CCO Pulsars as Anti-Magnetars:

Evidence for Neutron Stars Weakly Magnetized at Birth

E. V. Gotthelf
in Collaboration with Jules Halpern
(Columbia University)

INT Workshop, UW, Seattle - 2007 June 25

Talk Outline

- Overview of the CCOs (as a class, individually),
- The CCO pulsars (PSR J1210-5209, PSR 1852+0040),
- New results (steady pulsations, undetected spin-down),
- A new interpretation for the nature of CCOs,
- Implications and future work.

Distinctive Properties of Compact Central Objects (CCOs) in SNRs

- X-ray bright ($10^{33} < L_x < 10^{34}$ erg/s) unresolved point source located near the center of a SNR,
- Isolated NS, young by association with SNRs ($\lesssim 1\times10^4$ yrs),
- Steady emission, no evidence for nominal accretion,
- With distinct hot thermal spectrum (kT ~ 0.4 keV)
- No detected radio emission to interesting limits,
- Lacking optical counterpart (but high Galactic column),
- No evidence for a wind nebula emission at any wavelength.

Comparative Properties of Isolated NS Classes

	Radio Pulsar	INS	CCO	AXP	SGR
Examples	~ 1700	7-8	~ 6	~ 6	~ 5
L_x (erg/s)	$\lesssim 10^{42}$	$\sim 10^{32}$	10^{33} - 10^{34}	10^{34} - 10^{35}	10^{34} - 10^{35}
Emission	Broadband	X-ray/IR	X-ray only	X-ray/IR	γ/X-ray/IR
Spectrum	$\Gamma \sim 1.5$	kT ~ 0.1 keV	kT ~ 0.4 keV	kT ~ 0.4 keV $\Gamma \sim 4$	kT ~ 0.2 keV $\Gamma \sim 2$
Variable Flux?	Steady	Steady	Steady	Transient/ Bursts	Episodic/ Bursts
Periods	16 ms - 5 s	> 3 s	105, 424 ms	5 - 12 s	5 - 10 s
Age	all	$\sim 10^7$ yr	$\lesssim 10^4$ yr	$\sim 10^4$ yr	$\sim 10^4$ yr
PWN?	High $\dot{E}$	No	No	No	No

Compact Central Objects in Supernova Remnants
(CCOs) (SNRs)

(most secure examples)

CCO	SNR	Age (kyr)	Dist. (kpc)	P (ms)	f_p^a (%)
CXOU J232327.9+584843	Cas A	0.3	4	...	< 27
RX J0822−4300	Pup A	2	3	...	< 5
CXOU J085201.4−461753	G266.1–1.2	2	2	...	< 10
CXOU J185238.6+004020	Kes 79	7	7	105	80±20
1E 1207.4−5209	PKS 1209−51/52	8	3	424	9±2
1WGA J1713.4−3949	G347.3–0.5	10	6	...	< 6

[a] Pulsed fraction in the 0.5–10 keV energy band.
Upper limits are for a search down to 12 ms.

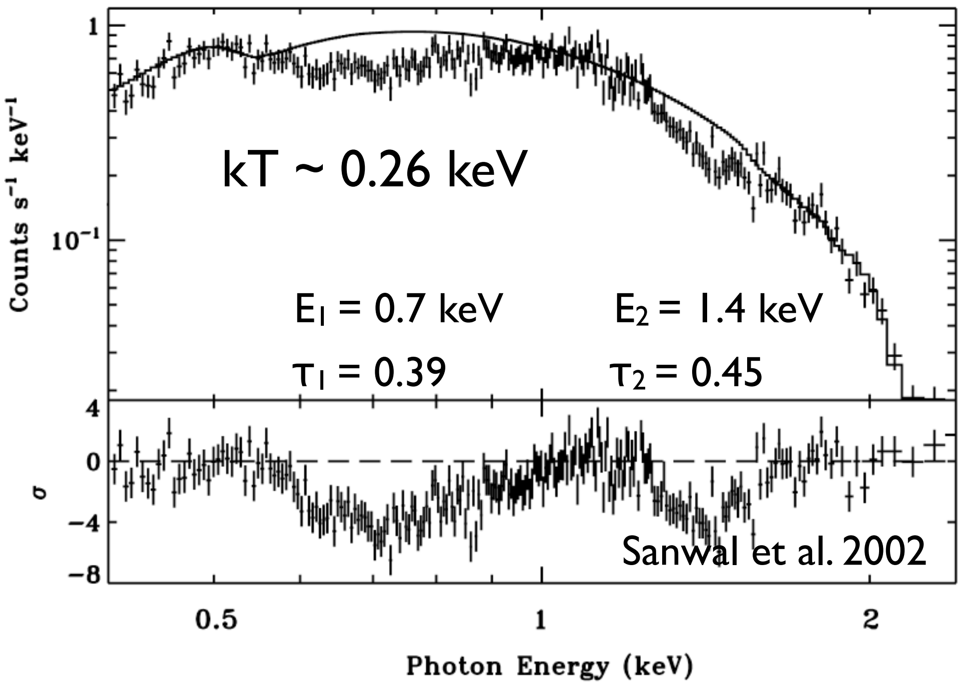
A Unique CCO: 1E 1207.4-5209

- Einstein discovered a central X-ray source in G296.5+10.0 (PKS 1209-51/52), a thermal supernova remnant.
- The location, spectrum, and flux, etc... is consistent with a CCO.
- P=424 ms pulsar detected in Chandra observation (Zavlin et al. 2000)
- Strong absorption features in X-ray spectrum (Sanwal et al. 2002)
- Using 15 observations spanning 13 year, no significant change in pulse period is found (Gotthelf & Halpern 2007),
- Steady flux, deep radio and optical limits,
- Lower limit on the pulsar's spin-down age exceeds the SNR age by 3 order of magnitude.

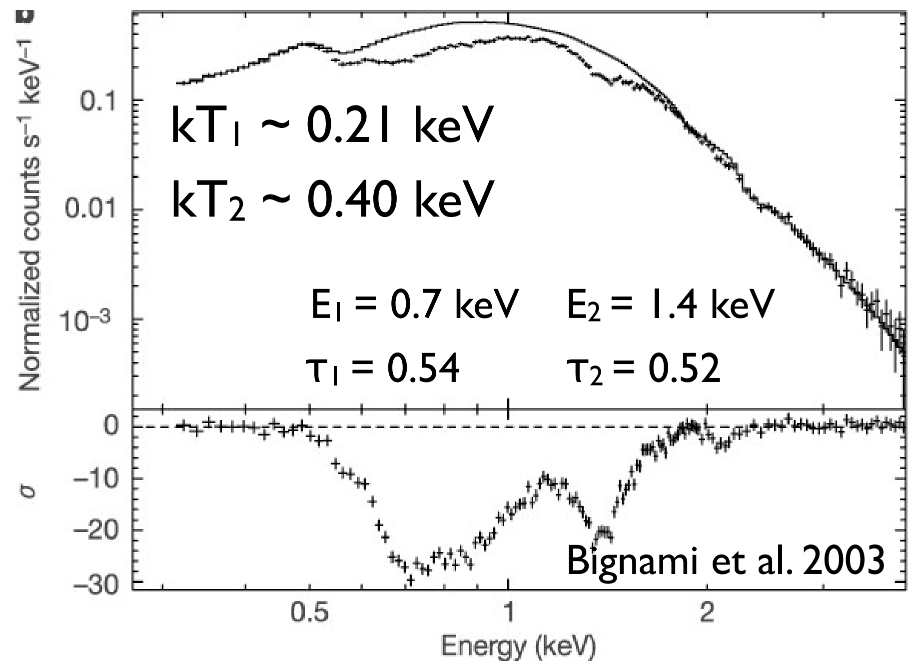
ROSAT PSPC IMAGE OF PKS 1209.4-5209

Broad Spectral Features in 1E 1207.4-5209

Chandra spectrum fitted with a blackbody model and 2 Gaussian absorption lines.



A deep XMM spectrum fitted with a double blackbody model and 2 Gaussians.



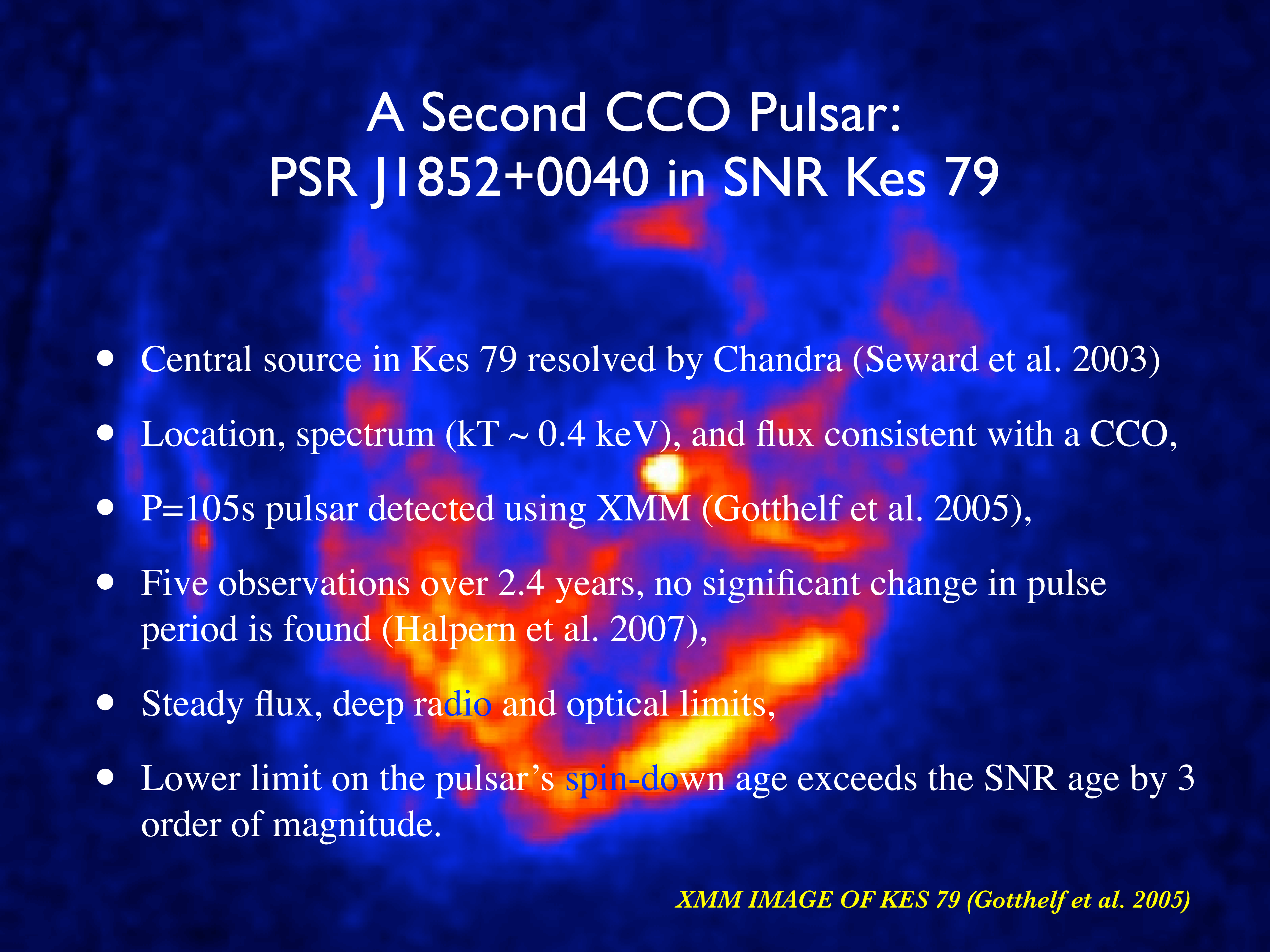
Bottom panel of each spectral plot show the residual w/o the Gaussians.

Cyclotron resonant harmonic feature?

Atomic transition at the NS surface or in the magnetosphere?

A Second CCO Pulsar: PSR J1852+0040 in SNR Kes 79

- Central source in Kes 79 resolved by Chandra (Seward et al. 2003)
- Location, spectrum (kT ~ 0.4 keV), and flux consistent with a CCO,
- P=105s pulsar detected using XMM (Gotthelf et al. 2005),
- Five observations over 2.4 years, no significant change in pulse period is found (Halpern et al. 2007),
- Steady flux, deep radio and optical limits,
- Lower limit on the pulsar’s spin-down age exceeds the SNR age by 3 order of magnitude.



XMM IMAGE OF KES 79 (Gotthelf et al. 2005)

Timing Measurements and Inferred Properties of the Two CCO Pulsars

	PSR J1210-5209	PSR J1852+0040
P (ms)	424.1307	104.9126
$\dot{P}$ (s/s)	$(6.3 \pm 6.0) \times 10^{-17}$	$(-3.4 \pm 2.7) \times 10^{-16}$
$\dot{E} \equiv I\Omega\dot{\Omega}^a$ (s/s)	$< 1.3 \times 10^{32}$	$< 7.0 \times 10^{33}$
$L(\mathrm{bol})/\dot{E}^b$	> 10	> 0.5
B_p (G)^a	$< 3.2 \times 10^{11}$	$< 1.5 \times 10^{11}$
$\tau \equiv P/2\dot{P}$ (kyr)^a	$> 24,000$	$> 8,000$
SNR age (kyr)	~ 8	~ 7

$^a 2\sigma$ upper limits assuming a rotation-powered pulsar.
$^b L(\mathrm{bol})$ is the bolometric luminosity at the nominal distance.

New Observational Results for the CCO Pulsars

1) In the magnetic dipole model, the lower limits on the pulsar spin-down ages exceeded their SNRs age by 3 order of magnitude...

   ...this implies that the pulsar was born spinning at its current period.

   Their long periods fall within range of radio-pulsar birth periods (<P> ~ 300 ms, σ_P ~ 150 ms; Faucher-Giguere & Kaspi 2006).

2) However, their X-ray luminosities are a large fraction of their spin-down luminosity...

   ... a strong challenge to the rotation-powered assumption above.

   An alterative source of energy must be responsible for the observed X-ray emission.

The Nature of CCOs

The birth B-field of CCOs, derived from a turbulent dynamo, is weaker if the NS is formed spinning slowly, which enables it to accrete SN debris.

A weak B-field is require by either a rotation-powered or accreting hypothesis, for both CCO pulsars.

Deep radio observations of both CCO pulsars place very strong limits on any radio signal, fainter then any young pulsars (Halpern et al. 2007)

Is weak B-field accretion a possible explanation for the lack of radio emission from CCOs?

What is Powering the Pulsed Emission from PSR J1852+0040?

The small inferred BB radius and large modulation suggests heating of a neutron star polar cap of R(BB) = 0.7 km.

Can interior cooling models, using anisotropic conduction, produce a sufficiently concentrated hot spot?

Perhaps the magnetic field at the pole is locally strong relative to the dipole field, sufficient to generate a hot spot?

Accreting at low rate of $\dot{m} \sim 3\times10^{13}$ g/s, possibly from fallback supernova material of a fossil disk, is sufficient to account for the observed luminosity.

Can accretion be the source of energy for the X-ray emission?

Normally excluded, but for a weak NS B-field, the accretion disk can penetrate the light cylinder if its mass loss rate (flung off material) is $\dot{M} \geq 1\times10^{13}$ g/s, for PSR J1852+0040.

Disk Accretion for a Low Magnetic Field NS

No radio pulsar are found with $B_p < 10^{11}$ G and $P > 0.1$ s, except for very old ($\tau > 40$ Myr) or recycled pulsars.

Radio emission for these pulsars may be shorted out by accretion?

If the magnetic field is weak enough the accretion disk can penetrate the light cylinder, $B < 10^{10}$ G for PSR J1852+0040.

The system is in the propeller regime for $\dot{M} \geq 10^{13}$ gm/s and is consistent with the upper limit measured for the period derivative.

For $B < 7 \times 10^8$ G and accreting $\dot{m} \geq 3 \times 10^{13}$ gm/s, the system can operate as a "slow rotator" with a period derivative of -1.3×10^{-18}, spinning up ever so slowly.

A Similar Explanation for PSR J1210-5209

For PSR 1210-5209, two BB spectral component are needed, the cooler one may be due to residual cooling.

The hotter BB component can be explained by weak B-field accretion from a fossil disk, as for PSR J1852+0040

Note - the low B-field is now ***consistent*** *with the picture of resonant electron cyclotron scattering to account for the broad spectral features in the X-ray spectral band, at least for one of these features*.

(a weak B-field is require by either a rotation-powered or accreting hypothesis.)

The relatively small pulse modulation could simply be due to a less favorable viewing geometry.

A Problem for the Accretion Disk Scenario

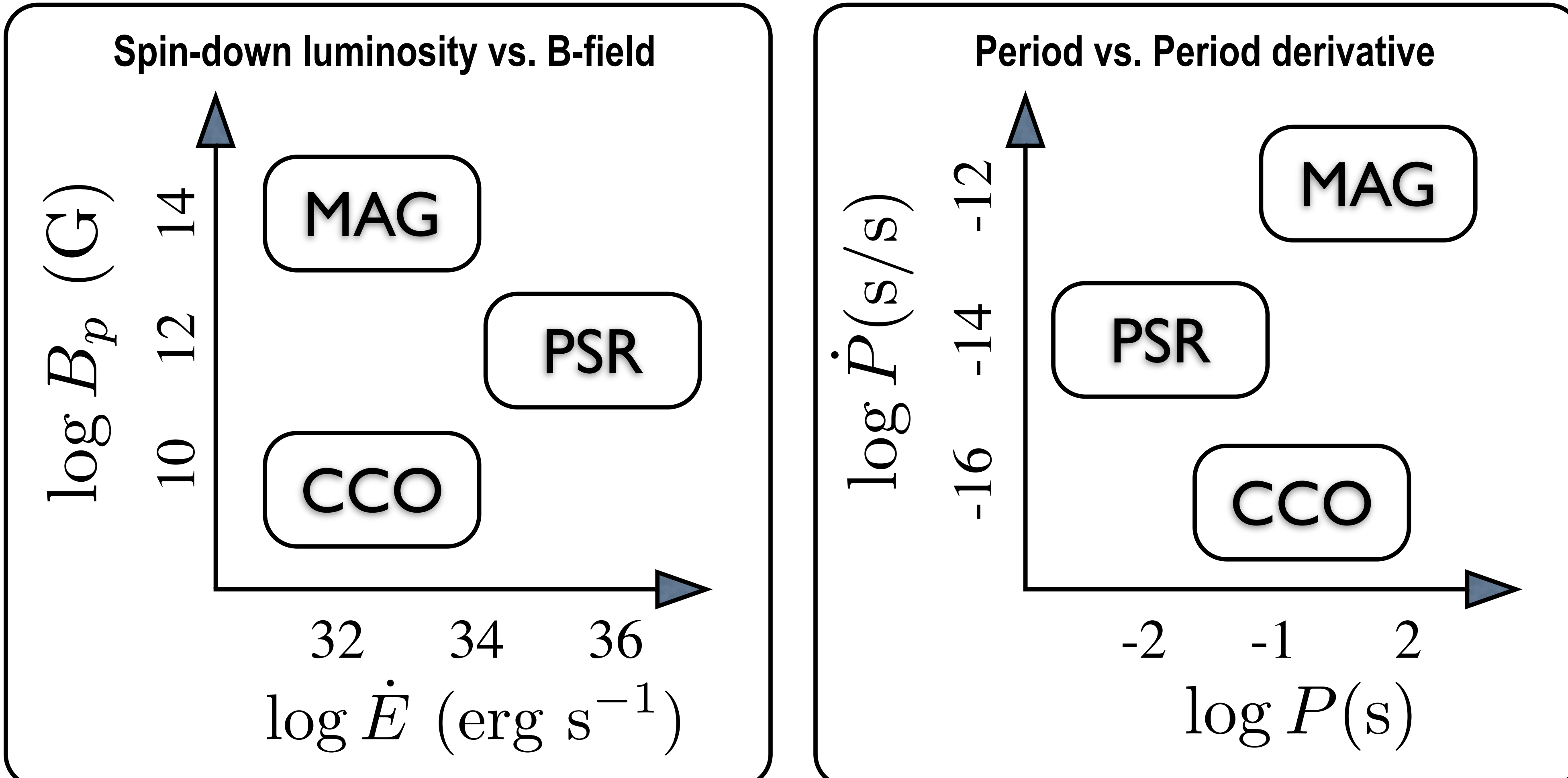
For a geometric thin, optically thick accretion disk:

Deep optical IR searches for PSR J1210-5209 place upper limits that are inconsistent with a disk accreting at a rate required to account for its X-ray luminosity (Zavlin et al. 2004; Wang et al. 2007).

A mechanism is required to account for this under the current hypothesis, e.g., radiative inefficient flow, or perhaps accretion of solid particles (Cordes & Shannon 2006).

This is so far not a problem for PSR J1852+0040.

Parameter Space for Young Pulsars



CCO Pulsars as Anti-Magnetars!

Implications

Low magnetic field during formation may be a defining property of the CCO class of isolated neutron stars.

A CCO born in SN 1987A could explain the lack of observed NS/pulsar, whose $\dot{E}$ is below detection.

Cas A: a magnetar or a CCO?

Future Work

Deep pulsar searches of other CCOs for periodic signal.

Deep observation of Kes 79 pulsar to search for absorption features.

Long term phase-connected timing solution for both CCO pulsars to measure their spin-down or torque noise accurately.