Nearby, Thermally Emitting Neutron Stars:

Laboratories for Extreme Physics

David L Kaplan
MIT Kavli Institute for Astrophysics and Space Research

Collaborators: M. van Kerkwijk, K. Mori (Toronto), J. Anderson (Rice), W. Ho (CfA), G. Pavlov (Penn State)

UW INT
June 25, 2007
Introduction
Introduction

- Exploit neutron stars to learn about matter
Introduction

- Exploit neutron stars to learn about matter
- Physics goals:
  - cooling
  - extreme densities
  - extreme magnetic fields
Introduction

- Exploit neutron stars to learn about matter
- Physics goals:
  - cooling
  - extreme densities
  - extreme magnetic fields
- What **observations** do we need?
Equation of State: Radius & Mass

(Lattimer & Prakash 2000)
Equation of State: Radius & Mass

(Lattimer & Prakash 2000)
Goal: Populate Cooling Diagram

- Models incorporate interior physics
- Include effects of:
  - Magnetic field
  - Elemental abundances
- **mass** can change cooling
Goal: Populate Cooling Diagram

- Models incorporate interior physics
- Include effects of:
  - Magnetic field
  - Elemental abundances
  - **mass** can change cooling
Goal: Populate Cooling Diagram

And Compare with Models

- Models incorporate interior physics
- Include effects of:
  - Magnetic field
  - Elemental abundances
  - **mass** can change cooling
Goal: Populate Cooling Diagram

And Compare with Models

- Models incorporate interior physics
- Include effects of:
  - Magnetic field
  - Elemental abundances
- **mass** can change cooling
Other Methods for EOS

- **Fastest spin** of millisecond pulsars (Chakrabarty): best limit does not constrain EOS (but see Kaaret et al. ‘06)
- **Binary mass measurements** (Thorsett & Chakrabarty): new measurements (Ransom; Nice) may be important
- **Quiescent X-ray Binaries** (Rutledge; Heinke): known distances, but *faint* & unknown physics
- **Gravitational redshift** (Cottam): one source, one observation (also see Özel ‘06)
- **Moment of inertia** of double pulsar (Kramer): may be possible in 5-10 years
Types of Cooling Isolated NSs

- Young (<\(10^4\) yrs) in supernova remnants
  - active (radio) pulsars (Crab, Vela, 3C 58)
  - radio-quiet Central Compact Objects (Cas A, Puppis A)
- Middle-aged (<\(10^6\) yrs)
  - active (radio) pulsars (Geminga, PSR B0656+14)
  - radio-quiet isolated neutron stars
Types of Cooling Isolated NSs

- Young (<$10^4$ yrs) in supernova remnants
  - active (radio) pulsars (Crab, Vela, 3C 58)
  - radio-quiet Central Compact Objects (Cas A, Puppis A)
- Middle-aged (<$10^6$ yrs)
  - active (radio) pulsars (Geminga, PSR B0656+14)
  - radio-quiet isolated neutron stars
Isolated Neutron Stars

ROSAT
Isolated Neutron Stars

RX J1856.5-3754 (Walter et al. 1996)

R Cr A Star-Forming Region

RX J1856.5-3754 (Walter et al. 1997)
Isolated Neutron Stars

- Bright, cool X-ray sources w/ very faint optical counterparts
- Currently 7 with no extra complications
- Properties:
  - temperatures ~ 1 million degrees
  - spin periods > 3 sec.
  - nearby, < 1 kpc
Isolated Neutron Stars

- Bright, cool X-ray sources w/ very faint optical counterparts
- Currently 7 with no extra complications
- Properties:
  - temperatures \( \sim \) 1 million degrees
  - spin periods > 3 sec.
  - nearby, < 1 kpc
- Why this sample?
  - Nearby \( \rightarrow \) bright
  - Relatively young \( \rightarrow \) can use for cooling curves
  - Emission is thermal \( \rightarrow \) comes only from surface
Why this sample?
- Nearby → bright
- Relatively young → can use for cooling curves
- Emission is thermal → comes only from surface

Bright, cool X-ray sources w/ very faint optical counterparts
- Currently 7 with no extra complications

Properties:
- Temperatures ~ 1 million degrees
- Spin periods > 3 sec.
- Nearby, < 1 kpc

Isolated Neutron Stars
- Geminga pulsar:
  - Also young & nearby
  - Optical: a mix
  - Gamma-rays: non-thermal

Non-thermal X-rays
Thermal X-rays
Optical Counterparts

RX J1856.5-3754 (Walter et al. 1997)

RX J1605.3+3249 (Kaplan et al. 2003)

RX J0720.4-3125 (Kulkarni & van Kerkwijk 1998; Motch & Haberl 1998)

RX J1308.6+2127 (Kaplan et al. 2003)
Optical Counterparts

RX J1856.5-3754 (Walter et al. 1997)

RX J0720.4-3125 (Kulkarni & van Kerkwijk 1998; Motch & Haberl 1998)

RX J1605.3+3249 (Kaplan et al. 2003)

RX J1308.6+2127 (Kaplan et al. 2003)
Optical Counterparts

RX J1856.5-3754 (Walter et al. 1997)

RX J0720.4-3125 (Kulkarni & van Kerkwijk 1998; Motch & Haberl 1998)

RX J1308.6+2127 (Kaplan et al. 2003)

RX J1605.3+3249 (Kaplan et al. 2003)

Maybe a 5th?
What Do We Need to Know?
What Do We Need to Know?

- For **radius**:
  - distance: *angular size* $\rightarrow$ *true size*
  - understanding of surface (abundances, $T$ & $B$ distributions): *received flux* $\rightarrow$ *true flux*
What Do We Need to Know?

For radius:
- distance: angular size $\rightarrow$ true size
- understanding of surface (abundances, $T$ & $B$ distributions): received flux $\rightarrow$ true flux

For cooling:
- age
- distance: flux $\rightarrow$ observed luminosity
- understanding of surface: observed luminosity $\rightarrow$ total luminosity
Proper Motions: Measuring Ages

- Massive star cluster
- Distant background stars

Position in 2000 → Position in 2004
4 years
Proper Motions: Measuring Ages

Distant background stars

Massive star cluster

Position 1 million years ago

Position in 2000

Position in 2004

1 million years

4 years
Parallaxes: Measuring Distances

- Distant background stars
- Apparent position in Dec.
- Apparent position in June
- Star of interest

Earth in June

Earth in Dec.
Parallaxes: Measuring Distances

We need to measure to about 1/2 milliarcsecond.
Parallaxes: Measuring Distances

We need to measure to about 1/2 milliarcsecond.

That is the size of a dime held in Boston seen in Seattle.

Earth in June

Earth in Dec.
Can We Do This? RX J1856:

Initial HST data:

Walter (2001)
Kaplan et al. (2002)
Walter & Lattimer (2002)
MHvK, DLK, & JA (about to be submitted)
Can We Do This? RX J1856:

Initial HST data:
Lots more data:

Walter (2001)
Kaplan et al. (2002)
Walter & Lattimer (2002)
MHvK, DLK, & JA (about to be submitted)
Can We Do This? RX J1856:

Initial HST data:
Lots more data:

Walter (2001)
Kaplan et al. (2002)
Walter & Lattimer (2002)
MHvK, DLK, & JA (about to be submitted)
Another Case: RX J0720

Can be done from the ground: Motch et al. (2003)
Another Case: RX J0720

Also see Motch et al. 2005 for another object

Kaplan et al. 2007
Another Case: RX J0720

Kaplan et al. 2007 also see Motch et al. 2005 for another object.
(OB assns adapted from de Zeeuw et al. ’99)
Age 0.5 Myr
Age 0.7 Myr

Age 0.5 Myr

(OM assns adapted from de Zeeuw et al. '99)
X-ray Timing: Magnetic Fields

Rotating dipoles lose energy, so they slow down
Rotating dipoles lose energy, so they slow down.

If we can measure the slow-down, we can measure the magnetic field.
X-ray Timing: Magnetic Fields

Rotating dipoles lose energy, so they slow down.

If we can measure the slow-down, we can measure the magnetic field.

Now done for 2 objects: $B=2.4$ and $3.4 \times 10^{13}$ G!
Is Emission Thermal?

- Compare:
  - X-ray luminosity $L_X$
  - Spin-down luminosity $\dot{E} = \frac{d}{dt}(\frac{1}{2}I\Omega^2)$

<table>
<thead>
<tr>
<th>Radio pulsars:</th>
<th>INS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_X \ll \dot{E}$</td>
<td>$L_X/\dot{E} \sim (10^{32}/4e30)\sim40$</td>
</tr>
<tr>
<td>Significant non-thermal emission, driven by $\dot{E}$</td>
<td>Little (if any) non-thermal emission</td>
</tr>
</tbody>
</table>
Is Emission Thermal?

- **Compare:**
  - X-ray luminosity $L_X$
  - Spin-down luminosity $\dot{E}=d/dt \left( \frac{1}{2}I\Omega^2 \right)$

- **Radio pulsars:**
  - $L_X \ll \dot{E}$
  - **Significant** non-thermal emission, driven by $\dot{E}$

- **INS**
  - $L_X/\dot{E} \sim (10^{32}/4e30) \sim 40$
  - **Little** (if any) non-thermal emission

But: bowshock implies higher $\dot{E}$ ($\sim 10^{32}$ erg/s) for this source (RX J1856), although $P$ is similar
What About Accretion?
What About Accretion?

- Predicted: ROSAT would see \(~1000\) accreting NSs (e.g., Treves & Colpi 1991)
What About Accretion?

• Predicted: *ROSAT* would see \(~1000\) accreting NSs (e.g., Treves & Colpi 1991)

• Found: 0 (indicated by \(\dot{P}, v\)
What About Accretion?

- Predicted: ROSAT would see \( \sim 1000 \) accreting NSs (e.g., Treves & Colpi 1991)
- Found: 0 (indicated by \( \dot{P}, v \))
- Why?
  - Velocity too high for accretion (\( \sim 200 \text{ km/s} \))
  - Magnetic field inhibits \( \dot{M} \) too
- See Perna et al. (2003)
Not Magnetars (?)

- X-ray emission we see is from cooling
- Could “normal” cooling be augmented by $B$ decay?
  - i.e., is energy in $B$ relevant?
Not Magnetars (?)

- X-ray emission we see is from cooling
- Could “normal” cooling be augmented by $B$ decay?
  - i.e., is energy in $B$ relevant?
- Answer: probably not (Zane et al. ‘02; Kaplan et al. ‘02)
- Based on simple models of field decay (Heyl & Kulkarni ‘98)
- Would need $B(\text{now}) > 2^{14}$ G to have decayed significantly in past
- Compare to $2^{13}$ G from spin-down
- Caveat: field decay is complicated
Spectroscopy: Measuring Surfaces

- Maximum flux → size
- Location of peak → temperature
- Overall shape → which elements
Spectroscopy: Measuring Surfaces

- Wavelength
- Flux
- Maximum flux
- Size
- Location of peak
- Temperature
- Overall shape
- Which elements

Chandra

XMM
Spectroscopy: Measuring Surfaces

- Flux
- Wavelength

- maximum flux → size
- location of peak → temperature
- overall shape → which elements
RX J1856.5-3754

A Blackbody Fits!

interstellar absorption

(Drake et al. '02; Pons et al. '02; Burwitz et al. '03)
RX J1856.5-3754

No It Doesn’t

(Drake et al. ‘02; Pons et al. ‘02; Burwitz et al. ’03)
RX J1856.5-3754

Hot & Small

Two Blackbodies? Phase-resolved spectroscopy (for other sources) does not agree

No It Doesn’t

Cool & Large

(Drake et al. ‘02; Pons et al. ‘02; Burwitz et al. ’03)
Complications

- Magnetic field is high: standard atmosphere models not valid
- X-ray blackbody does not match O/UV
- For most sources, 1 or 2 blackbodies do not fit
- We see pulsations: surface not uniform
- Variability!
Effects of $B$ on Hydrogen Atoms

- $B=10^{12}$ G, $\chi_H=161$ eV
- $B=10^{13}$ G, $\chi_H=310$ eV
- $B=10^{14}$ G, $\chi_H=541$ eV

Sources have:
- $kT \approx 50-100$ eV
- $B \approx 10^{12}-10^{13}$ G

see Lai 2001, Rev. Mod. Phys., 73, 629
RX J1856.5-3754

a more realistic model

- Thin (~1 g/cm²) layer of partially ionized H
- On top of condensed surface
- Even w/ dipole B (ℓ & T), does not predict strong pulsations (see Ho 2007; Tiengo & Mereghetti ‘06)

(Ho et al. 2007; also see Motch et al. ’03, Zane et al. ’04)
RX J1856.5-3754

a more realistic model

- Thin (~1 g/cm²) layer of partially ionized H
- On top of condensed surface
- Even w/ dipole B (& T), does not predict strong pulsations (see Ho 2007; Tiengo & Mereghetti '06)

- Is this unique?
- How to maintain thin layer?
- Are physics correct?

(Ho et al. 2007; also see Motch et al. ’03, Zane et al. ’04)
Spectra: Source Comparison

Flux $\nu F_\nu$ (erg/s/cm$^2$)

Frequency (Hz)

RX J0720

RX J1856
Spectra: Source Comparison

- Similar emission areas
- But:
  - 11% pulsations for 0720
  - ~1% pulsations for 1856
Spectral Absorption Features

Haberl et al. (2003, 2004)
van Kerkwijk et al. (2004)
Zane et al. (2005)
Spectral Absorption Features

Deficits = X-ray absorption

Haberl et al. (2003, 2004)
van Kerkwijk et al. (2004)
Zane et al. (2005)
What Causes Features?

- Cyclotron (proton)
- Neutral hydrogen
- Molecular H
- He (neutral, ionized, molecular,...)
- Other species

Need to consider vacuum resonance suppression
What Causes Features?

see: van Kerkwijk & Kaplan (2006)
What Causes Features?

broad, strong: cyclotron $B \sim 4 \times 10^{13}$

see: van Kerkwijk & Kaplan (2006)
What Causes Features?

![Graph showing magnetic field (G) vs. energy (eV)]

- **What Causes Features?**
  - Less broad, weaker: cyclotron w/ vac. res. \( B \sim 1 \times 10^{14} \)
  - Broad, strong: cyclotron \( B \sim 4 \times 10^{13} \)

**Graph Details:**
- **Energy (eV)** vs. **Magnetic Field (G)**
- Lines and markers indicating various processes:
  - \( e^- \) cyclotron
  - \( H^0 \) ionization
  - \( H^0 \) gnd \( \rightarrow \) wb
  - \( m=0 \rightarrow 1 \)
  - \( m=0 \rightarrow 2 \)
  - \( m=0 \rightarrow 3 \)
  - \( H_2 \) dissoc
  - \( 13.6 \text{ eV} \)
  - \( 10^9 \) to \( 10^{14} \)

**References:**
- van Kerkwijk & Kaplan (2006)
What Causes Features?

- Vacuum resonance suppression
- Cyclotron (proton)
- Neutral hydrogen
- Molecular H
- He (neutral, ionized, molecular,...)
- Other species

Magnetic Field (G) vs. Energy (eV):
- $e^{-}$ cyclotron
- $H^0$ ionization
- $H^0$ ground $\rightarrow$ wb
- $H^0$ ground $\rightarrow$ tb
- $H_2$ dissociation
- $p^+$ cyclotron
- $m=0 \rightarrow 1$
- $m=0 \rightarrow 2$
- $m=0 \rightarrow 3$

$13.6\ eV$

Vacuum Res

- Less broad, weaker: cycl. w/ vac. res.
- $B \approx 1 \times 10^{14}$

- Less broad, weak: $H\ m=0\rightarrow 2$
- $B \approx 2 \times 10^{13}$

- Broad, strong: cyclotron
- $B \approx 4 \times 10^{13}$

see: van Kerkwijk & Kaplan (2006)
Need to consider vacuum resonance suppression

- Cyclotron (proton)
- Neutral hydrogen
- Molecular H
- He (neutral, ionized, molecular, ...)
- Other species

Magnetic Field (G)

Energy (eV)

\[ e \rightarrow \text{cyclotron} \]
\[ p^+ \rightarrow \text{cyclotron} \]
\[ \text{H}_2 \text{ dissoc} \]
\[ \text{H}^0 \rightarrow \text{ionization} \]
\[ \text{H}_0 \rightarrow \text{gnd} \\ \rightarrow \text{wb} \]
\[ \text{H}_0 \rightarrow \text{gnd} \\ \rightarrow \text{tb} \]
\[ m=0 \rightarrow 3 \]
\[ m=0 \rightarrow 2 \]
\[ m=0 \rightarrow 1 \]

Less broad, weak: should be suppressed?

- Less broad, weaker: cyclotron w/ vac. res. \( B \sim 1 \times 10^{14} \)
- Less broad, weak: \( \text{H} \) \( m=0 \rightarrow 2 \) \( B \sim 2 \times 10^{13} \)
- Broad, strong: cyclotron \( B \sim 4 \times 10^{13} \)

see: van Kerkwijk & Kaplan (2006)
What Causes Features?

Less broad, weak: cyclotron with vacuum resonance

$B \approx 1 \times 10^{14}$

Less broad, weak: $H_{m=0} \rightarrow 2$

$B \approx 2 \times 10^{13}$

Broad, strong: cyclotron

$B \approx 4 \times 10^{13}$

Timing results

see: van Kerkwijk & Kaplan (2006)
What Causes Features?

Less broad, weak: should be suppressed?

But this is probably not right:
- Harmonics (or other lines)
- Spectral evolution

Timing results

see: van Kerkwijk & Kaplan (2006)
RX J0720: Variability

- Spectrum changed over ~months

[Graph showing spectral variability over time]
RX J0720: Variability

- Spectrum changed over ~months
- Same with pulse profile

Oct 2003

May 2000

rev=0078

rev=0711

\[ \text{Pulse phase} \]

\[ \frac{I}{I_{\text{max}}} \]

\[ \text{HR} \]

de Vries et al. (2004); Vink et al. (2004)
RX J0720: Variability

- Spectrum changed over ~months
- Same with pulse profile
- Causes:
  - Intrinsic change in surface?
  - or change in angle: i.e. free precession (Haberl et al. 2006)

![Graph showing variability over time](May 2000, Oct 2003)
RX J0720: Variability

- Spectrum changed over ~months
- Same with pulse profile
- Causes:
  - Intrinsic change in surface?
  - or change in angle: i.e. free precession (Haberl et al. 2006)

Fig. 2. Variation of temperature, line equivalent width (EW), and radius (R) over time (Date).

Haberl et al. (2006), de Vries et al. (2004)

Haberl et al. (2006), de Vries et al. (2004)
Spectrum Coupled to Timing?

van Kerkwijk et al. ‘07
Spectrum Coupled to Timing?

van Kerkwijk et al. ‘07
Spectrum Coupled to Timing?

van Kerkwijk et al. ‘07

![Graphs showing spectral change and timing glitch with data points and annotations.](image-url)
Spectrum Coupled to Timing?

- Change in surface composition?
- Still working on nature of change:
  - Glitch related to coupling of superfluid core to crust via $B$?
  - Change in $B$ topology?
  - Accretion of debris/dust?

van Kerkwijk et al. '07

---

**Spectral change**

**Short $\lambda$: flux increased**

**Mid $\lambda$: flux decreased**

**Long $\lambda$: slow increase**

**Timing glitch?**

$$\Delta \nu / \nu \approx 10^{-8}$$
Conclusions

• Too early to get real physics out

• Bring together:
  • Timing
  • X-ray spectroscopy
  • Optical photometry
  • Astrometry

• But are learning:
  • Atmospheres
  • NS population: how do these objects fit?

• Comparisons are vital
Conclusions

- Too early to get real physics out
- Bring together:
  - Timing
  - X-ray spectroscopy
  - Optical photometry
  - Astrometry
- But are learning:
  - Atmospheres
  - NS population: how do these objects fit?
- Comparisons are vital
Future Efforts

- Astrometry $\rightarrow$ distance(s) and ages
- X-ray timing $\rightarrow$ magnetic fields
  - Working on timing noise
- X-ray spectra $\rightarrow$ try to understand surface
  - Phase resolved? Multiple absorption lines?
- Optical/UV spectra $\rightarrow$ characterize emission
  - Non-thermal emission?
- Find more source $\rightarrow$ improve statistics (see recent results by Rutledge et al.)