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The Nature of the 10 Kilosecond X-ray Flare in Sgr A*

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Abstract. The X-ray mission *Chandra* has observed a dramatic X-ray flare – a brightening by a factor of 50 for only three hours – from Sgr A*, the Galactic Center supermassive black hole. Sgr A* has never shown variability of this amplitude in the radio and we therefore argue that a jump of this order in the accretion rate does not seem the likely cause. Based on our model for jet-dominated emission in the quiescent state of Sgr A*, we suggest that the flare is a consequence of extra electron heating near the black hole. This can either lead to direct heating of thermal electrons to $T_{\rm e} \sim 6 \cdot 10^{11}$ K and significantly increased synchrotron-self Compton emission, or result from non-thermal particle acceleration with increased synchrotron radiation and electron Lorentz factors up to $\gamma_{\rm e} \gtrsim 10^5$. While the former scenario is currently favored by the data, simultaneous VLBI, submm, mid-infrared and X-ray observations should ultimately be able to distinguish between the two cases.

Key words. Galaxy: center – galaxies: jets – X-rays: galaxies – radiation mechanisms: non-thermal – accretion, accretion disks – black hole physics

1. Introduction

Sgr A*, the compact radio core at the center of our Galaxy (Reid et al. 1999; Backer & Sramek 1999), has been perplexing modelers since its discovery (Balick & Brown 1974). In contrast to nearby LLAGN (Ho 1999), Sgr A* was until recently only positively detected as a radio source. Its mass is determined at $2.6 \cdot 10^6 M_\odot$ within ~ 0.01 pc (Haller et al. 1996; Eckart & Genzel 1996; Ghez et al. 1998) and its integrated radio luminosity has remained steady within a factor of two (Zhao, Bower, & Goss 2001), at $\sim 10^{-9}$ orders of magnitude less than its corresponding Eddington luminosity. All models to explain the radio emission so far have focused on radiative inefficiency as the primary explanation for this dimness, and are comprised mainly of accretion/inflow solutions (Melia, Liu, & Coker 2001; Narayan et al. 1998) outflow solutions (Falcke, Mannheim, & Biermann 1993; Falcke & Markoff 2000, hereafter FM00) and combinations thereof (Yuan, Markoff, & Falcke 2001). A recent review of Sgr A* can be found in Melia & Falcke (2001).

Recently, Sgr A* was finally detected in the X-rays by *Chandra* (Baganoff et al. 2001b) with a rather soft spectrum. During the second observational cycle, Baganoff et al. (2001a) detected an X-ray flare lasting about 10 ks and with a peak luminosity ~ 50 times higher than the quiescent state (Baganoff et al. 2001b). The averaged flare spectrum after taking into account dust scattering is best fit with a power-law (spectral index $\alpha \sim 0.3$), which is significantly harder than that of the quiescent state ($\alpha \sim 1.2$). The longest time scale (10 ks) corresponds to $\sim 390 r_{\rm s}$ where $r_{\rm s} = 2GM_\bullet/c^2$ is the Schwarzschild radius, which argues against thermal bremsstrahlung from the outer radii, e.g. from a standard Advection Dominated Accretion Flow (ADAF; Narayan et al. 1998). The smallest time scale in the flare is roughly 600 s, suggesting activity at scales of $\sim 20 r_{\rm s}$, which means the flare originated close to the central engine.

The variability and the spectral index of Sgr A* in the X-rays are consistent with synchrotron self-Compton (SSC) from the innermost regions near the black hole, e.g., the nozzle of a jet (FM00; Yuan, Markoff, & Falcke 2001) or a magnetic dynamo within the circularized accreting plasma (Melia, Liu, & Coker 2001). In this picture, the X-rays are inverse Compton up-scattered synchrotron photons from the so-called submm-bump (Serabyn et al. 1997; Falcke et al. 1998). Since the submm-bump is thought to be produced close to the black hole, very short time scale variability (several hundred seconds) was already predicted (FM00). In the following we would like to explore the various scenarios which could lead to a dramatic X-ray flare within the jet model.

2. Models

We start with our basic jet emission model (Falcke & Biermann 1999; FM00), consisting of a conical jet with pressure gradient and nozzle. The parameters in the noz-

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zle for the quiescent state are determined from the underlying accretion disk as described in Yuan, Markoff, & Falcke (2001), and as summarized below. All quantities further out in the jet are solved for using conservation of mass and energy, and the Euler equation for the accelerating velocity field. We take the distance to the Galactic center as $d_{gc} = 8.0$ kpc.

Clearly, in order to produce an X-ray flare, one or several parameters had to have suddenly changed in Sgr A*. In Figs. 2 and 3 in FM00, we showed how the radio and X-ray spectra in the jet model change if one changes the magnetic field – a similar result would be expected for an increase in particle density – or the electron temperature by a small amount. The former would be expected for an increased jet power or accretion rate, which would result in simultaneous flaring at all frequencies with little change in spectral index. In the latter scenario, however, the X-rays flare much stronger with a hardening of the spectrum, because SSC is very sensitive to changes in electron energies. This type of fast heating could in principle occur via instantaneous transfer of energy from the magnetized plasma in the accretion flow to the radiating particles, e.g. as would be expected from the sudden discharge of energy in magnetic flares through reconnection (e.g., Biskamp 1997).

On the other hand, we know that non-thermal particle distributions are quite common in jets in AGN and X-ray Binaries (XRBs), leading to the appearance of optically thin power laws in the spectra. Observations of jets in XRBs (e.g., Fender 2001) and some AGN (e.g., Meisenheimer, Yates, & Roeser 1997) seem to hint at a common type of power law with typical spectral index of $\alpha \sim 0.6-0.8$. While the exact mechanism is not yet firmly established, and reconnection may also contribute, first order diffusive shock acceleration leads more naturally to an electron distribution with the index $p \sim 2-2.6$ depending on the shock compression ratio ($\frac{dN}{dE} \propto E^{-p}$, see e.g., Jones & Ellison 1991). Such accelerated particles would result in a significant increase of optically thin synchrotron emission, with spectral slope $\alpha = (p-1)/2$.

In the following we therefore explore three scenarios for the origin of the X-ray flare: increased jet power or accretion rate, increased heating of relativistic particles, or sudden shock acceleration of the particles. We will refer to these three models as the $\dot{M}$-flare, the $T_{\rm e}$-flare and the shock-flare, respectively.

3. Results

Since no simultaneous radio or mid-infrared (MIR)observations are available we include in our figures an "upper radio envelope", showing the highest flux ever detected at each radio frequency in long-term monitoring of Sgr A* with the VLA (Zhao, Bower, & Goss 2001). While it is possible that this type of X-ray flare is so rare that it was never before captured by radio observations, it seems statistically unlikely given the huge radio database compared to only two cycles of Chandra observations. This argument does not hold for the poorly sampled data at other wavelengths and we only consider single-epoch measurements which most likely only reflect the quiescent Sgr A* spectrum.

The effects of the $\dot{M}$-flare and the $T_{\rm e}$-flare can be modeled simply by changing the jet power and temperature, respectively, in our published models (FM00, Yuan, Markoff, & Falcke 2001). We assume that the jet carries away a fixed fraction of the accretion energy $\dot{M}c^2$, and that this energy is divided evenly between the kinetic energy carried by the cold plasma, and the internal energy carried by the magnetic field and hot electrons. Once the electron temperature $T_{\rm e}$ in the nozzle is fixed, assuming a Maxwellian distribution, the jet nozzle density n_0 is determined via approximate equipartition from the magnetic field B_0. In the quiescent state, the relevant parameters for our most recent fit are $T_{\rm e} =\sim 2\cdot 10^{11}$ K, $n_0 \sim 9\cdot 10^5$ cm^{-3} and $B_0 \sim 20$ G. Fig. 1 shows the prediction for a) the $\dot{M}$-flare, with jet power ($\propto B^2$) raised by ~ 3 via increasing the jet nozzle magnetic field B_0 to ~ 35 G while holding $T_{\rm e}$ fixed (which in turn increases n_0 by ~ 3 to $\sim 3\cdot 10^6$ cm^{-3}) and b) the $T_{\rm e}$-flare for $T_{\rm e}$ raised by a factor of ~ 3 to $T_{\rm e} \sim 6\cdot 10^{11}$ K, while holding n_0 and B_0 fixed. The parameters were chosen to match the amplitude of the X-ray flare data, shown with its error box as well. For comparison we show in the figure also the quiescent jet+disk spectrum.

As expected, the $\dot{M}$-flare strongly over-predicts the radio flux by a large factor. In fact, such a huge flare in the radio has never been reported and in addition, the spectral index is far too steep. The $T_{\rm e}$-flare fares much better: the predicted radio flux is close to already observed radio flare maxima and the X-ray spectrum becomes very hard during the flare. The model also predicts significant brightening in the MIR range during the X-ray flare event, due to the shift of the submm-bump to higher frequencies, which should exceed currently available non-simultaneous MIR/NIR limits. In contrast to the radio, the MIR regime has not been sampled well enough to decide whether such flares exist. However, Genzel & Eckart (1999) and Serabyn et al. (1997) report observations where Sgr A* could have been detected during a brief period with unusually high flux densities at 350 μm and 2.2 μm. Clearly, this needs to be confirmed and reassessed in light of the new X-ray observations.

The shock-flare scenario requires more discussion, as it involves the effects of diffusive shock acceleration in the jet. This has been done already by Markoff, Falcke, & Fender (2001), where the scaled version of the jet model previously used to explain Sgr A* (Yuan, Markoff, & Falcke 2001; FM00) has successfully been applied to X-ray binaries in the low/hard state by including shock acceleration. Because the low/hard state is characterized by a very faint, possibly ADAF-like accretion disk as in Sgr A*, the ambient photon field is not strong enough to result in significant inverse Compton (IC) cooling, allowing shock accelerated electrons to achieve rather high energies.

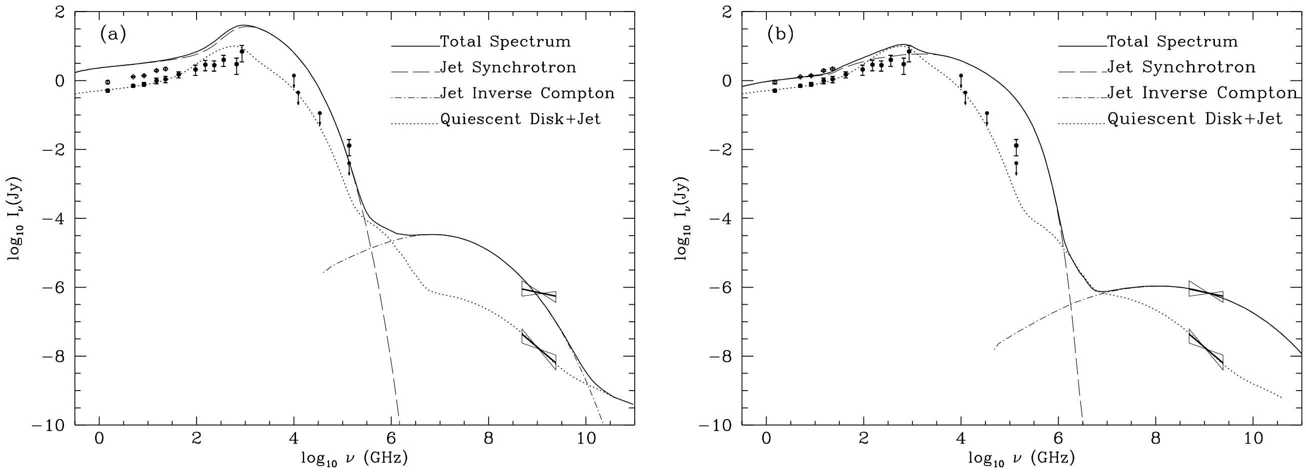

Fig. 1. Fit of the jet model **(solid line)** to the flare data of Baganoff et al. (2001a) (a) with the $\dot{M}$-flare, raising the jet power by a factor of ~ 3 , and (b) with the $T_{\rm e}$-flare by raising the temperature of the electrons by a factor of 3, compared to the quiescent jet and disk model **(dashed line)**. The radio data and IR upper limits are from the data set compiled and presented in Melia & Falcke 2001, where IR data are from single-epoch observations only. The upper radio points show the highest flux detected at that particular frequency, as compiled by Zhao, Bower, & Goss (2001). The lower X-ray data show the quiescent state spectrum of Baganoff et al. (2001b).

Following Markoff, Falcke, & Fender (2001) the particles would be accelerated up to a maximum energy $E_{\rm e,max} = \gamma_{e,max} m_{\rm e} c^2$, which is reached when the synchrotron loss rate equals that of acceleration. We use the simple parallel shock acceleration rate

$$t_{\rm acc}^{-1} = \frac{3}{4}\left(\frac{u_{\rm sh}}{c}\right)^2 \frac{eB}{m_{\rm e} c \xi \gamma_{\rm e}}, \quad (1)$$

where $u_{\rm sh}$ is the shock speed in the plasma frame. The parameter $\xi < c\beta_e/u_{\rm sh}$ (Jokipii 1987) is the ratio between the parallel diffusive scattering mean free path and the gyroradius of the particle, and ranges from a lower limit at $\xi = 1$ up to typically a few 10^2 (e.g., Jokipii 1987). For a magnetic field of ~ 20 G as found in our model of the quiescent state, the acceleration time scale is ~ 0.1 sec for even $\gamma_{\rm e} = 10^5$ electrons, and hence is shorter than the dynamical time scale at the black hole.

Setting the standard synchrotron loss rate $t_{\rm syn}^{-1} = \frac{4}{3}\sigma_{\rm T}\gamma_{\rm e}\beta_{\rm e}^2\frac{U_{\rm B}}{m_{\rm e}c} = t_{\rm acc}^{-1}$, we can solve for the maximum electron energy achieved by acceleration $\gamma_{\rm e,max}$. If we define as a reference value $\xi = \xi_2 100$, the maximum synchrotron frequency is then

$$\nu_{\rm max} = 0.29\nu_{\rm c} \simeq 1.2 \cdot 10^{20} \xi_2^{-1} \left(\frac{u_{\rm sh}}{c}\right)^2 \quad {\rm Hz} \quad (2)$$

where $\nu_{\rm c} \simeq \frac{3}{4\pi}\gamma_{\rm e,max}^2 (eB)/(m_{\rm e}c)$ is the critical synchrotron frequency. This value is not dependent on the magnetic field, the jet power, or the shock location as long as we are in the synchrotron cooling dominated regime.

Because the shock accelerated particles responsible for the X-ray synchrotron will have very high energies ($\gamma_{\rm e} \sim 10^5$) for the low magnetic fields further out in the jet, the synchrotron cooling time scale will be very short, on the order of $\sim 10^2$ s. This means that re-acceleration along the jet is required to maintain the population, and will result in rapid cooling if the acceleration is switched off. We thus approximate the shock acceleration as continuous starting at a distance $z_{\rm sh}$. For X-ray binaries we found that the shock acceleration must begin relatively close to the nozzle at $z_{\rm sh} \sim 10 \sim 10^2 r_{\rm s}$ (Markoff, Falcke, & Fender 2001; Markoff et al., in prep.). This location is determined from the data by extrapolating the synchrotron X-ray curve to where it meets the optically-thick, flattish spectrum in the radio-IR. This intersection is unique for a fixed spectral index, and gives $z_{\rm sh}$ because the self-absorption frequency scales inversely with z in the jet model.

If we then fix for simplicity the fraction of accelerated particles at 50% and keep the other parameters as in FM00 and Yuan, Markoff, & Falcke (2001) we can calculate the resultant shock-flare model spectrum as shown in Fig. 2. As the spectral index becomes harder for a fixed X-ray flux, the optically thick turnover must occur at lower frequencies, i.e. further out in the jet. For a standard spectral index of $\alpha \sim 0.8$ as typically seen in AGN, the shock acceleration region must be at $\sim 16 r_{\rm s}$, which is consistent with the observed time scales. However, the assumed standard AGN spectral index is only marginally compatible with the spectrum observed for the X-ray flare, which poses a problem for such a model. Taking on the other hand the reported best-fit X-ray spectral index at face value would imply $\alpha = 0.3$ and require $z_{\rm sh} \sim 10^4 r_{\rm s}$. This is very far in comparison to other jet systems and furthermore ruled out by the observed short time scales.

4. Discussion

We are able to explain the 10 ks flare in Sgr A* detected by *Chandra* by heating the radiating electrons within the jet model of FM00, either so they remain quasi-thermalized

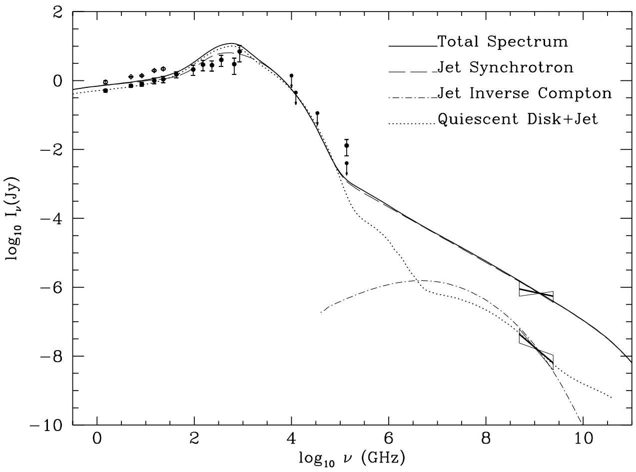

Fig. 2. Fit to the flare data of Baganoff et al. (2001a) for the shock-flare model, other data the same as Fig. 1.

(T_e-flare) or via the non-thermal process of shock acceleration (shock-flare). A flare due to an increase in accretion rate ($\dot{M}$-flare) appears very unlikely because of the generally low level of radio variability.

Of the two remaining scenarios, the shock-flare is more intriguing because it offers a solution where the X-ray flare occurs without a great effect on the lower-frequency emission, consistent with the observed lower radio variability of Sgr A* over the last decades. At the marginal end of the fit, it can also explain the shortest variations via the location of the shock or fast radiative cooling, and predicts a spectral index consistent with that seen in other AGN systems. Although the radio flux does not change much for this case, the presence of the optically thin tail would predict a significantly larger radio profile (more extended, optically thin jet emission; see FM00 for a discussion of this point) on the sky and a shift of the centroid of the radio emission. However, in the radio astrometric work of Reid et al. (1999) no such shift has been detected so far.

Alternatively, the T_e-flare with its sudden heating of hot ($T_e \simeq 6 \cdot 10^{11}$ K) electrons by, e.g., magnetic reconnection, can explain the X-ray flare via increased SSC emission, similar to models for the quiescent state spectrum. The fast variability can be explained by the small source size and outflow with $v \sim c$, leading to fast adiabatic cooling, while radiative cooling is not as important ($t_{\rm syn} \sim 5 \cdot 10^4$ for $T_e = 6 \cdot 10^{11}$ K electrons in the submm-bump). In contrast to the shock-flare model, the T_e-flare model fits the reported X-ray spectrum much better. However, the radio variability is larger than in the synchrotron case, but still falls along the "envelope" of highest radio fluxes observed so far (Fig. 1). In addition the model predicts simultaneous MIR flaring, in a regime where no monitoring data is currently available. So although the T_e-flare case is favored over the shock-flare case in terms of the fit to the X-ray flare data, only simultaneous submm/MIR/X-ray and VLBI observations in the near future will unequivocally determine its viability.

For the T_e-flare, assuming the protons have at least the same temperature one can compare the energy density of the plasma and the gravitational binding energy, $GM_\bullet m_p n/R$, yielding

$$\frac{\Gamma n k_b T}{GM_\bullet m_p n R^{-1}} \simeq 3.4 \left(\frac{\tau}{600\mathrm{sec}}\right)\left(\frac{T}{6\cdot 10^{11}\mathrm{K}}\right) \qquad (3)$$

for a $M_\bullet = 2.6 \cdot 10^6 M_\odot$ black hole and a relativistic plasma with $\Gamma = 4/3$ (e.g., Königl 1980) at a distance $R = c\tau$ from the black hole set by the variability time scale. Under such simple assumptions the plasma would not be gravitationally bound, which is certainly consistent with the jet scenario.

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