3 Ms Chandra Campaign on Sgr A*:
A Census of X-ray Flaring Activity in the Galactic Center

XVP Collaboration: http://www.sgra-star.com
Chandra Sgr A*
X-ray Visionary Project

- XVP PIs: Fred Baganoff (MIT), Sera Markoff (Amsterdam), Mike Nowak (MIT)
- 3 Ms on Sgr A* in 2012 (see overview talk by F. Baganoff), plus extensive multiwavelength coverage
- Keep up with collaboration at http://www.sgra-star.com
(Some of) Sgr A* in 3 Parts

- Introduction to (flaring) X-ray emission from Sgr A*
- First results from campaign: the brightest X-ray flare ever observed from Sgr A* (Nowak et al. 2012)
- Census of X-ray flares from 2012: statistics and relationship to quiescent emission
Why Study X-ray Flares from Sgr A*?

- Flares reveal a connection to weakly accreting black holes at all mass scales
- Origin of flares unknown
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Flares and the Fundamental Plane

See also Markoff (2005), talk by Salomé Dibi
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Some Flare Processes

**Physics/Energetics**
- Magnetic reconnection
- Shocks
- Stochastic acceleration in a jet
- Asteroid disruption

**Radiation Processes**
- Direct synchrotron (does IR extrapolate to X-rays?)
- Inverse Compton
- Synchrotron self-Compton (SSC)

Multiwavelength Flare Models

- Synchrotron models (left) and SSC models (right) both work, nonthermal electrons (Yuan et al. 2003), but see Dibi et al. 2013
Chandra XVP

What causes the flares from Sgr A*?
All About Flares

- Roughly $\sim 1.1-1.3$ X-ray flares per day
- Short: $\sim 1-3$ hrs, can be $L \sim 10^{35}$ ergs/s (Baganoff et al. 2001)
- Controversy: do all flares have the same spectra? (Belanger et al. 2005; but see Porquet et al. 2008; but now see Degenaar et al. 2013, talk by N. Barrière)
- Infrared: optically thin synchrotron, Sgr A* variability consistent with a single process, not “flare” and “non-flare” (see talks by L. Meyer, G. Witzel, B. Shahzamanian)
2012 Chandra XVP

- X-ray: small number statistics, lingering questions about flare origins, physical significance (but see talk by S. Dibi)

- 3 million seconds of observations with Chandra gratings (high spectral resolution), great for studying flare properties/statistics
Finding Flares

- First pass: Fit 300-s X-ray lightcurve to estimate baseline emission
  - N.B. Poisson errors, ML fit statistic
- Second pass automated:
  - Look for positive deviations in each 300-s bin
    - If found, try adding a narrow flare ($100 \leq \sigma \leq 1600$ s)
      - If significant at 99%, look for substructure
  - For each flare, record peak count rate, fluence, duration ($\pm 2\sigma$)

*NEILSEN ET AL. (2013)*
2012 Chandra Campaign

Observing Gaps Removed

NEILSEN ET AL. (2013)

2.99 MS
38 OBSERVATIONS
39 FLARES
First Results

CHANDRA/HETGS OBSERVATIONS OF THE BRIGHTEST FLARE SEEN FROM Sgr A*

M. A. Nowak¹, J. Neilsen¹, S. B. Markoff², F. K. Baganoff¹, D. Porquet³, N. Grosso³, Y. Levin⁴,⁵, J. Houck¹, A. Eckart⁶, H. Falcke⁷,⁸,⁹, L. Ji¹⁰, J. M. Miller¹¹, and Q. D. Wang¹²

SEE D. HAGGARD’ S TALK!
The New Brightest Flare EVER!

HAGGARD ET AL. 2013
Brightest Flares

- Bright flares seen by Chandra, XMM have similar spectra; harder than quiescent spectrum (Nowak et al. 2012)
- Moderate spectral index $\Gamma \sim 2$ doesn’t rule out any flare models
- What about weaker flares? Statistics of all flares in 2012!

NOWAK ET AL. (2012)
39 Flares: Demographics

- Strong correlation between peak count rate and fluence
- Sensible/expected if flares have same shape

NEILSEN ET AL. (2013)
39 Flares: Demographics

- ~4-6 ks characteristic time scale for the brightest flares? D. Haggard’s bright flare too!
- Gap in peak rate around 0.04 counts/s?
  - Significant at ~90%
- Careful treatment of pileup, background: no difference in spectral hardness above/below gap

NEILSEN ET AL. (2013)
Best fit power law: $dN/dL \sim L^{-1.9}$

Similar to observed solar flares, though not likely stellar in origin

Asteroid model (e.g. Zubovas et al. 2012) has $dN/dL \sim L^{-(1.6-2)}$

Other models: difficult to predict from first principles!
Fluence Distribution

- Flare duty cycle of 3.5%
- Observed flares still contribute 1/3 of the entire radiant energy of Sgr A* in 2012!
- Best fit power law: \( dN/dF \sim F^{-1.5} \)

Neilson et al. (2013)
Fluence Distribution

- Is the quiescent emission the superposition of many undetected flares?
- Integrate backwards: unobserved flares contribute less than ~10% of underlying quiescent emission
- Power spectral analysis confirms ~10% excess variability above Poisson noise in quiescent emission
- Two emission components in “quiescence”: 1 steady (90%), 1 variable (10%)

neilsen et al. (2013)
What Is This 10%???

Surface brightness distribution: point source and extended emission, 10-20% vs 80-90% of X-ray flux (Shcherbakov & Baganoff 2010; Wang et al. 2013; see D. Wang talk tomorrow!)

**UNDETECTED FLARES FROM ACCRETION FLOW!!!**

- Data – non-flaring 953ks total exposure (w/ super-resolution processing)
- Best fit with $\chi^2$/dof=1.45 (solid)
- PSF extracted from point source (dashed)
Summary

- Flare statistics, surface brightness models, & spectra (Wang et al. 2013) provide a sensible physical decomposition of quiescent emission
  - ~90% of emission is steady thermal plasma on large scales, ~10% is weak flares from the inner accretion flow. See also accretion flow simulations by Dibi et al. (2013), Drappeau et al. (2013)
  - Despite a duty cycle of 3.5%, flares contribute 1/3 of radiant output of Sgr A* in 2012!
  - No evidence for different flare spectra at different luminosities
Future Work


- No present evidence for different flare spectra at different luminosity (but see NuSTAR, N. Barrière talk, Degenaar et al. 2013). Need detailed spectral analysis of each flare: any evidence for changing properties with luminosity?

- Detailed multiwavelength modeling of flare SED; how do the IR/X-ray flux distributions compare?
Total X-ray Flux Distribution

- (Preliminary) X-ray flux $\sim F^{-1.5-2}$
- IR flux $\sim F^{-4.2}$ (Witzel et al. 2012)
- High luminosity IR tail? $\sim F^{-2.1}$ (Dodds-Eden et al. 2011)
- Constraining for flare models??!
Quiescent Variability

- Waiting times (inter-arrival times) between quiescent photons close to exponential (i.e. Poisson process)
- Small amount of correlated noise
- Power spectral analysis confirms: ~10% excess variability above Poisson!
Bright Flare

- Brightest flare in 2012 campaign
- Lasted 5600 s, substructure on time scales of 100 s
- Short time scale $\Rightarrow$ compact emission region!
- Spectral variations?
- $HR=\frac{(4-8 \text{ keV})}{(2-4 \text{ keV})}$
- K-S test: flare/quiescence differ at $>95\%$ confidence

NOWAK ET AL. (2012)
2.99 MS
38 OBSERVATIONS
~22000 PHOTONS
39 FLARES