Magnetars in Supernova Remnants

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Magnetars Formation

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The central question:

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

Two possible formation scenarios

1. progenitor star has high magnetic field (fossil field hypothesis)

2. - proto-neutron star is rapidly spinning
   - P< 3 ms (~ 3 ms proto NS convective overturn time),
     convective dynamo → growth of magnetic field to ~10^{15}G
     (Duncan & Thompson, 1992)
   C.f.: typical isolated neutron stars have B ~ 10^{12} G & P_i ~ 10 ms

Problems for rapid spinning scenario:

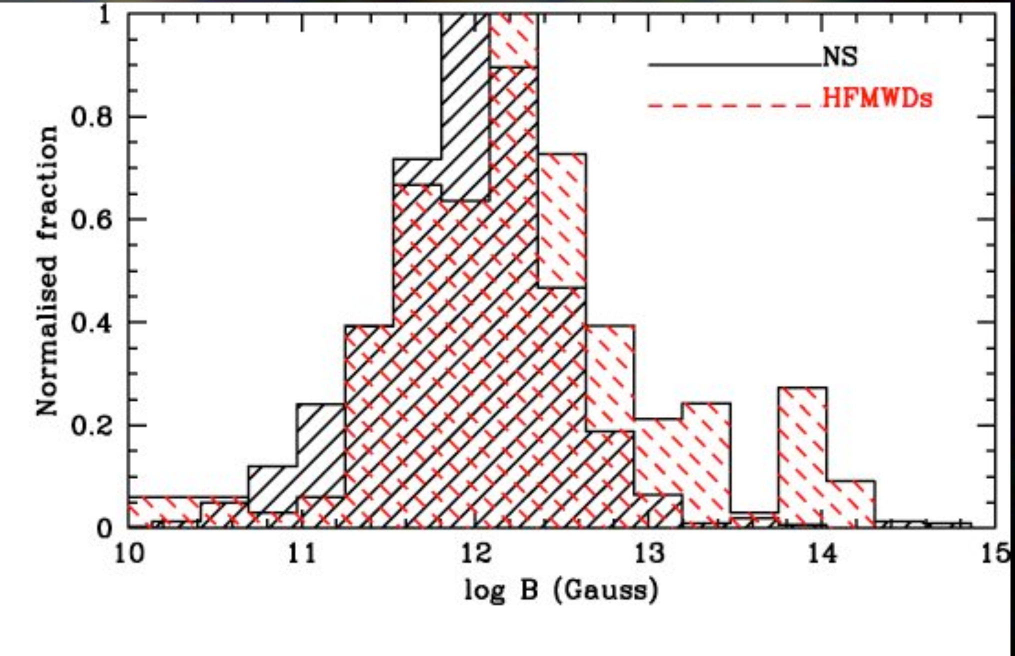
- If magnetars are from massive stars stellar winds may have removed most angular momentum
- Simulations don't show enough differential rotation (Fryer & Warren 2004)

The Fossil Field Hypothesis

- Similar distributions B-fields of White Dwarfs and Neutron stars (Ferrario & Wikramsinghe 2006)
- F&W: B-field variation reflects variation in the ISM
- High B-field WD/NSs should have slow rotation (rotational coupling of wind/core through B-field)
- But: giant flare of SGR1806 suggests even higher internal field:

  $B_{int} > 10^{16}$G

  (e.g. Stella et al. 2006)



Implications of ms proto-neutron stars

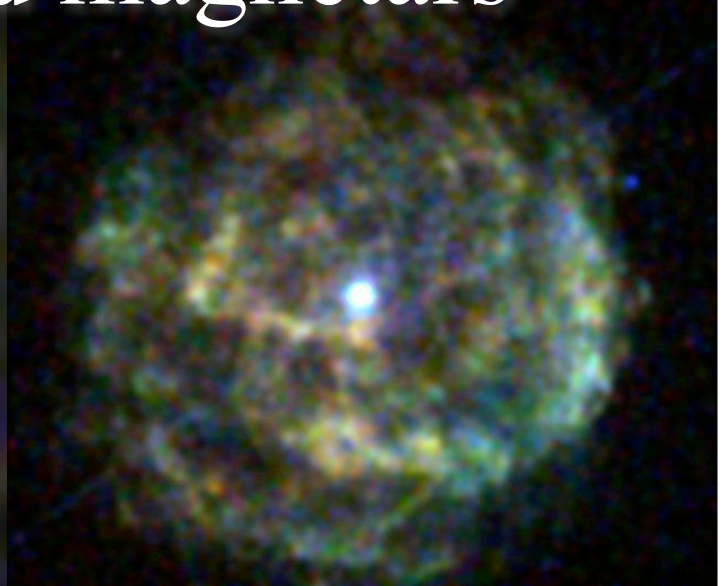
(c.f. Duncan&C.Thompson '92, T.Thompson et al. '04, Allen&Horvath '04)

- Dynamo results in magnetars fields on time scales of $\tau_d < 10$ s
- $B \sim 10^{15}$G magnetic breaking $\tau_B < 400\ \mathrm{s}\ (10^{15}\ \mathrm{G/B})^2 (P/1\mathrm{ms})^2$
  (upper limit, as propellor effect gives more rapid slow down)
- Short time scale suggests spin-down energy absorbed by supernova
- For P ~ 1 ms, rotational energy $E_{rot} \sim 3\mathrm{x}10^{52}$ erg
- If all E_{rot} converted to magnetic energy: $\langle B_{NS} \rangle \sim 3\mathrm{x}10^{17}$ G
- If $\langle B_{NS} \rangle \sim 10^{15\text{-}16}$ G, magnetars may power ***hypernovae***
  (T. Thompson et al. 2004)

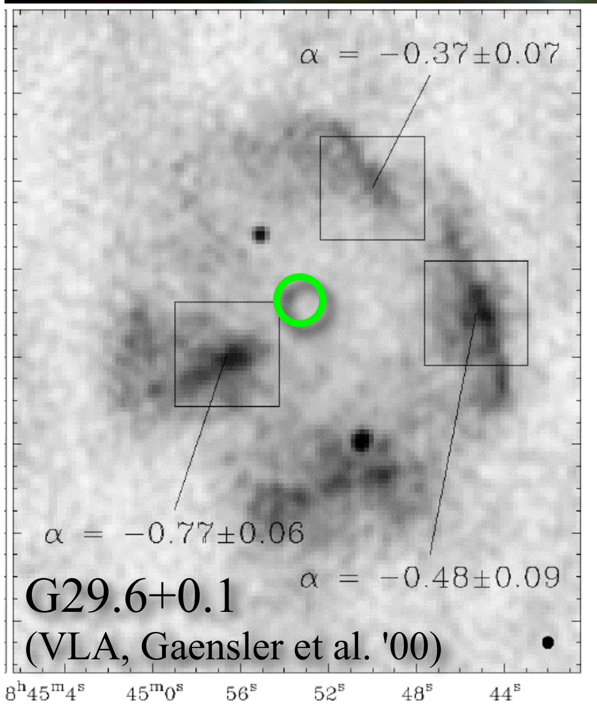
Can be tested with X-ray data of supernova remnants!

Association of SNRs and magnetars

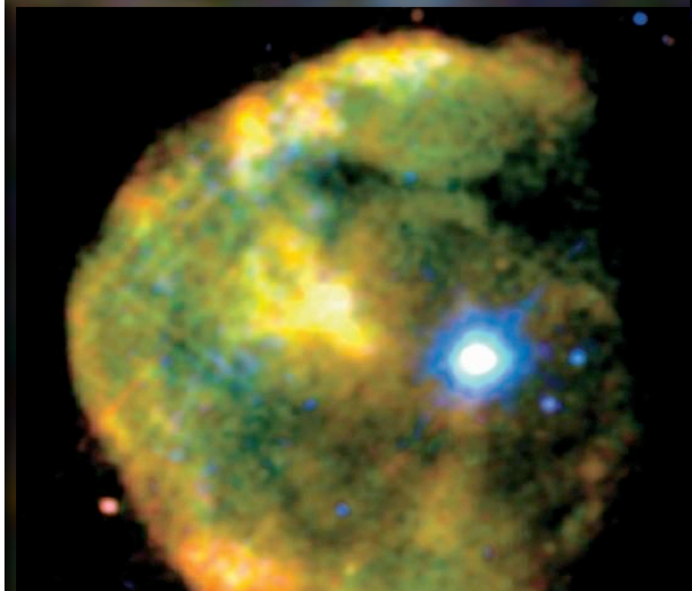
- 8 AXPs/4 SGRs known
- 1 SGR associated with supernova remnant:
  - N49/SGR0526-66 (LMC)
- 3 AXPs associated with SNRs:
  - Kes 73/1E1841-045 (~ 7 kpc)
  - CTB109/1E2259+586 (~3 kpc)
  - G29.6+0.1/AX J1845.0-0258 (~3 kpc)



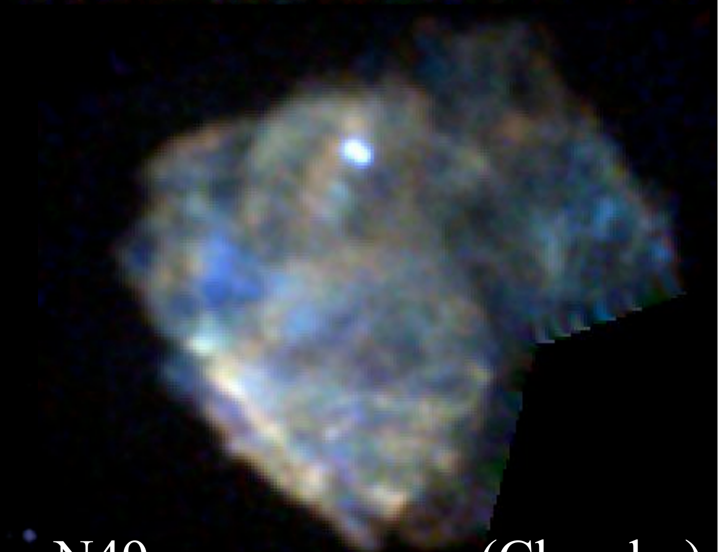
Kes 73 (Chandra)



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



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



N49 (Chandra)

Deriving the explosion energy

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

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

- Density low → time dependent ionization (NEI) → $n_e\, t$
- From X-ray data: $n_e\, t$, $kT\ (= 3/16 \langle m \rangle v_s^{\,2})$, emission measure ($\int n_e n_H dV$), and radius

  Sufficient to determine energy, age, density

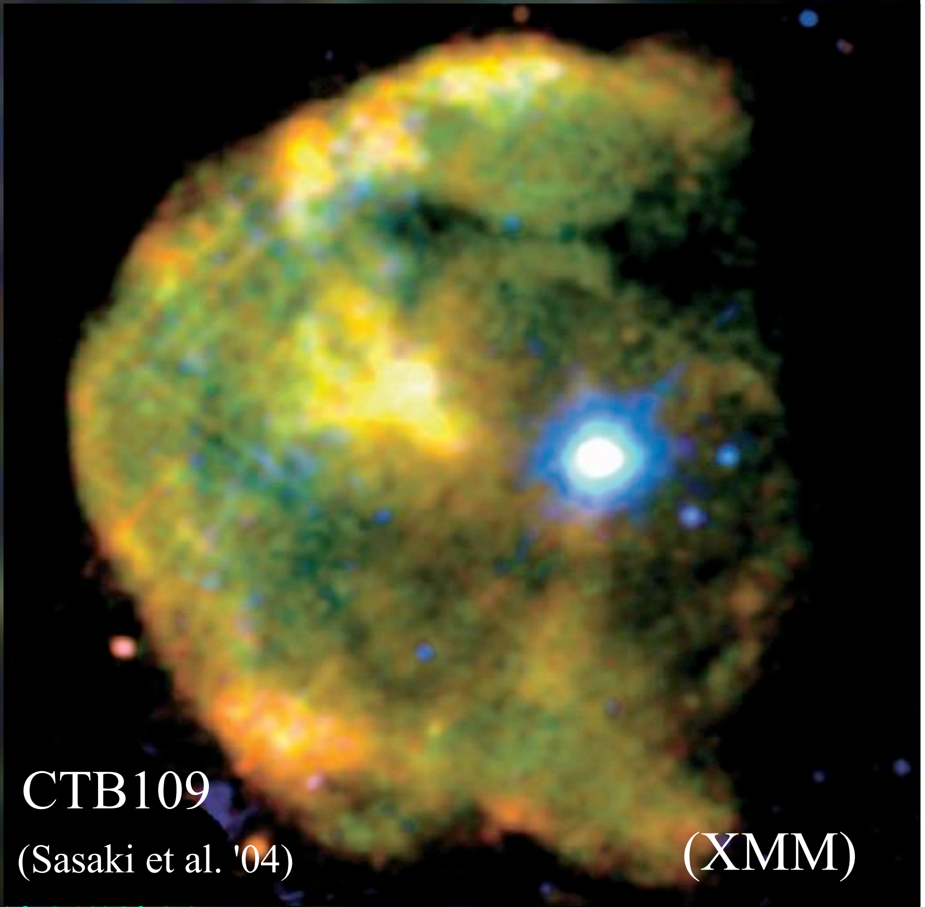
  (e.g. Hamilton et al. '83, Jansen&Kaastra '93, Borkowski et al.'01)
- Some redundancy from observations, e.g. age: $t=2/5\, r/v$, or $n_e\, t$
- Potential caveat: kT (electrons) ≠ kT (protons)
- However, equilibration is also dependent on $n_e\, t$

  (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

CTB109

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

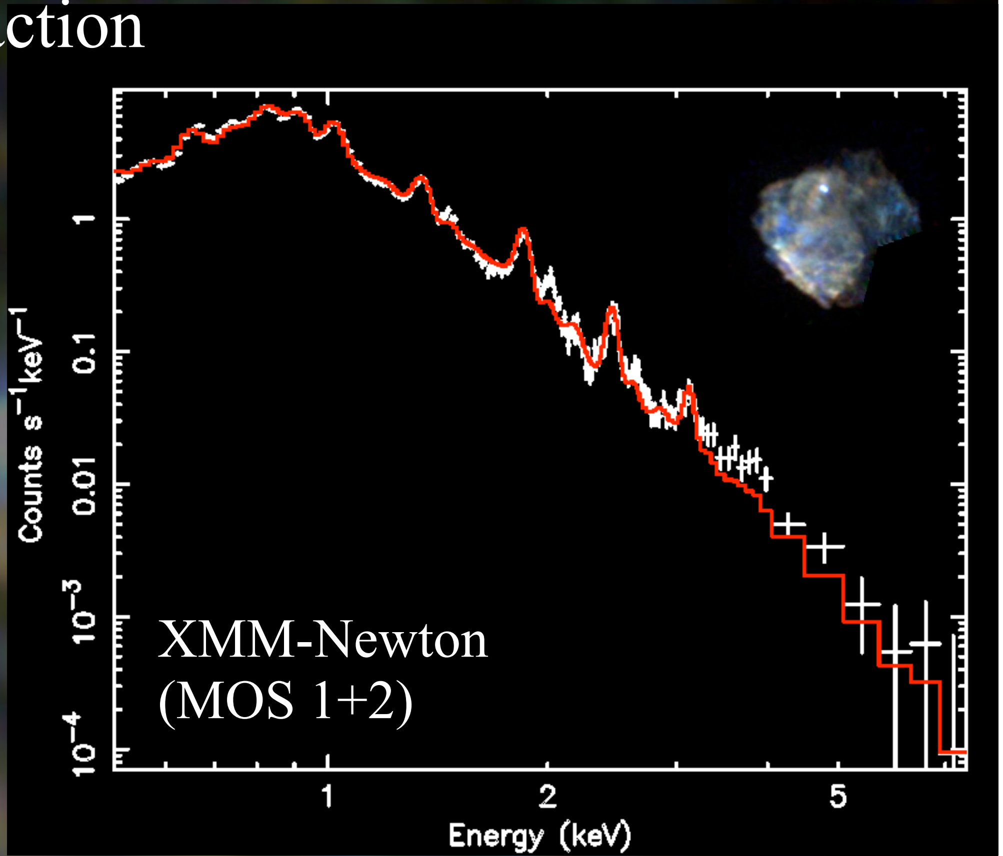
E_0 = (0.7±0.3) x 10^{51} erg from literature (Sasaki et al. '04)



N49/SGR 0526-66

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

- kT = 0.5 keV → V_s = 700 km/s
- $n_e t = 3 \times 10^{12} cm^{-3} s$
- $n_e = 3 \, cm^{-3}$
- mass = 320 M_{sun}

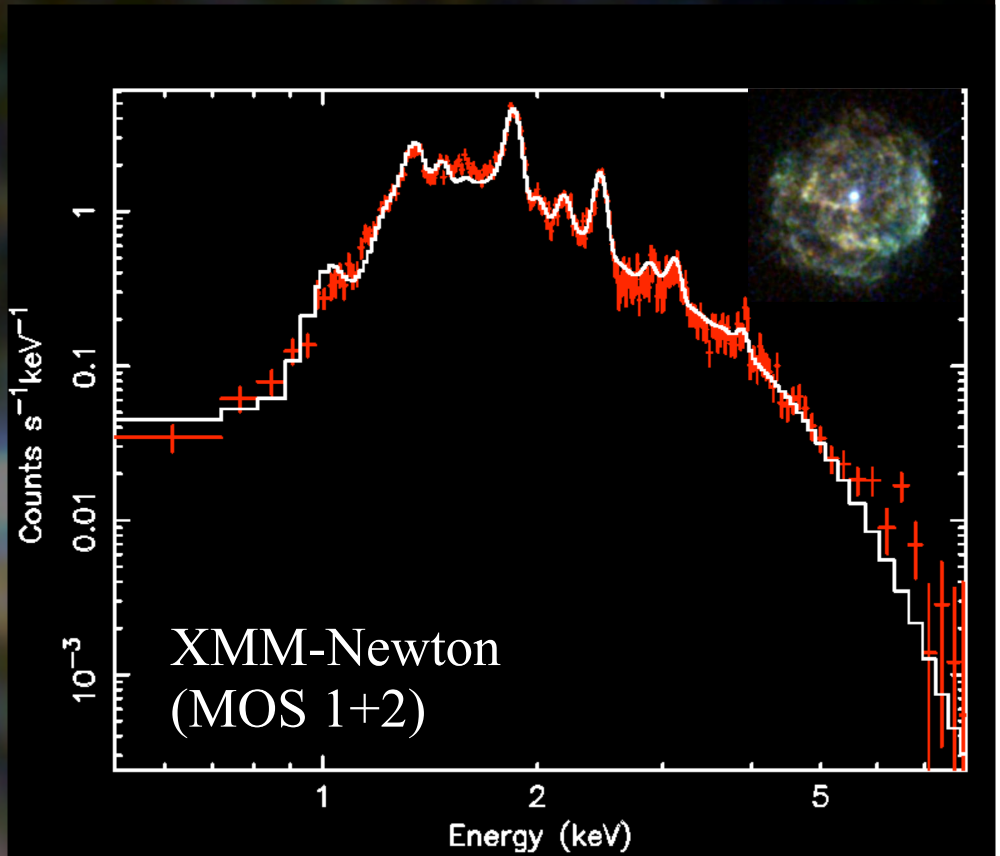


$E_0 = (1.3 \pm 0.3) \times 10^{51}$ erg
t = 6300±1000 yr
(see also Hughes et al. '98)

Kes 73/1E1841-045

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

- kT = 0.7 keV → V_s = 800 km/s
- $n_e\, t = 4\times10^{11}\,\mathrm{cm^{-3}s}$
- $n_e = 3\ \mathrm{cm^{-3}}$
- mass = 29 M_{sun}
- no overabundances



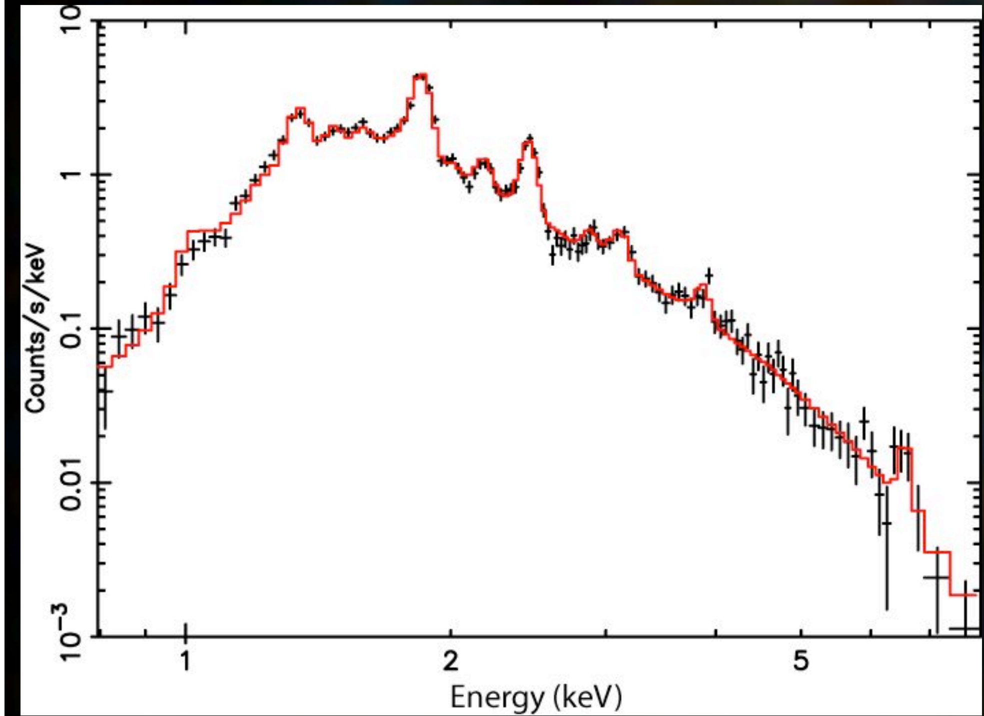
$E_0 = (0.5\pm0.3) \times 10^{51}$ erg
t = 1300±200 yr

Was Kes 73's progenitor a massive star?

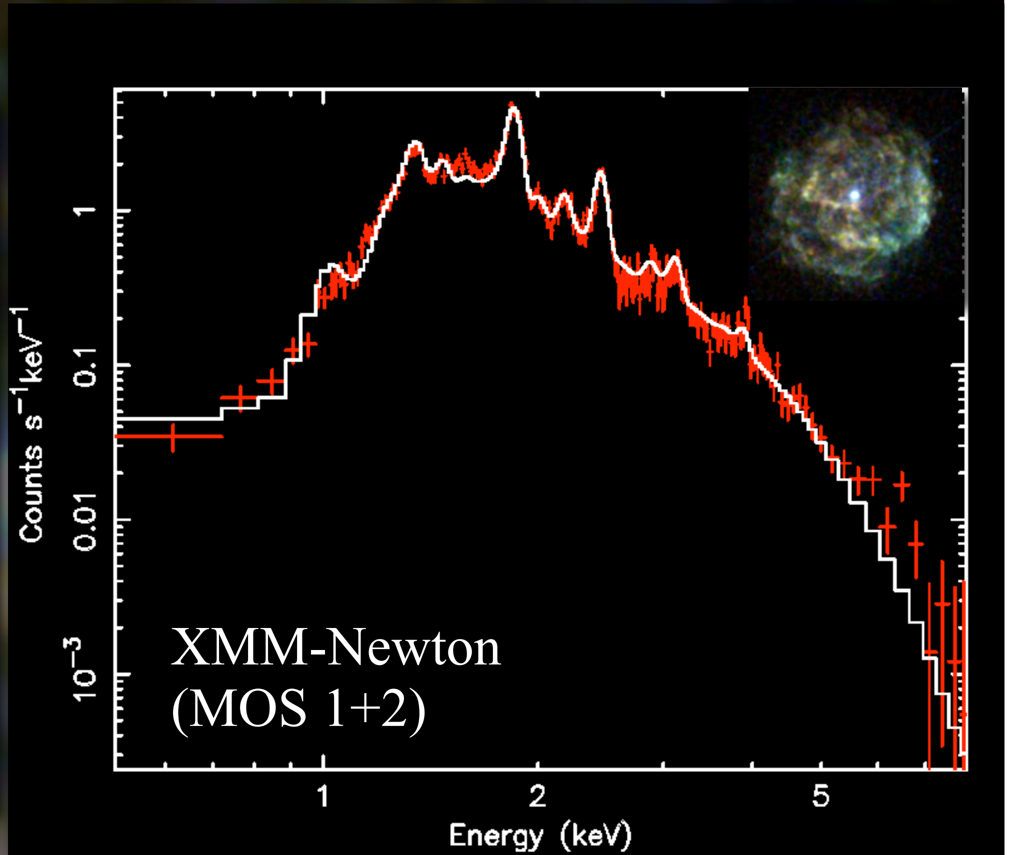
- Spectral models give different abundances
- SPEX program gives best fits, but consistent with solar abundances!!
- Not consistent with young SNR with oxygen rich ejecta!!
  (c.f. Cas A, G292+1.8)
- Suggest hydrogen rich envelope, i.e. progenitor MS mass of < 20 M_{sun}
- Suggests not all magnetars come from the most massive stars?
- Contrary to some evidence for SGRs (Gaensler)
- Could there be a difference between AXPs and SGRs?

	Kes 73	
Model	2 NEI	Sedov
EM (10^{12}cm^{-5})	26.9 ± 3.1	16.4 ± 1.5
kT_e (keV)	0.63 ± 0.06	0.72 ± 0.3
$n_e t$ (10^{11}cm^{-3}s)	3.1 ± 0.8	4.6 ± 0.2
EM_2 (10^{12}cm^{-5})	2.0 ± 0.5	
kT_{2e} (keV)	2.26 ± 0.35	
$n_e t_2$ (10^{11}cm^{-3}s)	0.47 ± 0.10	
O	(1)	(1)
Ne	(1)	(1)
Mg	1.13 ± 0.13	1.95 ± 0.15
Si	1.09 ± 0.07	1.7 ± 0.1
S	1.12 ± 0.06	1.6 ± 0.1
Ar	1.02 ± 0.18	1.1 ± 0.1
Ca	1.84 ± 0.42	0.77 ± 0.33
Fe	0.42 ± 0.15	4.3 ± 0.7
N_H (10^{21}cm^{-2})	27.3 ± 0.6	31.2 ± 0.6
Fit range (keV)	0.8–8.0	0.8–8.0
C-statistic/d.o.f.	186/110	956/468

Comparison of two models



Spectral model code: SPEX (2NEI)
Gives ~solar abundances



Spectral model code: XSPEC (Sedov)
Gives overabundances, but does fit as well

Potential Caveats

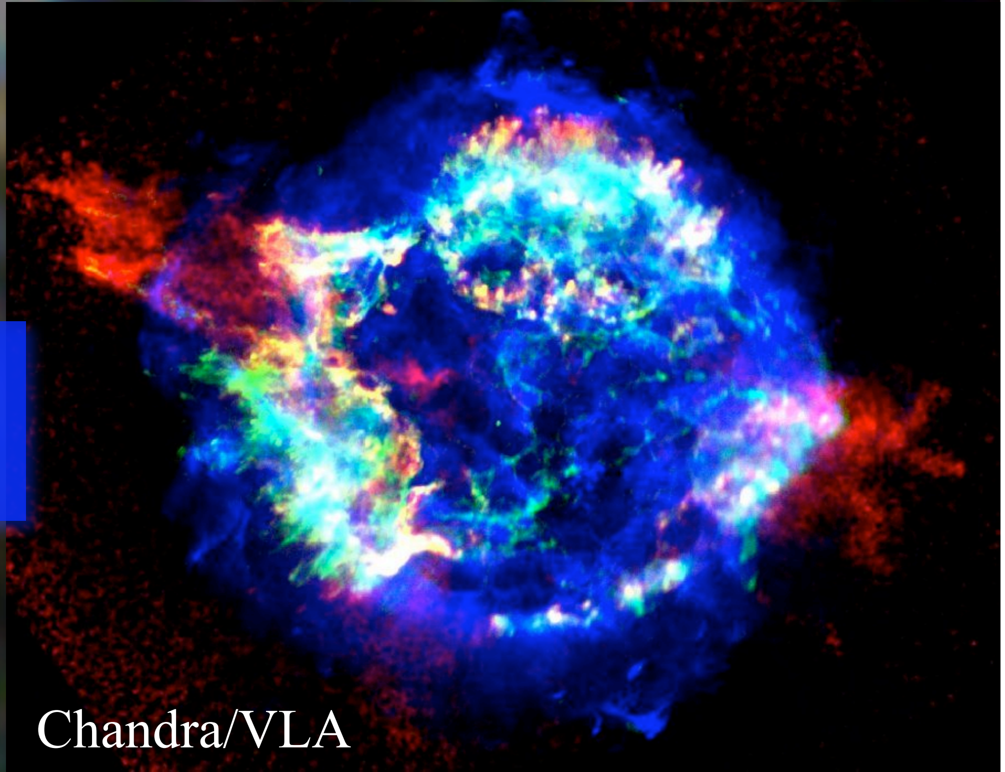
- Some SNRs in the Sedov phase, but in "ejecta phase"
  Only issue for Kes 73:
  - M rather low (argues against Sedov phase)
  - but abundance (sub)solar (against ejecta phase)
  - more elaborate models (Truelov&McKee '99) confirm E<0.5 foe
- Strongly non-uniform density structure
- Very efficient cosmic ray acceleration may have drained energy
- Additional energy ejected in form of jet
  - hard to confine jet for a long time
  - no morphological evidence for jet in 3 SNRs
  - jet only seen in Cas A

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

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 '03, Hwang et al. '04)
- Energy in jets 1 - 5x10^{50} erg
- Jets enriched in Si/S, some Fe, no Ne, Mg
- Suggest more efficient burning

E_0 = (2-2.5) x 10^{51} erg
t = 330 yr



Chandra/VLA

Conclusions

Presence of magnetar does not imply hypernova remnant!

- 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: < 10^{51}erg
- Equating energy to rotational energy gives:
  $P_i > 5\,(E/10^{51})^{1/2}$ ms
  (with P_i spin *after* formation of magnetar)
- No evidence that proto-NSs of magnetars had P ~ 1 ms

Discussion: explanations of results

1. Plausible formation scenario:
   Progenitor's magnetic field instead of angular momentum determines magnetic field of neutron star/magnetars
   (c.f. Ferrario's & Wickramsinghe 2006, B-field distribution in WDs vs NSs)

2. Angular momentum is taken away before magnetic braking:
   - spin energy is completely converted to magnetic energy
     $\rightarrow$ interior $\langle B \rangle \sim 3\times10^{17}$ G $>$ $B_{bip} \sim 10^{15}$ G
   - excess spin energy is lost through gravitation radiation
     - most plausible way: NS deformation due to high B-field
       ($B_{int} > 5\times10^{16}$ G, $B_{bip} \sim 10^{14}$G, Stella et al. 2005)
   - magnetic field is buried for some time preventing breaking
     but expect presence of pulsar wind nebula!

3. Magnetic field amplification is still possible around P~5 ms

How likely are points 2 & 3 ?
The case of Kes 73/1E1841-045

- According to this study: T=1300 yr, P_{psr}=11.8 s
- Magnetic braking, current B = 7 x 10^{14}G
- Needed to go from ~5 ms to 11.8 s: B_p = 1.6 x 10^{15}G
- Gravitational radiation only dominant for very fast periods ($\sim\Omega^5$)
- After having reached 10 ms magnetic braking more dominant
- Expect a fossil pulsar wind nebula in radio (not X-rays: losses)
- Instead: AXP is inside hole in radio emission
- AXP born with P > 1 s?
- Or AXP PWN quenched by some phenomenon (high B-field, early/fast formation inside ejecta)