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IDENTIFICATION OF A FAINT X-RAY SOURCE WITH THE W URSAE MAJORIS STAR VW CEPHEI

RUSSELL W. CARROLL
University of California at San Diego

AND

R. G. CRUDDACE, H. FRIEDMAN, E. T. BYRAM, K. WOOD, J. MEEKINS, D. YENTIS, G. H. SHARE, AND T. A. CHUBB
E. O. Hulburt Center for Space Research, Naval Research Laboratory
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ABSTRACT

The NRL instrument aboard the *HEAO 1* satellite has detected a faint X-ray source, which has been identified tentatively with the contact binary star (W UMa variable) VW Cephei. Its luminosity is between 3×10^{30} and 4×10^{31} ergs s^{-1} (0.1–10 keV), and the results suggest some variation of the X-ray flux with phase.

Subject headings: stars: W Ursae Majoris — X-rays: sources

I. INTRODUCTION

In this *Letter* we describe observations, by the NRL instrument aboard the *HEAO 1* satellite, of a weak X-ray source in Cepheus. A search of the error box for this source revealed only one peculiar object, VW Cephei, a nearby (24.4 pc; Hershey 1975) contact binary star. Our confidence in this identification was increased shortly afterward, when the *IUE* satellite discovered intense He II, N V, C IV, Si II, and Si IV emission lines in the far-ultraviolet spectrum of VW Cephei (Dupree *et al.* 1979). These lines were found also in the spectrum of a nearer contact binary system, 44 *i* Bootis (11.9 pc; Gliese 1969), which encourages a search for X-ray emission in other systems of this type.

VW Cephei has been studied optically for over 50 years, and in particular was the subject of an international campaign of photometric and spectroscopic observations in 1959 (Kwee 1966). Figure 1 shows typical u, r, and $u - r$ light curves for VW Cephei, taken from Kwee's (1966) paper. It is a W-type W Ursae Majoris

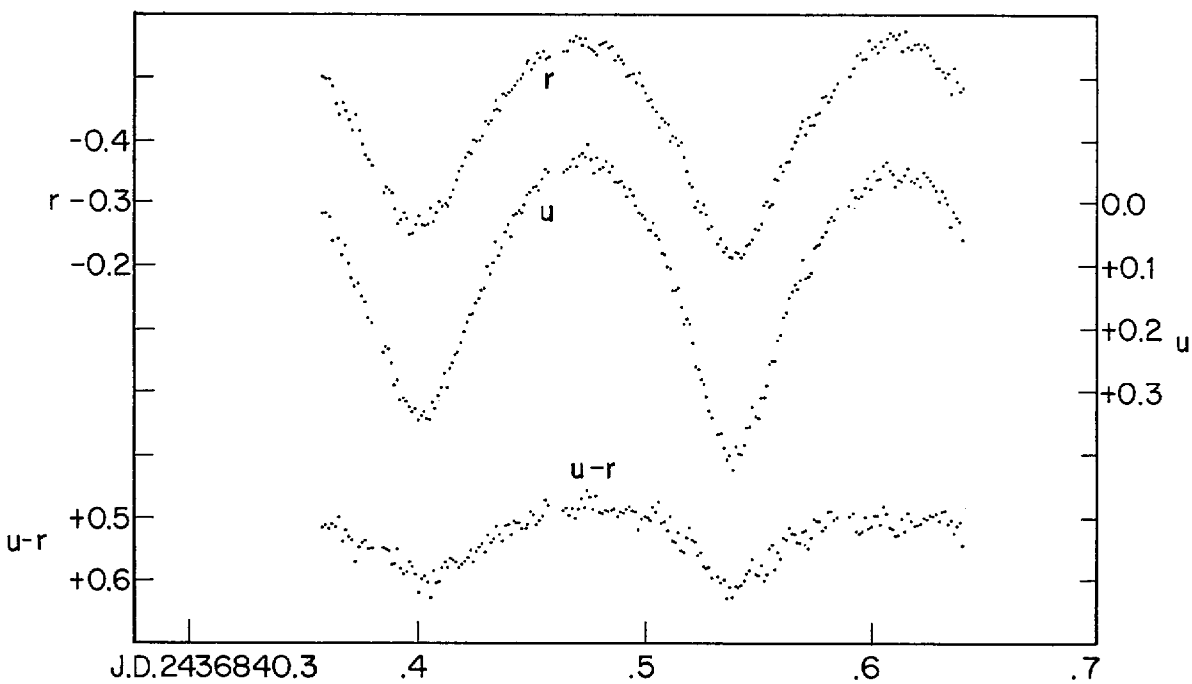

FIG. 1.—Light curves of VW Cephei, taken from Kwee (1966)

system (Binnendijk 1970) in which, although both stars lie close to the main sequence, the more massive and more luminous star is cooler than its companion. The system has a maximum visual magnitude of about 7.3 mag, a spectrum which is approximately G5, and a period currently of $0\overset{d}{.}2783141$ (Linnell 1979). Photometric and spectroscopic observations point to marked changes in the characteristics of VW Cephei over a wide range of time scales, extending from less than 1 hour to several decades. For example, the light curves in Figure 1 show changes in luminosity and color over periods of less than 20 minutes, and changes in the relative heights of consecutive maxima have been observed from one revolution to the next (Pustylnik and Sorgsepp 1976). The spectroscopic observations summarized by Kwee (1966) show marked changes over periods of a few years. Line doubling at elongation, clearly visible in 1947, could not be seen in 1959, and the Ca I line at 4227 Å broadened significantly between 1947 and 1959. These effects may be caused by varying turbulence in the stellar atmosphere. High-resolution coudé spectrograms taken at Mount Palomar in 1956 and 1957 showed evidence for sharp, variable calcium H and K emission lines, but no such lines were found in 1947 and 1959.

New information about the nature of VW Cephei has been obtained by Hershey (1975), who made astrometric measurements of plates taken between 1942 and 1974, and compiled measurements of times of minimum made between 1926 and 1974. He deduced, with the aid of spectroscopic measurements of the mass ratio, that the components of the binary have masses of $1.1 \pm 0.3\ M_{\odot}$ and $0.4 \pm 0.1\ M_{\odot}$, and that the period P decreased at an average rate of $1.22 \pm 0.05 \times 10^{-6}\ P$ per year between 1938 and 1969. This implies, in a conservative system, an average rate of mass transfer of about $1.3 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$. In addition, Hershey's analysis predicted the existence of a third component, a K-dwarf of mass $0.58 \pm 0.14\ M_{\odot}$, which then was found during an optical search. However, this component is distant from the binary (6.4 AU) and probably plays no role in the events leading to ultraviolet or X-ray emission.

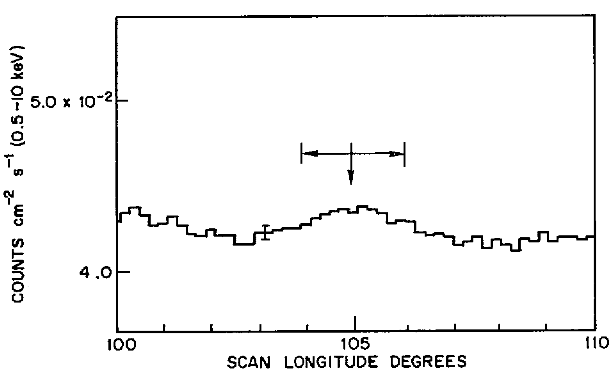

FIG. 2.—X-ray count rate in the 0.5–10 keV band plotted against scan longitude. Scan longitude is measured along the detector scan path from the point where the view axis crosses the ecliptic in a northerly direction. The data have been summed over 4 days in which the *HEAO 1* satellite scanned over VW Cephei. The vertical arrow indicates the position of the binary, and the horizontal bar is 2° long, the full collimator width.

VW Cephei was the brightest object in the error box for the source 3U 2041+75, but this source was omitted from the fourth *Uhuru* catalog.

II. RESULTS

The observations were made by four large, co-aligned proportional counters, each equipped with a 2.5 μm thick Mylar window and filled with a mixture of 77.5% xenon and 22.5% methane at a total pressure of 1.4 N cm^{-2} (2.1 psia). The array was fitted with $1° \times 4°$ (FWHM) collimators providing an aperture of area 6400 cm^2. The data were obtained in a four-day period between 1977 August 19 and 22, during which the satellite scanned the sky continuously with the spin axis pointed at the Sun. The observations were made soon after satellite turn-on, when VW Cephei already had moved 2° away from the scan plane. After rejection of data obtained during Earth-looking or periods of high background, the remainder was superposed and summed. Figure 2 shows the appearance of the source we have identified with VW Cephei. The significance of the detection is 6 σ. An error box for the source was found by sorting the data into eight sets, each summed over 12 hours, and fitting each set to a model containing two sources of arbitrary position and magnitude. The error box was determined by finding the best fit of a single source to the eight lines of position obtained, and then determining the 90% confidence contour, which is shown in Figure 3. This region was searched

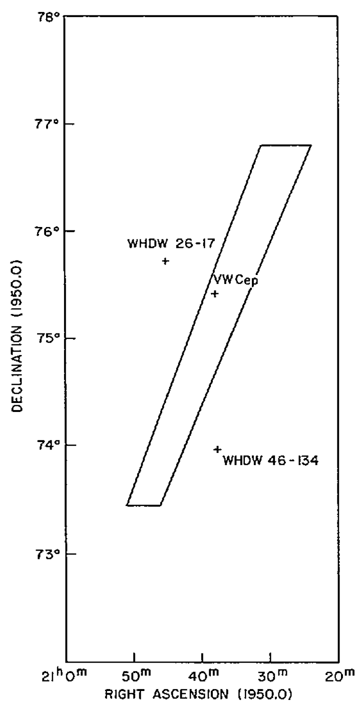

FIG. 3.—The 90% confidence error box for the weak X-ray source detected in Cepheus. The white dwarfs shown just outside the error box are listed in Luyten's (1970) white dwarf catalog.

in a large number of catalogs, which have been assembled for easy inspection by *HEAO* data processing software. They include such objects as nearby and variable stars, radio, infrared and X-ray sources, white dwarfs, flare stars, supernova remnants, globular clusters, peculiar galaxies, BL Lacertae sources, and clusters of galaxies. The search revealed only VW Cephei, and two white dwarfs lying just outside the error box (Fig. 3).

In order to seek stronger confirmation of the identification with VW Cephei, the data were sorted into four bins of equal phase (Fig. 4) centered at phases 0°, 90°, 180°, and 270°. Figure 4*a* shows the data for all phases, and Figures 4*b*–4*e* the data for each of the phase bins. In producing Figure 4 more stringent criteria were used for removing noisy data than in the case of Figure 2, and there are noticeable differences between the two results. In particular, the background is lower in Figure 4, and the feature seen in this plot at scan angles between 0° and 1°5 is not evident in Figure 1. The results of the phase binning, though of limited statistical significance, do suggest that the X-ray emission is most visible near phase 180°, and least visible near 0°. The source is observed at phase 180° with a significance of 3.9 σ, but cannot be distinguished among the noise at phase 0°.

We have estimated the luminosity of the source, assuming for the purpose of converting counts into ergs that it is a bremsstrahlung source with a temperature in the plausible range, 10^6–10^8 K, and assuming a distance of 24.4 pc (Hershey 1975). The result, subject to uncertainties caused by statistics and lack of knowledge about the spectrum, is between 3×10^{30} and 4×10^{31} ergs s^{-1} (0.1–10 keV).

III. DISCUSSION

The spectrum and color of a W UMa star show no dramatic variations as the phase changes. This and the disparate masses of the components of the binary (typically 2:1; Binnendijk 1970) have suggested models

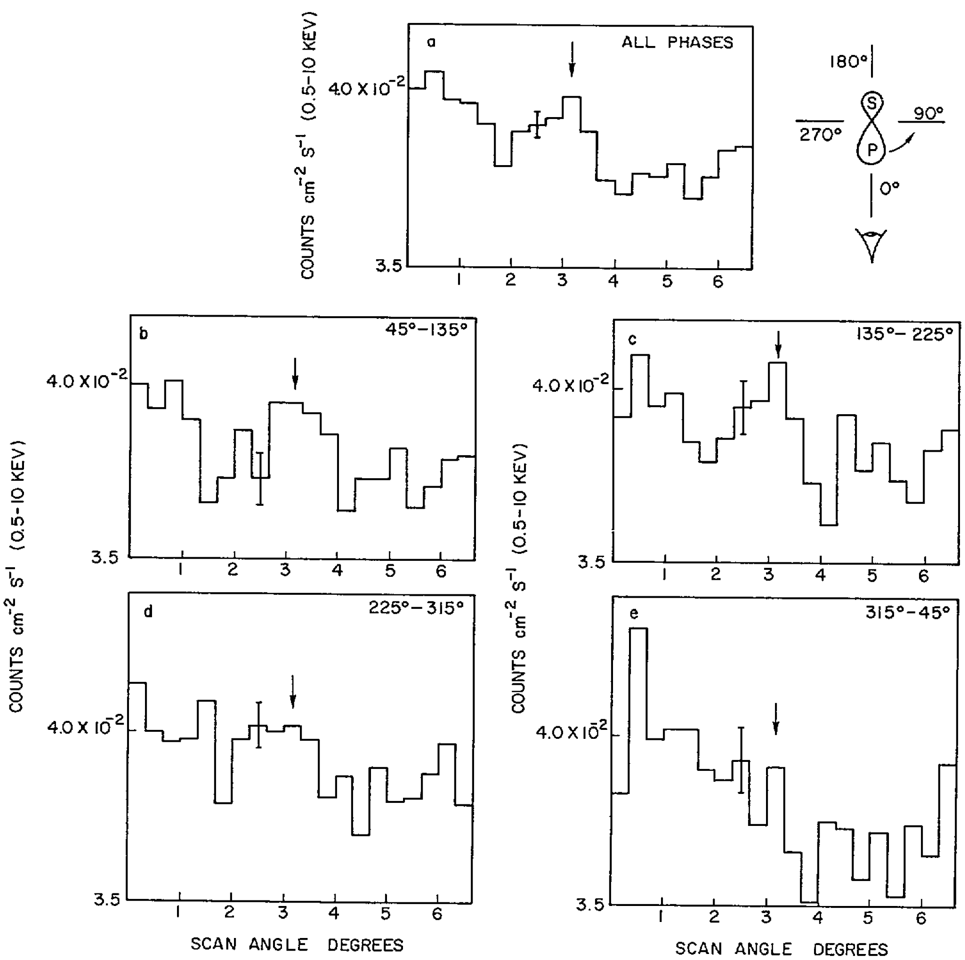

FIG. 4.—X-ray count rate in the 0.5–10 keV band plotted against scan angle, using data summed over 4 days in which the *HEAO 1* satellite scanned over VW Cephei (indicated by the arrows). All data are presented in (*a*), while (*b*), (*c*), (*d*), and (*e*) show the results of sorting the data into four bins, each corresponding to a quarter of the revolution of the binary. The phase angles in each plot may be interpreted using the sketch at top right, in which *P* is the primary star, and *S* the secondary.

in which the stars share a common envelope. The difficulties met by such models in satisfying the requirements of dynamics, and of stellar structure and energy generation, have been reviewed by Shu, Lubow, and Anderson (1976), who in this and two other papers (Lubow and Shu 1977; Shu, Lubow, and Anderson 1979) described a resolution of these problems. Their model invokes a discontinuity in thermodynamic properties between one star and the common envelope, and predicts that the envelope is filled with material welling up from the other star. In such a scheme it is plausible to imagine that VW Cephei has a chromospheric and coronal envelope common to both stars, which is emitting the far-ultraviolet and X-ray radiation observed by the *IUE* and *HEAO 1* satellites. However, the 0.5–10 keV luminosity of VW Cephei is about six orders of magnitude higher than the solar luminosity (4×10^{24}–4×10^{25} ergs s^{-1}, 0.5–7 keV; Allen and Yousef 1973), implying a coronal gas density 100–1000 times that of the Sun, and hence a much higher energy flux into the corona. Given the small amount of X-ray data and the complexity of the solar corona, speculation on the cause of such a flux is dangerous. We note simply that large energy sources are available. The energy flux between the stars, most of which must find its way into the envelope and cause extensive circulatory motions, is large ($\sim 10^{33}$ ergs s^{-1}), and in addition the binary contains a large store of rotational energy ($\sim 4 \times 10^{47}$ ergs), which can be transferred to the stellar magnetic field as the field lines are wound up. The phase dependence of the X-ray emission may be the result of a nonuniform energy flux generated mainly by the secondary, or by the region between the stars ("hot spot"). The existence of a "hot spot," or, more exactly, a region of relatively high temperature, between the stars, is suggested by the pronounced decrease in the $u \pm r$ color index between minimum and maximum (Fig. 1).

An alternative explanation of the X-ray emission is possible if it is assumed that the binary is semi-detached, with only one star filling its Roche lobe. Such a model has been proposed by Pustylnik and Sorgsepp (1976), in their attempt to explain various features in the light curve of VW Cephei, including, in particular, the color changes and the conspicuous changes in slope of the light curve near phases 0.12 and 0.88 (in Fig. 1, JD 2,436,840.51 and 2,436,840.57). In this model the secondary fills its Roche lobe, and gas from the L1 point is accreted by the primary. Impact of the gas stream with a "disklike shell" around the primary produces a hot spot, which is responsible for the "bumps" at phases 0.12 and 0.88, for some of the decrease in color index between minimum and maximum, and for the optical variability of the star. Accretion of gas at the surface of the primary star could be responsible for the X-ray emission, as shock heating could produce temperatures greater than 10^6 K, and a mass flux of less than $3 \times 10^{-10}\ M_\odot$ yr^{-1} would be required, about 4000 times less than the total mass flux in a conservative system. There are two unfortunate features of this model, quite apart from the difficulty of fitting it to the X-ray phase dependence suggested by Figure 4. First, Pustylnik and Sorgsepp (1976) made the secondary star the nearer one at primary minimum, which is in conflict with the classification of VW Cephei as a W-type W UMa star. The latter would place the hot spot nearer the secondary. Second, we calculate the distance of L1 from the center of the primary in such a system to be between 0.33 and 0.85 $R_\odot$, assuming the measured period and Hershey's (1975) mass estimates. Therefore, a main-sequence primary would fill its Roche lobe, and this model must assume the primary to be some kind of compact star. However, such models should not be forgotten in studying W UMa systems, bearing in mind the long-held suspicion (reviewed by Warner 1974) that they are ancestors of the dwarf novae.

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RUSSELL W. CARROLL: Department of Physics, C-011, University of California at San Diego, La Jolla, CA 92093

E. T. BYRAM, T. A. CHUBB, R. G. CRUDDACE, H. FRIEDMAN, J. MEEKINS, G. SHARE, K. WOOD, and D. YENTIS: Code 7129, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375