AN INVERSE COMPTON SCATTERING ORIGIN OF X-RAY FLARES FROM Sgr A*

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ABSTRACT

The X-ray and near-IR emission from Sgr A* is dominated by flaring, while a quiescent component dominates the emission at radio and submillimeter (sub-mm) wavelengths. The spectral energy distribution of the quiescent emission from Sgr A* peaks at sub-mm wavelengths and is modeled as synchrotron radiation from a thermal population of electrons in the accretion flow with electron temperatures ranging up to ~5–20 MeV. Here, we investigate the mechanism by which X-ray flare emission is produced through the interaction of the quiescent and flaring components of Sgr A*. The X-ray flare emission has been interpreted as inverse Compton, self-synchrotron Compton, or synchrotron emission. We present results of simultaneous X-ray and near-IR observations and show evidence that X-ray peak flare emission lags behind near-IR flare emission with a time delay ranging from a few to tens of minutes. Our inverse Compton scattering modeling places constraints on the electron density and temperature distributions of the accretion flow and on the locations where flares are produced. In the context of this model, the strong X-ray counterparts to near-IR flares arising from the inner disk should show no significant time delay, whereas near-IR flares in the outer disk should show a broadened and delayed X-ray flare.

Key words: black hole physics – Galaxy: center – infrared: general – ISM: clouds – ISM: general – X-rays: general

Online-only material: color figures

1. INTRODUCTION

Observations of stellar orbits in the proximity of the enigmatic radio source Sgr A*, located at the dynamical center of our galaxy, have shown compelling evidence that it is associated with a $4 \times 10^6 \, M_\odot$ black hole (Ghez et al. 2005; Gillessen et al. 2009; Reid & Brunthaler 2004). The extremely high spatial resolution made possible by its relative proximity provides the best laboratory for studying the properties of low-luminosity accreting black holes; ~1″ corresponds to 0.039 pc at the Galactic center distance of 8 kpc (Reid 1993). The emission from Sgr A* is assumed to be produced from radiatively inefficient accretion flow as well as outflows. The bulk of the continuum flux from Sgr A* is considered to be generated in an accretion disk, where identifying the source of variable continuum emission becomes essential for our understanding of the launching and transport of energy in the nuclei of galaxies.

The emission from Sgr A* consists of both quiescent and variable components. The strongest variable component is detected as flares at near-IR and X-ray wavelengths (Baganoff et al. 2003; Genzel et al. 2003; Goldwurm et al. 2003; Eckart et al. 2006; Yusef-Zadeh et al. 2006a; Hornestein et al. 2007; Porquet et al. 2008; Dodds-Eden et al. 2009; Sabha et al. 2010; Trap et al. 2011), whereas only moderate flux variation is found at radio and submillimeter (sub-mm) wavelengths (Falcke et al. 1998; Zhao et al. 2001; Herrnstein et al. 2004; Miyazaki et al. 2004; Yusef-Zadeh et al. 2006b; Marrone et al. 2008). The spectral energy distribution (SED) of the quiescent component peaks at sub-mm wavelengths and is identified in radio, millimeter, and sub-mm wavelengths (see Genzel et al. 2010, and references therein). This emission is thought to be produced by synchrotron radiation from a thermal population of electrons with $kT \sim 10–30$ MeV participating in an accretion flow. A variety of models have been proposed to explain the quiescent emission from Sgr A* by fitting its SED, including a thin accretion disk, a disk and jet, an outflow, a advection-dominated accretion flow, a radiatively inefficient accretion flow, and advection-dominated inflow/outflow solutions (Blandford & Begelman 1999; Melia & Falcke 2001; Yuan et al. 2003; Liu et al. 2004; Genzel et al. 2010, and references cited therein). Unlike the quiescent component, which originates over a wide range of physical conditions and length scales of the accretion flow, flares are localized, allowing emission models to be directly tested with observations. As a supermassive black hole candidate, Sgr A* presents an unparalleled opportunity to closely study the process by which gas is captured, accreted, or ejected, by characterizing the emission variability over timescales of minutes to months. Because the timescale for variability is proportional to the mass of the black hole, this corresponds to variability on timescales 100 times longer than that of more massive black holes in the nuclei of other galaxies.

Studying near-IR emission from Sgr A* is crucial to track the acceleration of energetic particles as well as the accretion flow. Near-IR flares are produced by synchrotron radiation from a transient population of accelerated electrons. The near-IR emission is dominated by flaring activity that occurs a few times per day, with a small fraction of events showing simultaneous X-ray flares. The X-ray flare mechanism has been interpreted as either inverse Compton scattering (ICS), self-synchrotron Compton (SSC), or synchrotron emission (Markoff et al. 2001; Liu & Melia 2002; Yuan et al. 2004; Yusef-Zadeh et al. 2006a; Eckart et al. 2009; Marrone et al. 2008; Dodds-Eden et al. 2009). The X-ray synchrotron mechanism implies that the acceleration mechanism must continuously resupply the 100 GeV...
electrons for the 30 minute duration of the observed flares, because the synchrotron loss time of the $\sim 100$ GeV electrons that are responsible for the synchrotron emission is $\sim 30$ s. The synchrotron self-Compton model requires that the local magnetic field be extremely large or that the number density of electrons is high. This is necessary to avoid overproducing the near-IR synchrotron emission from the large number of energetic electrons that are required to upscatter infrared photons into the X-ray band (Dodds-Eden et al. 2009; Marrone et al. 2008; Sabha et al. 2010; Trap et al. 2011). The typical parameters of the magnetic field—$B \sim 1$–10 G or electron density $n_e \sim 10^9$ cm$^{-3}$—correspond to an energy density in the accelerated electrons a thousand times larger than that in the magnetic field. It is then difficult to understand how these particles are accelerated and confined.

In the case of X-ray emission produced by ICS, two possibilities have been explored. First, sub-mm photons arising from the quiescent component of Sgr A* may be upscattered by the transient electron population that is producing the IR synchrotron emission during IR flares (Yusef-Zadeh et al. 2006a). Alternatively, near-IR photons emitted during the flare may be upscattered by the mildly relativistic $\sim 20$ MeV electrons responsible for the quiescent radio–submm emission (Yusef-Zadeh et al. 2006a, 2008, 2009). If the sub-mm emission region were optically thin, this would produce a similar X-ray luminosity as the upscattering of sub-mm seed photons. However, because the sub-mm source is optically thick below $\sim 1000$ GHz, the observed sub-mm flux is produced by a fraction of the underlying electrons. The exact frequency at which the quiescent emission becomes optically thick is unknown. However, sub-mm measurements between 230 and 690 GHz (Marrone et al. 2006) indicate a flattening of the spectral index and thus a deviation from the rising spectrum observed at lower frequencies (An et al. 2005). The emission region is optically thin to near-IR photons, so all of these electrons are available to upscatter near-IR seed photons to X-ray energies (Yusef-Zadeh et al. 2009). The ICS luminosity produced through this scenario compares favorably with the observed near-IR and X-ray luminosities (Yusef-Zadeh et al. 2009). This is the model on which we will focus, as described below.

One of the predictions of the ICS model, in which near-IR photons are upscattered by $\sim 10$–30 MeV electrons, is a time delay between the peaks of the near-IR and X-ray flares (Yusef-Zadeh et al. 2009; Dodds-Eden et al. 2009). Wardle (2011) provided the theoretical framework for the X-ray echo picture of the ICS. We present evidence for a time delay between the peaks of X-ray and near-IR flare emission based on seven new and archival observations. These measurements provide support for X-ray production via ICS of IR flare photons by relativistic electrons of the accretion flow. The cross-correlation profiles of the peaks are generally skewed toward positive time lags, but show maximum likelihood values that have low signal-to-noise (S/N), due to the limited number of detections of simultaneous X-ray and near-IR flares.

2. OBSERVATIONS

2.1. X-Rays

X-ray observations used in this study come from the Chandra observatory. Data obtained on 2004 July 6–7 and 2005 July 30 consist of 50.2 and 46 kilosecond (ks) observations, respectively, (ObsIDs 4683,5953), which were described previously by Eckart et al. (2006) and Mun et al. (2005). Data obtained in 2008 (not previously reported) consist of six 28 ks observations, starting May 5, May 6, May 10, May 11, July 25, and July 26 (ObsIDs 9169, 9170, 9171, 9172, 9174, 9173, respectively), scheduled to match nighttime IR observations in Chile (see below). All observations placed Sgr A* at the ACIS-I aim point and took data in FAINT mode.

We checked for any time intervals of strong background flaring (none were found) and then reprocessed the data using CIAO 4.3. This involved applying corrections to the energy scales to compensate for time-dependent gain changes and charge-transfer inefficiency, removing pixel randomization and improving spatial resolution, as well as creating an updated bad pixel map. We filtered the data for “bad” grades and status.

We extracted light curves (in spacecraft TT time) from a 1” circular region around the position of Sgr A*, in the 1.5–8 keV energy range, using Gehrels (1986) errors. We converted the time stamps to UTC time following the prescription by A. Rots.8 The baseline quiescent X-ray emission from Sgr A* is spatially extended (Baganoff et al. 2003), but we see no variations in other local background emission. We tested several choices of binning the data for comparison to other wavelengths, settling on 1500 s binning for the 2008 data, 300 s binning for the major flare on 2004 July 6–7, and 600 s binning for the flare on 2005 July 30. Using the absorbed thermal plasma model of Baganoff et al., the ratio of 1.5–8 keV counts to 2–10 keV unabsorbed flux is $8 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ per count/s. Recent measurements indicate a distance of 8.3 kpc to Sgr A* (Gillissen et al. 2009), but we assume a distance of 8 kpc, which gives $L_X(2-10)=6 \times 10^{32}$ erg s$^{-1}$ per count s$^{-1}$, or a typical quiescent luminosity of $3 \times 10^{33}$ erg s$^{-1}$, in agreement with Baganoff et al. (2003).

We used Kolmogorov–Smirnov (K-S) tests (using the lcstats FTOOL9) on the 2008 Chandra light curves (binned to 32.41 s) to search for evidence of variability. We find evidence for variability in three of the 2008 observations, while another three show no evidence of variability. ObsIDs 9169, 9172, and 9173 give K-S probabilities of a constant light curve of $5 \times 10^{-6}$, $2 \times 10^{-4}$, and $1 \times 10^{-8}$, respectively, while the remaining observations give K-S probabilities greater than 5%. This significantly strengthens the evidence of variability from Sgr A* at very low levels, as Baganoff et al. (2003) reported a much larger K-S probability of constancy of $7 \times 10^{-3}$ during quiescence. Given that the quiescent X-ray emission arises from much larger scales, presumably due to Bondi–Hoyle accretion (Baganoff et al. 2003), we suggest that the X-ray variability noted here is due to low-level flare emission superimposed on the steady quiescent emission. Alternatively, the X-ray variability on hourly timescales could arise from coronally active stars producing giant flares (Sazonov et al. 2012).

2.2. Near-IR

For the near-IR observations we use archival data taken with the Very Large Telescope (VLT) and Hubble Space Telescope (HST). The near-IR data taken in 2004, 2005, and 2008 were observed with the near-IR adaptive optics (AO) assisted imager NACO at the VLT (Lenzen et al. 2003; Rousset et al. 2003). We used $K_s$-band 13 millisecond (ms) pixel imaging data from 2004 (nights of July 6–7) and 2005 (night of July 30–31) first presented by Eckart et al. (2006, 2008), and $K_s$-band

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8 For example, http://cxc.harvard.edu/ciao/threads/createl2/
9 http://heasarc.gsfc.nasa.gov/heasoft/ftools/xronos.html
13 mas pixel polarimetric imaging data from 2008 (nights of May 4/5, 5/6, 9/10, 10/11 and July 25/26, 26/27) first presented in Dodds-Eden et al. (2011). We did not apply any data quality cut for the latter observations, except for the elimination of 11 images from 2008 July 25, due to a bad AO correction (quadfoils, or a “waffle” pattern).

We used both aperture photometry and point-spread function (PSF) photometry methods to produce light curves, both carried out in the way described in Dodds-Eden et al. (2011). In particular we note that, for the purposes of that paper, the aperture method used two small apertures, one centered on the position of Sgr A* and the other on the star S17 (confused with Sgr A* in 2006–2008), in order to measure their combined flux. Since S17 was further from Sgr A* in 2004 and 2005 and the combined measurement of the flux is not important for the purposes of this paper, the use of the above method unnecessarily decreases the S/N. As a result, for the near-IR/X-ray comparison we supplemented the data set with higher S/N light curves obtained from PSF photometry, though the data were sparsely sampled. We provide the light curve of S17 in the 2008 data set and the light curve of the comparison star S7 for the 2004 and 2005 data sets. The stellar background is estimated to be 3.4 ± 0.2 mJy in 2008 (Dodds-Eden et al. 2011).

Near-IR HST observations used in this study are NICMOS archival data obtained on 2007 April 4 as part of a larger Sgr A* monitoring campaign. Full observational details have been presented in Yusef-Zadeh et al. (2009). Briefly, the exposures used NICMOS camera 1, which has a pixel scale of 0.043, and the medium-band filters F170M and F145M, which have central wavelengths of 1.71 and 1.45 μm, respectively, and FWHMs of 0.2 μm. Individual exposures had a duration of 144 s, with non-destructive detector readouts occurring every 16 s. We averaged the readouts to sampling intervals of 64 and 128 s in the 1.71 and 1.45 μm bands, respectively, to obtain adequate S/N. Aperture photometry was performed on Sgr A* in each sampling interval, using an aperture diameter of 3 pixels in order to limit contamination by nearby stars.

All of the near-IR measurements presented here have been corrected for reddening using extinction values of A$_V$ = 2.42 (2.2 μm), 4.34 (1.71 μm), and 6.07 (1.45 μm) from Fritz et al. (2011).

3. RESULTS

The middle two panels of Figure 1 show the light curves from the archival Ks-band and X-ray observations of Sgr A* that were taken on 2005 July 30. The near-IR light curve of the comparison star S7 is shown in the top panel. The X-ray and near-IR light curves of Sgr A* were sampled at intervals of 200 and 600 s, respectively. These measurements, first reported in Eckart et al. (2008), indicate a flare with a peak X-ray luminosity of 8 × 10$^{33}$ erg s$^{-1}$. The bottom panel shows the cross-correlation of these light curves. The cross-correlation analysis uses the Z-transformed discrete correlation function (ZDCF) algorithm (Alexander 1997). The ZDC function is an improved solution to the problem of investigating correlation in unevenly sampled light curves. Maximum likelihood values as well as 1σ and 2σ confidence intervals around those values are estimated using the start time of each bin. This analysis finds that the X-ray peak lags the near-IR peak in Figure 1 by ~8.0 (±10.1) and 8.0 (±20.2, −17.9) minutes for 1σ and 2σ maximum likelihood values, respectively. We varied the sampling interval in the near-IR and X-ray data between 1.5 and 10 minutes, but the maximum likelihood lag value remained the same. Eckart et al. (2008) compared the X-ray and near-IR flare emission and found that the peaks are coincident within ±7 minutes.

The aperture photometry technique that was used to reanalyze the near-IR VLT data from 2004 produced a light curve that is quite similar to that published by Eckart et al. (2006), who deconvolved their images. The only difference is that the present analysis uses data extending up to 4 hr UT on July 7, which is longer than that of Eckart et al. (2006). The bottom three panels of Figure 2 show the cross-correlation of these near-IR and X-ray data with a maximum likelihood lag of 7.0 (±1.3, −1.1) minutes and (±7.5, −6.9) minutes with 1σ and 2σ errors, respectively. The lag is larger than zero at the 1σ level. The near-IR light curve of the comparison star S7 is shown in the top panel. The light curve of S7 is constant and supports the variable emission from Sgr A* between 3 and 4 h UT. The sampling of the near-IR data reduced using PSF photometry is much more sparse than the aperture photometry data. The 1σ cross-correlation peak using the PSF photometry showed a time lag 7.7 (±2.9, −3.4) minutes within the error bars of that reduced by aperture photometry. Eckart et al. (2006) also cross-correlated their data and showed no time delay within 10 minutes.

Next we examined the X-ray and near-IR light curves obtained on 2007 April 4 using XMM and VLT observations (flare 2 in Porquet et al. 2008; Dodds-Eden et al. 2009). These data contain the second brightest X-ray flare (flare 2 in
Porquet et al. (2008) coincident with one of the strongest near-IR flares that has ever been detected. The cross-correlation of the X-ray and near-IR data for this bright flare shows a 1σ maximum likelihood time delay of $-0.5(±7.0, -6.5)$ minutes, which is consistent with zero time delay (Dodds-Eden et al. 2009; Yusef-Zadeh et al. 2009). The peak luminosity of the brightest flare is $24.6 \times 10^{38}$ erg s$^{-1}$ (Porquet et al. 2008). Two other moderate X-ray flares (flares 4 and 5) were detected on 2004 April 4 following the bright X-ray flare. X-ray flares 4 and 5, with peak luminosities of $\sim 6 \times 10^{38}$ and $\sim 8.9 \times 10^{34}$ erg s$^{-1}$, respectively, are covered in the near-IR 1.71 and 1.45 μm NICMOS data. The cross-correlations of the X-ray and near-IR light curves for flares 4 and 5 are presented in Figures 3(a)–(d). The NICMOS observations alternated between the 1.71 and 1.45 μm bands every 6 minutes. In all of the four cases studied, the maximum likelihood values of flares 4 and 5 show positive lags ranging between 5 and 10 minutes. Similar to the other cases analyzed here, the peaks of the cross-correlations are all skewed toward positive time lags.

Finally, we compared near-IR (VLT) and X-ray data taken in 2008 May and July. Figure 4 shows the light curves from the two different days of observations. These X-ray flares are an order of magnitude less luminous than those detected in earlier observations. We have carried out K-S tests indicating the reality of these low-level X-ray visibilities (Section 2.1).

The cross-correlations of the light curves from these two days give maximum likelihood lags of 19 (+6.8, −2.4) and 14.6 (5.6, −2.9) minutes with 2σ error bars. Figure 4 also shows the cross-correlation of X-ray with near-IR light curves derived from PSF photometry. The resulting time delays of 26.5 (+19, −29) and 16.6 (14.8, −11.8) minutes are well within the error bars of the aperture photometry data. To provide additional support for the reality of the variability of Sgr A*, Figure 5 compares the light curves of Sgr A* and S17 using the 2008 May 5 and 2008 July 26 observations, which are based on PSF photometry. In these data, where Sgr A* and S17 are separated from each other, each source is detected independently.

Although most of the individual cross-correlation results that are presented here have low S/N, the 1σ maximum likelihood peaks in eight different measurements show a tendency for X-ray emission to lag near-IR emission rather than lead. The cross-correlation gives maximum likelihood near-IR-to-X-ray lag values that are systematically higher than zero. The strongest simultaneous near-IR and X-ray flares (Flare 2 in Porquet et al. 2008) do not show any time delay, whereas the faintest X-ray flares seem to show the longest time delays.

## 4. SSC MODELS

Several alternative models for the relationship between near-IR and X-ray flares have been proposed. Synchrotron emission from a high-energy tail of the accelerated electron population responsible for the near-IR flaring may be responsible for the observed X-ray flaring (Dodds-Eden et al. 2009, 2010). SSC models, in which the same population of electrons produce the near-IR synchrotron emission and upscatter lower-energy synchrotron photons, require an unrealistic compact, and hence over-pressured, source region (Dodds-Eden et al. 2009) or a very weak magnetic field or a high electron density to avoid overproducing the IR synchrotron emission (Marrone et al. 2008; Sabha et al. 2010; Trap et al. 2011).

In SSC models the observed ratio of the X-ray and IR fluxes demands a certain Thomson optical depth in relativistic electrons. SSC flare models (Marrone et al. 2008; Sabha et al. 2010; Trap et al. 2011) adopt source region radii $R$ of order $R_*$.

The requisite electron densities then imply a particular magnetic field strength, so that the synchrotron emission from the electron population matches the observed near-IR flaring. These SSC models have electron energy densities ranging between $10^9$ and $2 \times 10^7$ times the magnetic energy density. Because electron acceleration mechanisms invoke magnetic fields, the energy density in the field should be comparable to or greater than the energy density of the accelerated particles. Thus, scaling the SSC models to equipartition fields by reducing the electron density while increasing the magnetic field to keep the product $n_e B^{(p+1)/2}$ and hence the near-IR synchrotron flux fixed, one finds that a reduction in electron density by a factor of 40 or more is required. Thus, SSC contributes at most 1/40 of the observed X-ray flux in such a model.

Alternatively, one can attempt to construct SSC models in which the field is in equipartition by reducing the source size $R$, while keeping the products $n_e B^{(p+1)/2} R^3$ and $n_e R$ fixed to preserve the synchrotron and SSC fluxes, respectively. Equipartition between the relativistic electrons and magnetic field is attained when $R$ is reduced by a factor of a thousand.
Figure 3. (a) The light curves of flare 4 of 2007 April 4 in near-IR (1.70 μm) and X-ray (2–10 keV) are taken by HST/NICMOS, and XMM-Newton/EPIC, with a time sampling of 64 and 300 s, respectively. (b) Same as (a) except that the 1.45 μm are sampled at 144 s interval to improve the S/N. (c) Same as (a) except that the light curves of flare 5 are displayed at 1.70 μm. (d) Same as (c) except that the light curves of flare 5 are displayed at 1.45 μm. The cross-correlation and the maximum likelihood values with 2σ error bars are shown in bottom panels. The 1σ error bars for flares 4 and 5 at 1.70 μm are given in Table 2.

(A color version of this figure is available in the online journal.)
Figure 4. (a) Using the aperture photometry technique, the top two panels show the light curves of $K_s$-band (2.2 $\mu$m) and X-ray (2–8 keV) data taken simultaneously with VLT and Chandra on 2008 May 5. The sampling interval for X-ray and near-IR data are 25 and $\sim$2 minutes, respectively. The cross-correlation of the light curves is plotted in the bottom panel. (b) Similar to (a) except that the data were taken on 2008, July 26+27. (c) Similar to (a) except the light curve of Sgr A* is calibrated using PSF photometry technique. (d) Similar to (b) except the light curve of Sgr A* is calibrated using PSF photometry technique. The cross-correlation and the maximum likelihood values with 2$\sigma$ error bars are shown in bottom panels. The 1$\sigma$ error bars for aperture photometric data are given in Table 2.

(A color version of this figure is available in the online journal.)
or more, with corresponding field strength in the $10^4$–$10^5$ G range, which is orders of magnitude more than what is reasonable.

5. X-RAY ECHO DUE TO ICS

Here we focus on an inverse Compton scenario for the X-ray flares, suggested by Yusef-Zadeh et al. (2009) and outlined in more detail by Wardle (2011). In this model, near-IR flare photons are upscattered to X-ray energies by the thermal electrons ($kT_e \sim 10$ MeV) in the accretion flow. This process dominates the alternative inverse Compton pathway, in which the nonthermal energetic electrons responsible for the near-IR synchrotron emission upscatter sub-millimeter photons emitted by the thermal electrons in the accretion flow into the X-ray band (Rybicki & Lightman 1986, chapter 7.5). This alternative ICS pathway is less effective because the accretion flow is optically thick in the submillimeter, so that the ratio between sub-mm photons and the thermal electrons producing them is reduced by a factor of the optical depth. Then the upscattering of near-IR photons proportionately produces more emission than would be inferred by implicitly assuming that the submillimeter synchrotron flux is optically thin (e.g., Dodds-Eden et al. 2009). In this process, the second-order scattering echo can also produce MeV $\gamma$-ray emission with a luminosity $L_\gamma$ that is lower than that of X-rays $L_X$ by a factor of a few (i.e., $L_\gamma/L_X \sim L_X/L_{NIR}$).

One significant difference of the ICS picture from the synchrotron and SSC pictures is that the longer path from the near-IR source to the observer taken by an upscattered photon detected in the X-ray compared to the straight-line path taken by a photon received in the near-IR introduces a time delay between flaring in the near-IR and X-rays. In addition, because scattering occurs from a range of locations within the accretion flow, with a corresponding range of time delays, the reflection signal tends to be broadened compared to the near-IR seed photon light curve. While there is some evidence of systematic delays between the near-IR and X-ray flaring, the X-ray flares appear to generally have a narrow FWHM compared to their corresponding near-IR flares.

5.1. Modeling

To explore whether this model can plausibly explain the X-ray flaring, we compute the X-ray “echoes” of the observed near-IR flares to compare with our simultaneous X-ray observations. We make a number of simplifying assumptions, none of which are severe. We assume that the observed near-IR flare comes from a point located in the accretion flow with a power-law spectrum and Gaussian light curve, $S_\nu(t) \propto \nu^{-0.5} \exp\left(-\left(t-t_0\right)^2/2\sigma^2\right)$. Because the X-ray flares are narrower than the near-IR we have assumed that the FWHM of the near-IR flaring narrows as $\lambda_{0.5}$ below 2.2 $\mu$m. The physical justification is that the synchrotron loss timescale scales as $\lambda_{0.5}$ and becomes comparable with the observed FWHM at about 2 $\mu$m.

The energy of an upscattered photon with initial energy $h\nu_{IR}$ is assumed to be $(4/3)\gamma^2h\nu_{IR}$, where $\gamma$ is the electron Lorentz factor. Because the upscattered photon energies are much lower than the electron rest energy, the scattering occurs in the Thompson regime. Assuming isotropic upscattering, the total production rate of upscattered photons per unit volume is $n_{IR}n_e\sigma_Tc$, where $n_{IR}$ and $n_e$ are the...
number densities of infrared photons and relativistic electrons, respectively. We ignore relativistic effects such as the Doppler boosting associated with the bulk motion of the accretion flow, because the corresponding Lorentz factor is small compared to that of the individual electrons. We also ignore the time delay, gravitational redshift and lensing effects of the Kerr metric, which only become important close to the event horizon in highly inclined systems.

The electron density and temperature profiles in the accretion flow are assumed to be steady, axisymmetric power laws in cylindrical radius $r$, with $n_e \propto r^{-0.75}$ and $T_e \propto r^{-1}$ and the density truncated within $2 R_s$ and beyond $20 R_s$. The accretion flow is assumed to be confined to a thick disk with scale height/radius ($h/r$) of 0.5. The electron population is characterized by an approximate relativistic Maxwellian $f(x) = 1/2 x^2 \exp(-x)$, where $x = E/(kT_e)$, which is a good approximation for $kT_e > 0.1$ MeV. The adopted profiles are within the typical ranges considered in analytic estimates (e.g., Loeb & Waxman 2007), semi-analytic models for the accretion flow (e.g., Yuan et al. 2003), and MHD simulations (e.g., Moscibrodzka et al. 2009).

The remaining parameters specify the flare location relative to the line of sight and relative to the accretion flow: the inclination $i$ of the disk to the line of sight, and the flare location ($r, \phi, z$) in the natural cylindrical coordinate system. The low optical depth of the accretion flow to near-IR photons means that the results are insensitive to the inclination $i$ and the azimuthal angle $\phi$ between the flare location and the poloidal plane containing the line of sight and the $z$-axis. We therefore fix these at typical values $i = 45^\circ$ and $\phi = 90^\circ$, respectively. Similarly, the results are insensitive to the height $z$ of the near-IR flare for $z > r$, so we simply assume that the flare occurs in the disk midplane, i.e., that $z = 0$.

The free parameters are the electron density $n_0$ and temperature $T_0$ at the fiducial radius $2 \times 10^{12}$ cm, and the radial location of the flare, $r$. The noisiness of the observed light curves preclude formal fitting, so for each near-IR/X-ray flare combination we adjust these parameters by hand to approximately match the X-ray light curve. Reasonable matches to the observed X-ray profile are obtained with flares occurring at $r \sim 10 R_s$, and electron densities $10^{7.5} - 10^8 \text{ cm}^{-3}$ and temperatures $5 - 20 \text{ MeV}$, as listed in Table 1.

In the context of the ICS picture, we fit a sample of light curves that have good time coverage in near-IR and X-ray wavelengths in order to illustrate the point that this model can potentially be a powerful tool to quantify the physical characteristics of the accretion flow. The light curves presented in Figures 1 and 2 are modeled following the second brightest X-ray flare that has ever been recorded on 2007 April 4 (Porquet et al. 2008). The light curves of the moderate flare that followed this bright flare (flare 2) is presented in Figure 3. The time delays of the peak emission shown in Figures 1, 2, and 3 are 8, 7, and 8 minutes, respectively, whereas the bright flare on 2007 April 4 showed a time delay consistent with zero. Given the limited simultaneous time coverage of the flares shown in Figures 3 and 4, we focus only on modeling these four flares. Figure 6 shows the observed and modeled light curves for the simultaneous near-IR and X-ray flares that occurred on 2005 July 30, 2004 July 6/7, and 2007 April 4 (the main flare and flare 4). Parameters of the fit for each of the four examples are shown in Table 1. Substructures corresponding to two weak flares in Figure 6(a) are also modeled with the same parameters as the main flare, as listed in Table 1. A baseline level has been subtracted from the near-IR light curves before constructing the theoretical light curves. If we restrict the evaluation of $\chi^2$ to just the flare part of the X-ray light curve, $\chi^2$/df is between 3 and 4. The reason is that there is often point-to-point variability in the light curve that throws points well away from the smooth “prediction”. In addition, the near-IR light curve in Figure 6(c) shows substructures that could be arising from different flares, which would have different time delays in the context of ICS. Thus we have not formally fit the light curves as our models are illustrative only. Given these limitations, we obtain reasonable parameters from the theoretical X-ray light curves, which are superimposed on the observed light curves in Figure 6.

In each case a Gaussian form of the near-IR light curve has been adopted to represent the observed (extinction-corrected) near-IR flare at 3.8 $\mu$m, 2.2 $\mu$m, and 1.7 $\mu$m. However, in our models, the X-ray flare arises from scattered optical photons. We assume the peak flux of the synchrotron flare (emitting at near-IR to optical) scales as $\nu^{-0.5}$ with frequency. Because the X-ray flare is narrower than the near-IR we have assumed that the FWHM is constant below 2.2 $\mu$m and narrows as $\lambda^{0.5}$ shortward of this. Reasonable matches to the observed X-ray profile are obtained with the flare occurring at the inner edge of the density profile and electron densities, as their estimated values are given in Table 1. The FWHM assumption requires both the rise and the decay timescale of the flare to be faster at optical frequencies than at near-IR. For the decay timescale, this is a natural result of synchrotron cooling (the synchrotron loss timescale scales as $\nu^{-0.5}$). The rise timescale depends on the acceleration mechanism. While the acceleration mechanism of flare production is not understood, it is plausible that optically emitting electrons are produced later than IR emitting electrons (Kusunose & Takahara 2011).

Another issue involves the prediction that the spectral index between X-rays and near-IR/optical emission be identical in the context of ICS with the assumption that the electron distribution has a single power-law spectrum. It is, however, possible that the energy spectrum of electrons has a broken power law, thus producing a different spectral index in near-IR and X-rays. The mismatch in spectral index is in fact noted for the bright X-ray flare coincident with a strong near-IR flare of 2007 April 4 (Dodds-Eden et al. 2009). Although these authors discuss the difference in the spectral index using a synchrotron mechanism, the broken power law of NIR emitting electrons with a steeper spectral index shortward of 3.8 $\mu$m was also argued in the ICS scenario (Yusef-Zadeh et al. 2009).

Although the spectral index measurements in X-ray and near-IR cannot distinguish between the synchrotron and ICS

| Flare     | $kT_0$ (MeV) | $n_0$ (cm$^{-3}$) | $r^0$ (cm) |
|-----------|--------------|------------------|------------|
| 2004 Jul 7 | 9            | $2.9 \times 10^8$ | $1.0 \times 10^{13}$ |
| 2005 Jul 30 | 20           | $2.3 \times 10^7$ | $1.0 \times 10^{13}$ |
| 2004 Jul 7 | 7            | $2.1 \times 10^8$ | $4.0 \times 10^{12}$ |
| 2007 Apr 4 flare 2 | 5          | $7.9 \times 10^8$ | $1.0 \times 10^{13}$ |

**Notes.**

a. Accretion flow temperature profile $T_e(r) = T_0(r/r_0)^{-1}$ where $r_0 = 2 \times 10^{12}$ cm.

b. Density profile $n_e(r, z) = n_0(r/r_0)^{0.75} \exp(-2z^2/r^2)$.

c. Radial location of near-IR flare in equatorial plane ($R_s \approx 1.2 \times 10^{12}$ cm for $M_{\text{BH}} = 4 \times 10^{6} M_\odot$).
models for the production of X-rays, it is predicted that the ratio of near-IR to X-ray flare emission can increase with increasing time delay in the ICS scenario. This is because bright X-ray flares are generated in the inner disk where the time delay is expected to be small. Although the available data are limited to test this aspect of the proposed model, we note a trend that is consistent with this expectation. Table 2 shows the ratio of 2.2 μm peak flux (mJy) to peak X-ray luminosity (10^{35} erg s^{-1}) for seven different measurements. The 1σ error bars of the maximum likelihood values are given in Column 7. The smallest to largest flux ratios, as shown in Column 6 of Table 2, support the trend that near-IR/X-ray flux ratios increase with the time delay.
delay, as expected in the context of the ICS model. For the near-IR observations on 2007 April 4 obtained at 3.8 and 1.7 \mum, we convert the peak flux to 2.2 \mum using the spectral index of $-0.7$, where $S \propto \nu^{-0.7}$, before we estimate the flux ratio. Future simultaneous measurements of X-ray and near-IR flares should examine the correlation of the peak near-IR to X-ray flux as a function of increased observation time delay.

In summary, we have presented cross-correlations of simultaneous X-ray and near-IR flare light curves from Sgr A* and found a time lag of the X-ray peak flare emission with respect to the near-IR. Such an X-ray echo provides support for ICS of near-IR flare photons by $\sim$5–20 MeV electrons. A fraction of near-IR flare photons must upscatter from the accretion flow into the X-ray band. This can be significant for plausible accretion models, and therefore may explain the observed near-IR flares, or at least place significant constraints on the accretion flow. Future cross-correlations based on more continuous near-IR and X-ray observations should give us better S/N in the maximum likelihood values of the time lag. In the context of the ICS model, future measurements will place better constraints on the density and temperature profiles of the accretion flow and the location of near-IR flares.

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**Table 2**

Flux Ratios versus Time Delay

| Flare | IR Backg. | X-Ray Backg. | IR Peak (mJy) | X-Ray Peak $(1 \times 10^{35} \text{erg s}^{-1})$ | Peak Ratio IR/X-Ray | Time Delay (minutes) |
|-------|-----------|--------------|--------------|---------------------------------|-------------------|---------------------|
| 2007 Apr 4 flare 2 | 5.0 | 0.2 | 16.5 | 4.8 | 3.4 | $-0.5 (+7, -6.5)$ |
| 2007 Apr 4 flare 5 | $-0.2$ | 0.2 | 2.63 | 1.23 | 2.1 | $5.0 (+1.9, -1.5)$ |
| 2007 Apr 4 flare 4 | $-0.2$ | 0.2 | 4.67 | 1.22 | 3.8 | $5.0 (+1, -1.4)$ |
| 2004 Jul 7 | 1.5 | 0.03 | 6 | 0.39 | 15.5 | $7 (+1.3, -1.2)$ |
| 2005 Jul 30 | 0.0 | 0.002 | 5.9 | 0.13 | 45.4 | $8 (+10, -10.1)$ |
| 2008 Jul 26+27 | 5.5 | 0.003 | 3.7 | 0.05 | 68.5 | $14.6 (+5.6, -7.4)$ |
| 2008 May 5 | 6 | 0.003 | 2.74 | 0.021 | 130.0 | $19 (+6.8, -2.4)$ |