SIMULTANEOUS CHANDRA, CSO, AND VLA OBSERVATIONS OF SGR A*:
THE NATURE OF FLARING ACTIVITY

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ABSTRACT

Sgr A*, the massive black hole at the center of the Galaxy, varies in radio through X-ray emission on hourly timescales. The flare activity is thought to arise from the innermost region of an accretion flow onto Sgr A*. We present simultaneous light curves of Sgr A* in radio, submillimeter and X-rays that show a possible time delay of 110 ± 17 minutes between X-ray and 850 μm suggesting that the submillimeter flare emission is optically thick. At radio wavelengths, we detect time lags of 20.4 ± 6.8, 30 ± 12, and 20 ± 6 minutes between the flare peaks observed at 13 and 7 mm (22 and 43 GHz) in three different epochs using the VLA. Linear polarization of 1% ± 0.2% and 0.7 ± 0.1% is detected at 7 and 13 mm, respectively, when averaged over the entire observation on 2006 July 17. A simple model of a bubble of synchrotron-emitting electrons cooling via adiabatic expansion can explain the time delay between various wavelengths, the asymmetric shape of the light curves, and the observed polarization of the flare emission at 43 and 22 GHz. The derived physical quantities that characterize the emission give an expansion speed of \( v_{\text{exp}} \approx 0.003–0.1 \, c \), magnetic field of \( B \approx 10–70 \, \text{G} \), and particle spectral index \( p \approx 1–2 \). These parameters suggest that the associated plasma cannot escape from Sgr A* unless it has a large bulk motion.

Subject headings: accretion, accretion disks — black hole physics — Galaxy: center

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1. INTRODUCTION

Recent observations provide compelling evidence that the compact nonthermal radio source Sgr A* can be identified with a massive black hole at the center of the Galaxy. A major breakthrough in our understanding of this source came from stellar orbital measurements showing a mass \((3–4) \times 10^6 \, M_\odot\) within 45 AU of the position of Sgr A* (e.g., Schödel et al. 2003; Ghez et al. 2004; Eisenhauer et al. 2005). This dark, massive object has been uniquely identified with the radio source Sgr A* through limits on the proper motion of the radio source, which show that Sgr A* must contain \( >4 \times 10^8 \, M_\odot\), and does not orbit another massive object (Reid & Brunthaler 2004).

A “submillimeter bump” was detected in the broadband spectrum of Sgr A* (Zylka et al. 1995; Serabyn et al. 1997; Falcke et al. 1998); the submillimeter peak is thought to reflect the transition between optically thin emission at higher frequencies, and optically thick emission at lower frequencies. Observations of the time variability and polarization (Bower et al. 2005; Marrone et al. 2006; Macquart & Bower 2006; Yusef-Zadeh et al. 2007) are providing additional opportunities to study the innermost regions, within just a few Schwarzschild radii of the black hole event horizon, a region currently inaccessible via high spatial resolution imaging.

The energy radiated by Sgr A* is thought to be liberated from gas falling toward the black hole after being captured from the powerful winds of members of its neighboring cluster of massive stars (e.g., Melia 1992). The radiated power is several orders of magnitudes lower than expected, prompting a number of theoretical models to explain the very low efficiency (e.g., Melia & Falcke 2001; Yuan et al. 2003; Goldston et al. 2005; Liu & Melia 2001; Liu et al. 2006a). The spectrum of Sgr A* has been successfully modeled as a radiatively inefficient flow which is carried across the event horizon before radiating away its energy (Narayan et al. 1998). More recently, detection of radio and submillimeter polarization has allowed estimates of the integrated electron density in the accretion region from ~10 to 1000 Schwarzschild radii (Bower et al. 2003; Marrone et al. 2006). These estimates indicate much lower electron densities than predicted, implying that perhaps most of the material is not reaching the central black hole. Theoretical work (e.g., Yuan et al. 2003; Sharma et al. 2007) supports this picture, but leaves unanswered the question of whether infalling material finds itself in a convective flow (Narayan et al. 2002), a low-velocity outflow (Blandford & Begelman 1999; Iguменщев et al. 2003), or a fast jet (Yuan et al. 2002). The frequency-dependence of the size of Sgr A* in the radio and submillimeter bands (e.g., Shen et al. 2005; Bower et al. 2006) suggests that the plasma responsible for the emission at these frequencies is not bound to the black hole but is escaping in a wind (Loeb & Waxman 2007).

Numerous multiwavelength observations have studied Sgr A* in its flaring state. However, there are limited simultaneous observations able to measure the correlation of the variability of Sgr A* in different wavelength bands. (e.g., Eckart et al. 2004, 2006; Yusef-Zadeh et al. 2006b; Hornein et al. 2007). A variety of mechanisms have been proposed to explain the origin of the variability in the near-IR (NIR) and X-rays (e.g., Melia & Falcke 2001; Yuan et al. 2002, 2003; Liu & Melia 2002; Eckart et al. 2004, 2006; Goldston et al. 2005; Gillessen et al. 2006; Liu et al. 2006a, 2006b). These studies imply that the NIR is synchrotron emission while the X-rays are most likely produced by synchrotron-self-Compton (SSC) or inverse Compton emission (Liu et al. 2004). Modeling of the processes responsible for heating and cooling the transient population of electrons responsible for
the NIR and X-ray flares implies that it is produced in localized regions in the inner part of the accretion flow (Liu et al. 2006a, 2006b; Bittner et al. 2007).

The situation is less clear at submillimeter and radio frequencies, where less dramatic short-term variability coexists with longer term variations presumably due to global changes in the accretion flow, and optical depth effects likely play a role in moderating the short-term variability (e.g., Goldston et al. 2005). Previous simultaneous near-IR and submillimeter measurements have shown two near-IR flares with durations of about 20–35 minutes within 2.5 hr of an 850 μm flare with an estimated duration of 2 hr (Yusef-Zadeh et al. 2006b). The first near-IR flare appeared to coincide with the submillimeter flare, whereas the second flare was delayed roughly by 160 minutes with respect to the submillimeter flare. Two important points could be drawn: First, assuming that near-IR and submillimeter flares are related to each other, this implies that the same synchrotron-emitting electrons are responsible for production of both near-IR and submillimeter flares. The second point is that it is not clear whether the submillimeter flare is correlated simultaneously with the second bright near-IR flare, or is produced by the first near-IR flare but with a time delay of roughly 160 minutes. A delay between the peak emission in the near-IR and submillimeter suggests that the enhanced synchrotron emission in the compact region dominating the flaring emission is initially optically thick in the submillimeter, becoming optically thin due to expansion (van der Laan 1966).

To follow up this idea, we studied the light curves of Sgr A* at 7 and 13 mm taken in 2005. The light curves at both wavelengths show a 5%–10% increase of flux with respect to their quiescent levels. We found that the emission at 13 mm may lag that at 7 mm by ~20 minutes, although with large uncertainty (Yusef-Zadeh et al. 2006a). To confirm the time delay between flares at successively longer wavelengths and to search for a time lag or other systematic correlation between other wavelength bands, we undertook a series of detailed observations using the VLA, CSO, and Chandra telescopes.

This paper discusses the results of observations made on 2006 July 17 when all three telescopes participated in observing Sgr A* simultaneously. The Keck and SMA also joined the 2006 July 17 observation, and their results will be described in an accompanying paper (Marrone et al. 2008). We also present the results of short observations made on 2006 July 16 using the VLA and CSO, as well as the cross correlation of flare emission at 7 and 13 mm observed with the VLA on 2005 February 10 and 2006 February 10. Finally, fitting a simple adiabatically expanding plasma model gives reasonable matches to the light curve at two or more frequencies placing strong constraints on the physical parameters and size of the expanding plasma that are consistent with the parameters inferred for the accretion flow around Sgr A* and for the emission regions responsible for the NIR flares (Liu et al. 2006a, 2006b; Bittner et al. 2007).

2. RADIO, SUBMILLIMETER, AND X-RAY OBSERVATIONS

2.1. VLA Observations

Using the Very Large Array (VLA) of the National Radio Astronomy Observatory,7 we carried out observations in the B-array configuration on 2006 July 16 and 2006 July 17 for a total of 4 and 6 hr, respectively. Details of the total intensity and polarization calibration procedures observations are identical to previous measurements, as described in Yusef-Zadeh et al. (2007), with the exception that these observations used two subarrays simultaneously at 43 and 22 GHz. Thus, the measurements presented here are truly simultaneous in two observing bands. Two phase calibrators 1733-130 and 17444-31166 were employed. The VLA is undergoing an expansion, and these observations used seven new Expanded (EVLA) antennas and 20 original (VLA) antennas. Because of higher and more variable amplitude gains of the EVLA antennas than the VLA antennas, we did not use any of the EVLA antennas in our analysis. Thus, on the average a total of eight to 10 antennas are used in each subarray. The light curves at 43 and 22 GHz have used $uv$ spacings longer than 100 kλ. We discarded data from antennas that showed large variation or high-amplitude gains during the run. All antennas had similar gain amplitude during the entire observation. The 43 GHz data on 2006 July 16 were noisy and could not be salvaged for time variability analysis. The light curve of the fast switching calibrator is obtained by calibrating it with the second calibrator 1733-130. Instrumental calibration was done in two steps, one for the entire period of observation and the other on a short timescale. We only used 17444-31166 for polarization calibration in both steps. A more detailed account of short-timescale polarization calibration can be found in Yusef-Zadeh et al. (2007).

Two other observations made on 2005 February 10 and 2006 February 10 used both the BnA and A+Pt array configurations of the VLA to study the time variability of Sgr A*. Both observations used fast switching techniques alternating between 43 and 22 GHz every few minutes. Early results including polarization results of these measurements are given in Yusef-Zadeh et al. (2006b, 2007). These observations used the same calibrators as in the 2006 July observations. These radio observations are different when compared with previous snapshot measurements (e.g., Zhao et al. 2004). First of all, the radio observations that have conducted in snapshot mode have no way of determining the flux stability of the complex gain calibrators. The 44 and 23 GHz observations are most affected by the opacity variability of the atmosphere. Unlike previous observations, we specifically used two nearby calibrators (one to independently calibrate the other) in a fast switching mode (30 s on calibrator and 90 s on source) in order to make sure that the change in the flux of Sgr A* is not due to the atmospheric effects. These tests and techniques cannot work when the data are taken in a snapshot mode. Even if the calibration is done correctly in a snapshot observing mode, and the observed variability is intrinsic to Sgr A*, it is not clear whether this is due to the change in the quiescent flux or true flaring activity. Lastly, the lack of simultaneous coverage make it difficult to claim time delays between peaks of emission in different wavelength bands.

2.2. CSO Observations

A ~3′ field surrounding Sgr A* was observed at 850 μm using the Caltech Submillimeter Observatory and the SHARC II camera. The observations on 2006 July 16 began at 5:36 UT and ended at 10:50 UT, and the observations on 2006 July 17 began at 5:20 UT and ended at 10:21 UT. As was done in the past (Yusef-Zadeh et al. 2006b), the field was observed with Lissajous scanning of the telescope with an amplitude of ~100′ and a period of ~20 s. The scanned observing permits an accurate measurement of all of the relative detector gains, and coverage of the surrounding dust emission allows the atmospheric transmission to be tracked better than using the CSO 225 GHz radiometer alone.

Absolute calibration was accomplished with observations of Callisto (13.6 Jy assumed) and Neptune (27.5 Jy assumed), with an estimated uncertainty of 10%. At the 20′ resolution of CSO at

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7 The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.
850 μm the emission of Sgr A* is somewhat confused with the emission from the surrounding molecular ring. We estimate an absolute uncertainty of 1 Jy in the flux of Sgr A* due to confusion, while noting that the accuracy of changes in flux is considerably better.

2.3. Chandra Observations

The imaging array of the Advanced CCD Imaging Spectrometer (ACIS-I; Garmire et al. 2003) on board the Chandra X-Ray Observatory (Wiesskopf et al. 2002) was used to observe Sgr A* simultaneously with the CSO and the VLA for 29.8 ks from 2006 July 17 04:15 to 12:37 (UT; ObsID 6363 [obs/6363]). ACIS-I was operated in timed exposure mode with detectors I0–3 and S2 turned on; the time between CCD frames was 3.141 s. The event data were telemetered in faint format. The data were analyzed using the Chandra Interactive Analysis of Observations (CIAO) version 3.3.0.1 and the calibration database version 3.2.2.8.

Figure 1 shows the (net) Chandra ACIS-I light curve of Sgr A* in the 2–8 keV band obtained using a source aperture radius of 1.5 and a surrounding sky annulus extending from 2″ to 4″, excluding regions around discrete sources and bright structures (see Baganoff et al. 2003). The bin size is 207.3 s. For more details about the Chandra data, see Marrone et al. (2008).

3. RESULTS

Figure 1 shows a composite light curve of flaring activity in the X-ray (2–10 keV), 850 μm, and 7 and 13 mm bands on 2006 July 17. The most interesting result of this multiwavelength
campaign is the detection of a strong X-ray and submillimeter flare. The 43 and 22 GHz light curves also show a relatively strong flare preceded by a weak flare near 4.25 UT at 43 GHz. The X-ray flare lasts for at least 90 minutes with a sharp rise and a slow decay having a peak X-ray luminosity of $4 \times 10^{34}$ ergs s$^{-1}$ (Hornstein et al. 2007). The asymmetric profile of the 850 $\mu$m flare shows a slower rise and decay in its light curve than that of its X-ray counterpart. The duration of the submillimeter flare is greater than 3.5 hr. The morphology, the duration and the time lag of the submillimeter flare with respect to the bright X-ray flare can all be understood in the context of expanding hot plasma (see § 4). We also note a weak flare near 6 hr UT in the submillimeter band with a peak flux of 200 mJy at 850 $\mu$m. This weak flare was also detected at 1.2 mm based on simultaneous SMA observations during this campaign (Marrone et al. 2008).

Simultaneous near-IR observations on 2006 July 17 also detected a near-IR counterpart to the X-ray flare at K$^\prime$-L$^\prime$ bands. However, near-IR observations started 36 minutes after the peak X-ray emission. In spite of incomplete time coverage in near-IR wavelengths, Hornstein et al. (2007) argue that the near-IR and X-ray flare emissions are associated with each other and simultaneous with no time delay.

### 3.1. Cross Correlation Study

#### 3.1.1. 2006 July 17 and 2006 July 16

Our cross-correlations use the Z-transformed discrete correlation function algorithm (Alexander 1997; see also Edelson & Krolik 1988). This algorithm is particularly useful for analyzing sparse, unevenly sampled light curves. We identify the peak likelihood value, and a 1 $\sigma$ confidence interval around that value, using a maximum likelihood calculation (Alexander 1997).

The top panel of Figure 2a shows the light curves of Sgr A* at 850 $\mu$m and X-rays; the corresponding cross correlation peak is displayed in the bottom panel. Assuming that the two flares are related to each other, the cross correlation plot suggests that the submillimeter peak lags the X-ray peak by 110 ± 17 minutes. Also, assuming that the X-ray flare has a simultaneous near-IR counterpart, as Hornstein et al. (2007) suggest, the 110 minute time delay seen in Figure 2a is consistent with that observed between the near-IR and submillimeter peaks measured on 2004 September 4 (Yusef-Zadeh et al. 2006b). These time delay measurements imply that submillimeter flare emission at 850 $\mu$m is optically thick.

Figure 2b shows a cross-correlation peak between 7 and 13 mm emissions for the 2006 July 17 data. The maximum likelihood peak is 20.4 ± 6.8 minutes. The time lag between the 7 and 13 mm peak flare emission, as shown in Figure 2b, is consistent with a 20 minute time delay at these frequencies reported earlier (Yusef-Zadeh et al. 2006a).

We also performed a cross correlation analysis between the radio and submillimeter flare emission of 2006 July 17 (Fig. 3a). However, the strong flare emission in radio wavelengths occurs before the strong submillimeter peak seen near 7:30 hr UT. There is a weak submillimeter flare that is evident near 6 hr UT. This weak submillimeter peak, which is clearly visible in the SMA light curve of 2006 July 17, has a better signal-to-noise ratio at 1.3 mm than at 850 $\mu$m (Marrone et al. 2008). Due to the long duration and relatively high frequency of the radio and submillimeter flares, as well as the lack of simultaneous temporal coverage between VLA and CSO observations, the association of flares in radio and submillimeter wavelengths is not clear. One possibility is that the strong 7 mm flare that peaks near 6:30–7:00 hr UT, as seen in Figure 1, is associated with the strong submillimeter flare that peaks near 7:30 hr UT. The strong peak in the cross correlation plot in Figure 3a shows a negative time lag of ~1 hr for these two strong flares in radio and submillimeter wavelengths. This result, however, implies that the strong submillimeter peak is delayed with respect to the strong 7 mm peak by $66^{+18}_{-18}$ minutes. This is, of course, not consistent with the plasmon model of expanding plasma which predicts that low frequencies are delayed relative to high frequencies. On the other hand, Figure 3a also

![Figure 2](image-url)
shows a weaker cross correlation peak with a positive time lag. Thus, we infer that the faint submillimeter flare and quiescent emission with a peak flux of 2.7 Jy centered around 6 hr UT is likely to be associated with the strong 7 mm flare and quiescent emission with a peak flux of 1.7 Jy. This also suggests that both the X-ray and the strong submillimeter flares are not related to the radio flares observed at 7 and 13 mm. Given the uncertainty due to incomplete time coverage, the time lag between the weak 850 μm and 7 mm flares is estimated to be greater than 1.25 hr.

We also investigated the cross correlation of 850 μm data with 13 mm data taken on 2006 July 16. Figure 3b shows enhanced submillimeter emission between 6:45 and 8:00 hr UT. Radio emission at 13 mm also shows the beginning of a flare between 7:30 and 8 hr UT. Again, the lack of simultaneous temporal coverage between VLA and CSO observations makes the cross correlation analysis quite uncertain. However, a peak is noted with a positive time lag in the bottom panel of Figure 3b. The delay between 850 μm and 13 mm is estimated to be roughly 65 ± 10 minutes. This time delay is consistent with the time lag noted with the 2006 July 17 cross correlation data, as shown in Figure 3a.

### 3.1.2. 2006 February 10 and 2005 February 10

We applied the cross correlation analysis to the 7 and 13 mm data taken on 2006 February 10 and on 2005 February 10 in the A-array plus Pie Town and the BnA hybrid configurations of the VLA, respectively (Yusef-Zadeh et al. 2006b, 2007). Figure 4 shows the cross correlation plots of 7 and 13 mm data corresponding to these observations. The 7 and 13 mm light curves from both observations are made based on uv data greater than 100 kλ. The maximum likelihood values with one σ error bar are 30 ± 12 and 20 ± 6 minutes for the 2006 February 10 and 2005 February 10 data, respectively. In both measurements, the strong peak indicates clearly that the 13 mm peak lags behind the 7 mm peak flare emission. Table 1 gives a summary of the time lag measured from cross correlating radio, submillimeter and X-ray data sets.

### 3.2. 43 and 22 GHz Polarization

The four panels of Figure 5 shows the variation of the polarization plots at 7 and 13 mm, respectively, taken on 2006 July 17. The top three panels show the Stokes $Q$, $U$, and $I$, whereas the bottom two panels show the degree of polarization and polarization angle. The data are binned every 20 minutes at both 7 and 13 mm. The average degree of polarization at 7 and 13 mm are 1% ± 0.2% and 0.7% ± 0.1%, respectively.

We also obtained light curves of Stokes $Q$, $U$, and $I$ using 1733-130 instead of 17444-31166. We could not confirm the light curves of Stokes $Q$ and $U$, as shown in Figure 5. We believe the reason for such a discrepancy is due to the residual instrumental errors of the calibrators as a function of elevation. If the residual errors are not taken out properly, they create different polarization light curves. We believe that 17444-31166 is a better polarization calibrator for this purpose as was observed every 90 s while tracking Sgr A* within 2° of its position. On the other hand, 1733-130 is observed once every 20 minutes and is 16° away from Sgr A*. It is possible that the stress due to gravity is responsible for not accounting properly the instrumental polarization correction using 1730-130 as a function of time. Future observations with additional polarization calibrators are needed to confirm the low level of polarization we have reported here.

We note that both the degree of polarization and polarization angle tend to change during the flaring state when compared with those during the quiescent phase of Sgr A*. In particular, we note a possible increase in the degree of polarization to 2.5% and 1.5% at 7 and 13 mm, respectively. The polarization angle during the quiescent phase is close to 180° or 0° at 7 and 13 mm, but a variation of about 100° is detected during the flaring phase at both 7 and 13 mm. The average values of polarization angle at 7 and 13 mm during the flaring phase (i.e., >6 hr UT) are estimated to be 106° and 87°. The errors in the polarization angle for individual data points are obtained by taking the nominal Stokes $Q$ and $U$ values plus the derived 1 σ errors in the respective Stokes
parameter to determine one limit in the polarization angle. The nominal $Q$ and $U$ values minus the $1/\sqrt{27}$ errors are used to determine the other limit relative to the nominal polarization. The polarization angle measurements correspond to a rotation measure (RM) of $-2.5 \times 10^{7}$ rad m$^{-2}$ with no phase wrap; the RM estimate assumes the quadratic relationship between RM and the observed frequency. However, recent analysis of polarized emission from Sgr A$^*$ suggests that relativistic RM of polarized radiation should be considered (Ballantyne et al. 2007; Yusef-Zadeh et al. 2007).

4. MODELING OF SUBMILLIMETER AND RADIO FLARES

Models for the variable emission from Sgr A$^*$ have primarily focussed on the relationship between the dramatic flaring observed in the NIR and X-ray bands (Baganoff et al. 2003; Eckart et al. 2004, 2006; Yusef-Zadeh et al. 2006b; Hornstein et al. 2007). In these models the IR emission is produced by synchrotron emission from a transient population of near-Gev electrons in a $10^{-100}$ G magnetic field, with the X-rays produced either by synchrotron from higher energy electrons (Yuan et al. 2003) or by inverse Compton scattering of either the submillimeter from the surroundings or directly associated with the transient population (i.e., synchrotron-self-Compton) (e.g., Yuan et al. 2003, 2004; Liu et al. 2004, 2006a, 2006b). Scattering of NIR photons by the electrons responsible for the quiescent submillimeter emission may also contribute to the X-ray flux (Yusef-Zadeh et al. 2006b). These models constrain the size of the emitting region to be a few Schwarzschild radii or less (Liu et al. 2004). The transient population of accelerated electrons may be produced via reconnection, acceleration in weak shocks (e.g., Yuan et al. 2003) or by heating by plasma waves (Liu et al. 2006a, 2006b) driven by instabilities in the accretion flow or dissipation of magnetic turbulence. Detailed modeling of the latter process implies that the regions are compact suggesting that the flaring may be used to study the detailed evolution of the accelerated electron population in response to heating and radiative mechanisms (Bittner et al. 2007).

At lower frequencies, successive delays have been tentatively detected between flares at 350, 43, and 22 GHz (Yusef-Zadeh et al. 2006b), behavior that is reminiscent of the emission from an adiabatically expanding synchrotron source that is initially optically thick, and becomes optically thin at successively lower frequencies as the source expands (see van der Laan 1966). This may reflect (for example) the expansion of a buoyant blob of

### TABLE 1

| DATE            | 7 mm (Jy) | 13 mm (Jy) | 850 $\mu$m (Jy) | X-Ray (erg s$^{-1}$) | X-Ray–850 $\mu$m (minutes) | 7–13 mm (minutes) | 850 $\mu$m–13 mm (minutes) |
|-----------------|-----------|------------|-----------------|----------------------|-----------------------------|------------------|-----------------------------|
| 2006 July 17    | 1.76      | 1.2        | 3.35            | $4 \times 10^{14}$   | 110 $\pm$ 17                | 20.4 $\pm$ 6.8   | ...                         |
| 2006 July 16    | ...       | 1.2        | 3.09            | ...                  | ...                         | ...              | 65$^{20}_{-13}$             |
| 2005 Feb 10     | 1.76      | 1.15       | ...             | ...                  | 30 $\pm$ 12                 | ...              | ...                         |
| 2006 Feb 10     | 2.6       | 1.76       | ...             | ...                  | 20 $\pm$ 6                 | ...              | ...                         |
| 2006 Feb 10     | 2.5       | 1.80       | ...             | ...                  | 20 $\pm$ 6                 | ...              | ...                         |
synchrotron-emitting plasma created in a corona by a disk instability or a bright emission spot advected by an expanding wind in the vicinity of the black hole. Here we adopt a phenomenological approach focussed on the empirical behavior of the flares that is divorced from the uncertain global structure and dynamics of the outflow.

It turns out that this model matches the shapes of the profiles and the delay between frequencies surprisingly well, and that the derived emission region size, density, and magnetic field strength are in broad agreement with the conditions inferred in global models of the accretion flow and in the detailed models for flaring in the NIR (Bittner et al. 2007).

Our earlier phenomenological modeling of the time delay assumed that at 350 GHz the flare emission was initially optically thin and showed that a steep energy spectrum ($\sim E^{-3}$) could explain the relative flux of the peak emission at lower, initially optically thick frequencies. Here we further test this model by applying it to the delayed flaring seen in the current observations. The presence of a possible 110 minute time delay between the peaks of X-ray and 850 μm light curves suggests that the submillimeter flare emission may, in this case, be optically thick. Thus, here we investigate optically thick submillimeter and radio emission in the context of adiabatic expansion of hot plasma (van der Laan 1966) using different energy spectra of nonthermal particles.

We also determine the physical parameters of the expanding blob models, which then are used to model the polarization characteristics of the observed light curves in radio and submillimeter wavelengths.

4.1. Time Delay as a Function of Spectral Index

The phenomenological model assumes that the flaring emission at submillimeter to radio frequencies is dominated by synchrotron emission from a compact expanding region filled with relativistic electrons with an energy spectrum $n(E) \propto E^{-p}$ threaded by a magnetic field. For simplicity, the particle density and spectrum and magnetic field strength are taken to be uniform. As the emitting region expands the magnetic field declines as $R^{-2}$ because of flux-freezing, the energy of each relativistic particle declines as $R^{-1}$ because of adiabatic cooling and the energy-integrated density of relativistic particles scales as $R^{-3}$. Following van der Laan (1966), the flux density scales as

$$S_{\nu} = S_{0} \left(\frac{\nu}{\nu_{0}}\right)^{3/2} \left(\frac{R}{R_{0}}\right)^{-3} \frac{1 - \exp(-\tau_{\nu})}{1 - \exp(-\tau_{0})},$$

(1)

where the synchrotron optical depth at frequency $\nu$ scales as

$$\tau_{\nu} = \tau_{0} \left(\frac{\nu}{\nu_{0}}\right)^{-(p+4)/2} \left(\frac{R}{R_{0}}\right)^{-(2p+3)}.$$  

(2)

Here $\tau_{0}$, the optical depth at which the flux density for any particular frequency peaks, depends only on $p$ through the condition

$$e^{\tau_{0}} - (2p/3 + 1)\tau_{0} - 1 = 0$$

(3)

and ranges from 1 to 1.9 as $p$ ranges from 1 to 3 (Yusef-Zadeh et al. 2006a). Thus given the particle energy spectral index $p$ and the peak flux $S_{0}$ in the flaring component of the light curve at a reference frequency $\nu_{0}$, this model predicts the variation in flux density at any other frequency. A model for $R(t)$ is required to convert the dependence on radius to time: as a first approximation we adopt a simple linear expansion at constant speed $v$, so that $R = R_{0} + v(t - t_{0})$, where $t_{0}$ is the time of the peak flux at frequency $\nu_{0}$.

By way of illustration, we choose a peak flux $S_{0} = 1.5$ Jy at $\nu_{0} = 350$ GHz, consistent with the observations presented here. Figure 6 shows the resulting light curves at submillimeter and radio frequencies for particle energy indices $p = 2$ and 0.5. This behavior reflects the combined effects of adiabatic cooling and declining magnetic field, which imply that the initial energy of the electrons responsible for the peak emission increases as the

![Figure 5](https://example.com/figure5.png)

**Fig. 5.** — Left: Light curves of Stokes $Q$, $U$, and $I$, the degree of polarization, and the polarization angle at 7 mm. Right: Similar to the left panes, except at 13 mm. The time interval sampled at 7 and 13 mm are 1200 s.
plasma evolves. A flatter spectrum implies a relatively larger number of high-energy particles at $t = 0$, and therefore a greater expansion is required to cool them. The consequence of flattening the energy spectrum of particles is therefore to increase the time delay between peaks at various frequencies and to lengthen their durations.

4.2. Modeling the Light Curves

For a single frequency the functional form for a flare at one frequency uses one more parameter than a Gaussian fit (i.e., $p$ and the expansion speed $v$, instead of the Gaussian FWHM), so that one expects a better fit than would be obtained with a Gaussian, regardless of the merits of the model. Fortunately the contemporaneous light curves at other frequencies—including the delay time—are then fully determined without additional parameters. Therefore, simultaneous light curves at two or more frequencies form a good test of the model.

The observables measured from a typical light curve at frequency $v_0$ are the timing and magnitude of the peak flux ($t_0$, and $S_0$), the particle index $p$ and expansion speed in units of $R_0$ per unit time (which together determine the asymmetry and width of the flare), and the background level. The most uncertain of these is the value of the background, i.e., the quiescent flux, as this may slowly vary over the course of a flare.

The physical parameters of the emitting region are then determined as follows. The index $p$ determines $t_0$, and so the value of $S_0$ fixes the radius $R_0$ via $S_0 = \pi R_0^2 / d^2 \times [1 - \exp(-\tau_0)]$, where $d$ is the distance to the Galactic center. Then the expansion speed is determined in physical units. The determination of the magnetic field and electron density from the optical depth and size of the emitting region relies on assuming minimum and maximum energies (we adopt $E_{\text{min}} = 1$ MeV and $E_{\text{max}} = 100$ MeV, respectively) and equipartition between the magnetic field and relativistic electrons.

We do not perform maximum likelihood fitting given the phenomenological nature of the model, being content to achieve reasonable matches with the observed light curves. We modeled the submillimeter and radio light curves on 2006 July 17 and the radio data on 2005 February 10 and 2006 February 10. The model parameters are presented in Table 2.

The model for the submillimeter light curve of 2006 July 17 is plotted as a solid line in Figure 7a. The submillimeter flare shows a slow decay and its asymmetric profile is fitted with a peak (excess) flux of 0.82 Jy at 850 $\mu$m (350 GHz) at 7.65 hr UT. The particle spectral index $p = 1$ (or $\alpha = 1$), an expansion speed of $v = 0.0028 c$ and a magnetic field of $B = 76$ G are derived from the fit. Note that the synchrotron cooling time for electrons emitting at 350 GHz is ~45 minutes, so that this may play a role in determining the decay of the light curve.

Separately from the submillimeter data, the light curves of the radio flare that peak prior to the rise of the submillimeter flare on 2006 July 17 are jointly fitted, as shown in Figure 7b. The peak flux of 0.23 Jy at 7 mm (43 GHz) at 6.55 hr UT is used to derive the value $p = 1$, $v = 0.12 c$ and a magnetic field of 11 G, as shown in Figure 7b. The quiescent flux was estimated to be 1 and 1.46 Jy at 22 and 43 GHz, respectively, with a spectral index of 0.58.

The model light curves of the 2005 February 10 data at 43 and 22 GHz are shown in Figure 8a. The derived quantities are $p = 1.5$, $v = 0.018 c$, and $B = 12$ G. We also derived the physical parameters of the flare emission for the 2006 February 10 observation. The light curve of this observation shows two overlapping flares.

**TABLE 2**

| DATE          | Quiescent Flux 7 mm (Jy) | Quiescent Flux 13 mm (Jy) | Quiescent Flux 850 $\mu$m (Jy) | Particle Index $p$ | Expansion Speed $(v/c)$ | Initial $B$ (G) | Initial Radius $(R_0)$ |
|---------------|--------------------------|---------------------------|-------------------------------|-------------------|-------------------------|-----------------|------------------------|
| 2005 Feb 10   | 1.62–1.64                | 160                       | ...                           | 1.5               | 0.018                   | 12              | 1.9                    |
|               | 1.09                     | 75                        | ...                           | 1.5               | 0.018                   | 12              | 1.9                    |
| 2006 Feb 10   | 2.06                     | 300                       | ...                           | 1                 | 0.013                   | 10.7            | 2.5                    |
|               | 2.33                     | 240                       | ...                           | 2                 | 0.016                   | 10.4            | 3.2                    |
|               | 1.65                     | 150                       | ...                           | 1                 | 0.013                   | 10.7            | 2.5                    |
|               | 1.67                     | 110                       | ...                           | 2                 | 0.016                   | 10.4            | 3.2                    |
| 2006 July 17  | 1.45                     | 230                       | ...                           | 1                 | 0.15                    | 11              | 2.2                    |
|               | 1.0                      | 120                       | ...                           | 1                 | 0.15                    | 11              | 2.2                    |
|               | 2.40                     | 820                       | ...                           | 1                 | 0.0028                  | 76              | 0.50                   |
on top of a fairly strong quiescent emission when compared to the flare emission observed on 2005 February 10. The fit to the light curve is shown in Figure 8b. The model uses peak flux of 300 and 240 mJy at 43 GHz centered at 14.3 and 16.3 hr UT for the first and second flare, respectively. The derived physical parameters for both flares are quite similar to each other (see Table 2) except that the value of particle energy index of the first flare \( p = 1 \) is flatter than that of the second flare \( p = 2 \).

### 4.3. Theoretical Polarization Curves

The parameters derived from modeling the variation in intensity can be used to compute the polarization properties of the transient emitting region, in other words to produce light curves in all four Stokes parameters \( I, Q, U, \) and \( V \). To illustrate this we compute the variations in \( Q \) and \( U \) for the physical parameters inferred of the emitting region inferred for the 2006 July 17 flare. To do this we use the analytic (but complicated!) solutions for the Stokes vector emerging from a homogeneous synchrotron-emitting sphere threaded by a uniform magnetic field given by Jones & O'Dell (1977).

The predicted polarization is sensitive to the assumption that the magnetic field in the emitting region is constant, as any spatial variation in \( B \) will tend to reduce the amplitude of the polarization. Indeed, we find that the model overpredicts the degree of polarization by a factor of around 3, so for the purposes of illustration we reduce \( U \) and \( Q \) by this factor. Two additional parameters are needed to account for the orientation of the magnetic field to the line of sight: we find a reasonable match to \( U \) and \( Q \) at 43 GHz for a field lying in the plane of the sky with P.A. = 20°.

The quiescent emission at 43 GHz is linearly polarized with \( Q = -4 \) mJy and \( U = 6.6 \) mJy, so we add these amounts to the model curves.

Figure 9 shows the fit to all Stokes parameters of the 43 and 22 GHz light curve of the 2006 July 17 flare. The match at 22 GHz is less compelling, but despite the uncertainties, both in the data and the model, these results indicate the potential for improved measurements of polarization at multiple frequencies to severely test the emission model.

### 5. DISCUSSION

The particle acceleration mechanism responsible for the NIR flaring associated with Sgr A* is not yet conclusively identified. Possibilities include acceleration in weak shocks (e.g., Yuan et al. 2003), magnetic reconnection events in a disk corona (e.g., Yuan et al. 2004) or acceleration by a spectrum of plasma waves associated with the dissipation of magnetically driven turbulence (Liu et al. 2004, 2006a, 2006b). Modeling of the NIR and X-ray flaring implies that the emission regions are compact, so that the flaring can be used to study the detailed evolution of the accelerated electron population in response to time-dependent heating and radiative mechanisms (Liu et al. 2006a, 2006b; Bittner et al. 2007).

At the frequencies of interest here—below 350 GHz—we cannot directly investigate the mechanism responsible for the energization of the electrons because the flaring emission is optically thick and the synchrotron cooling time of the emitting particles is longer than the flare duration. However, the decaying part of the light curves are sensitive to the electron spectrum over a range of energies because a weakening magnetic field means that the...
energy of the electrons responsible for the synchrotron emission at a particular frequency increases with time; in addition adiabatic cooling of the particles implies that the electrons had an even higher energy at the onset of the flare. Adiabatic cooling in the absence of significant synchrotron losses implies that the energy of a particular electron scales as $1/R$, and the magnetic field strength scales as $R/C_0^2$. Thus the energy of the electrons largely responsible for synchrotron emission at a particular frequency scales as $R$ and their energy when the population was created scales as $R/C_0^2$. Thus modeling of the flare profiles potentially tells us something of the initial accelerated population over about a factor of 5--10 in energy.

In our modeling we assumed for simplicity a power-law spectrum ($E^{-p}$) and inferred $p = 1$--2 for the asymmetric and more symmetric profiles of light curves, respectively. Fermi acceleration by a single adiabatic shock produces a power-law energy distribution with $p \sim 2$ (e.g., Blandford and Eichler 1987). A harder particle spectrum can be produced if relativistic particles carry away a substantial fraction of the kinetic power of the shock (Drury & Völk 1981), or toward high energies by acceleration in multiple shocks (Melrose and Pope 1993; Pope and Melrose 1994). Note, however, that many plausible models predict a relativistic Maxwellian by competition between accelerating and radiative processes (e.g., Bittner et al. 2007). It would therefore be of interest to compute the flaring at low frequencies assuming such spectra, but we leave that exercise to the future, noting that our inferred value of $p$ may reflect the slope of the electron spectrum over a restricted range of energies.

The variation of energy index of particles may also have implications on the origin of the flaring component of X-ray emission. It has been argued previously that the X-ray counterparts to the near-IR flares are unlikely to be produced by synchrotron radiation in the typical $\sim 10$ G magnetic field for two reasons. First, emission at 10 keV would be produced by 100 GeV electrons, which have a synchrotron loss time of only 20 s, whereas individual X-ray flares rise and decay on much longer timescales (Baganoff et al. 2001). Second, the observed spectral index of the X-ray flares, $S_\nu \propto \nu^{-0.6}$ (Belanger et al. 2005), does not match the near-IR to X-ray spectral index of $-1.35 \pm 0.2$ (Eckart et al. 2006). We favored an inverse Compton model for the X-ray emission, which naturally produces a strong correlation with the near-IR flares. In this picture, submillimeter photons are up-scattered to X-ray energies by the electrons responsible for the near-IR synchrotron radiation. In the inverse Compton scattering (ICS) picture, the spectral index of the near-IR flare must match that of the X-ray counterpart. The spectral indices of the X-ray and of the decaying part of the near-IR light curve on 2006 July 17 are estimated to be $\alpha = -0.3 \pm 0.6$ and $-0.6 \pm 0.2$, respectively, where $F_\nu \propto \nu^{-\alpha}$ (Hornstein et al. 2007). These spectral indices are consistent within errors with the ICS picture. Hornstein et al. (2007)
report a peak X-ray flux of $4 \times 10^{34}$ ergs s$^{-1}$. In the ICS picture, the peak flux at $\alpha$ band is estimated to be $\sim$45 mJy assuming that the magnetic field is $B = 20$ G and the near-IR spectral index $\alpha = -0.5$. The estimated near-IR flux depends on the submillimeter source size and is assumed to have a radius of $3R_*$, which is quite uncertain.

The emission from the innermost region of Sgr A$^*$ can be divided into quiescent and flaring components. The quiescent flux dominates the emission at low energies (e.g., radio and submillimeter wavelengths), whereas the flaring emission dominates at near-IR and X-ray wavelengths. Although a number of models have been proposed to explain the low luminosity of the quiescent flux and the origin of the flaring activity, the relationship between the quiescent and flaring states of Sgr A$^*$ is not fully understood. It is instructive to examine the relationship between these two components. The light curves shown in Figures 2 and 3 indicate clearly that the quiescent emission at 43 and 22 GHz varies on different days. The most dramatic increase of about 30% from 2005 February 10 to 2006 February 10 is noted. Figure 3 shows the quiescent emission of 2006 February 10 ranging between 2.2 and 2.3 Jy at 43 GHz whereas the light curve of Sgr A$^*$ a year earlier on 2005 February 10 shows a flux of $\sim 1.65$ Jy at the same frequency. Similar percentage daily changes can also be noted at 22 GHz. At submillimeter band, the 850 $\mu$m (350 GHz) mean flux dropped by 1.5 Jy between 2005 July-August and 2006 July. This corresponds to a drop of 50% of the quiescent flux in 2006 July with a very high statistical error. This suggests that the emission at submillimeter and radio wavelengths, like those in near-IR and X-rays, could be mainly due to flaring activity and there is no true quiescent flux in the broadband spectrum of Sgr A$^*$.

Thus, it appears that some similarities that can be drawn from comparing the broadband and flaring spectra of the quiescent flux of Sgr A$^*$. One is the fact that submillimeter and radio emission is optically thick in both regimes. The peaks of both the broadband quiescent and flare spectra turnover somewhere in the submillimeter band. In addition, the fact that both quiescent and flare components vary in the optically and optically thin regions gives additional support to the idea that much of the quiescent emission could be due to flaring events. Near-IR light curves show that Sgr A$^*$ is active as much as 30% of the time. In the context of expanding hot plasma blobs, the variation of flux at optically thick submillimeter and radio wavelengths may indeed be responsible for varying quiescent flux of Sgr A$^*$. A more detailed study of the relationship between flaring and quiescent flux of Sgr A$^*$ should explore the possibility that much of the quiescent emission may be generated as a result of a sea of simultaneous low-amplitude flare emission.

6. CONCLUDING REMARKS

In summary, the results presented here confirm the picture of expanding synchrotron emitting plasma as a number of observations in radio show evidence of time delay between the peaks of flare emission. The first evidence of a time delay between X-rays and 850 $\mu$m emission provides additional support for the optically thin near-IR/X-ray flare emission leading the optically thick submillimeter and radio flares by about 2–3 hr. In fact, this time delay clarified earlier simultaneous near-IR and submillimeter observations in 2004 that reported submillimeter flare lagging a near-IR flare by 160 minutes (Yusef-Zadeh et al. 2006b). The observed duration and the time delay of optically thick flare emission is consistent with the model.

The modeling of the light curves has given us a handle on a number of physical quantities associated with flaring activity including the initial magnetic field, the energy spectrum of the particles and the expansion speed, the magnetic field with a strength of 76 G derived from fitting optically thick submillimeter light curve of 2006 July 17 is relatively high compared to the estimate of the magnetic field from model fitting of radio data. This high magnetic field corresponds to a synchrotron cooling time of 45 minutes in submillimeter band, comparable to the decay of the submillimeter flares. This partially undermines the argument that dynamical cooling of submillimeter flares must be important, because of the long synchrotron lifetime of submillimeter emitting electrons. Obviously, future correlation of submillimeter and radio light curves are critical to examine the model and measure the initial magnetic field of the expanding plasma.

The suggestion that the emitting regions responsible for the flaring in the submillimeter and radio are undergoing expansion is consistent with the idea of a significant large-scale outflow of the material associated with the submillimeter radio quiescent spectrum of Sgr A$^*$ (e.g., Loeb & Waxman 2007). Note, however, that our inferred expansion speeds need not correspond to the bulk velocity in the flow. Assuming that the bulk motion is large, then there may be some signature of outflowing material from Sgr A$^*$, although it is not clear if the outflowing material will be collimated as there is no definitive evidence that Sgr A$^*$ has a disk. Indeed, there are some hints that a collimated outflow may arise from Sgr A$^*$ in the past. For example, there is the intriguing radio continuum image of the inner few arcseconds of Sgr A$^*$ (Yusef-Zadeh et al. 1990). We speculate that these large-scale (10$^1$ cm) bloblike structures could potentially be associated with a past outflow activity from Sgr A$^*$.

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