# The Giant Flare of 2004 Dec 27 from SGR1806-20 and Fundamental Physics from Magnetars

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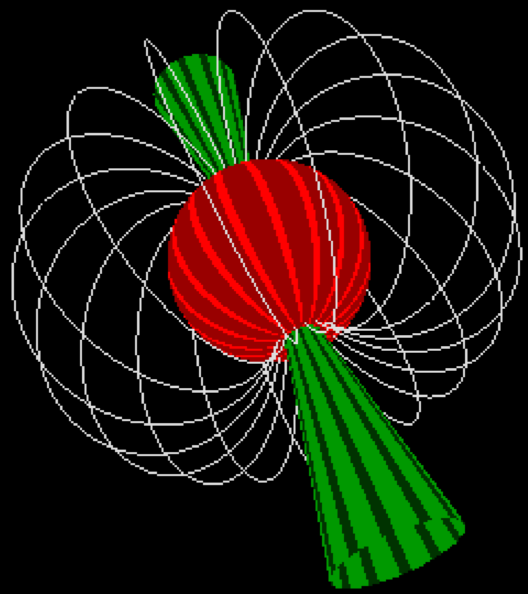
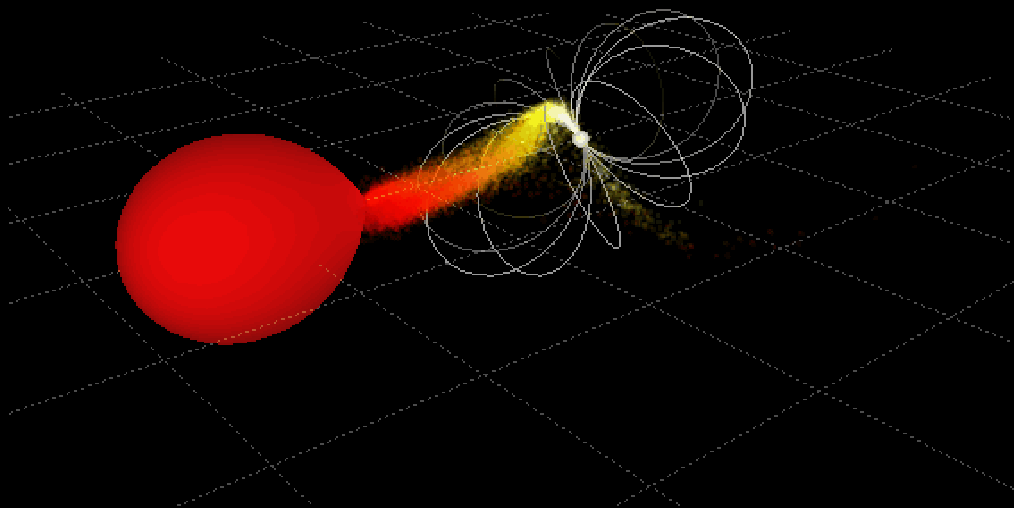
And also…
***Belloni, Mereghetti, Covino, Campana, Re, Rea, Casella, Gotz, Turolla, Tiengo, Mignani, Zane, Oosterbroek, Mendez, Rothschild, Raphaeli, Gruber, Perna + others***

# Neutron Stars

- Radio Pulsars
  (rotation power)
  B ~ $10^8$-$10^{13}$ Gauss
  P(spin) ~ 1.5 ms – 8 s



- Accreting neutron stars
  (accretion power)
  B ~ $10^8$-$10^{13}$ Gauss
  P(spin) ~ 1.5 ms – 2000 s



# Superstrong B-fields ?: a bit of history

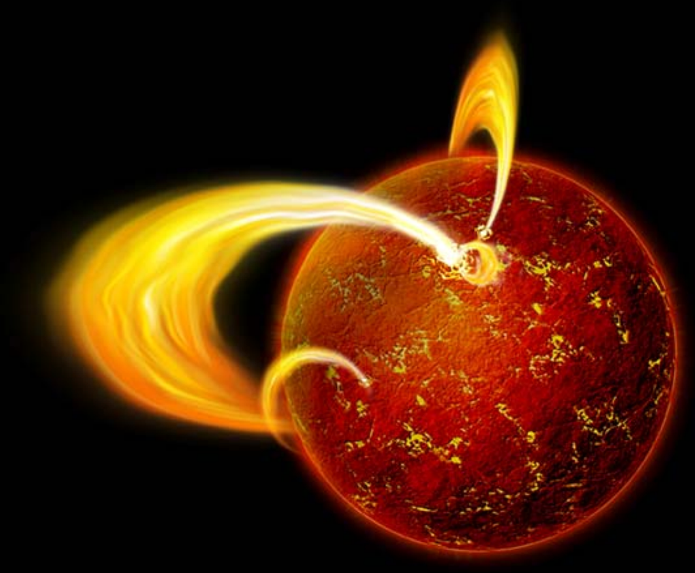
- $B \sim 10^{14}$-$10^{15}$ G from magnetic flux conservation in progenitor star (Woltjer 1964)

Radio Pulsars: $B \sim 10^{8}$-$10^{13}$ G
Accreting X-ray pulsars: $B \sim 10^{8}$-$10^{13}$ G

- Superstrong B-fields to cause outflows in stellar collapse ?

- Strong toroidal field as a residual of differential rotation at birth ?

- Superstrong B-fields from dynamo action in proto-neutron star
  (+ magnetic energy dissipation !)
  Modern idea of Magnetar (Duncan & Thompson 1992 -> )
  (developed also in connection with GRBs)



# Two classes of high energy sources contain magnetars

(They are in highly absorbed regions in the galactic plane)

| | Soft Gamma Repeaters<br>SGRs (1987) | Anomalous X-ray Pulsars<br>AXPs (1995) |
|---|---|---|
| • No. of sources | 5+1 | 8+1 |
| • Spin Period | 2-8 s | 2-12 s |
| • Period Derivative | $\sim 10^{-11}$ s/s | $\sim 10^{-11}$-$5 \times 10^{-13}$ s/s |
| • Isolated | yes | yes |
| • Recurrent Bursts | $\sim 10^{38}$-$10^{41}$ erg/s | $\sim 10^{37}$-$10^{38}$ erg/s |
| • Giant Flares | yes | no |
| • Persistent emission | $\sim 10^{35}$ erg/s | $\sim 10^{34}$-$10^{35}$ erg/s |
| • Association to SNRs | ? | in some cases |
| • Radio pulsations | no | in 2 cases |

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# SGR Bursts

- Concentrated in time ("outbursts")
- Relatively simple profiles (faster rise than decay)
- Broad distribution of wait times (~7 decades) : similar to that of earthquakes; no waiting-time correlations
- Energy distribution $dN/dE \sim E^{-5/3}$ : similar to earthquakes
- Most bursts release $\sim 10^{38}$-$10^{41}$ ergs

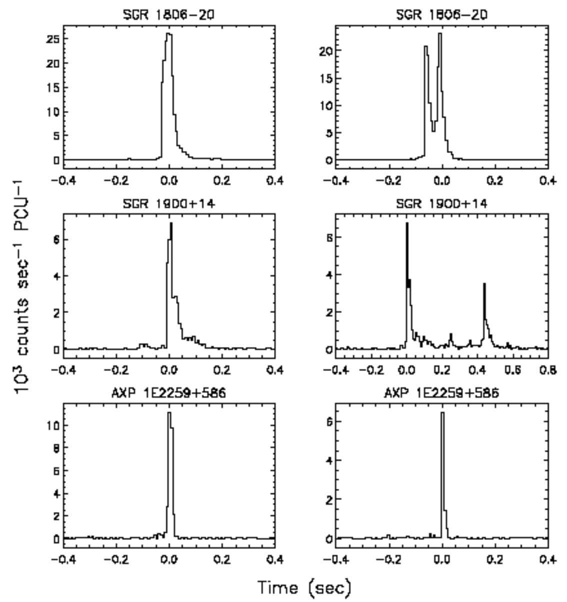
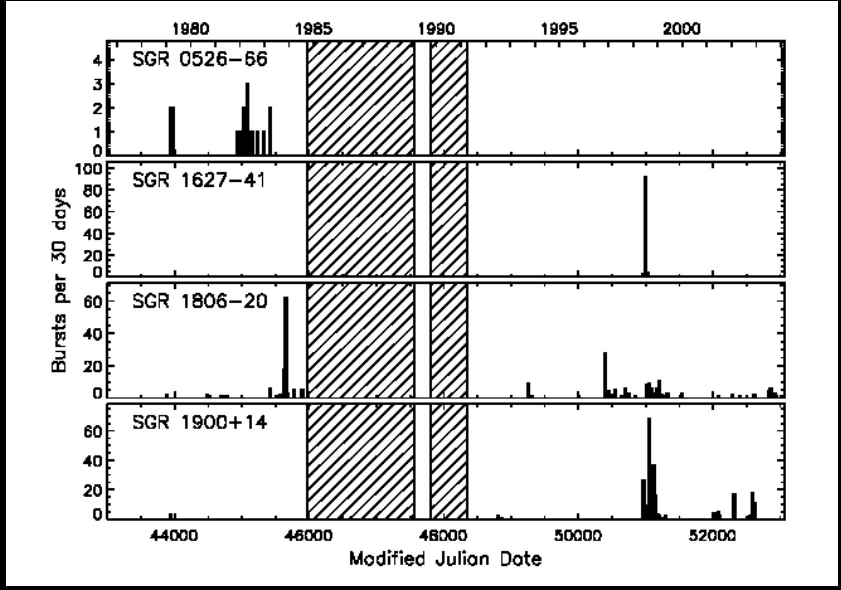



Fig. 14.1. A selection of common burst morphologies recorded from SGR 1806−20, SGR 1900+14 and 1E 2259+586, as observed with the *RXTE* PCA. All light curves display counts in the energy range 2−20 keV, with a time resolution of 7.8 ms. See text for further details.



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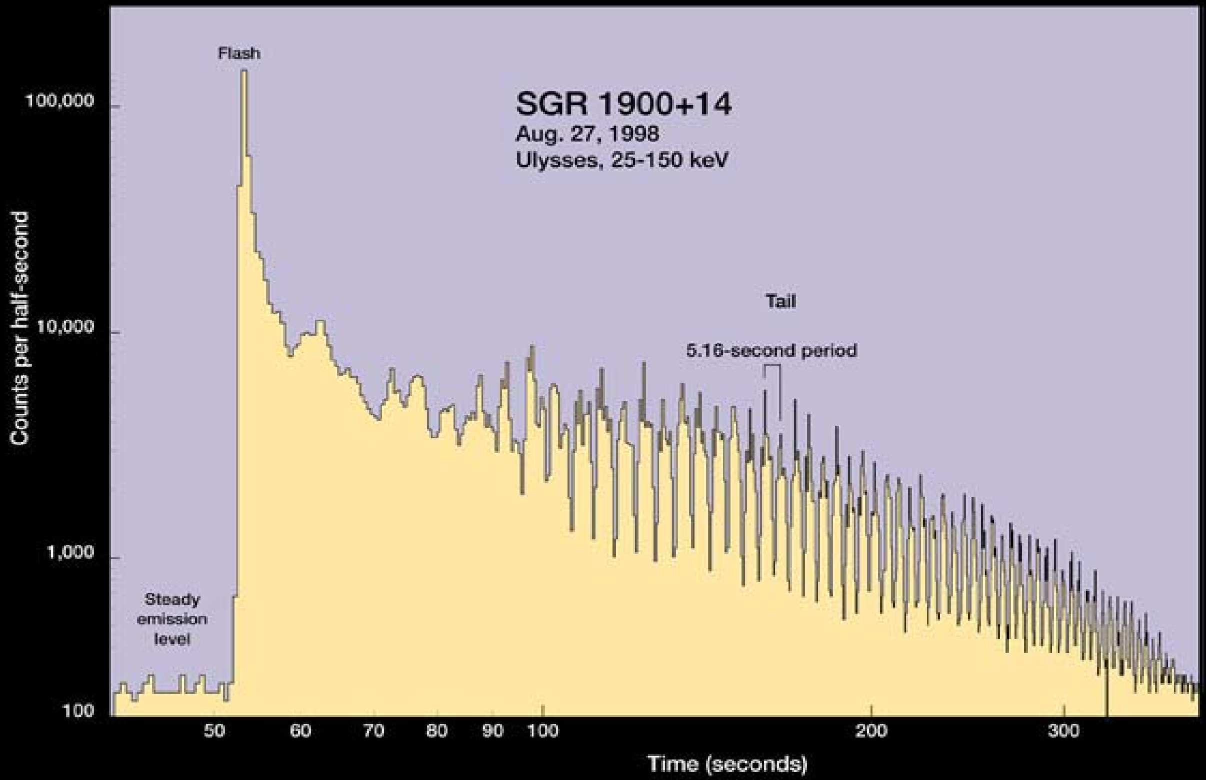
# Giant Flares

- 1979 March 5 from SGR 0526–66: energy released ~$10^{44}$ ergs
- 1998 August 27 from SGR1900+14: energy released ~$10^{44}$ ergs
- Main peak ~0.2 s; variability down to ms, hard BB-like spectrum (kT~ 100 keV)
- 2-3 min long ringing tail: (nearly) exponential decay
  pulsations at 5-8 s (spin period)
  TB temperature of ~30-50 keV.
- In Magnetar model: GFs due to large scale rearrangements of core B-field



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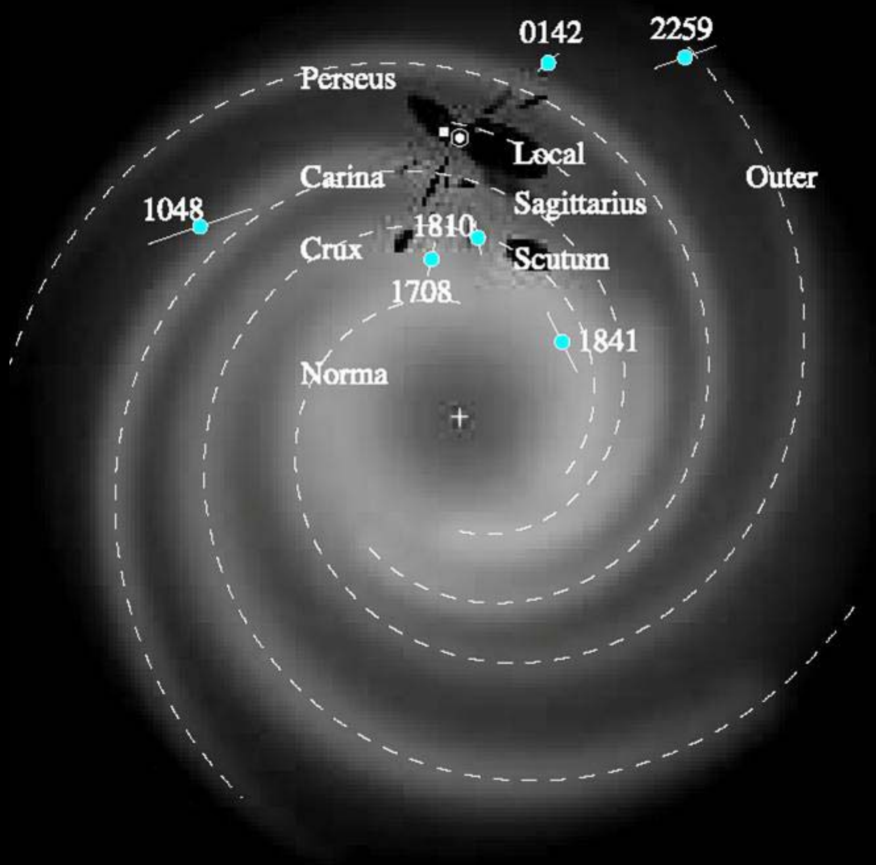
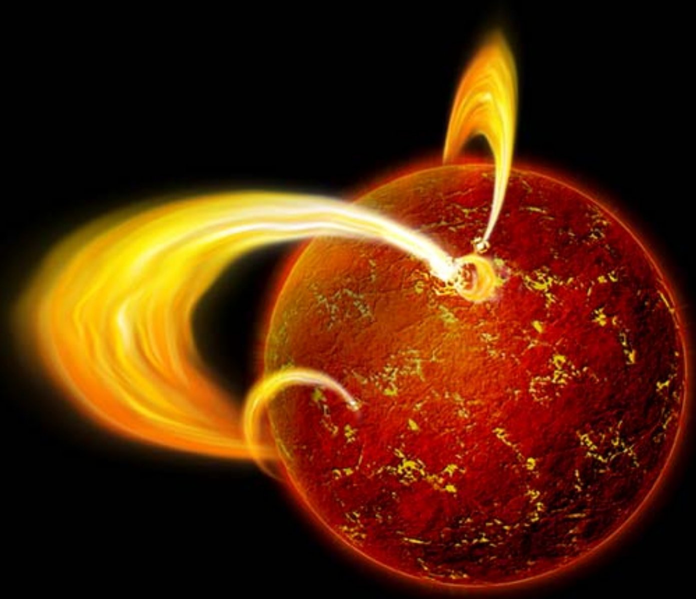
# Magnetars in our Galaxy



# Magnetars: Neutron Stars powered by magnetic energy

- "Magnetars" (MAGNEtic sTARS): neutron stars with very high magnetic fields ($B>10^{14}G$)

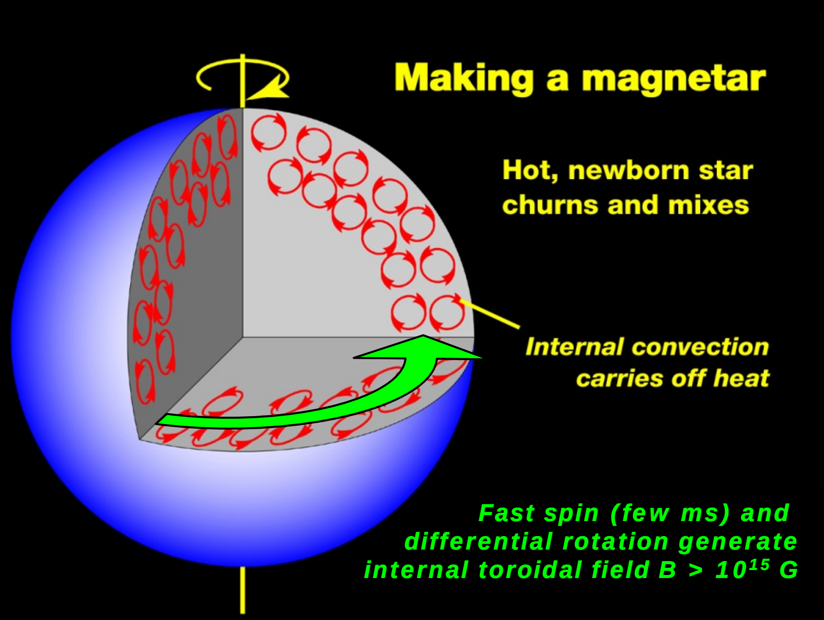
  Why magnetic energy ? (Magnetic energy propagating through fractures in the crust)

Persistent luminosity 10-100 times higher than spin down power

-> rotational energy ruled out

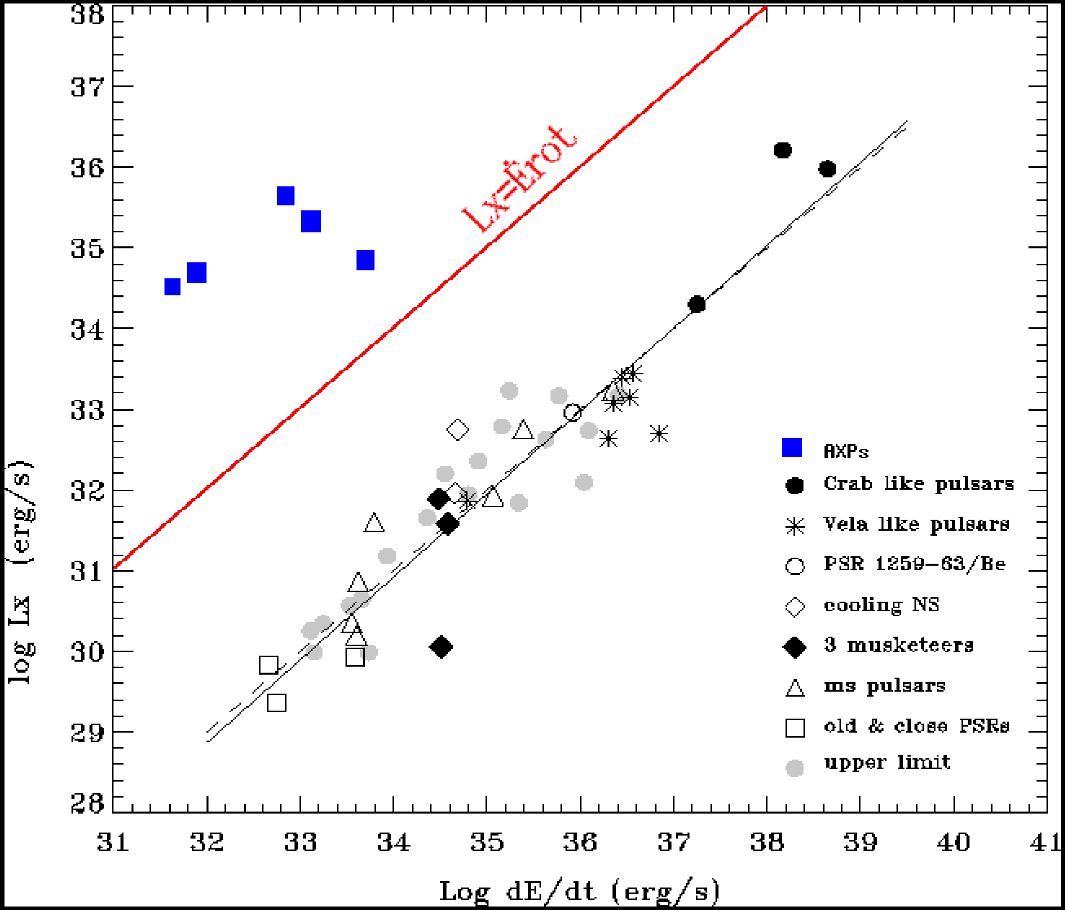
Recurrent flares reach $10^{41}$ erg/s ~ 1000 $L_{Edd}$ , giant flares $10^{44}$ erg/s ~ $10^6$ $L_{Edd}$

-> accretion energy ruled out



# Persistent X-ray emission of AXPs

Rotational energy losses are orders of magnitudes smaller ($10^{32-33}$erg/s) than observed $L_x$!!




$\dot{E}_{rot} = I\Omega\dot{\Omega} = 4\pi^2\dot{P}P^{-3}$

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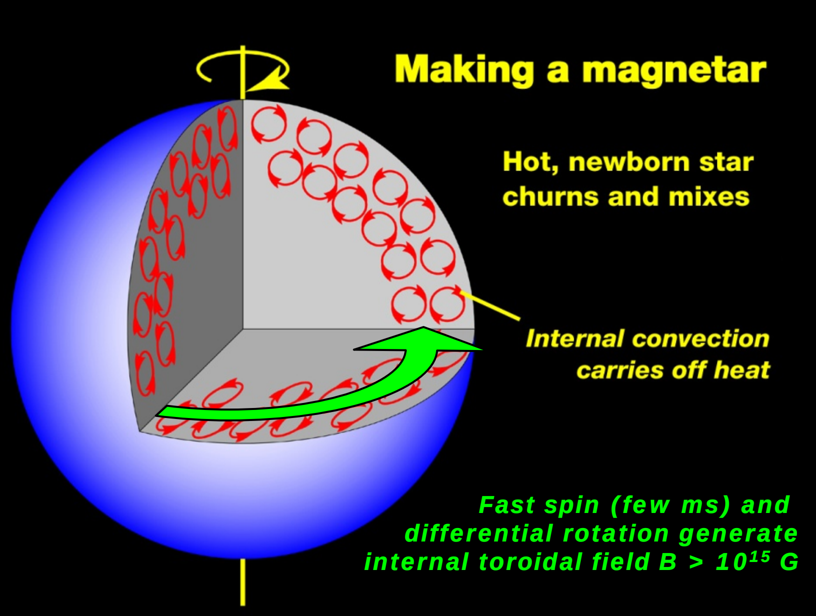
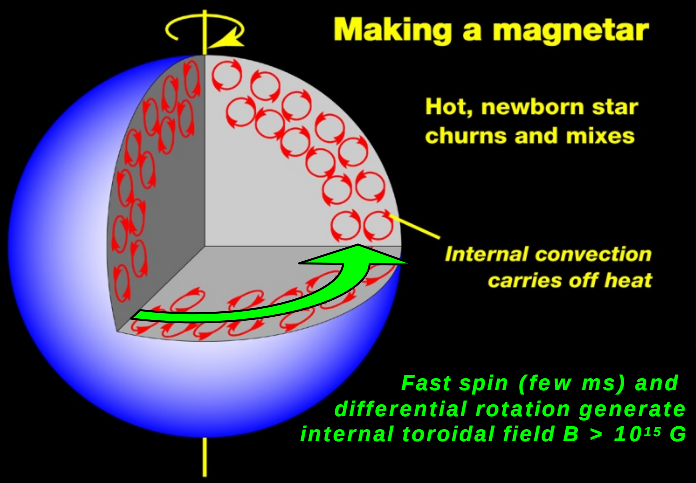
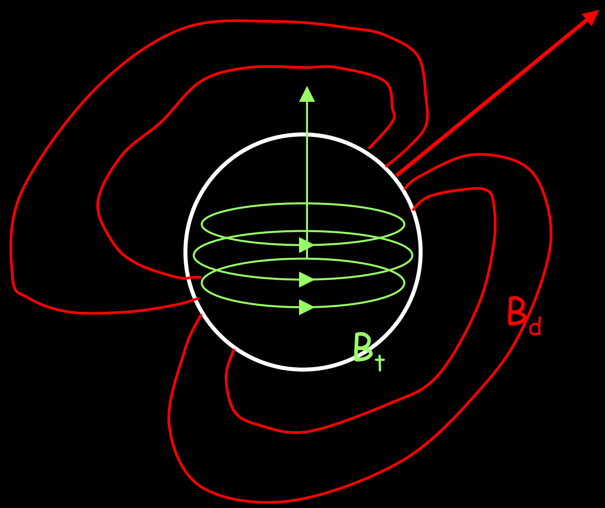


# The B-field of Magnetars

Very strong internal *B*-fields in a newborn differentially rotating fast-spinning neutron star

For initial spin periods of $P_i \sim 1$–2 ms, differential rotation can store $\sim 10^{52} (P_i/1\ \mathrm{ms})^2$ ergs, that can be converted into a magnetic field of up to $3 \times 10^{17} (P_i/1\mathrm{ms})^{-1}$ G.
(efficient dynamo might be limited to ~$3 \times 10^{16}$ G) (Duncan & Thompson 1992)




$B_d \sim 10^{14\text{-}15}$ G outer dipole field (spin-down, pulsations)
inferred from spin-down rate (and confirmed through the energetics and fast variability properties of the "ringing tail" of Giant Flares from SGRs)

$B_t > 10^{15}$ G inner toroidal field (energy reservoir):
lower limit from: L(persistent) x age ~ $10^{47}$ ergs

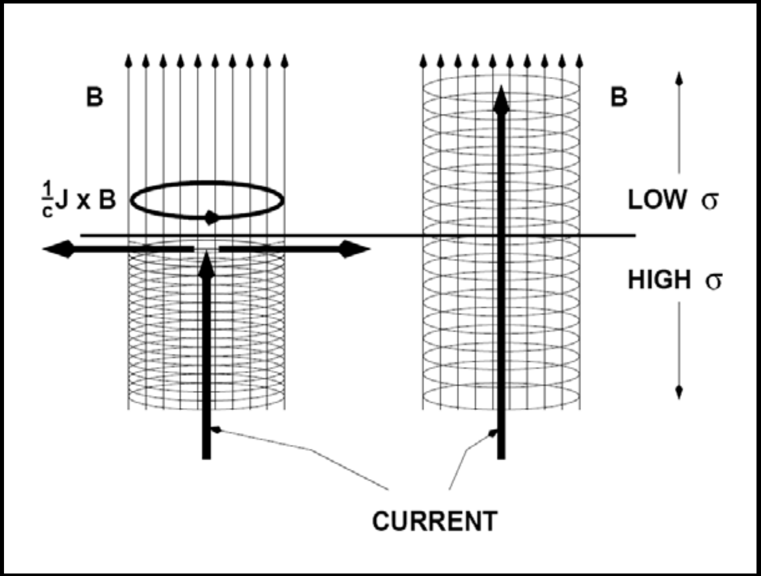
# Bursts/Flares in the Magnetar Model

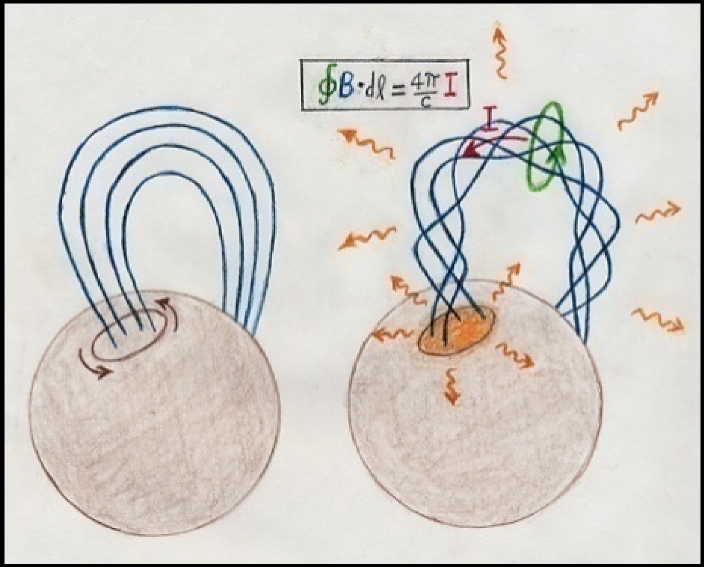
- Energy fed to neutron star magnetosphere through Alfven waves driven by local crustquakes of various amplitude, giving rise to recurrent bursts

- Giant flares result from large-scale rearrangements of the core magnetic field:

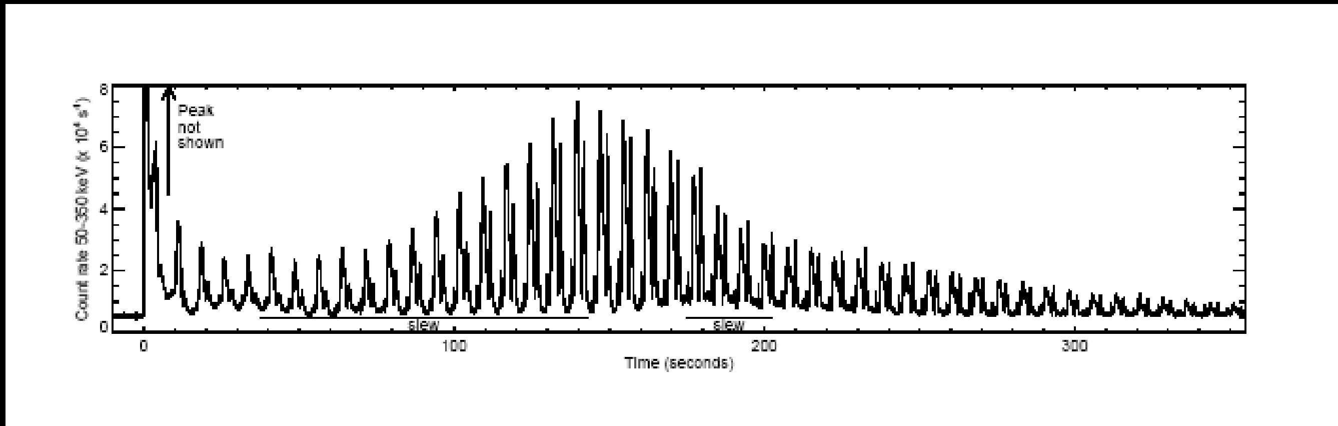
  - core field evolves through ambipolar diffusion, building up magnetic stresses
  - crustal yield strain is overcome, large-scale fracturing occurs that leads to sudden release of very large amounts of energy into the magnetosphere
  - fireball of pair-dominated plasma expanding at ~ c -> Initial Spike of Giant Flares.

**External field: mainly poloidal**
**Internal field: mainly toroidal**

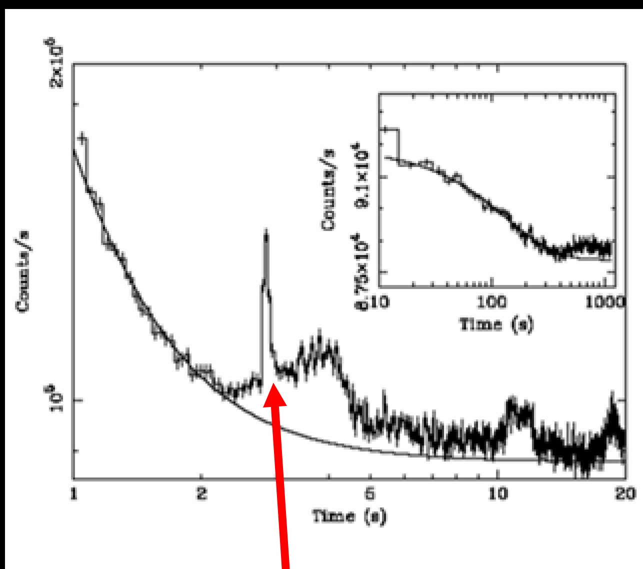


# SGR 1806-20: Giant Flare of 2004 Dec 27




(Palmer et al. 2005
Hurley et al. 2005)



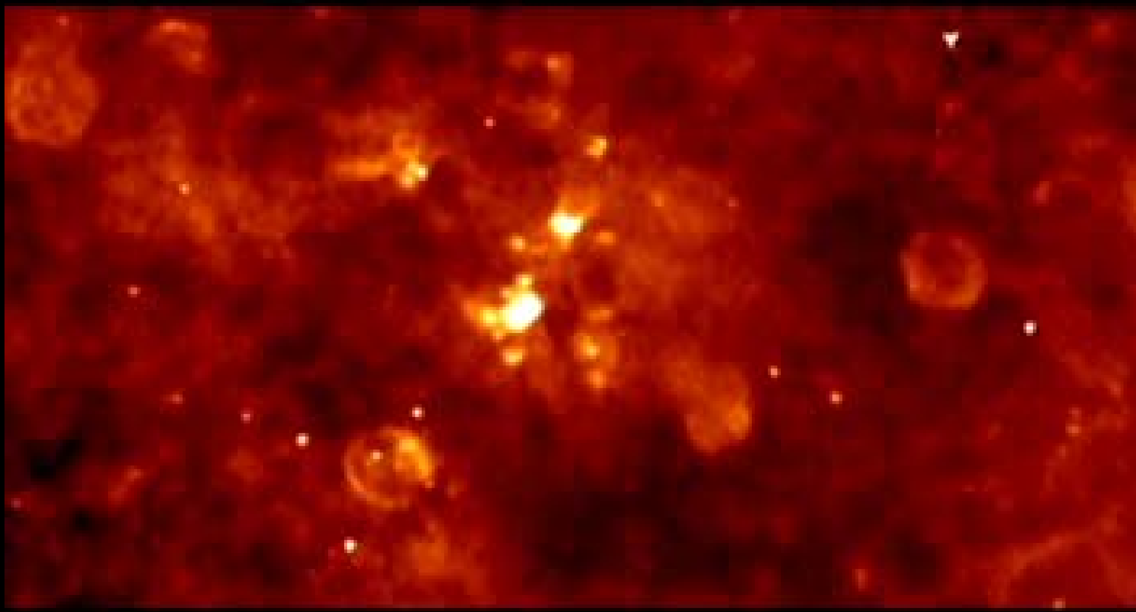

Moon reverberation seen !

| Giant Flare<br>Source<br>Assumed distance | March 5, 1979<br>SGR 0526–66<br>55 kpc | August 27, 1998<br>SGR 1900+14<br>10 kpc | December 27, 2004<br>SGR 1806–20<br>15 kpc |
|---|---|---|---|
| **Initial Spike** | | | |
| Duration (s) | ~0.25 | ~0.35 | ~0.5 |
| Peak luminosity (erg $s^{-1}$) | 3.6 $10^{44}$ | >3.7 $10^{44}$ | (2÷5) $10^{47}$ |
| Fluence (erg $cm^{-2}$) | 4.5 $10^{-4}$ | >5.5 $10^{-3}$ | 0.6÷2 |
| Isotropic Energy (erg) | 1.6 $10^{44}$ | >6.8 $10^{43}$ | (1.6÷5) $10^{46}$ |
| **Pulsating tail** | | | |
| Duration (s) | ~200 | ~400 | ~380 |
| Fluence (erg $cm^{-2}$) | 1 $10^{-3}$ | 4.2 $10^{-3}$ | 5 $10^{-3}$ |
| Isotropic Energy (erg) | 3.6 $10^{44}$ | 5.2 $10^{43}$ | 1.3 $10^{44}$ |
| Spectrum | kT~30 keV | kT~20 keV | kT~15–30 keV |
| Pulse Period (s) | 8.1 | 5.15 | 7.56 |

(Mereghetti et al. 2005)

# SGR 1806-20: Radio Band observations

Expanding radio source travelling at ~ 0.5 c



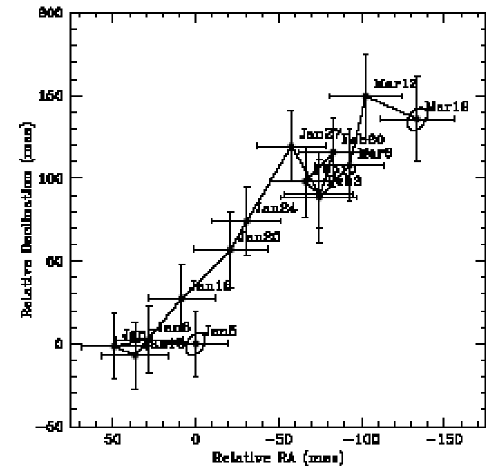
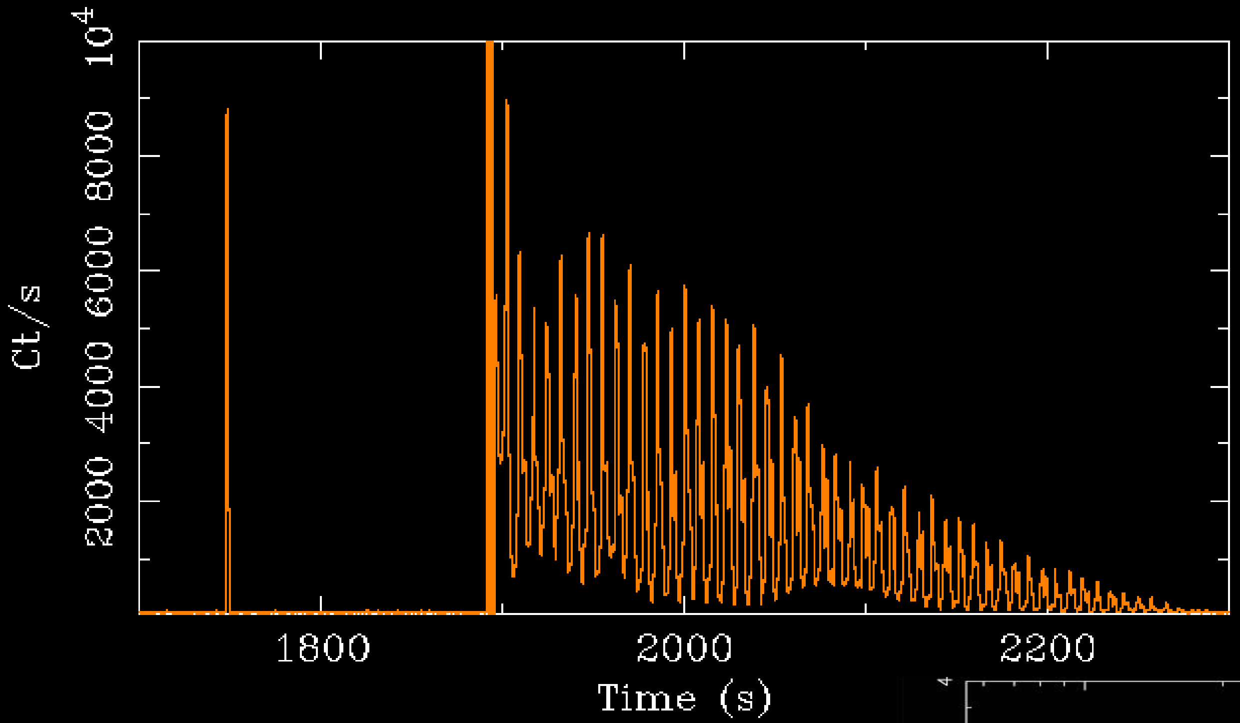


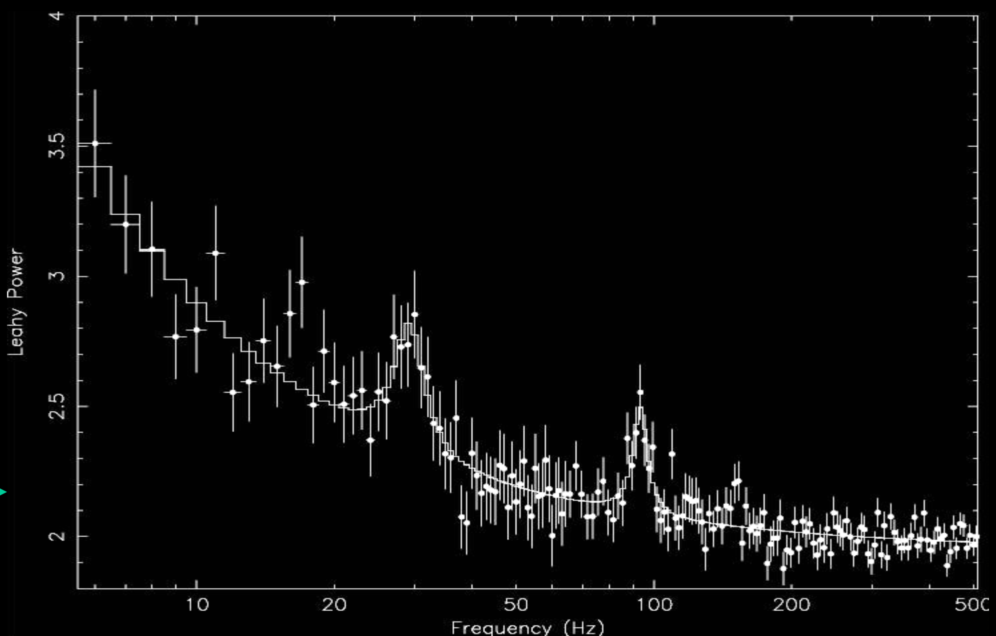

FIG. 3.— The trajectory of the afterglow of SGR 1806-20. Dates are labeled. The small ellipses denote the first and last days used.

# 2004 Dec 27 giant flare from SGR1806-20: fast timing




XTE was observing a cluster of galaxies, a constant and low "background" level for the SGR1806-20 hyperflare

Total power spectrum of XTE high resolution data

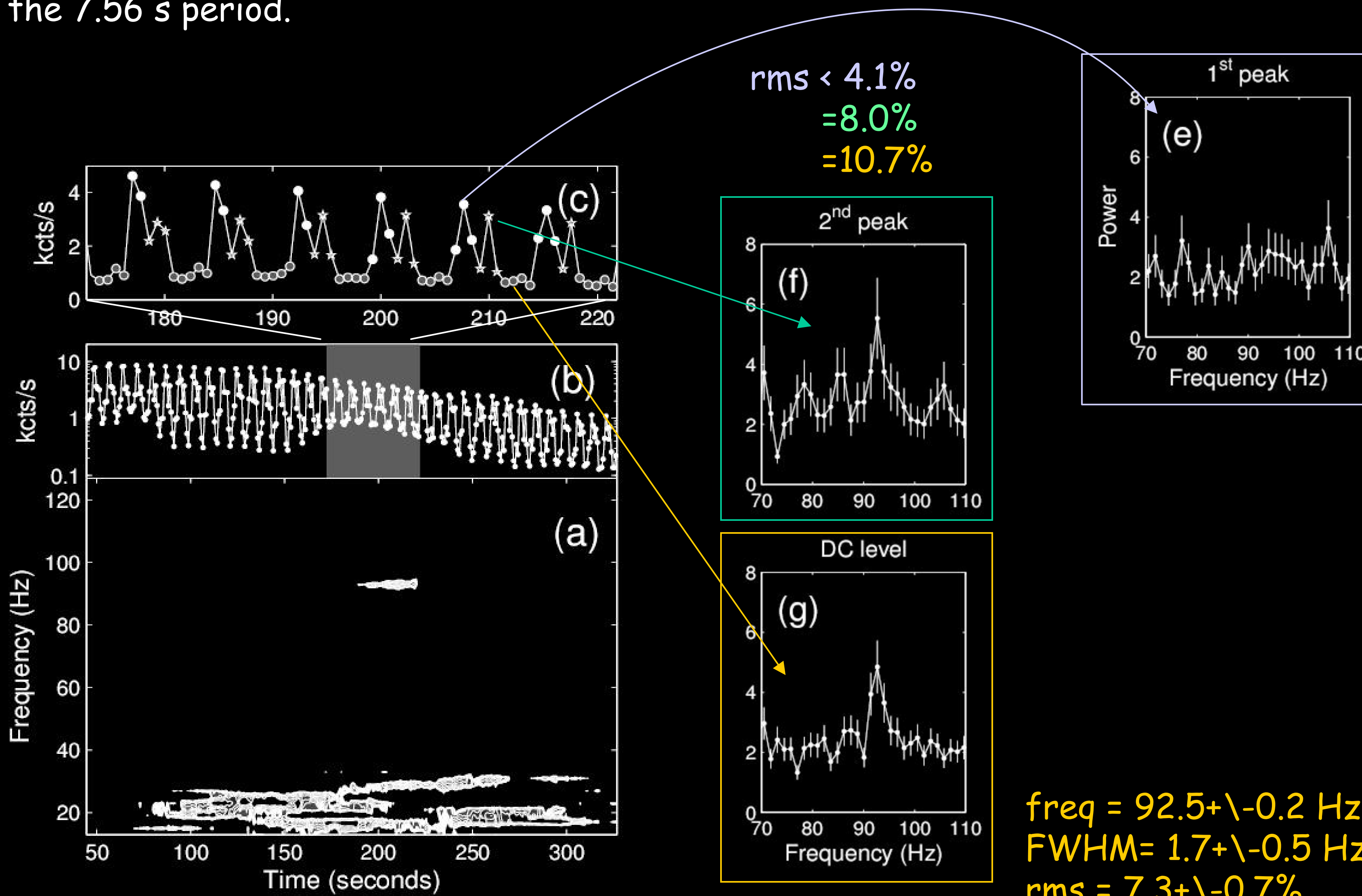


# First detection of QPOs in a SGR

(Israel et al. 2005)

QPO properties depend on "DC" flux level and phase of the 7.56 s period.

rms < 4.1%
=8.0%
=10.7%

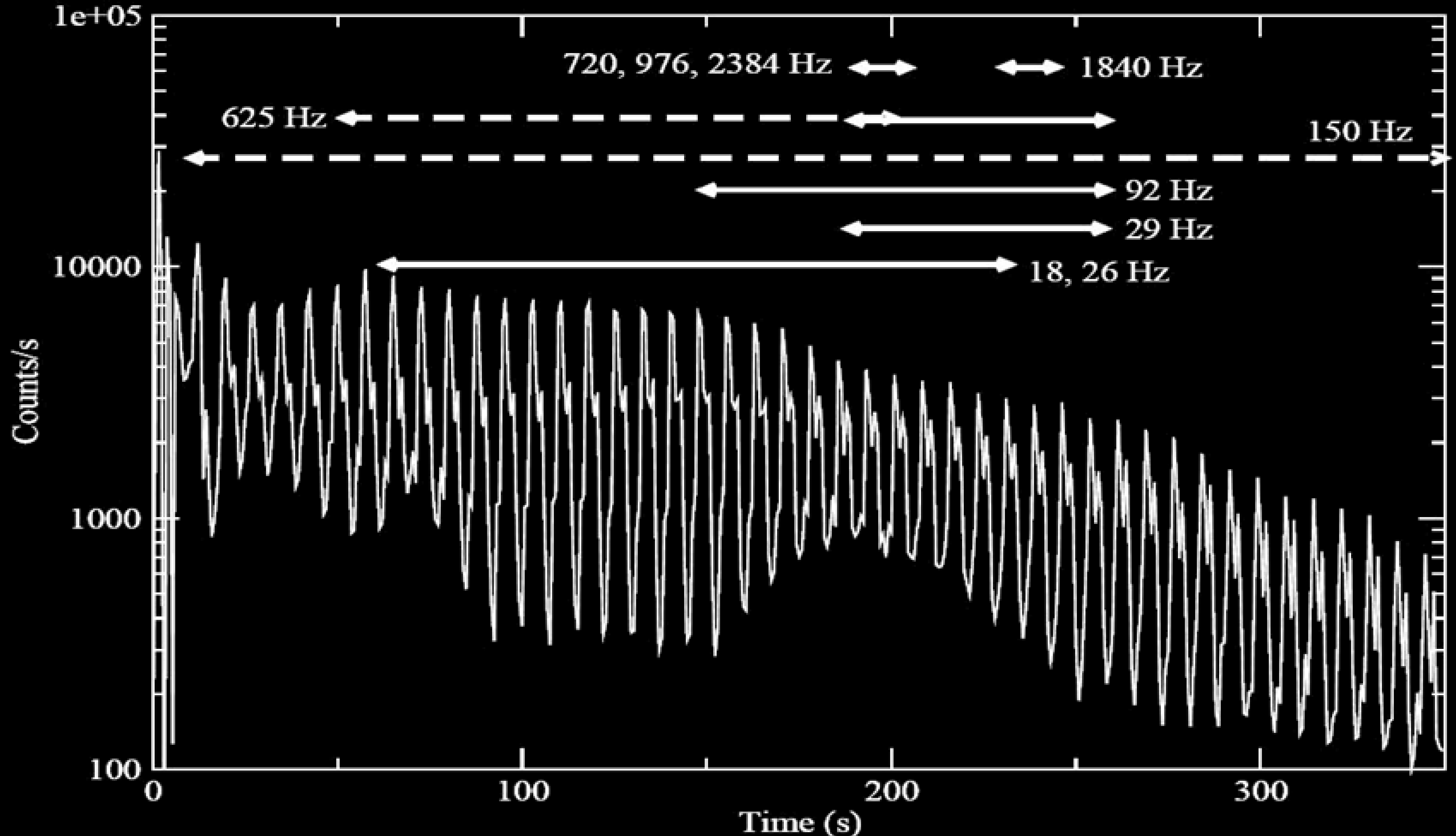



(Israel et al. 2005, astro-ph/0505255)

freq = 92.5+\-0.2 Hz
FWHM= 1.7+\-0.5 Hz
rms = 7.3+\-0.7%
Prob ~ $1.5\times10^{-5}$ – $1.3\times10^{-4}$

# Q POs signals: time and pulse phase dependent !

- Observed frequencies consistent with those of seismic oscillations
- Large scale crust fracturing -> elastic energy driving seismic waves
- Mechanical motions -> relatively high coherence of oscillations
- The spin phase-dependence -> oscillations are generated in specific regions of the NS surface: emission regions DO NOT expand!



# Beyond the CFR limit in a strong B field

$\Delta L/\Delta t \sim 6 \times 10^{43}$ erg/s$^2$ in SGR1806-20

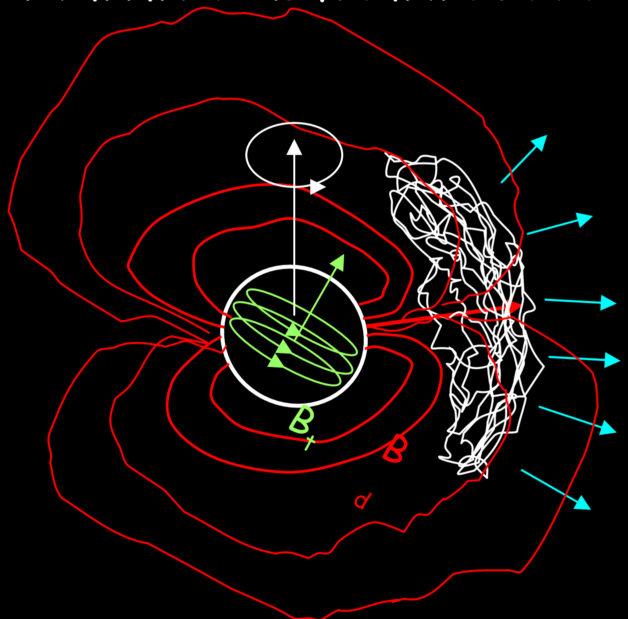
How can the CFR limit be circumvented ?

$\Delta L/\Delta t = \eta\,(2\pi\, m_p c^4 / 3\sigma_t) = \eta\; 2 \times 10^{42}$ erg/s$^2$

$\sigma$ differs from the Thomson cross section due to B.
In the E mode $\sigma_t$ is reduced by a factor $[\varepsilon B_q/(m_e c^2 B)]^2$ (e.g. Meszaros 79)
By imposing $(\varepsilon B_q/(m_e c^2 B))^2 < \eta/30$ we get

$B \geq 1.5\, Bq\, (0.1/\eta)1/2 \approx 6.6 \times 10^{13}$ G

Using a typical photon energy of $\varepsilon \sim 14$keV from the $kT_{BB} \sim 5$ keV BB fit:
Minimum radius from which the observed Lx can be radiated ~ $R_{BB} \sim 30$km




Rescaled to the surface this gives

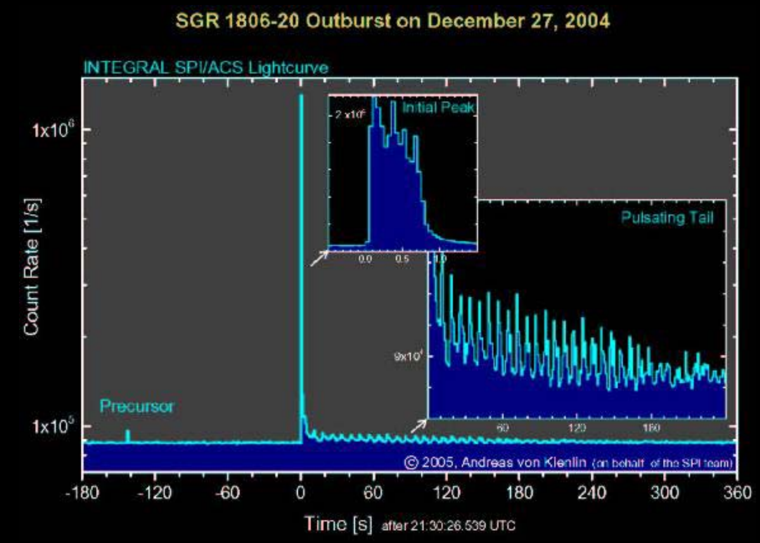
$B \geq 1.8 \times 10^{15}$ G $(10\ \text{km}/R_{ns})\,(0.1/\eta)^{1/2}$

(Vietri et al. 2007)

In SGR 1806-20 $B_d \sim 8 \times 10^{14}$ G from spin down

# The 2004 Dec 27 Event and the Internal B-field of Magnetars

- Energy of ~ $5\times 10^{46}$ ergs released in initial 0.6 s long spike
  (Terasawa et al. 2005; Hurley et al. 2005)




- 1 such event in ~30 yr of monitoring of 5 SGRs
  -> Recurrence time ~ 150 yr/magnetar

- ~70 events like the 2004 Dec 27 event expected in ~$10^4$ yr (SGR lifetime)
  -> Total energy release (independent of beaming) ~$4\times10^{48}$ ergs

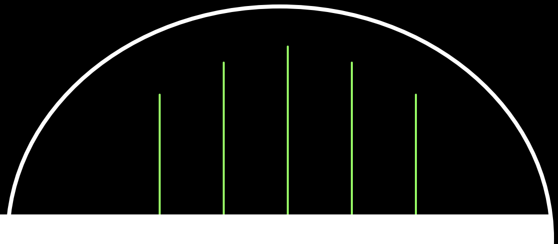
<u>If internal field is the energy source, then $B > 10^{15.7}$ G</u>

| | |
|---|---|
| <u>Including total neutrino energy release: $B > 10^{15.9}$ G</u> | New limit on $B_t$ |

# Shape of a highy magnetic star

Star with a constant inner B-field cannot be spherical

(Chandrasekhar & Fermi 1953)



# PROBLEMS OF GRAVITATIONAL STABILITY IN THE PRESENCE OF A MAGNETIC FIELD

S. Chandrasekhar and E. Fermi

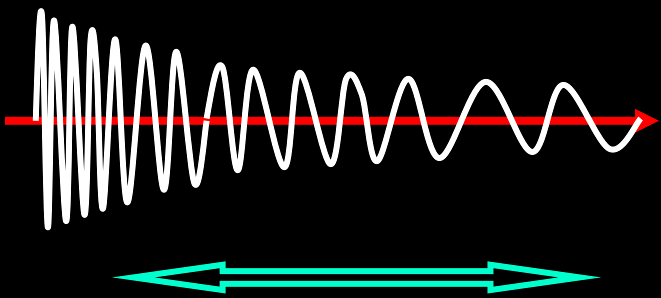
University of Chicago

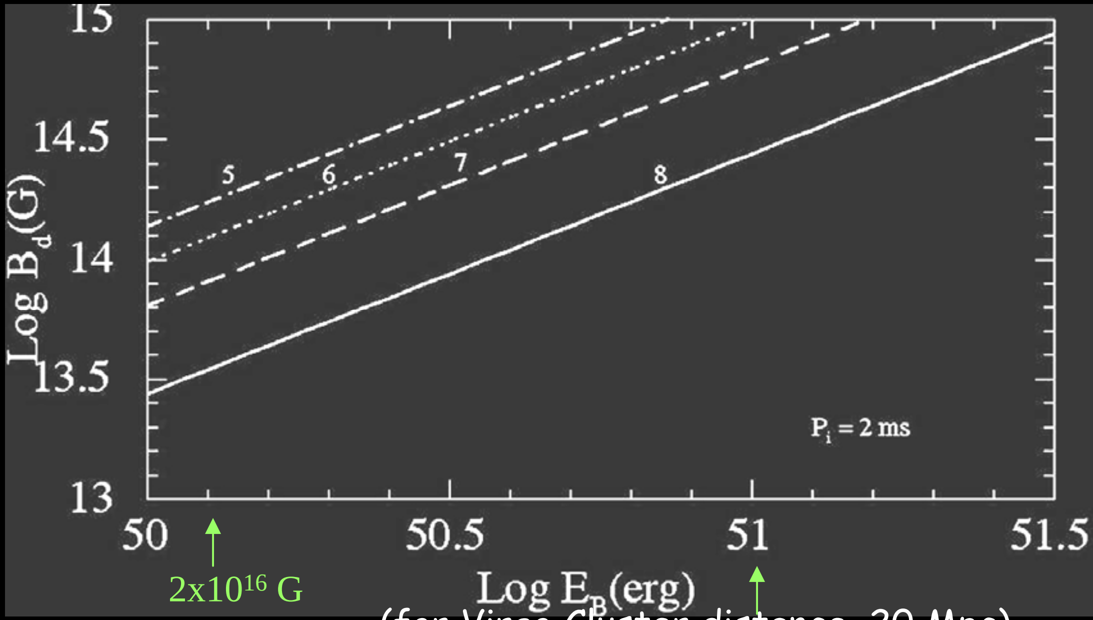
*Received March 23, 1953*

## ABSTRACT

In this paper a number of problems are considered which are related to the gravitational stability of cosmical masses of infinite electrical conductivity in which there is a prevalent magnetic field. In Section I the virial theorem is extended to include the magnetic terms in the equations of motion, and it is shown that when the magnetic energy exceeds the numerical value of the gravitational potential energy, the configuration becomes dynamically unstable. It is suggested that the relatively long periods of the magnetic variables may be due to the magnetic energy of these stars approaching the limit set by the virial theorem. In Section II the adiabatic radial pulsations of an infinite cylinder along the axis of which a magnetic field is acting is considered. An explicit expression for the period is obtained. Section III is devoted to an investigation of the stability for transverse oscillations of an infinite cylinder of incompressible fluid when there is a uniform magnetic field acting in the direction of the axis. It is shown that the cylinder is unstable for all periodic deformations of the boundary with wave lengths exceeding a certain critical value, depending on the strength of the field. The wave length of maximum instability is also determined. It is found that the magnetic field has a stabilizing effect both in increasing the wave length of maximum instability and in prolonging the time needed for the instability to manifest itself. For a cylinder of radius $R = 250$ parsecs and $\rho = 2 \times 10^{-24}$ gm/cm$^3$ a magnetic field in excess of $7 \times 10^{-6}$ gauss effectively removes the instability. In Section IV it is shown that a fluid sphere with a uniform magnetic field inside and a dipole field outside is not a configuration of equilibrium and that it will tend to become oblate by contracting in the direction of the field. Finally, in Section V the gravitational instability of an infinite homogeneous medium in the presence of a magnetic field is considered, and it is shown that Jeans's condition is unaffected by the presence of the field.

# Newborn Magnetars as Gravitational Wave Sources




(for Virgo Cluster distance, 20 Mpc)

- GW signal at ~1 kHz evolving in 1 week
- Consider initial spin period of 2ms

Most promising region is $B_t > 10^{16.5}$ G and $B_d < 10^{14}$ G

- Required no. of templates is very large

Expected magnetar birth rate in the ~2000 galaxies of Virgo: ~ 1 $yr^{-1}$ !

Potentially Very Interesting GW Event Rate in Advanced LIGO/Virgo-class instruments

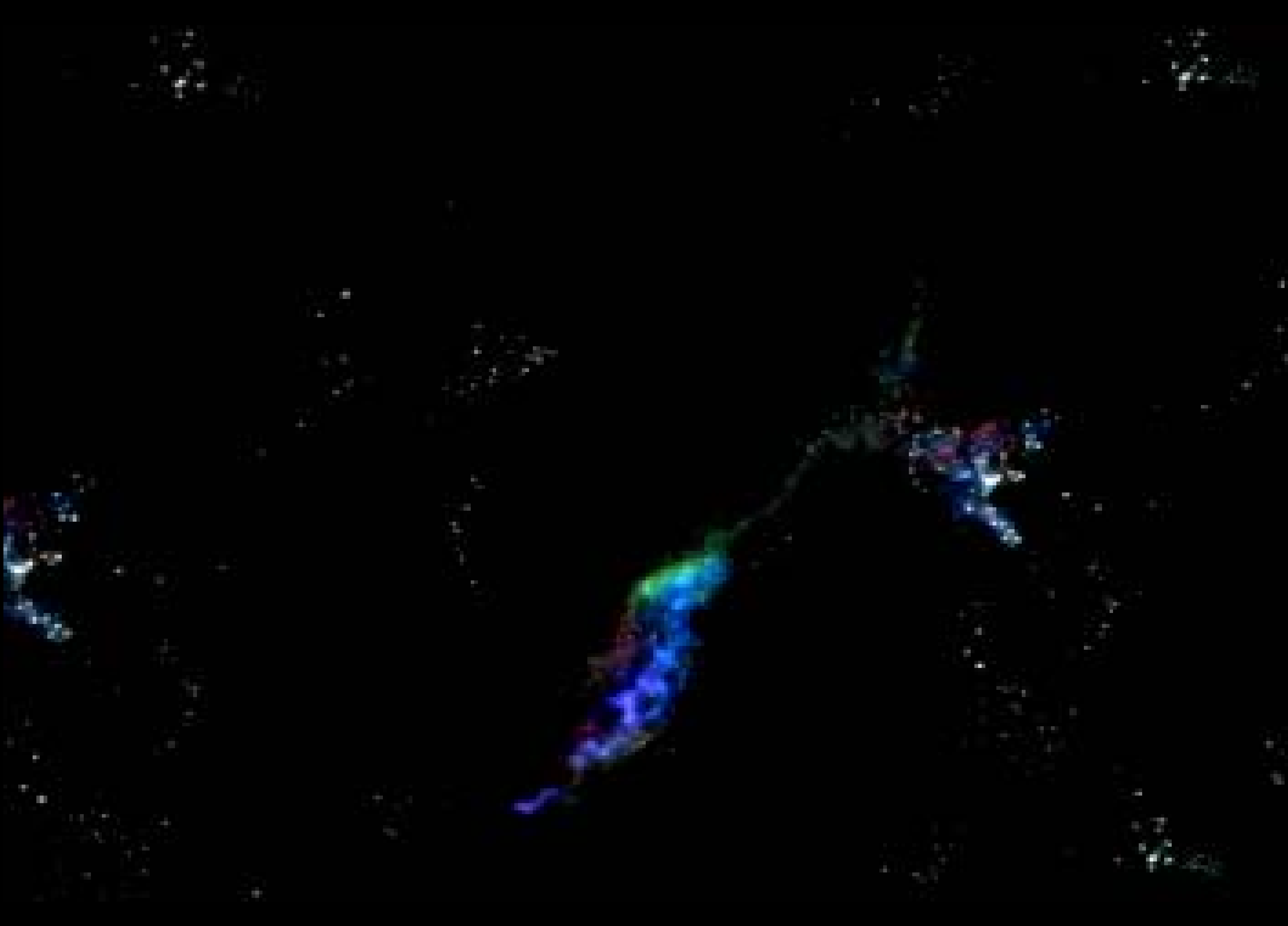
# Magnetar Studies

- A few transient magnetars discovered: magnetars might be more numerous than currently believed and their birth rate higher

- Frequency of occurrence of very high energy SGR Giant Flares to be determined: INTEGRAL program on the Virgo Cluster

- Search for magnetars in binaries

# Magnetars Giant Flares: consequences for the Earth



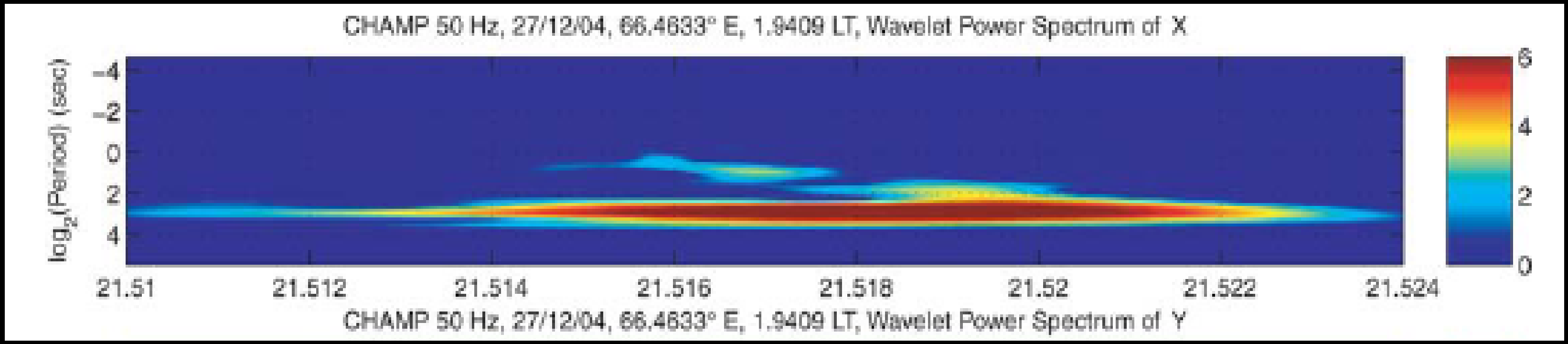
# The 2004 Dec 27 Giant Flare and the earth magnetosphere

-Ionospheric disturbance: recorded as a change in the signal  strength from very low-frequency (VLF) radio transmitters by stations around the globe (Campbell *et al.* 2005)

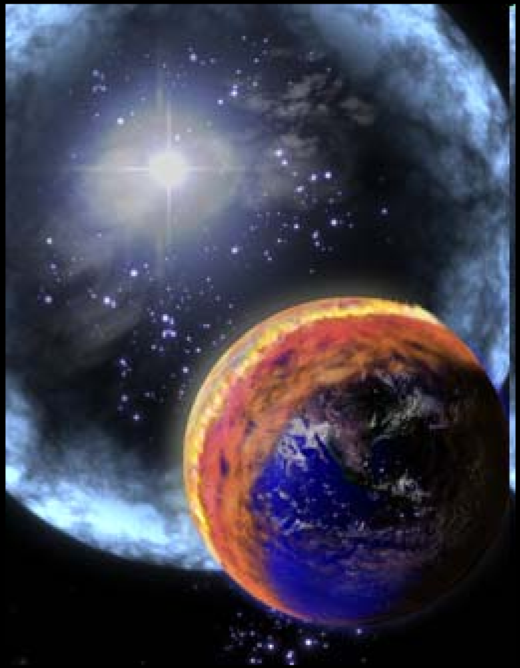
- These changes were caused by X-rays arriving fromSGR 1806-20, which ionized the upper atmosphere and modified the radio propagation properties of the Earth's ionosphere.

-21.4 kHz signal that originates in Hawaii and propagates along an ionosphere waveguide to Palmer Station, Antarctica (Inan et al. 2005).

-Ørsted, CHAMP and SAC-C satellites:  magnetic field measurements (Mandea & Balais 2007)



# Giant Flares from Magnetars and Mass Extinctions



- A Giant Flare at ~1 pc or a GRB at 100 pc would cause long term, large scale damage to the earth atmosphere
- X- and gamma rays are absorbed in the lower stratosphere (20 - 30 km). They ionise molecular Nitrogen, resulting in the formation of NOx compounds, which destroy ozone
- Increase in UV radiation would deplete the lower food chain, with drastic consequences to life worldwide.
- Attenuation length of UV radiation in water is tens of meters.
- Candidate for a GF/GRB based Mass extinction: late Ordovician, 440 Myr ago: planktonic organisms and species living in shallow water were especially affected

# Summary

The 2004 Dec 27 Giant Flare from SGR 1806-20 has yielded a wealth of new, unexpected results, some of them related to research in fundamental physics.

- neutron star astroseismology
- radiative transfer in superstrong magnetic fields
- gravitational wave signals from newborn fast spinning magnetars

But there is also a lot more to magnetars, in a variety of fields in science …, even the history of life on our planet