SOFT GAMMA REPEATERS AND MAGNETARS

Kevin Hurley
UC Berkeley
Space Sciences Laboratory
khurley@ssl.berkeley.edu

SHORT HISTORY

- **January 7, 1979: a soft γ-ray burst was detected from the Galactic center region**
- **March 5, 1979: a hard, intense γ-ray burst was detected from the N49 SNR in the LMC (55 kpc); >1000 times Eddington luminosity. It was followed by weaker bursts. Many exotic theories proposed**
- **March 24-27, 1979: a repeating soft burst source discovered when it emitted 3 bursts**
- **July-December, 1983: another repeating soft burst source discovered; same source as the January 7 1979 one. Called an SGR (soft gamma repeater) because it was in Sagittarius, and to distinguish it from gamma-ray bursts**

- **Duncan, R., and Thompson, C., Formation of Very Strongly Magnetized Neutron Stars: Implications for Gamma-Ray Bursts, Ap. J. Lett. 392, L9, 1992**

- **Paczyński, B., GB 790305 as a Very Strongly Magnetized Neutron Star, Acta Astronomica 42, 145, 1992**

- **Thompson, C., and Duncan, R., The Soft Gamma Repeaters as Very Strongly Magnetized Neutron Stars. I. Radiative Mechanism for Outbursts, Mon. Not. R. Astron. Soc. 275, 255, 1995. The word "magnetar" was used to describe these neutron stars**

- **Large magnetic field**
  - **Confines e^-e^+ pair plasma**
  - **Suppresses Compton scattering of outgoing radiation from neutron star so it greatly exceeds the Eddington limit, without beaming**

MAGNETARS

- ***Definition:*** **a neutron star in which the magnetic field, rather than rotation, provides the main source of free energy; the decaying field powers electromagnetic radiation (R. Duncan & C. Thompson, 1992; C. Thompson & R. Duncan, 1995, 1996)**

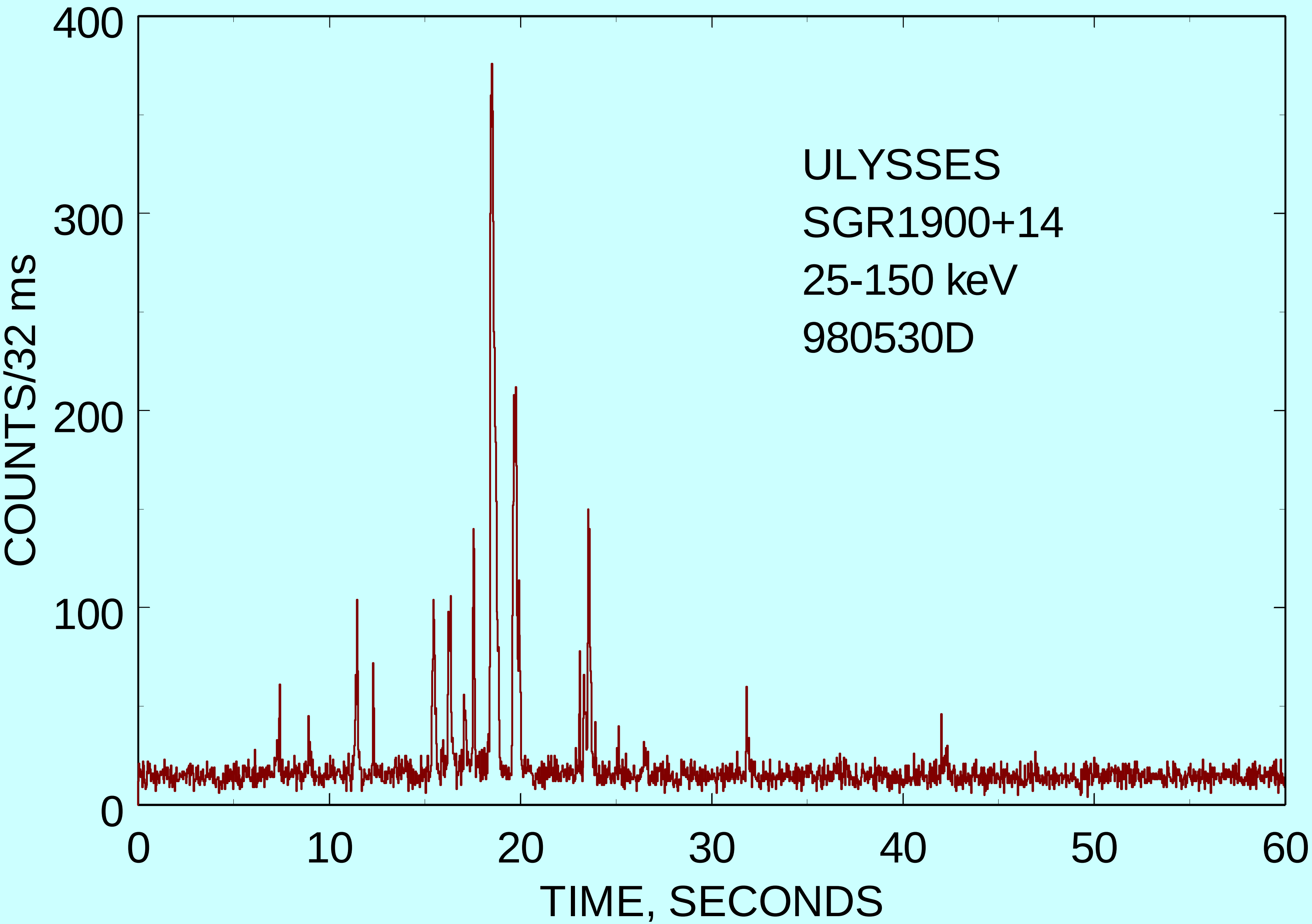
- **We know of several possible manifestations of magnetars; soft gamma repeaters are one**

- **With B~10^{15} Gauss, magnetars have the strongest cosmic magnetic fields that we know of in the universe**

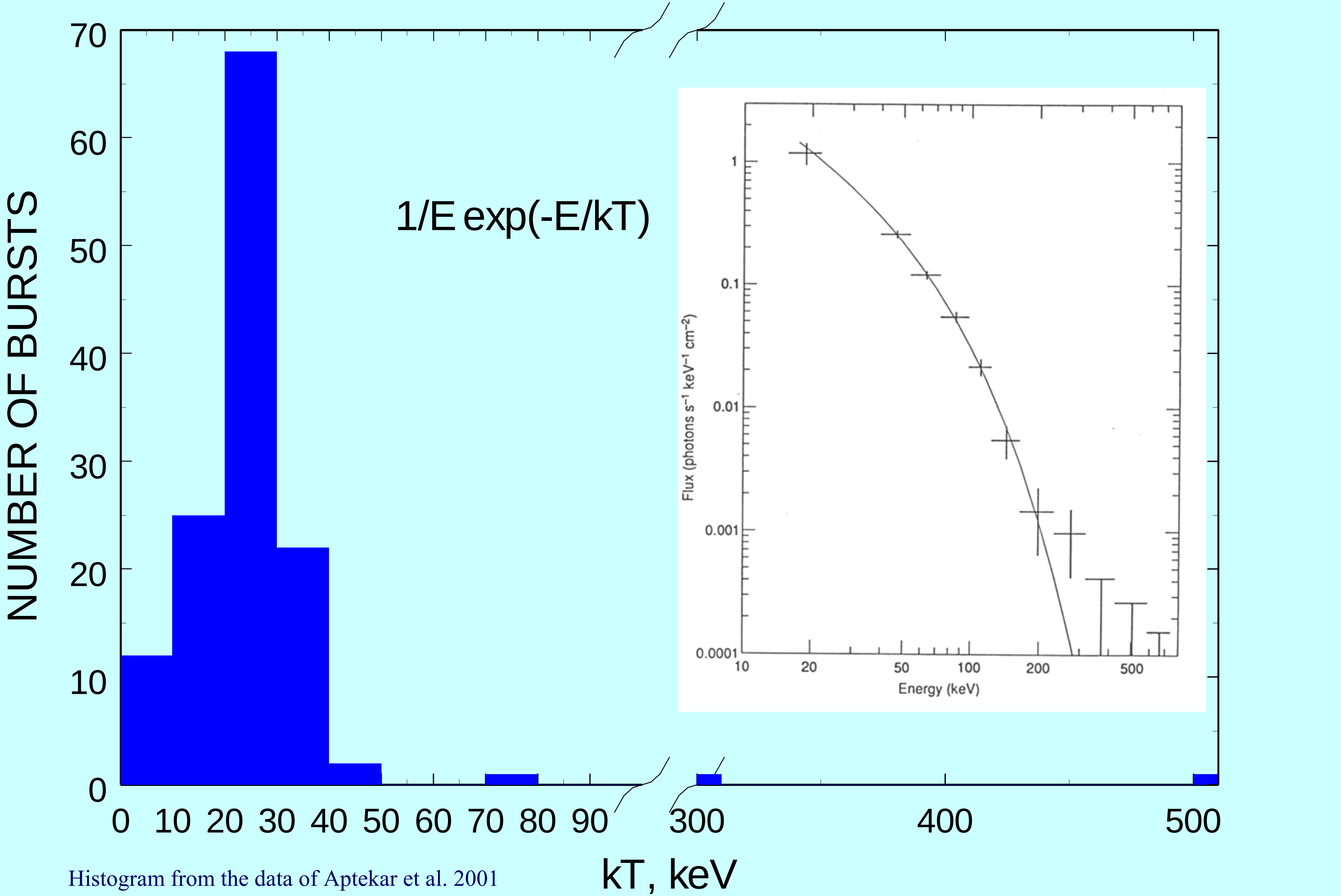
THE BASIC FACTS

- **SGRs are sources of short (~100 ms), repeating bursts of soft γ-radiation (<100 keV)**

SHORT, REPEATING BURSTS



SGR ENERGY SPECTRA ARE TYPICALLY CHARACTERIZED BY kT≈25 keV FOR THE SHORT BURSTS



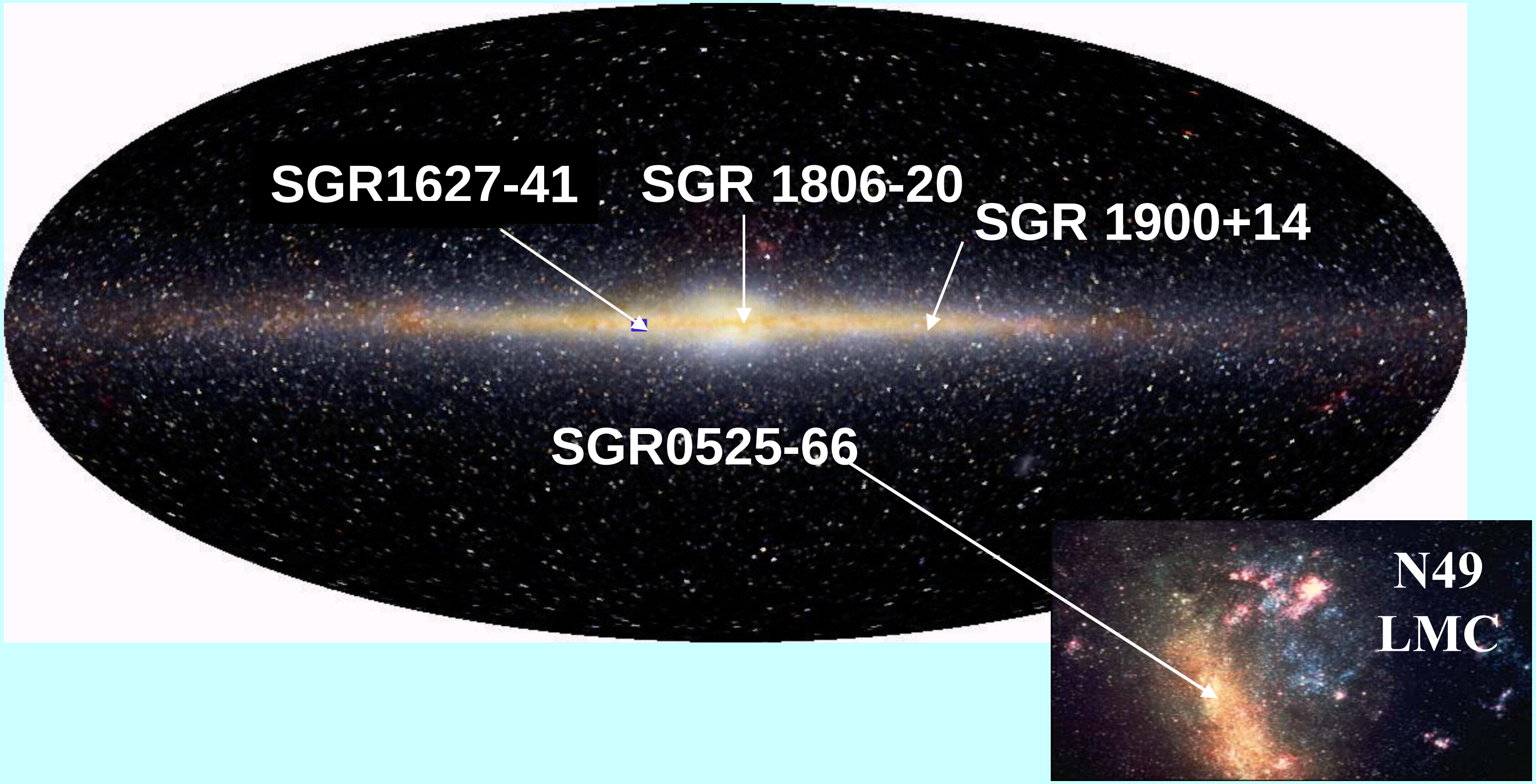
Histogram from the data of Aptekar et al. 2001

THE BASIC FACTS

- SGRs are sources of short (~100 ms), repeating bursts of soft γ-radiation (<100 keV)

- 4 are known
  - 3 in our galaxy (SGR1806-20, 1900+14, 1627-41)
  - 1 in the direction of the Large Magellanic Cloud (SGR0525-66)

LOCATIONS OF THE FOUR KNOWN SGRS



⇒ **Magnetars are young objects**

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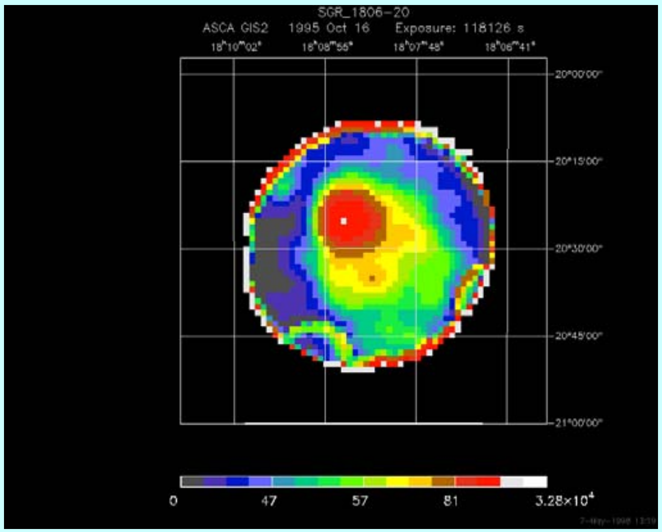
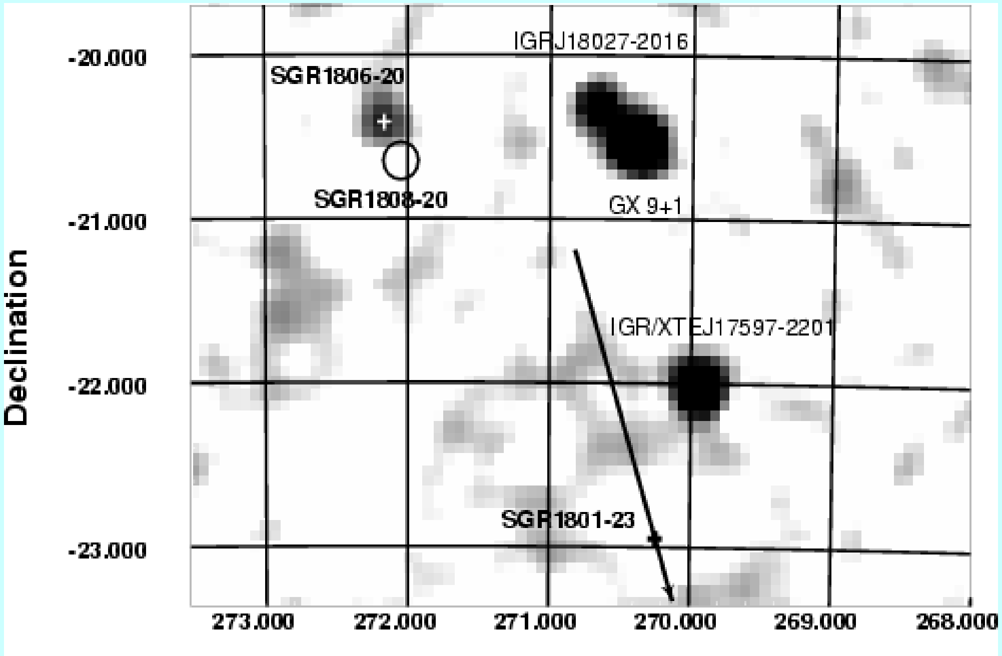
- **They are quiescent X-ray sources (2-150 keV)**

QUIESCENT X-RAY SOURCE ASSOCIATED WITH SGR1806-20





ASCA, 2-10 keV

10^{-11} erg cm^{-2} s^{-1}

INTEGRAL-IBIS, 18-60 keV

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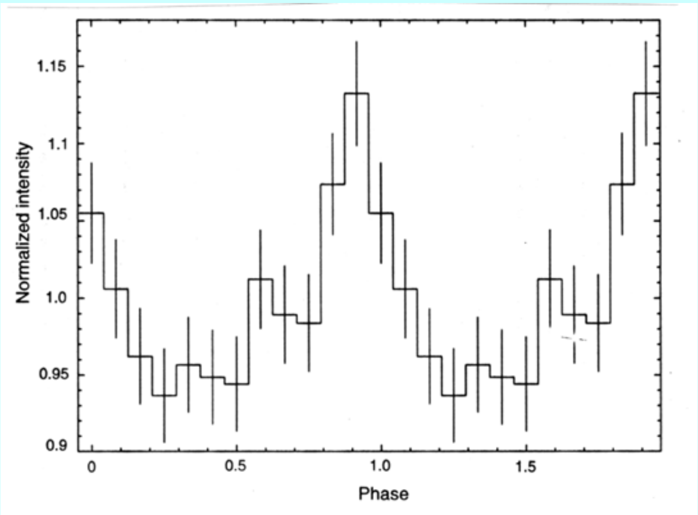
  - 1 in the direction of the Large Magellanic Cloud (SGR0525-66)

- They are quiescent X-ray sources (2-150 keV)

- **They have rotation periods in the 5-8 s range, which are increasing with time**

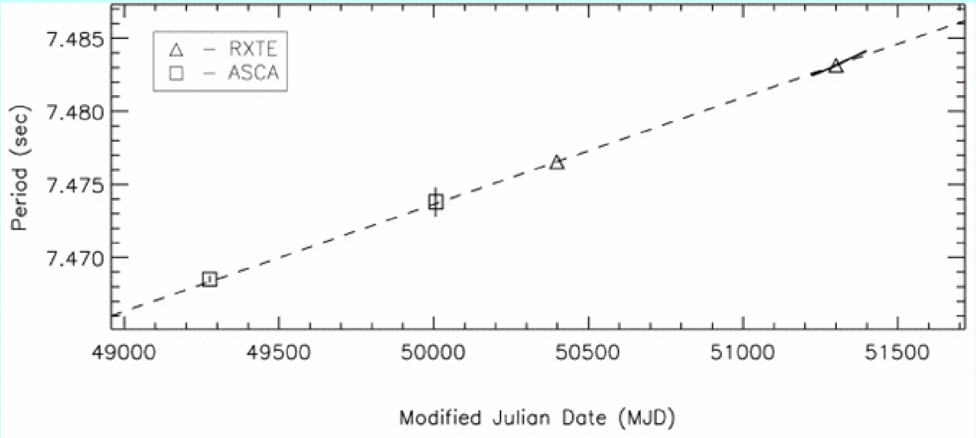
THE PERIOD OF SGR1806-20 AND ITS DERIVATIVE FROM QUIESCENT SOFT X-RAYS (2-10 keV)



P=7.47 s

Kouveliotou et al. 1998

6.8 years



$\dot{P} \sim 10^{-10}$ s/s

High spindown rate ⇒ Large magnetic field

Woods et al. 2000

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- They are quiescent X-ray sources (2-150 keV)

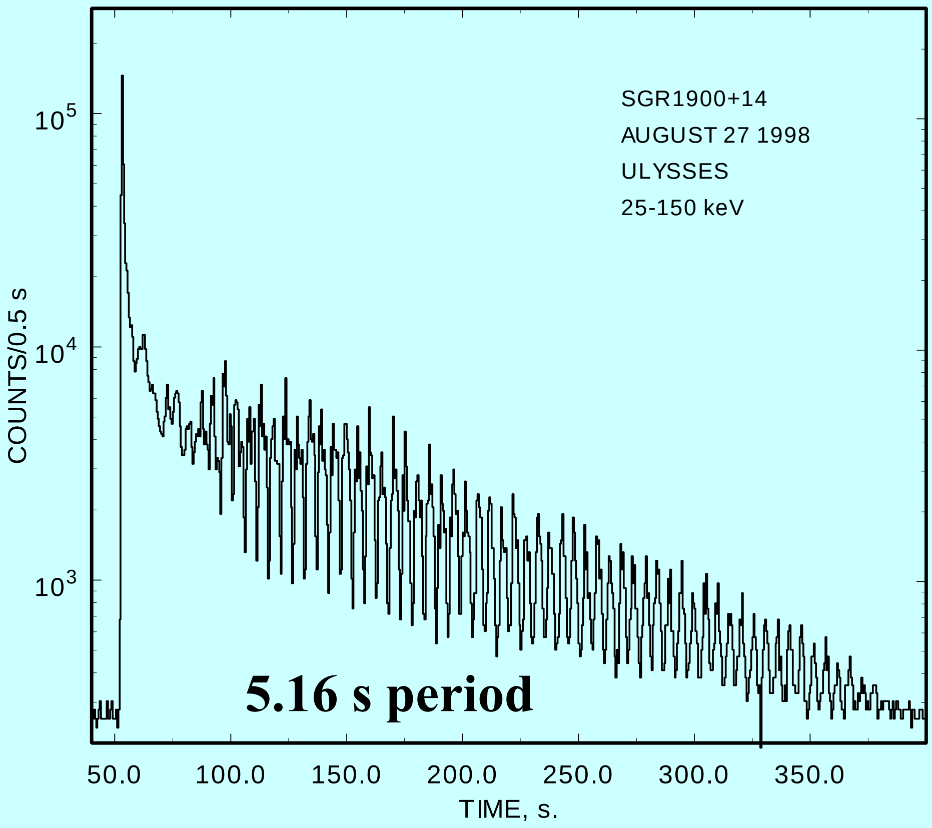
- They have rotation periods in the 5-8 s range, which are increasing with time

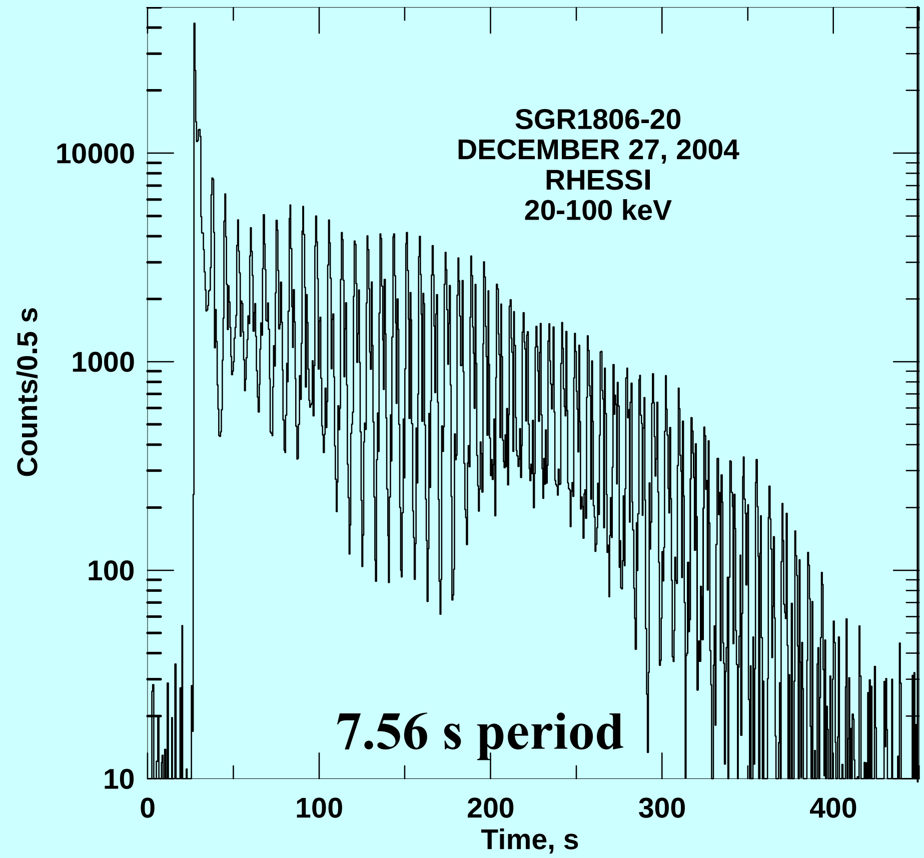
- **Occasionally they emit long *giant flares*, which produce the most intense cosmic gamma-ray fluxes ever measured at Earth (3 observed so far)**

GIANT SGR FLARES ARE SPECTACULAR!

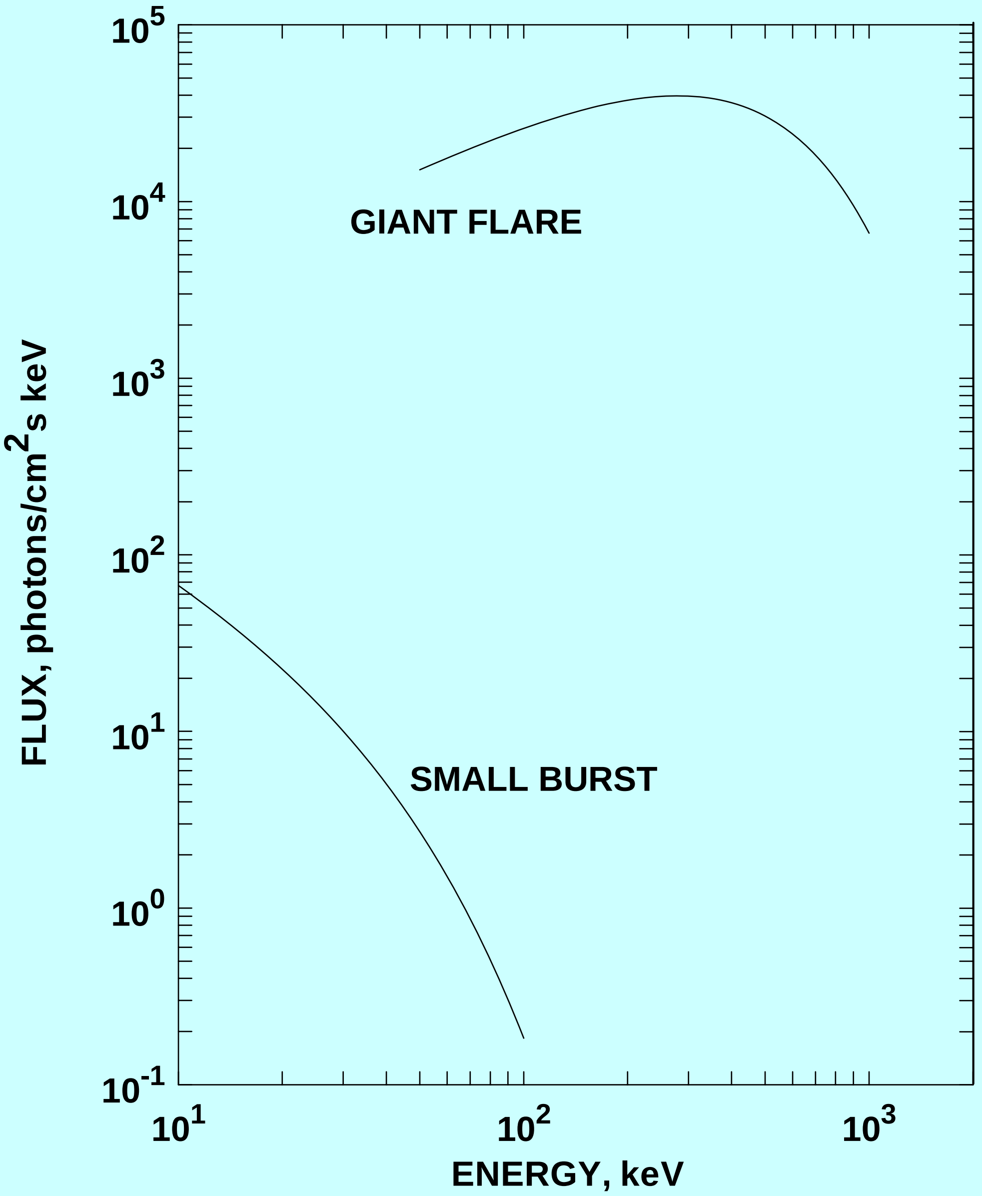
- Occur perhaps every 30 years on a given SGR
- Intense ($3x10^{46}$ erg at the source, 1 erg/cm^2 at Earth), ~5 minute long bursts of X- and gamma-rays with very hard energy spectra (up to several MeV at least)
- Are modulated with the neutron star periodicity
- Create transient radio nebulae, dramatic ionospheric disturbances

TWO GIANT FLARES



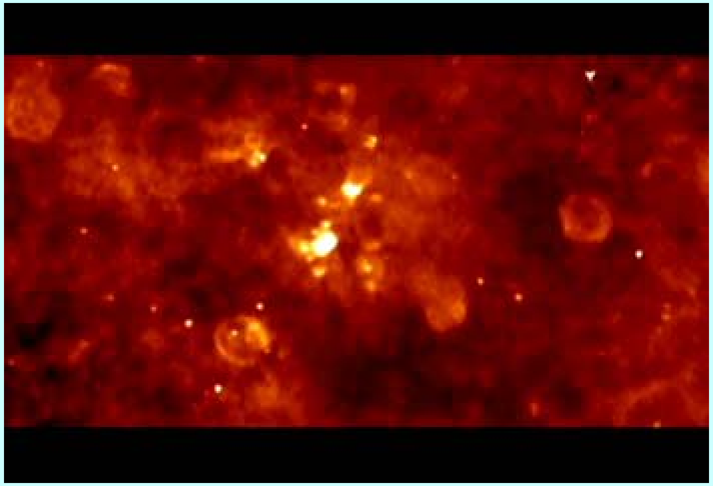


Three phases: 1) fast rise (<1ms), 2) very intense initial spike (~100 ms), 3) periodic decay (~300 s)



FLUX, photons/cm2s keV
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
GIANT FLARE
SMALL BURST
10^1
10^2
10^3
ENERGY, keV

TRANSIENT RADIO NEBULA CREATED BY GIANT FLARE FROM SGR1806-20 (Taylor et al. 2005)

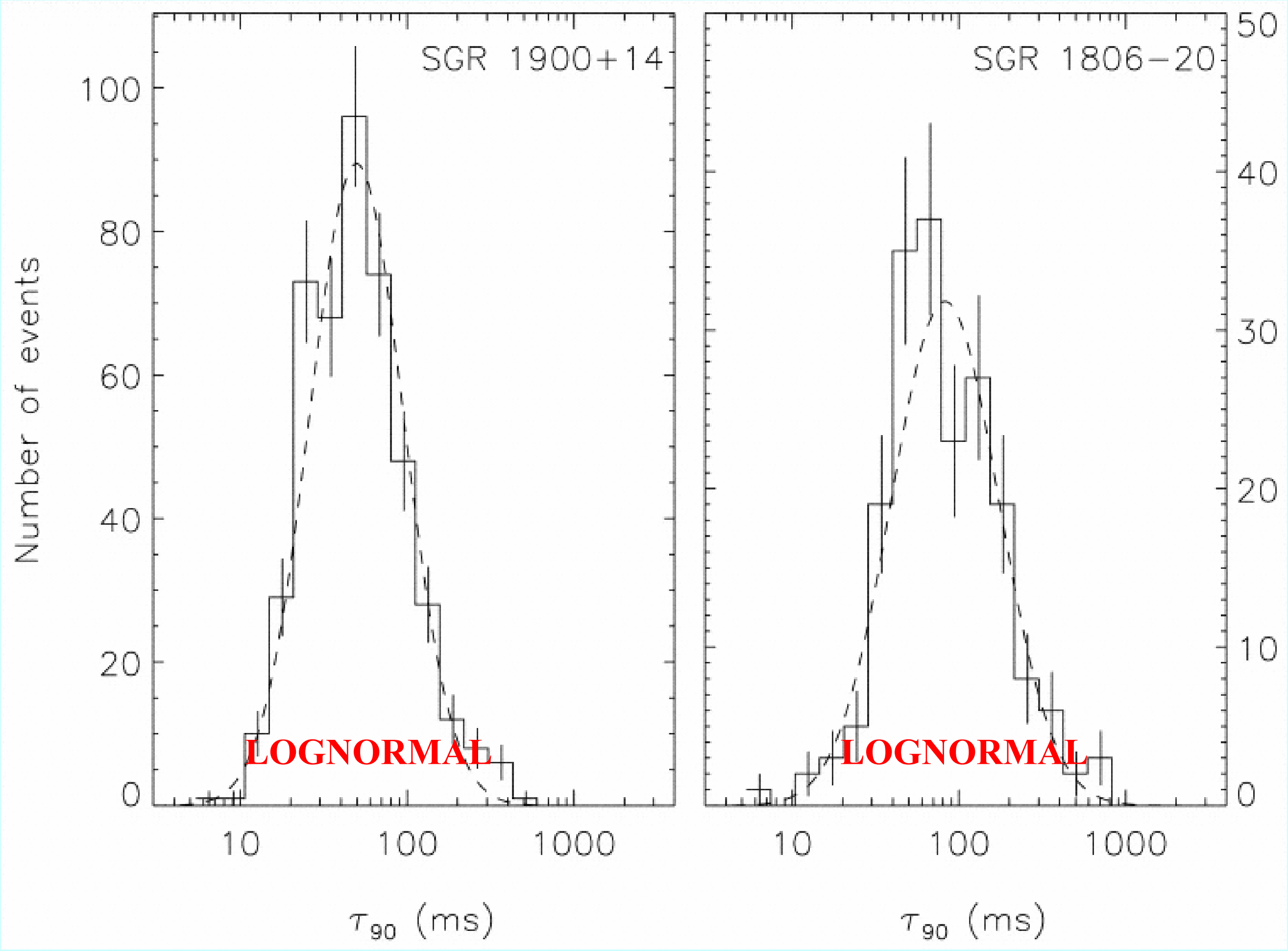


VLA

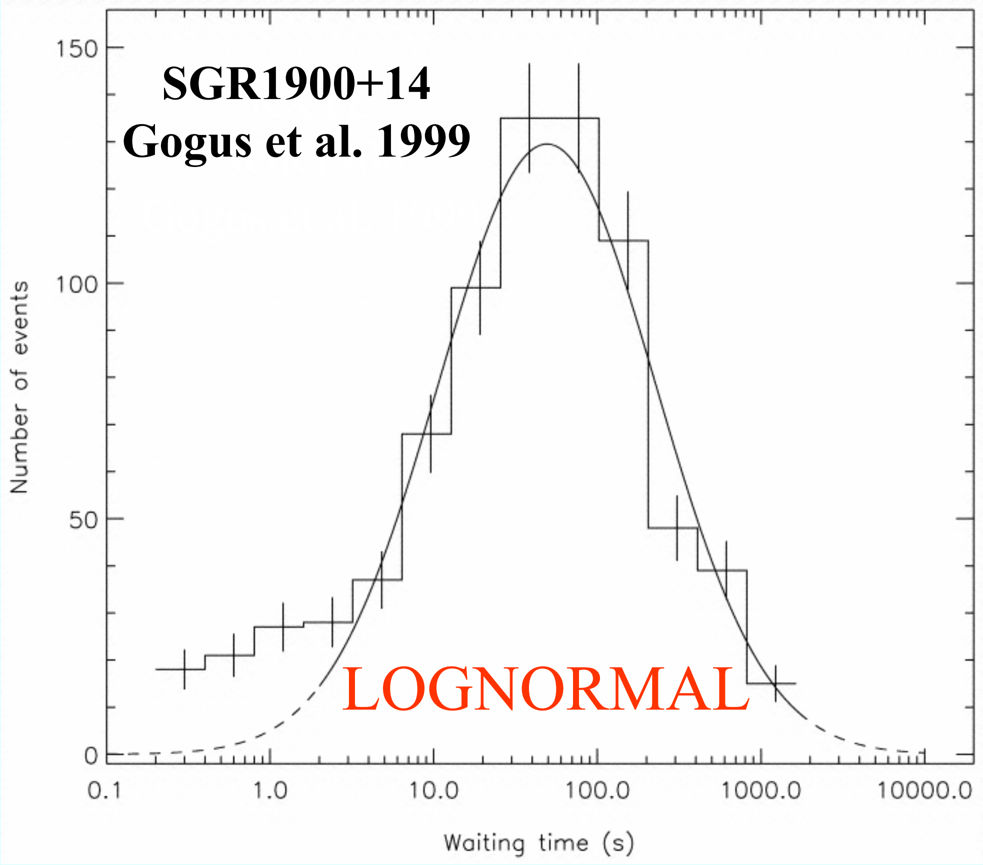
SOME DETAILS

- **STATISTICS**
- **LINE FEATURES IN ENERGY SPECTRA**
- **BURST ACTIVITY AND ITS RELATION TO OTHER PROPERTIES**
- **COUNTERPARTS**
- **3 MYSTERY OBJECTS WHICH MAY BE SGRs**

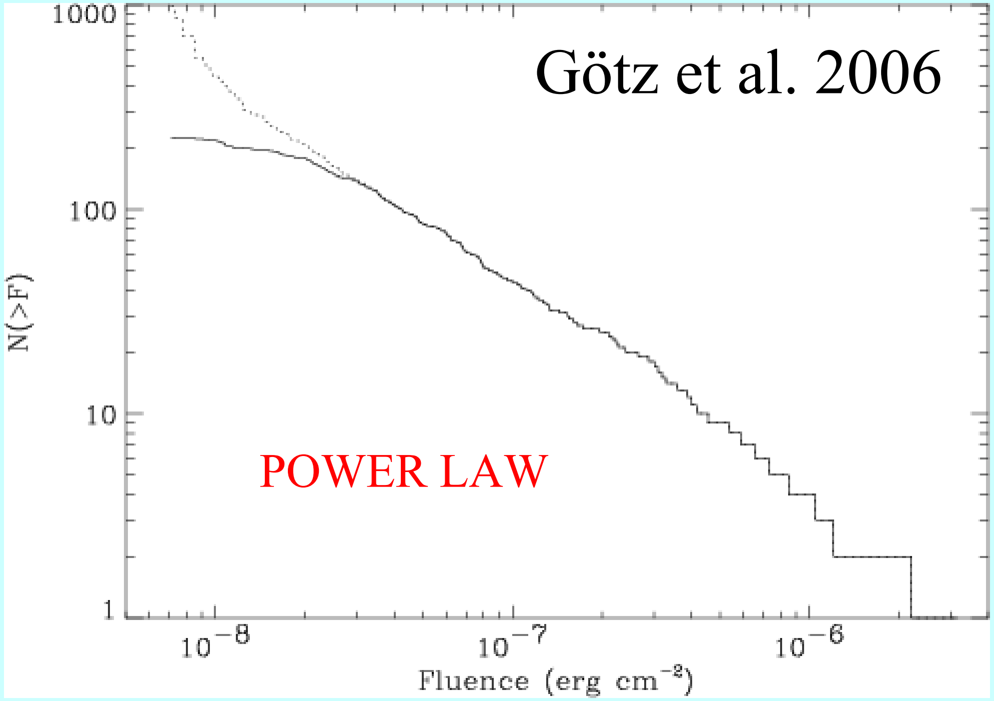
STATISTICS
DURATIONS OF SHORT BURSTS FOLLOW A LOGNORMAL DISTRIBUTION (Gogus et al. 2001)



STATISTICS
WAITING TIME DISTRIBUTION



STATISTICS
NUMBER-INTENSITY DISTRIBUTION



STATISTICS
DISTRIBUTIONS OF SGR PROPERTIES

- **Lognormal duration and waiting time distributions, and power law number-intensity distribution, are consistent with:**

- **Self-organized criticality (Gogus et al. 2000)**
  - **system (neutron star crust) evolves to a critical state due to a driving force (magnetic stress)**
  - **slight perturbation can cause a chain reaction of any size, leading to a short burst of arbitrary size (but not a giant flare)**

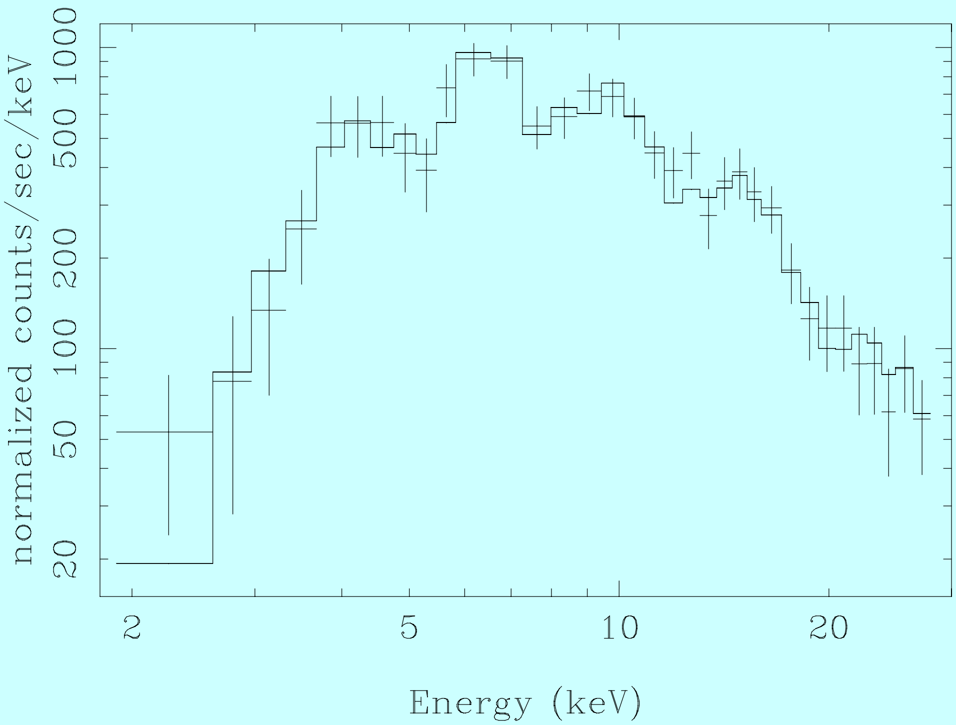
- **A set of independent relaxation systems (Palmer 1999)**
  - **Multiple, independent sites on the neutron star surface accumulate energy**
  - **Sudden releases of accumulated energy (short bursts)**

LINE FEATURES IN SGR1806-20 BURST SPECTRA (Ibrahim et al. 2002)

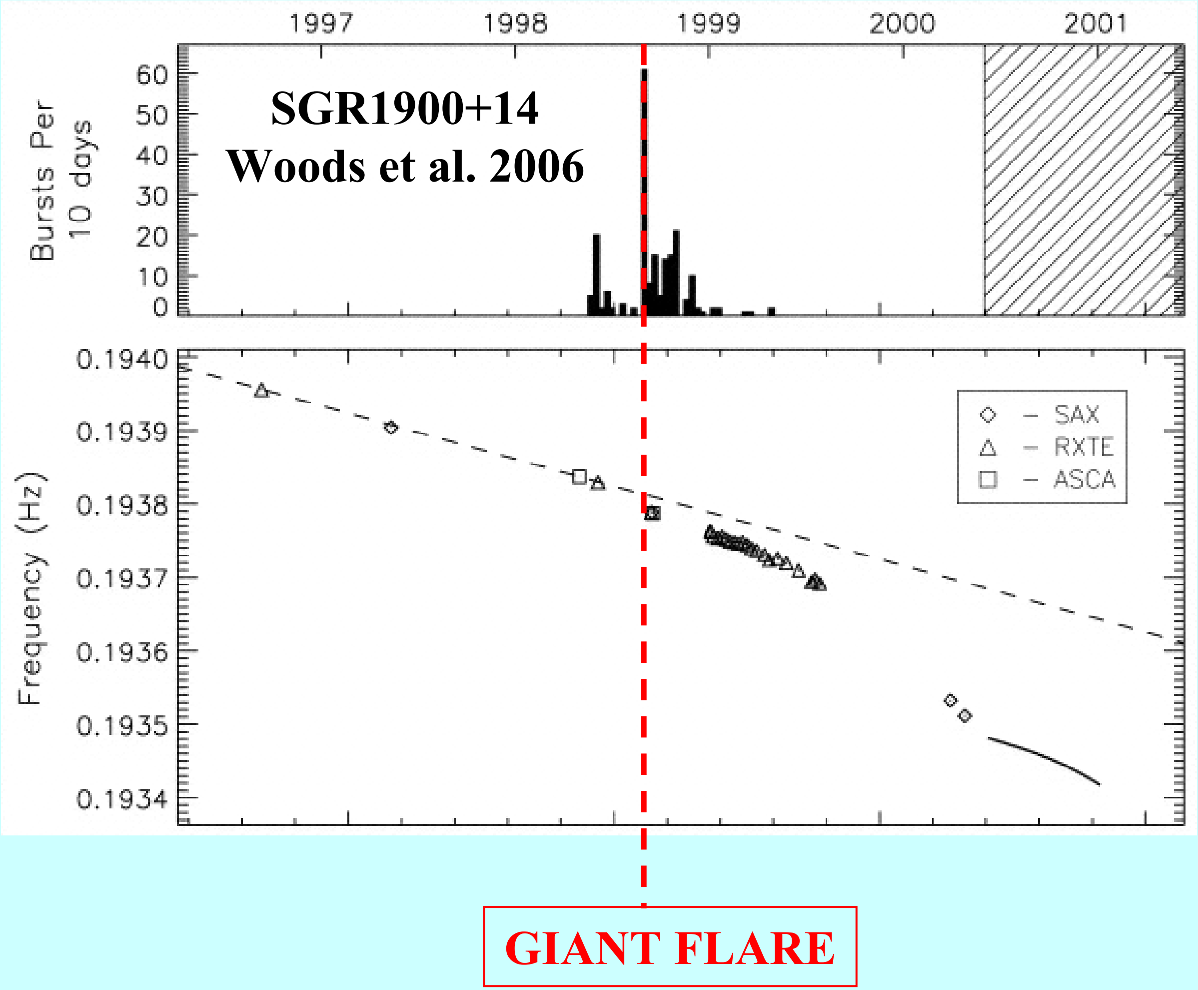
- **RXTE PCA spectra of ~6 bursts show evidence for one or more cyclotron features (~5, 11, and 17 keV)**

- **If electron cyclotron features, B~6x10^{11} G, but much greater line widths are expected due to thermal broadening**

- **If proton cyclotron features, B~8x10^{14} G**

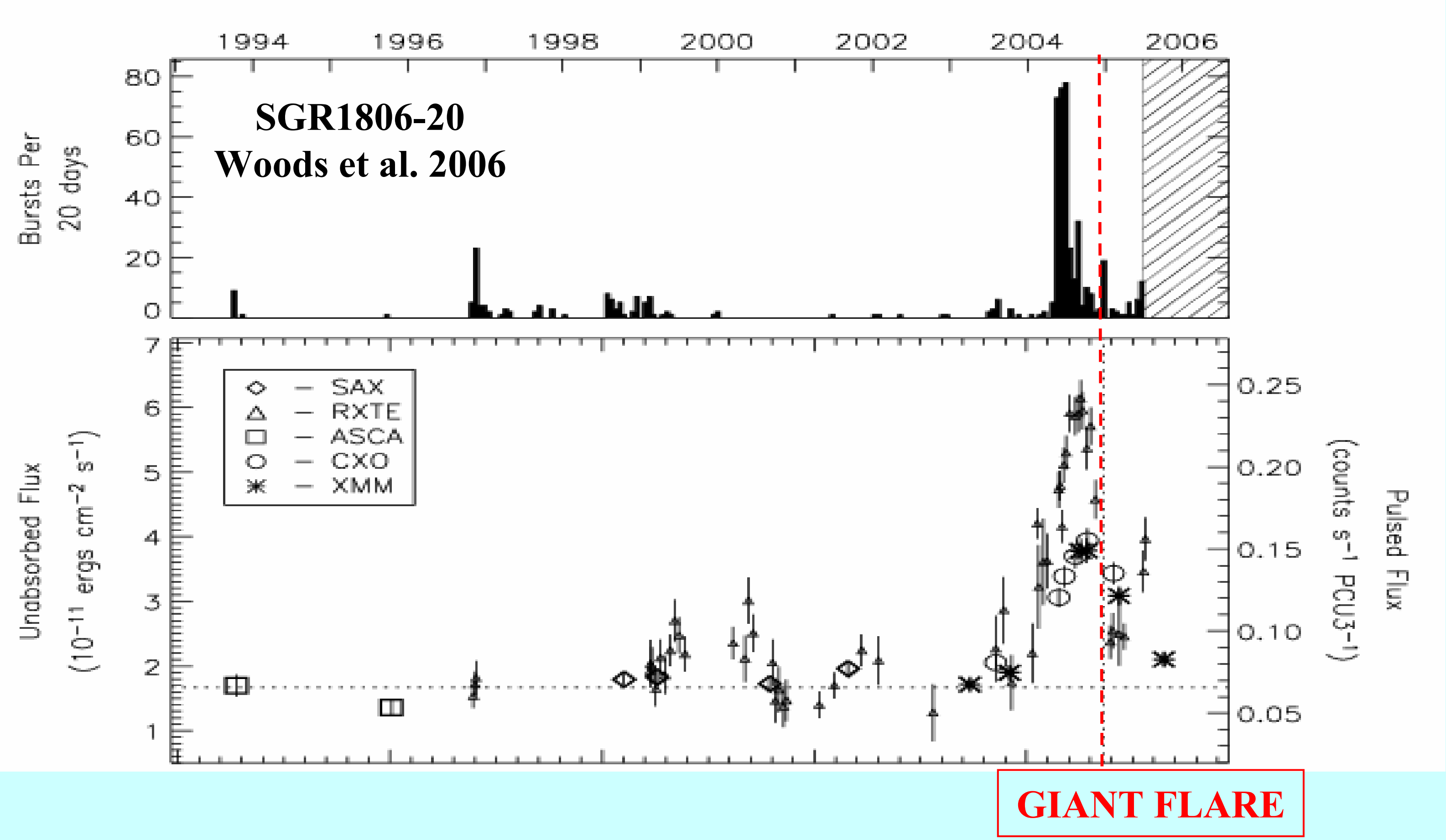


SPINDOWN IS IRREGULAR, BUT NOT RELATED TO BURSTING ACTIVITY (Woods et al. 2002, 2006)



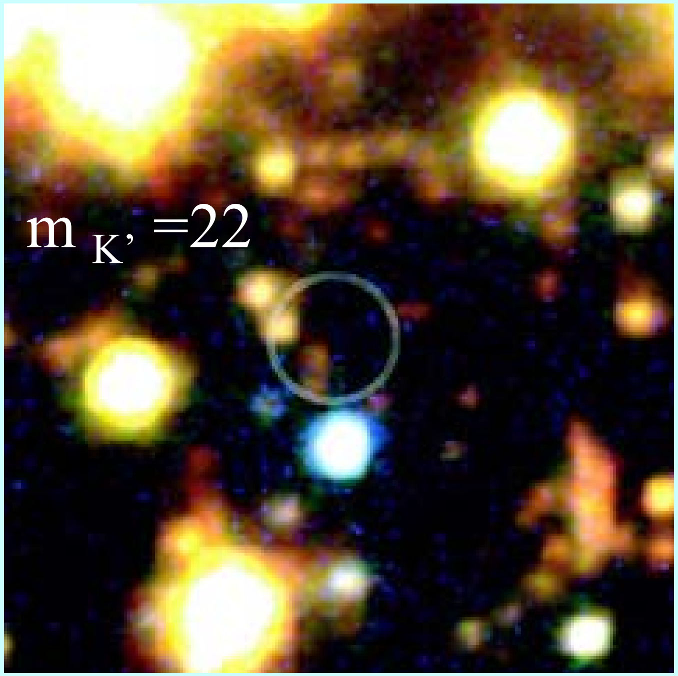
This argues against accretion as the cause of the bursts

QUIESCENT X-RAY FLUX LEVEL IS RELATED TO THE BURSTING ACTIVITY

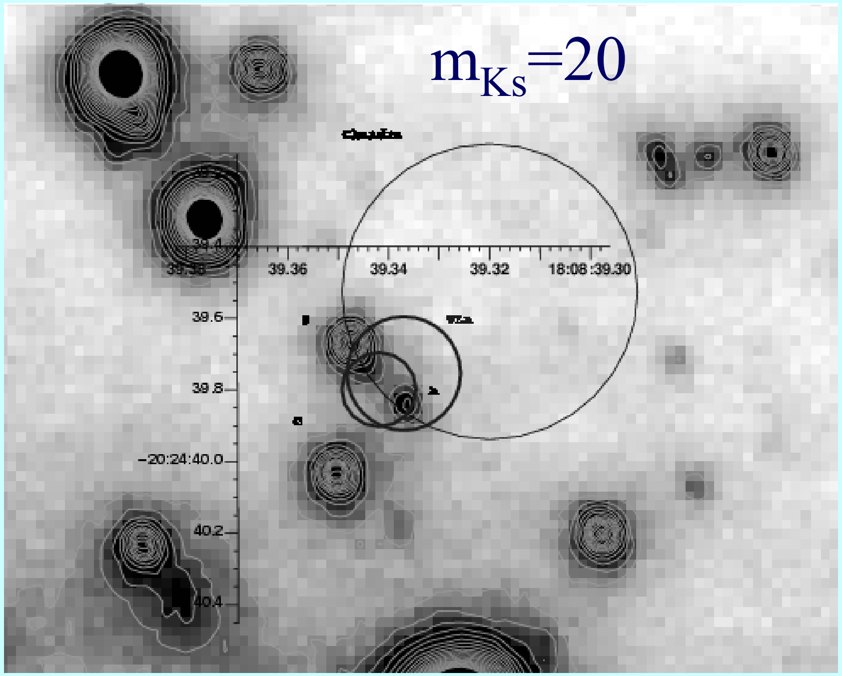


Reasons are probably complex, but related to magnetic stresses on the surface of the neutron star

SGR1806-20 IS INVISIBLE IN THE OPTICAL (n_H~$6x10^{22}$ cm^{-2}), BUT JUST BARELY VISIBLE IN THE INFRARED



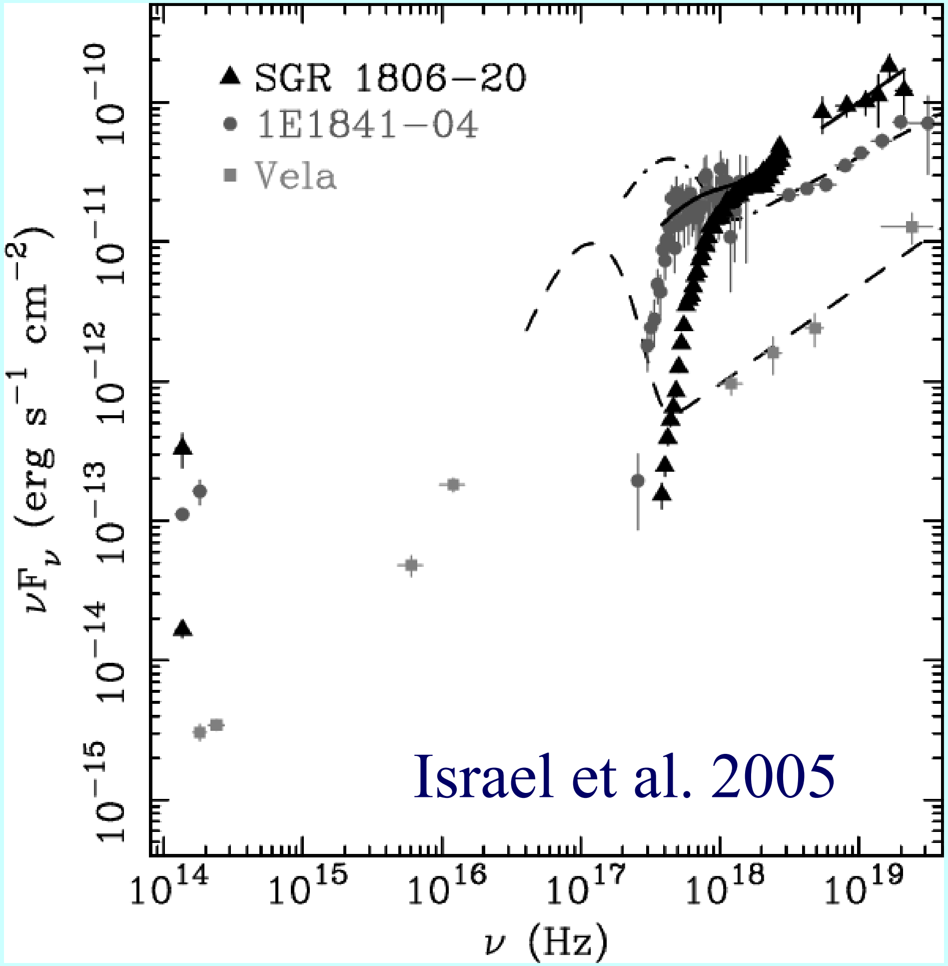
Kosugi et al. 2005



Israel et al. 2005

This is the only optical or IR counterpart to an SGR so far

IR FLUX IS NOT AN EXTRAPOLATION OF HIGH ENERGY QUIESCENT FLUX



- But the IR flux varies with the quiescent flux and/or with bursting activity

THREE MYSTERY OBJECTS – POSSIBLE SGRs

- **SGR1801-23?**
  - **Discovered by the interplanetary network**
  - **2 short bursts**
- **SGR1808-20?**
  - **Discovered by the HETE spacecraft**
  - **1 short burst**
- **GRB050925?**
  - **Discovered by Swift**
  - **1 short burst**

- **All lie in the Galactic plane and have soft energy spectra**

- **No quiescent X-ray source has been found for these possible SGRs**

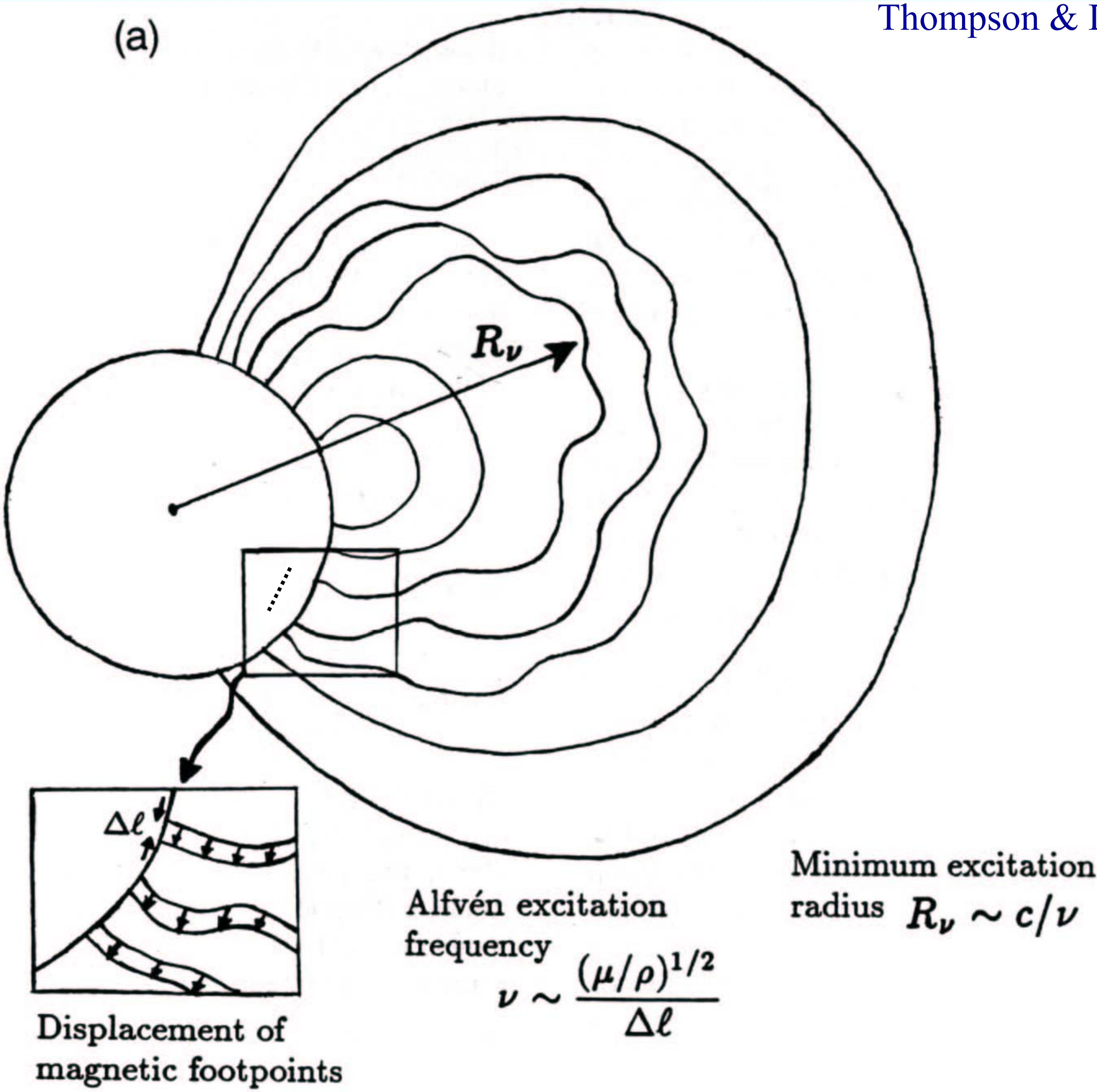
SGRs AND AXPs
OBSERVATIONAL PROPERTIES COMPARED

	SGRs	AXPs
Small Bursts	Frequent	Rare
Giant Flares	Yes	No
Quiescent X-rays	Yes	Yes
Periods	5.2 – 8 s	5.5 – 11.8 s
Spindown	$6.1 – 20 \times 10^{-11}$ s/s	$0.05 – 10 \times 10^{-11}$ s/s
Counterparts	Massive star clusters?	SNRs?

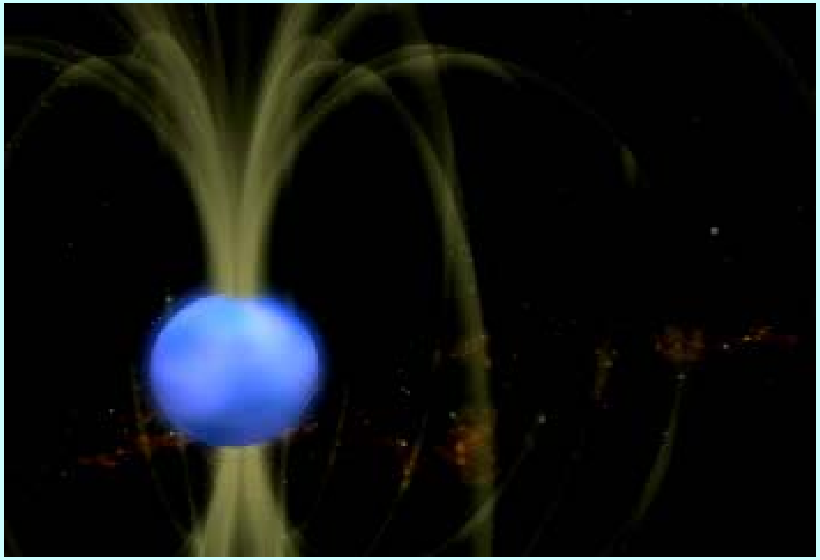
THE MAGNETAR MODEL (R. Duncan & C. Thompson)

- **In some rare supernova explosions, a neutron star is born with a fast rotation period (~ ms) and a dynamo which creates a strong magnetic field (up to 3×10^{17} G theoretically possible)**
- **Differential rotation and magnetic braking quickly slow the period down to the 5-10 s range**
- **Magnetic diffusion and dissipation create hot spots on the neutron star surface, which cause the star to be a quiescent, periodic X-ray source**
- **The strong magnetic field stresses the iron surface of the star, to which it is anchored**
- **The surface undergoes localized cracking, shaking the field lines and creating Alfvèn waves, which accelerate electrons to ~100 keV; they radiate their energy in short (100 ms) bursts with energies 10^{40} – 10^{41} erg (magnitude 19.5 crustquake)**

Thompson & Duncan 1995



- Localized cracking can’t relieve all the stress, which continues to build for decades
- The built-up stress ruptures the surface of the star profoundly – a magnitude 23.2 starquake
- Magnetic field lines annihilate, filling the magnetosphere with MeV electrons
- Initial spike in the giant flare is radiation from the entire magnetosphere ($>10^{14}$ G required to contain electrons)
- Periodic component comes from the surface of the neutron star



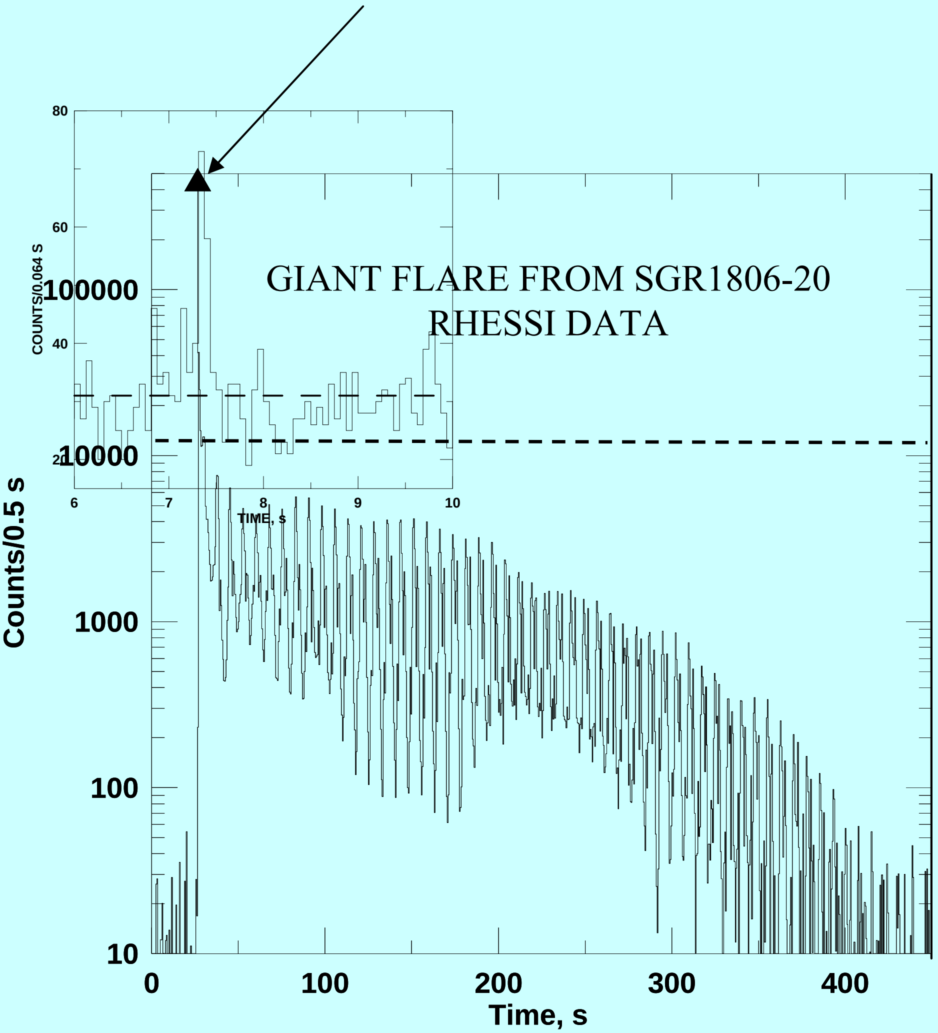
MAGNETAR MANIFESTATIONS

1. **Soft gamma repeaters: Galactic population 4 - 7**

2. **Anomalous X-ray pulsars: Galactic population ~7**

3. **Short-duration cosmic gamma-ray bursts in disguise: extragalactic population unknown**

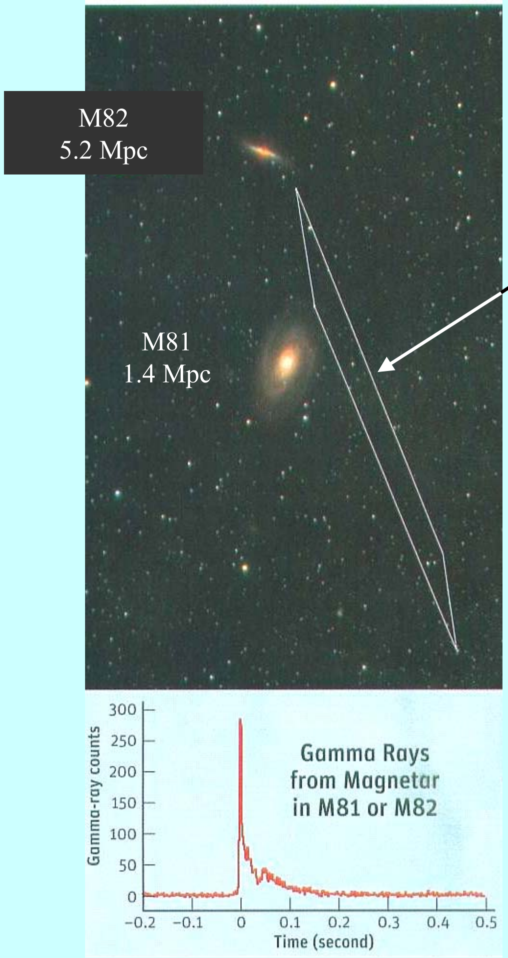
ARE SOME SHORT GRBs ACTUALLY MAGNETAR FLARES IN NEARBY GALAXIES?



- Giant flare begins with ~0.2 s long, hard spectrum spike
- The spike is followed by a pulsating tail with ~1/1000th of the energy
- Viewed from a large distance, only the initial spike would be visible
- It would resemble a short GRB
- It could be detected out to 100 Mpc
- Some short GRBs are almost certainly giant magnetar flares, but how many?

GRB051103 – A POSSIBLE GIANT MAGNETAR FLARE FROM M81

Sky & Telescope, February 2006



Interplanetary network error box

The magnetar would have to be in the halo!

OPEN QUESTIONS

- What are the distances of the Galactic magnetars?
  - Energetics
  - Relation between giant flares and short GRBs

- What is the number-intensity relation for giant magnetar flares?
  - Relation between giant flares and short GRBss

- What is the SGR birth rate?
  - How many are in our galaxy
  - Lifetimes

- What kind of supernova produces an SGR?

- What is the relation between SGRs and AXPs?
  - Does one evolve into the other, or are they separate manifestations of magnetars?
- How many other manifestations of magnetars are there?

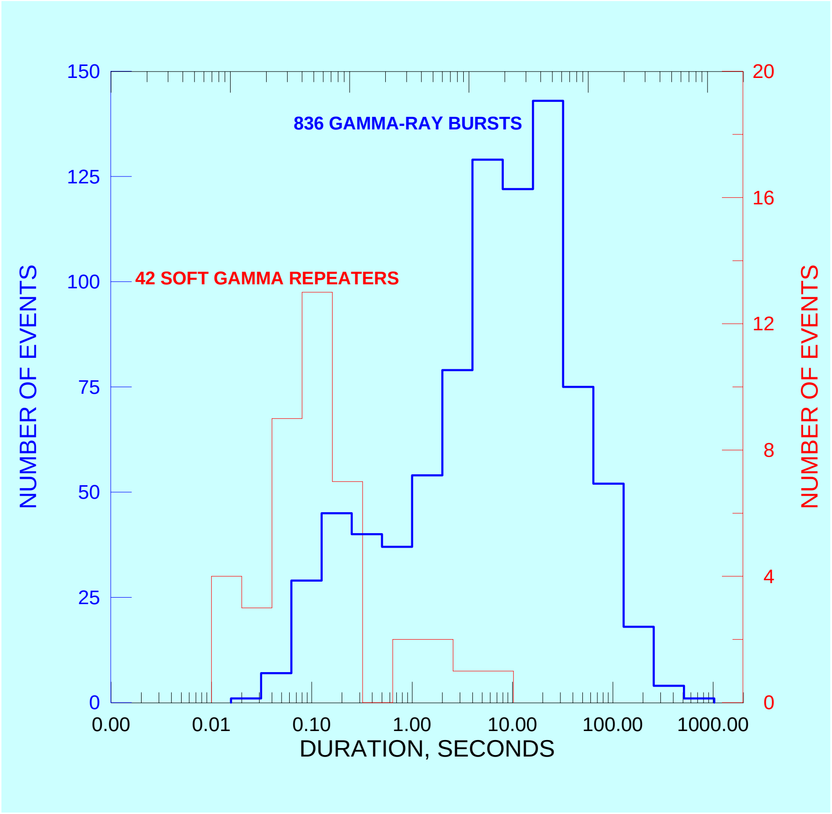
HOW TO ANSWER THEM

- More detailed theory
- More sensitive instruments
- 30 years of data

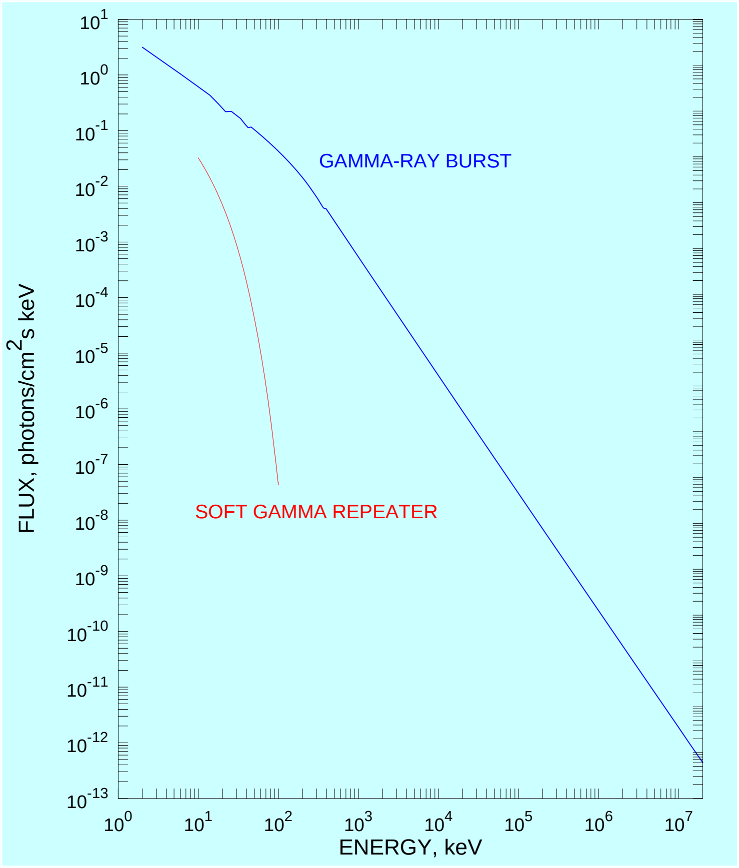
Kevin Hurley
UC Berkeley
Space Sciences Laboratory
khurley@ssl.berkeley.edu

SGRs AND GRBs COMPARED

DURATIONS

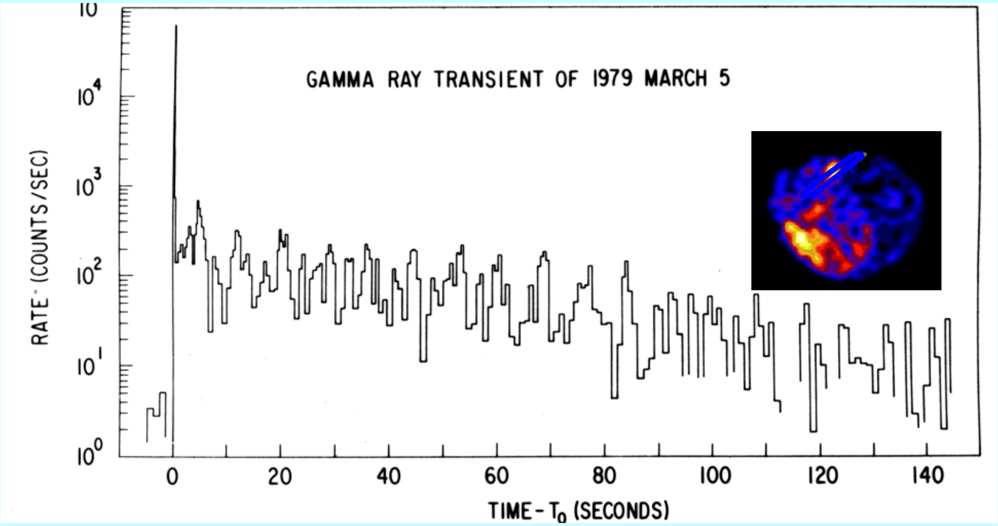


SPECTRA



MAGNETARS?

- In 1992, two papers appeared which attempted to explain the March 5 1979 event as a burst from a highly magnetized neutron star



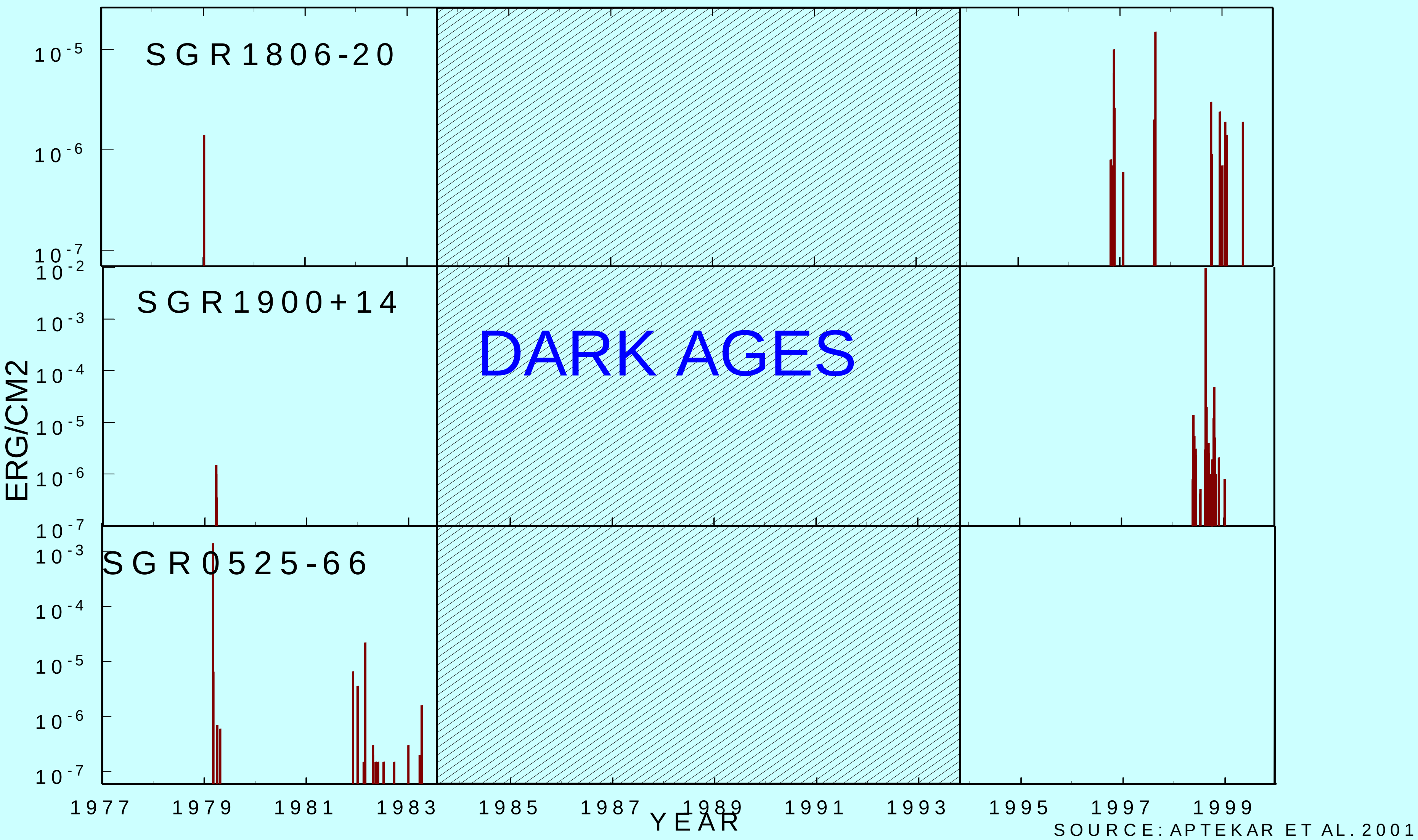
- Reasoning:

1 The age of the SNR (10^4 y) and the 8 s period gave ~$6x10^{14}$ G

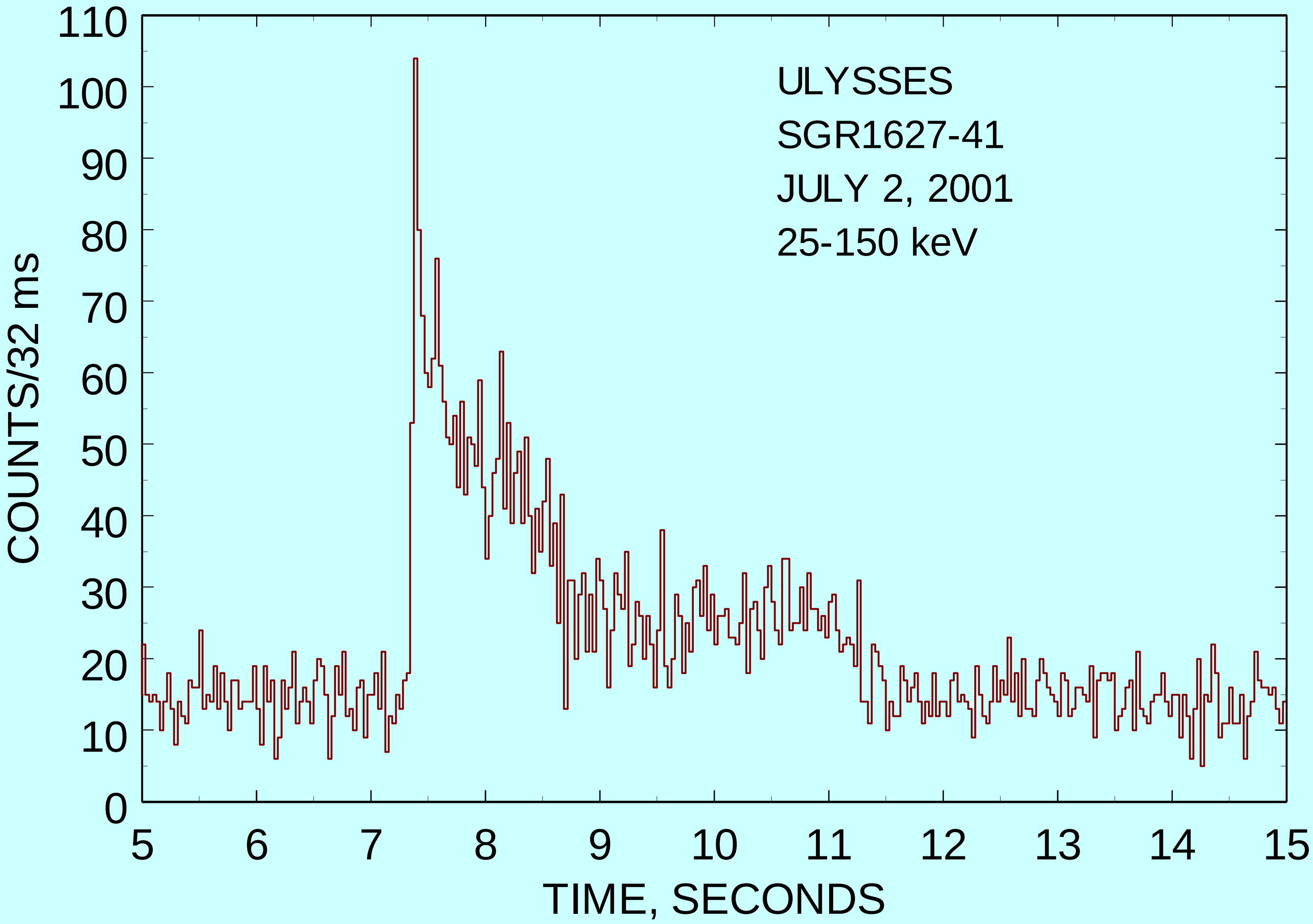
2 High B ⇒ low opacity, so $L>>L_{Eddington}$ is allowed

3 High B ⇒ neutron star magnetosphere can contain the energy of radiating electrons for the entire burst

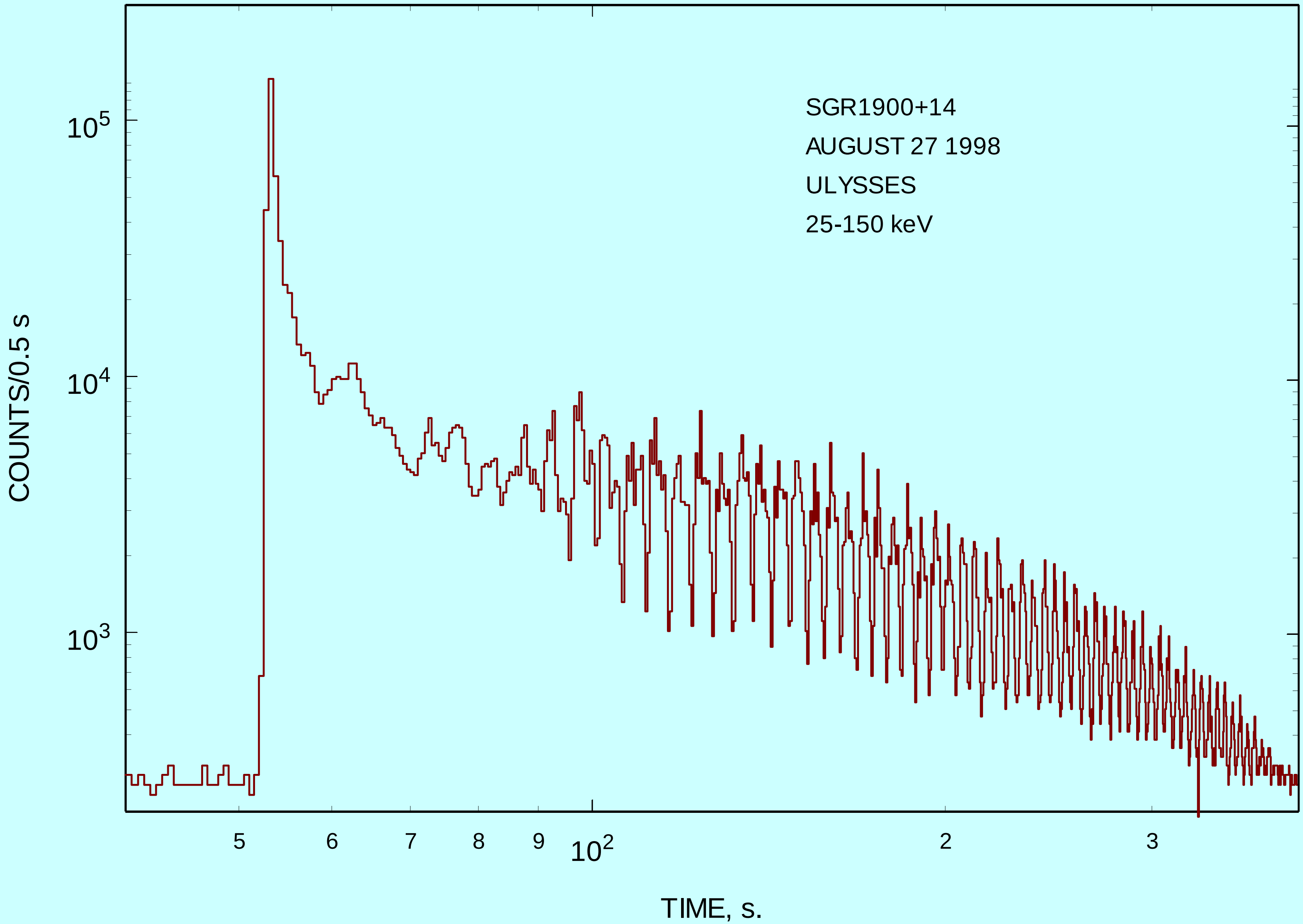
SOME SGR ACTIVITY CYCLES



“STRANGE” BURSTS, 1000 TIMES LONGER (RARE)

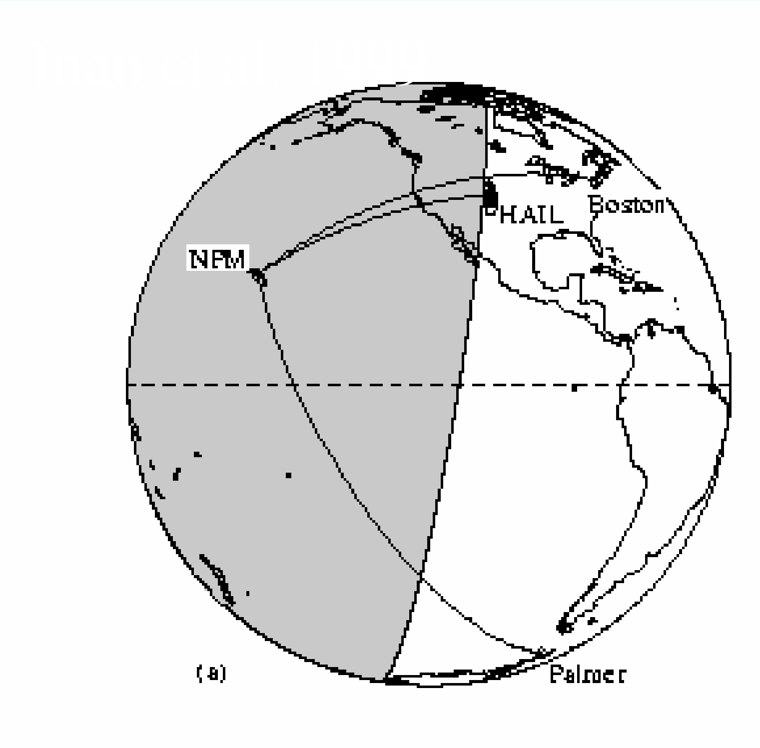


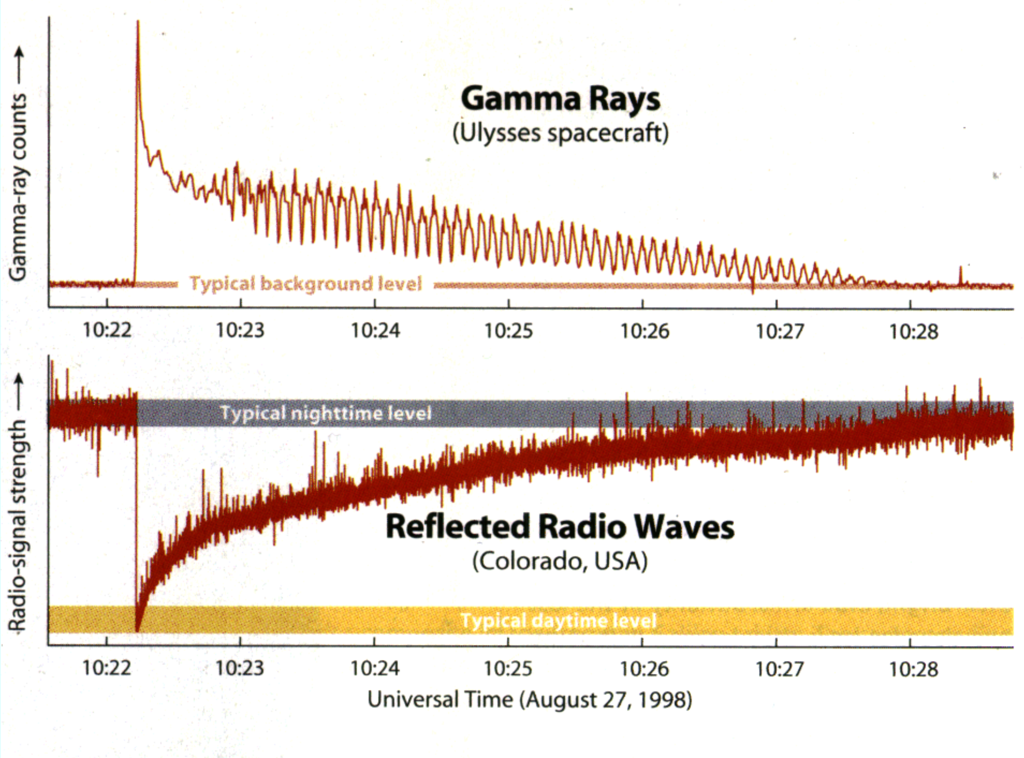
GIANT FLARES, WITH PERIODICITY (RARER STILL)



GIANT FLARES TURN NIGHT INTO DAY

Effect of the giant flare of 1998 August 27 from SGR1900+14

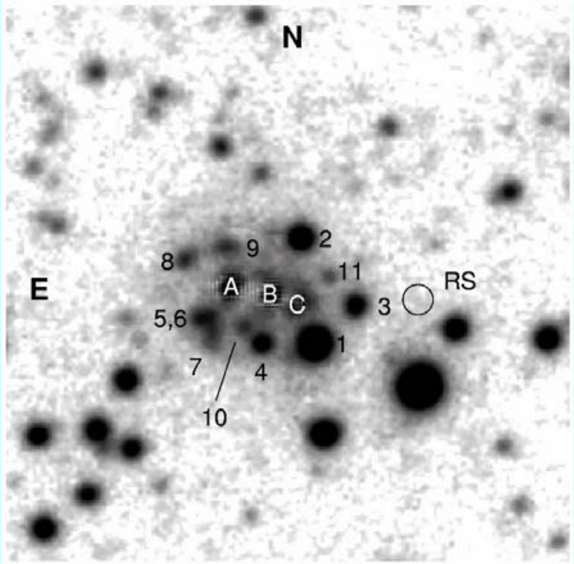




Level of the ionosphere as measured by propagation of VLF signal from Hawaii (21.4 kHz) descends to daytime value, due to ionization by 3-10 keV X-rays at 30-90 km

BUT SGR1900+14 IS ALSO CLOSE TO A MASSIVE STAR CLUSTER, LIKE SGR1806-20

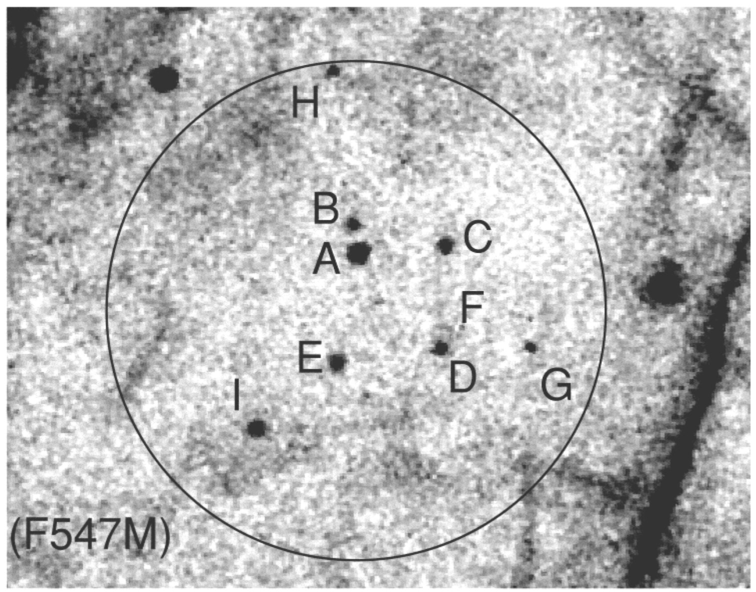
- The massive star cluster is not associated with G42.8+0.6
- Alternate hypothesis: SGR is part of the cluster, has low proper motion, and is not associated with G42.8+0.6; supernova responsible for the SGR triggered massive star formation, and did not leave a remnant behind



Vrba et al. 2000

AND LOCATION

- SGR0525-66 lies in the direction of the N49 SNR in the LMC
- This association has been controversial since March 6 1979
- Important to resolve, because
  - it is the *only* unobscured SGR, and
  - if the SGR is in N49, it is the *only* SGR with an accurately known distance and age;
- HST measurements reveal no optical counterpart (Kaplan et al. 2001); accretion disk ruled out
- *Chandra* measurements indicate that the quiescent X-ray spectrum resembles that of an AXP, suggesting that the neutron star may be intermediate between and SGR and an AXP



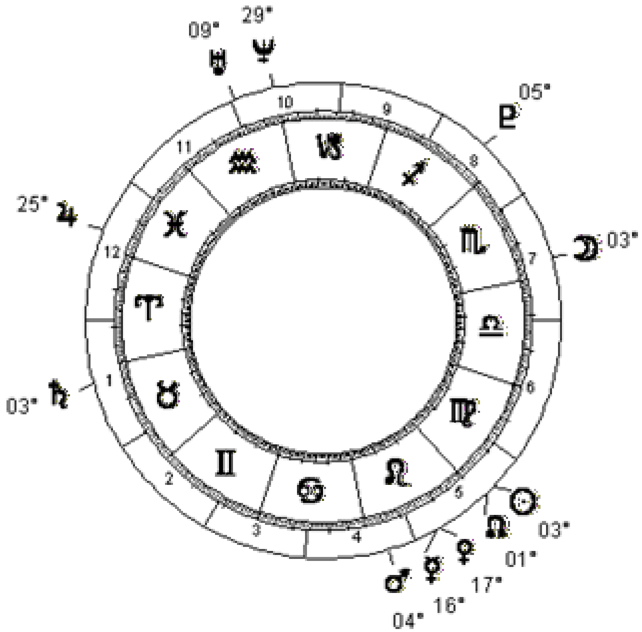
ESSENTIAL SGR PROPERTIES

	Super-Eddington bursts?	Giant Flare?	Periocity observed in flare?	Quiescent Soft X-ray Source, erg/s	Periodicity in Quiescent Source?	Spindown s/s	Cyclotron lines?	B, G
SGR1806-20	10^3x	Dec 27 2004	7.46 s	$2x10^{35}$	7.47 s	$\sim 10^{-10}$	Yes	$8x10^{14}$
SGR1900+14	10^6x	Aug 27 1998	5.16 s	$3x10^{34}$	5.16 s	$\sim 10^{-10}$	No	$2-8x10^{14}$
SGR0525-66	10^6x	Mar 5 1979	8 s	10^{36}	8.04 s	$\sim 7x10^{-11}$	No	$7x10^{14}$
SGR1627-41	$4x10^5$x	No	No	10^{35}	6.4 s (?)	No	No	?

LESS WELL KNOWN SGR PROPERTIES

Name	Possible SNR Association	Distance, kpc	Age, kyr	Massive Star Cluster?
SGR1806-20	G10.0-0.3	6 - 15	?	Yes
SGR1900+14	G42.8+0.6	5 - 15	5 - 20	Yes
SGR0525-66	N49	55	10	No
SGR1627-41	G337.0-0.1	6-11	1-5	No

Toward an Astrology of Magnetars



Earth - or half of it, any rate - got blasted at 10:22 UT on August 27, 1998.[1] During the following five minutes, our home planet was on the receiving end of a cosmic ray barrage (of gamma-rays, X-rays and radio waves) so intense that it ionized Earth's upper atmosphere to levels normally seen only during the daytime. Researchers at Stanford University who measured the ionization described it as "the first direct evidence of a physical effect on the Earth's environment by a distant star, or by any star other than our own Sun."[2]

The blast came from SGR 1900+14, a newly recognized type of star called a magnetar, in the constellation Aquila (the Eagle). At its source, the phenomenal five-minute cosmic ray surge was the energy equivalent of our Sun's entire output for the next 300 years, according to UC Berkeley physicist Kevin Hurley.[3] Fortunately for us, SGR 1900+14 is so far away that it took the surge of cosmic radiation over 20,000 years just to reach us. Our distance from the source of the blast was one major protective factor. Another is that Earth's upper atmosphere absorbed the lion's share of the interstellar burst. By the time it reached ground level, the intensity of that flare had been reduced to the point that anyone on the receiving end only got the equivalent of a normal dental X-ray. (Two satellites in Earth orbit, outside the protective blanket of our atmosphere, were overwhelmed by the blast. They went into automatic shutdown to preserve their shielded electronics from destruction by the onslaught of cosmic radiation.)

MAKING A MAGNETAR (Duncan & Thompson 1992)

- A neutron star undergoes vigorous convection in the first ~30 s after its formation

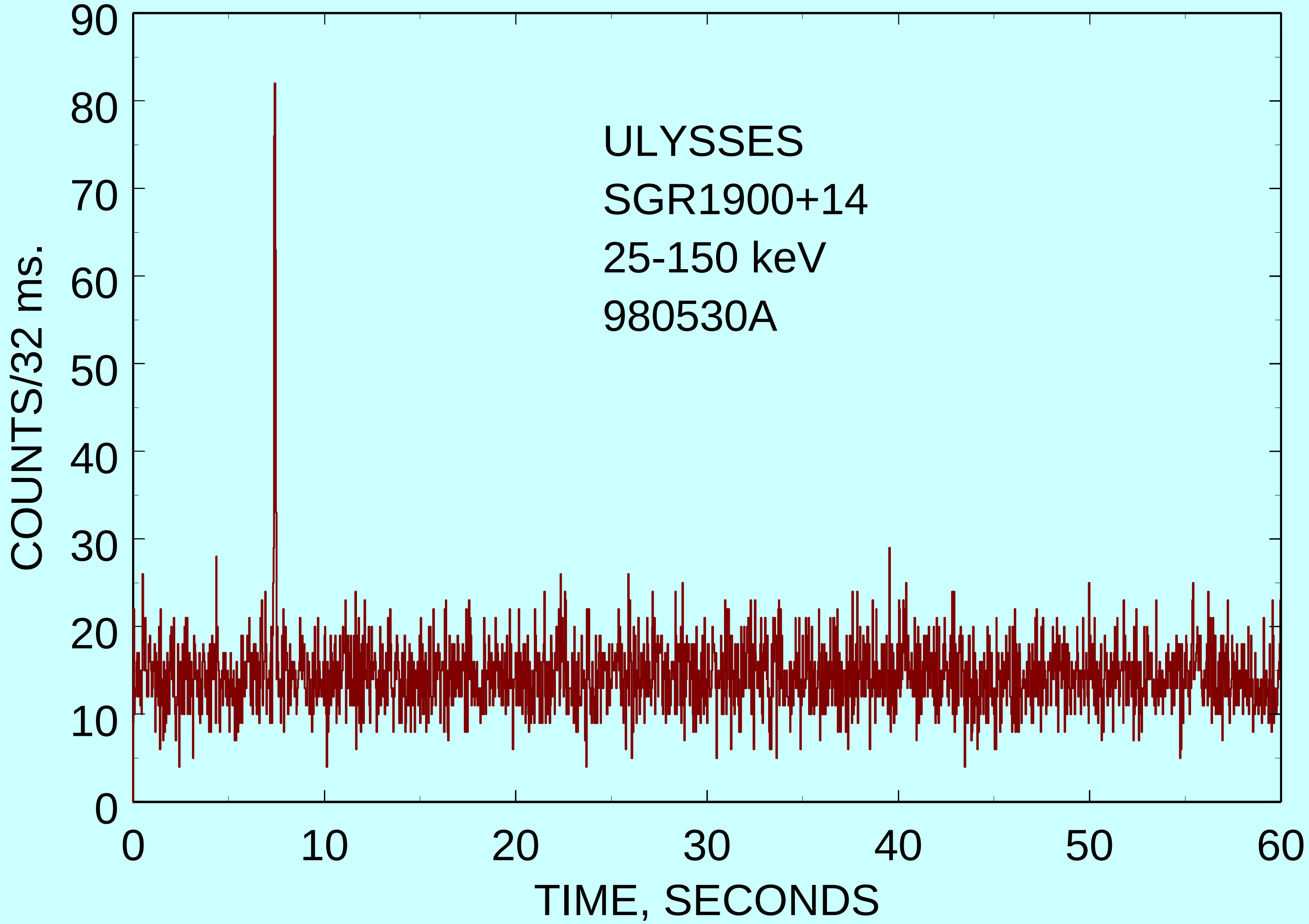
- Coupled with rapid rotation (~1 ms period), this makes the neutron star a likely site for dynamo action

- If the Rossby number (=rotation period/convective overturn time) <1, magnetic field amplification is not suppressed

- In principle, $B \sim 3 \times 10^{17}$ G can be generated

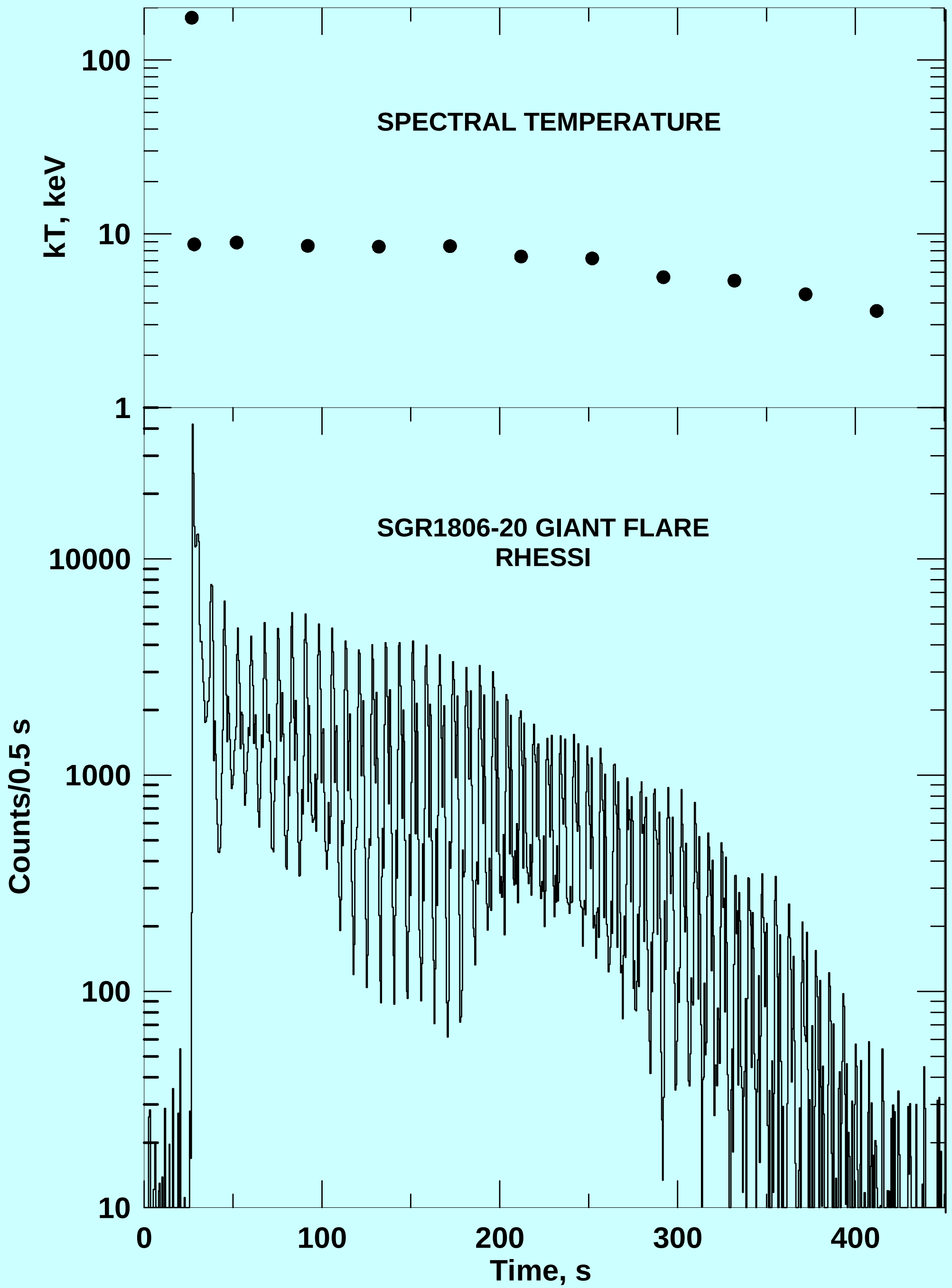
- Bursting activity lasts $\sim 10^4$ y

SINGLE, ~100 ms LONG BURST (MOST COMMON)



THE GIANT FLARE FROM SGR1806-20

- **December 27 2004 21:30:26 UT**
- **SGR1806-20 was over longitude 146.2º W, latitude +20.4º (near Hawaii)**
- **Detected by at least 24 spacecraft (and probably numerous military spacecraft) – most of which had no X- or gamma-ray detectors!**
- **The most intense solar or cosmic transient ever observed**
- **Measured X- and gamma-ray flux at the top of the atmosphere: 1.4 erg/cm^2**
- **X- and gamma-ray energy released at the source: 3x10^{46} erg**
- **This should be considered a lower limit to the energy released (saturation effects, limited energy ranges)**


SPECTRAL TEMPERATURE
kT, keV
100
10
1
SGR1806-20 GIANT FLARE
RHESSI
Counts/0.5 s
10000
1000
100
10
0
100
200
300
400
Time, s

A FEW NUMBERS FOR COMPARISON

- **Peak luminosity: $2x10^{47}$ erg/s**
  - **Peak luminosity of all the stars in the Galaxy: $8.7x10^{43}$**
- **Total energy released: $3x10^{46}$ erg in ~ 1 second**
  - **=300,000 years of the sun's energy output**
  - **=$8x10^{18}$ times the yearly world energy consumption**
  - **=$8x10^{19}$ times the energy in the world's nuclear arsenal**
- **But the dose outside the Earth's atmosphere, 0.14 rem, was roughly equivalent to a medical X-ray**
- **To cause damage to the biosphere, SGR1806-20 would have to be about 16000 times closer, at the distance of the nearest stars**

SHOULD YOU BUY A MAGNETAR SHELTER? (WORST CASE CALCULATION)

- Say each giant flare releases 3×10^{46} erg
- $\sim 10^6$ erg/cm^2 absorbed by the atmosphere (a giant flare at 15 pc) would cause an effect similar to "nuclear winter" (ozone depletion, destruction of the food chain)
- Assume magnetars are distributed uniformly throughout the disk of the galaxy (900 kpc^3), and that ~10 are active at any given time
- Probability ~ 10^{-6}

EMISSION LINE IN BURST SPECTRUM FROM SGR1900+14 (Strohmayer & Ibrahim 2000)

- 6.4 keV; weaker line at 13 keV
- Chance probability ~2x10^{-4}
- Fe fluorescence from ablated material after giant flare?
- Proton cyclotron?

RXTE PCA August 29 1998