The Giant Flare From SGR 1806-20 and Its Aftermath

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VE RI TAS

Magnetars

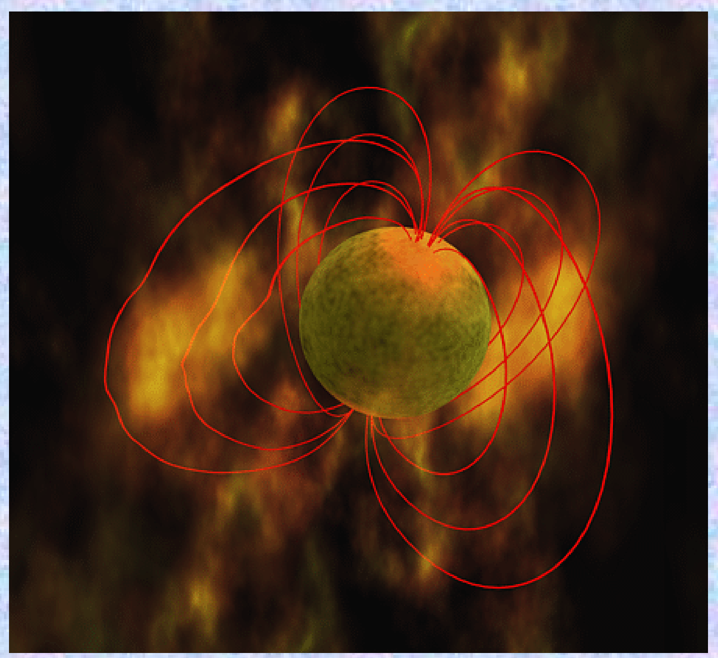
- **Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs)**
  - occasional X-ray/γ-ray bursts
  - very rare giant γ-ray flares
  - slow X-ray periods ($P \sim 5$–12 sec)
  - rapid spin-down, sudden changes in torque
  - low Galactic latitude, some in SNRs
  - not seen in radio, no companions

$\rightarrow$ young neutron stars, but not ordinary pulsars, not accreting binaries

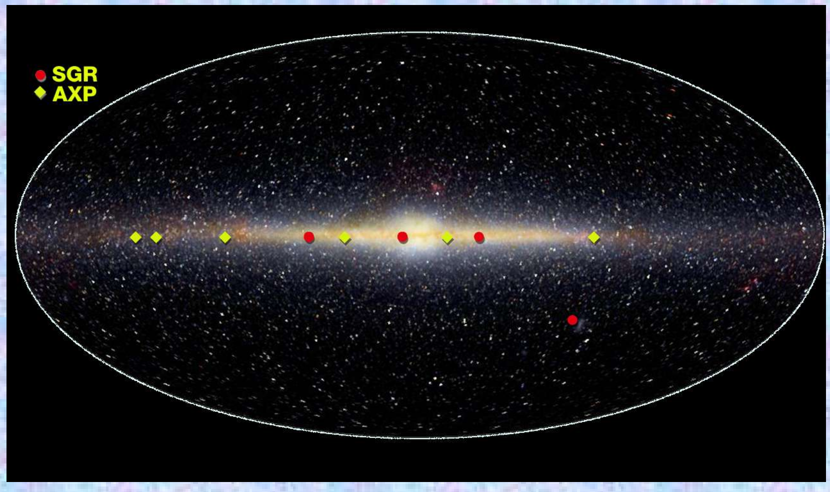
$\Rightarrow$ *"magnetars"*, isolated neutron stars with $B_{surface} \sim 10^{14}$–10^{15} G

(Duncan & Thompson 1992; Kouveliotou et al 1998)

- Rare objects: only ~12 magnetars known
  - active lifetimes ~10 kyr
  - ~10% of neutron star population?



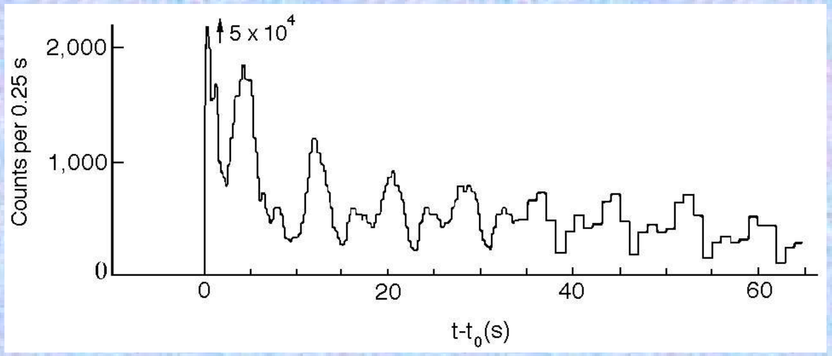
Robert S. Mallozzi, UAH / NASA MSFC



E. L. Wright (UCLA), COBE Project, Courtesy MSFC, NASA

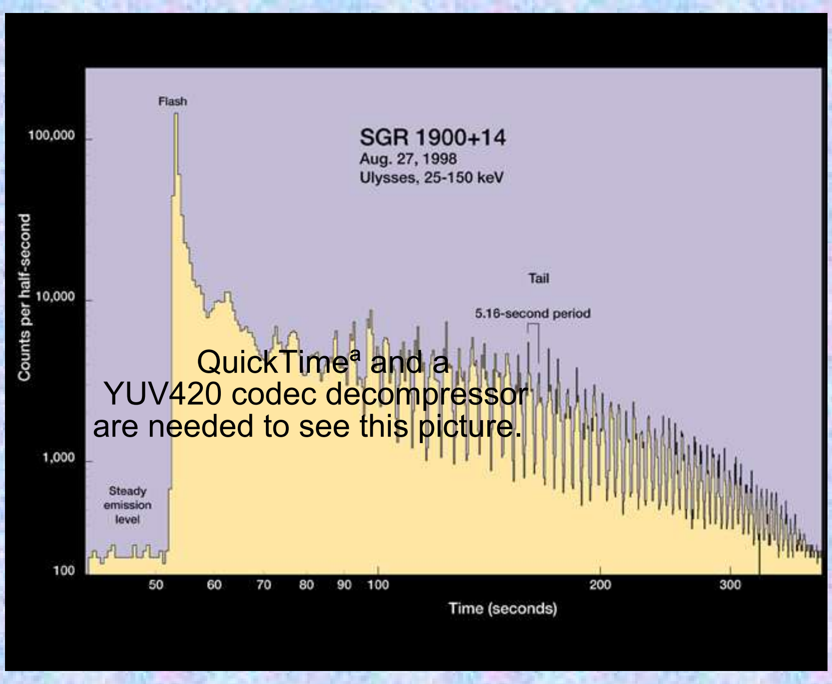
Magnetar Giant Flares

- **5 Mar 1979 from SGR 0526-66 in the LMC**
  - 0.2 sec spike of γ-rays, L ~ 5 x 10^{44} erg/s
  - fading 3-min tail with 8.1 sec pulsations
- **27 Aug 1998 from SGR 1900+14**
  - 1 sec spike of γ-rays, L ~ 2 x 10^{43} erg/s
  - fading 6-min tail with 5.2 sec pulsations



Mazets et al. (1979)

- Intense internal magnetic field, B ~ 10^{16} G
- Twists in internal field strain crust
- Produces sudden propagating fracture
  - catastrophic rearrangement of external magnetic field
  - enormous sudden energy release in ultrarelativistic outflow
  - trapped fireball produces fading tail at star's rotation period



Hurley et al. (1998)

NASA

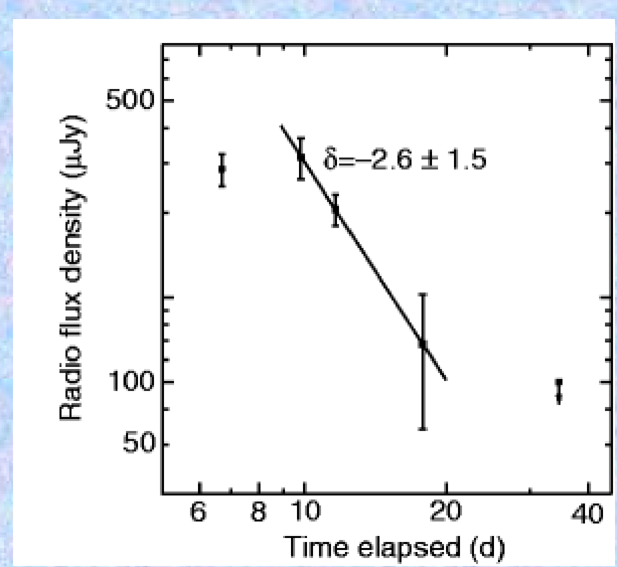
Aftermath of 27 Aug 1998

- Radio "afterglow" seen from SGR 1900+14 following giant flare (Frail et al. 1999)

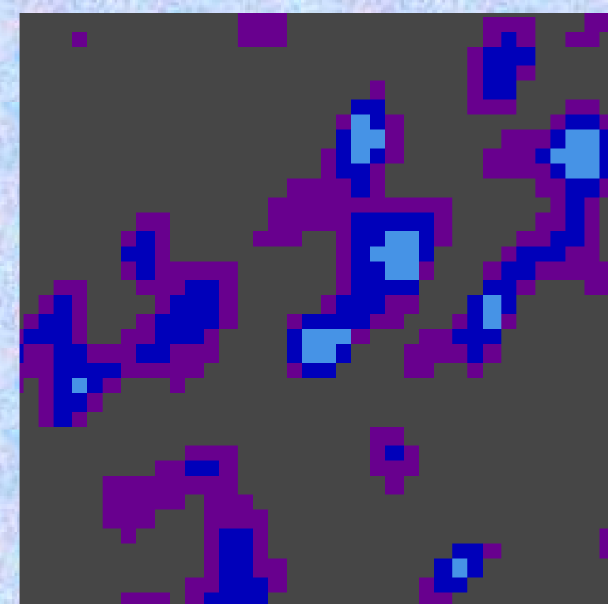
  - faint (peak < 1 mJy after ~7 days)
  - unresolved
  - non-thermal ($S \propto \nu^{-0.75}$)
  - rapid decay ($S \propto t^{-2.6}$)
  - undetectable after 3 weeks
  - $E_{equipartition} \sim 7 \times 10^{37}$ ergs

- Interpretation:

  - injection of relativistic particles by giant flare
  - "mini Crab nebula"
  - quickly expands and fades



Frail et al. (1999)


Frail et al. (1999) / NRAO

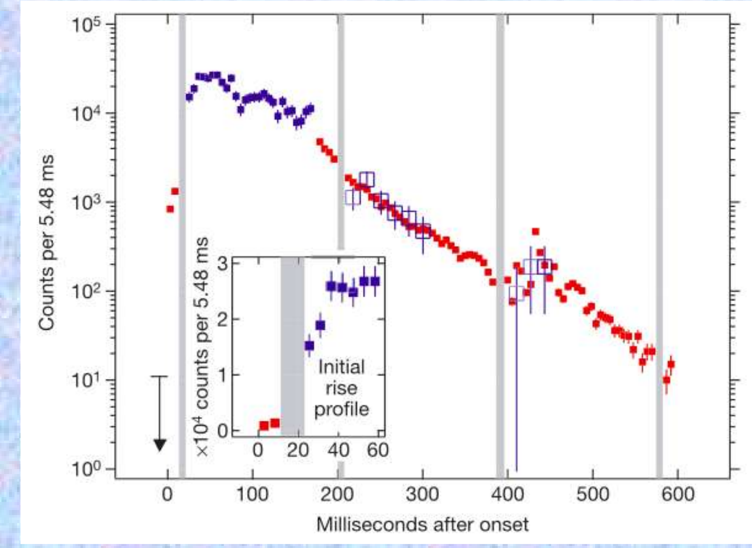
The 2004 Giant Flare

- **27 Dec 2004 from SGR 1806-20** (Borkowski et al. 2004)

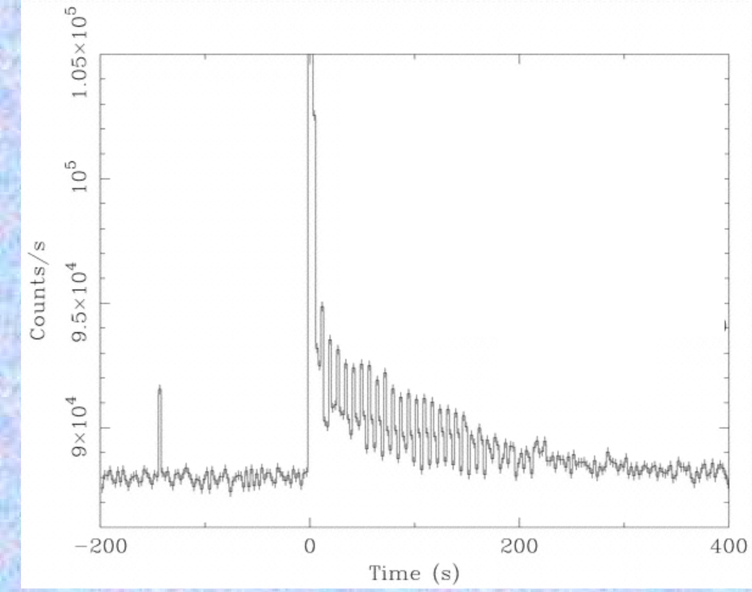
- 0.2 sec spike of γ-rays
  - $L_{peak} \sim 2 \times 10^{47}$ erg/s ~ 1000 x L_{MW}
  - $E_{bol} \sim 4 \times 10^{46}$ erg/s ~ 300 kyr x L
  - fluence at Earth ~ 1 erg cm^{-2}
  - saturated all but particle detectors
  - created detectable disturbance in ionosphere (Campbell et al. 2005)
  - echo detected off Moon (Mazets et al. 2005)

- Fading 6-min tail with 7.6 sec pulsations (= known rotation period of star), similar intensity to tails in previous two giant flares

- Strength of spike reflects degree of reconnection; strength of tail indicates ability to trap particles



Terasawa et al. (2005)



Mereghetti et al. (2005)

The Spike

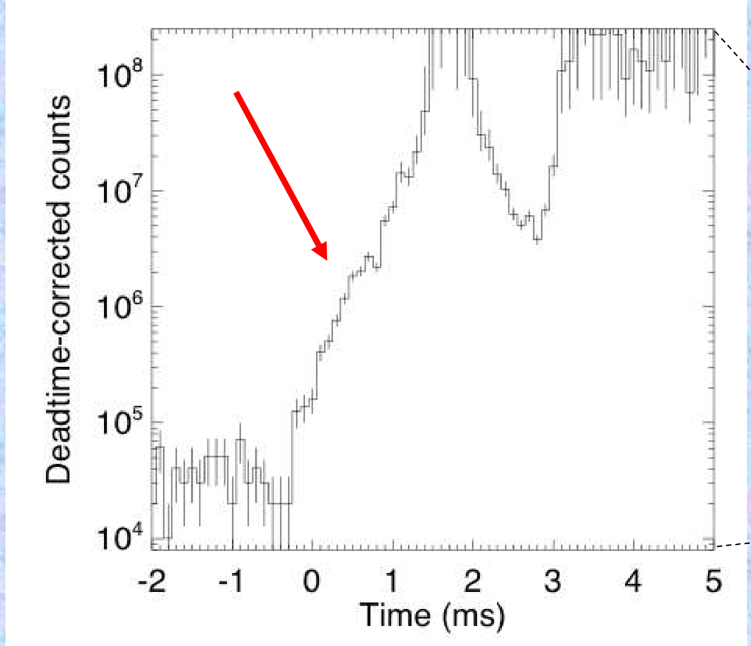
- Three characteristic time scales

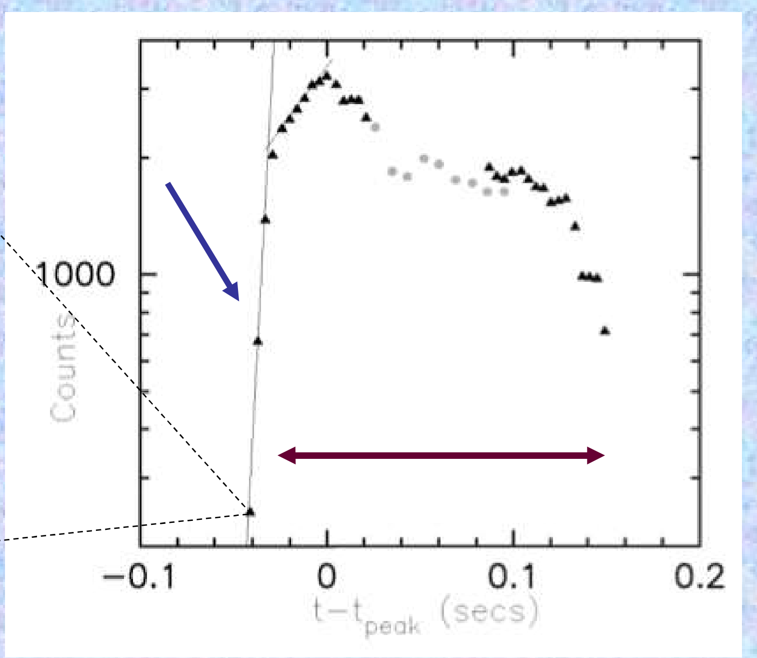
  1) leading edge of flare: 1 ms
  2) rise to main peak: 5 ms
  3) duration of spike: 0.2 s

- Possible interpretation (Palmer et al 2005; Schwartz et al 2005)

  1) 1 ms = timescale for propagation & reconnection in magnetosphere
  2) 5 ms = propagation time of 5-km fracture in crust
  3) 0.2 s = Alfven crossing time of interior

Palmer et al. (2005)



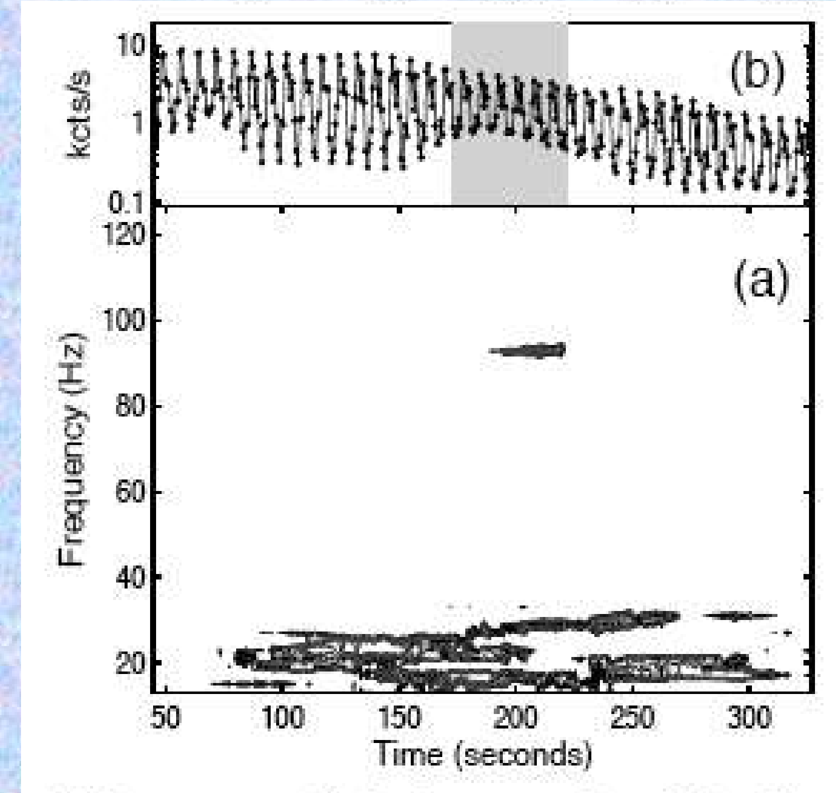


Schwartz et al. (2005)

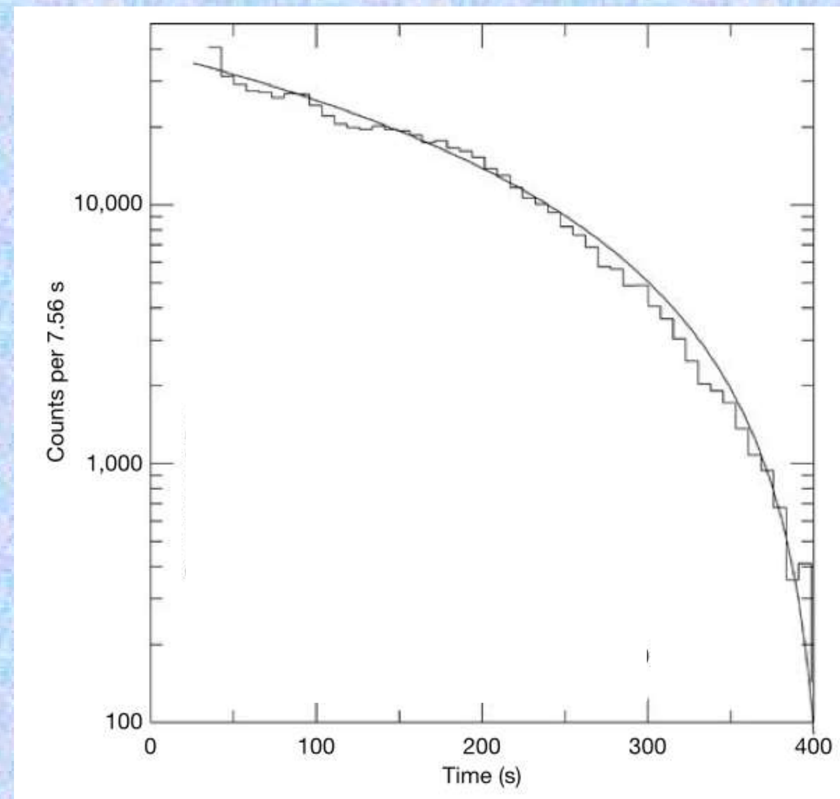
The Tail

- Quasi-periodic oscillations at 18, 30.4, 92.5 Hz (Israel et al. 2005)
  - possibly represent seismic modes on neutron star surface, coupled to magnetosphere (30, 92 Hz) and to 7 x 10^{15} G interior field (18 Hz)

- Unpulsed component of tail good fit to trapped fireball model (Hurley et al. 2005)



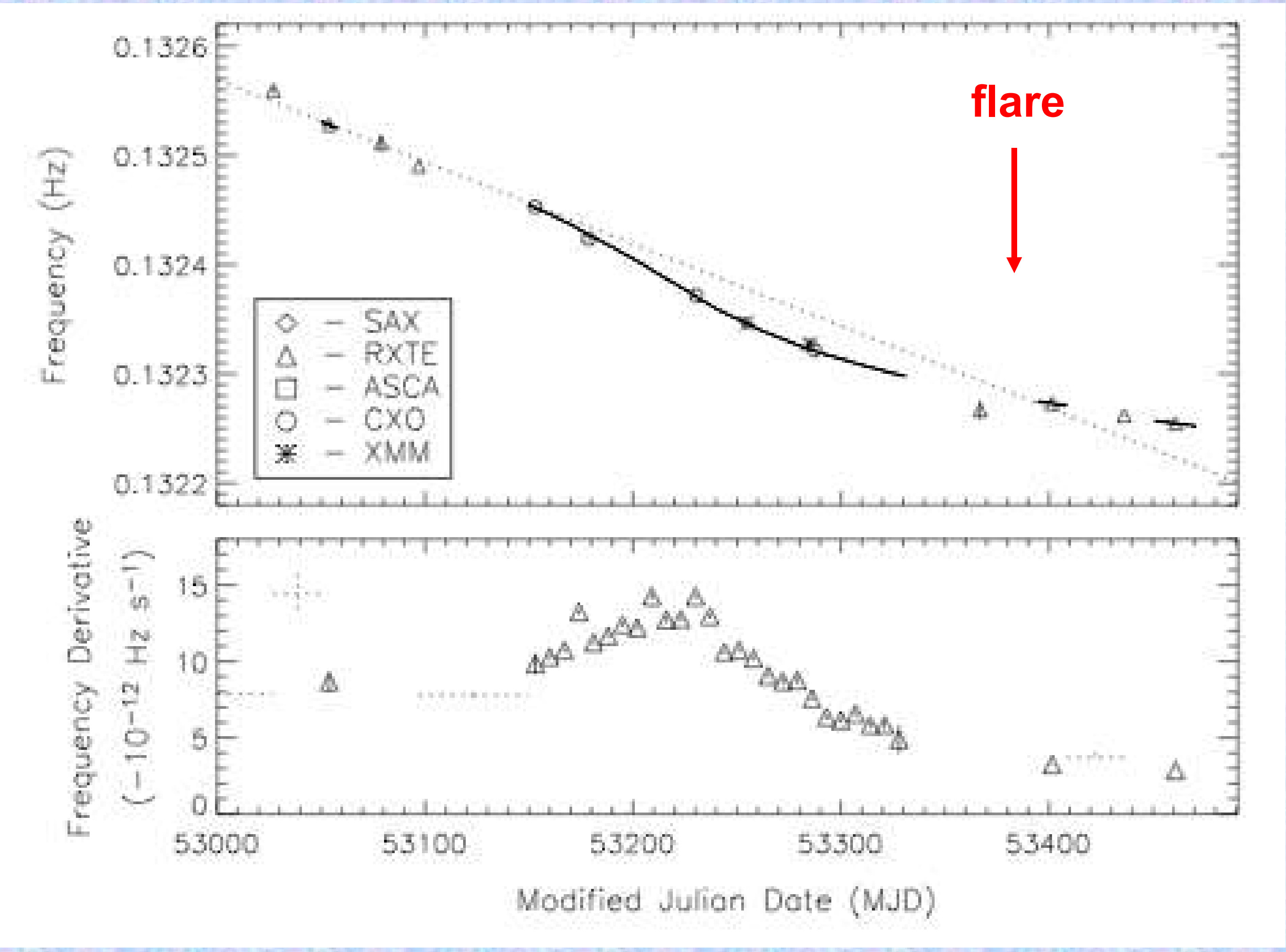
Israel et al. (2005)



Hurley et al. (2005)

Timing Behaviour

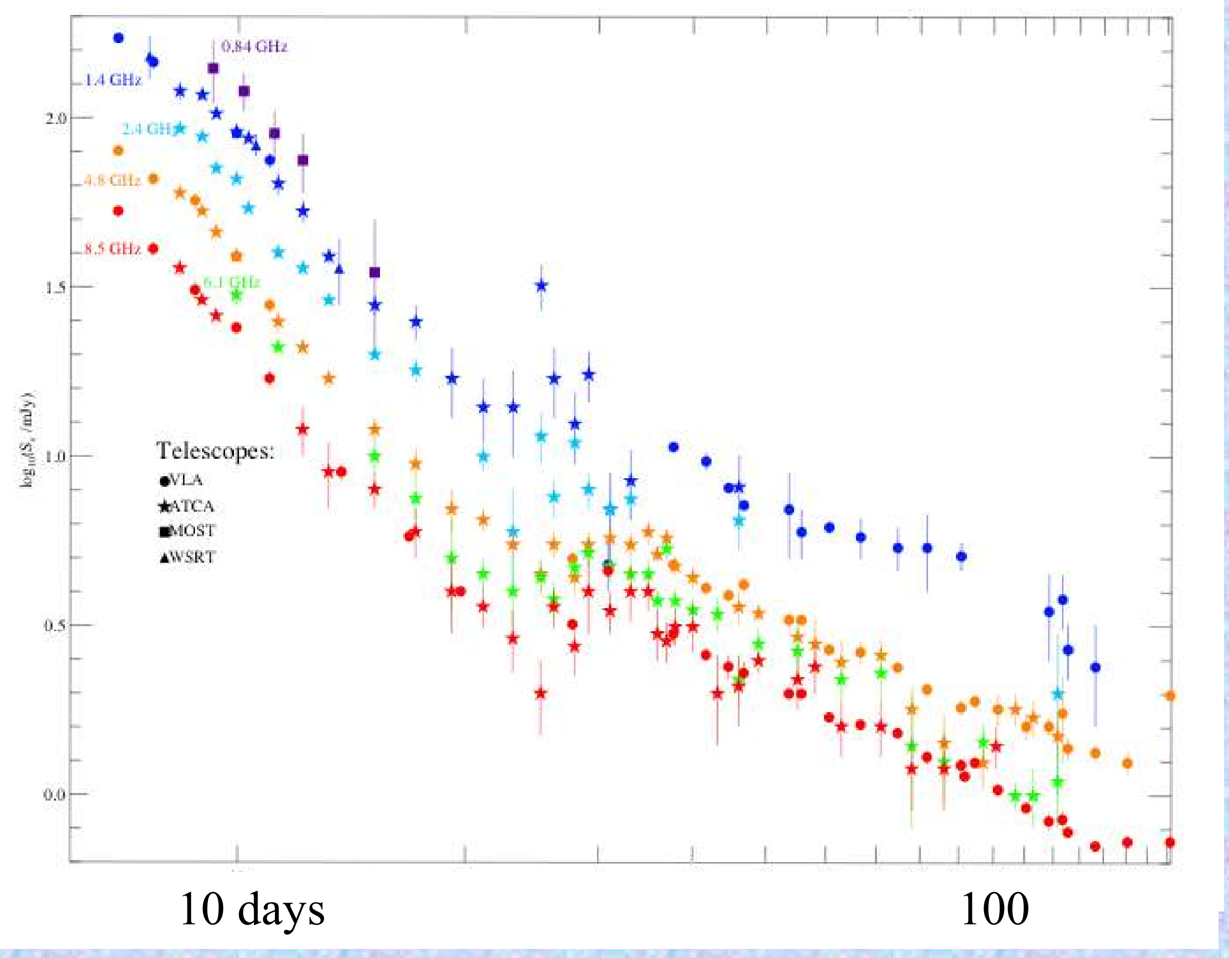
- No change in spin or spin-down associated with flare!



Woods et al. (2005)

The Radio Nebula

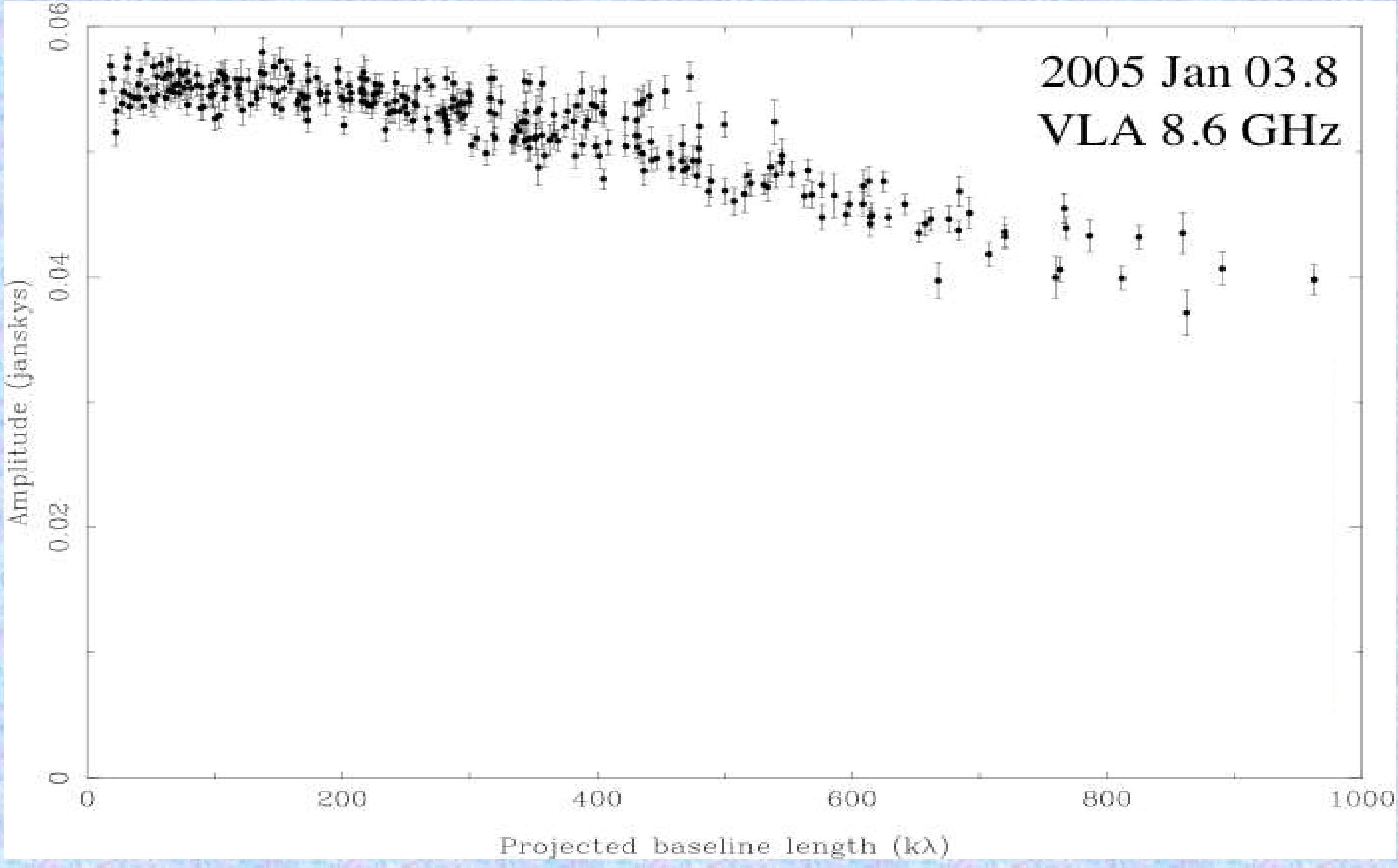
- VLA observed SGR 1806-20 in "A" array on day 7 (Gaensler et al. 2005; Cameron et al. 2005)
  - 0.17 Jy at 1.4 GHz! (recall 0.5 mJy for SGR 1900+14 in 1998)
  - already optically thin at first epoch $\rightarrow n_0 < 0.1$ cm^{-3}
  - multi-wavelength / multi-telescope campaign activated
  - chromatic decay until day 9, then break to $S \propto t^{-2.7} \nu^{-0.75}$
  - rebrightening from days 25 to 35
  - $S \propto t^{-1.1}$ from day 35 onwards
  - potentially observable until 2020!



Gelfand et al. (2005)

Source Structure

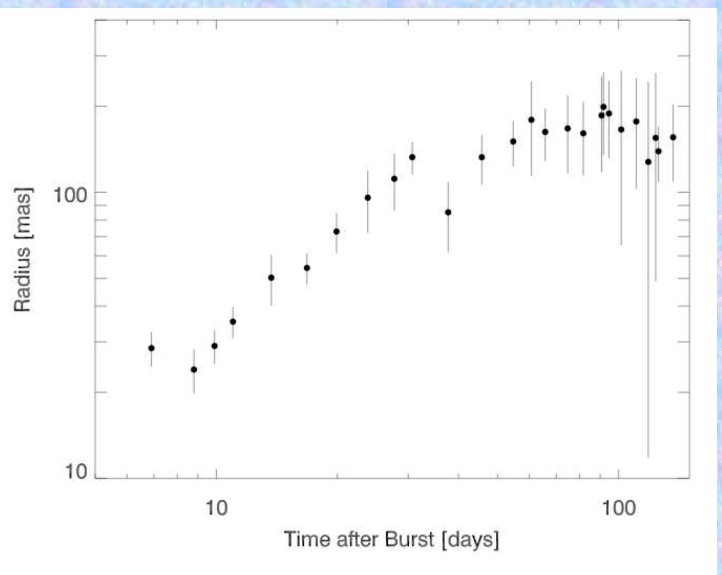
- Source is resolved and elongated : (Gaensler et al. 2005)
  - 79 mas x 41 mas at PA -58^{o} on day 7
  - implies two-sided expansion of 0.49c x 0.26c at distance of 15 kpc
  - ~2% linearly polarized; *B* vectors at -60^{0} after Faraday correction



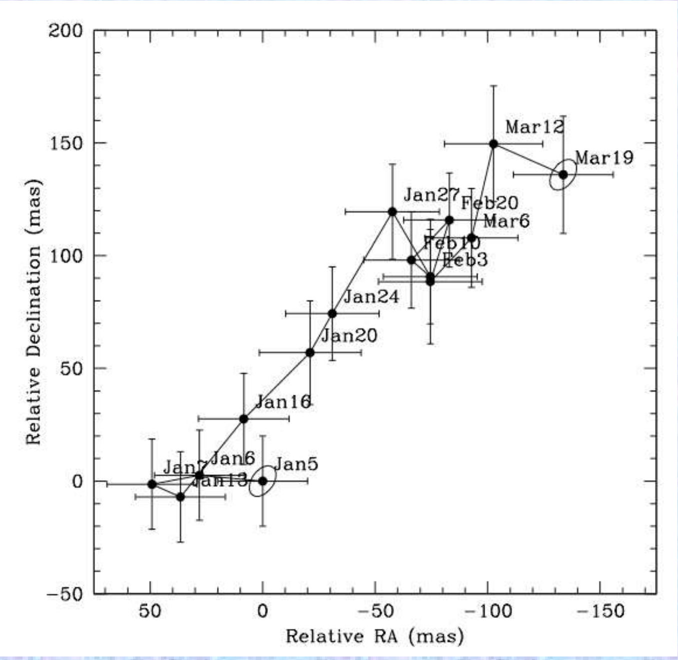
Gaensler et al. (2005)

Source Expansion & Motion

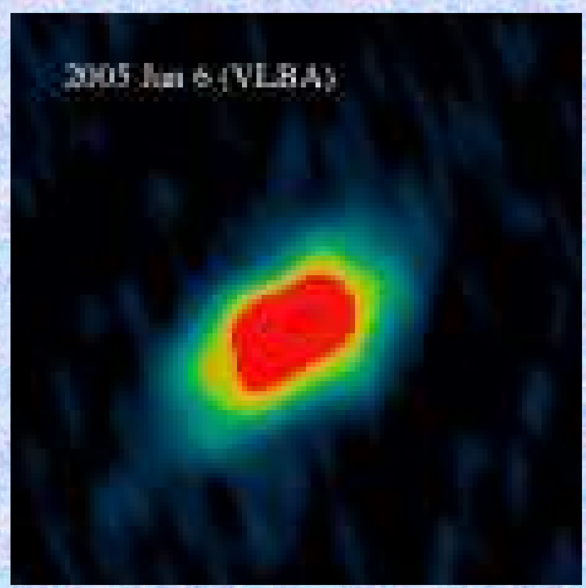
- Expanded steadily at β=0.4 (2-sided) for 30 days, maintaining axial ratio and position angle
  - confirmed by VLBI observations
- Centroid moving at β=0.26 along elongation direction
- Decelerated to β < 0.2 around time light curve rebrightened



Gelfand et al. (2005)



Taylor et al. (2005)



Fender et al. (2005)

Basic Interpretation

- γ-ray spike is not beamed (?)
- Equipartition : $E_{nebula} \approx 10^{44}$ ergs << E_γ
- Rapid decay from day 9-20, $S \propto t^{-2.7}$
- Mildly relativistic expansion

} unlike GRB afterglows (Cameron et al. 2005; Gaensler et al. 2005)

- After annihilation, E_{pairs} << E_{nebula}
- Prolonged coasting phase indicates ejecta have inertia
- >10^{46} ergs released in & around crust will unbind outer layers of NS at V_{escape} ~ 0.5c

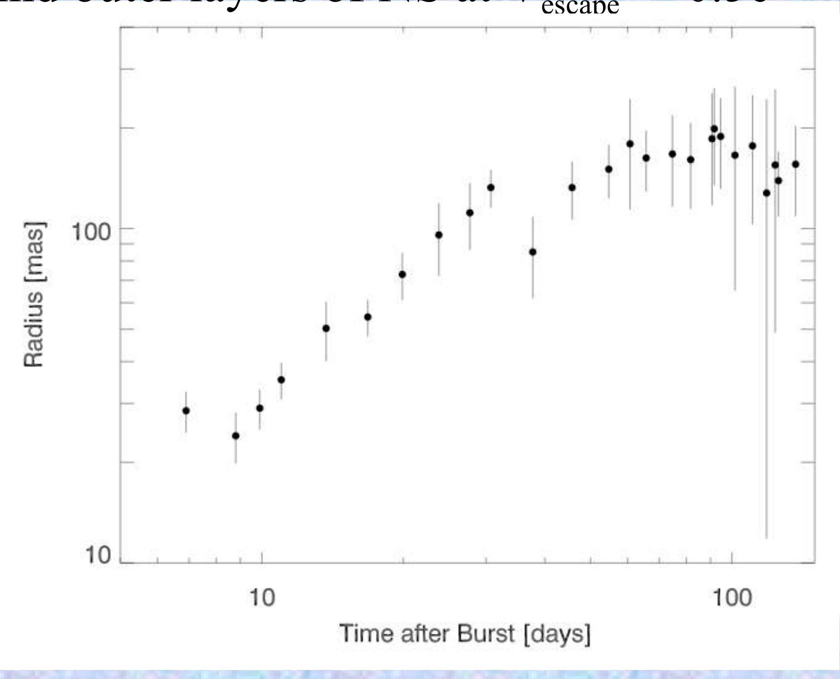
⇒ baryonic ejection of material shocks surroundings, & powers radio nebula (Gaensler et al. 2005; Granot et al. 2005)

- Rapid decay: collision with pre-existing shell, which then emits & expands
- Rebrightening & deceleration: Sedov phase; swept-up ambient gas now dominates

⇒ $M_{ejected} > 3 \times 10^{24}$ g $= 10^{-9} M_{NS}$

⇒ $E_{kinetic} > 3 \times 10^{44}$ ergs

(Gelfand et al. 2005)



Gelfand et al. (2005)

Further Considerations

- Pre-existing shell
  - bow shock? (Gaensler et al. 2005)
  - shock driven by flare? (Granot et al. 2005)
  - data at t < 7 days are needed! (Fan et al. 2005)

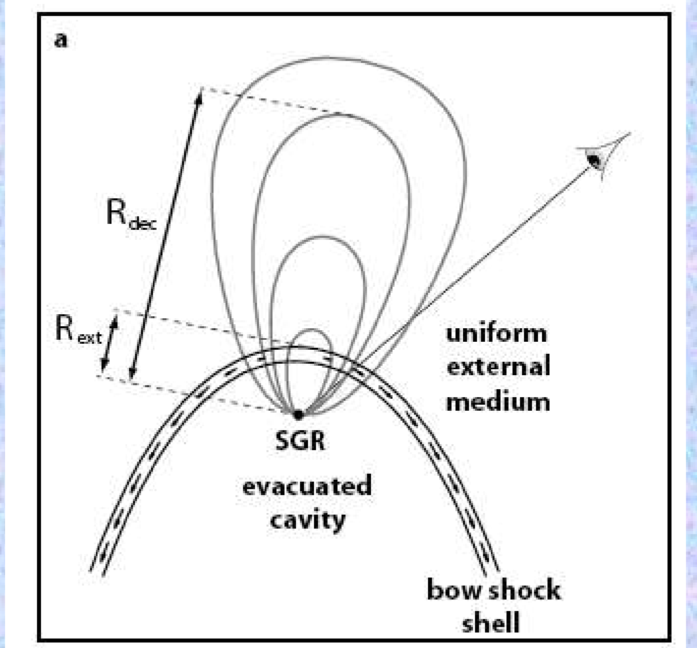
- Motion of centroid implies outflow was anisotropic (Taylor et al. 2005; Granot et al. 2005)
  - hemispherical outflow? wide jet?
  - for outer edge of source expanding at β,

    $\Gamma\beta = \beta_{apparent} \approx 1.0 \rightarrow \beta \approx 0.7$

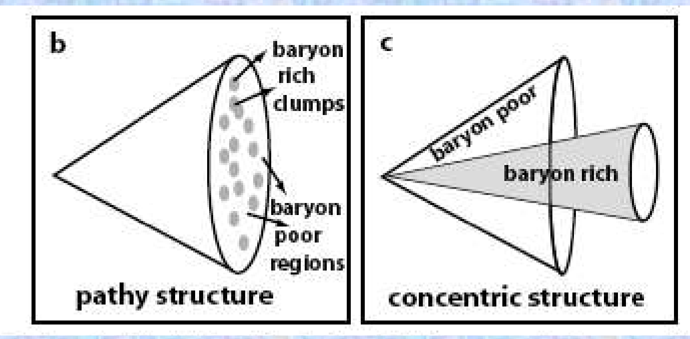
  $\rightarrow M_{ejected} > 9 \times 10^{24}$ g , $E_{kinetic} > 7 \times 10^{44}$ ergs

- Compactness (Gelfand et al. 2005; Granot et al. 2005)
  - patchy ejecta, or concentric structures
  - low baryon content along line of sight

- Late time features in light curve
  - continued activity from SGR 1806-20?



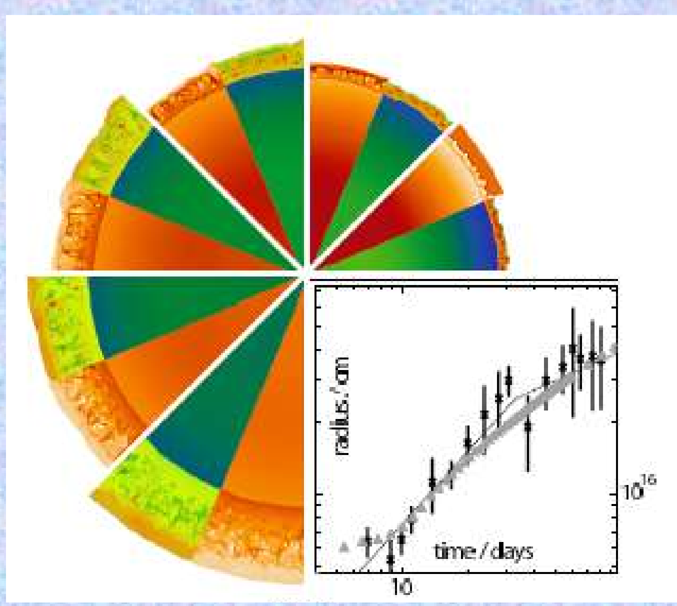
Granot et al. (2005)



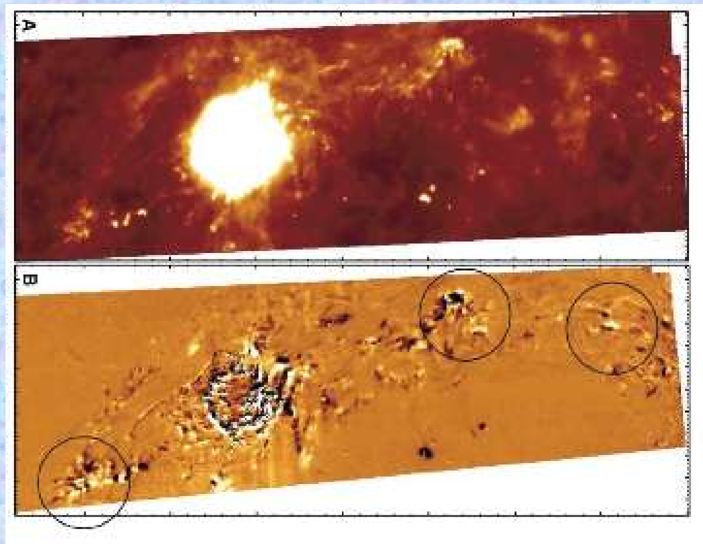
Granot et al. (2005)

Future Work, Questions, Conclusions

- Best observation had $\theta_{nebula} \approx 0.5 \times \theta_{VLA}$
  - "A" array in 2006 will give $\theta_{nebula} > 3 \times \theta_{VLA}$
  - X-ray nebula with *Chandra*
- MHD simulations now underway
- No gravity waves seen, but neutrinos, cosmic rays potentially detectable (Baggio et al. 2005; Eichler 2005)
- How often do magnetars flare? Light echoes from previous flares?
- Initial spike could be detected with *Swift* out to 70 Mpc, tail to 10 Mpc
  - 1% - 20% of short GRBs are extragalactic magnetars? (Hurley et al. 2005; Palmer et al. 2005; Nakar et al. 2005; Lazzati et al. 2005)
- Unique probe of mildly relativistic outflows, magnetic energy release, and neutron star interiors



Ramirez-Ruiz et al. (2005)



Krause et al. (2005)