Constraints on the formation of **magnetars** from associated **supernova remnants**

Jacco Vink
SRON Netherlands Institute for Space Research
Astronomical Institute, Utrecht University

The central question:

What is the origin
of the high magnetic fields of magnetars?

Two possible formation scenarios

1. pre-supernova star has high magnetic field progenitor
   (fossil field hypothesis, see also Lilia Ferrario's talk)

2. - proto-neutron star is spinning close to break-up limit
   - P~ 1 ms, progenitor star has high angular momentum
   → α-dynamo → magnetic field amplification $10^{12} \rightarrow 10^{15}$G
   (Duncan & Thompson, 1992)
   For comparison: typical isolated neutron stars have B ~ 10^{12} G & P_i ~ 10 ms

Problem for rapid spinning scenario:

If magnetars are from massive stars (suggested by some observational evidence), stellar winds may have removed most angular momentum

Implications of ms proto-neutron stars

(c.f. Duncan&C.Thompson '92, T.Thompson et al. '04, Allen&Horvath '04)

- Dynamo results in magnetars fields on time scales of τ_d<10 s
- B~10^{15}G magnetic breaking τ_B < 400 s $(10^{15}$ G/B$)^2$(P/1ms$)^2$

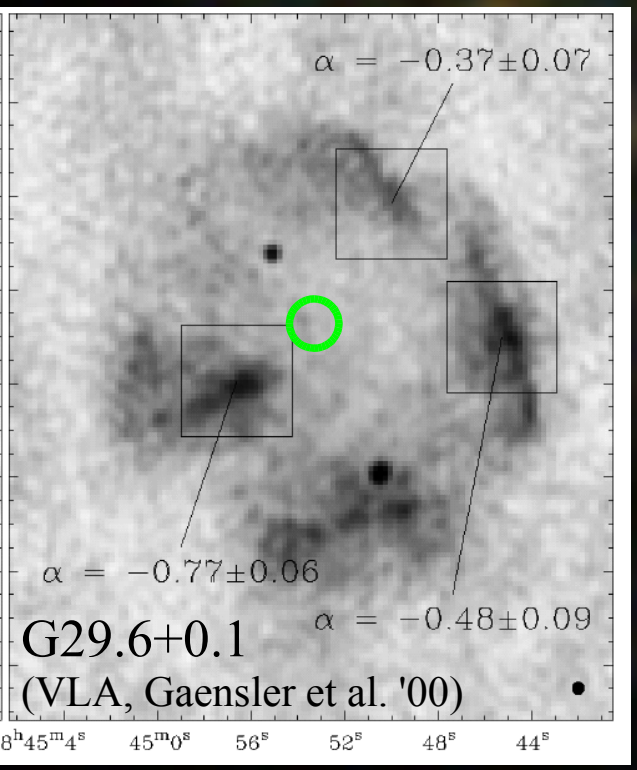
(upper limit, as propellor effect gives more rapid slow down)

- Short time scale suggests spin-down energy absorbed by supernova
- Rotational energy $E_{rot} = 3 \times 10^{52}$ erg
- If all E_{rot} converted to magnetic energy: $\langle B_{NS} \rangle \sim 3\times10^{17}$ G
- If $\langle B_{NS} \rangle \sim 10^{15\text{-}16}$ G, magnetars leads to rotation powered ***hypernovae***

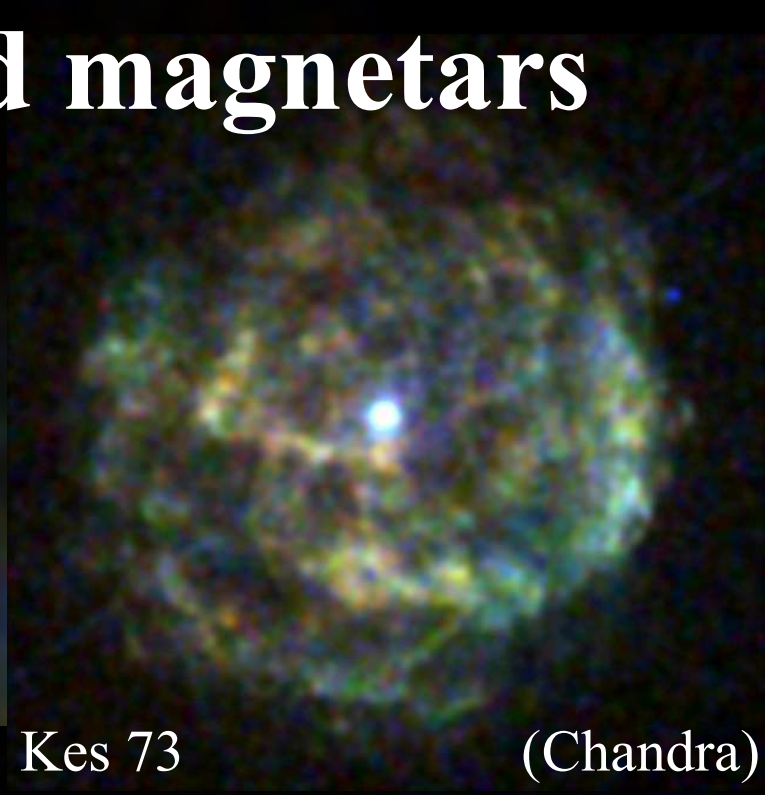
Can be tested with X-ray data of supernova remnants!

Association of SNRs and magnetars

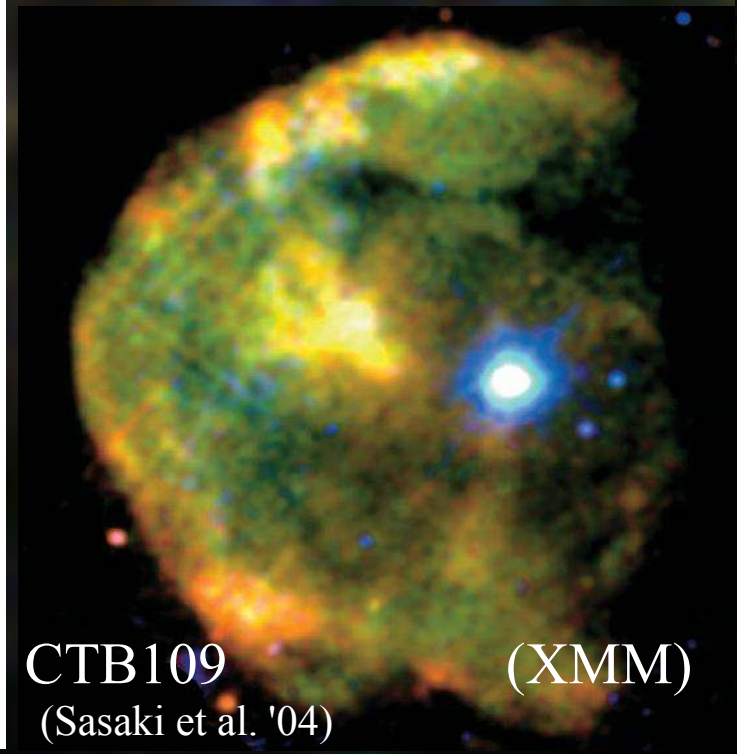
- 4 SGRs and 8 AXPs known
- 1 SGR associated with supernova remnant:
  - N49/SGR0526-66 (LMC)
- 3 AXPs associated with SNRs:
  - Kes 73/1E1841-045 (~ 7 kpc)
  - CTB109/1E2259+586 (~3 kpc)
  - G29.6+0.1/AX J1845.0-0258 (~3 kpc)



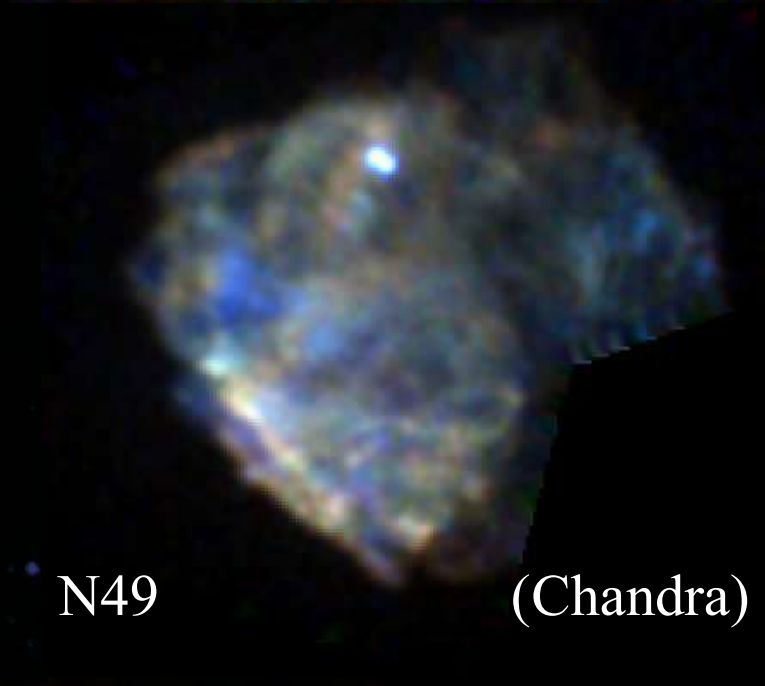
G29.6+0.1
(VLA, Gaensler et al. '00)



Kes 73 (Chandra)



CTB109 (XMM)
(Sasaki et al. '04)



N49 (Chandra)

Deriving the explosion energy

- At late times evolution is assumed to be self-similar (Sedov):

$$r^5 = 2.02\ E_k\ t^2/\rho_0,\ \ v_s = 2/5\ r/t$$

- Density low → time dependent ionization (NEI) → $n_e\ t$
- From X-ray data: $n_e\ t$, kT (= 3/16 <m> v_s^2),

emission measure ($\int n_e n_H dV$), and radius

Sufficient to determine energy, age, density

(e.g. Hamilton et al. '83, Jansen&Kaastra '93, Borkowski et al.'01)

- Some redundancy from observations, e.g. age: t=2/5 r/v, or $n_e\ t$
- Potential caveat: kT (electrons) ≠ kT (protons)
- However, equilibration is also dependent on $n_e\ t$

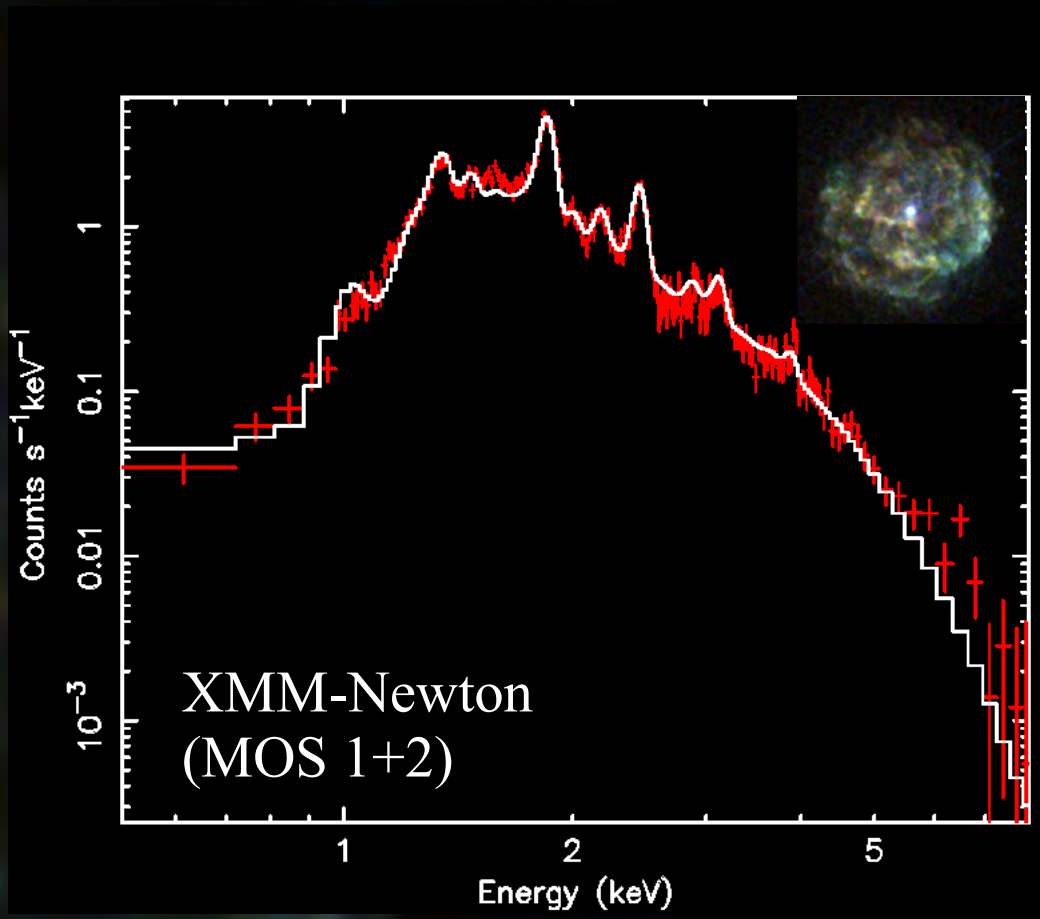
(incorporated in some spectral mode codes)

- Spectral codes: XSPEC (Hamilton/Borkowski), SPEX (Kaastra, Mewe)
- Method used by e.g. Hughes et al. '98 for LMC SNRs: E = 0.5-7 foe

Kes 73/1E1841-045

- Spherical morphology
- Distance ~ 6-7.5 kpc (HI abs.)
- Radius = 4 kpc
- Spin down age: 4500 yr
- Spectral modeling:

- kT = 0.7 keV → V_s= 800 km/s
- $n_e\ t = 4 \times 10^{11} cm^{-3} s$
- $n_e = 4\ cm^{-3}$
- mass = 27 M_{sun}
- no overabundances

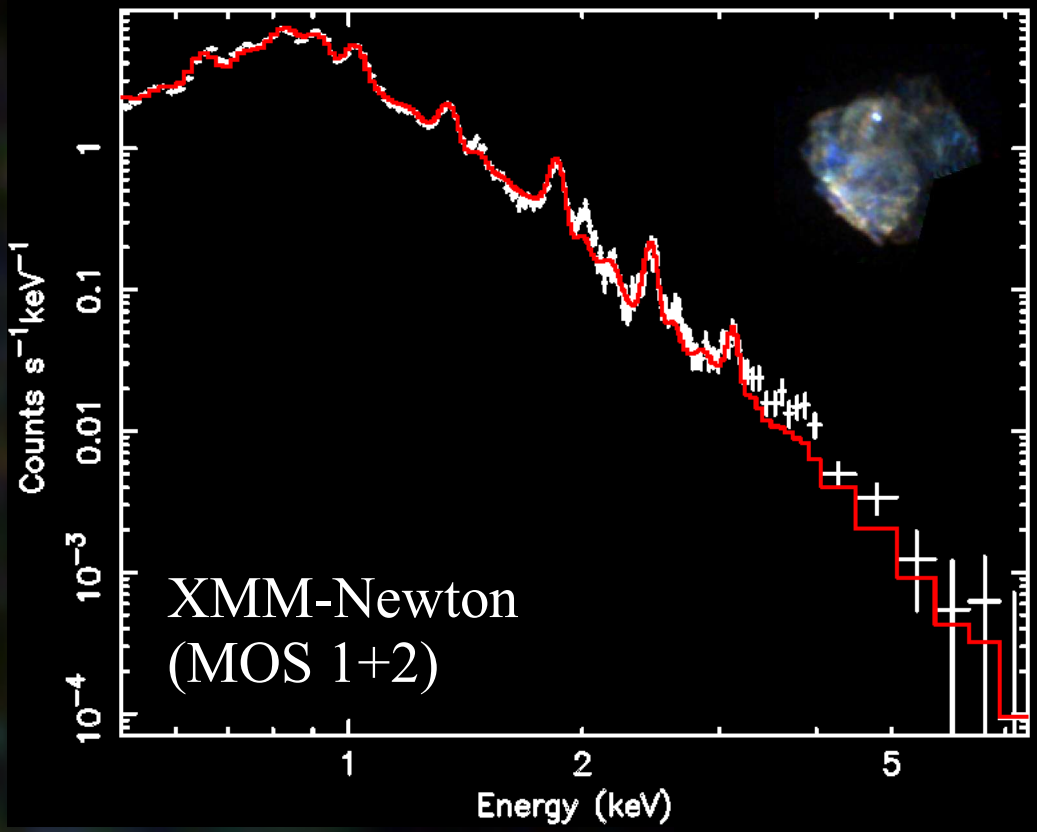


E_0 = (0.8±0.6) x 10^{51} erg
t = 970±100 yr

N49/SGR 0526-66

- Non-spherical, SNR-cloud interaction
  (e.g. Park et al. '03)
- Distance ~ 50 kpc
- Radius = 10 kpc
- Spindown age: 1900 yr
- Connection SGR/SNR requires ~1000 km/s kick
  (Gaensler et al '01)
- Spectral modeling indicates:

- $kT = 0.5$ keV $\rightarrow$ $V_s = 700$ km/s
- $n_e\ t = 4 \times 10^{12} cm^{-3} s$
- $n_e = 3\ cm^{-3}$
- mass = 346 M_{sun}
- no overabundances

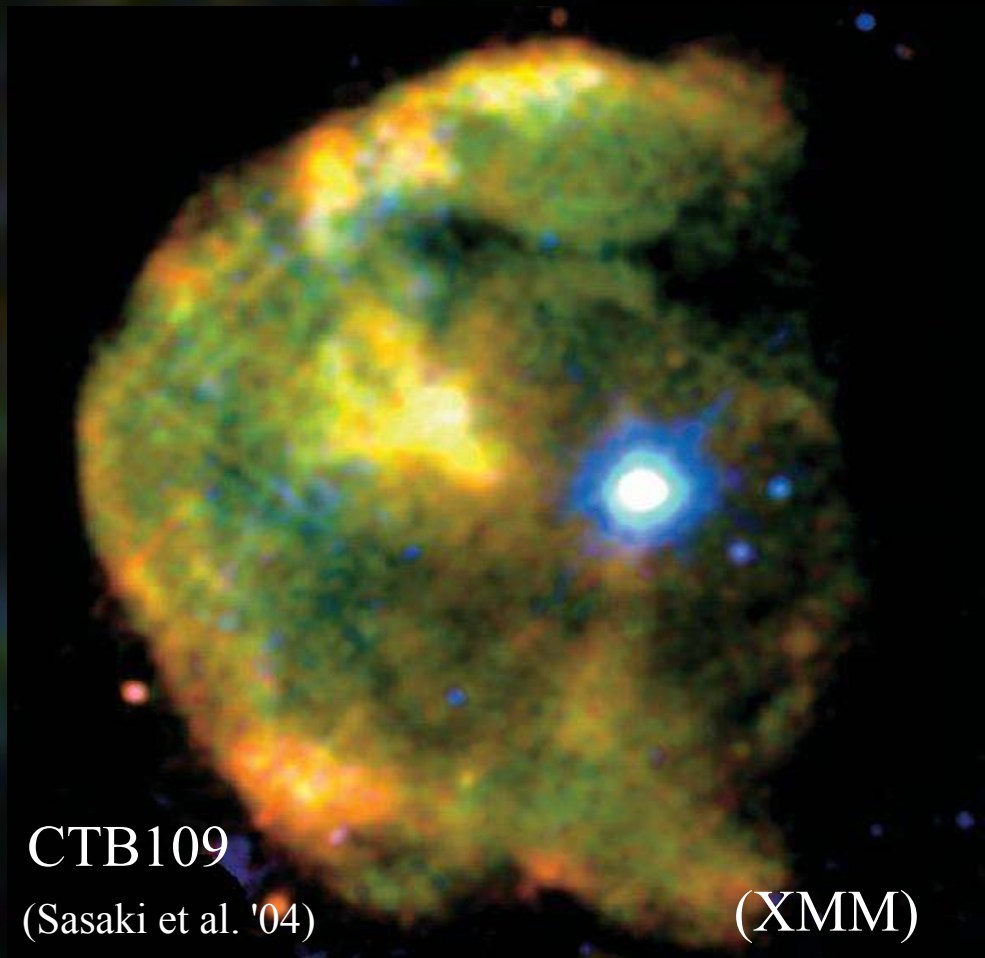


$E_0 = (2.0 \pm 0.4) \times 10^{51}$ erg
$t = 5800 \pm 2000$ yr
(see also Hughes et al. '98)

CTB109

- CTB 109 (1E2259+586): complex morphology
- AXP showed SGR-like burst
- Very long spindown age: 220 kyr

E_0 = (0.7±0.3) x 10^{51} erg from literature (Sasaki et al. '04)



CTB109

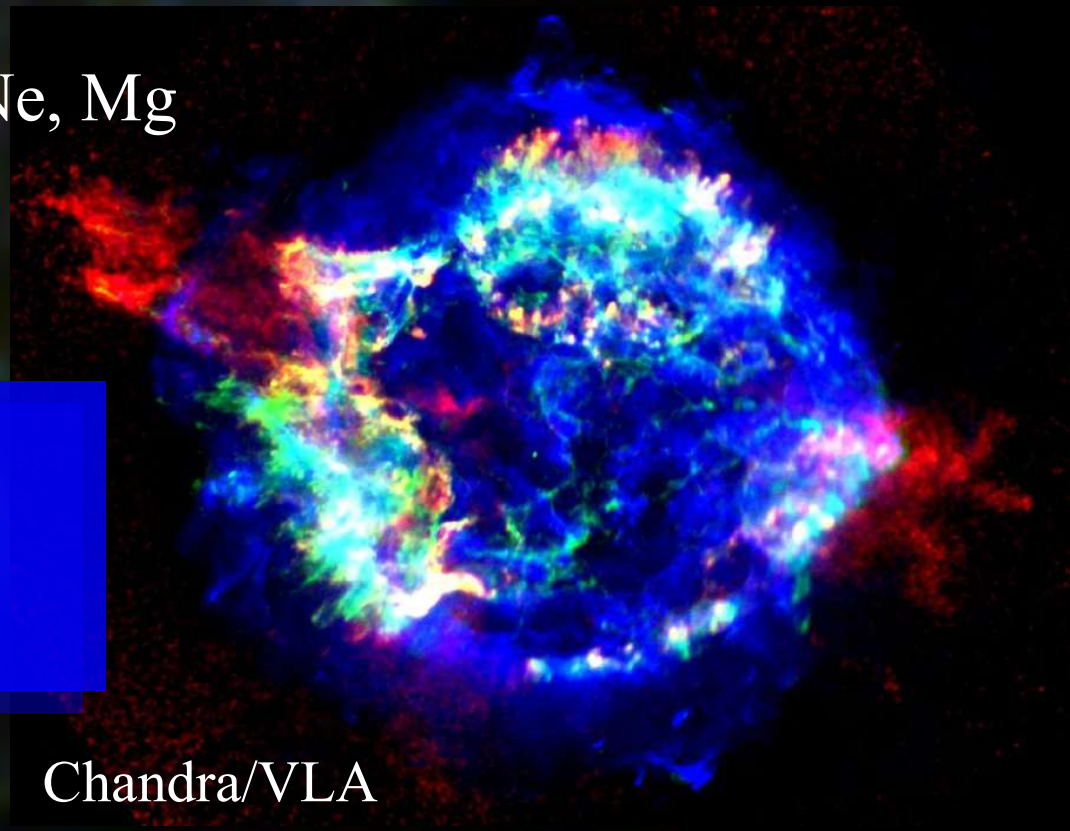
(Sasaki et al. '04)

(XMM)

Cassiopeia A

- Cas A: central compact object is potential magnetar
  (evidence for big SGR-like?- flare in ±1950, Krause et al '05)
- Not in Sedov phase, but measured shock velocity of 5000 km/s
- Evidence for jet/counter jet, mini GRB?
  (Vink '04, Hwang et al. '04)
- Energy in jets may be as high as 5×10^{50} erg
  For Hans-Thomas Janka:
- Jets enriched in Si/S, some Fe, no Ne, Mg

$E_0 = (2\text{-}2.5) \times 10^{51}$ erg
t = 330 yr
(Laming&Hwang '03, Vink '04)



Chandra/VLA

Potential Caveats

- Some SNRs in the Sedov phase, but in "ejecta phase"
  Only issue for Kes 73:
  - M rather low (argues against Sedov phase)
  - but abundance (sub)solar (against ejecta phase)
- Strongly non-uniform density structure
- Very efficient cosmic ray acceleration may have drained energy

But...
Caveats apply also to ordinary SNRs,
which have similar measured energies

Conclusions

No evidence that birth of magnetar coincides with a hypernovae!

- Magnetar hosts Kes 73, N49 and CTB109 are not more energetic than other supernova remnants
- Typical energies of (0.5 -2) x 10^{51}erg, so additional energy from magnetic breaking: $\leq \sim 10^{51}$erg
- Equating energy to rotational energy gives:

$$P_i > 5.6\ (E/1e51)^{1/2}\ \text{ms}$$

(with P_i spin *after* formation of magnetar)

- No evidence that proto-NSs spun close to break-up limit

Discussion

1. Most plausible formation scenario:
   Progenitor's magnetic field instead of angular momentum determines magnetic field of neutron star/magnetars
   (c.f. Lilia Ferrario's talk)

2. Rotational energy lost before magnetic breaking is important:
   a) spin energy is completely converted to magnetic energy
   $\rightarrow$ interior $\langle B \rangle \sim 3 \times 10^{17}$ G $>$ $B_{bip} \sim 10^{15}$ G
   b) excess spin energy is lost through gravitation radiation
   - r-mode instability (e.g. Anderson et al. '99)
   - requires rapid gravitational energy dissipation:
   $\tau_{dynamo} = 10$ s $< \tau_{Grav} < \tau_{Breaking} < 400$ s
   in conflict with recent estimates $\tau_{Grav} \sim$ few days (Arras et al. '03)
   c) magnetic field is buried for some time preventing breaking but expect presence of pulsar wind nebula!

Most likely formation scenario for magnetars: massive stars with high magnetic fields