Ultraviolet Emission from Isolated Neutron Stars

26 years of HST observations: Overview of results

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Contents

Ultraviolet: $\lambda \sim 120 – 4000$ A, $h\nu \sim 3 – 100$ eV

Near-UV (NUV): $\lambda \sim 2000 – 3000$ A, $h\nu \sim 4 – 6$ eV

Far-UV (FUV): $\lambda \sim 912 – 2000$ A, $h\nu \sim 6 – 13.6$ eV

Extreme UV (**EUV**): $\lambda \sim 120 – 912$ A, $h\nu \sim 13.6 – 100$ eV, virtually unobservable because of absorption in ISM

Why important for NS studies:

Can detect thermal emission from cold (**old**, >1 Myr) NSs, undetectable in X-rays, and Rayleigh-Jeans tails of thermal emission from **middle-aged** (0.1 – 1 Myr) NSs.

NUV/FUV unobservable from the ground

Requires Space Telescope

Isolated NSs = non-accreting NS

They include

- **Rotation powered pulsars (RPPs, ~2500)**
- **Thermally emitting isolated NS (TEINSs, 7)**
- **Magnetars (~20)**
- **“Central Compact Objects” (CCOs) in SNRs (~10)**

Beginning of the story:

1987: First HST proposal submitted, accepted

UV imaging of old nearby pulsars

B0950+08, B1133+16, B1929+10

(Pavlov 1990, Proc. IAU Coll. 128)

1991 Program canceled because of HST aberration problem

1992 Proposal submitted to observe *middle-aged* PSR **B0656+14** and *old* PSRs **B0950+08, B1929+10** in several filters, accepted for only one broad-band filter **FOC**/F130LP centered in NUV

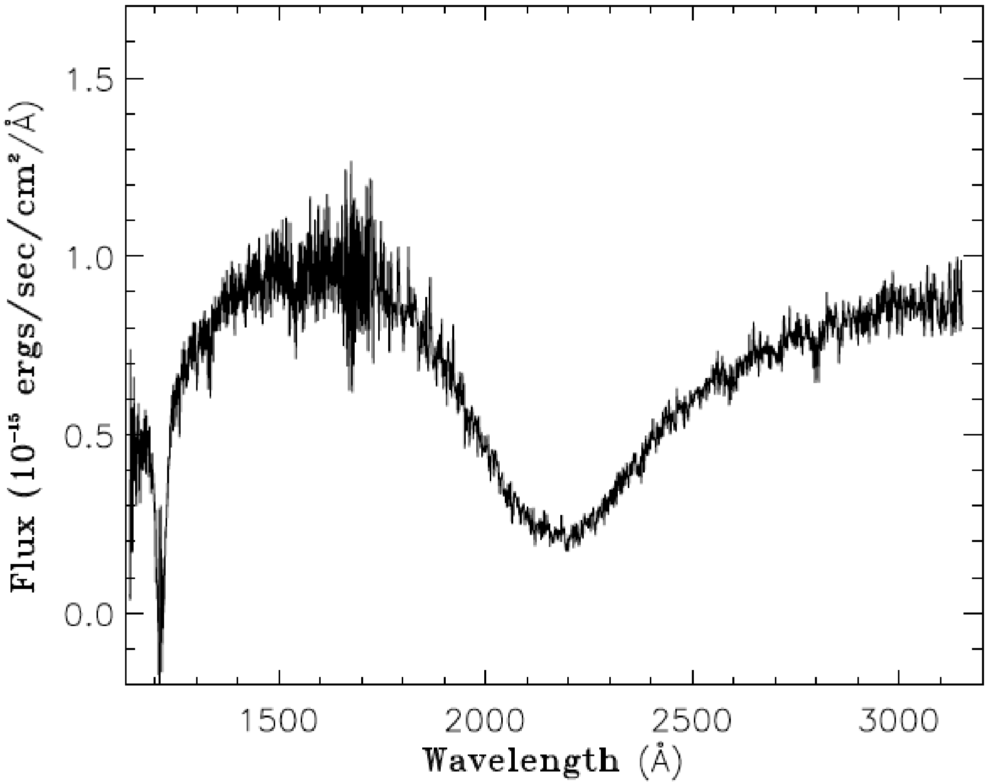
1994 Observations completed, all targets detected, the origin of radiation remained uncertain, likely a mixture of thermal and nonthermal **(Pavlov et al 1996a)**

1. Very young pulsars

Crab pulsar (~1 kyr, Edot=4.5×10^{38} erg/s, P=34ms, d=2 kpc)

1991-1992: Observed with **HSP** in NUV (Percival et al. 1993)
1997: **STIS** NUV grating (Gull et al. 1998)
1998: **STIS** FUV grating (Sollerman et al. 2000)

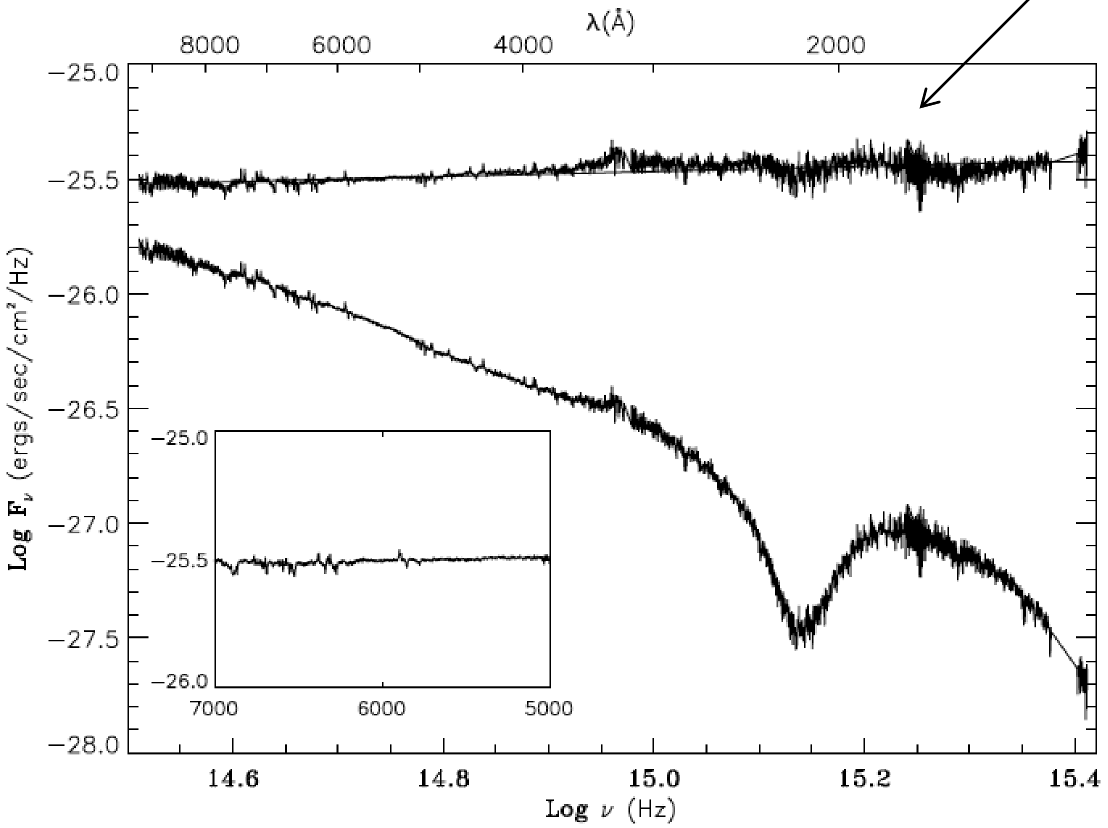
Observed NUV+FUV spectrum



(Sollerman et al. 2000)

Crab – cont.

Optical – NUV – FUV spectrum



dereddened spectrum,
E(B-V) = 0.52,
fits power law (PL)

$$F_\nu \sim \nu^\alpha$$

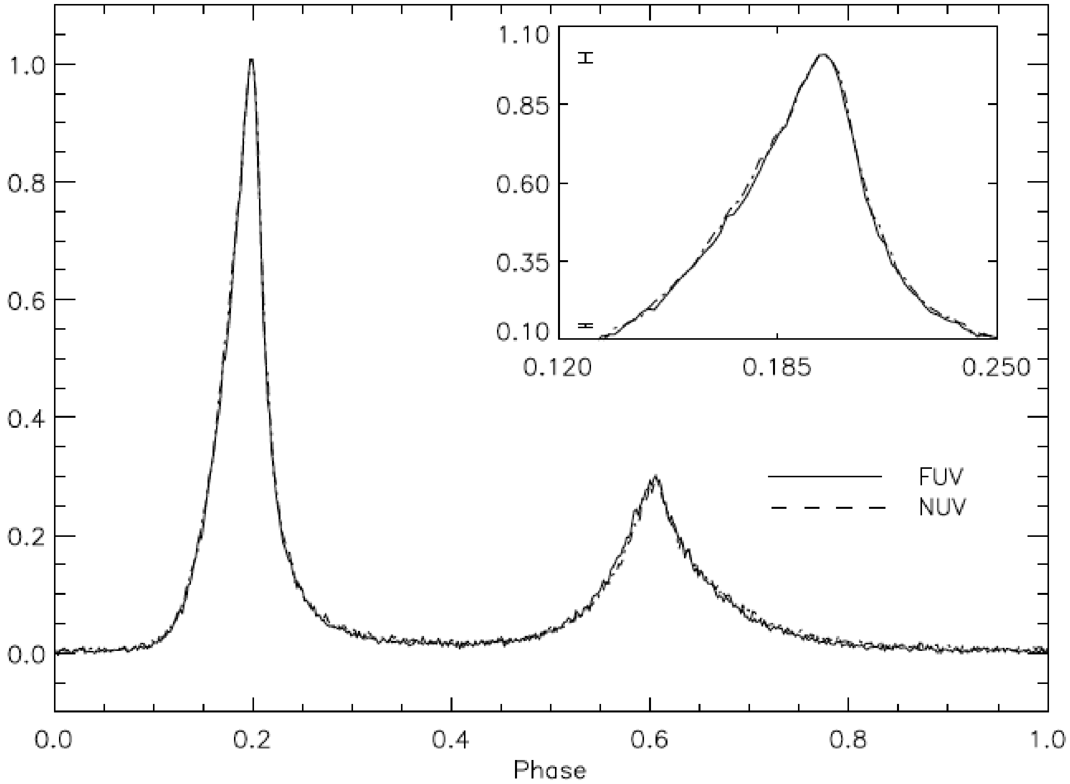
$$\alpha = 0.11 \pm 0.04$$

Magnetospheric (synchrotron) emission

Same slope in UV and optical

Crab – cont.

Pulsations in FUV and NUV



Same pulse shape in FUV, NUV and optical

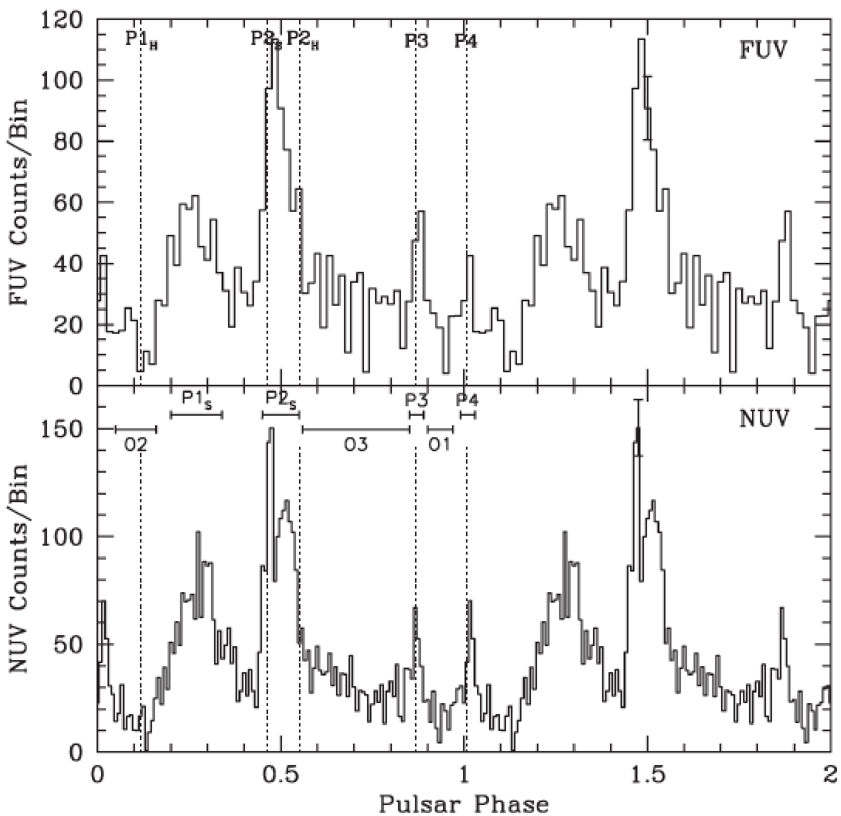
(Sollerman et al. 20000

Spectrum and pulsations of the Crab are the same in UV and optical.

Vela pulsar (~20 kyr, Edot=6.9×10^{36} erg/s, d=0.3 kpc, P=89 ms

2002: observed with **STIS** FUV grating + NUV imaging (Romani et al. 2005)

Sharp pulsations in FUV and NUV, 4 peaks per period

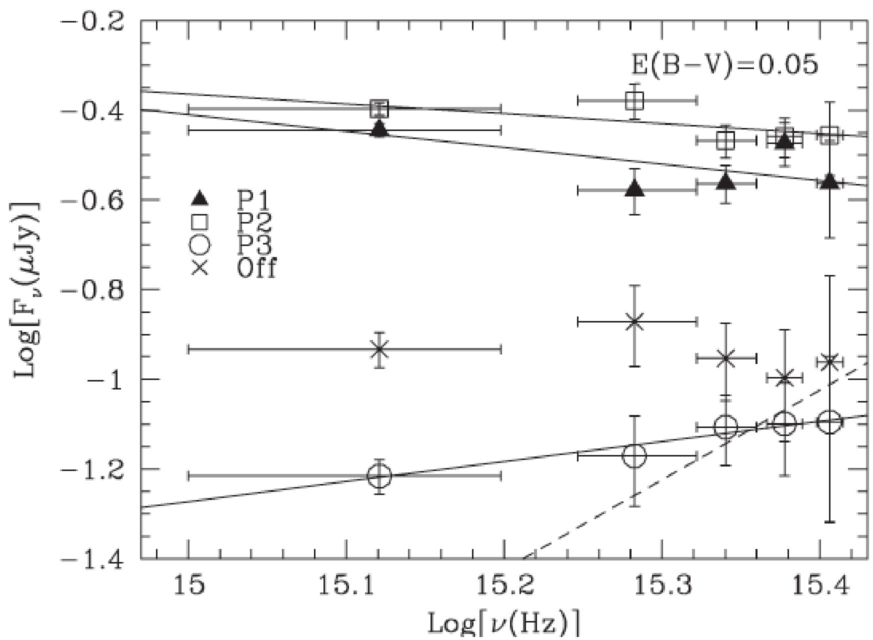


Flat PL NUV – FUV spectra in 3 phase intervals → nonthermal emission

Phase-averaged slope $\alpha \sim 0$,

may vary with phase: $-0.4 < \alpha < +0.4$

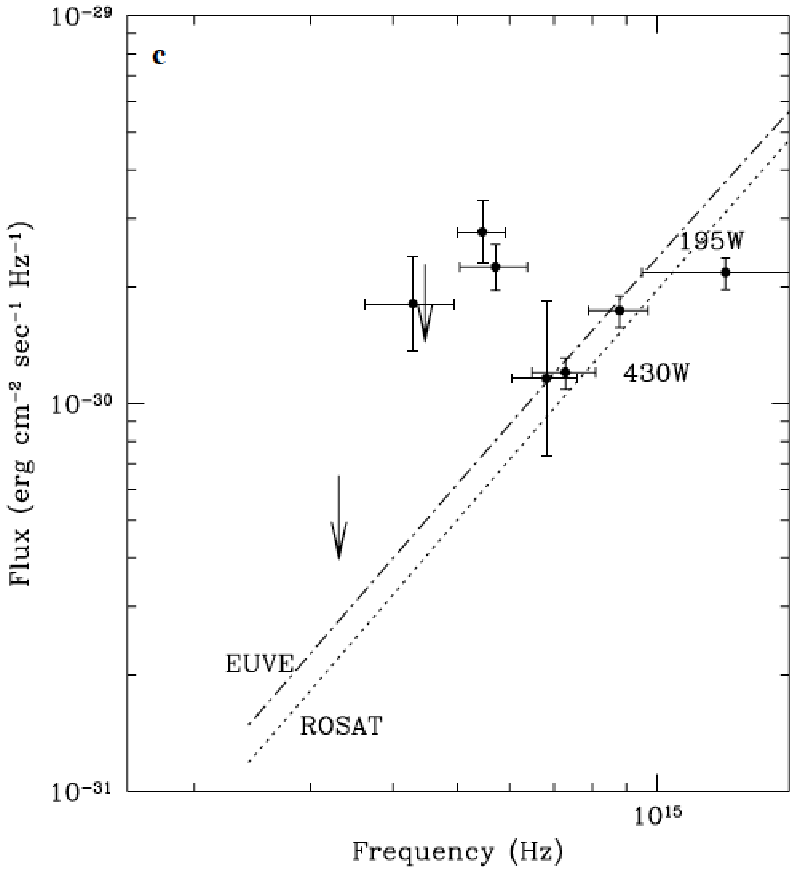
$T < 4.5\times10^{5}$ K @ R=14 d_{300} km



2. Middle-aged pulsars

Geminga Radio-quiet γ–ray pulsar, ~340 kyr,
Edot=3.2 × 10^{34} erg/s, d~0.2 kpc, P= 237 ms

1996: Observed with **FOC** in 2 optical and one NUV filter
(Mignani et al. 1998)

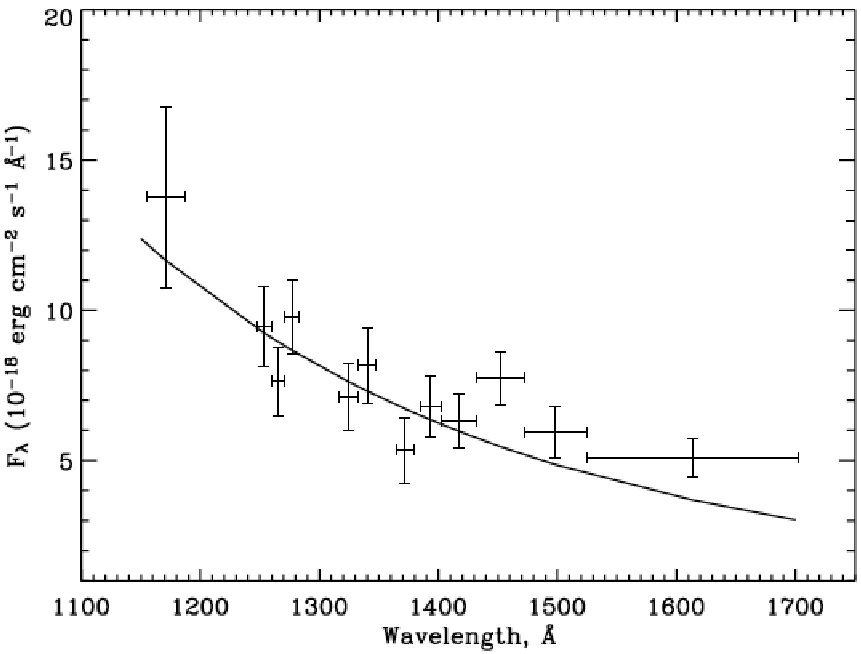


Blue – NUV points consistent with Rayleigh-Jeans spectrum, $F_\nu \sim \nu^2$

A spectral feature in the optical claimed (proton cyclotron emission?)

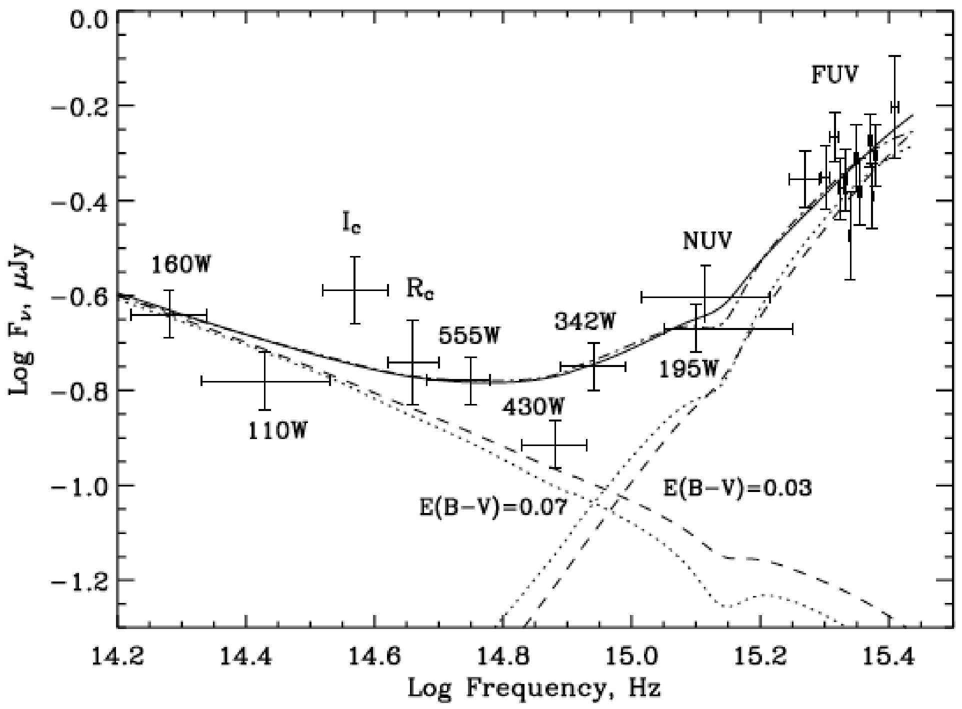
Geminga – cont.

2002: **STIS**/FUV grating and NUV imaging observations (Kargaltsev et al. 2005)



FUV spectrum and R-J fit.

$T = 3.1 \times 10^5$ K @ R=13 d_{200} km



NIR – FUV spectrum fits

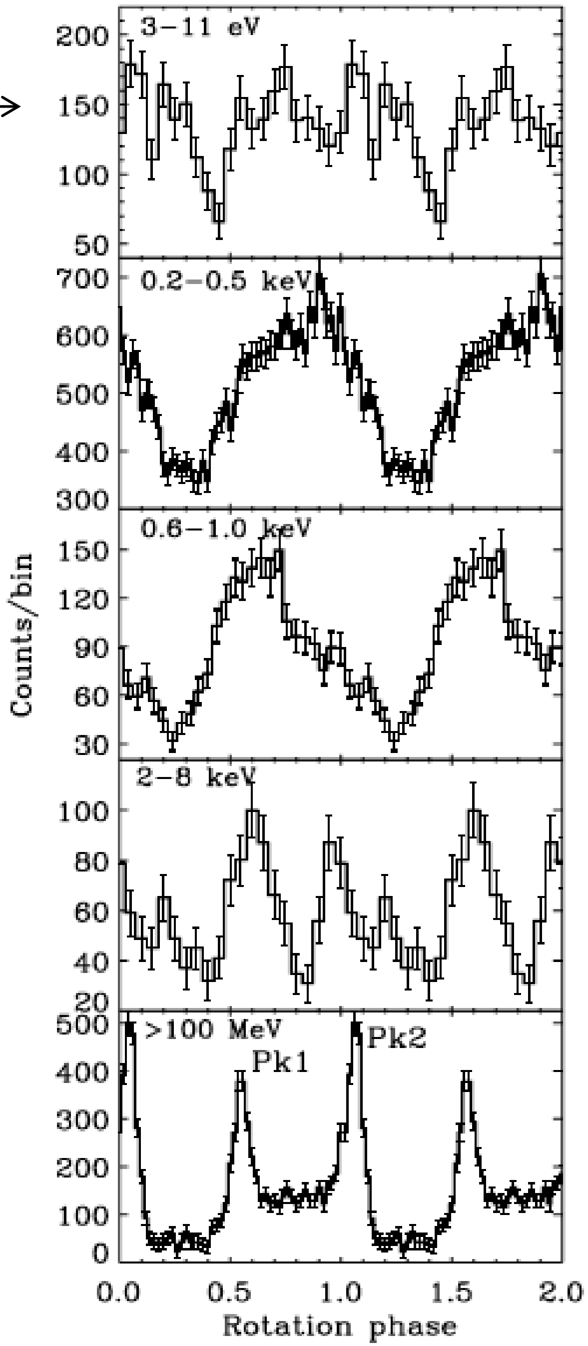
(PL; $\alpha \sim -0.4$) + blackbody (BB);

(magnetospheric + thermal)

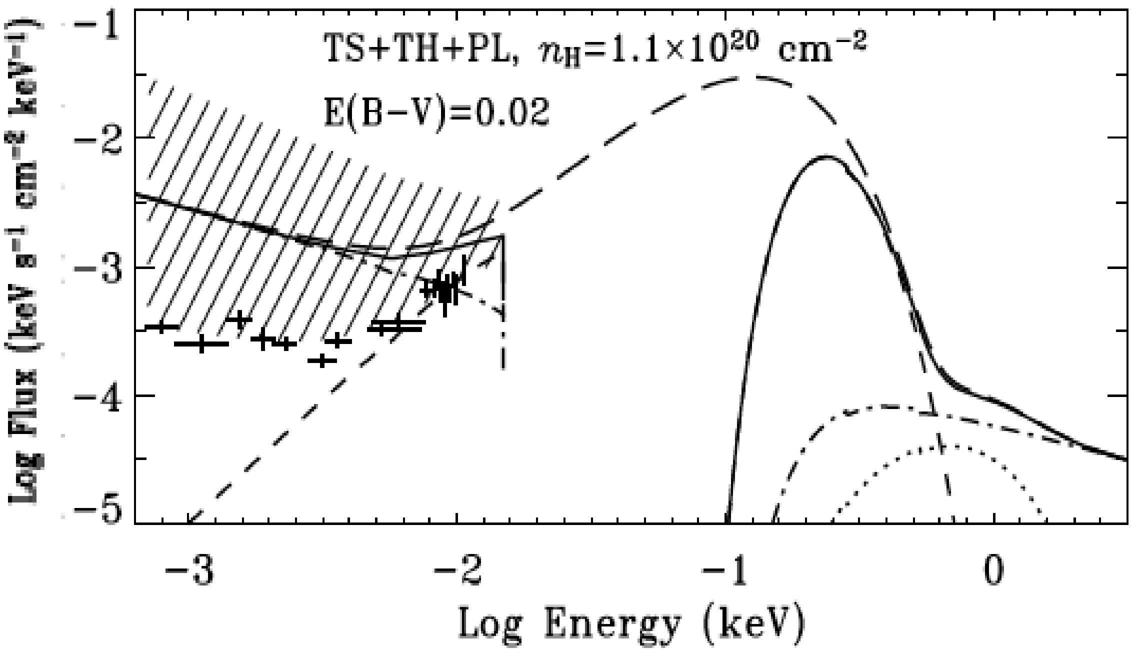
Geminga – cont.

FUV and NUV pulsations discovered →

Nonuniform temperature?
Admixture of magnetospheric emission?
Absorber in magnetosphere?

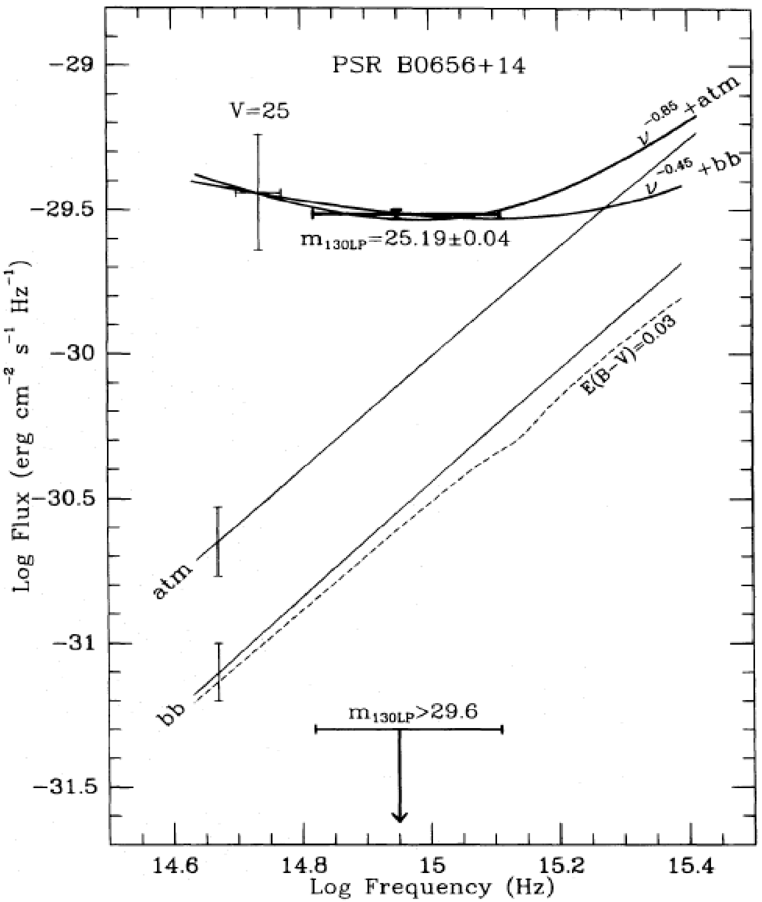


Consistent UV and X-ray thermal components.
Optical PL component below extrapolation from X-rays ↓



PSR B0656+14 (~110 kyr, Edot=3.8×10[34] erg/s, d=0.3 kpc, P=385 ms)

1994: First HST observation with a very broad **FOC**/F130LP filter centered in NUV (Pavlov et al. 1996)

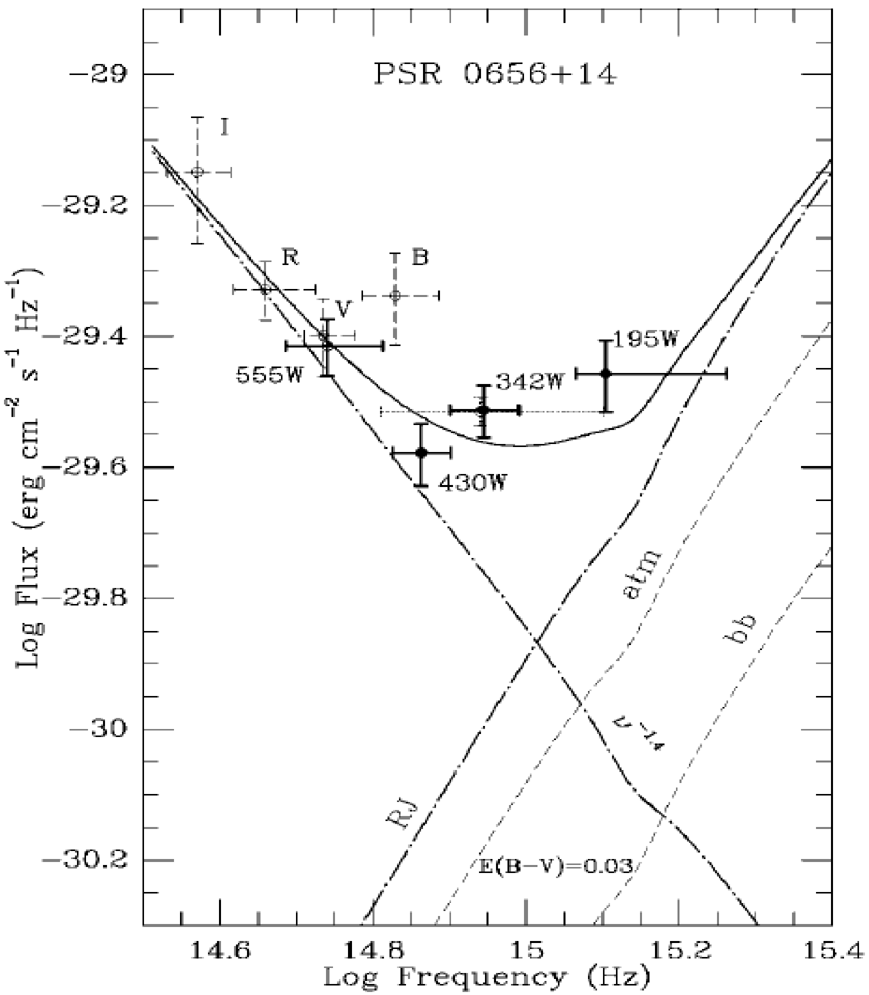


Origin of radiation remained unclear, likely a mixture of thermal and nonthermal

More points needed (several filters were originally proposed, only one accepted)

B0656+14 – cont.

1996: observed with 2 optical and one NUV (**FOC**/F195W) filters (Pavlov et al. 1997)



Optical emission is nonthermal (magnetospheric)

NUV emission is a combination of magnetospheric ($\alpha \sim -1.4$) and thermal

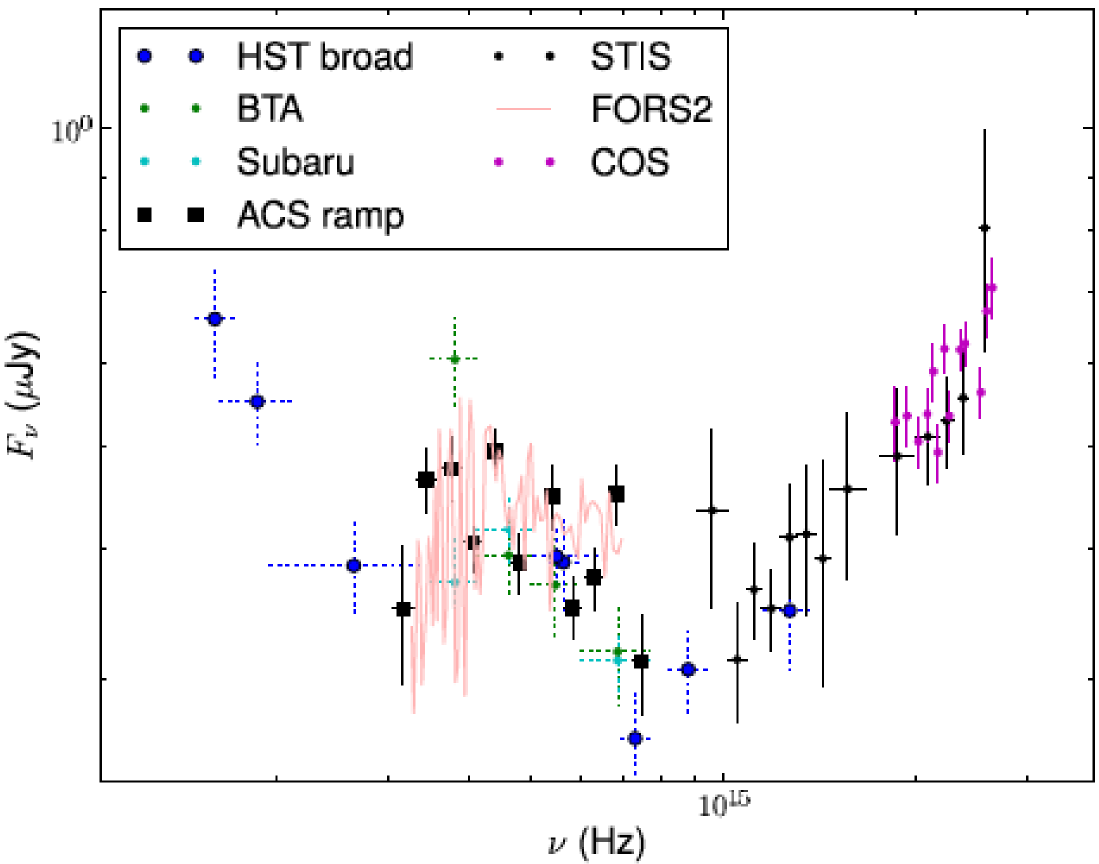
Best-fit Rayleigh-Jeans component lies above the extrapolation of thermal X-ray spectrum ("*optical excess*" – should depend on state and composition of NS surface; Pavlov et al. 1996b).

B0656+14 – cont.

2004: Observed with **STIS** FUV grating and NUV prism (Kargaltsev & Pavlov 2007)

2010: Observed with **COS** FUV grating (Durant et al. 2011)

NIR-FUV spectrum



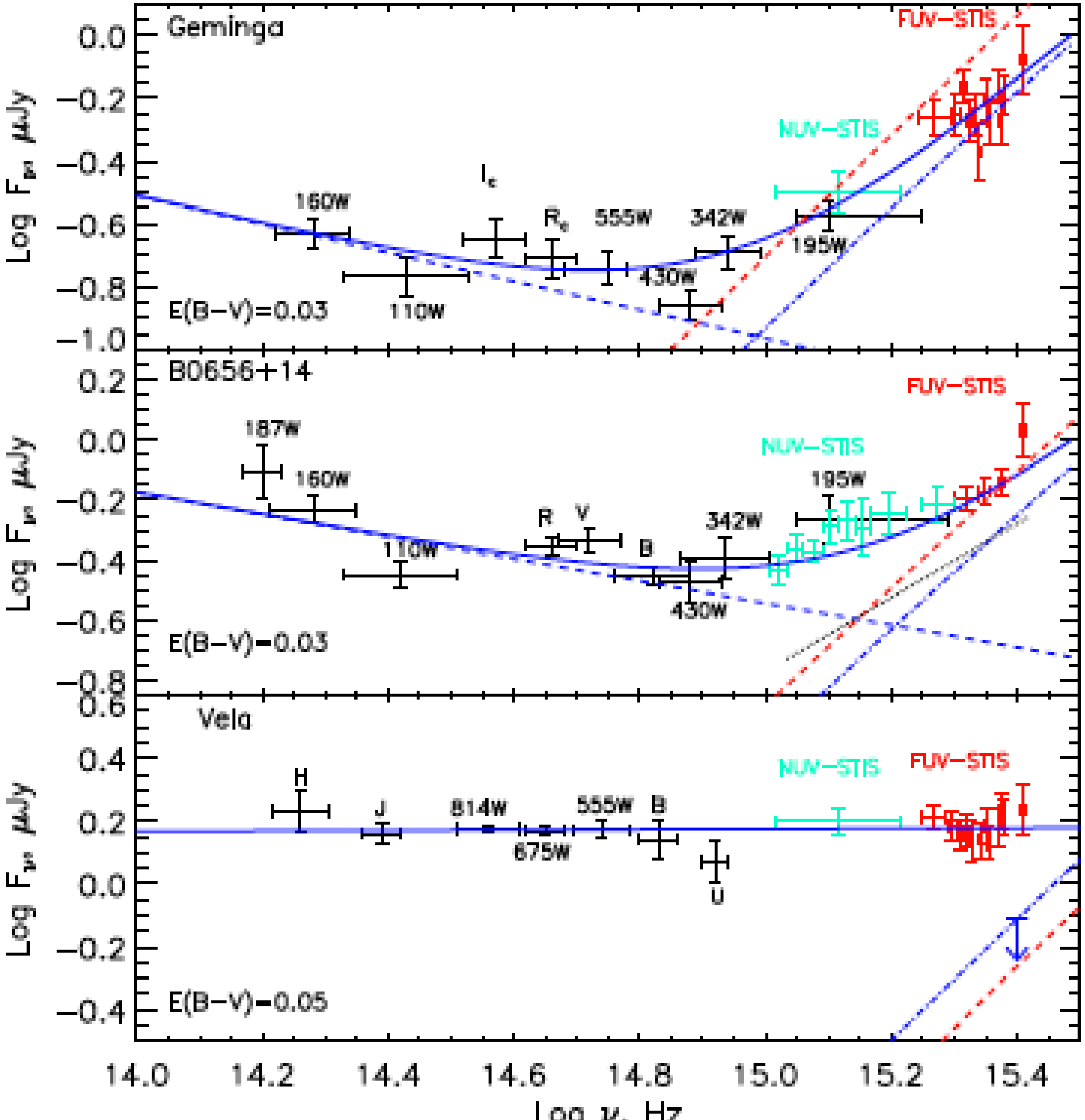
R-J spectrum in FUV

$T \sim 7 \times 10^5$ K

@ R = 13 km

NIR-optical spectrum possibly shows spectral features?

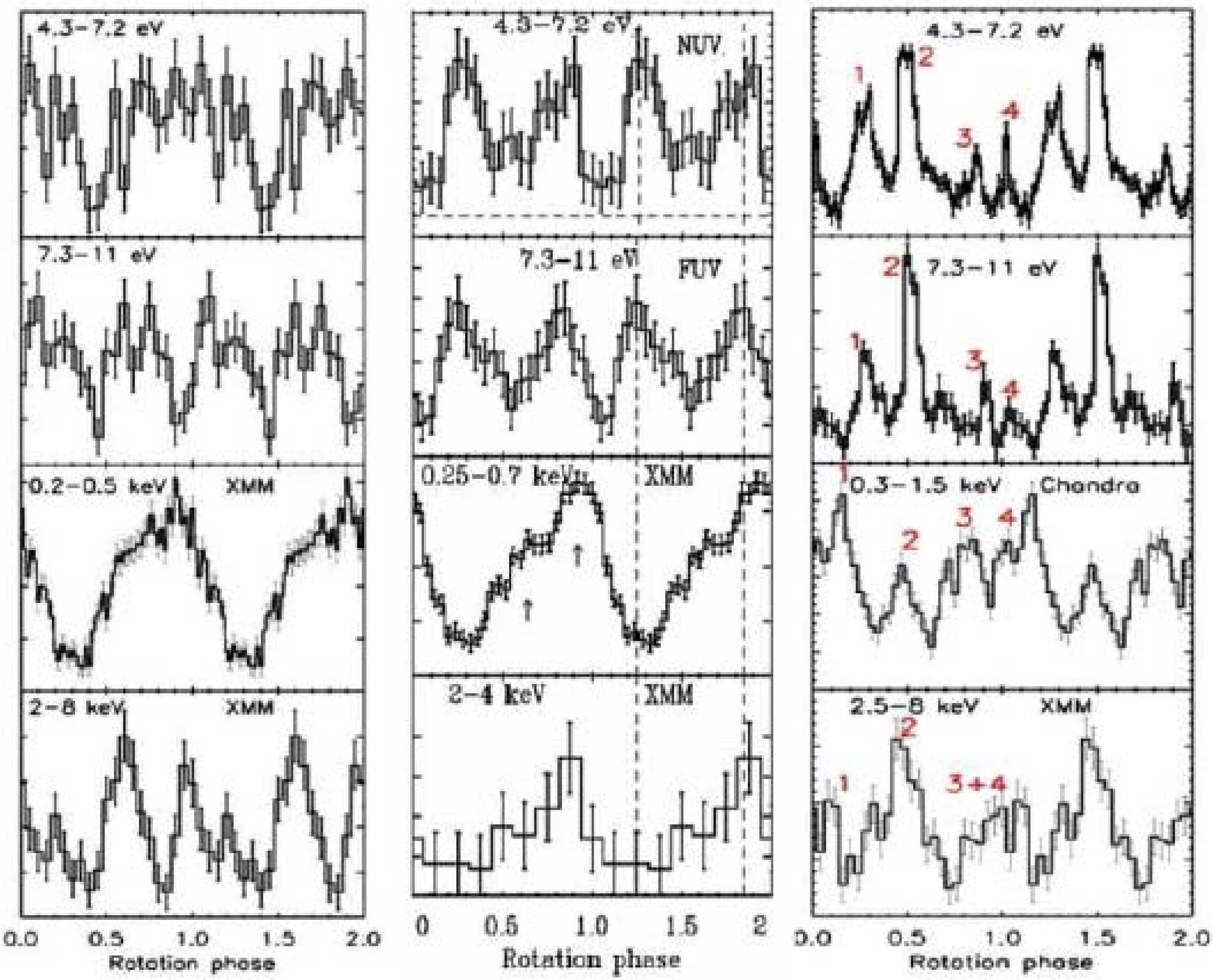
Comparison of NIR–FUV spectra of **Geminga**, **B0656** and **Vela** (Kargaltsev & Pavlov 2007)



B0656 spectrum similar to **Geminga** (PL + BB), different from **Vela** pulsar

Comparison of pulsations (Kargaltsev & Pavlov 2007)

Geminga **B0656+14** **Vela PSR**



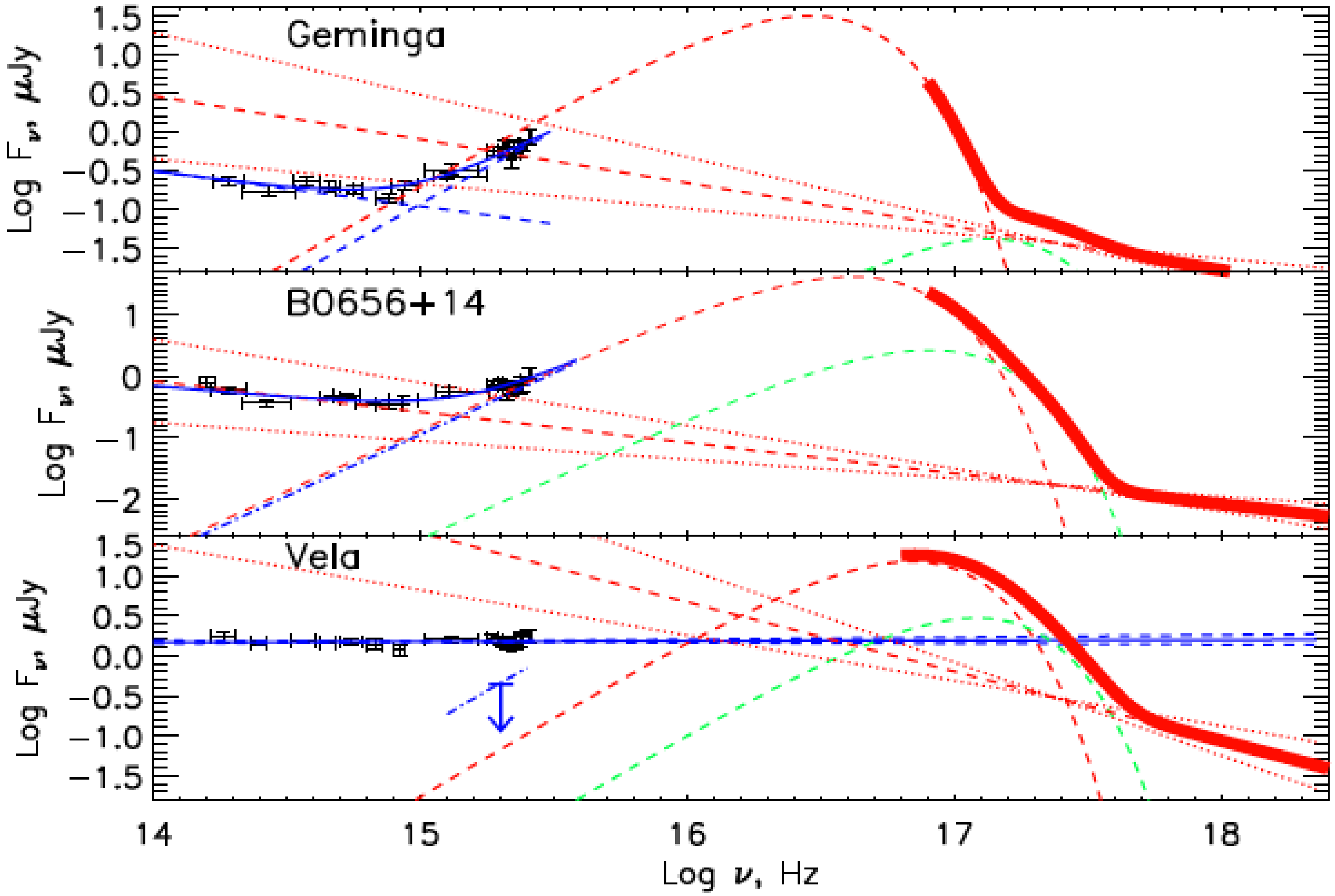
NUV, 4 – 7 eV

FUV, 7 – 11 eV

Soft X-rays,
< 1.5 keV

Harder X-rays,
~ 2 – 8 keV

Comparison of NIR-optical-UV – X-ray spectra



No (or small) mismatches in X-ray – UV thermal spectra of B0656 and Geminga

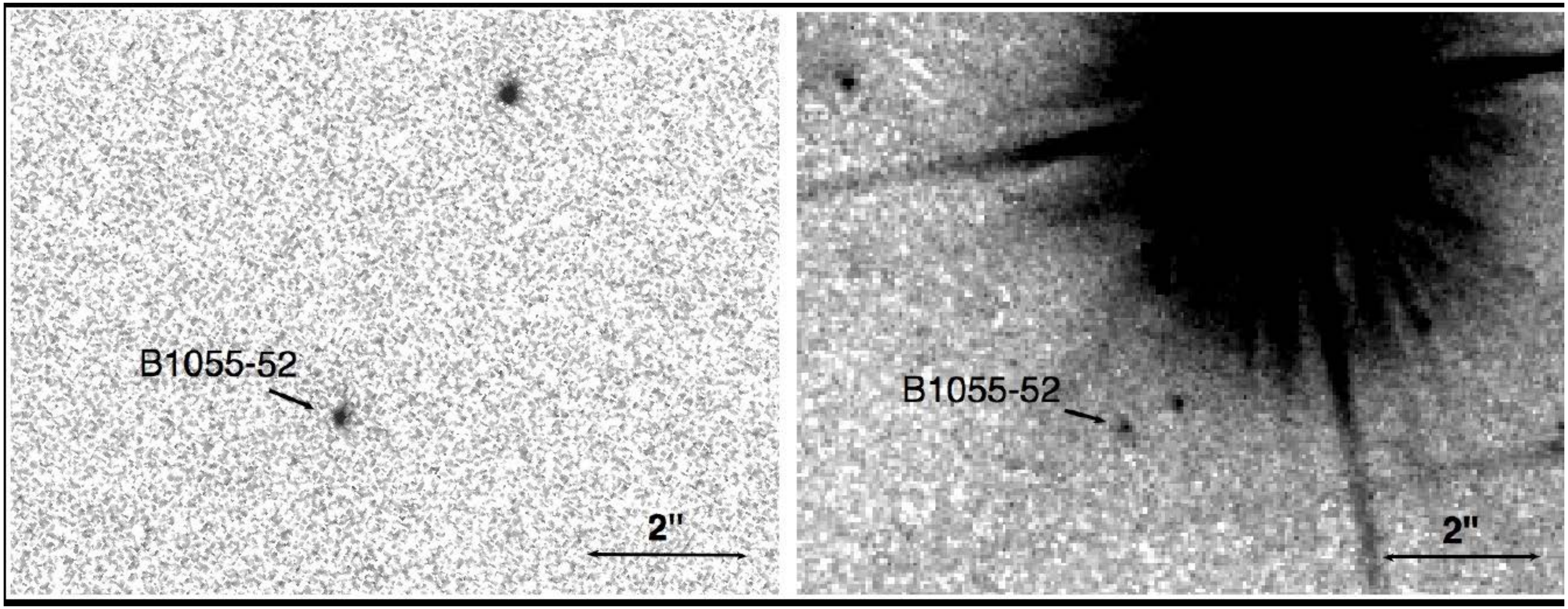
Bent optical-UV magnetospheric spectra in Vela and Geminga

PSR 1055-52 (~540 kyr, Edot=3×10^{34} erg/s, d=?, P=197 ms)

2008: **ACS/SBC** (FUV) and WFPC2 (optical) imaging (Mignani et al 2010)

[We had to switch to ACS/SBC (lacks timing; limited spectral capabilities) because of STIS failure in 2006]

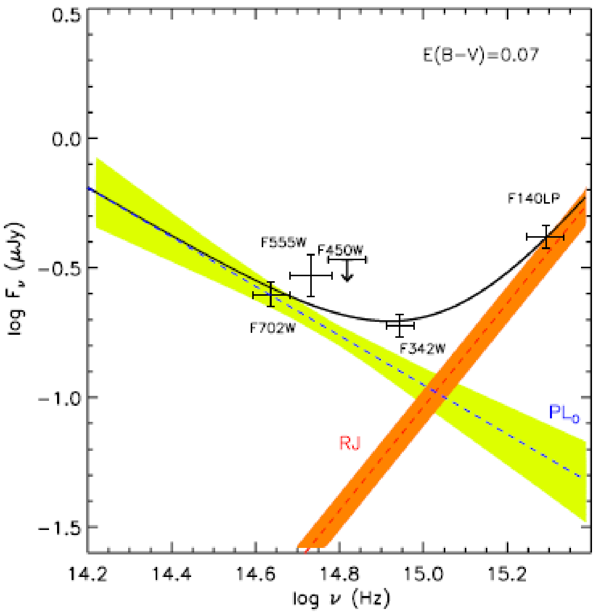
ACS/SBC F140LP (FUV) WFPC2 F702W (red)

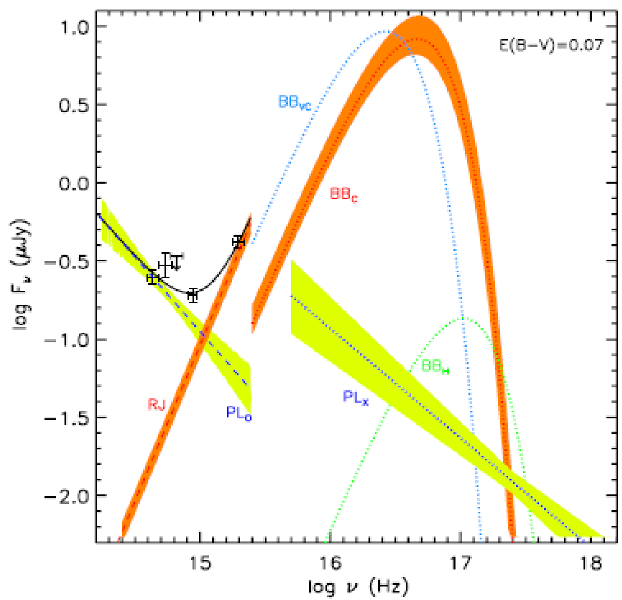


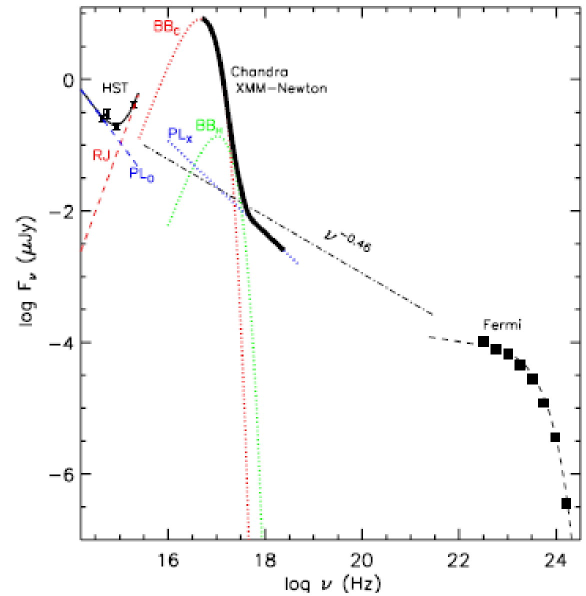
Neighboring 13 mag F-type star is only slightly brighter than the PSR in FUV

PSR B1055-52 – cont.

Spectra







Optical-UV spectrum: magnetospheric (optical, PL$_O$) and thermal (UV; R-J) 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.

Optical – UV - X-ray spectrum: clear 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?);

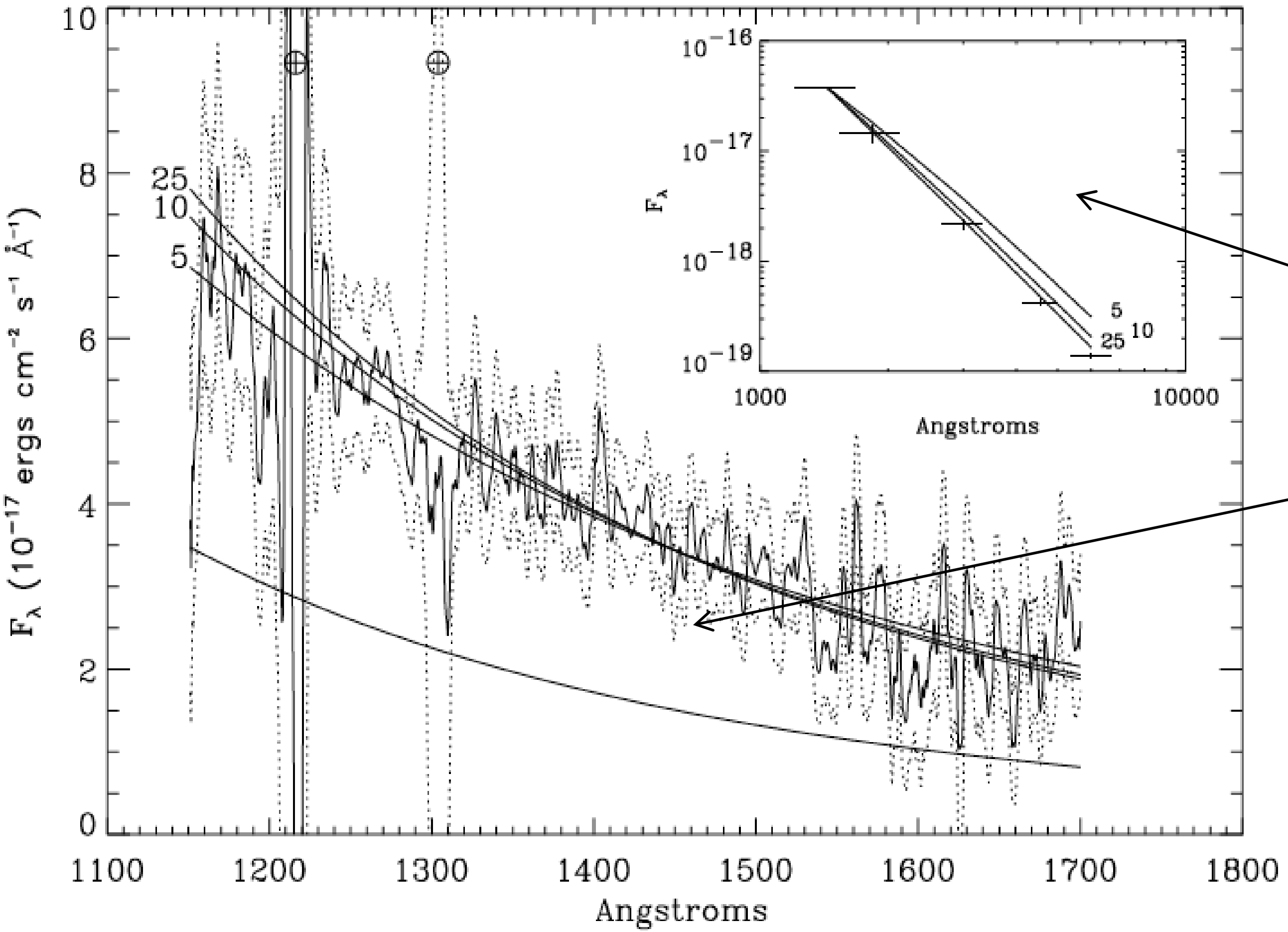
Optical – UV – X-ray – γ-ray spectrum: possibly the same spectral slope from optical (eV) to GeV? (should be measured more accurately)

More HST observations needed; 7 proposals rejected

3. TEINSs (Magnificent Seven) Ages ~1 Myr

RX J1856.5-3754 Edot=3.3 × 10^{30} erg/s, d = 160 pc, P=7 s

2000: **STIS** FUV grating observation (Pons et al. 2002)



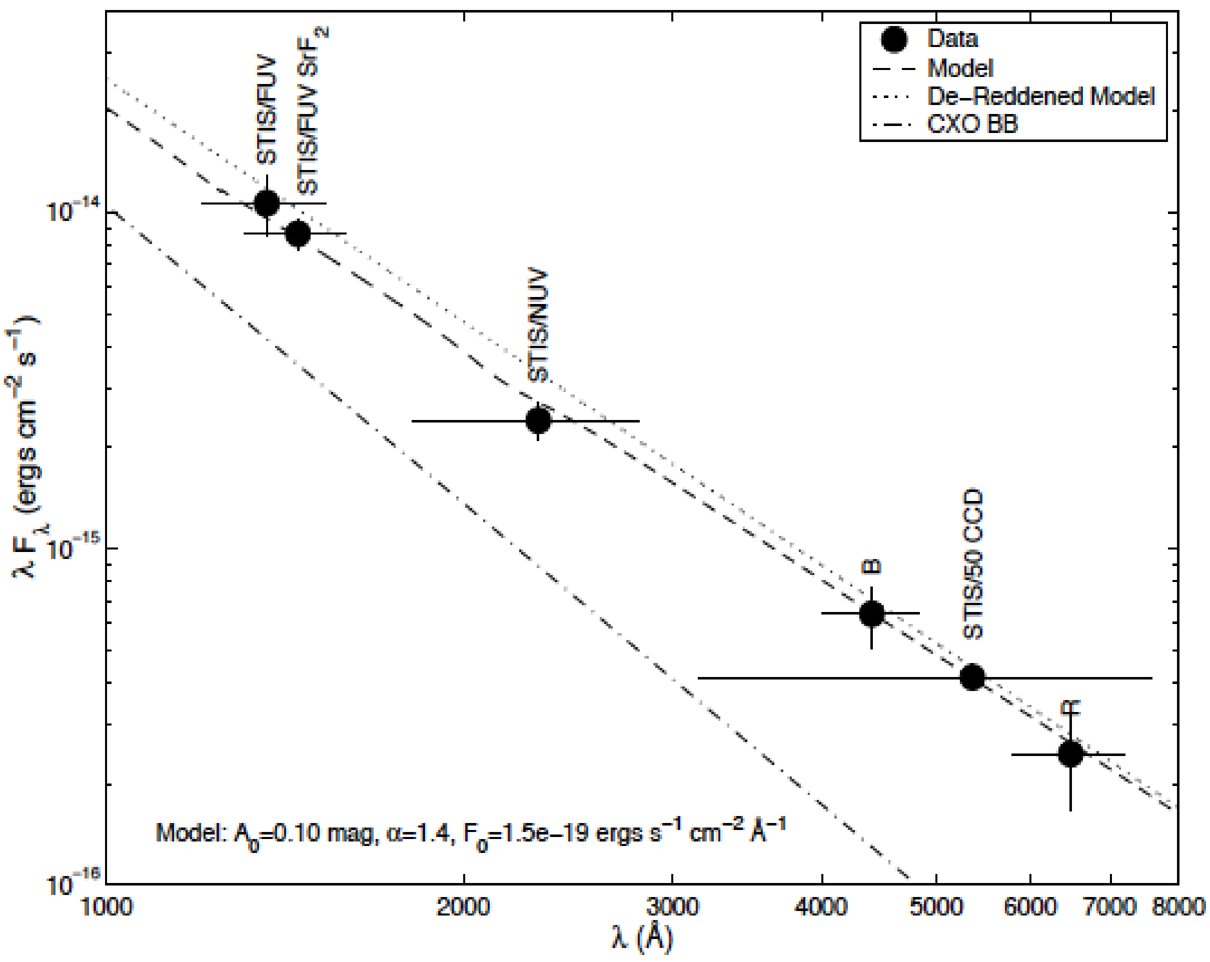
FUV + optical spectrum consistent with Rayleigh-Jeans

Shows "optical excess"

No pulsations

RX J0720.4-3125 Edot=4.7×10^{30} erg/s, d~0.4 kpc, P=8.4 s

2001-2002: **STIS** NUV and FUV imaging (Kaplan et al. 2003)



FUV-NUV-optical spectrum close to R-J, but some deviation possible

Optical excess over extrapolation of X-ray thermal spectrum

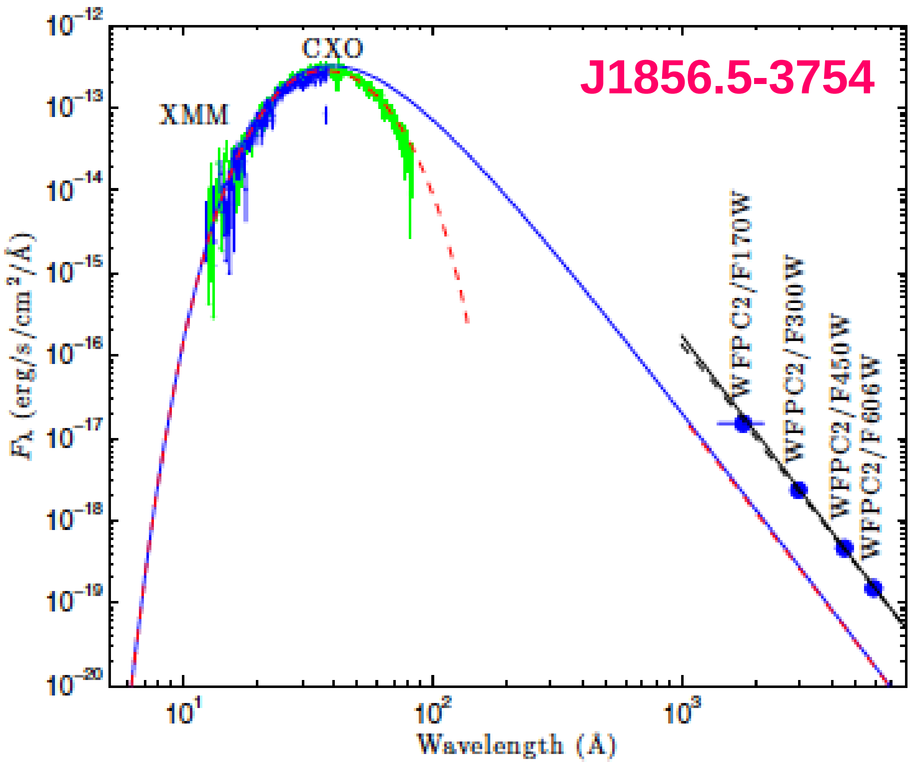
T ~ 2.4×10^5 K
@ R=$15d_{300}$ km

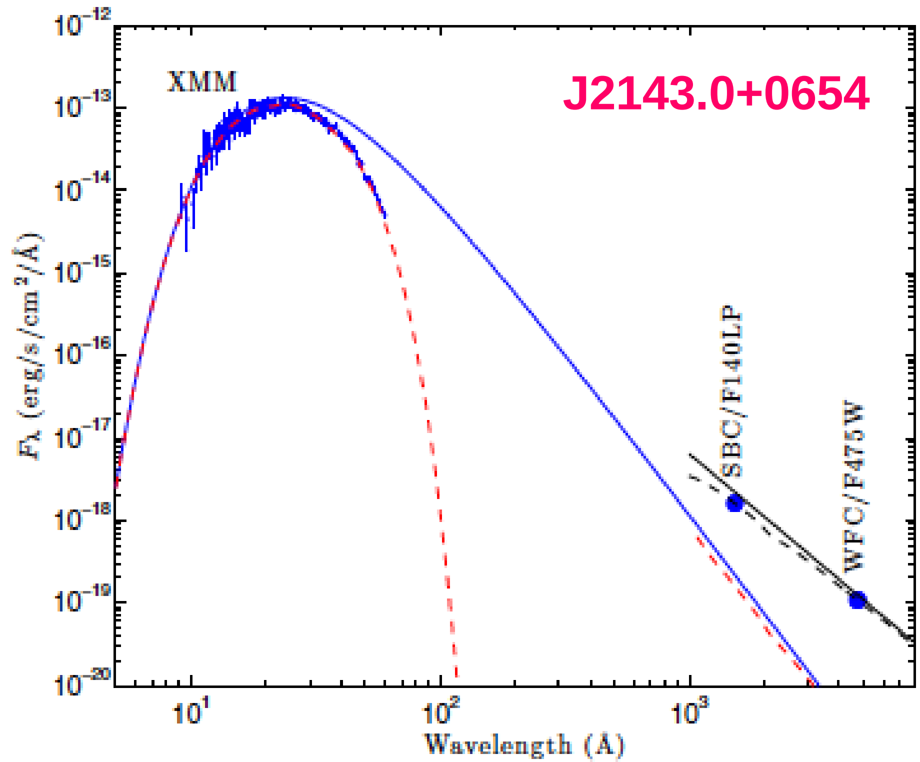
No UV/optical pulsations

RX J0420.0-5022, J0806.4-4123, J1308.6+2127, J1605.3+324, J2143.0+0654

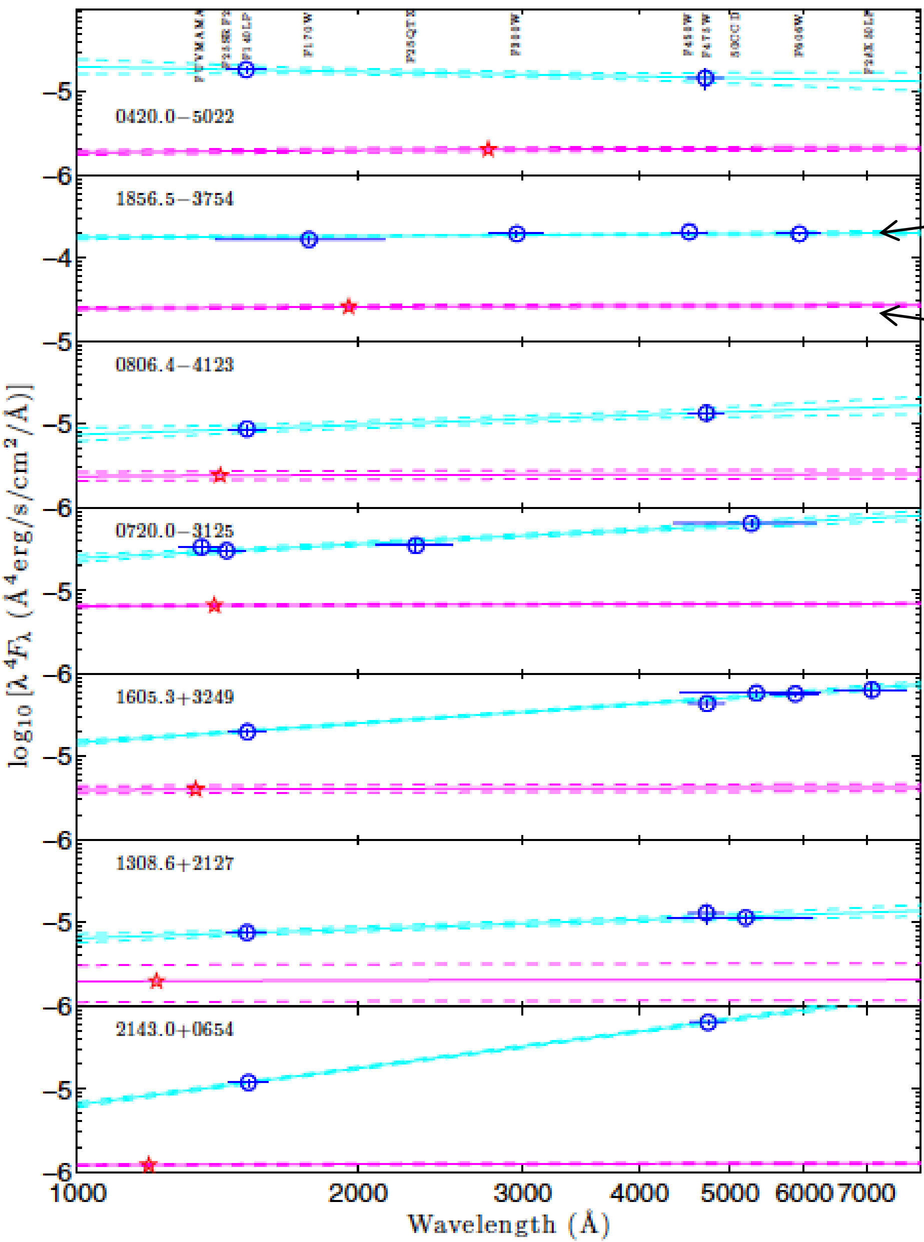
2009 – 2010: **ACS/SBC** (FUV) and ACS/WFC (optical) imaging of 5 TEINSs (Kaplan et al. 2011)

UV-optical spectra are not thermal in some of TEINSs! (but conclusion is based on 2 points in some cases)





5 TEINSs – cont.



FUV – optical spectra ($\lambda^4 F_\lambda$) for 7 TEINSs

measured spectrum

extrapolation from X-rays

Thermal (R-J) spectra would look like horizontal lines, some are clearly nonthermal

All 7 TEINSs show optical excess, a factor of ~ 5 – 50

New observations required to resolve the puzzle

6 proposals rejected

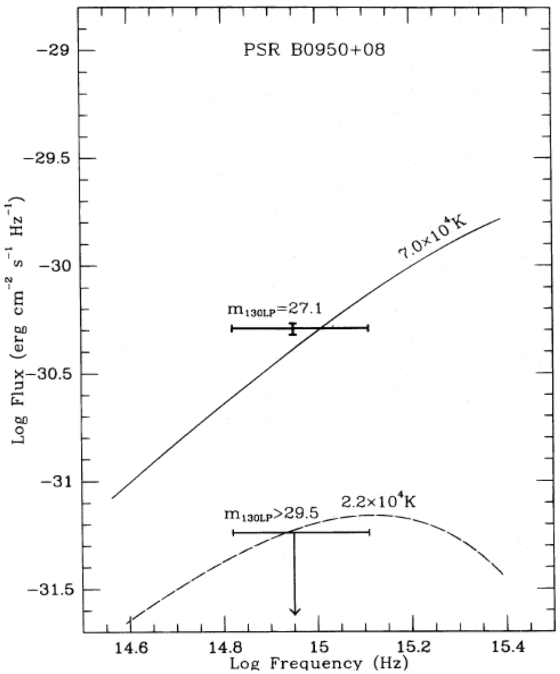
4. Old "ordinary" pulsars

B0950+08 (17 Myr, Edot=5.6 × 10^{32} erg/s, d =260 pc, P=253 ms

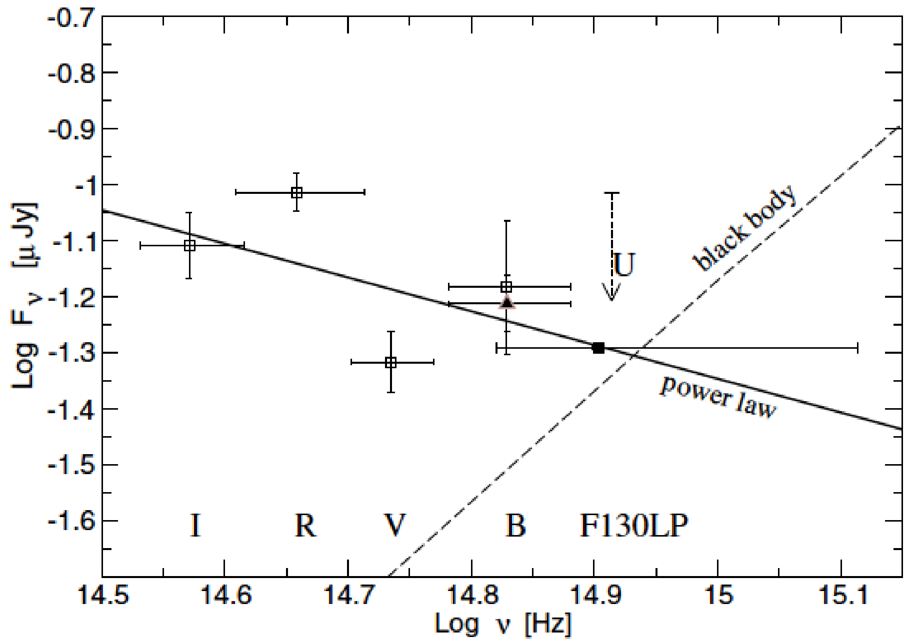
1994: FOC/F130LP (NUV) imaging (Pavlov et al 1996)

2016: ACS/SBS (FUV) imaging (Pavlov et al 2017)

FOC point (P+96)



Optical points added (Zharikov et al 2004)

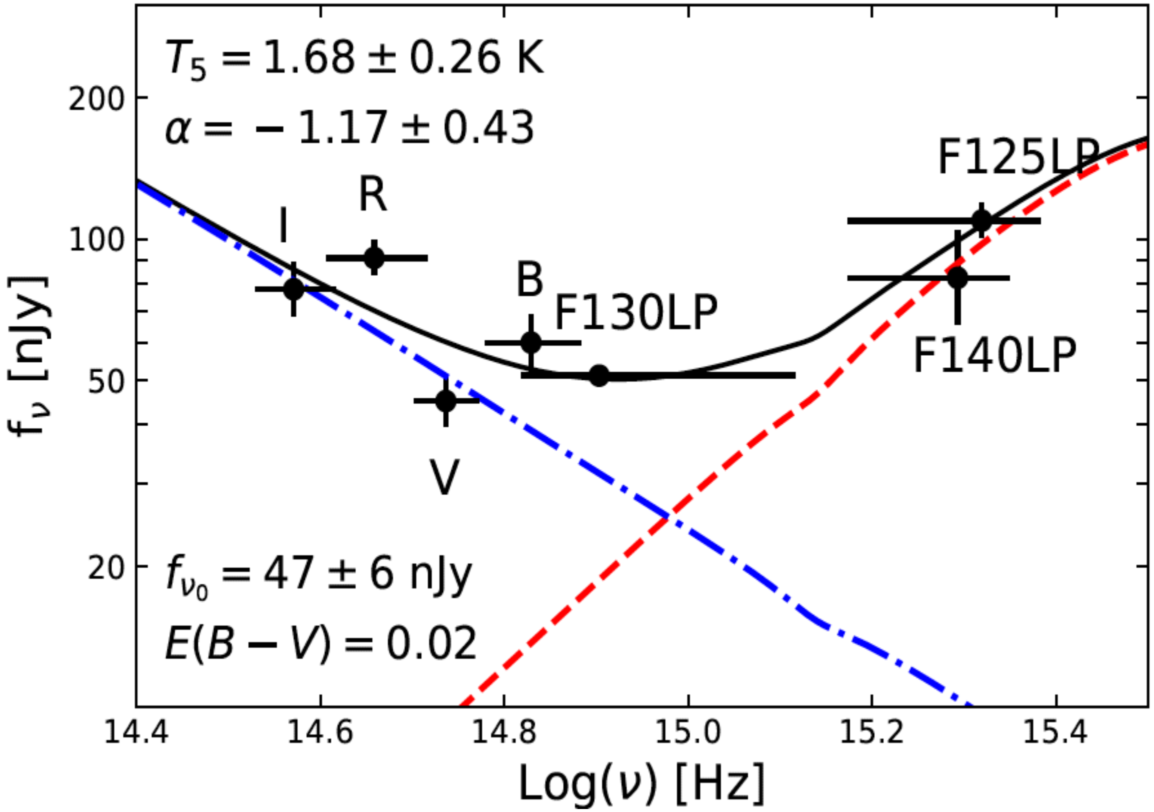


Optical emission nonthermal (α ~ −0.65).

Is there indeed a thermal component?

B0950+08 – cont.

FUV observation revealed thermal component (P+17)



T = (1.4 – 2.4) × 10^5 K

much higher than predicted by NS cooling theories (< ~ 10^4 K)

NS heating required

Main source of uncertainty: scatter of optical points caused by red bgd galaxy → uncertain α → uncertain T.

High-res (HST) optical observation required; proposal rejected.

PSR J2144-3933 (270 Myr, Edot = 3.2×10^{28} erg/s, 165 pc
P=8.5 s; **the oldest, slowest, closest ordinary RPP**

2015: **ACS/SBS** FUV + WFC2/UVIS F475X optical imaging

Not detected, neither in FUV nor in optical

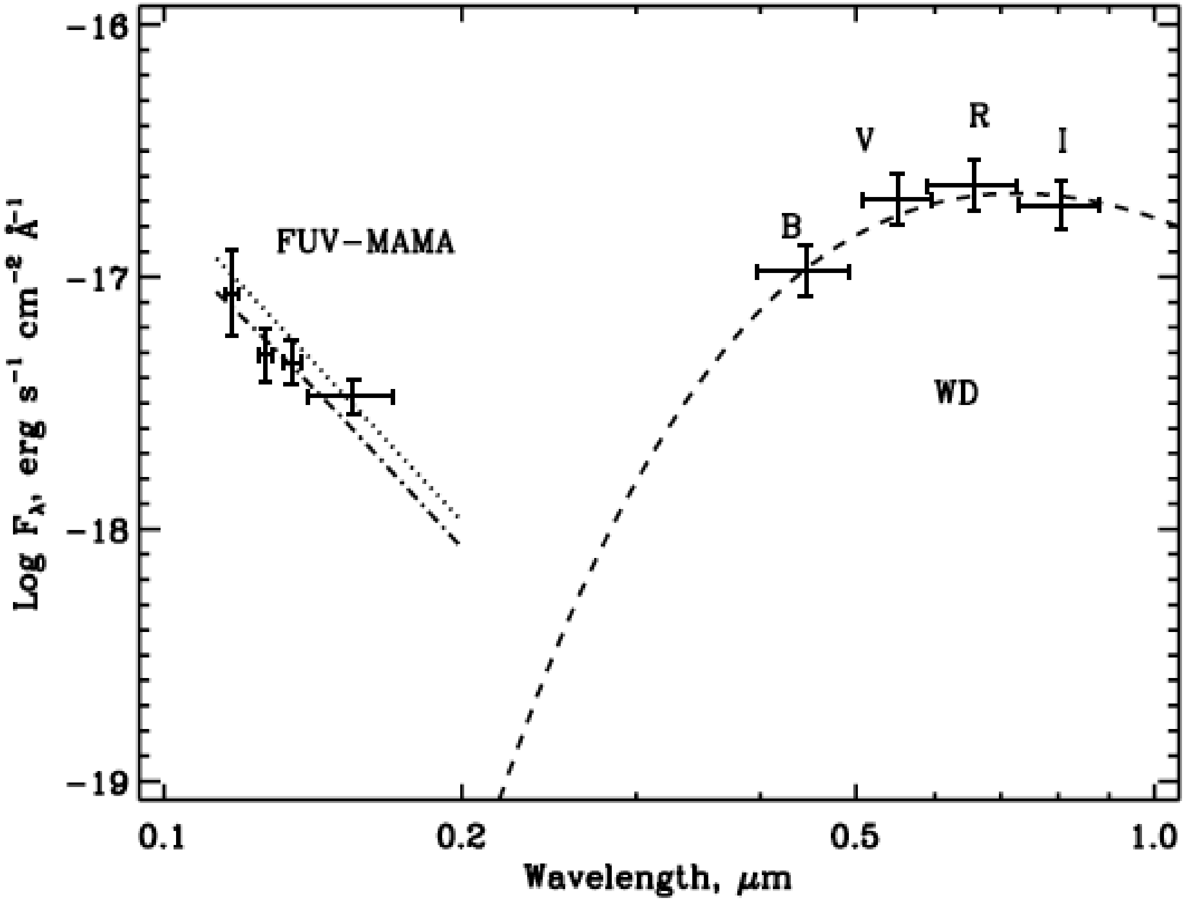
$T < 4 \times 10^4$ K - record low upper limit on bulk surface T

Very old ordinary pulsars are indeed cold.

5. Millisecond pulsars

PSR J0437-4715 Edot = 3×10^{33} erg/s, d =157 pc, in 5.5 d binary with WD

2001: **STIS**/FUV grating observation (Kargaltsev et al. 2004)



Optical emitted from WD companion

FUV spectrum fits Rayleigh-Jeans

Brightness temperature ~1×10^5 K – very high for a few Gyr old NS

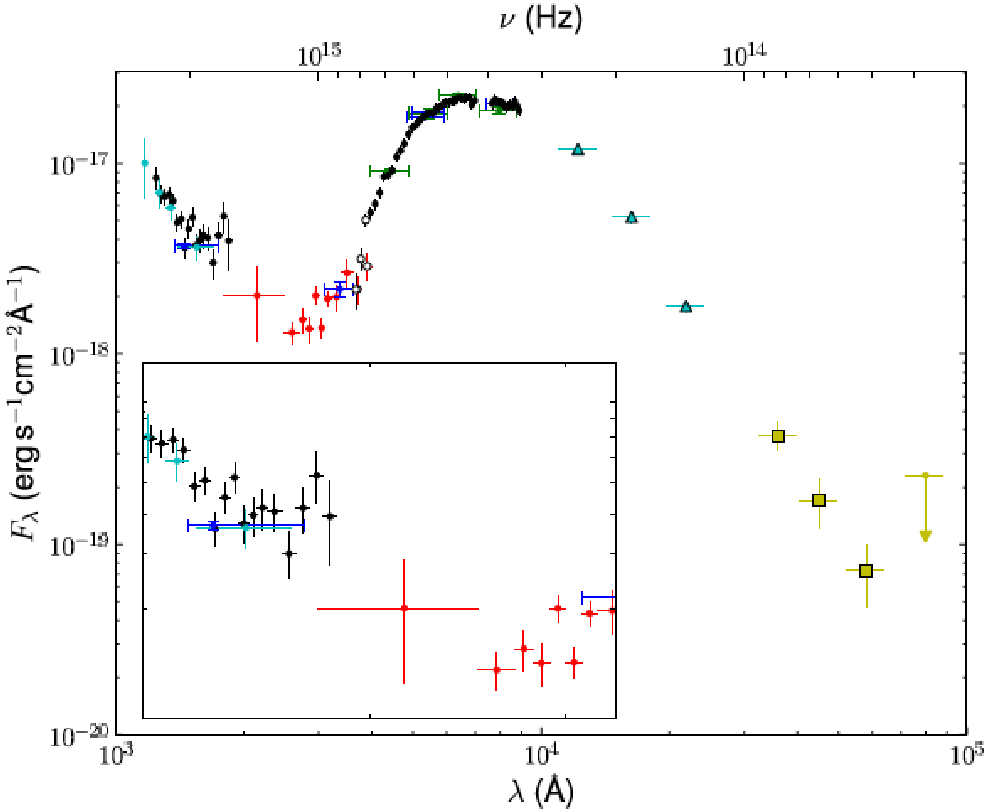
Heating required!

No FUV pulsations

J0437-4715 – cont.

2006: **ACS/SBC** FUV and NUV prisms + many optical, NIR and IR (Spitzer) observations (Durant et al. 2012)

FUV – IR spectrum



WD emission and nonthermal PSR component accurately separated from thermal component

T = (1.5±0.3)×10^5 K
(bulk NS surface)

Heating firmly established

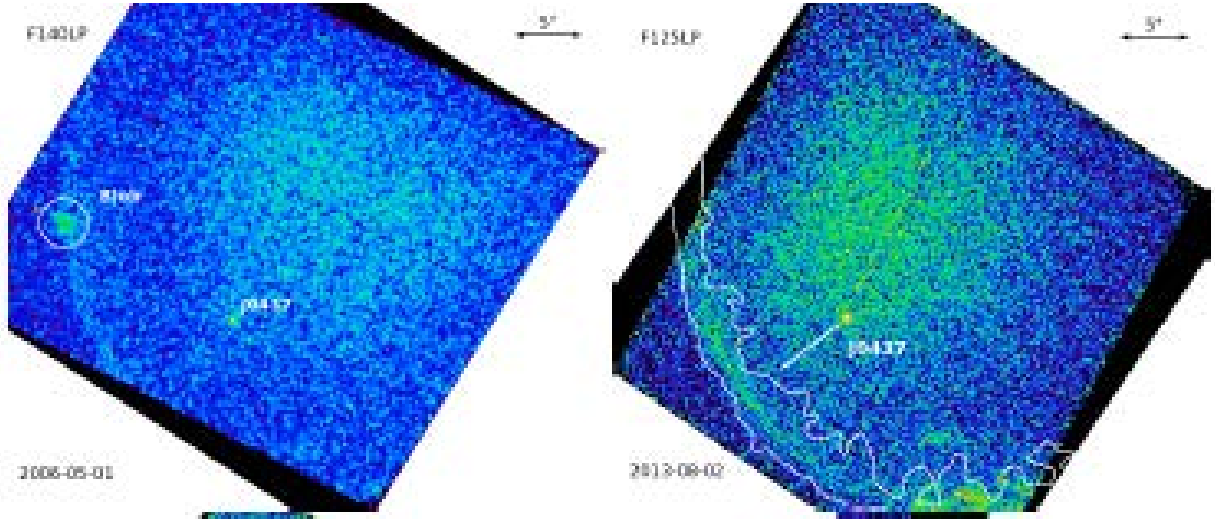
Rotochemical heating?
(Reisenegger 1995)

Vortex creep heating?
(Larson & Link 19990

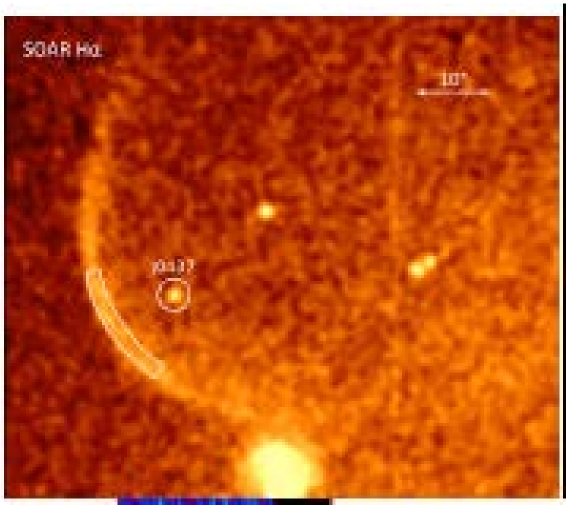
Decay/annihilation of dark matter particles trapped by the NS??
(Kouvaris 2008)

J0437-4715 – cont.

First FUV bow shock discovered (Rangelov et al. 2016)



ACS/SBC FUV images (1400 -- 2000 A and 1250 – 2000 A bands)

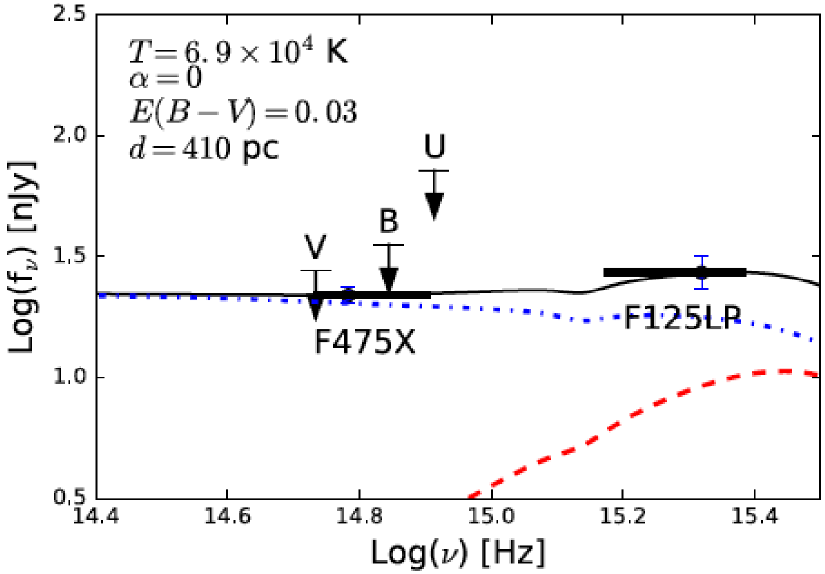


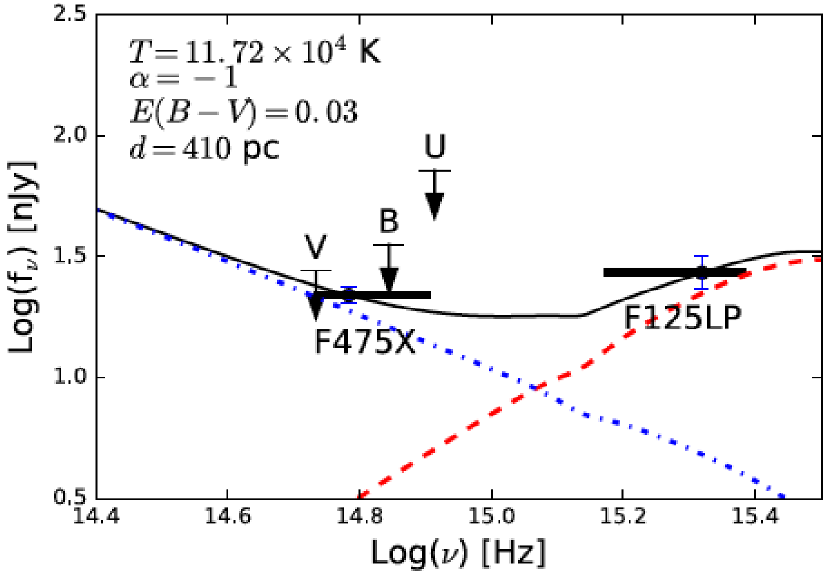
H-alpha image (Brownsberger & Romani 2014)

FUV: Bow-like structure coincident with Hα bow shock, L(1250-2000 A) = 5×10^{28} erg/s ~ $10 \times$ L(Hα) from the same area. Continuum and lines produced by shocked ISM matter? Synchrotron emission from relativistic pulsar wind electrons confined by magnetic field fluctuations in forward shock?

PSR J2124-3358 Solitary psr, Edot = 2.4×10^{33} erg/s, d~410 pc

2015: **ACS/SBC** (FUV) and WFC3/UVIS (broad optical filter) imaging (Rangelov et al. 2017)



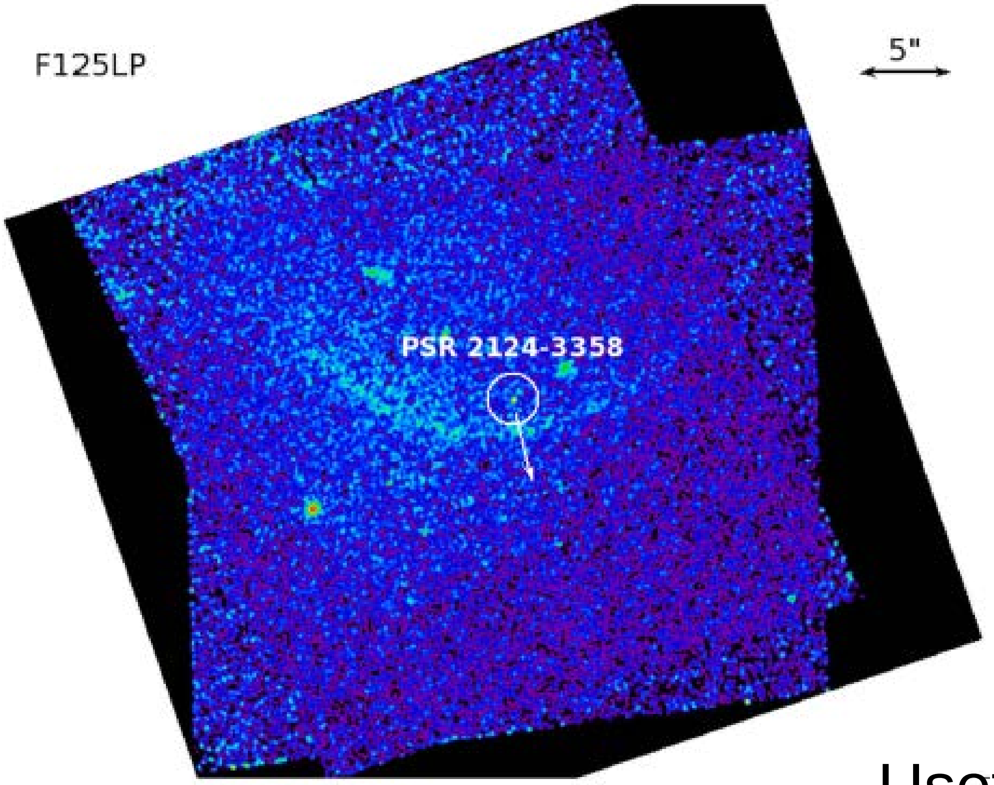


Most likely, FUV is dominated by thermal emission.

T = (0.5 – 2.1) × 10^5 K, similar to J0437 (uncertainty due to poorly constrained slope of nonthermal component and distance uncertainty). **Heating required**.

PSR J2124-3358 – cont.

Bow shock detected in FUV (but not in the broad optical band)



Bow shock properties very similar to J0437

No bow shock is seen in the very deep observation with a broad optical filter (but the pulsar is detected -- first detection of an MSP in the optical)

FUV bow shocks could be seen from many pulsars?

Useful for probing properties of ISM and pulsar winds and studying their interaction

Summary

17 NSs observed in UV in 26 HST years; 16 detected

Very young RPPs: UV spectra are magnetospheric, slope varies with pulsation phase

Middle-aged RPPs: Thermal FUV spectra, mismatch with extra-polation from X-rays in some; puzzling pulsations. Nonthermal optical emission, optical spectrum flatter than X-ray one.

TEINSs: Mostly thermal UV spectra, always above extrapolation from X-rays; in some cases strong deviations from thermal (!?)

Old ordinary RPPs: Hotter than expected (but only 2 observed)

Millisecond pulsars: Two observed MSPs are rather hot; both show FUV bow shocks.

HST will retire soon; no other space observatories with sensitive UV detectors

We should use the unique UV capabilities of HST until it is too late

Please take this into account if you are HST TAC member!

Thank you