Recent NIR-optical-UV Observations of Rotation-powered Pulsars

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Rotation-Powered Pulsars (RPPs):

Neutron stars (NSs) whose radiation is powered by NS rotation (via creation-acceleration of e+e- pairs in strong magn. field)

Luminosity ***L*** proportional to spin-down power ***Edot***

$$\boldsymbol{L = \eta\, Edot}$$

η – radiative efficiency

Detected RPPs:

~2000 in radio
~10 in optical (+NIR+UV)
~100 in X-rays
~100 in γ-rays

Why so few in the optical?

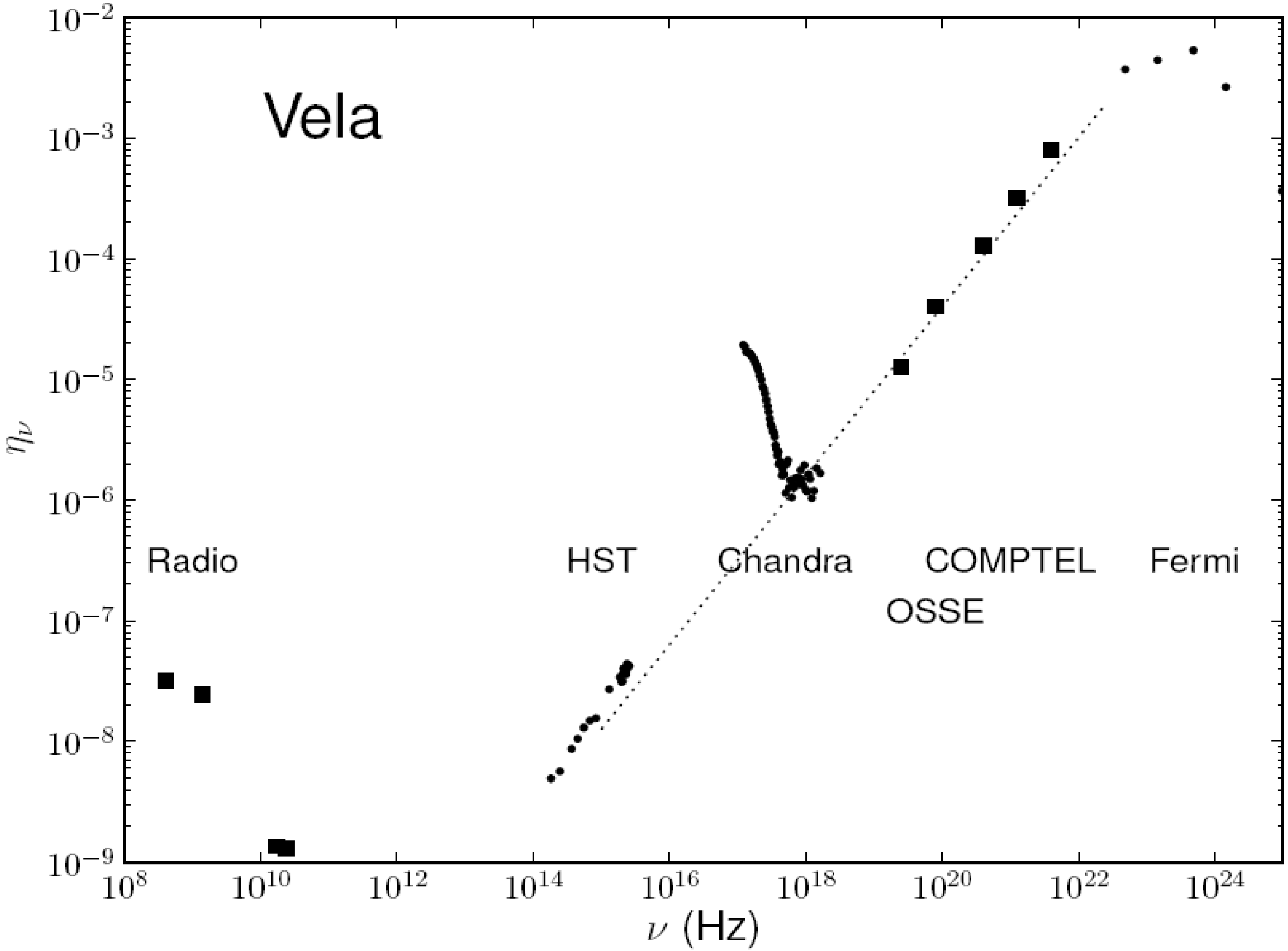
(1) Intrinsically faint (most of them require HST)
(2) Hostile attitude of "classical" optical astronomers

9 (+4?) RPPs detected in NIR-opt-UV (in 40+ years!)

Name	log Edot	log 'age'	mag	d(kpc)	log L_{opt}	- log η_{opt}
Crab	38.66	3.10	16.6 (V)	2.0	33.8	4.9
B1509-58 **?**	37.25	3.19	~26(R)	4.2	30.8	6.5
B0540-69	37.18	3.22	22.0(V)	50	33.9	3.3
Vela	36.84	4.05	23.6(V)	0.29	28.8	8.0
B1951+32 **?**	36. 6	5.02	~25 (V)	2.5	~31	~6
B0656+14	34.58	5.05	25.0(V)	0.29	28.2	6.4
Geminga	34.51	5.53	25.5(V)	0.25	27.6	6.9
B1055-52	34.48	5.73	24.9(U)	0.35**?**	28.1	6.4
J0437-4715	33.60	9.82	~26 (U)	0.156	~27	~6.6
B1929+10	33.59	6.49	25.6(U)	0.33	27.6	6.0
B0950+08	32.75	7.24	27.1(V)	0.26	27.4	5.4
B1133+16 **?**	31.94	6.70	~28 (B)	0.35	~27	~5
J0108-1431 **?**	30.76	8.30	27 (U)	0.24	~27	~4

Radio-to-γ-rays spectrum of an RPP

$\eta_\nu = \nu F_\nu 4\pi d^2 / Edot$ -- "spectral efficiency"



Three main components: coherent magnetospheric (radio), incoherent magnetospheric (NIR through gamma-rays), thermal from NS surface (FUV – soft X-rays)

Recent results from our group (2010-2011)

PSR B1055-52 (Mignani, GP, Kargaltsev 2010)

***Edot* = 3e34 erg/s; age = 535 kyr; *B* = 1e12 G; *d* ~ 700 pc** (from DM),

The oldest of the *Three Musketeers* (J. Trümper);
thermal soft X-rays, bright in Gev range

Many attempts to detect with ground-based telescopes,
unsuccessful because of a bright star (V=14) 4” from the pulsar

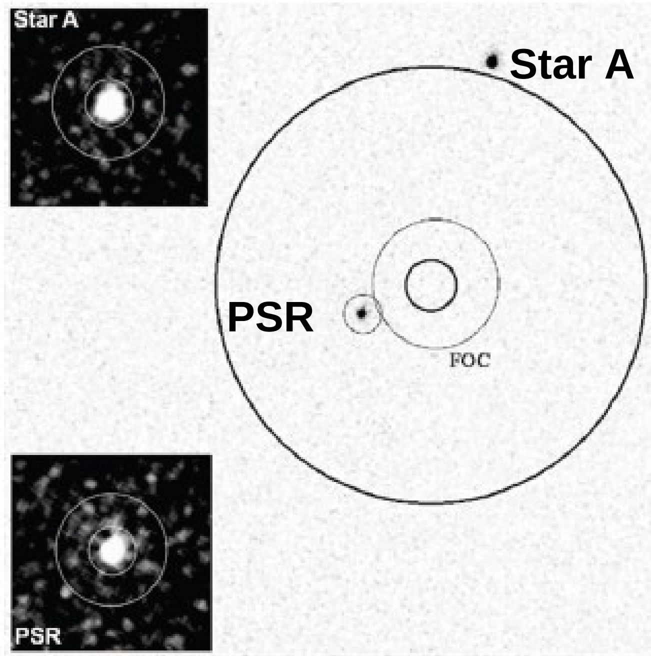
Possible detection with *HST FOC*: ***U* = 24.8** (Mignani et al 1997)

Ten (!) unsuccessful attempts to get another *HST* observation

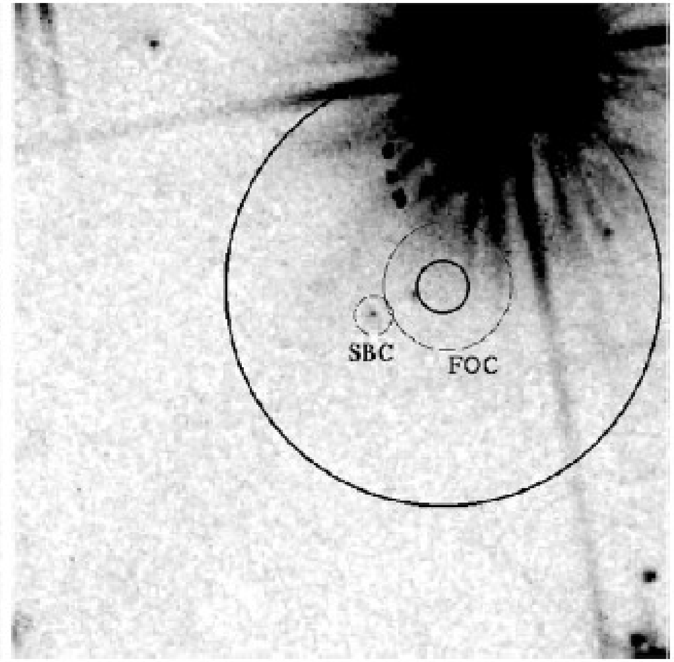
HST proposal accepted in Cycle 16, when *STIS* and *ACS/WFC* were dead

Pulsar detected with *ACS/SBC (F140LP)* and *WFC2 (F555W, F702W)*

PSR B1055-52: HST Images



ACS/SBC F140LP image
(1300-1600 A)

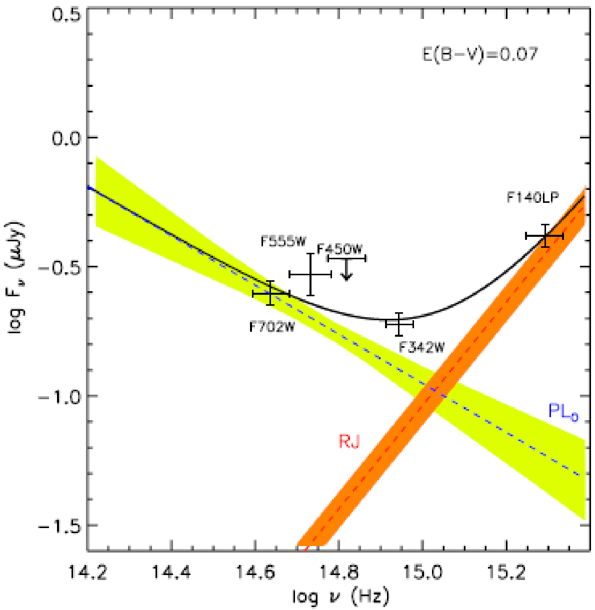


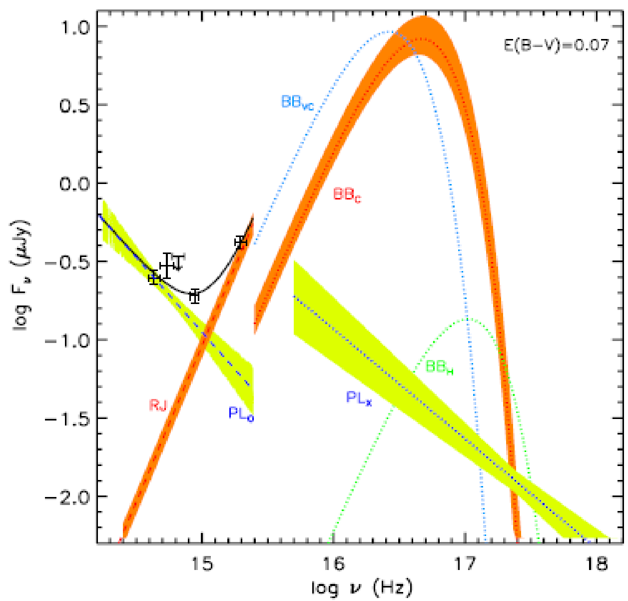
WFC2 F702W image
(6300-7700 A)

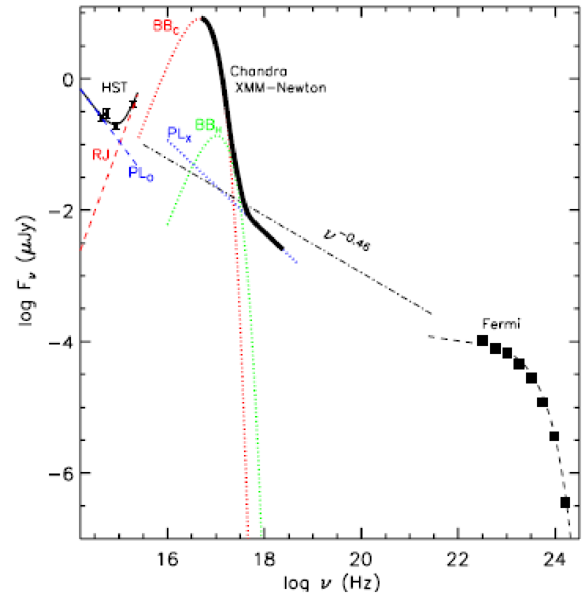
The pulsar candidate has moved ~0.5” wrt “Star A” in 11 years.

Proper motion **42+/-5 mas/yr, P.A. =94+/-7 deg; V = 70 d_{350} km/s**
first measurement of proper motion, confirmed by radio timing

PSR B1055-52: **Spectra**







<u>Optical-UV spectrum</u>: likely magnetospheric (optical, PL_O) and thermal (UV; Rayleigh-Jeans) components. Spectral slope in the optical **α_O = =1.05+/-0.34**; brightness temperature **T_O = (0.66+/- +/-0.10) d_{350}^{2} $R_{O,13}^{-2}$ MK**.

<u>Optical – UV - X-ray spectrum:</u> some mismatch of the components: e.g., a factor of 4 excess of the RJ spectrum over extrapolation of the X-ray thermal compo-nent (X-rays from a smaller area?);

<u>Optical – UV – X-ray – γ-ray spectrum</u>: possibly the same spectral slope from optical (eV) to GeV? (should be measured more accurately)

PSR B1055-52: Summary

- **Optical-UV counterpart confirmed**
- **Proper motion measured**
- **Likely, two components – magnetospheric and thermal**
- **Likely, the distance is about twice lower than that determined from DM**

New HST observations needed to measure phase-dependent spectrum and separate thermal and magnetospheric components, measure T, etc

A proposal was submitted, and …

Strengths: . … The need for HST is well documented.

Weaknesses: This was a good proposal, but to some degree the projected results
seemed incremental. More discussion about the larger role neutron star evolution
plays in astrophysics would also be helpful. The panel also felt that the imaging
observations are probably feasible from the ground

PSR J0437-4715 (Durant et al. 2011, subm.)

The only millisecond (recycled) RPP detected in the optical (UV)

***P* = 5.8 ms , *Edot* = 2.3*10^{33} erg/s, age = 6.7 Gyr**,
***d* = 156.3 +/- 1.3 pc** (from parallax; Deller et al. 2009)

Binary: **P_{bin} = 5.5 d**, cold WD with ***T*~4000 K**, dominates in NIR-optical;
$M_{WD} = 0.254\ M_{sol}$, $M_{NS} = 1.76\ M_{sol}$

First optical-UV observation of the pulsar: *HST/STIS FUV-MAMA* (1100-1800 A),
Rayleigh-Jeans spectrum, **brightness temperature ~ 10^5 K** – (re)heating?
(Kargaltsev et al 2004)

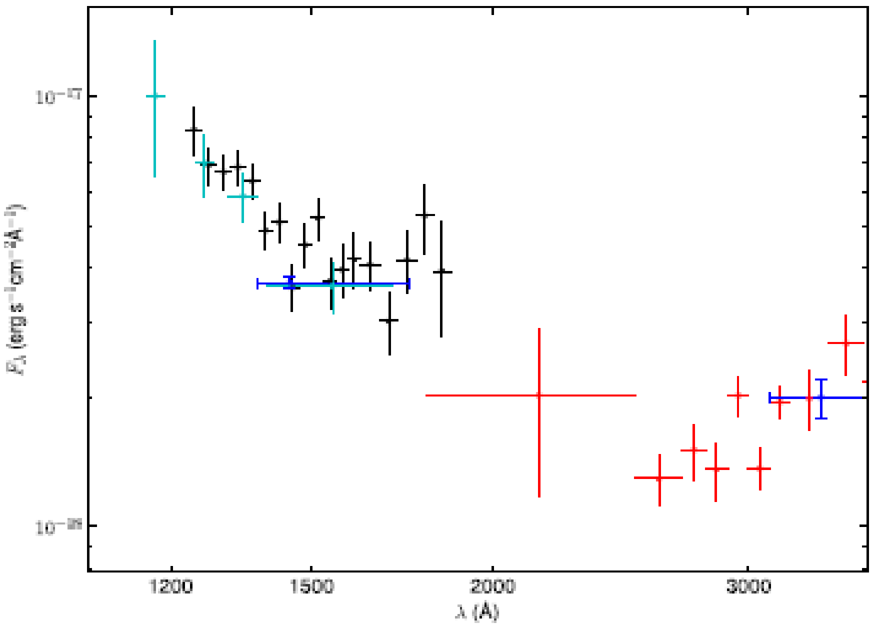
HST proposal accepted for Cycle 14 with *STIS/FUV-MAMA*;
STIS died a few days before the scheduled observation date.

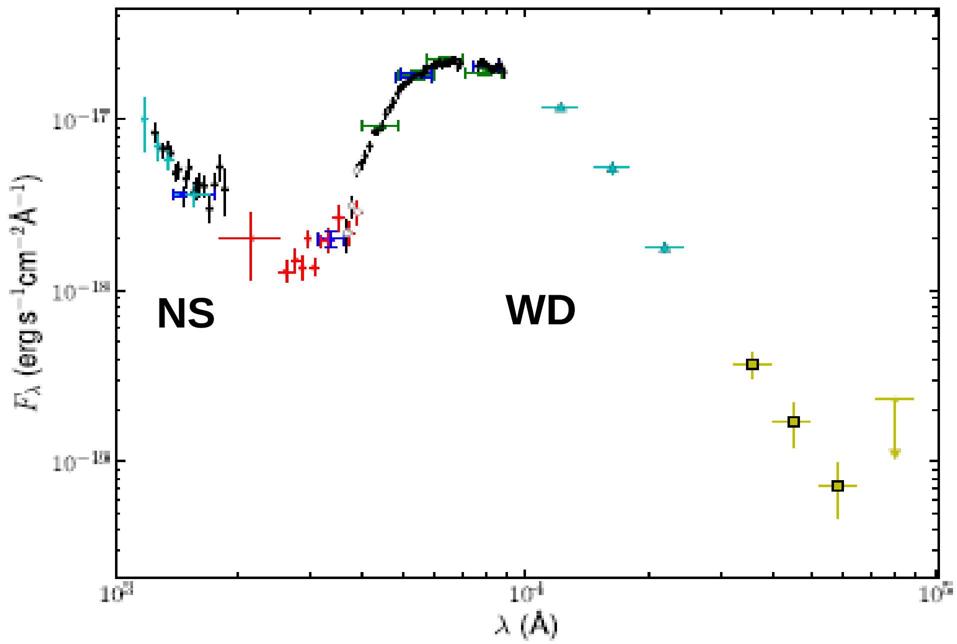
New *HST* proposal accepted for Cycle 15 to observe with *ACS/SBC* (FUV) and *ACS/HRC* (NUV)

Independently observed with *Spitzer* (*IRAC* and *MIPS*), *Magellan (PANIC), VLT/FORS1*

We collected and analyzed all the observations.

PSR J0437-4715: UV and UV-optical-IR spectra (F_λ vs λ)





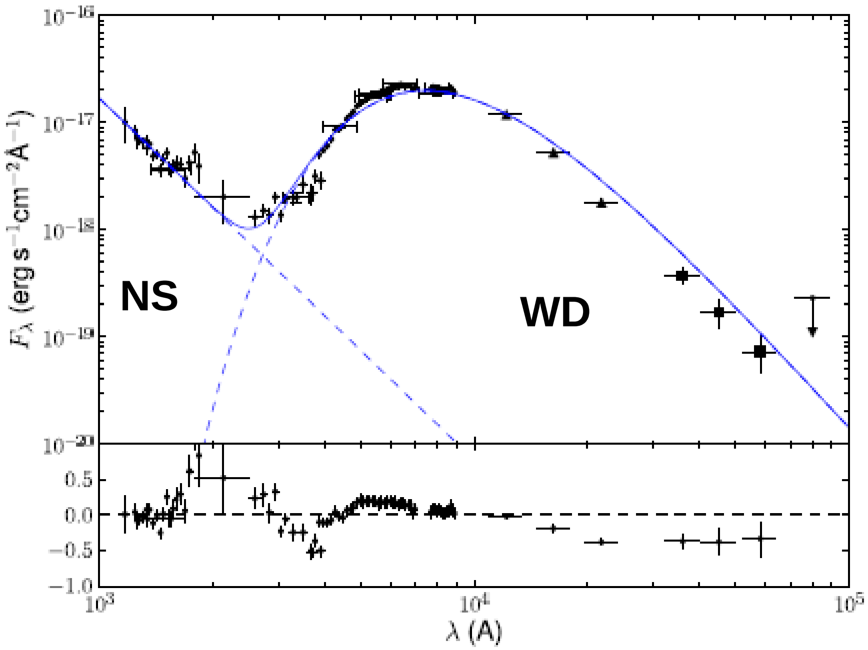
λ = 1100 – 3500 A (4 instruments);

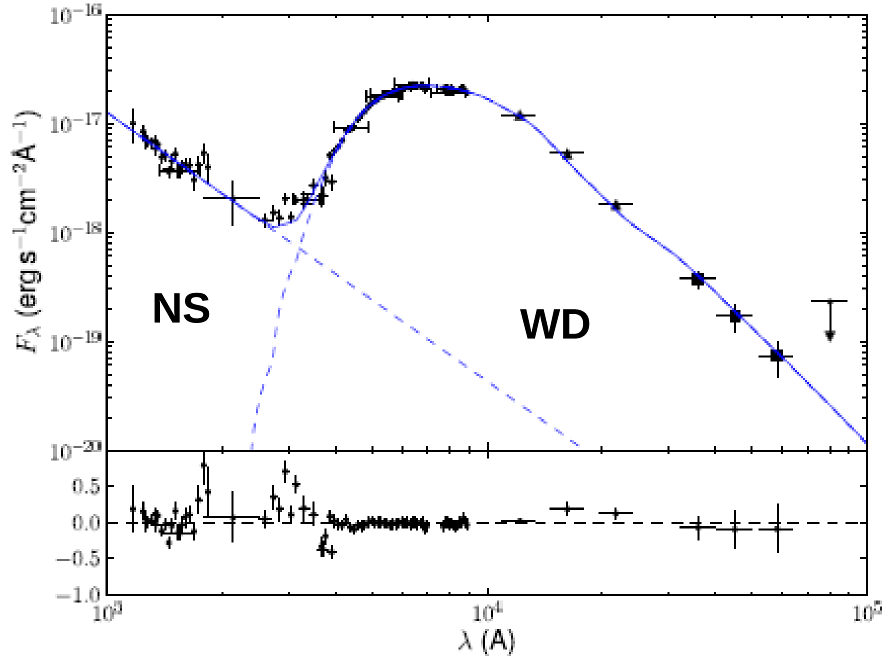
F_λ* ~ *λ^{-4} at shorter λ (Rayleigh-Jeans), rise at longer λ

λ = 0.1 – 6 μm (8 instruments);

Neutron star + white dwarf spectrum

J0437-4715: Spectral fits for UV-opt-IR





<u>Power-law + blackbody</u>
(poor fit)

<u>Power-law + hydrogen WD atmosphere</u>
(good fit)

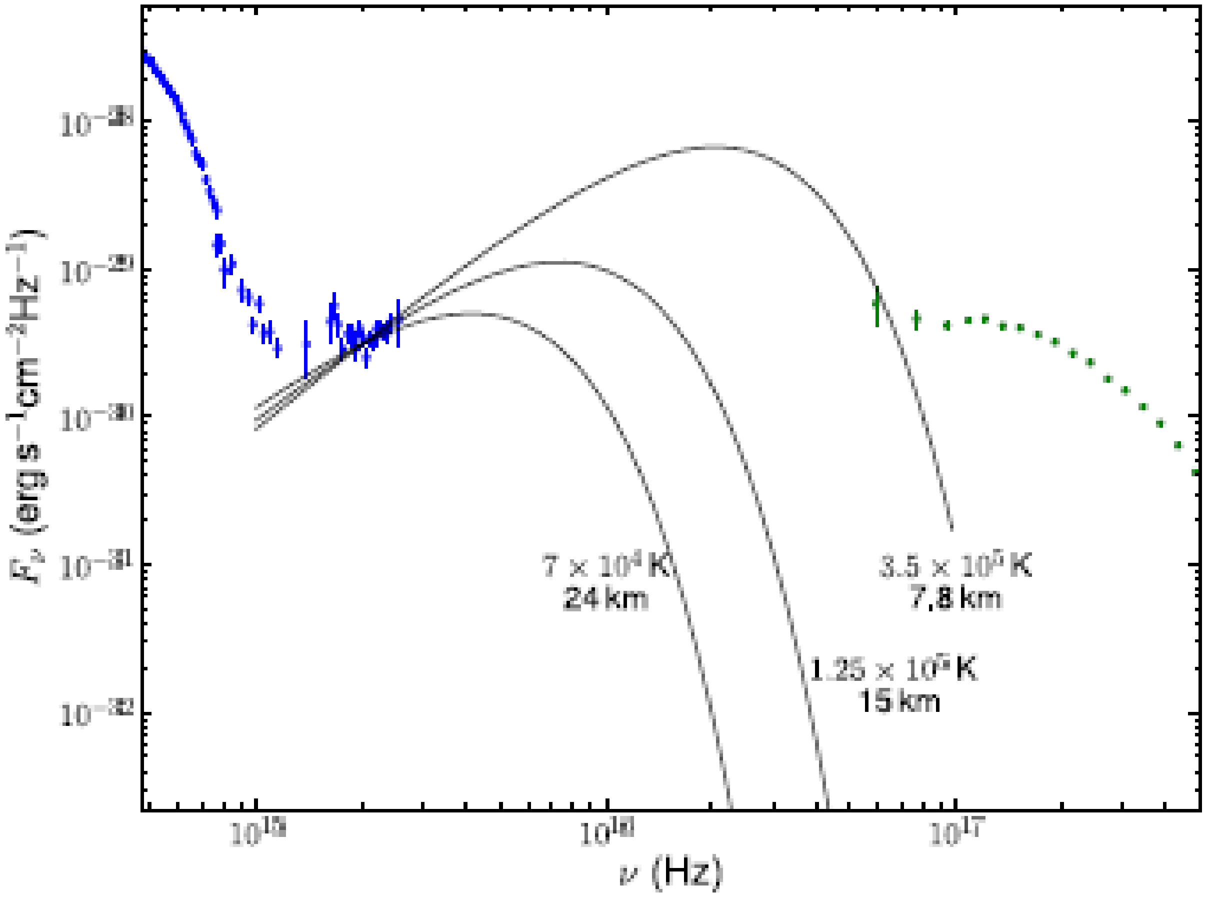
NS: $\boldsymbol{\alpha_\lambda}$ **= - 3.4 +/- 0.4,** $\boldsymbol{\alpha_\lambda}$ **= - 2.5 +/- 0.2,**

WD: T_{BB} **= 3910 +/- 40 K** T_{eff} **= 3950 +/- 150 K** (age **6.0+/-0.5 Gyr**)

R_{BB} **= (20 +/- 1)*10^3 km** **log g = 6.98 +/- 0.15** (He core WD)

M_{WD} = 0.254 M_{sol} → R_{WD} = (19 +/- 2)*10^3 km

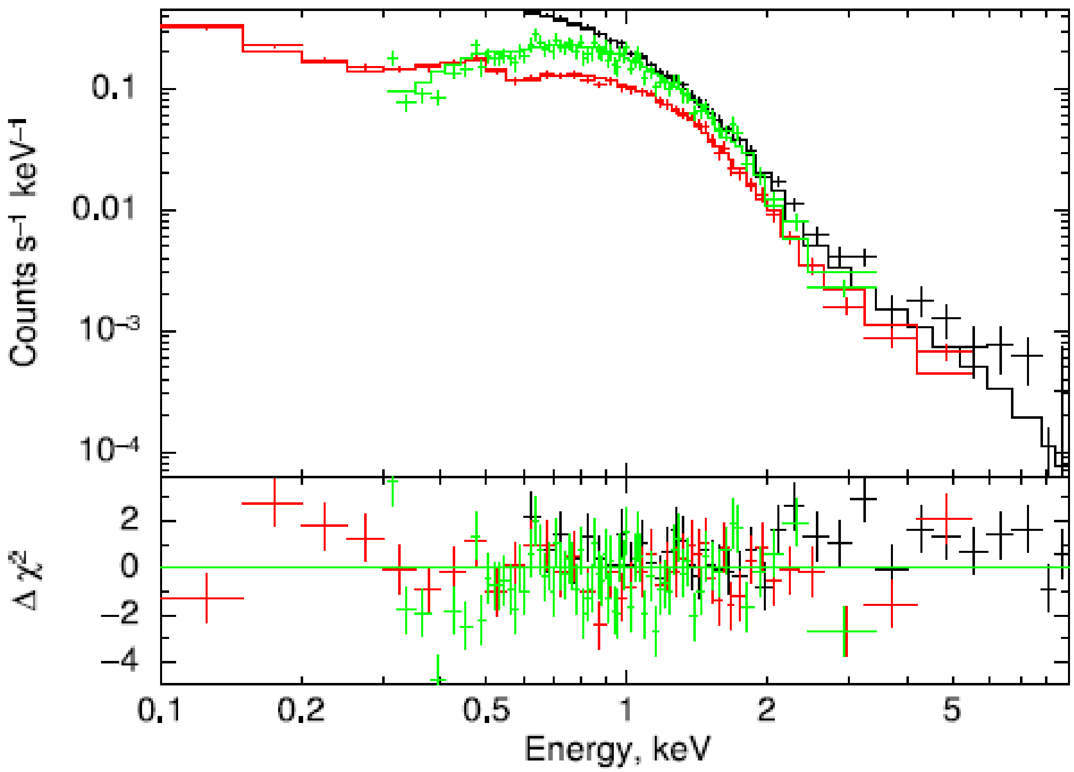
PSR J0437-4715: Thermal fits to FUV spectrum (F_ν vs ν)



0.7 < (T /10^5 K) < 3.5 ; 8 < (R/1 km) < 24 (formal limits)

T* = 1.25*10^5 K** for ***R* = 15 km** (T*** and ***R*** for distant observer)

J0437-4715: X-ray spectrum (Chandra + XMM-Newton)

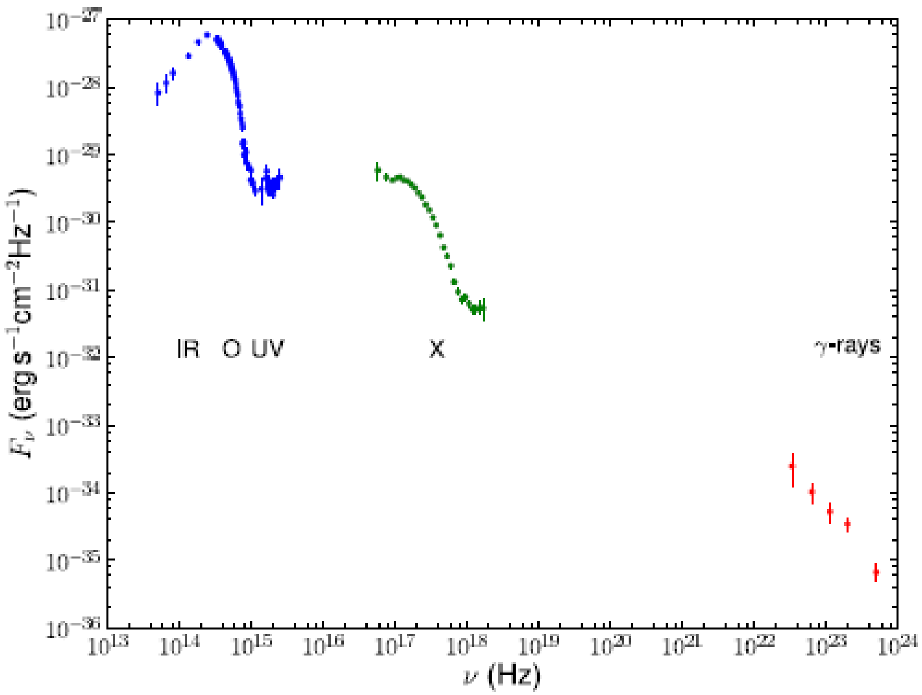


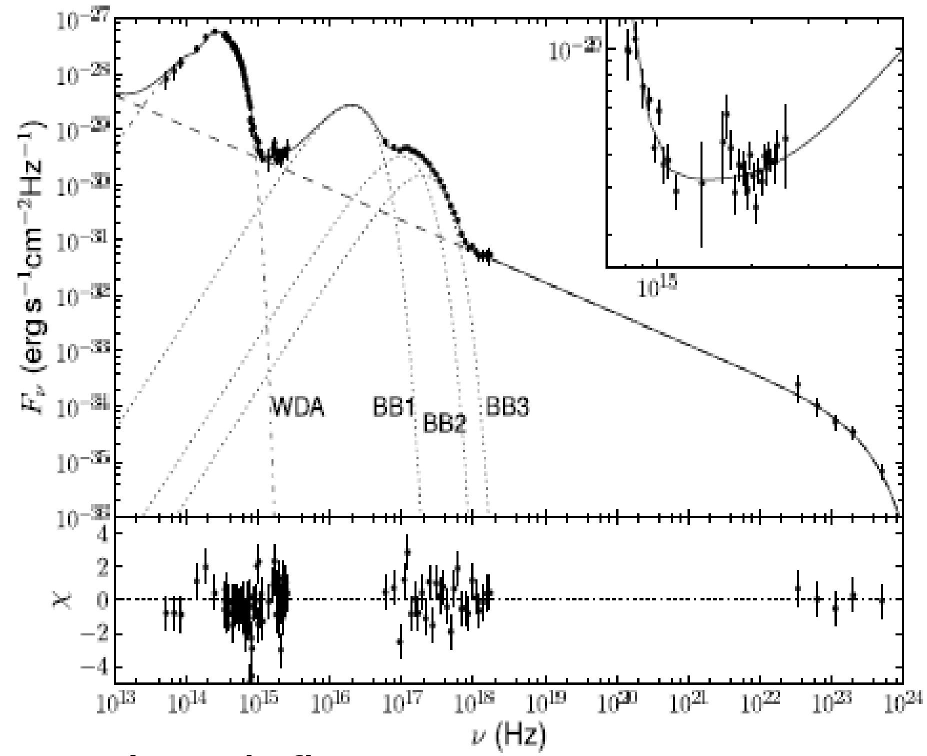
NSA(tmosphere) **+ PL fit:**

***kT* = 138 +/- 2 eV (*T* = 1.5*10^6 K), *R* = 0.29 +/- 0.02 km –** hot, small;
photon index **Γ = 2.69 +/- 0.03; N_H = 7*10^{19} cm^{-2}**

Better fit is given by **NSA+NSA+PL** model**: kT_1= 140 eV, R_1 = 0.4 km;**
kT_2 = 30 eV, R_2 = 7 km; Γ = 1.9 → nonuniform *T* + magnetosphere

PSR J0437-4715: Multiwavelength spectrum (F_ν vs ν)





Multiwavelength fit:

WD atm + BB1 + BB2 +BB3 + cut-off PL

Γ = 1.56(1), E_{cut} = 1.1(2) GeV,

L_{PL}=8*10^{31} erg/s = 0.03 Edot

T = 3.3(3), 16.9(6), 33.9(8) *10^5 K

R = 5.3(5), 0.162(7), 0.038(3) km

PSR J0437-4715: Summary

- IR-optical observations → **most detailed investigation of a very old, very cold WD** (Helium core, Hydrogen envelope)

- **UV → surface of the very old NS is hot, $T \sim 1.5*10^5$ K for $R = 13$ km → → (re)heating,** possibly **rotochemical heating** (Reisenegger 1995)

- **Temperature distribution is strongly nonuniform: $0.12 < T < 3.5$ MK; high temperatures in polar caps (**Harding & Muslimov 2001)

- **A single PL component ($\Gamma = 1.6$, $\eta = 0.03$) may be responsible for magnetospheric emission from UV to GeV γ-rays – synchrotron radiation of electrons with a wide PL spectrum ($p = 2.1$; $10^2<\gamma<10^7$, if $B = B_{LC} = 3*10^4$ G)?**

PSR B0656+14 (Durant et al. 2011, subm.)

The youngest Musketeer, one of the best studied RPPs

***P*=385 ms, *Edot* = 3.8*10^{34} erg/s, age = 110 kyr, *d*=288+/-30 pc** (Brisken et al 2003)

Detailed X-ray observations with *Chandra and XMM-Newton* (Pavlov et al 2002; de Luca et al. 2005)

Optical emission discovered with *NTT* (Caraveo et al 1994), studied in many *HST* observations, from NIR to FUV
(Pavlov et al 1996,1997; Mignani et al 200; Koptsevich et al 2001; Shibanov et al. 2005; Zharikov et al. 2007; Kargaltsev & Pavlov 2007)

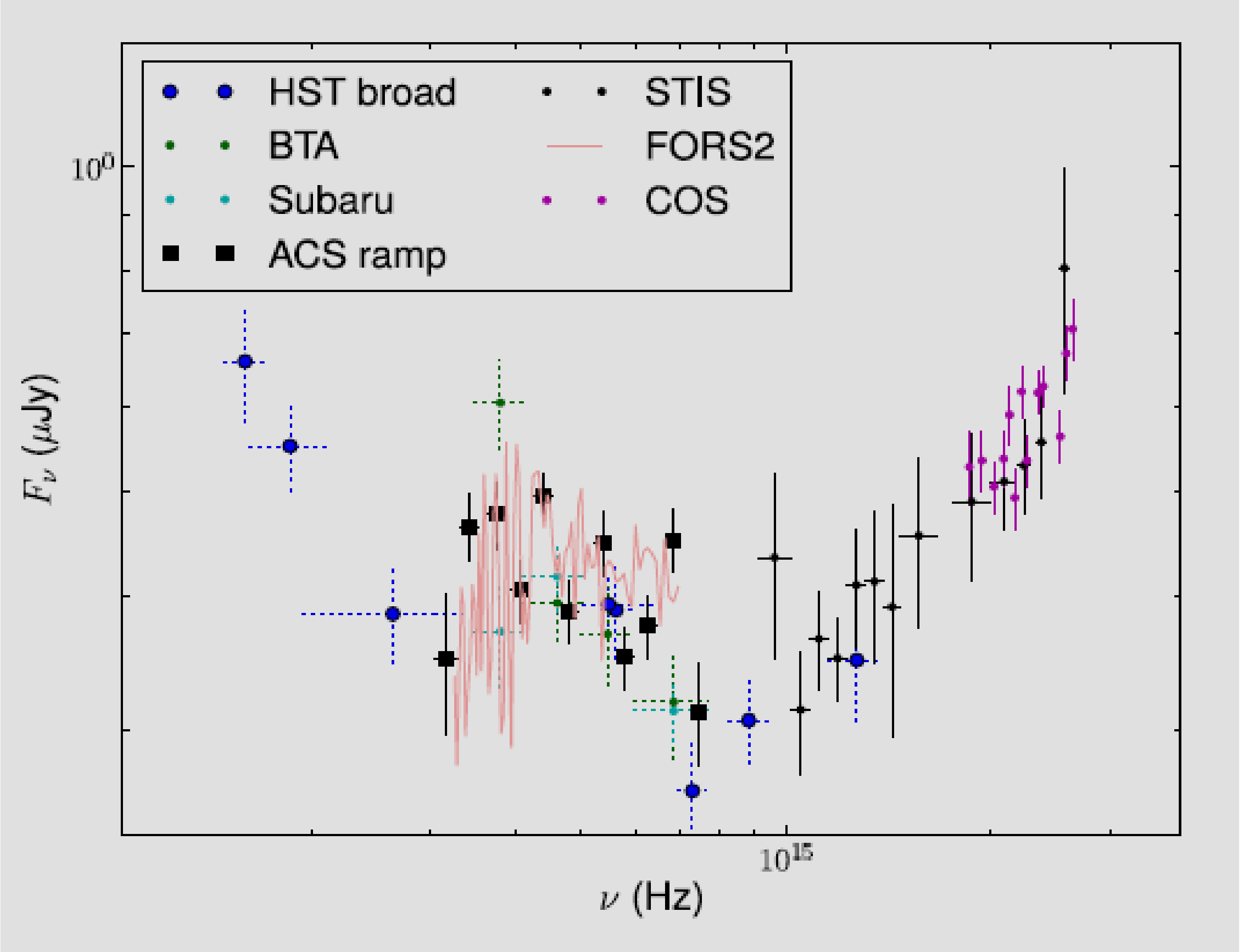
Pulsations were discovered in optical, NUV and FUV (Kern et al 2003, Shibanov et al 2005; Kargaltsev & Pavlov 2007), polarization in the optical (Kern et al 2003)

Broad-band optical-UV spectrum was interpreted as the sum of two components: power-law (magnetospheric) and Rayleigh-Jeans (thermal emission from the NS surface) – Pavlov et al (1997), Kargaltsev & Pavlov (2007).

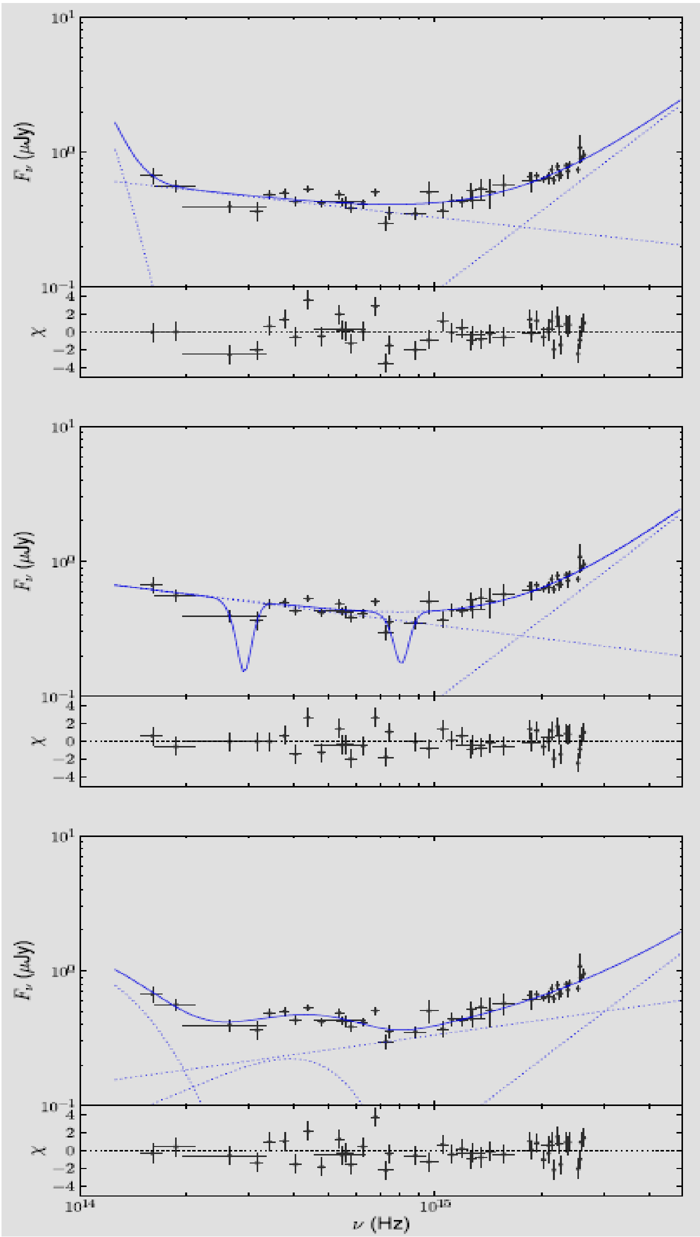
Spectral observation with *VLT/FORS1* has shown hints of spectral features (Zharikov et al 2007)

We observed B0656+14 with ***HST ACS/WFC*** (10 ramp filters), ***STIS/FUV-MAMA/G140L*** and ***COS/FUV*** to better understand the spectrum, reanalyzed ***NICMOS*** and ***STIS/NUV-MAMA*** data, and added all the observations.

Composite NIR – FUV spectrum (F_ν vs. ν)



PSR B0656+14: Spectral features



Two continuum components do not fit.

Fit with **power-law (α_ν= - 0.29 +/- 0.06) + Rayleigh-Jeans + cold BB (500 K)** – marginally acceptable

Power-law (α_ν = - 0.32 +/- 0.05) + two absorption lines (0.37 +/- 0.4 μm and 1.0 +/- 0.1 μm) – acceptable

Power-law (α_ν = 0.4) + cold BB (1200+/- 400 K) + emission feature (0.77 +/- 0.1 μm) - acceptable

PSR B0656+14: Interpretation of spectral features

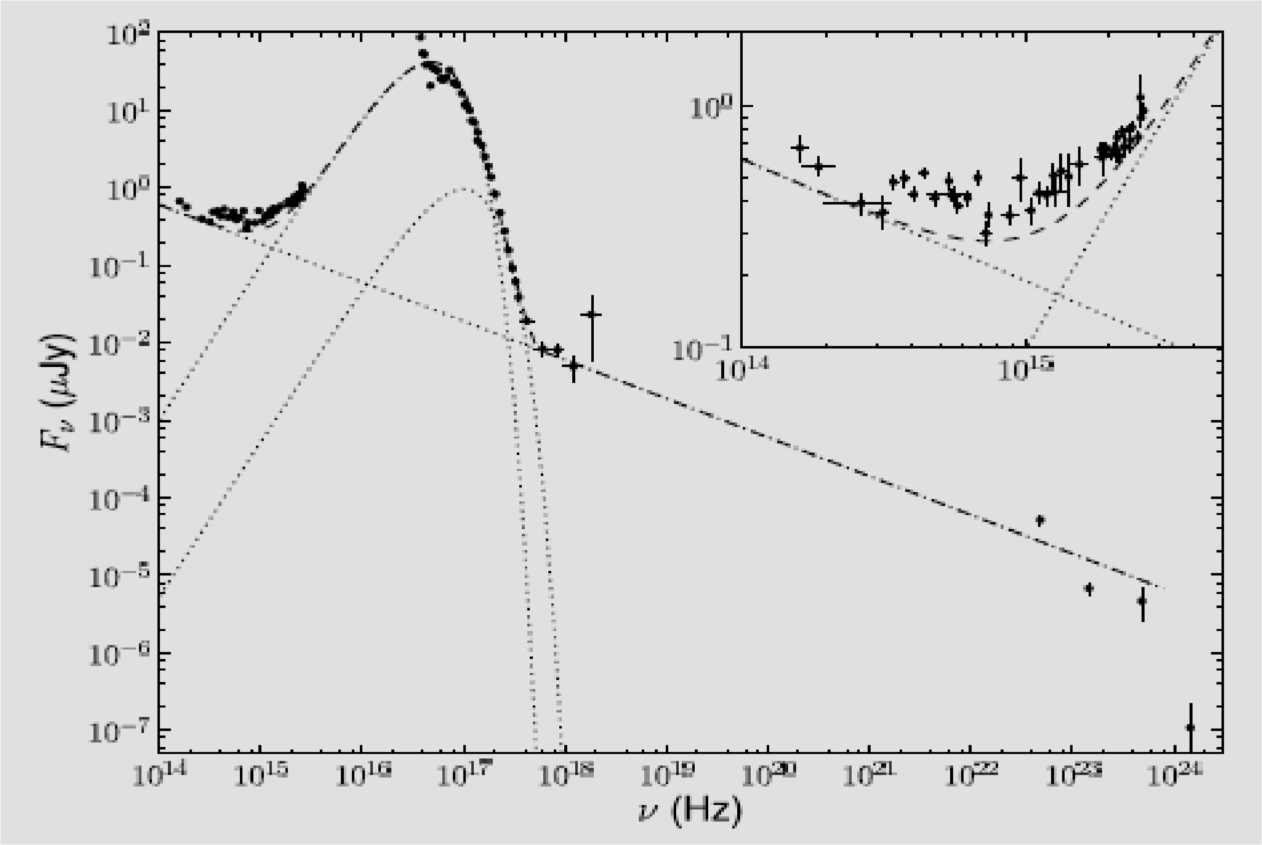
Electron cyclotron absorption/emission requires magnetic fields ***B* ~ a few 10^8 G – could** only occur in the magnetosphere**,** at ***R* ~ 300 R_{NS}.** Absorbing/emitting electrons should be in a relatively narrow layer(s) to be consistent with the feature width(s). Looks somewhat artificial but not ruled out.

Proton (ion) cyclotron absorption/emission requires ***B* ~ a few 10^{11} G (**vs **B_{NS} = 5*10^{12} G** for the dipole component). Looks rather improbable.

Transitions between highly excited ("H-like") atomic levels in the NS atmosphere – requires calculations, but does not look very probable

The "absorption" at 1 μm (the rise to longer λ in the NIR) could be indicative of a **fall-back disk (*T* ~ 500 – 1200 K);** unfortunately, observations in IR are complicated by the presence of a red galaxy projected near the pulsar (at ~1'' – 2'').

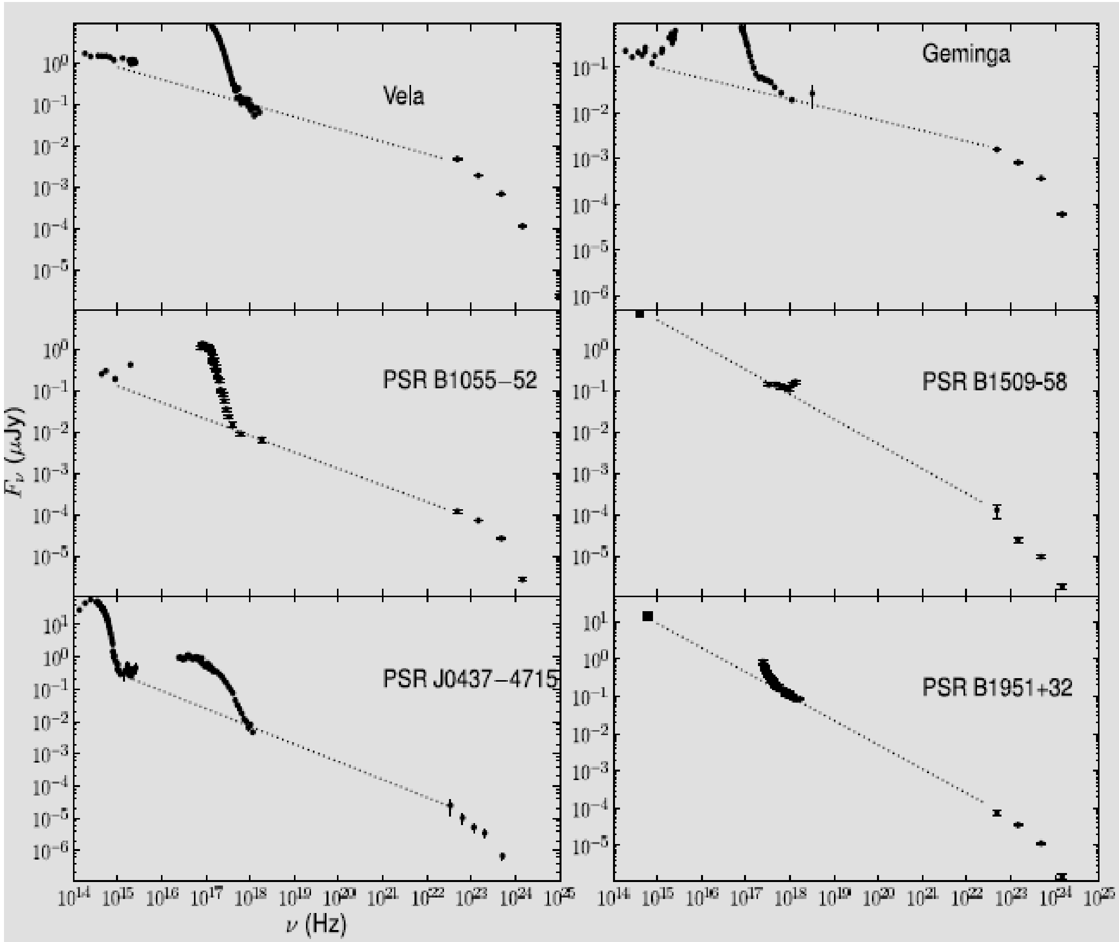
B0656+14: Multiwavelength spectrum (F_ν vs. ν)



NIR – γ-ray (1 eV – 1 GeV) spectrum can be described by **BBcold + BBhot + PL (Γ = 1.5 +/- 0.05) –** synchrotron emission from a very wide electron spectrum **($10^3 < \gamma < 10^7$ in $B = B_{LC}$ = 800 G) ?**

Observation in hard X-rays – soft γ-rays would be particularly useful

Multiwavelength spectra of other RPPs with optical detections

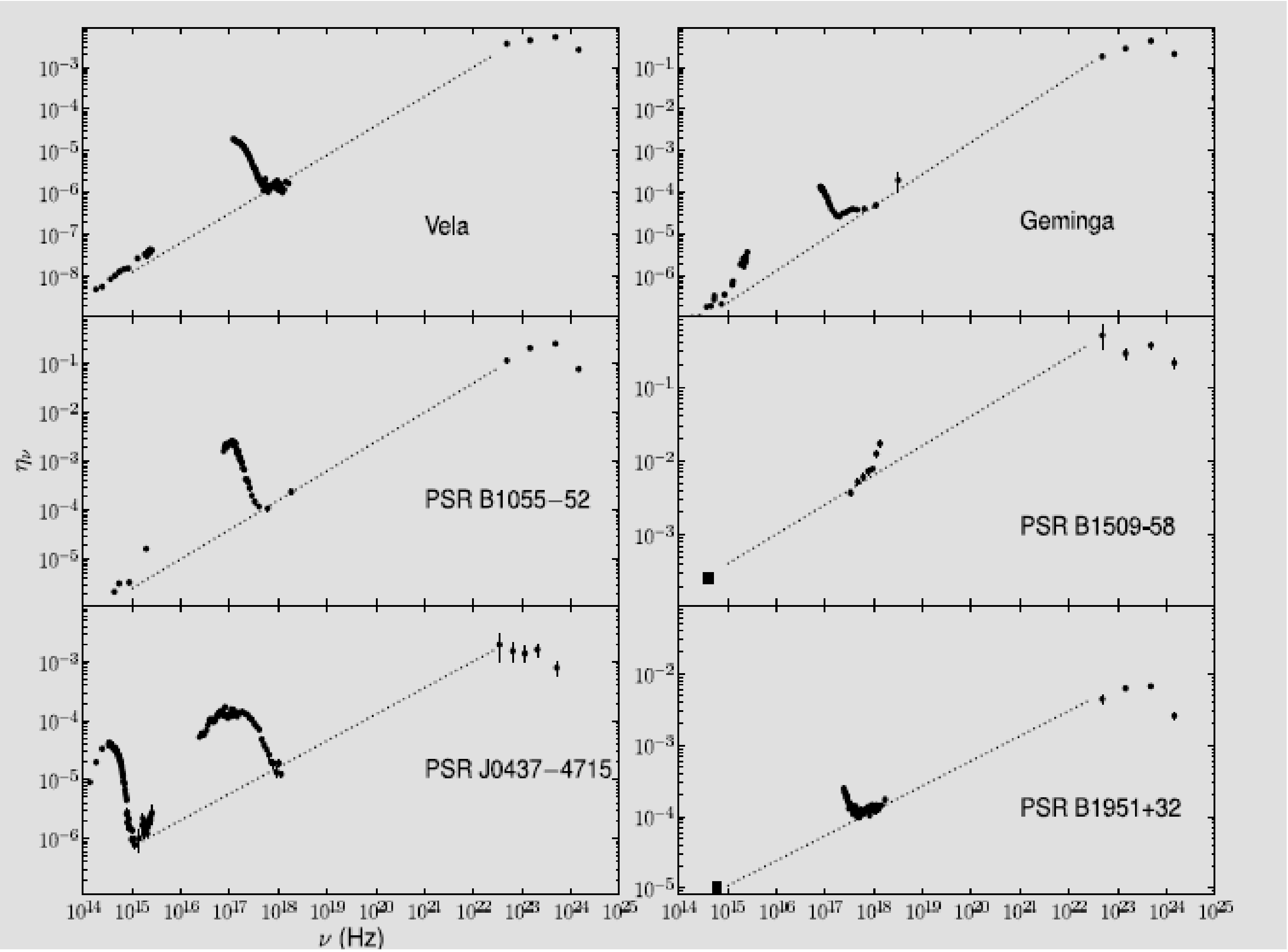


Each pulsar's nonthermal spectrum can be described by a single PL with a break or cut-off at GeV energies? (not so for Crab and B0540-69.)

$1.20 < \Gamma < 1.65$, $0.7 < E_{cut} < 4.5$ GeV

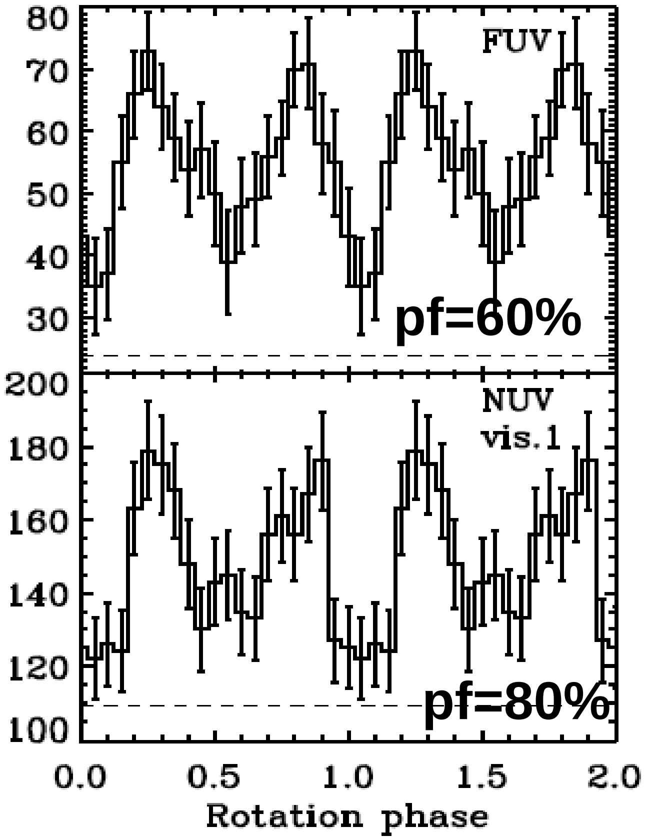
Spectral efficiencies of the same 6 pulsars

$$\eta_\nu = 4\pi d^2 \nu F_\nu / \dot{E}$$



PSR B065+14: Pulsations

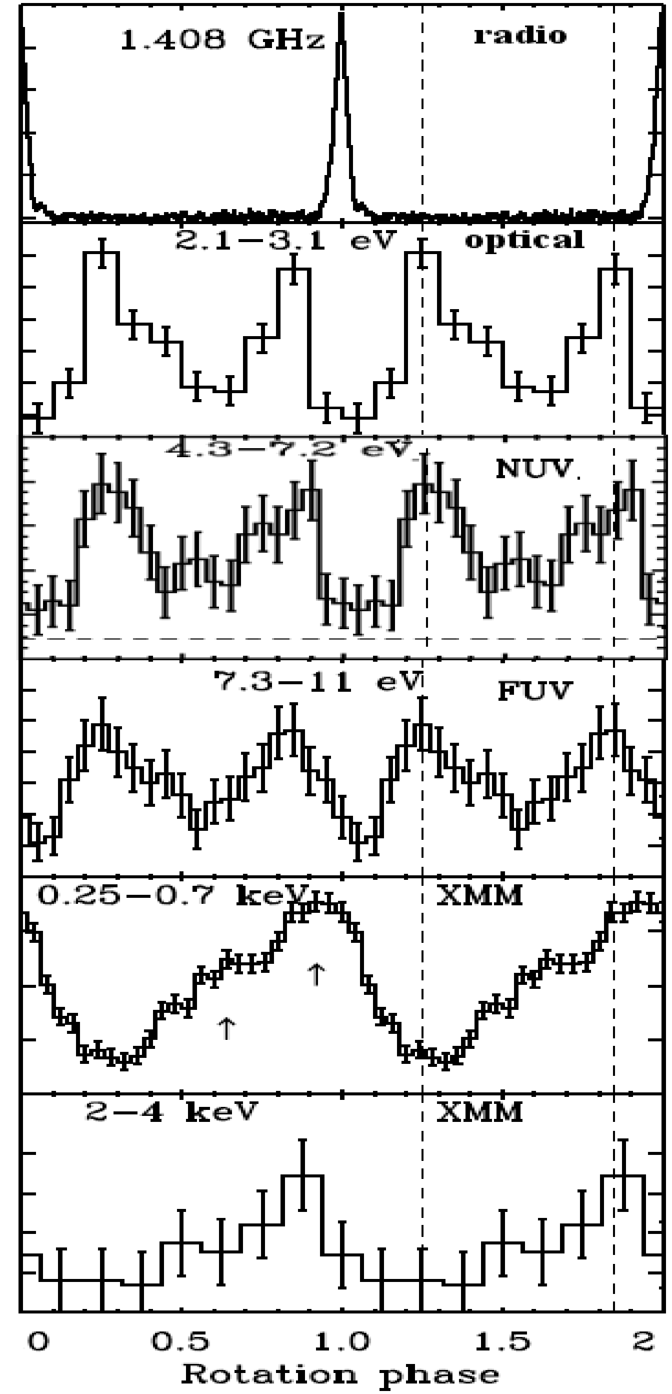
- Pulsations in FUV weaker than in NUV
- NUV and optical pulse profiles are is very similar
- Two peaks in FUV, NUV and optical but only one in hard X-rays.



1. FUV emission is dominated by thermal radiation from NS surface, with 2 non-thermal peaks seating on top of the shallow thermal pulse.

2. NUV dominated by non-thermal emission.

3. Single peak in hard X-rays implies different geometry of emitting regions for the non-thermal emission



Some other highlights of recent work

We detected the **Vela pulsar with Spitzer IRAC**, found a mIR excess; another spectral component? fall-back disk? ultra-compact PWN? (Danilenko et al 2011) -- see **poster by Andrey Danilenko** (session 9).

Young pulsars embedded in pulsar wind nebulae have likely been detected in optical/NIR: **PSR J0295+6449 in 3C58** (Shibanov et al 2008), **PSR 1124-5916 in G292.0+1.8** (Zharikov et al 2008; Zyuzin et al 2009) – **talk by Yurii Shibanov** and **poster by Dmitry Zyuzin.**

A candidate optical counterpart of the young **PSR J1357-6429** has been detected - see **poster by Ada Kirichenko** (session 9).

RPPs: Overview of current status

- **Nine RPPs are firmly detected in NIR-opt-UV**, 4 (7?) require confirmation; much more RPPs could be detected with HST
- RPP spectra show at least two components: **magnetospheric (optical)** and **thermal (UV),** perhaps a third component in **IR-NIR (a disk?)**
- Strange **spectral features** are seen in at least one RPP (B0656+14); origin uncertain
- **Magnetospheric spectra** of not too young/powerful pulsars show about **the same slope from NIR-optical (eV) to γ-rays (GeV)** – a very broad power-law energy spectrum of radiating particles + the same emission mechanism?
- **Mismatch of Rayleigh-Jeans (UV) tails of thermal components with Wien (X-ray) tails** are smaller than in "INSs" (MFDPP? – talks by Kaplan and Kamble) ; can be explained by **nonuniformity of surface temperature**
- The only recycled RPP detected in optical (UV) shows a high surface temperature – **(re)heating is important at least in recycled pulsars**