STOCHASTIC ELECTRON ACCELERATION DURING THE NEAR-INFRARED AND X-RAY FLARES IN SAGITTARIUS A*  

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ABSTRACT

Recent near-IR (NIR) and X-ray observations of Sagittarius A*’s spectrum have yielded several strong constraints on the transient energizing mechanism, justifying a reexamination of the stochastic acceleration model proposed previously for these events. We here demonstrate that the new results are fully consistent with the acceleration of electrons via the transit-time damping process. But more importantly, these new NIR and X-ray flares now can constrain the source size, the gas density, the magnetic field, and the wave energy density in the turbulent plasma. Future simultaneous multiwavelength observations with good spectral information will, in addition, allow us to study their temporal evolution, which will eventually lead to an accurate determination of the behavior of the plasma just minutes prior to its absorption by the black hole.

Subject headings: acceleration of particles — black hole physics — Galaxy: center — plasmas — turbulence

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1. INTRODUCTION

On 2000 October 27, the Chandra X-Ray Observatory detected a highly variable X-ray flare coincident with the position of Sagittarius A* (Baganoff et al. 2001). The transient lasted a couple of hours, with a peak luminosity ~45 times greater than the quiescent emission. Even more surprising was the realization that during the event, the X-ray output dropped abruptly by a factor of 5 in under 10 minutes, recovering just as quickly. Light travel time arguments therefore place the source of this unusual radiation within a region no bigger than about 10 light-minutes or ~1013 cm across.

Sgr A*, a compact radio source at the Galactic center, is thought to be the radiative manifestation of a ~3.4 × 106 M⊙ supermassive black hole with the Schwarzschild radius Rs = 2GM/c2 ≈ 1012 cm, where G, M, and c are the gravitational constant, the black hole mass, and the speed of light, respectively. Earlier theoretical modeling of its spectrum and polarization properties (Melia et al. 2000, 2001; see also Falcke & Markoff [2000] for an alternative model in which this emission is produced within a jet) had already anticipated an emission region within the inner 10 Schwarzschild radii of a hot, magnetized Keplerian flow.

Not long after Chandra’s first detection of the X-ray flare, XMM-Newton followed with its own measurements, including the discovery of two unusually strong bursts a couple of years later (Goldwurm et al. 2003; Porquet et al. 2003). None of the previous X-ray satellites had the sensitivity and spatial resolution to identify such low-luminosity events at the distance of the Galactic center. Chandra and XMM-Newton now detect them at a rate of about one per day, most of which are usually weak and last tens of minutes. The best-fit photon index during the majority of these bursts is ~1.3, representing a flattening of about 1 compared to the Sgr A* spectrum in the quiescent state, which includes a significant contribution from thermal emission at large radii (Melia 1992; Baganoff et al. 2003). In addition, the 2000 October 27 event appears to show a soft-hard-soft spectral evolution.

But the most intriguing X-ray flare of all may actually be the most recently detected event, in which a significant modulation with an average period of 21.4 minutes was seen over the course of its ~3 hour duration (Bélangier et al. 2005a, 2005b; an earlier identification of X-ray periods in Sgr A* was reported by Aschenbach et al. [2004], although their significance is questionable). The separation between the flux minima actually decreases from about 25 down to 17.5 minutes as the flare evolves, presumably corresponding to the passage of an emitting plasma in a Keplerian motion from a radius r ~ 2.9rS to 2.4rS. This region therefore appears to lie somewhere below the marginally stable orbit (MSO) for a nonspinning black hole; it would, however, be outside the MSO for a Kerr black hole with a large spin. The monotonic decrease of the X-ray period is strongly reminiscent of what was seen in near-IR (NIR) flares detected just a few years earlier, where an average period of 17 minutes was associated with a similar chirping behavior with the period decreasing from 23 to 13 minutes (Genzel et al. 2003). These two sets of observations—one ground-based in the NIR, the other at X-ray energies from space—support the view that we are probably witnessing the evolution of an event moving inward through the last portion of the accretion disk inside or very near the MSO. The inferred radial velocity vr ~ 108 cm s−1 is consistent with an accretion driven by the magnetic viscosity of the turbulent Keplerian flow.

Not surprisingly, previous speculation on the underlying mechanism for these events (Liu & Melia 2002) focused on the view that such X-ray flares might be driven by an accretion instability. While this may still be true in light of all the more recent observations, the process by which the actual emission occurs is uncertain. However, the fact that the NIR spectrum (Eisenhauer et al. 2005) is much steeper than that of its X-ray counterpart excludes a direct extrapolation of the spectrum (see Liu & Melia 2001 and Fig. 2 below). The currently favored scenario is one in which the millimeter/submillimeter-to-NIR portion of the spectrum is due to synchrotron, whereas the X-rays are produced by synchrotron self-Compton (SSC). (This constraint is empirically

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motivated and is independent of whether the emission occurs within a disk or a jet.) It turns out that producing the right blend of physical conditions to fit both the NIR and X-ray flare emission (under the assumption that the two occur more or less simultaneously—a concept that is yet to be confirmed compellingly) is not trivial. In the next section we describe the observational constraints on the model parameters under this scenario. Our work with stochastic acceleration (SA) in producing Sgr A*’s quiescent spectrum (Liu et al. 2004, hereafter LPM04) motivates us to consider a picture in which the flare itself is produced by a magnetic event, possibly driven by an accretion instability. A toy model of this acceleration and its fit to the flare spectra are described in § 3, and § 4 summarizes the main results and discusses the model limitations.

2. OBSERVATIONAL CONSTRAINTS ON THE SSC MODEL

The NIR and X-ray flares in Sgr A* have peak luminosities as high as \( \sim 10^{35} \) erg s\(^{-1}\) (Baganoff et al. 2001; Ghez et al. 2004). Several relatively long duration flares, two in the NIR (Genzel et al. 2003) and another in X-rays (Béland et al. 2005), also displayed quasi-periodic modulations with a period decreasing from \( \sim 25 \) to 13 minutes as the flare evolved. Assuming Keplerian motion, this corresponds to a transition in radius from \( \sim 2.9 R_\odot \) to \( 1.9 R_\odot \). Two flares have also been observed simultaneously in the NIR and X-ray bands, with a peak X-ray luminosity, respectively, 3 and 18 times the quiescent level of \( \sim 2 \times 10^{35} \) ergs s\(^{-1}\) and their spectroscopy still being processed (Eckart et al. 2004). The first NIR spectroscopy was completed in 2004 July: a power-law fit to the power spectrum \( \nu F_\nu \propto \nu^{-\alpha} \) (with \( \nu \) the emission frequency) yields \( \alpha = 2.2 \pm 0.3 \) during the peak of the flare observed 2004 July 15 and \( \alpha = 3.7 \pm 0.9 \) during the rising and decay phases. For the flare of 2004 July 17, \( \alpha = 3.5 \pm 0.4 \) (Eisenhauer et al. 2005). If the NIR emission is produced via the synchrotron process, the radiating electron distribution \( N(\gamma) \propto \gamma^{-p} \) (with \( \gamma \) the Lorentz factor) must have an index \( p > 7.4 \), suggesting an exponential cutoff of the electron distribution presumably dictated by the acceleration process, at \( \gamma_{cr} \approx (\nu_{\text{NIR}}/\nu_p)^{1/2} \), where \( \nu_p = eB_{\perp}/m_e c \) is the electron gyrofrequency and \( e, m_e, \) and \( B_{\perp} \) are the electron charge, mass, and the perpendicular magnetic field, respectively. The X-ray flares, on the other hand, often display a very hard spectrum with \( \alpha \approx -0.7 \pm 0.5 \) (Baganoff et al. 2001; Goldwurm et al. 2003). In the SSC (or in general IC) scenario, this requires a flat electron spectrum (\( p \gtrsim 1.6 \)). (This is different from a power law commonly assumed, or a broken-power-law distribution caused by radiative cooling.) At the longer submillimeter-wavelength the flares usually have a much smaller flux increase above their quiescent value than the NIR flares, which suggests a photon spectral index \( \alpha < 2.2 \), requiring a flattening of the electron distribution at lower energies. As we show below, a fairly flat power-law spectrum with an exponential cutoff \( N(\gamma) = N_0 \gamma^{-p} \exp(-\gamma/\gamma_{cr}) \) can reproduce these observed spectra and is a natural consequence of a simple SA model, where \( N_0 \) is a normalization factor. Because most of the observed NIR and X-ray emissions are produced by electrons near \( \gamma_{cr} \), and for \( p < 0.4 \) the radiation spectrum is almost identical, we set \( p = -2 \), corresponding to a relativistic Maxwellian distribution, in what follows. The observed emission characteristics can then set strict limits on the model parameters, such as the source size \( R \), the magnetic field \( B \), the gas density \( n \), and \( \gamma_{cr} \).

Before describing the acceleration model we discuss how the existing observations limit the possible ranges of these parameters. As mentioned above, the very steep NIR spectrum requires the cutoff frequency of the synchrotron emission \( \nu_{cr} = 3 e B_{\perp} \gamma_{cr}^2/4 \pi m_e c = 1.7 \times 10^{12} (\gamma_{cr}/100)^2 (B_{\perp}/40 \text{ G}) \) Hz in the submillimeter-to-NIR range (Eisenhauer et al. 2005). This sets an upper limit on \( \gamma_{cr} B_{\perp} \). The spectrum of the SSC photons is also very sensitive to \( B_{\perp} \) and \( \gamma_{cr} \). In the SA model described below, the scattering rate is much higher than the acceleration and energy loss rates. The electron distribution is isotropic. We therefore consider the pitch-angle-averaged results. The solid and long-dashed lines in Figure 1 (left) represent three spectra produced by electrons with a Maxwellian distribution with the spectral indexes \( \alpha \equiv -d \ln (\nu F_\nu)/d \ln (\nu) \) at \( \nu = 1.4 \times 10^{14} \text{ Hz} (\alpha_{\text{NIR}}) \) and \( \nu = 10^{18} \text{ Hz} (\alpha_X) \) indicated by the label on the lines. The change in \( \alpha \) as one moves about the \( B-\gamma_{cr} \) plane is due solely to the dependence of \( \gamma_{cr} \) on \( B \) and \( \gamma_{cr} \). For flares with a soft NIR spectrum (\( \alpha_{\text{NIR}} > 0 \)) and a hard X-ray spectrum (\( \alpha_X < 0 \)), one can exclude the upper right and lower left portions of the \( B-\gamma_{cr} \) plane.

The acceleration time \( \tau_{ac} \), which is independent of energy and equal to one-quarter of the energy loss time at \( \gamma_{cr} \) in the SA model discussed below, must be shorter than or comparable to the flare rise time \( \tau_{\text{ris}} \) \( < 60 \) minutes, except that the source is strongly Doppler-boosted toward the observers. Because the luminosity of X-ray flares is usually smaller than that of the submillimeter-to-NIR flares, we can set the energy loss time equal to the synchrotron time \( \tau_{\text{syn}}(\gamma) = 9 m_e c^2/4 e^2 B^2 \gamma = \tau_0/\gamma \), where we have assumed that the source is optically thin. (The SSC cooling due to a radiation field with an energy density \( U_{\text{syn}} \) can be readily incorporated by replacing \( B^2 \) by an effective field \( B_{\text{eff}}^2 = B^2 + 2 \pi U_{\text{syn}} \) whenever there exists an observational justification.)

The dashed lines in Figure 1 (left) give three acceleration times. The left-hand side of the \( B-\gamma_{cr} \) plane can be excluded because \( \tau_{ac} > 60 \) minutes there. So to produce a flare with \( \alpha_{\text{NIR}} > 0, \alpha_X < 0, \) and \( \tau_{\text{ris}} < 60 \) minutes via synchrotron and SSC, the maximum Lorentz factor and magnetic field must be located within the central blank region of Figure 1. In principle, simultaneous NIR and X-ray spectroscopy during the flares can thus directly fix \( B \) and \( \gamma_{cr} \).

Let us now consider how simultaneous NIR and X-ray observations with good spectral information for both can in addition provide us with a measurement of \( R \) and the density \( n \) of the radiating electrons. The synchrotron luminosity due to an isotropic relativistic Maxwellian electron population can be estimated as follows (Pacholczyk 1970):

\[
\mathcal{L}_{\text{syn}} = \frac{16 e^4}{3 m_e c^5} N B^2 \gamma_{cr}^2
\]

\[
= 2.0 \times 10^{36} \left( \frac{N}{10^{43}} \right) \left( \frac{B}{40 \text{ G}} \right)^2 \left( \frac{\gamma_{cr}}{100} \right)^2 \text{ ergs s}^{-1},
\]

where \( N = 2N_0 \gamma_{cr}^3 \) is the total number of the accelerated electrons. For an isotropic radiation field, the corresponding X-ray emission produced via SSC is then given by

\[
\mathcal{L}_{\text{SSC}} = \frac{U_{\text{syn}}}{U_B} \mathcal{L}_{\text{syn}} \approx \frac{8 \pi e^2}{c A B^2} \mathcal{L}_{\text{syn}}
\]

\[
= 5.2 \times 10^{35} \left( \frac{\mathcal{L}_{\text{syn}}}{10^{30} \text{ ergs s}^{-1}} \right)^2 \left( \frac{B}{40 \text{ G}} \right)^{-2} \left( \frac{A}{\gamma_{cr}^2} \right)^{-1} \text{ ergs s}^{-1},
\]

where \( U_B = B^2/8 \pi \) and \( A \) are the magnetic field energy density and the surface area of the source, respectively, and \( \mathcal{L}_{\text{syn}} \approx U_{\text{syn}} c A \).
From these we can obtain $A$ and $N$. For a uniform spherical source, $A = 4\pi R^2$ and $N = 4\pi R^3 n/3$, we have

$$R \approx 0.64 \left( \frac{L_{\text{syn}}}{10^{36} \text{ ergs s}^{-1}} \right) \left( \frac{L_{\text{SSC}}}{10^{35} \text{ ergs s}^{-1}} \right)^{-1/2} \left( \frac{B}{40 \text{ G}} \right)^{-1} R_s,$$

$$n \approx 4.6 \times 10^{6} \left( \frac{L_{\text{syn}}}{10^{36} \text{ ergs s}^{-1}} \right)^{-2} \left( \frac{L_{\text{SSC}}}{10^{35} \text{ ergs s}^{-1}} \right)^{3/2} \left( \frac{B}{40 \text{ G}} \right) \left( \frac{\gamma_{\text{cr}}}{100} \right)^{-2} \text{ cm}^{-3}.$$  

This source size and density are typical values expected in the accretion torus of Sgr A* (LPM04) and, in general, depend on the source structure and geometry. The right panel of Figure 1 shows how these quantities may be read directly from simultaneous NIR and X-ray spectroscopic observations: From the NIR (solid lines) and X-ray (long-dashed lines) spectral indexes, one can locate the flare in this parameter space. The bottom axis then gives the magnetic field. With the NIR and X-ray flux density measurements, $R$ can be read from the top axis. The left and right axes then give the density $n$ of the accelerated electrons and the turbulence to magnetic field energy density ratio $f_{\text{turb}}$, which we shall discuss in the next section.

Flares are likely triggered by some plasma instability or by changes in the dynamics of the accretion flow—for example, the dissipation of angular momentum is different above and below the MSO, which may lead to a strong gravitational dissipation and acceleration of electrons. It is important to note that the total number of energetic electrons required to produce these bright flares can set a limit on the mass accretion rate $\dot{M}$ and accretion time $\tau_{\text{accr}}$: $\dot{M} \gtrsim N m_p$, where $m_p$ is the proton mass. If $\tau_{\text{accr}} \approx \tau_{\text{ris}}$, then

$$\dot{M} \approx 0.9 \times 10^{16} \left( \frac{N}{10^{43}} \right) \left( \frac{\tau_{\text{ris}}}{30 \text{ minutes}} \right)^{-1} \text{ g s}^{-1},$$

which is consistent with the value inferred from Sgr A*’s quiescent state spectrum and can account for the observed flares for a radiation efficiency of $\sim$10%.

3. TOY MODEL OF STOCHASTIC ELECTRON ACCELERATION

Let us now turn our attention to the SA of electrons and examine how this process meets the challenges posed by the above constraints. Electrons can be accelerated by turbulent plasma waves via the transit-time damping process (TTD) and cyclotron resonances. The former dominates in plasmas where the gas pressure is higher than the magnetic field pressure (Yan & Lazarian 2004), and the pitch angle scattering rate $\tau_{\text{sc}}^{-1}$ is higher than the acceleration rate when the Alfvén velocity $v_A = B(4\pi n m_p)^{1/2} < c$: $\tau_{\text{sc}}^{-1} \approx (v/v_A)^2 \tau_{\text{accr}}^{-1}$, where $v \approx c$ is the particle velocity (Schlickeiser & Miller 1998), resulting in a nearly isotropic electron distribution. The corresponding acceleration

5 In the MHD region, only particles with $\mu > v_A/c$ can be scattered via TTD. However, if the exact dispersion relation is adopted (André 1985), one can show that TTD works for particles with any pitch angles and energies, especially for Alfvénic turbulence that cascades preferentially perpendicular to the magnetic field (Goldreich & Sridhar 1995). Moreover, for $\mu < v_A/c$, cyclotron resonances and synchrotron cooling can have significant contributions to the scattering.
rate is proportional to the electron energy, giving rise to an energy-independent acceleration time:

\[
\tau_{ac} = \frac{cR}{\pi^2 f_{ac} f_{\text{urb}}},
\]

which is determined by the turbulence generation length \( \sim R \), \( f_{\text{urb}} \), and \( v_A \) (Miller et al. 1996).\(^6\) The SA can therefore be addressed by solving the following kinetic equation for the spatial and pitch angle integrated electron distribution function \( N \) (Petrosian & Liu 2004)

\[
\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \frac{\partial N}{\partial \gamma} - (4\gamma - 4\gamma^2 \tau_{ac}^2 \gamma_0) N \right] - \frac{N}{T_{\text{esc}}} + \dot{Q},
\]

where the source term \( \dot{Q} \) and \( N/T_{\text{esc}} \) give the rate of particles entering and escaping from the acceleration site, which we identify as the emission region. As we see below, the energy density of energetic electrons is at least one order of magnitude higher than the magnetic field energy density. We therefore envision that the plasma is excited by certain internal instability. In such a scenario, the escape time \( T_{\text{esc}} \) can be much longer than the duration of the flare.

For a constant injection rate \( \dot{Q}(\gamma) = \dot{Q}_0 (\gamma - \gamma_{in}) \) with \( \gamma_{in} < \gamma_{cr} \), where

\[
\gamma_{cr} = 2 \left( \frac{9 \gamma_{in} c^2 n}{4 \tau_{ac}} \right)^{\gamma_{in}} = 30 \left( \frac{R}{R_S} \right)^{-1} \left( \frac{n}{10^7 \text{ cm}^{-3}} \right)^{-1} \left( \frac{f_{\text{urb}}}{0.1} \right)^{-1},
\]

the steady state spectrum cuts off exponentially above \( \gamma_{cr} \) but is different from the Maxwellian one (Park & Petrosian 1995; Schlickeiser 1984):

\[
N(\gamma) = N_0 \gamma^{\delta + 2} \exp \left( - \frac{\gamma}{\gamma_{cr}} \right) \int_{0}^{\infty} x^{\delta - 1} (1 + x)^{3+\delta} \exp \left( - \frac{\gamma x}{\gamma_{cr}} \right) dx,
\]

with \( \delta = \frac{9}{4} + 2\gamma_{ac}^2 / T_{\text{esc}}^{1/2} \). Tablets.

The left panel of Figure 2 shows this distribution for \( \gamma_{in} = 0.13 \gamma_{cr} \) and for several values of \( \delta \) as indicated. The solid line gives the Maxwellian distribution. For large \( T_{\text{esc}} \) or small \( \delta \), most of the observed emissions are produced by electrons near or above \( \gamma_{cr} \); consequently, the slope of the spectrum below \( \gamma_{cr} \) is unimportant, and the Maxwellian distribution provides a good approximation of the accelerated particle spectrum. For \( N(\gamma) = N_0 \gamma^{-p} \exp \left( - \gamma / \gamma_{cr} \right) \), our calculations show that nearly identical photon spectra can be produced for different values of \( p \) by adjusting \( N_0 \).

There are therefore four model parameters: \( B, R, n, \) and \( f_{\text{urb}} \) (or \( \gamma_{cr} \)). In \( \S \) 2, we showed that the observed emission characteristics of NIR and X-ray flares set strict limits on these quantities. A detailed spectral fitting for individual flares can be used to measure them. The thick solid line in the right panel of Figure 2 fits the peak spectrum of the NIR flare of 2004 July 15, using \( R = 0.4 R_S, B = 40 \text{ G}, n = 1.4 \times 10^7 \text{ cm}^{-3}, \) and \( f_{\text{urb}} = 0.14 \) (or

\( \gamma_{cr} \). Eq. (8) shows that \( f_{\text{urb}} \approx 0.1 \) is required to accelerate electrons to GeV energies.

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Here the NIR spectrum alone determines $B^2\gamma_{cr}^2$ and $N$, and the X-ray spectrum, which we assume to be hard and a factor of $\sim 20$ above the flux density of the quiescent state, constrains $R$ and $B\gamma_{cr}^4$. This model is designated by the black dot in Figure 1. If the NIR flares always have very soft spectra, say, with $\alpha > 1.4$, then the magnetic field associated with these flares will fall into the narrow range $16(\tau_{\text{syn}}/60 \text{ minutes})^{-1/3} G < B < 120 \text{ G}$, and $\gamma_{cr}$ will be between 53 and 140(\tau_{\text{syn}}/60 \text{ minutes})^{-1/3}.

The source is self-absorbed in the submillimeter and longer wavelength range. For the source size inferred from the NIR flares the expected submillimeter flux will be $\sim 0.3$ Jy, which would be difficult to detect decisively. However, the SA accompanying these flares in a large volume can produce energetic electrons, which produce strong mm and longer wavelengths emission in situ or in the process of escaping toward larger radii (Zhao et al. 2004). It is also interesting to note that the acceleration time $\tau_{\text{ac}}$ is 27 minutes for this model, and the energy flux associated with the cascading Kolmogorov turbulence is $\sim C_0 f_\text{turb}^{2/3} R^2 v_{\text{A}} U_B \sim 10^{35}$ erg s$^{-1}$, where we have adopted $C_0 \sim 10$ (Miller et al. 1996). These values are fully consistent with the flare observations. The wave cascade time $\tau_{\text{cas}} \simeq (9 f_{\text{turb}} R_k)^{2/3} / R v_{\text{A}} = 150(R_k)^{2/3}$ s is comparable to the wave period for $k \sim 1/R$. For smaller scales the wave period is much shorter than the cascade time. Therefore, the resonant SA is much more efficient than the nonresonant SA (Petrosian et al. 2005). The particle scattering time $\tau_{\text{sc}} \simeq (v_{\text{A}}/c)^2 \tau_{\text{ac}} = 10$ s, which is comparable to the light transit time $R/c$ of the acceleration region. Because $\tau_{\text{ac}}$ is much longer than these timescales, the electrons have to cross the emission region hundreds of times to reach $\gamma_{cr}$. As expected, this corresponds to a slow acceleration process. However, because the electron energy density is $\sim 40$ times higher than the magnetic field energy density, the plasma is highly dominated by the gas pressure. The relativistic electrons will be bounded by the protons, which itself are trapped by the gravitational potential of the black hole and may not escape the acceleration region over a short period.

In the right panel of Figure 2, the thin solid line corresponds to a model with $B = 32$ G, which fits the rising and decay phase spectrum of the NIR flare of 2004 July 15. The dashed line fits correspond to another model with $B = 90$, which fits the peak flux of the X-ray flare of 2000 October 27. All other model parameters have the same values as those described above. These results suggest that the variations in flare characteristics may be attributed to changes in the magnetic field. However, we emphasize that the optically thin NIR emission only depends on the total number of energetic electrons, while the X-ray emission also depends on the source area. To demonstrate this effect, the dotted line shows a spectrum produced with the area of the emission region increased by a factor of 4 (i.e., $R = 0.8 r_s$; note that $N$ is fixed). As expected, the NIR spectrum is unaffected, while the X-ray flux decreases by a factor of 4, as expected from equations (1) and (2).

4. CONCLUSIONS AND DISCUSSION

The simultaneous detection of flares in the NIR and X-ray bands suggests that there is an intimate connection between these emission mechanisms. The fact that NIR flares have very steep spectra, whereas X-ray flares always have a much flatter spectrum, rules out the possibility of producing the NIR and X-ray photons together via synchrotron emission. The simplest model for production of X-ray is the SSC model, but it faces several challenges. In this paper we have shown how the simultaneous observation of NIR and X-ray flares may be used to determine the source size, the magnetic field, and the distribution of electrons, should the NIR and X-ray emission be produced, respectively, via synchrotron and SSC. We have shown that the emission characteristics suggest an electron distribution cutting off at $\gamma_{cr} \sim 100$. The size of the source must be a fraction of a Schwarzschild radius in order to produce prominent X-ray flares. The rapid rise in the NIR emission suggests a magnetic field of a few tens of gauss. A lower magnetic field is required should the source be Doppler-boosted, producing flares with soft NIR and hard X-ray spectra.

We have demonstrated that the SA model we proposed previously is fully consistent with the current observation of flares from Sgr A*, and with the transit-time damping acceleration taking the place of the parallel propagating waves we used before, the acceleration only depends on the turbulent energy density. However, depending on details of the flare excitation mechanism, the electron distribution below $\gamma_{cr}$ can be quite different. This model therefore can be a powerful tool in probing the plasma energizing and particle acceleration processes near the event horizon of the black hole.

The rest-frame acceleration time is slightly longer than the typically observed rise time. This suggests that a time-dependent treatment of the SA model is necessary unless the emitting plasma is Doppler-boosted by a boosting factor in the electron distribution below $\gamma_{cr}$ can be quite different. This model therefore can be a powerful tool in probing the plasma energizing and particle acceleration processes near the event horizon of the black hole.

It is also important to note that should the magnetic field be anchored to a slow, large-scale flow, it would exert a stress on the plasma, leading to a transport of its angular momentum. In a Newtonian potential, where the angular momentum density in a Keplerian orbit is given by $L = m_p (G M r)^{1/2}$, we have $m_p (G M r)^{1/2} r^{-1/2} v_r \sim (\nabla \times \mathbf{B}) \cdot \mathbf{B} \nabla v_r \simeq B^2 r/R$, or

$$v_r \sim 2.3 \times 10^{10} \left( \frac{R}{3 r_s} \right)^{-1} \left( \frac{r}{3 r_s} \right)^{3/2} \left( \frac{B}{40 \text{ G}} \right)^2 \left( \frac{n}{10^7 \text{ cm}^{-3}} \right)^{-1} \text{ cm s}^{-1},$$

which is comparable to the Keplerian velocity at $r = 3 r_s$ and is much higher than the radial velocity $v_r \sim 10^8$ cm s$^{-1}$ suggested by the chirping behavior of the X-ray and NIR flares. The variation length of this external magnetic field may therefore be much larger than $r_s$. We may be able to detect the magnetic field within the plasma itself. Should neither of these scenarios be viable, a large black hole spin would then be required.

This model is also in line with our previous study of Sgr A*’s emission in the quiescent state (LPM04) and with our study of proton and electron acceleration on larger scales ($\sim 20 r_s$). Clearly an appropriate modeling of the magnetic field structure in the accretion flow of Sgr A*, and in any possible outflow, is required in order for us to have a complete understanding of this intriguing object. With it, we hope to test its predicted correlated variability over a broad range in frequencies.

We have shown that SA is a viable mechanism for energizing plasmas near the black hole, producing the observed emission of Sgr A*. It is not yet possible, however, to rule out other acceleration mechanisms. On the basis of the recent detection of a near-infrared flare with a very hard spectrum (Fig. 2, right panel), Ghez et al. (2005) suggested that the corresponding X-ray flares might therefore be produced by a continuation of the synchrotron emissivity that also produces the infrared photons, although by very energetic electrons with $\gamma \sim 10^5 (B/40 \text{ G})^{-1/2}$. Should this be the case, the electron acceleration time has to be a few seconds,
requiring an acceleration process much more efficient than SA. But we emphasize that this NIR observation does not constrain the X-ray emission mechanism directly and is fully consistent with the model presented here. According to Figure 1, such a flare simply suggests a larger $\gamma_C$ and/or a higher $B$. Should the emission region be compact, we expect an X-ray flare with a very hard spectrum ($\alpha_X < -0.3$) accompanying this NIR flare.

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