The Zoo of Neutron Stars in Supernova Remnants (SNR): An X-ray View

Neutron Stars Diversity ↔ SNR connection

Birth and evolution (part I)
SN Progenitors (part II)
Supernova Remnants
The Big Picture

• Our Galaxy’s dynamics and magnetism (ENERGY)
  - The non-thermal Universe (see talk by Emma de Ona Wilhelmi)
  - Galactic B-field (see talk by Jennifer West)
Our Galaxy’s dynamics and magnetism (ENERGY)

- The non-thermal Universe

Nucleosynthesis (MATTER)
— the thermal Universe

- SN progenitors (this talk)
- See also talk by Paolo Mazzali
Supernova Remnants
Our Cosmic Connection to the Elements

Nucleosynthesis (MATTER)

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adapted, credit: NASA (+ personal photos)
Supernova Remnants
The Big Picture

- Our Galaxy’s dynamics and magnetism

- Nucleosynthesis (MATTER) — the thermal Universe

- Nearby Laboratories for Extreme Physics
  - Link to GRBs (see N. Gehrels’ and P. Mazzali’s talks)
  - Neutron Stars (this talk; see also GianLuca Israel’s talk)

Their magnetic fields: formation and evolution through SNR studies!
Neutron Stars: The Big Picture

M~1.4 solar masses
R~10 km
Period~ms-sec
B~10^9-10^{15} Gauss

discovered as pulsars by Jocelyn Bell

The physics of the “extreme”!
Pulsars’ Intrinsic Properties
Spin (P), Spin down (Pdot) => Magnetic Field (B) and “Age”

\[ E = \frac{d}{dt} \left( \frac{1}{2} I \Omega^2 \right) = I \cdot \dot{\Omega} \cdot \ddot{\Omega} \]

\[ = \frac{2}{3c^3} |m|^2 \Omega^4 \sin^2 \alpha \]

Surface dipole magnetic field

\[ B = \sqrt{\frac{3c^3}{8\pi^2 R^6 \sin^2 \alpha}} \frac{I}{P \dot{P}} = 3.2 \cdot 10^{19} \sqrt{P \dot{P}} \text{ Gauss} \]

Credit: Pearson Prentice Hall, Inc.
Pulsars’ Intrinsic Properties
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surface dipole magnetic field

\[ B = \sqrt{\frac{3c^3 I}{8\pi^2 R^6 \sin^2 \alpha}} P \dot{P} = 3.2 \cdot 10^{19} \sqrt{P \dot{P}} \text{ Gauss} \]

“True” age

\[ \dot{\Omega} = -k \Omega^n \]

\[ \tau = \frac{P}{(n-1) \dot{P}} \left[ 1 - \left( \frac{P_0}{P} \right)^{(n-1)} \right] \]

n=braking index (=3: dipole)

\[ n = \nu \dot{\nu} / \dot{\nu}^2 \]
Pulsars’ Intrinsic Properties

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\[ n = \frac{\nu \ddot{\nu}}{\dot{\nu}^2} \]

“True” age

“characteristic” age

(assumes constant B, Magnetic Dipole, and P0<<P)

IAU Honolulu
Division D, Aug (2015)

S. Safi-Harb
The Crab PSR-SNR association

P=33 ms
Slows down with time:
\[ \frac{dP}{dt} \approx 1.3 \text{ ms/century} \]

Rotation-powered Pulsar (RPP)
powering a Pulsar Wind Nebula (PWN)=non-thermal synchrotron

\[ \dot{E} = -I \Omega \dot{\Omega} = \frac{4\pi^2 I \dot{P}}{P^3} \]
The Crab
PSR-SNR association

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Slows down with time:
\( \frac{dP}{dt} \approx 1.3 \text{ ms/century!} \)

Rotation-powered Pulsar (RPP)

powering a Pulsar Wind Nebula (PWN)=non-thermal synchrotron

\( B \approx 5 \times 10^{12} \text{ Gauss} \)
Spin Down age\( \approx 1.3 \text{ kyr} \)
comparable to \( 961 \text{ yr (SN1054)} \)
The Crab
PSR-SNR association

P=33 ms
Slows down with time:
dP/dt~1.3 ms/century!

A “shell-less” or “Naked” SNR!
- unseen cold ejecta/CSM far out?
- low-energy (<~1e50 ergs) explosion of 8-10 Mo progenitor with early dense CSM interaction (type IIln-P)? Smith+13

B~5 x 10^{12} Gauss
Spin Down age~1.3 kyr
comparable to 961 yr (SN1054)
"P-Pdot" Diagram of Pulsars => Neutron Stars Diversity (Zoo)

"Isolated":
- RPP
- Magnetars
- HBPs
- CCOs

+ XDINSs (INS),
+ RRATs…

\[ B (\text{Gauss}) = 3.2 \times 10^{19} [P(s)\dot{P}(s/s)]^{1/2} \]

\[ \tau = \frac{P}{2\dot{P}} \]
"P-Pdot" Diagram of Pulsars => Neutron Stars Diversity (Zoo)

- **Isolated**: RPP, Magnetars, HBPs, CCOs
- XDINSs (INS), RRATs...

- **Rotation-powered (RPP)**
- **Accretion-powered**

\[
B \text{ (Gauss)} = 3.2 \times 10^{19} [P(s)\dot{P}(s/s)]^{1/2}
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\tau = \frac{P}{2\dot{P}}
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“Isolated”:
- RPP
- Magnetars
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- CCOs
- XDINSs (INS), RRATs...

Rotation-powered (RPP)
Magnetars (magnetically powered)
Accretion-powered

\[ B \text{ (Gauss)} = 3.2 \times 10^{19} [P(s) \dot{P}(s/s)]^{1/2} \]

\[ \tau = \frac{P}{2P} \]
"P-Pdot" Diagram of Pulsars => Neutron Stars Diversity (Zoo)

“Isolated”: RPP
Magnetars
HBPs
CCOs

XDINSs (INS), RRATs...

\[ B \text{ (Gauss)} = 3.2 \times 10^{19} \left[ P(s) \dot{P}(s/s) \right]^{1/2} \]

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"P-Pdot" Diagram of Pulsars => Neutron Stars Diversity (Zoo)

- Magnetars
- High-B Pulsars (HBPs)
- Rotation-powered (RPP)
- Accretion-powered
- Central Compact Objects (CCOs): Anti-magnetars? Accreting??

\[ B (\text{Gauss}) = 3.2 \times 10^{19}[P(s) \dot{P}(s/s)]^{1/2} \]
The many “faces” of Neutron Stars in Supernova Remnants

- Rotation-Powered Pulsar (RPP)
- High-B Pulsar (HBP)
- Anomalous X-ray Pulsar (AXP)
- Soft Gamma-ray Repeater (SGR)
- Central Compact Object (CCO)

AXPs (magnetars) and CCOs are exclusively X-ray objects!
Distinction between magnetars and the other classes has been blurred with the discovery of...

- **Magnetar-like behaviour** from a high-B pulsar (HBP) thought to be rotation-powered (Crab-like)
Distinction between magnetars and the other classes has been blurred with the discovery of....

- Magnetar-like behaviour from a high-B pulsar (HBP) thought to be rotation-powered (Crab-like)

HBP J1846-0258 in SNR Kes75

Kumar & SSH 2008

Gavriil et al. 2008
Distinction between magnetars and the other classes has been blurred with the discovery of:

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- Discovery of transient magnetars (e.g. Ibrahim et al. 2003)

- Discovery of radio emission from transient magnetars (Camilo et al. 2006)
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- Discovery of radio emission from transient magnetars (F. Camilo et al.)

- Discovery of “low-B” (below QED) magnetars!

adapted from Rea et al: Rea et al. 2010 (SGR0418), 2012; Scholz et al. 2012 (Swift source), Zhou et al. 2014 (3XMM source near SNR Kes79)
How about the **CCOs (Central Compact Objects)**

**Anti-magnetars?**

- Central Compact Objects (~15 known in SNRs)
- **X-ray** emitters ONLY
- **No pulsar wind nebulae**
- \( L_x > E_{\text{dot}} \), steady, thermal
- quiescent magnetars? cooling? accreting?
- **X-ray pulsations** (3 objects):
  - 105 ms, 112 ms, 424 ms
  - \( B = 3.1/2.9/9.8 \times 10^{10} \) G (\(< 10^{11} \) G)
  - => “anti-magnetars”!

**PSR ages>>> SNR ages**

**How connected to the other neutron star classes?**

**Are they “low” or “high” B-field neutron stars?**

- e.g. Gotthelf & Halpern’13, ‘09 (timing); Ho & Heinke’09 (spectroscopy of CasA CCO);
- Gotthelf+13, Bogdanov+14, Luo+15 (Descendants of CCOs); Ho 2011, Bernal & Page 11 (B growing/submerged);
- De Luca+08, Pavlov+08 (reviews)
Neutron Stars Diversity

The age and braking index “problem” \iff SNR association

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<tr>
<th>PSR</th>
<th>( P ) (s)</th>
<th>( \dot{P} ) (10^{-11} \text{s s}^{-1} )</th>
<th>( n )</th>
<th>( \tau_{\text{PSR}} ) kyr</th>
<th>SNR</th>
<th>( \tau_{\text{SNR}}^- ) kyr</th>
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<td>11.783</td>
<td>3.930</td>
<td>4.750</td>
<td>G27.4+0.0 (Kes 73)</td>
<td>0.750</td>
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<td>CXOU J171405.7–381031</td>
<td>3.825</td>
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<td>SGR 1627–41</td>
<td>2.595</td>
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<td>2.164</td>
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<td>HBP J1119–6127</td>
<td>0.408</td>
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<td>2.684 ± 0.002 [14]</td>
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<td>PSR J0537–6910</td>
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<td>PSR B0833–45</td>
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AXPs  
SGRs  
HBPs  
RPPs  
CCOs

See Poster DDp.2.50 (Rogers & SSH)

SNR ages in SNRcat
www.physics.umanitoba.ca/snr/SNRcat
Neutron Stars Diversity

The age and braking index “problem” \( <=> \) SNR association

Secure associations only with known SNR age

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\[ \dot{\Omega} = -k\Omega^n, \quad k = \frac{2m^2 \sin^2 \alpha}{3Ic^3} \]

\( n = \nu \dot{\nu}/\dot{\nu}^2 \)

See Poster DDp.2.50 (Rogers & SSH)

SNR ages in SNRcat

www.physics.umanitoba.ca/snr/SNRcat
Neutron Stars Diversity

The age and braking index “problem” $\Rightarrow$ SNR association

Secure associations only with known SNR age

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**Standard Assumption (B, t):**

B is constant

$P_0 \ll P$, magnetic dipole ($n=3$)

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See Poster DDp.2.50 (Rogers & SSH)

SNR ages in SNRcat

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**Formula:**

\[ \dot{\Omega} = -k\Omega^n, \quad k = \frac{2m^2 \sin^2 \alpha}{3Ic^3} \]

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The age and braking index "problem" <=> SNR association

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Secure associations only with known SNR age

X-ray spectroscopy/dynamics

The age and braking index "problem" <=> SNR association

\( \Omega = -k \Omega^n \), \( k = \frac{2m^2 \sin^2 \alpha}{3Ic^3} \)

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See Poster DDp.2.50 (Rogers & SSH)
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**How is the SNR age determined?**

**SNR ages in SNRcat**
www.physics.umanitoba.ca/snr/SNRcat

See Poster DDp.2.50 *(Rogers & SSH)*
Probing SN properties (energetics, density, **SNR age**) through X-ray spectroscopy (SNR)

- **Temperature** (=>thermal continuum) $\sim V_s^2$

  $$T_s (K) \sim 1.13 \times 10^5 \left(\frac{V_s}{10^7}\right)^2$$

- (also) Proper motion measurements (Chandra)
Probing SN properties (energetics, density, **SNR age**) through X-ray spectroscopy (SNR)

- **Temperature** \( (\Rightarrow \text{thermal continuum}) \)

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(Caveat: \( T_e \) is not necessarily the same as \( T_p \))
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- (also) Proper motion measurements (Chandra)

- **Density** from emission measure (EM):
  
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- Assuming a Sedov-Taylor phase solution*:
  
  => Estimate SNR age (t) and Explosion Energy (E)
Probing SN properties (SNR age, also ambient density, Explosion energy) through X-ray spectroscopy (SNR)

- **Temperature** (=>thermal continuum) $\sim V_s^2$
  
  $T_s (K) \sim 1.13 \times 10^5 \left(\frac{V_s}{10^7}\right)^2$

- (also) Proper motion measurements (Chandra)

- **Density** from emission measure (EM):
  
  $EM = \int n_H n_e dV$

- Assuming a Sedov-Taylor phase solution*:
  
  $R_s = \left(\xi \frac{Et^2}{\rho_0}\right)^{1/5}$

  $V_s = \frac{dR_s}{dt} = \frac{2}{5} \left(\xi \frac{E}{\rho_0}\right)^{1/5} t^{-3/5} = \frac{2}{5} \frac{R_s}{t}$

*Ideally: modelling the hydrodynamical, ionization state, and radiative evolution into a CSM medium (e.g. Patnaude+15; Gelfand+09, Reynolds & Chevalier’84)
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  => Estimate SNR age (t) and Explosion Energy (E)

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- For a low-density and/or young SNR:
  Ionization timescale: $n_e t$ (another handle on “age”, t)
Solving the PSR-SNR age discrepancy

\[ \frac{dB}{dt} = -aB(t)^{1+\alpha} \]

B-decay
(e.g. Colpi+00, D’Allosso+12)
Solving the PSR-SNR age discrepancy

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PSR=SNR age

Rogers & SSH (submitted)
Rogers & SSH (in prep)

See Poster DDp.2.50 (Rogers & SSH)
Solving the PSR-SNR age discrepancy

\[
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(\(\alpha \approx 0\) (exponential decay))

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(e.g. Colpi+00, D’Allosso+12)

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CCOs: decay here would have to be exponential!

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CCOs:
- - - - - (α = 0.6),
- - - (α = 1.0)
.... (α = 1.4).

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decay doesn’t work here… (HBPs)

CCOs: (\(\alpha = 0.6\)), (\(\alpha = 1.0\)), (\(\alpha = 1.4\)).

See Poster DDp.2.50 (Rogers & SSH)
Solving the PSR-SNR age discrepancy

- Exponential decay doesn’t work here…
- B-growth?
- CCOs: decay here would have to be exponential!
- B-decay (e.g. Colpi+00, D’Allosso+12)
- PSR=SNR age

---

CCOs: decay here would have to be exponential!

- AXP (magnetar)
- CCO
- SGR
- HBP

---

See Poster DDP.2.50 (Rogers & SSH)

Rogers & SSH (submitted)
Rogers & SSH (in prep)
HBP J1119-6127 in G292.2-0.5

**Age**

**PSR char. age** = 1.6 kyr

\[ \tau = \frac{P}{(n-1)\dot{P}} \left[ 1 - \left( \frac{P_0}{P} \right)^{(n-1)} \right] \]

Kumar, SSH & Gonzalez 2012
Weltevrede et al. 2011
HBP J1119-6127 in G292.2-0.5

Age

SNR age
4.2-7.1 kyr

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But \( n \) (measured) = 2.7

\( \Rightarrow \) variable \( n \)

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B-growth?

\[ n = 3 - 4 \tau_c \frac{B}{B_0} \]

> 0

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B “submerged” in CCOs?

a way around the age and B measurement?

CCO
P=105 ms
B=3.1e10 Gauss
(Seward et al; Gotthelf et al.)

CCO

transient low-B magnetar
Zhou et al. 2014

SNR age: 5.4-7.5 kyr
(see new study: Zhou et al. Poster DDP.2.37)

CCO char. age: 1.9E5 kyr!

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Highly modulated pulsed signal =>
non-uniform surface temperature in a
“CCO” (dipole: \( 3.1 \times 10^{10} \text{ G} \))
requires a much **higher internal B.**

**Submerged due to accretion?**
(Gotthelf+13, Bogdanov’14; Bernal+10, Ho’11, 15.....)
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Connecting the Neutron Stars Diversity through B-evolution?

"Isolated": RPP Magnetars HBPs CCOs

B=Constant B-Decay B-Growth

Rogers & SSH (see also: Ho 2011 (CCOs), 2015 (for RPPs/growing B); Pons+07, Popov, Turolla+12, Vigano+13)

$B = \sqrt{\frac{3c^3}{8\pi^2 R^6 \sin^2 \alpha}} \cdot \frac{I}{PP} = 3.2 \cdot 10^{19} \sqrt{PP}$ Gauss

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SNR ages are better indicators for the “true” ages:
The zoo can be attributed (at least partly) to B-evolution
B-evolution (growth) still under hot debate!
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On their Progenitors
and environment
(for the highly magnetized neutron stars)
II. On their Progenitors
(Linking SNRs to their SN progenitors in X-rays)

• Ia vs core-collapse, SN typing:
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**IAU Honolulu**
Division D, Aug (2015)

S. Safi-Harb
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\[ \text{Fe-K line centroids (Yamaguchi+14, Patnaude+15)} \]
Magnetars

\( B \sim 10^{14} - 10^{15} \) Gauss

- High-energy sources (AXPs, SGRs)
  - burst, \( P \sim 2-12 \) s

- \( L_x > E_{\text{dot}} \) (spin-down energy)
  - can NOT be powered by rotation
    - Decay of their super-strong B
    - accretion
    - quark stars?

- \( B > B_{\text{QED}} \) (4.3e13 Gauss)
  - although we now know of 3 “low-B” magnetars
  - Proton Cyclotron Features?

**Big/Debated questions:**

- Link to other classes of neutron stars (part I)

- What is the origin of their super-strong B field?

- On their progenitors

---

IAU Honolulu
Division D, Aug (2015)

S. Safi-Harb
Magnetar Progenitors, origin of B
Two “competing”/popular models

- Predict: $P_0 < \sim 3\ ms$
- super-energetic ($\gg 10^{51}\ ergs$) SNRs
  - see e.g. Vink 2008

Very massive (20-45 solar masses) progenitors
(Ferrario & Wickramasinghe 2008)

Proto-Neutron-Star
- dynamo post birth

Making a magnetar
- Hot, newborn star churns and mixes
- Internal convection carries off heat
- If spinning faster than 200 revolutions/second, the dynamo action quickly builds up the magnetic field

Fossil-field hypothesis
- magnetic flux conservation

from Ferrario 2015

Main Sequence stars
- magnetars
- white dwarfs
- HBP

Dave Cook, NASA Marshall Space Flight Center
Magnetar Progenitors, origin of B
Two “competing”/popular models

Multi-wavelength Observations:

• HI bubble around an AXP

20-45 solar-mass progenitors=>

• SGR 1806-20 and magnetar CXO U J164710.2-455216 associated with very massive star clusters
• Wolf-Rayet progenitor inferred for the HBP J1846-0258/Kes 75
• But...~17 solar-mass progenitor inferred for SGR 1900+14

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Gaensler+05

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What can we learn from X-ray spectroscopy of associated SNRs (environment)?

- Proto-Neutron-Star hypothesis from Ferrario 2015
  - dynamo post birth
  - Internal convection carries off heat

- Fossil-field hypothesis
  - magnetic flux conservation

- Main Sequence stars
  - HBP

- \( \log_{10}(\Psi_P/\text{G cm}^2) \)
  - \( \log_{10}(M/M_\odot) \)
  - from Ferrario 2015
SN properties:

<table>
<thead>
<tr>
<th>Name</th>
<th>E (1e51 ergs)</th>
<th>n₀ (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXP 1E1841-045</td>
<td>0.3-1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Kes73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTB37B/HESS J1713–381</td>
<td>0.3-1.0</td>
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</tr>
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<td>AXP J171405.7–381031</td>
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</tr>
<tr>
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<td>0.2</td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>SGR0526-66</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>N49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G292.2-0.5</td>
<td>0.6</td>
<td>0.02</td>
</tr>
<tr>
<td>CTB109</td>
<td></td>
<td></td>
</tr>
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References:
- Aharonian et al. 2008
- Kumar, SSH et al. (in prep)
- Nakano et al. 2014
- Sasaki et al. 2004, 2013
- Park et al. 2012
- Gelfand et al. 2014
- Kumar, SSH & Gonzalez 2012
- CXC/U. Manitoba/Kumar, SSH, Slane & Gotthelf 2014
SN properties:

E \(1\text{e51 ergs}\)

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**Typical Explosion Energies**

low ambient/CSM density

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  - 0.005-0.1

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~30

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Kumar & SSH
Morton+09

Kes75

Nakano+ 2015

SGR0526-66

Park+12
(type Ia or CC?)

N49

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Highly magnetized neutron stars (HBPs and magnetars):

While the SNR explosion energies appear to be “typical” (~$10^{50}-10^{51}$ ergs), the progenitors appear to be very massive (or expanding into wind bubbles/very low-density medium)

*Supports the Fossil Field Model for highly magnetized NSs*
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If true => such massive stars do not necessarily all form black holes!
(cf. A. Heger et al. 2003; Smith 2014)

Q: Is SS433/W50 the only Black Hole (?)-SNR system in our Galaxy?
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The future with Astro-H (and Athena) High-Resolution X-ray spectroscopy era
Limitations:

a) CCD-type spectra
b) Different Nucleosynthesis models and yields
c) Energetics neglects gravitational radiation
d) Small Sample
e) (PSR ages not to be trusted) but SNR ages and shock velocities also need to be accurately determined!
The future with Astro-H (and Athena)
High-Resolution X-ray spectroscopy era
ASTRO-H will provide a leap in high-resolution X-ray spectroscopy:

1) **Progenitors** of the PSRs zoo, and other SNRs (SXS)
2) Accurate **SNR age and shock velocity** measurements (SXS)
3) search for thermal emission in synchrotron dominated SNRs (e.g. shell-less PWNe)
4) direct measurement/origin of B (SXS/SXI/HXI, broadband): cyclotron features

See “AstroH White papers” on SNRs and compact objects (arXiv:1412.1165/66/69/75)
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See “AstroH White papers” on SNRs and compact objects (arXiv:1412.1165/66/69/75)
Summary:

SNRs offer laboratories to study the physics of exotic objects

- Age: magnetic field evolution linking the different faces of neutron stars
- SN progenitor/Energetics studies: very (?) massive progenitors for magnetars/HBPs

The future is promising for upcoming high-resolution X-ray spectroscopy
(soon, ASTRO-H: <7eV resolution, better sensitivity in Fe-K, broadband 0.5-600 keV;
Late 2020’s: Athena in synergy with other planned multi-wavelength missions)

Thank you!

(also with thanks for the SNR group members and collaborators)

Check out our on-line and regularly updated high-energy (X+γ) SNR catalogue (SNRcat):
http://www.physics.umanitoba.ca/snr/SNRcat
Comments, corrections, input … are welcome!