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IMPLICATION OF STELLAR PROPER MOTION OBSERVATIONS ON RADIO EMISSION OF SAGITTARIUS A*

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ABSTRACT

It is suggested that a flying-by star in a hot accretion disk may cool the hot accretion disk by the Comptonization of the stellar emission. Such a stellar cooling can be observed in the radio frequency regime since synchrotron luminosity depends strongly on the electron temperature of the accretion flow. If a bright star orbiting around the supermassive black hole cools the hot disk, one should expect a quasi-periodic modulation in radio, or even possible an anti-correlation of luminosities in radio and X-rays. Recently, the unprecedentedly accurate infrared imaging of the Sagittarius A* for about ten years enables us to resolve stars around it and thus determine orbital parameters of the currently closest star S2. We explore the possibility of using such kind of observation to distinguish two quite different physical models for the central engine of the Sagittarius A*, that is, a hot accretion disk model and a jet model. We have attempted to estimate the observables using the observed parameters of the star S2. The relative difference in the electron temperature is a few parts of a thousand at the epoch when the star S2 is near at the pericenter. The relative radio luminosity difference with and without the stellar cooling is also small of order 10^{-4}, particularly even when the star S2 is near at the pericenter. On the basis of our findings we tentatively conclude that even the currently closest pass of the star S2 is insufficiently close enough to meaningfully constrain the nature of the Sagittarius A* and distinguish two competing models. This implies that even though Bower et al. (2002) have found no periodic radio flux variations in their data set from 1981 to 1998, which is naturally expected from the presence of a hot disk, a hot disk model cannot be conclusively ruled out. This is simply 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. In other words, even if there is a hot accretion disk the star like S2 has imprints in the frequency range at $\nu \lesssim 100$ MHz.

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

I. INTRODUCTION

The compact radio source in our Galactic center Sagittarius A* is believed to be associated with a supermassive black hole (SMBH) whose mass is $\sim 10^6 M_\odot$ (Eckart & Genzel 1997; Ghez et al. 1998; Eckart 2002). It is therefore natural to accept the idea that emissions from the source over the energy spectrum covering from radio to X-rays are generated by 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.

Lower radio/X-ray luminosities from Sagittarius A* than expected by a standard accretion disk theory have been puzzling until Narayan, Yi, & Mahadevan (1995) suggested that the SMBH at the Galactic center is fed via the radiatively inefficient accretion flow, that is, advection-dominated accretion flows (ADAFs). The radiative luminosity of the ADAFs is much less than that of the standard thin disk (Shakura & Sunyaev 1973). The ADAFs have a low luminosity since most of the energy in the flows is stored in hot ions and advected with the hot plasma into the central black hole due to the low efficiency of heat transfer from ions to electrons, which actually cool the flows (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994; Manmoto, Mineshige, & Kusunose 1997; Kato, Fukue, & Mineshige, 1998; Narayan, Mahadevan, & Quataert 1998). The ADAFs are optically thin and geometrically thick, i.e., quasi-spherical. The electron temperature is very high, $\sim 10^9 - 10^{10}$ K, and thus the electrons are relativistic. The angular velocity of the flow is less than the Keplerian velocity.

Following the success in describing the low lumi-

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nosity of the Sagittarius A* with the ADAFs, several different scenarios have been further introduced to account for the detailed spectrum of the Sagittarius A*. Other versions of the radiatively inefficient accretion flow which have been suggested, for instance, are accretion flows with significant macroscopic convection (Chang 2001a; Narayan, Igumenshchev & Abramowicz 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 & Markoff 2000; Beckert & Falcke 2002). They have both virtues and drawbacks in explaining the spectrum in details. Moreover, the recent observation of X-ray flare needs to be answered in terms of the model of the central source of the Sagittarius A* (Baganoff et al. 2001). Different models for Sagittarius A*'s flared state make very disparate predictions for the emission at wavelengths between the X-ray and radio regimes (Markoff et al. 2001; Liu & Melia 2002). A main difference between these two explanations is essentially a different physical process for the central engine of the radio emission that powers the Sagittarius A*, that is, accretion disk and jet. Hence, the independent observations resolving the central part are required to settle down related issues.

This paper is motivated by the recent observational report on the proper motion of stars close to the Sagittarius A*. We explore the possibility of using such kind of observation to distinguish two quite different physical models for the radio emission of the Sagittarius A*. Stellar proper motion data covering an interval from 1992 to 2002 and allowing to determine orbital accelerations for some of the most central stars of the Galaxy have been reported (Schödel et al. 2002; Ghez et al. 2003). The observations covering both pericenter and apocenter passages show that the star is on a bound, highly elliptical Keplerian orbit around it, with an orbital period of $\sim$ 15 years, a pericenter distance of only 124 AU, the eccentricity of 0.87. Dramatic improvements in the capabilities of the infrared instruments produced high quality data on the distribution of stars near the Sagittarius A*. According to the observations, the majority of the stars around the Sagittarius A* are bright early type stars (Gezari et al. 2002). It has been already suggested that the three dimensional orbits of stars such as S2, currently closest star to the Sagittarius A*, could be used to test putative accretion disk theories (Cuadra, Nayakshin, & Sunyaev 2003). They concluded that there could exist no cool disk near the Sagittarius A*. That is, the cool disk must have a large inner edge. In this paper we review some of potentially observable signatures of a hot and quasi-spherical accretion flow, such as ADAFs, in our Galactic center, and then apply the model to the particular case of the Sagittarius A* by recalculating the model studied by Chang (2001b) with the orbital parameters from the observation.

We adopt the following dimensionless variables throughout the paper : mass of the SMBH $m = M/M_{\odot}$; radius from the SMBH $r = R/R_g$, where $R_g = 2GM/c^2 = 2.95 \times 10^5\ m$ 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 the accreting gas as a two-temperature plasma assuming that the flows are spherically symmetric. The quantities of interest are the volume-integrated quantities which are obtained by integrating throughout the volume of the flows. As canonical values in a model for the ADAFs parameters are taken to be $r_{\rm min} = 3$, $r_{\rm max} = 10^5$, $\alpha = 0.3$, and $\beta = 0.5$ (see, e.g., Narayan & Yi 1995). We review the physical processes which may occur during the stellar encounter with the hot disk in §2, and present results in §3. We then discuss the results and conclude in §4.

II. STELLAR INTERACTION WITH ADAF

Making the simplest assumption of an optically thin and quasi-spherical hot accretion disk, we discuss observational features due to the hot accretion disk around the SMBH through its interaction with a closely flying-by star. A hot accretion disk is believed to exist in low luminosity AGNs (Ho 1999). It may also exist in dormant galaxies and in the center of our own Galaxy (e.g., Narayan, Yi, & Mahadevan 1995; Narayan et al. 1998). If there is an accretion disk around the SMBH, gentle processes may occur due to the interaction of a flying-by star and the accretion disk around the SMBH (Syer, Clarke, & Rees 1991; Hall, Clarke, & Pringle 1996), without mentioning the tidal disruption events (Rees 1988; Ivanov & Novikov 2001; Chang et al. 2002; Choi et al. 2001, 2002). The process has become more interesting particularly when the accretion disk is relativistically hot. Stellar interactions with a hot accretion flow around the SMBH play a role in that an flying-by star may cool the hot accretion disk as a result of Comptonization. It is shown that the Comptonization of the stellar emission will take place in a hot accretion disk such as the ADAFs around the SMBH (Chang 2001b). Observational consequences of flying-by of a star in a hot accretion disk, that is, the ADAFs are the increase of the total X-ray flux due to Comptonized photon and the decrease of the electron temperature and subsequently the radio flux of the hot accretion disk. The X-ray flux change due to the stellar Comptonization may be inappreciable, since the Comptonized photons are likely to be smoothed out. On the other hand, the radio flux change due to the change in the electron temperature of the ADAFs is sensitive enough, if the star may reside very inner part of the accretion disk.

In the followings it is briefly summarized what happens when a bright star encounters a hot accretion disk. Firstly, when a star passes through the accretion disk around the SMBH dynamical friction causes the vis-

cous heating. The power is given by $P = F_{\rm df} \times v_{\rm rel}$, where $F_{\rm df}$ is the drag force, $v_{\rm rel}$ 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 the relative velocity $v_{\rm rel}$ is estimated as follows

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

where the negative sign indicates that the force acts in the opposite direction of the star, G is the gravitational constant. 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 choose the supersonic estimate of I, as it gives an upper limit on the heating due to the drag force. Note that under the condition of the ADAFs, $v_{\rm rel} \sim c_{\rm s} \sim v_K$, where v_K is the Keplerian speed, and therefore the Mach number is of order unity.

Secondly, on the other hand, the stellar emission may heat or cool a gaseous medium, depending on the ambient environment. In the ADAFs a star and the stellar 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 proportionally to the square of the density (Stepney & Guilbert 1983). Comptonization is also possible because the electrons in the ADAFs are relativistic. Radiation emitted by the star is an important source of soft photons. The cooling rate of the accretion disk due to the stellar light is dependent upon the position of the star in the accretion flows, and its physical properties, such as, the mass accretion rate, the temperature, the density. The spectrum of the emitted radiation can be approximated as a blackbody. The outgoing flux at radius R is given by

$$F_*(R) = \frac{L_*}{4\pi R^2}, \qquad (2)$$

where L_* is the stellar luminosity. When the star is at a distance from the central SMBH d, the distance from an arbitrary position in the accretion disk to the star R is related with the distance from the position to the SMBH r as given by

$$R^2 = \left|d^2 + r^2 - 2rd\cos\theta\right|, \qquad (3)$$

where θ is the angle between two position vectors **Or** and **Od** with respect to the central SMBH. Now we are in a position to calculate the Comptonization of the stellar flux (cf. Narayan & Yi 1995). We have the stellar cooling rate as

$$\begin{aligned} q^-_{*,C} &= 3\frac{F_*}{R}\left(\frac{\theta_e}{x_b}\right)^3 \left\{ \frac{\eta_1}{3}\left[\left(\frac{x_{max}}{\theta_e}\right)^3 - \left(\frac{x_c}{\theta_e}\right)^3\right] \right. \\ &- \left. \frac{\eta_2}{3+\eta_3}\left[\left(\frac{x_{max}}{\theta_e}\right)^{3+\eta_3} - \left(\frac{x_c}{\theta_e}\right)^{3+\eta_3}\right]\right\}, \qquad (4) \end{aligned}$$

where $\theta_e = kT_e/m_ec^2$, k being the Boltzmann constant, T_e being the electron temperature, m_e being the electron mass, c being the speed of light, $x_b = h\nu_b/m_ec^2$, h being the Plank constant, $\nu_b = 5.61 \times 10^{10}T_*$, $x_{max} = max(x_b, 3\theta_e)$, x_c is given by the critical frequency ν_c, η'_k s are defined by Dermer, Liang, & Canfield (1991). The stellar cooling rate per volume due to Comptonization becomes relatively important than those due to other processes of accretion disk cooling when the mass accretion rate becomes small and the star is at large distance.

III. RESULTS

By adopting the model of the disk cooling suggested by Chang (2001b) we estimate observational features due to the hot accretion flow present around the Sagittarius A* through its interaction with the closely flying-by star, that is, S2. Using the orbital parameters and the observed positions of the currently closest star S2 (Schödel et al. 2002; Ghez et al. 2003), we are able to calculate the radio flux difference which could have been observed with a similar period of the orbital period of the star.

Provided that the background gas environment is described by the ADAF model and that stellar cooling rate per volume due to Comptonization is calculated, the volume-integrated cooling rate due to stellar emission $dQ^-_{*,\rm C}$ over the spherical shell at r can be obtained. We plot $dQ^-_{*,\rm C}$ with other volume-integrated cooling rates as a function of r in Figure 1, when the S2 star just passes its pericenter, that is, $r \sim 2000$. We adopt its bolometric luminosity is $\sim 10^5 L_\odot$ (Cuadra, Nayakshin, & Sunyaev 2003). The continuous line represents $dQ^-_{*,\rm C}$, the dotted curve and the dashed curve represent volume-integrated cooling rate due to synchrotron cooling $dQ^-_{\rm sync} + dQ^-_{\rm sync,C}$ and bremsstrahlung cooling $dQ^-_{\rm br} + dQ^-_{\rm br,C}$. These volume-integrated cooling rates are subject to the mass accretion rate to the central SMBH. The synchrotron cooling $dQ^-_{\rm sync}$ and bremsstrahlung cooling $dQ^-_{\rm br}$ 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 the mass accretion rate is $\dot{m} = 10^{-4}$ (Quataert, Narayan, & Reid 1999). This corresponds to the accretion rate estimation from the observation when the favored ADAF model is assumed (Quataert, Narayan, & Reid 1999; Quataert & Gruzinov 2000b). Even a lower accretion

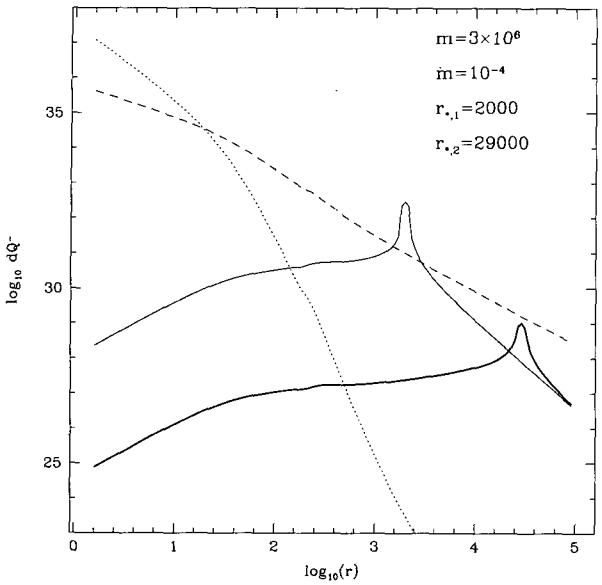

Fig. 1.— The volume integrated cooling rate over the spherical shell due to various mechanisms are shown as a function of r in log scales where $m = 3 \times 10^6, \dot{m} = 10^{-4}$. The thin continuous curve represents the $dQ^-_{*,\mathrm{C}}$ due to a star at $r = 2000$ and the thick curve at $r = 29000$, the dotted curve and the dashed curve represent due to synchrotron cooling $dQ^-_{\mathrm{sync}}+dQ^-_{\mathrm{sync,C}}$ and bremsstrahlung cooling $dQ^-_{\mathrm{br}}+dQ^-_{\mathrm{br,C}}$. The dQ^-'s are in ergs s^{-1}. Similar plots also appear in Chang & Choi (2003).

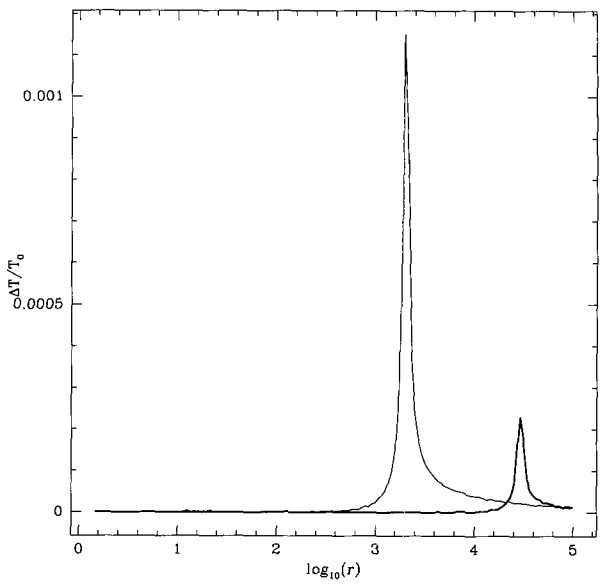

Fig. 2.— The relative electron temperature differences are shown as a function of r. The thin and thick solid curves represent the cases when the cooling star is at $r \sim 2000$ and $r \sim 29000$, respectively. The relative electron temperature difference is defined as $(T_0 - T_*)/T_0$, where T_0 is the electron temperature of the case without the stellar cooling. Similar plots also appear in Chang & Choi (2003).

rate was claimed when a CDAF or a jet model were employed (Agol 2000; Bower et al. 2003). The thick continuous curve represents a hypothetical $dQ^-_{*,\mathrm{C}}$ when the S2 star is at apocenter, $r \sim 29000$.

In Figure 2 we show that the relative difference in the electron temperature as a function of r when the cooling star is at $r \sim 2000$ and $r \sim 29000$ 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 of the case without the 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 the mass accretion rate the suppression of the temperature due to the stellar cooling becomes less significant as the cooling star is at farther away from the central SMBH.

In Figure 3, we show the radio spectrum of the ADAFs in the upper panel and the relative difference of the radio spectrum with and without the stellar cooling in the lower panel. The relative difference of radio spectrum has been given for two different epochs, that is, when the star is at pericenter and at apocenter, by the dotted and dashed curves, respectively. Since the dominant effects on the spectrum is due to the inner parts of the ADAFs, the stellar cooling at farther from the SMBH changes the spectrum less significantly. The suppression of the radio spectrum due to the stellar cooling is the greatest at the frequency corresponding to the position where the star cools the accretion disk (see Mahadevan 1997). It 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.

In Figure 4, we show the expected light curve in radio bands in terms of the orbital phase of S2. The pericenter corresponds to the orbital phase 0.5. We estimated the relative difference at three different radio bands, that is, 10 MHz, 30 MHz, and 100 MHz. Since the star S2 spends most of time in its orbit around at apocenter, the possibly detectable signature appears as a somewhat broad peak.

IV. DISCUSSIONS AND CONCLUSION

Flux variations in X-rays and radio have been of great interests for observers (Baganoff et al. 2001; Eckart 2002; Goldwurm et al. 2003; Zhao, Bower, & Goss 2001; Zhao et al. 2003). However, most of vari-

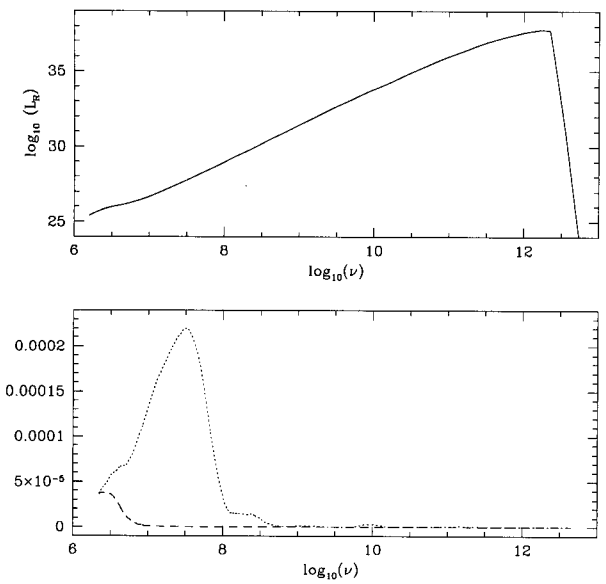

Fig. 3.— The radio spectrum of the ADAFs and the relative difference of the radio spectrum with and without the stellar cooling are shown in the upper panel and in the lower panel, respectively. In the upper panel we show the radio spectra of the ADAFs without the stellar cooling by the solid curve, and with the 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. In the lower panel the relative difference of radio spectrum with and without the stellar cooling has been calculated for two different epochs, that is, when the star is at pericenter and at apocenter, and denoted by the dotted and dashed curves, respectively. The luminosity is in ergs s^{-1} and the frequency in Hz is shown in the log scale. Similar plots also appear in Chang & Choi (2003).

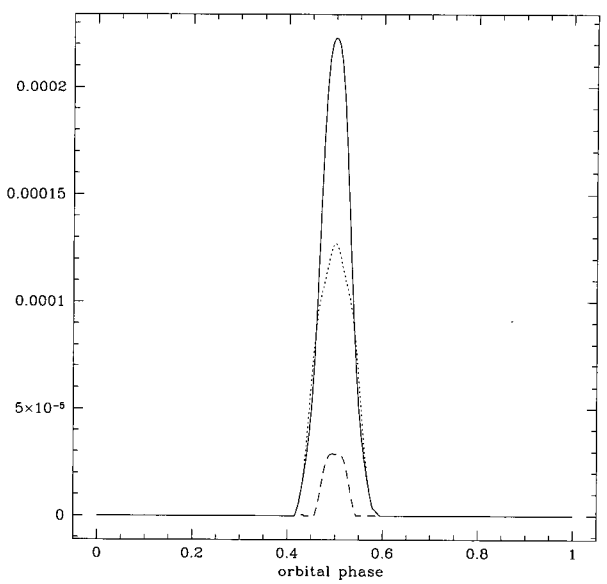

Fig. 4.— The relative difference of radio luminosity with and without the stellar cooling has been shown in terms of orbital phase. The horizontal axis represent the orbital phase of S2 such that the pericenter corresponds to the orbital phase 0.5. The relative luminosity differences at 10 MHz, 30 MHz, and 100 MHz are shown with the dotted curve, the solid curve, and the dashed curve, respectively.

ation study have been focused on a short time-scale variation. The short time-scale variation is of course important since it may provide the information on the physical change in the inner part of the accretion disk (Mushotzky, Done, & Pounds 1993). Observing efforts in another energy band should be also pursued. Hornstein et al. (2002) showed that IR observation can indeed constrain two physically different models for the Sagittarius A* using IR variation observation. Unlike the situation at radio wavelengths, however, the limited time coverage and spatial resolution of IR experiments prevent meaningful constraints on the flared state's IR emission.

On the other hand, the long term variation can also provide the decisive information on the central engine of the source like the Sagittarius A*. In particular, when a star interacts with the accreting matter inspiring to the central SMBH one would expect many interesting effects. Physical consequences of a stellar encounter with a hot accretion disk such as the ADAFs are the increase of the total X-ray flux due to Comptonized photon and the decrease of the radio flux of the hot accretion disk. In addition, flux variation in radio produced by the encountering star could show periodic or quasi-periodic features. Quantitative implications are subject to the condition of the accretion flow and the physical parameters of the encountering star.

Schödel et al. (2002) reported ten years of high resolution astrometric infrared imaging that allows them to trace the orbit of the star S2 currently closest to the compact radio source Sagittarius A*. It is interesting to consider a way to constrain the central source of the Sagittarius A* using this kind of observation. Cuadra, Nayakshin, & Sunyaev (2003) have already discussed that the orbit of star S2 alone requires the disk to be optically thin with near infrared optical depth no larger than 0.01. They claimed that the optically thick and geometrically thin disk should have exhibited observational signatures over the period of the observation campaign, which we have no indications. This claim is in agreement with the radio observations (Duschl & Lesch 1994), which demonstrated using the radio variability that the radio flux the Sagittarius A* is due to the optically thin synchrotron radiation from the relativistic electrons.

Motivated by this observation, we have attempted to calculate what one may expect using observed param-

eters of the currently closest star S2. Following what Chang (2001b) suggested, we have calculated the stellar cooling effects with the observed orbital parameters of star S2, the currently closest star to the Sagittarius A*. The relative electron temperature difference is a few parts of a thousand at the epoch when the star S2 is near at the pericenter. The subsequent radio spectrum of the ADAFs shows the suppression of the radio spectrum due to stellar cooling which is the greatest at the frequency at $\nu \lesssim 100$ MHz for stellar soft photons from the star at $r \gtrsim 10^3$. The relative radio luminosity difference with and without the stellar cooling is small, particularly even when the star S2 is near at the pericenter is order of 10^{-4}. We conclude that if the observational precision reaches better than a few parts in 10^4 in $\nu \lesssim 100$ MHz band, this stellar cooling effect can be confirmed and, hence, the nature of the accretion disk around Galactic SMBH may be more accurately determined. Of course, the conclusion depends on changes of the structure of the accretion disk due to the presence of a star and on responses of the star to the strong gravity of the SMBH. The observational data in this frequency range is not available.

There is one interesting point to make out. Bower et al. (2002) have reported multiepoch, multifrequency observations of the Sagittarius A*, from 1981 to 1998, of which data have been taken at 1.4, 4.8, 8.4, and 15 GHz bands. They have found no periodic radio flux variation with a period $\sim$ 15 years, which is naturally expected from the presence of a hot disk. We suggest that this observation cannot be used to distinguish two competing models. That is, even though no periodic radio flux variations have been found a hot disk model cannot be conclusively ruled out. This is simply 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, as mentioned above. We consider this type of long monitoring can be eventually useful even for other LLAGNs. For an accreting SMBH with a lower mass accretion rate and more closely flying-by star may exhibit its existence.

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REFERENCES

Agol, E. 2000, Sagittarius A* polarization: no advection-dominated accretion flow, low accretion rate, and non-thermal synchrotron emission, ApJ, 538, L121.

Baganoff, F. K., Bautz, M. W., Brandt, W. N., Chartas, G., Feigelson, E. D., Garmire, G. P., Maeda, Y., Morris, M., Ricker, G. R., Townsley, L. K., & Walter, F. 2001, Rapid X-ray flaring from the direction of the supermassive black hole at the Galactic center, Nature, 413, 45.

Beckert, T., & Falcke, H. 2002, Circular polarization of radio emission from relativistic jets, A&A, 388, 1106.

Blandford, R. D. & Begelman, M. C. 1999, On the fate of gas accreting at a low rate on to a black hole, MNRAS, 303, L1.

Bower, G. C., Falcke, H., Sault, R. J., & Backer, D. C. 2002, The spectrum and variability of circular polarization in Sagittarius A* from 1.4 to 15 GHz, ApJ, 571, 843.

Bower, G. C., Wright, M. C. H., Falcke, H., & Backer, D. C. 2003, Interferometric detection of linear polarization from Sagittarius A* at 230 GHz, ApJ, 588, 331.

Chang, H.-Y. 2001a, Can a wind model mimic a convection-dominated accretion flow model?, JASS, 18, 1.

Chang, H.-Y. 2001b, Cooling a hot disk around a supermassive black hole by a star, ApJ, 551, L159.

Chang, H.-Y., & Choi, C.-S. 2002, Iron line profiles from relativistic elliptical accretion disks, JKAS, 35, 123.

Chang, H.-Y., & Choi, C.-S. 2003, Radio variability of the Sagittarius A* due to an orbiting star, to appear in A&A, astro-ph/0306496.

Choi, C.-S., Dotani, T., Yi, I., Fletcher, A., & Kim, C. 2001, X-Ray archival data analysis of time variabilities in Seyfert galaxy MCG–2-58-22, JKAS, 34, 129.

Choi, C.-S., Dotani, T., Chang, H.-Y., & Yi, I. 2002, Long-term X-ray variabilities of the Seyfert galaxy MCG-2-58-22: secular flux decrease and flares, JKAS, 35, 1.

Cuadra, J., Nayakshin, S., & Sunyaev, R. 2003, Bright stars and an inactive disk in Sgr A* and other dormant galaxy centers. I. The optically thick disk, astro-ph/0304533.

Dermer, C. D., Liang, E. P., & Canfield, E. 1991, Luminosity enhancement factor for thermal Comptonization and the electron energy balance, ApJ, 369, 410.

Duschl, W. J., & Lesch, H. 1994, The spectrum of SGR A* and its variability, A&A, 286, 431.

Eckart, A. 2002, Astronomy: X-rays reveal the Galaxy's centre, Nature, 415, 148.

Eckart, A., & Genzel, R. 1997, Stellar proper motions in the central 0.1 PC of the Galaxy, MNRAS, 284, 576.

Falcke, H., & Markoff, S. 2000, The jet model for Sgr A*: radio and X-ray spectrum, A&A, 362, 113.

Gezari, S., Ghez, A. M., Becklin, E. E., Larkin, J., McLean, I. S., & Morris, M. 2002, Adaptive optics near-infrared spectroscopy of the Sagittarius A* cluster, ApJ, 576, 790.

Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, High proper-motion stars in the vicinity of Sagittarius A*: evidence for a supermassive black hole at the center of our Galaxy, ApJ, 509, 678.

Ghez, A. M., Duchene, G., Matthews, K., Hornstein, S. D., Tanner, A., Larkin, J., Morris, M., Becklin, E. E., Salim, S., Kremenek, T., Thompson, D., Soifer, B. T., Neugebauer, G., & McLean, I. 2003, The first measurement of spectral lines in a short-period star bound to the Galaxy's central black hole: a paradox of youth, ApJ, 586, L127.

Goldwurm, A., Brion, E., Goldoni, P., Ferrando, P., Daigne, F., Decourchelle, A., Warwick, R. S., & Predehl, P. 2003, A new X-ray flare from the galactic nucleus detected with

the XMM-Newton photon imaging cameras, ApJ, 584, 751.

Hall, S. M., Clarke, C. J., & Pringle, J. E. 1996, Energetics of star-disc encounters in the non-linear regime, MNRAS, 278, 303.

Ho, L. C. 1999, The spectral energy distributions of low-luminosity active galactic nuclei, ApJ, 516, 672.

Hornstein, S. D., Ghez, A. M., Tanner, A., Morris, M., Becklin, E. E., & Wizinowich, P. 2002, Limits on the short-term variability of Sagittarius A* in the near-infrared, ApJ, 577, L9.

Ichimaru, S. 1977, Bimodal behavior of accretion disks - theory and application to Cygnus X-1 transitions, ApJ, 214, 840.

Ivanov, P. B., & Novikov, I. D. 2001, A new model of a tidally disrupted star, ApJ, 549, 467.

Kato, S., Fukue, J., & Mineshige, S. 1998, Black hole accretion disks (Kyoto: Kyoto Univ. Press).

Liu, S., & Melia, F. 2002, An accretion-induced X-ray flare in Sagittarius A*, ApJ, 566, L77.

Mahadevan, R. 1997, Scaling laws for advection-dominated flows: applications to low-luminosity galactic nuclei, ApJ, 477, 585.

Manmoto, T., Mineshige, S., & Kusunose, M. 1997, Spectrum of optically thin advection-dominated accretion flow around a black hole: application to Sagittarius A*, ApJ, 489, 791.

Markoff, S., Falcke, H., Yuan, F., & Biermann, P. L. 2001, The nature of the 10 kilosecond X-ray flare in Sgr A* , A&A, 379, 13.

Mushotzky, R. F., Done, C., & Pounds, K. A. 1993, X-ray spectra and time variability of active galactic nuclei, ARA&A, 31,717.

Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2000, Self-similar accretion flows with convection, ApJ, 539, 798.

Narayan, R., Mahadevan, R., & Quataert, E. 1998, Advection-dominated accretion around black holes, in *Theory of Black Hole Accretion Disks*, edited by M. A. Abramowicz, G. Bjornsson, & J. E. Pringle. Cambridge University Press, p.148

Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C. 1998, Advection-dominated accretion model of Sagittarius A*: evidence for a black hole at the Galactic center, ApJ, 492, 554.

Narayan, R., & Yi, I. 1994, Advection-dominated accretion: a self-similar solution, ApJ, 428, L13.

Narayan, R., & Yi, I. 1995, Advection-dominated accretion: underfed black holes and neutron stars, ApJ, 452, 710.

Narayan, R., Yi, I., & Mahadevan, R. 1995, Explaining the spectrum of Sagittarius A* with a model of an accreting black-hole, Nature, 374, 623.

Quataert, E., Narayan, R., & Reid, M. J. 1999, What is the accretion rate in Sagittarius A*?, ApJ, 517, L101.

Quataert, E., & Gruzinov, A. 2000a, Convection-dominated accretion flows, ApJ, 539, 809.

Quataert, E., & Gruzinov, A. 2000b, Constraining the accretion rate onto Sagittarius A* using linear polarization, ApJ, 545, 842.

Rees, M. J. 1984, Black hole models for active galactic nuclei, ARA&A, 22, 471.

Rees, M. J. 1988, Tidal disruption of stars by black holes of 10 to the 6th-10 to the 8th solar masses in nearby galaxies, Nature, 333, 523.

Rees, M. J., Phinney, E. S., Begelman, M. C., & Blandford, R. D. 1982, Ion-supported tori and the origin of radio jets, Nature, 295, 17.

Schödel, R., Ott, T., Genzel, R., Hofmann, R., Lehnert, M., Eckart, A., Mouawad, N., Alexander, T., Reid, M. J., Lenzen, R., Hartung, M., Lacombe, F., Rouan, D., Gendron, E., Rousset, G., Lagrange, A.-M., Brandner, W., Ageorges, N., Lidman, C., Moorwood, A. F. M., Spyromilio, J., Hubin, N., & Menten, K. M. 2002, A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way, Nature, 419, 694.

Shakura, N. I., & Sunyaev, R. A. 1973, Black holes in binary systems. observational appearance, A&A, 24, 337.

Stepney, S., & Guilbert, P. W. 1983, Numerical FITS to important rates in high temperature astrophysical plasmas, MNRAS, 204, 1269.

Syer, D., Clarke, C. J., & Rees, M. J. 1991, Star-disc interactions near a massive black hole, MNRAS, 250, 505.

Turolla, R., & Dullemond, C. P. 2000, Advection-dominated inflow/outflows from evaporating accretion disks, ApJ, 531, L49.

Zhao, J.-H., Bower, G. C., & Goss, W. M. 2001, Radio variability of Sagittarius A* -a 106 day cycle, ApJ, 547, L29.

Zhao, J.-H., Young, K. H., Herrnstein, R. M., Ho, P. T. P., Tsutsumi, T., Lo, K. Y., Goss, W. M., & Bower, G. C. 2003, Variability of Sagittarius A* : flares at 1 millimeter, ApJ, 586, 29.