M} \gg 1$, $I_{\rm supersonic} \rightarrow \ln(v_{\rm rel}t/r_{\rm min})$, where $r_{\rm min}$ is the effective size of the regime where the gravity of the star dominates. We take the supersonic estimate of I, as it gives an upper limit to the heating due to the drag force, which makes the total cooling estimate obtained here a lower limit of the stellar cooling effect.

Secondly, the stellar emission may cool the gaseous medium. In the ADAFs a star and its motion may enhance the cooling by bremsstrahlung and Comptonization processes. The gas density in front of the star may be increased as the motion of the star may compress the gas. The bremsstrahlung cooling rate per volume is increased as the density increases proportional to the square of the density (Stepney & Guilbert 1983). Comptonization is also possible because the electrons in the ADAFs are relativistic since radiation emitted by the star is an important source of soft photons. The stellar cooling rate due to Comptonization becomes relatively more important than those due to other processes of accretion disk cooling when the mass accretion rate becomes small.

3. Radio variation due to stellar cooling

Making the simplest assumption of an optically thin and quasi-spherical hot accretion disk, we examine observational features due to the hot accretion flow present around Sgr A* through its interaction with S2. Using the orbital parameters and the observed positions of this currently closest star (Schödel et al. 2002; Ghez et al. 2003), we are able to calculate the radio flux variation which could have been observed with a period similar to the orbital period of the star. We adopt the following dimensionless variables throughout the paper : mass of the SMBH $m = M/M_\odot$; radius from the SMBH $r = R/R_{\rm g}$, where $R_{\rm g} = 2GM/c^2 = 2.95 \times 10^5\ m$ cm; and mass accretion rate $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$, where $\dot{M}_{\rm Edd} = L_{\rm Edd}/\eta_{\rm eff}c^2 = 1.39 \times 10^{18}\ m$ g s^{-1} (the Eddington accretion rate assuming $\eta_{\rm eff} = 0.1$). We model

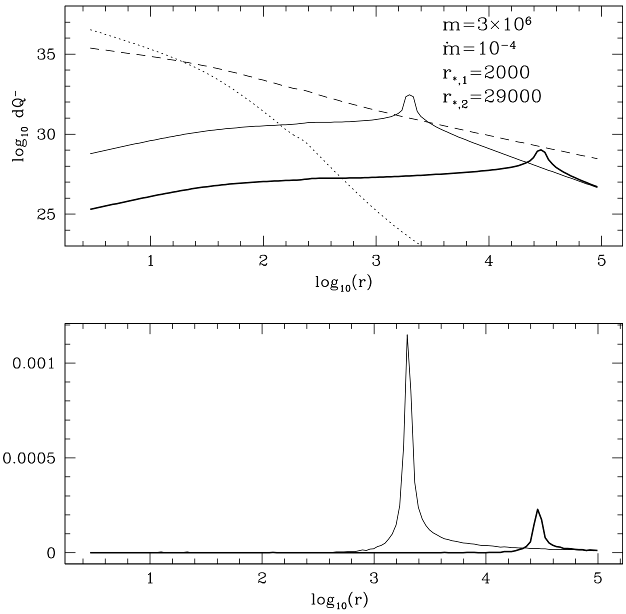

Fig. 1. Upper panel: The volume integrated cooling rates over the spherical shell due to various cooling mechanisms are shown as a function of r in log scales. The $\mathrm{d}Q^-$'s are in ergs s^{-1}. Lower panel: The relative electron temperature differences are shown as a function of r. The relative electron temperature difference is defined as $(T_0 - T_*)/T_0$, where T_0 is the electron temperature of the case without the stellar cooling. The thin and thick solid curves represent the cases when the cooling star is at $r \sim 2000$ and $r \sim 29\,000$, respectively. The dotted curve and the dashed curve represent volume-integrated cooling rate due to synchrotron cooling and bremsstrahlung cooling, respectively.

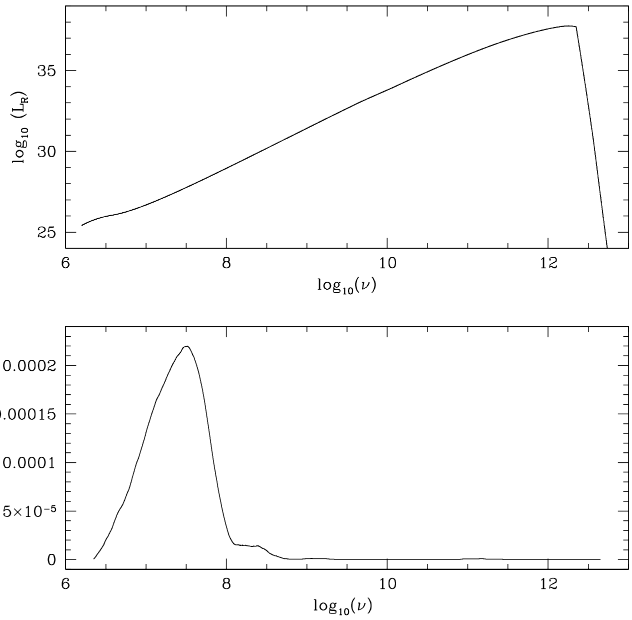

Fig. 2. Upper panel: We show the radio spectra of the ADAFs without stellar cooling by the solid curve, with stellar cooling at the pericenter by the dotted curve and at the apocenter by the dashed curve. Note that all the curves are indistinguishable at this scale. The luminosity in ergs s^{-1} and the frequency in Hz are shown in the log scale. Lower panel: The relative difference of the radio spectrum at two different epochs is shown.

the accreting gas as a two-temperature plasma. In the model for the ADAF we take the following values: $r_{\min} = 3$, $r_{\max} = 10^5$, $\alpha = 0.3$, $\beta = 0.5$, and $\delta = 0.0$ (see, e.g., Narayan & Yi 1995; Quataert & Narayan 1999).

Provided that the background gas environment is described by the ADAF model, the volume-integrated cooling rate due to stellar emission $\mathrm{d}Q^-_{*,\mathrm{C}}$ over the spherical shell at r can be obtained. We plot $\mathrm{d}Q^-_{*,\mathrm{C}}$ with other volume-integrated cooling rates as a function of r in Fig. 1. We adopt the bolometric luminosity of S2 as that of an O8 dwarf (Ghez et al. 2003). The dotted curve and the dashed curve represent the volume-integrated cooling rate due to synchrotron cooling $\mathrm{d}Q^-_{\mathrm{sync}} + \mathrm{d}Q^-_{\mathrm{sync,C}}$ and bremsstrahlung cooling $\mathrm{d}Q^-_{\mathrm{br}} + \mathrm{d}Q^-_{\mathrm{br,C}}$. The thin and thick continuous curve represent $\mathrm{d}Q^-_{*,\mathrm{C}}$ when the S2 star is at pericenter and at apocenter, respectively. These volume-integrated cooling rates are subject to the mass accretion rate to the central SMBH. The synchrotron cooling $\mathrm{d}Q^-_{\mathrm{sync}}$ and bremsstrahlung cooling $\mathrm{d}Q^-_{\mathrm{br}}$ are reduced as the mass accretion rate is decreased. The stellar cooling rate behaves similarly. However, its relative contribution becomes more significant compared with others as the mass accretion rate is small. We adopt a mass accretion rate of $\dot{m} = 10^{-4}$ (Quataert et al. 1999; Quataert & Gruzinov 2000b), which corresponds to the favored accretion rate estimation from the observation when the ADAF model is assumed. We also show the relative differences in the electron temperature as a function of r when the cooling star is at $r \sim 2000$ and $r \sim 29\,000$, denoted by the thin and thick solid curves, respectively. The relative electron temperature difference is defined as $(T_0 - T_*)/T_0$, where T_0 is the electron temperature when there is no stellar cooling. The electron temperature is again averaged over the volume of the shell. As shown in the plot, for a given SMBH mass and mass accretion rate the suppression of the temperature due to stellar cooling becomes less significant as the cooling star is farther away from the central SMBH.

In Fig. 2, we show the radio spectrum of the ADAFs in the upper panel and the relative difference in the radio spectrum due to stellar coolings at two different epochs, viz. when the star is at pericenter and at apocenter. Since the dominant effect on the spectrum is due to the inner parts of the ADAFs, stellar cooling farther from the SMBH changes the spectrum less significantly. The suppression of the radio spectrum due to stellar cooling is the greatest at the frequency corresponding to the position where the star cools the accretion disk (see Mahadevan 1997). This can be understood by the fact that the synchrotron radio emission of the ADAFs at each frequency is closely related to a specific radius. For instance, the emission at higher frequencies originates at smaller radii, or closer to the central supermassive black hole. As shown in the lower panel, Comptonization of stellar soft photons from the star at $r \gtrsim 10^3$ affects the radio spectrum at $\nu \lesssim 100$ MHz.

4. Summary and discussions

When a star interacts with a hot accretion disk such as the ADAF in the Galactic center one would expect many interesting effects. One observable signature of a stellar encounter with the hot accretion disk is the depression of the radio flux due to the stellar cooling, whose variation could show periodic or quasi-periodic modulation. We have attempted to calculate what one may actually expect using the observed parameters of the currently closest star S2. The relative electron temperature difference is a few parts in a thousand without and with the stellar cooling in the case when the star S2 is near the pericenter. Subsequently the radio spectrum shows the suppression of the radio spectrum due to stellar cooling which is greatest for $\nu \lesssim 100$ MHz for stellar soft photons from the star at $r \gtrsim 10^3$. The relative radio luminosity difference without and with the stellar cooling is small, order of 10^{-4}. Bower et al. (2002) have reported multiepoch, multifrequency observations of Sgr A*, from 1981 to 1998, where data were taken at 1.4, 4.8, 8.4, and 15 GHz bands. They have found no periodic radio flux variation with a period ~15 years, which is naturally expected from the presence of a hot disk. We suggest that this observation cannot be used yet to distinguish two competing models, i.e., hot accretion disk and jets. That is, even though no periodic radio flux variations have been found in the observations a radiatively inefficient hot accretion disk model cannot be conclusively ruled out. This is because the currently available sensitivity is insufficient and because the energy bands they have studied are too high to observe the effect of the star S2 even if it indeed interacts with the hot disk.

We tentatively conclude that even the currently closest pass of the star S2 is insufficiently close to meaningfully constrain the nature of Sgr A*. Yet, we would like to emphasize that currently available data are out of the range which the star S2 would have affected. Quantitative implications may be subject to what parameters we adopt for the background accretion flow model and the physical parameters of the encountering star. One may employ another version of the radiatively inefficient accretion flow, for instance, CDAFs. Changing the background from ADAFs to CDAFs does not modify our conclusions significantly since the convection in the hot accretion flows alters the very inner part of the accretion flows and therefore the spectrum at high frequency range, $\nu \gtrsim 1$ GHz (see Ball et al. 2001). The mass loss in ADIOS also has a significant effect only at higher frequency range than we are interested in. However, we point out that a long monitoring of radio flux and stellar proper motion observation are still worthwhile since a hypothetical star orbiting a very eccentric orbit might exist near its apocenter where it spends most of the orbital period and yet pass by Sgr A* more closely than the star S2. If that happens we may observe radio flux variation at $\nu \gtrsim 1$ GHz, where one should be more careful in choosing the background accretion flow model. One may also attempt to monitor LLAGNs, which are believed to host ADAFs or their variations (Ho 1999). For an accreting SMBH with a lower mass accretion rate and a star flying by more closely may exhibit their existence.

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