Spectrum of Sgr A*

- Wide range of $\nu$ 's
- Peaks in sub-mm
- Extremely faint sub-Eddington
- Variability detected in almost all wavelengths but not simultaneous
  - Is the variability correlated?
    - Will it address the emission mechanism?

Outline

- Light curves in NIR, X-rays & sub-mm wavelengths
- Cross correlation:
  - NIR vs X-ray
  - NIR vs. sub-mm
- Explain:
  - X-ray /soft $\gamma$-ray emission by ICS
  - NIR and sub-mm by Synchrotron

Yuan et al. 2003
The Nature of Simultaneous near-IR and X-ray Flares from Sgr A* at the Galactic center

F. Yusef-Zadeh

<table>
<thead>
<tr>
<th>X-Ray (XMM)</th>
<th>Near-IR (HST)</th>
<th>Sub-millimeter (CSO, SMT)</th>
<th>Soft $\gamma$-Ray (INTEGRAL)</th>
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<tbody>
<tr>
<td>G. Belanger</td>
<td>H. Bushhouse</td>
<td>D. Dowel</td>
<td>G. Belanger</td>
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<td>A. Goldwurm</td>
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<td>B. Warwick</td>
<td>S. Shapiro</td>
<td>G. Novak</td>
<td>R. Terrier</td>
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Radio (VLA+ATCA+BIMA)

- D. Roberts
- G. Bower
Two Epochs of Observations of SgrA* in 2004

March Campaign

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sub-mm</th>
<th>mm</th>
<th>Radio</th>
<th>X/(\gamma)-ray</th>
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<tr>
<td>SMT CSO</td>
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<td>BIMA NMA</td>
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September Campaign

<table>
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<tr>
<th>Instrument</th>
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<th>NIR</th>
<th>X/(\gamma)-ray</th>
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</tbody>
</table>
• NIR Light Curves of SgrA* (blue, red, green)

• **Amp:** 10% to 25% or 3 to 4 times the quiescent flux (2.8mJy at 1.6µm)

• **Duration:** multiple peaks, lasting from 20 minutes to hours

• **Flare activity:** overall fraction of activity is about 30-40% of the observed time

• **Spectrum:** Unknown

NIR variability in 1.6, 1.87 (Paα line), 1.9µm
• **X-ray Light Curves of Sgr A* (2-10 keV)**

• **Amp:** 35 times the quiescent X-ray flux

• **Duration:** multiple peaks, lasting from 10 minutes to 3 hours

• **Spectrum:**
  - Power-law with $\alpha = 0.6 \pm 0.5$
  - $L(2-10 \text{ keV}) = 7.7 \times 10^{35}$ erg/s

• **Flare activity:** Two clusters of flares in one week

Belanger et al. 2005
NIR (1.6-1.9μm) vs. X-Ray (September Campaign)

No time delay
• Simultaneous NIR and sub-mm light curves of Sgr A*

• **Amp:** 11 mJy at 1.6 micron; 4.7 Jy at 350 micron

• **Duration:** multiple peaks in near-IR lasting for 40 min;

• One peak lasting for two hours

• **Spectrum:**
  – First evidence of variability in sub-mm
Simultaneous X-ray, NIR & Sub-mm Flares

**Near-IR**
- Due to Synchrotron: $E_e=1.1$ GeV, $B_{eq}=10$ G, $\tau_{nir}=40$ min

**Sub-mm**
- Due to Synchrotron $\tau_{nir}=12$ h
  - Similar to NIR (the same population of electrons)
  - $F_{850 \mu m}=0.6$ Jy, $E_e=50$ MeV, $F_{1.60 \mu m}=11$ mJy, $E_e=1$ GeV, $\alpha=0.6$

**X-rays**
- X-Rays cannot be due to Synchrotron: ($E_e$ proportional to $\sqrt{\nu/B}$)
  - $\tau_{nir}=1$ min, $B=10$ G, $E_e=10$ GeV
  - Spectral index between NIR and X-ray is steep
- X-Rays due to ICS: ($E_{photons}$ proportional to $E_e^2 \times \nu_{seed photons}$)
  - (a) diameter=10$R_{sch}$, $F_{850 \mu m}=4$ Jy, $E_e=1$ GeV
  - (b) diameter=10$R_{sch}$, $F_{nir}=10$ mJy, $E_e=50$ MeV
  - $E_{predict}=2\times10^{-12}$ erg/cm$^2$/s/keV, $E_{obs}=1.2\times10^{-12}$ erg/cm$^2$/s/keV
- Lack of one-to-one X-ray detection:
  - Spectral index
  - Magnetic field
NIR Flares with and without X-ray Counterparts

- The softer (steeper) the particle spectrum, the higher the X-ray flux
- The harder (flatter) the particle spectrum, the weaker the X-ray emission

X-ray Flux as a function of spectral index

Flare 1
Flare 2
First IBIS / ISGRI Images of the Galactic Center

- Six known high-energy sources in the central $2^\circ \times 2^\circ$ of the Galaxy
- Detection of IGR J1746-290 coincident with Sgr A*
- A significant excess ($8.7 \sigma$) at $\sim 1'$ from Sgr A* ($4.7 \sigma$ in 40-100 keV)
- Power-law $\alpha = 2.04 \pm 0.98$ and $L(20-120 \text{ keV}) = 4.8 \times 10^{35} \text{ erg/s}$
- Belanger et al. (2005b)
INTEGRAL and XMM Variability

• INTEGRAL:
  — 20-30 keV light curve of IGR J17456-290

• Cross Correlation
  — During the 2 bright SgrA* flares seen with XMM INTEGRAL was in the radiation belts (Belanger et al. 2005b)
Soft $\gamma$-ray Flux as a function of spectral index

- The spectral index in NIR ranges $\sim 0.5$-$4$ (Ghez et al. 2005;

- The population of particles producing NIR emission can explain the soft $\gamma$-ray emission
Conclusions

• Correlation between a near-IR and X-ray/soft $\gamma$-ray flare: the same population of particles
  – ICS may account for steady X-ray/$\gamma$-ray source

• Lack of one-to-one correlation: spectral index and/or magnetic field variation

• Correlation between a near-IR and sub-mm flare: the same population of particles
  – Low-energy component of power-law spectrum

• The flow always fluctuates even in its quiescent phase

• Duration of flaring set by dynamical mechanisms (adiabatic expansion)
TeV Emission From the Galactic Center

- Aharonian et al. (2004)
Radio (7mm) vs X-ray (March Campaign)

- Lag time between X-ray/NIR flare and sub-mm peak 4-5 hours
- Time delay between X-ray/NIR and radio peak is one day
- An expanding synchrotron source in an optically thick medium
- As the electrons cool, the synchrotron self-absorption frequency moves to longer wavelengths
- Delay as a function of frequency expected
• The dispersion plot is minimum at ~20min

• An expanding self-absorbed synchrotron source with a delay of 20min implies plasma ejection took place 54min before the 7mm peak (van der Laan 1966).

• No near-IR or submillimeter data)

• Continuous ejection?
6 and 1.2cm VLA images of the Galactic Center
Conclusions

- Flare correlation: simultaneous vs delayed
- Correlation between a near-IR and X-ray/soft $\gamma$-ray flare: the same population of particles
- Evidence for a NIR flare with quasi-periodic 35min behavior
- The flow always fluctuates even in its quiescent phase:
  - ICS may account for steady X-ray/$\gamma$-ray source
- An expanding synchrotron self-absorbed blob: outflow
Radio Time Lags Between 7mm and 13mm

- Light curves of SgrA* observed simultaneously at 7mm and 1.2cm

- The spectral index steeper at higher frequencies and during flares consistent with Herrnstein et al. (2004)

- The 7mm peak is leading the 1.2cm peak