Part 5
High Energy Phenomena

Section A
Optical and UV Properties

https://doi.org/10.1017/S0252921100041749 Published online by Cambridge University Press

Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

EUV Observations of Pulsars

Jerry Edelstein and Stuart Bowyer

Center for EUV Astrophysics
University of California
2150 Kittredge Street
Berkeley, CA 94720-5030 USA

Abstract. Three pulsars have been detected with the Lexan (100 Å)filter of the EUVE Deep Survey telescope: the middle-aged isolated pulsars, PSR B0656+14 and Geminga, plus the aged millisecond pulsar PSR J0437−4715. The EUV detections have been used both alone and in combination with observations in other bandpasses to limit the physical state of the objects and to test theories regarding neutron star cooling and re-heating mechanisms. For Geminga, the EUVE data suggests the presence of an optical cyclotron spectral feature superimposed on the Rayleigh-Jeans continuum tail from a hot pulsar surface. We summarize EUV pulsar observations and results.

1. Introduction

Pulsars can provide extreme ultra-violet (EUV, 44 -1000 Å) radiation via several mechanisms including: magnetospheric synchrotron radiation seen as a power law emission; hot polar-cap thermal emission originating from the impact of relativistic particles from the magnetosphere; blackbody flux from the cooling surface of a hot pulsar; and interactions of a relativistic particle pulsar wind with the ISM. In the case of pulsars older than a few million years, the presence of thermal surface emission in the EUV is inconsistent with standard neutron star cooling models (Shibazaki & Lamb 1989) and would require some form of reheating. Postulated reheating mechanisms, besides accretion from a binary companion, include: frictional heating from neutron superfluid interaction with normal matter in a neutron star's crust; gravitational accretion of ISM pulsars with sufficiently slow velocities i.e., $v \leq 10$ km s^{-1} (Paczynski 1990); accretion of stellar material ablated from a binary companion by the pulsars' high-energy particle wind; and exotic mechanism such as heating by magnetic monopole catalyzed nucleon decay (Freese *et al.* 1983; Kolb & Turner 1984).

2. EUV Pulsars

Three pulsars have been detected with the EUVE Deep Survey telescope: PSR J0437−4715, PSR B0656+14 and Geminga (see Table I). The detections used the Lexan filter which is most responsive to 80 – 110 Å radiation for objects

https://doi.org/10.1017/S0252921100041749 Published online by Cambridge University Press

with absorbing column densities $N_H < 5 \times 10^{20}$ cm^{-2}. Consequently, the EUVE Lexan band is well suited for observing black body emission from nearby objects with temperatures ranging from 10^5 to several 10^6 K. EUVE's sensitivity to low temperatures and ability to discriminate among low N_H values is un-paralleled by soft x-ray observatories.

Table 1. EUVE Pulsars

Source	Observed ksec	Count ct/s	Age years	DM pc cm^{-3}	Distance pc	log N_H cm^{-2}
B0656+14	91	0.024	1×10^5	14	100–800	< 20.6
J0437−4715	80	0.014	3×10^9	2.65	140	< 20.1
	500					
Geminga	240	0.008	5×10^5	–	157	19.7–20.7

3. PSR J0437−4715

The binary millisecond pulsar J0437−4715 was observed by EUVE during an 80 ksec exposure (Edelstein *et al.* 1995) and a follow-up 500 ksec exposure (Halpern *et al.*, 1996). Edelstein *et al.*, (1995) found the EUV emission consistent with black-body flux from a 10km radius pulsar surface with a temperature of $1.6 - 3.2 \times 10^5 d_{140pc}^{-0.5}$ K . A thermal source with these properties could not have been detected in the ROSAT observations of this object (Becker & Trumper, 1993). Edelstein *et al.* (1995) considered possible surface re-heating mechanisms and EUV emission sources and found crust-core friction from pulsar spin-down, Bondi-Hoyle type accretion from the ISM and accretion from material ablated from the companion star to be insufficient to explain the EUV flux. The predicted EUV pulsar-wind nebular luminosity (Arons & Tavani, 1993) was found to be an order of magnitude smaller than the observed flux, however with special tuning the model may still be viable. The upper limit to the surface temperature of PSR 0437−4715 and the object's extreme age provide an upper limit to magnetic monopole flux that is 3 orders of magnitude lower than the limit derived from PSR 1929+10 (Freese *et al.*, 1983).

Halpern *et al.*'s (1996) follow-up observations of J0437-4715 found EUV emission to be 25% pulsed and commensurate with the 5.75 ms rotational period. They re-analyzed the ROSAT data simultaneously with the EUVE data to determine allowable parameters for a single power-law source, a combined power-law and hot-spot source, or a combined thermal source. The inclusion of EUVE data constrains the allowable parameters by factors of several for all of the different source models. Combined thermal sources are allowed for soft-body temperatures above 4.5×10^5 K and $N_H < 7 \times 10^{19}$ cm^{-2}. Combined power-law thermal sources are allowed for hot-spot temperatures of $1.2 - 3.2 \times 10^6$ K and $N_H = 3 - 7 \times 10^{19}$ cm^{-2}. A single power-law source is allowed for $\alpha = 1.2 - 1.45$ and $N_H = 4.5 - 7.5 \times 10^{19}$ cm^{-2}. A direct measurement of N_H to J0437-4715 in combination with these data would severely restrict the source parameters. In fact, the upper limit $N_H < 5 \times 10^{19}$ cm^{-2} would eliminate a single power law source origin.

4. Geminga

The gamma-ray pulsar Geminga was observed during a 240 ksec EUVE observation (Bignami *et al.*, 1995). The object was clearly detected in the Lexan band and independently detected at 2.6 σ significance by the Short Wavelength Spectrometer in the $88 - 92\AA$ bandpass. Foster *et al.* (1996) found an EUV intensity modulation of about 20% with a phase profile similar to that of the lowest energy ROSAT band (Halpern & Ruderman, 1993). The mild modulation is consistent with surface thermal emission as localized magnetospheric phenomena would be highly pulsed. Bignami *et al.* (1995) found Geminga's EUV radiation could originate from a 10 km radius isothermal blackbody with $T = 2 - 3 \times 10^5$K after absorption by an interstellar column of $N_H = 0.5 - 1.0 \times 10^{20}$ cm^{-2} at a distance of 160 pc. The N_H value was estimated from the compilation of Fruscione *et al.* (1994) using the 157^{+59}_{-34} pc distance derived from HST parallax measurements of the Geminga's optical counterpart (Caraveo *et al.*, 1994). The Short Wavelength Spectrometer's sensitivity to an absorbed blackbody emission for these conditions peaks strongly in the 88-92 Å bandpass, where the flux was detected.

Given Geminga's spin-down age of $\sim$ 350,000 yrs, the detection of surface thermal emission was anticipated and indeed reported after the ROSAT X-ray data (Halpern & Ruderman, 1993). The black body temperature and absorbing N_H combinations derived from the ROSAT data disagree with those allowed by the *EUVE* data. In fact, the temperatures deduced from the X-ray data (Bignami *et al.*, 1988, Halpern & Tytler, 1988 and Halpern & Ruderman, 1993) were too high to account for the optical counterpart's flux. Alternatively, Bignami's *EUVE* data are compatible with both prior and new optical photometry data as shown in Figure 1. The optical data, while bracketed by the Rayleigh-Jeans tail of the *EUVE* curves, are not well described by any single one of them. The authors suggest that ion cyclotron resonance spectral features from the star's intensely magnetic atmosphere could account for this discrepancy. A magnetic field of $7.0\ 10^{11}\ G$, reasonably close to Geminga's canonical magnetic field $B \propto (P\dot{P})^{1/2} = 1.5\ 10^{12}\ G$ could produce a He cyclotron feature near the V band (Bignami *et al.*, 1988). More complete optical photometry is needed to clarify the situation. The combination of EUV and optical data has provided the first evidence of cyclotron features from a pulsar atmosphere.

5. PSR B0656+14

The isolated pulsar B0656+14 was observed during a 91 ksec EUVE observation (Finley, *et al.* 1994). An upper limit of $\approx$ 10% to EUV modulation was found at the radio period (Foster *et al.*, 1996; Foster, 1995). The interpretation of this flux is confounded by the uncertain distance and interstellar column to the object. Einstein (Cordova *et al.*, 1989), X-ray observations (Finley *et al.*, 1993) and observations of the candidate optical counterpart (Caraveo *et al.*, 1994) offer distance estimates ranging from 100 to 600 pc, while radio dispersion models

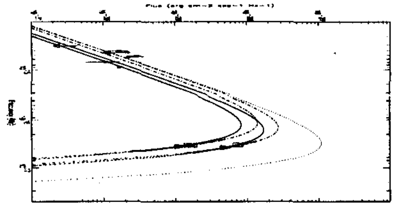

Figure 1. Geminga: the un-attenuated energy flux from a black body source consistent with the EUVE Deep Survey data and the optical counterpart data (Bignami *et al.*, 1995). The upper and lower curves (solid for 10 km radius, dashed for 15 km radius) are computed for blackbody temperatures corresponding to $N_H = 10^{20} cm^{-2}$ and $N_H = 5 \times 10^{19} cm^{-2}$. The large triangles mark the flux value at the peak of the 100 Å filter response convolved with interstellar absorption. The thick sections and triangles show the wavelength peak and coverage of the 100 Å bandpass. The squares mark the flux for the 88-92 Å EUVE spectrometer detection. The small triangles mark the R to FOC "optical" data. The arrows mark the I and F675W upper limits. The distance to Geminga is from its annual parallax measurement, i.e. 157^{+59}_{-34} pc.

place the pulsar at 760 pc (Taylor *et al.*, 1993). The Einstein data sets an upper limit of $N_H < 4 \times 10^{20}$ cm^{-2}. If the EUV source is an iso-thermal black-body with a $10 - 15$ km radius, and the optical counterpart radiation $m_v = 25.0 \pm 0.5$ bounds the Rayleigh-Jeans tail of the EUV thermal source, then the a source $T_{min} = 1.6 \times 10^5$K is found for a distance of 100 pc, and a maximum a source distance of 260 pc is found for a source $T = 1.2 \times 10^6$K.

Analyses of a compilation of ROSAT data (Possenti *et al.*, 1996) found the soft-xray data to be well fit by black-body emission plus a hard component dominating flux above 1 keV. Although these authors used a 760 pc source distance, their allowed temperatures $T = 0.86 - 1.07 \times 10^6$K, were similar to Finley *et al.*'s (1993) black-body model using a 500 pc distance. The higher temperatures and implied large distances required by the ROSAT data would require a non-thermal component to explain the optical counterpart's emission. Sensitive photometry and parallax distance measurements of the B0656+14 optical counterpart would be of immense value to understanding this object, as would a direct N_H measurement or sensitive upper limits ($N_H < 1.0 \times 10^{20}$ cm^{-2}).

6. Conclusion

EUV observations of pulsars have established important pulsar physical parameters. Direct measurements of N_H toward EUV pulsars would leverage the value of these conclusions. The EUV data offer the first evidence of optical cyclotron spectral features.

Acknowledgments. The *Extreme Ultraviolet Explorer* is supported by NASA contract NAS5-30180.

References

Arons, J. & Tavani, M. 1993, ApJ, 403, 249

Becker, W. & Trumper, J. 1993, Nature, 365, 528

Bignami, G.F, Caraveo, P.A , Mignani R., Edelstein, J., and Bowyer, S. 1996, ApJ, 456, L111

Bignami, G.F., Caraveo, P.A. and Paul, J.A. 1988 å, 202, L1

Caraveo, P.A., Bignami,G.F., Mereghetti, S. 1994 ApJ, 422, L87

Cordova, F.A. et al. ApJ, 1989, 345, 451

Edelstein, J., Foster, R. S., & Bowyer, S. 1995, ApJ, 454, 442

Finley, J.P, Ogelman, H., & Kiziloglu, U 1992, ApJ, 394, L21

Finley, J.P, Ogelman, H., & Edelstein, J 1994, BAAS, 26, 870

Foster, R. S., Edelstein, J. & Bowyer, S. 1996, "Astrophysics in the EUV", Kluwer, Dortrecht

Foster, R. S. 1995, private communication

Freese, K., Turner, M., & Schramm, D. N. 1983, Phys.Rev.Lett, 51, 1625

Fruscione, A., Hawkins I., Jelinsky, P., & Wiercigroch A., 1994, ApJS, 94, 127

Halpern, J.P. and Ruderman M. 1993, ApJ, 415, 286

Halpern, J.P. and Tytler, D. 1988, ApJ, 330, 201

Haplern, J.P, Marshall, H.M and Martin, D.C, submitted, 1996.

Kolb, E. & Turner, M. 1984, ApJ, 286, 702

Possenti, A., Mereghetti, S. & Colpi, M. 1996, A&A, in press.

Shibazaki, N. & Lamb, F. K. 1989, ApJ, 346, 808

Taylor, J. H., Manchester, R. N. & Lyne, A. G. 1993, ApJS, 88, 529