An Apparent Correlation Between S_X/S_{IR} and Submm Lag in Sgr A* Flares

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Motivation

Sgr A* is a radio, IR, and X-ray source associated with an ~ 3.7×10^6 M_{sun} black hole at the center of the Milky Way (Fig. 1). It is extremely under-luminous, radiating at ~ 10^{-9} Eddington, either because the accretion rate is very low or because the accretion flow is radiatively inefficient, or both. Sgr A* flares daily at random intervals in the X-ray (Baganoff et al. 2001), NIR (Ghez et al. 2004), and mm/submm (Mauerhan et al. 2005). The origin of these flares is under vigorous debate. Some models propose that a weak jet is radiatively dominant, while others counter that the flares originate in a magnetized rotating plasma. In either case, the flares must originate from the inner few Schwarzschild radii (R_S), thus providing an unique probe of the physical environment just outside the event horizon of the nearest supermassive black hole.

Several multiwavelength monitoring campaigns have been performed over the past six years to study these flares. Here we report observations and analyses of *the first two flares with simultaneous monitoring in the X-ray, NIR, and submm* (Marrone et al. 2008). The first flare occurred on 2005 July 31 and the second on 2006 July 17. Using an adiabatically expanding relativistic plasmon model (e.g., van der Laan 1966), we show that the X-ray-to-NIR flux ratio (S_X/S_{IR}) or inverse compton-to-synchrotron flux ratio (S_{IC}/S_{sync}) and the lag of the peak flux of the submm light curve (τ_{submm}) are related through the electron column density (n_eR) of the plasma bubble, where n_e is the electron density and R is the radius of the bubble. Future monitoring campaigns will test the proposed correlation and determine the scaling parameters for the dynamical evolution of the electron density, size, and magnetic field of the plasma bubbles. *Simultaneous fits to the temporally evolving spectra, fluxes, and polarization properties with realistic time-dependent shock/particle-acceleration codes may ultimately determine whether the flares originate in a jet or a magnetized rotating accretion flow.*

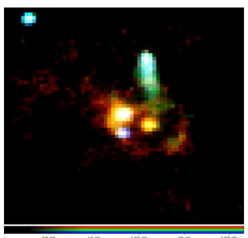

Figure 1. 1-Ms Chandra/ACIS-I image of the central parsec of the Galaxy (0.5-8 keV). Sgr A* is the yellow/white object at center. The purple source below Sgr A* and the blue source at upper left are transient X-ray binaries. Below and to right of center is the young, windy, emission-line star cluster IRS13. The extended blue/green object at upper center is a probable pulsar wind nebula discovered by Chandra.

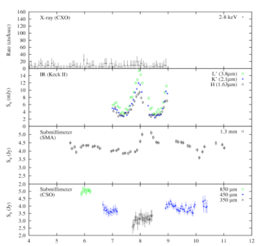

Figure 2. X-ray, NIR, and submm flux light curves of Sgr A* on 2005 July 31.

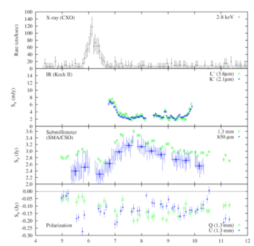

Figure 3. X-ray, NIR, and submm flux and submm polarization light curves of Sgr A* on 2006 July 17.

Simultaneous X-ray, NIR, and Submm Monitoring of Two Sgr A* Flares

- 2005 July 31 Flare (see Fig. 2):
  - Chandra detects no significant variability in 0.5-8 keV bandpass above constant diffuse emission in central parsec (top panel)
  - Keck detects strong NIR flare at H, K', and L' (second panel from top); constant NIR spectral index for all flares (α_{IR} = -0.6) independent of flux indicates electron distribution has index p ~ 2.2 (Hornstein et al. 2007)
  - SMA detects flare at 1.3 mm that lags NIR peak by ~ 20 minutes (third panel from top)
  - Perfectly ordinary NIR flare, so why is there no comptonized X-ray flare?
- 2006 July 17 Flare (see Fig. 3):
  - Chandra detects strong X-ray flare in 0.5-8 keV bandpass (top panel)
  - Keck observations begin 36 minutes after X-ray peak; decaying NIR flare detected at K' and L' (second panel from top); NIR spectral index consistent with all other flares detected with Keck
  - SMA detects strong flare at 1.3 mm (green) that rises as X-ray and NIR flares decay and peaks 97 +/- 15 minutes after X-ray peak
  - CSO detects flare at 0.85 mm (blue); excellent agreement seen between 1.3 mm and 0.85 mm light curves
  - NIR and submm decay timescales are too fast for synchrotron cooling: adiabatic expansion required to explain cooling timescale
  - SMA detects change in polarization fraction and polarization angle across peak that is consistent with an expanding synchrotron bubble transitioning from optically thick to thin

Applying a Relativistic Plasmon Model

1) Ratio of flux light curve maxima at two wavelengths:

$$S_{m,1}/S_{m,2} = (\upsilon_1/\upsilon_2)^{\delta} \quad \text{and} \quad \delta = (7p+3)/(4p+6) \quad \text{(Dent 1968)}$$

Predicts $S_{\lambda,1}/S_{\lambda,2}$ = 1 to 1.46 for p = 1 to 5. For observed p ~ 2.2 in NIR, we expect $S_{0.85\,mm}/S_{1.3\,mm}$ ~ 1.7; however we see $S_{0.85\,mm}/S_{1.3\,mm}$ = 1.15 +/- 0.15, which is consistent with p ~ 0.

2) X-ray (IC) to NIR (S) flux ratio depends on the product of electron density (n_e) and the radius of the plasma blob (R):

$$S_\upsilon^{IC} \propto n_e^2 R^4 B^{(1+p)/2} \upsilon^{(1-p)/2} \quad \text{and} \quad S_\upsilon^{S} \propto n_e R^3 B^{(1+p)/2} \upsilon^{(1-p)/2} \quad \text{implies that} \quad S_\upsilon^{IC}/S_\upsilon^{S} \propto n_e R \quad \text{(Rybicki \& Lightman 1979)}$$

3) Lag of peak submm flux also depends on electron column density through dependence on optical depth:

$$\tau_\upsilon \propto n_e R B^{(2+p)/2} \upsilon^{-(4+p)/2} \quad \text{(Rybicki \& Lightman 1979)}$$

Assume: $R \propto t^{\beta}$; $B \propto R^{k_B} \propto t^{\beta k_B}$; $n_e \propto R^{k_n} \propto t^{\beta k_n}$, then $\tau_\upsilon \propto \tau_{\upsilon,0} t^{\beta\mu}$, where $\mu = 1 + \left(\frac{p+2}{2}\right) k_B + k_n$

Inverting and taking the ratio:

$$t_\upsilon \propto \left[\frac{S_\upsilon^{IC}}{S_\upsilon^{S}} B_0^{(p+2)/2} \upsilon^{-(4+p)/2} \right]^{-1/\beta\mu}$$

4) van der Laan (1966) assumes β = 1, k_B = -2, and k_n = -3 so μ = -6.2. According to this model, we expect the 1.3 mm light curve to lag the 0.85 mm light curve by 16 to 30 minutes, but the measured lag is 2 +/- 12 minutes.

5) Plugging the 2006/2005 flux ratio in X-rays (> 20) and NIR (> 0.6), and the ratio of submm lags (4.8) indicates that βμ < -2.2, which is consistent with βμ = -6.2 for the van der Laan model. *The observed upper limit on βμ predicts that IR-to-submm lags shorter than 50 minutes should not exhibit detectable X-ray flares. Future monitoring campaigns will test this prediction.*

Conclusions

- Observed submm and NIR properties reveal flare emissions are from adiabatically expanding relativistic plasmas: submm is optically thick synchrotron emission, while NIR is optically thin; X-ray is SSC.
- Simplest model (e.g., van der Laan 1966; Yusef-Zadeh et al. 2008) fails:
  - Observed submm spectrum is flat, whereas van der Lann (1966) predicts ~2x flux ratio
  - Measured lag between 1.3 mm and 0.85 mm is too short
  - These problems may be alleviated if the optical depths of the bubbles are inhomogeneous
- Other models predict different scaling relations or more complicated variations.

Future Work

- Increase sample: observe more flares simultaneously in X-ray, NIR, and submm.
- Look for correlated structural variations using 1 mm VLBI.
- Test proposed correlation between S_X/S_{IR} flux ratio and lag of submm peak.
- Derive scaling parameters for dynamical evolution of adiabatically expanding synchrotron bubbles that produce flare emission.
- Model spectral and temporal evolution of flares to determine whether they originate in a jet or a magnetized accretion flow.
- Need time-dependent shock/particle-acceleration models!

References

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