EUVE J0425.6−5714: A Newly Discovered AM Herculis Star

J. P. Halpern and K. M. Leighly
Columbia Astrophysics, Columbia University, 550 West 120th Street, New York, NY 10027
H. L. Marshall
Eureka Scientific, Inc., 2452 Delmer Street, Suite 100, Oakland, CA 94602
M. Eracleous1
Department of Astronomy, University of California, Berkeley, CA 94720
AND
T. Storchi-Bergmann2
Departamento de Astronomia, IF-UFRGS, CP 15051, CEP 91501-970, Porto Allegre, RS, Brazil

Received 1998 August 17; accepted 1998 September 13

ABSTRACT. We detected a new AM Her star serendipitously in a 25 day observation with the EUVE satellite. A coherent period of 85.82 minutes is present in the EUVE Deep Survey imager light curve of this source. A spectroscopic optical identification is made with a 19th magnitude blue star that has H and He emission lines, and broad cyclotron humps typical of a magnetic cataclysmic variable. A lower limit to the polar magnetic field of 50 MG is estimated from the spacing of the cyclotron harmonics. EUVE J0425.6−5714 is also detected in archival ROSAT HRI observations spanning 2 months, and its stable and highly structured light curve permits us to fit a coherent ephemeris linking the ROSAT and EUVE data over a 1.3 yr gap. The derived period is 85.82107 ± 0.00020 minutes, and the ephemeris should be accurate to 0.1 cycles until the year 2005. A narrow but partial X-ray eclipse suggests that this object belongs to the group of AM Her stars whose viewing geometry is such that the accretion stream periodically occults the soft X-ray emitting accretion spot on the surface of the white dwarf. A nondetection of hard X-rays from ASCA observations that are contemporaneous with the ROSAT HRI shows that the soft X-rays must dominate by at least an order of magnitude, which is consistent with a known trend among AM Her stars with large magnetic fields. This object should not be confused with the Seyfert galaxy 1H 0419−577 (=LB 1727), another X-ray/EUV source that lies only 3.95 away and that was the principal target of these monitoring observations.

1. INTRODUCTION

AM Her stars, or polars, are the subclass of cataclysmic binaries in which the white dwarf is highly magnetized, typically $B_p > 10$ MG, and Roche-lobe overflow from a low-mass companion proceeds through an accretion stream directly onto the magnetic pole(s) of the white dwarf without the intermediary of an accretion disk. The magnetic field in polars is also strong enough to synchronize the rotation of the white dwarf with the orbital period of the system. Hard X-rays are produced by bremsstrahlung from the hot gas, which is heated by an accretion shock above the surface of the white dwarf. Soft X-ray/EUV radiation is powered by reprocessing of the hard X-rays on the surface, and also by direct heating of the subphotospheric layers by dense blobs raining down from the accretion stream. Most of the known AM Her stars were discovered because of their X-ray radiation. For reviews, see Cropper (1990) and Beuermann & Burwitz (1995).

This is the third in a series of papers that demonstrate the value of long EUVE observations for obtaining interesting timing results on more than one source in the field (see Halpern, Martin, & Marshall 1996; Halpern & Marshall 1996).

2. EUVE OBSERVATION

We began a long EUVE observation of the Seyfert galaxy 1H 0419−577 ($z = 0.104$) on 1997 December 15. It was immediately apparent in quick-look data that a pair of sources of equal brightness was present near the target position. Only 3.95 apart, they are nevertheless well separated in the EUVE Deep Survey imager. This instrument is sensitive in the range 65−190 eV, although interstellar absorption limits the detected flux from extragalactic sources to energies greater than 100 eV. Figure 1

1 Hubble Fellow.
2 Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, which is operated by AURA, Inc., under a cooperative agreement with the National Science Foundation.
Fig. 1.—Lightcurves of the two neighboring sources in the EUVE Deep Survey imager. Each point corresponds to one satellite orbit. Background subtraction, and all relevant exposure corrections have been applied. The fact that the two sources do not show correlated variability assures us that the periodic signal detected in EUVE J0425.6–5714 is real and not the result of some unknown systematic effect. The short gap near the beginning of the observation is due to an unsuccessful attempt to detect the afterglow of the gamma-ray burst of 1997 December 14, which occurred elsewhere on the sky (Boer et al. 1997).

shows the light curves of both sources, where each point represents one satellite orbit. In order to construct these light curves, counts were extracted from a circular aperture of radius 75" around each source. Background was obtained from adjacent regions and subtracted, and the light curves were corrected for variable dead time and "Primbschinger" (lost counts due to telemetry sharing). The total exposure time is 651,405 s, and the net counts are 44,403 and 44,498, respectively, from the Seyfert galaxy 1H 0419–577 and the new source denoted EUVE J0425.6–5714. Table 1 contains a log of this observation.

While the Seyfert galaxy is only moderately variable, the new source shows large-amplitude modulation, which is the result of the beating between the EUVE satellite orbit (94.6 minutes) and the intrinsic variability of the source. The latter was determined unambiguously to be a 85.822 ± 0.002 minute coherent period both from epoch folding ($x$ squared) analysis, and from a discrete Fourier transform of the individual photon arrival times. The fact that the light curves of the two sources in Figure 1 do not show correlated variability assures us that the periodic signal detected in EUVE J0425.6–5714 is real and not the result of some unknown systematic effect. We interpret the 85.822 minute period as both the orbital period and the spin period of a synchronously rotating magnetic CV (see § 4). We searched for additional periods as short as 10 s, but none were found.

Figure 2 is the mean folded light curve of EUVE J0425.6–5714. All phase bins are well covered, despite the proximity of the source period and the satellite orbital period, because the observation is very long. Phase 0 is defined as the midpoint of the narrow dip feature. The partial reversal inside the dip appears to be real and is present throughout the entire 25 day observation. In fact, the entire light curve appears to be stable over the duration of this observation. An ephemeris for mid-dip (phase 0) is

$$T_{dip}(EUVE) = \text{HJD } 2,450,798.08606(60) + 0.0595990(14) \times E.$$ 

| Instrument      | Date (UT)      | Exposure Time (s) | Count Rate (s$^{-1}$) |
|-----------------|----------------|-------------------|-----------------------|
| ROSAT PSPC      | 1992 Apr 7     | 4094              | <0.0025               |
| ROSAT HRI       | 1994 May 15    | 2114              | 0.1420                |
| ROSAT HRI       | 1994 Sep 19–23 | 6015              | 0.0387                |
| ROSAT HRI       | 1996 Jun 30–Sep 1 | 171,841         | 0.0289                |
| ASCA SIS        | 1996 Jul 22    | 24,370            | <0.0030               |
| ASCA SIS        | 1996 Aug 10    | 24,397            | <0.0033               |
| EUVE DS         | 1997 Dec 15–1998 Jan 10 | 651,405     | 0.0683                |
Fig. 2.—Folded light curve of the AM Her star EUVE J0425.6−5714 in the EUVE Deep Survey imager. Background has been subtracted. Phase 0 corresponds to HJD 2,450,798.08606, the epoch of the ephemeris in § 2.

Fig. 3.—Folded light curve of the AM Her star EUVE J0425.6−5714 in the ROSAT HRI observations of 1996. Background has been subtracted. Phase 0 corresponds to HJD 2,450,264.5651, the epoch of the ephemeris in § 3.

The numbers in parentheses are the uncertainties in the last digits.

3. ROSAT AND ASCA OBSERVATIONS

This field has been observed many times by ROSAT, also with the Seyfert galaxy 1H 0419−577 as the intended target. A log of the ROSAT observations is given in Table 1. An X-ray source at the position of EUVE J0425.6−5714 is present in ROSAT HRI observations beginning in 1994 May, when it may have been in its brightest X-ray state. The HRI is sensitive in the range 0.2−2.0 keV. This source was not detected in the only ROSAT PSPC observation, obtained on 1992 April 7. Since the PSPC is several times more sensitive than the HRI at all energies, the source must have been in an “off” state at the time of the PSPC observation. There are no reports of previous soft X-ray detections of EUVE J0425.6−5714, and two ASCA pointings obtained contemporaneously with the ROSAT HRI detection (see Table 1) show that it is apparently not a hard X-ray source in the 0.5−10 keV range, even in the “on” state. Because the ASCA image of the bright Seyfert galaxy has a complex, extended point-spread function, the upper limits quoted in Table 1 were derived with the help of ray-tracing software, written by Andy Ptak, which we used to simulate the appearance of a second source at the location of the star.

The HRI monitoring observations obtained in 1996 have sufficient exposure to produce a folded light curve. Here we describe the analysis of EUVE J0425.6−5714 from these repeated HRI observations. A total exposure time of 171,841 s was divided into approximately daily observations of one or two satellite orbits each, spanning a 2 month period. In addition, denser coverage was obtained for 5 days within this interval. From all these observations, a total of 4974 net counts were extracted from the source after background subtraction. The average flux was fairly steady throughout this period. Epoch folding of these data reveal a highly significant signal at a period consistent with the EUVE measured value. The best-fitting period in the HRI is 85.8213 ± 0.0016 minutes. The HRI folded light curve, shown in Figure 3, is nearly identical to that of EUVE, including the timing of the narrow dip relative to the broad modulation. An ephemeris for mid-dip (phase 0) in the HRI is

\[ T_{\text{dip}} (\text{HRI}) = \text{HJD} 2,450,264.5651(12) + 0.0595981(11) \times E. \]

As a result of the apparent stability of the light curve, the sharpness of the dip, and the long time span of the observations, both of the above ephemerides are precise enough to count cycles over the 1.5 yr interval between the epochs \( T_0 (\text{HRI}) \) and \( T_0 (\text{EUVE}) \). The HRI ephemeris predicts that 8951.98 ± 0.15 cycles elapsed between \( T_0 (\text{HRI}) \) and \( T_0 (\text{EUVE}) \), while the EUVE ephemeris predicts that 8951.84 ± 0.21 cycles elapsed. Therefore, we conclude that there is a unique cycle count of 8952 between the epochs. The resulting coherent ephemeris is

\[ T_{\text{dip}} = \text{HJD} 2,450,264.5651(12) + 0.05959796(13) \times E. \]

The resulting best period, 85.82107 ± 0.00020 minutes, is consistent with the values measured individually by ROSAT and EUVE. This joint ephemeris is expected to be accurate to 0.1 cycles until the year 2005.

4. OPTICAL IDENTIFICATION AND SPECTROSCOPY

Armed with a precise X-ray position, which was confirmed by relative astrometry with respect to the known AGN, it was
Fig. 4.—A finding chart that you can trust for the AM Her star EUVE J0425.6−5714 at J2000 coordinates 4°25′38″65; −57°14′36″5 (center), and the Seyfert galaxy 1H 0419−577 (= LB 1727) at J2000 coordinates 4°26′0″76; −57°12′1″6 (upper left). The field is 10′ × 10′ from a digitized SERC Southern Sky Survey IIIa-J plate. North is up, east is to the left, and black is white.

a simple matter to identify EUVE J0425.6−5714 with a 19th magnitude blue star on the ESO Sky Survey plates. This star is listed in the USNO A1.0 astrometric catalog (Monet et al. 1996) at J2000 coordinates 4°25′38″65; −57°14′36″5, with approximate magnitudes $B = 19.1$, $R = 18.7$. A finding chart is given in Figure 4. The Seyfert galaxy 1H 0419−577 is also marked on this chart, at J2000 coordinates 4°26′0″76; −57°12′1″6. We note that the position of this almost stellar Seyfert galaxy is consistent with that of the blue “star” LB 1727, given as (1950) 4°25′0″; −57°19′ by Luyten & Anderson (1958). However, there are several references to an erroneous position for this Seyfert galaxy in the literature. The finding chart in Shara, Shara, & McLean (1993) for the ROSAT Wide Field Camera catalog points to the wrong object, as does Shara et al. (1997) for the EUVE catalog. As a result, an incorrect position was measured by Veron-Cetty & Veron (1996) and was adopted by several of the metacatalogs that are in wide use today.

We obtained optical spectra of the 19th magnitude optical counterpart of EUVE J0425.6−5714 on the CTIO 1.5 m telescope on 1998 January 3 and 4, simultaneously with the ongoing EUVE observation. Figure 5 shows a summed spectrum amounting to 1 hr of exposure. Its continuum flux corresponds to $B = 19.3$. When accounting for slit losses, this is probably consistent with its appearance on the ESO Sky Survey and with the USNO A1.0 catalog. Strong emission lines of H, He i, and He ii λ4686 are seen, together with the broad cyclotron humps that are characteristic of AM Her type cataclysmic binaries. Cyclotron peaks are located at approximately 4350 and 5350 A. Their separation of 4300 cm$^{-1}$ corresponds to a lower limit
on the polar magnetic field of 50 MG according to equation (4) of Cropper (1988). An actual measurement of the magnetic field and the temperature/viewing parameter $T \sin^2 \theta$ would require time-resolved spectra with broader wavelength coverage to identify and accurately measure several more harmonics.

5. INTERPRETATIONS AND CONCLUSIONS

It is difficult to derive quantitative information about luminosity and distance to this system from existing data. We did not detect the secondary star in the optical spectrum; for this short orbital period it is expected to be a late M dwarf. Although the EUV and ROSAT light curves are of high quality, they lack any spectral information from which temperatures and fluxes can be measured. (The source is too faint for a useful spectrum to be extracted from the EUVE short wavelength spectrometer). However, based on the similarity of the EUV and ROSAT light curves, we conclude that both of these represent soft blackbody emission coming from the heated accretion spot(s) on the white dwarf, and we hypothesize that the accretion rate may have been similar during both epochs. Under these assumptions, the ratio of the EUVE and ROSAT count rates can be interpreted in terms of an allowed range of blackbody temperature and intervening column density. We find that the range of parameters that is consistent with both count rates is $21 < kT < 30$ eV and $0 < N_H < 3 \times 10^{19}$ cm$^{-2}$, with $kT$ strongly anticorrelated with $N_H$. The lower bound on the temperature is actually set by the additional requirement that the Rayleigh-Jeans tail of the blackbody not exceed the observed $U$-band flux obtained from Figure 5. The actual effective temperature of a real stellar atmosphere could, however, be lower than the blackbody estimate due to nongray opacity. The bolometric flux of these fitted blackbody models is in the range $(1.4-6.8) \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$.

With respect to hard X-rays, there is a dearth of evidence for any from EUVE J0425.6−5714. The two ASCA nondetections listed in Table 1 correspond to a combined $3 \sigma$ upper limit on the hard X-ray flux of $3.78 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–2.0 keV band, assuming a 10 keV thermal bremsstrahlung spectrum. Since these observations were contemporaneous with the ROSAT HRI monitoring, we can use the ASCA nondetections to place an upper limit on the fraction of the HRI flux that can be thermal bremsstrahlung. A flux of $3.78 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–2.0 keV band would produce $\approx 0.0018$ counts s$^{-1}$ in the HRI. Since the actual HRI count rate is 0.029 counts s$^{-1}$, a factor of 16 larger, we can safely conclude that EUVE J0425.6−5714 is one of those AM Her stars whose soft X-ray luminosity is at least an order of magnitude larger than its hard X-ray luminosity. Hard X-ray emission in AM Her stars is attributed to bremsstrahlung from an accretion shock above the surface of the white dwarf. Approximately half of this energy should be reprocessed into thermal soft X-rays on the surface. But several other AM Her stars are known to be very soft sources without significant hard X-ray flux (e.g., de Martino et al. 1998). Beuermann &Burwitz (1995) showed that the ratio of bremsstrahlung flux to blackbody flux in the ROSAT band is less than 0.05 for all systems in which $B > 30$ MG. Our lower limit of 50 MG from the cyclotron features is consistent with this correlation. When soft X-ray emission dominates over hard X-rays, it is attributed either to the suppression of bremsstrahlung by the more efficient cyclotron cooling, which occurs in a high magnetic field (Woelk & Beuermann 1996) or to accretion in the form of dense blobs that deposit their energy below the photosphere of the white dwarf (Kuijpers & Pringle 1982).

The narrow partial eclipse is most likely caused by cold gas in the accretion stream that occults the hot spot. The light curves of several AM Her stars are interpreted in this way (Patterson, Williams, & Hiltner 1981; Greiner, Remillard, & Motch 1998 and references therein). We note that the dip is approximately twice as broad in EUVE as in ROSAT. This favors an inter-
pretation as photoelectric absorption whose angular extent can vary either as a function of observed X-ray energy, with harder X-rays being less vulnerable to absorption in the tenuous outskirts of the accretion stream or as a function of accretion rate.

In contrast, occultation by the secondary star is more likely to produce a total eclipse that is independent of energy, since both hard and soft X-rays come from a relatively compact region near the surface of the white dwarf. The narrow reversal in the EUVE dip also argues against eclipse by the secondary, even though we do not know exactly what does cause it. A similar feature appears to be present in the EUVE light curve of QS Tel (Rosen et al. 1996).

It is difficult to determine whether the light curve signifies accretion onto one or both magnetic poles. The waveform might be described as being double peaked with a separation of about 0.4 in phase, indicating emission from two poles that are not diametrically opposite. Alternatively, if the entire region between phase 0.7 and 0.1 is affected by photoelectric absorption or scattering, then the underlying light curve resembles a broad, single peaked cosine function that is characteristic of a single bright spot on a rotating star. Several other AM Her stars have broad dips that precede an accretion-stream eclipse; their EUV light curves have been modeled by Warren, Sirk, & Vallerga (1995) and Sirk & Howell (1998). These studies conclude that either Compton scattering or absorption by ionized matter in the accretion column just above the accretion spot can explain broad dips occurring over phases that are not susceptible to occultation by the part of the accretion stream that is far from the white dwarf. Such models would seem to be consistent with the light curve of EUVE J0425.6–5714, with a geometry such that the single accretion spot is never completely occulted by the limb of the white dwarf. Further progress in interpreting the accretion and viewing geometries of this star will have to await spectrally resolved soft X-ray observations, as well as phase-resolved optical spectroscopy and polarimetry. The ephemeris already obtained from existing X-ray data should permit absolute phasing of any optical observations obtained over the next few years.

Results on the Seyfert galaxy 1H 0419–577 will be presented in a separate paper.

We thank Joe Patterson for helpful discussions. M. E. acknowledges support from Hubble fellowship grant HF-01068.01-94A from the Space Telescope Science Institute, which is operated for NASA by the Association of Universities for Research in Astronomy, Inc., under contract NAS 5-26255.

REFERENCES

Beuermann, K., & Burwitz, V. 1995, in ASP Conf. Ser. 85, Cape Workshop on Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner (San Francisco: ASP), 99
Boer, M., Roberts, B. A., Malina, R., Feroci, M., Piro, L., & Hurley, K. 1997, IAU Circ. 6795
Cropper, M. 1988, MNRAS, 236, 29P
———. 1990, Space Sci. Rev., 54, 195
de Martino, D., et al. 1998, A&A, 332, 904
Greiner, J., Remillard, R. A., & Motch, C. 1998, A&A, 336, 191
Halpern, J. P., & Marshall, H. L. 1996, ApJ, 464, 760
Halpern, J. P., Martin, C., & Marshall, H. L. 1996, ApJ, 462, 908
Kuijpers, J., & Pringle, J. 1982, A&A, 114, L4
———. 1990, Space Sci. Rev., 54, 195
Luyten, W. J., & Anderson, J. H. 1958, A Search for Faint Blue Stars. XII. The Far Southern Hemisphere (Minneapolis: Univ. Minnesota)
Monet, D., et al. 1996, USNO–SA1.0 (Washington: US Naval Obs)
Patterson, J., Williams, G., & Hiltner, W. A. 1981, ApJ, 245, 618
Rosen, S. R., et al. 1996, MNRAS, 280, 1121
Shara, M. M., Bergeron, L. E., Christian, C. A., Craig, N., & Bowyer, S. 1997, PASP, 109, 998
Shara, M. M., Shara, D. J., & McLean, B. 1993, PASP, 105, 387
Sirk, M. M., & Howell, S. B. 1998, preprint (astro-ph/9805182)
Veron-Cetty, M.-P., & Veron, P. 1996, A&AS, 115, 97
Warren, J. K., Sirk, M. M., & Vallerga, J. V. 1995, ApJ, 445, 909
Woelk, U., & Beuermann, K. 1996, A&A, 306, 232