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ROSAT OBSERVATION OF THE OLD CLASSICAL NOVA CP PUPPIS

ŞÖLEN BALMAN,[1,2] MARINA ORIO,[1,3] AND HAKKI ÖGELMAN[1]
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ABSTRACT

We present X-ray observation of the old nova CP Puppis obtained by the *ROSAT* Position Sensitive Proportional Counter in 1993 April. The source is detected with a count rate of 0.067 ± 0.004 counts s^{-1}. The total observed X-ray flux between 0.1 and 2.4 keV is $\sim 3 \times 10^{-12}$ ergs s^{-1} cm^{-2}. The spectrum of the source is best fit by a thermal bremsstrahlung emission model with temperature ≥1 keV. The X-ray count rates are modulated with the previously known spectroscopic period $\sim 0\overset{d}{.}0614$ (~88.4 minutes) of the system at the 3 σ confidence level. The hard X-ray flux and the detected X-ray modulations suggest that CP Puppis is an intermediate polar system.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (CP Puppis) — X-rays: stars

1. INTRODUCTION

CP Puppis is an old classical nova that had an outburst in 1942 as one of the fastest and brightest of this class of cataclysmic variables (CVs) ($\Delta m = 17$ mag; $t_3 = 6.5$ days; $V_{ej} \geq 1000$ km s^{-1}; Payne-Gaposkin 1957). The system is believed to have reestablished accretion (O'Donoghue et al. 1989), and thus we see CP Puppis as an accreting white dwarf binary (i.e., CV). Other than the outburst characteristics, another important classification criterion of CVs is the magnetic field of the white dwarf. In unmagnetized CVs, mass is transferred through a boundary layer at the inner edge of the accretion disk (Wade & Ward 1985; Warner 1987). Magnetized CVs have two main subclasses. In polar systems (AM Hers; $B \sim 10^7$ G; $P_{orb} \leq 4$ hr), the mass is channeled directly from the secondary to the poles of the white dwarf by an accretion column (Beuermann 1988; Cropper 1990). In intermediate polar systems (DQ Hers; $B \leq 10^6$ G; $P_{orb} \geq 3$ hr), accretion occurs via a disk truncated at the Alfvén radius of the white dwarf, and the matter is channeled to the poles via accretion columns (Patterson 1994, and references therein). In diskless systems (polars), the white dwarfs are found to rotate synchronously with the orbital period, while the white dwarfs in intermediate polar systems spin faster than the orbital period, giving rise to two distinct periods in the light curve.

CP Puppis is a candidate magnetic CV because of its close resemblance in outburst characteristics to another nova, V1500 Cyg, that has been determined to be an AM Her system (O'Donoghue et al. 1989). CP Puppis is observed to have two distinct periods in optical wavelength observations. The spectroscopic period, $\sim 0\overset{d}{.}0614$ (~88.4 minutes), is interpreted as the orbital period of the system. The photometric period is detected at the spectroscopic period or at different longer periods (up to 11% longer) with a large range in amplitude that suggests beating of two or more unresolved frequencies (Bianchini, Friedjung, & Sabbadin 1985, 1990; Warner 1985; O'Donoghue et al. 1989; White, Honeycutt, & Horne 1993, and references therein). The system is found to have a low inclination angle of 30° ± 5° by Duerbeck, Seitter, & Duemmler (1987) and Szkody & Feinswog (1988). Further, Szkody & Feinswog (1988), looking in the infrared, have detected a best-fit double-sinusoid with a period of $0\overset{d}{.}067$ (~96.48 minutes) for their CP Puppis observations which might represent reprocessing of X-ray radiation by structures in the system. The existence of two periods for the system, the absence of significant circular polarization (Cropper 1986), along with the presence of high-excitation lines and modulation of line structure with the spectroscopic and photometric periods, all support the possibility that CP Puppis is an intermediate polar (White et al. 1993). On the other hand, modulations of up to 0.5 mag in the optical brightness of the system, a photometric period longer than the spectroscopic period (11%), are evidence of SU UMa (a nonmagnetic CV class) type of behavior (White et al. 1993). Thus, an SU UMa or a DQ Her interpretation is equally likely in view of the data available until now.

In general, the X-ray spectra of both classes of CVs (magnetic and nonmagnetic) show hard X-ray emission produced in hot postshock regions (Patterson & Raymond 1985a; Eracleous, Halpern & Patterson 1991b). Some nonmagnetic systems and all polars also show a blackbody radiation at temperatures 15–55 eV (Patterson & Raymond 1985b; Cropper 1990). CP Puppis was first observed in X-rays by the *Einstein* IPC (Becker & Marshall 1981; Eracleous, Patterson & Halpern 1991a). The X-ray flux between 0.15 and 4.5 keV was found to be 1.4×10^{-12} ergs cm^{-2} s^{-1} with a temperature ~10 keV. No X-ray periodicity was detected below 3000 s because of the limited data span. The source was also observed by the *EXOSAT* ME (medium energy detector; O'Donoghue et al. 1989) between 2–6 keV, and there was no significant X-ray modulation found in the data. CP Puppis was first detected by *ROSAT* in the all-sky survey (Orio et al. 1992) with a count rate of 0.060 ± 0.005 counts s^{-1}. In this paper, we present the pointed *ROSAT* observation of CP Puppis, discussing the details of spectral and the temporal analysis.

2. THE OBSERVATION AND ANALYSIS

The pointed observation presented in this paper was carried out by the *ROSAT* PSPC (Position Sensitive Proportional Counter) between 1993 April 30 and May 2. The angular resolution of PSPC is 25″ for on-axis observations, and the

[1] Department of Physics, University of Wisconsin-Madison, 1150 University Avenue, Madison, WI 53706.
[2] solen@astrog.physics.wisc.edu.
[3] Osservatorio Astronomico di Torino, I-10025 Pino Torinese (TO), Italy.

TABLE 1

SPECTRAL MODELS AND PARAMETERS (RANGES CORRESPOND TO 3 σ ERRORS)

Parameter	Thermal bremsstrahlung[a]	Raymond-Smith[b]	Power law[c]
N_H[d]($\times 10^{21}$ cm^{-2})	0.5–7.0	0.5–4.5	0.2–8.0
kT (keV) ($\sim 10^7$ K)	>0.5	>1.4	...
Flux[e]($\times 10^{-12}$ ergs cm^{-2} s^{-1})	1.0–11	0.5–1.2	>1.7
Emission measure ($\times 10^{55}$ cm^{-3})	...	0.5–2	...
Photon index	...	...	−3.2 to 1.3
L_x[e, f]($\times 10^{32}$ ergs s^{-1})	0.6–6.5	0.3–0.7	>0.8
$\chi^2_{\min}$ (reduced)	1.0	1.1	1.1

[a] The energy flux distribution function for the bremsstrahlung model is $F(E) = A_1 e^{-E/kT} (E/E_0)^{-1} g(E; kT) e^{-Nh\,\sigma(E)}$, where A_1 is the normalization constant in photons cm^{-2} s^{-1} keV^{-1}, E is the photon energy in keV, (E/E_0) is the photon energy normalized to 1 keV, T is the temperature in k, k is the Boltzmann constant, $g(E; kT)$ is the Gaunt factor (Kellog et al. 1975), and $\sigma(E)$ is the photoelectric absorption cross section (Morrison & McCammon 1983).

[b] Emission spectrum from hot, diffuse gas based on the Raymond & Smith 1977 calculations.

[c] The energy flux distribution function for the power-law model is $F(E) = A_2 (E/E_0)^{-\alpha} e^{-Nh\,\sigma(E)}$, where A_2 is the normalization constant in photons cm^{-2} s^{-1} keV^{-1} and α is the power-law index.

[d] Neutral hydrogen column density in the line of sight in cm^{-2}.

[e] Between 0.1 and 2.4 keV.

[f] At an assumed distance of 700 pc (Mac Laughlin 1960).

energy resolution of the XRT (X-ray telescope) is ($\Delta E/E$) $\sim$ 0.43 at 0.93 keV (Trümper 1983; Pfeffermann et al. 1986). The source was detected in a pointed observation of Nova Puppis 1991 about 8′ off center with a count rate of 0.067 ± 0.004 counts s^{-1}. The effective exposure time was 9877 s, and the total number of events detected from the source was about 700. The X-ray data presented in this paper were analyzed using the EXSAS/MIDAS software package (Zimmermann et al. 1993).

2.1. *Spectral Analysis*

In order to study the spectrum of CP Puppis, the data were extracted from a radius of 105″ and the background-subtracted count rates were corrected for vignetting and dead time. The energy channels were binned with a signal-to-noise ratio of 3 σ, and the first 10 were excluded from the analysis because of low statistics and poor calibration. The count rate spectrum was relatively hard, peaking around 1 keV. We fitted the spectrum with thermal bremsstrahlung and Raymond-Smith (Raymond & Smith 1977) emission models as expected from radiatively cooling postshock regions. For comparison, a power law model was also attempted. The results are displayed in Table 1. The spectrum of the source was consistent with either a thermal bremsstrahlung or a Raymond-Smith model (see Fig. 1). The best-fit parameters for the thermal bremsstrahlung model were a temperature $\sim$1 keV and an X-ray flux $\sim 3 \times 10^{-12}$ ergs cm^{-2} s^{-1}. The Raymond-Smith model yielded a similar temperature, $\sim$3 keV, and a slightly lower X-ray flux, $\sim 9 \times 10^{-13}$ ergs cm^{-2} s^{-1}. The luminosity of the source is $\sim 10^{32}$ ergs s^{-1} for both spectral models at an assumed distance of 700 pc (Mac Laughlin 1960). The low-energy resolution of *ROSAT* prevented us from distinguishing between these two types of spectra. There was no soft component detected in X-rays below 0.6 keV. The upper limit on the soft X-ray flux was calculated using a blackbody model with an N_H (neutral hydrogen column density) $\sim 2 \times 10^{21}$ cm^{-2} [the N_H used is the maximum acceptable value derived using the value of $E(B-V)$ obtained with optical and *IUE* data; Duerbeck et al. 1987, de Martino 1994]. For a 15 eV blackbody temperature, the upper limit on the soft X-ray flux was

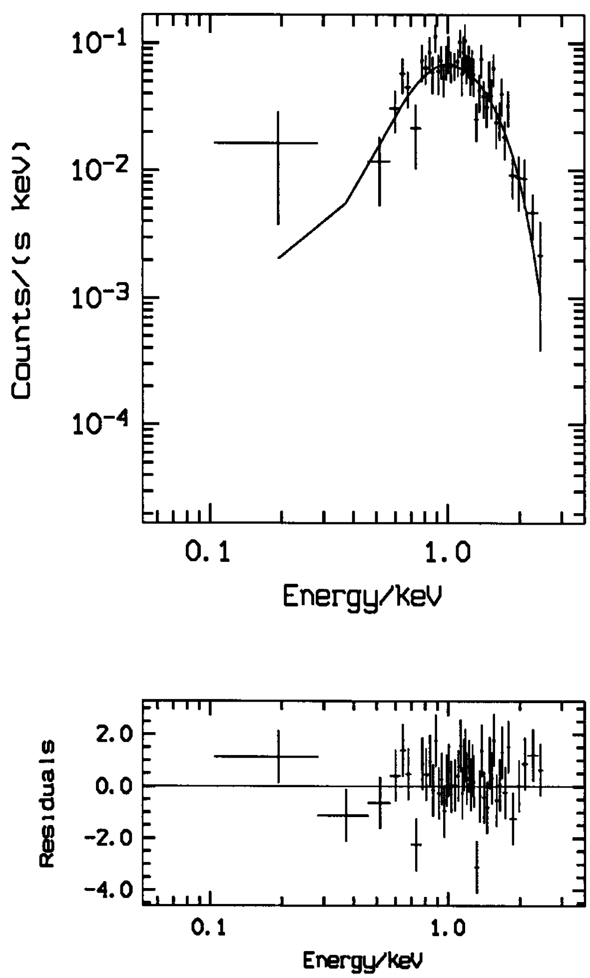

FIG. 1.—The X-ray data fitted with a thermal bremsstrahlung emission model with neutral hydrogen absorption. Smooth curve is the PSPC response to the model spectrum, and the actual PSPC data are indicated with crosses. Lower figure shows the residuals between the data and the model in standard deviations.

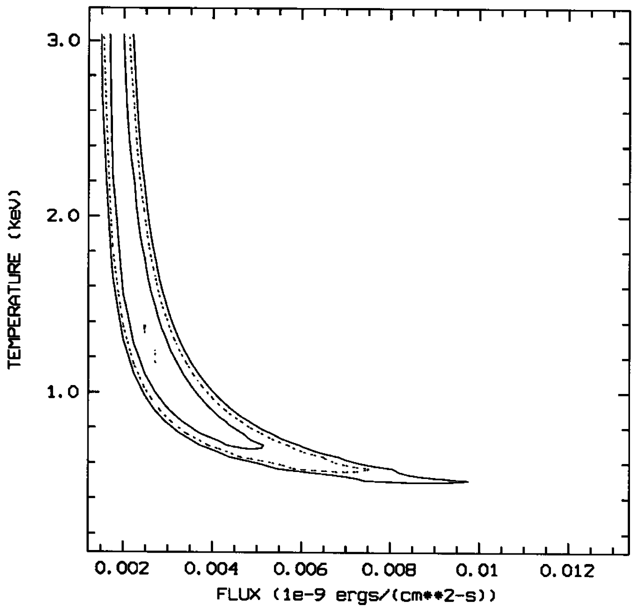

FIG. 2.—The two-dimensional parameter space of temperature vs. flux for the thermal bremsstrahlung model. Contours correspond to 1 σ, 2 σ, and 3 σ confidence levels.

5×10^{-9} ergs s^{-1} cm^{-2}, and for a temperature of 55 eV, the limit decreased to 2×10^{-12} ergs s^{-1} cm^{-2}.

Figure 2 shows the allowed values of flux and plasma temperatures in two-dimensional parameter space for a thermal bremsstrahlung spectrum. The 3 σ lower limit on the X-ray temperature was ~0.5 keV, and the contours showed no upper limit for the temperature at the 3 σ confidence level, allowing values as high as 30 keV within 2 σ errors. This is consistent with the fact that *ROSAT* operates in a band between 0.1 and 2.4 keV, and thus it cannot satisfactorily predict temperature regimes above the operational energy band. This could also be explained by a double temperature model for the system, where the lower temperature is ~1 keV and the other temperature regime is at a higher temperature, ~10 keV, out of the *ROSAT* energy band. On the other hand, the X-ray flux in the 0.1–2.4 keV range was well constrained between 1–11 $\times 10^{-12}$ ergs cm^{-2} s^{-1}. A grid between $N_{\rm H}$ and temperature for the thermal bremsstrahlung model resulted in a similar parameter space unbounded in temperature, with $N_{\rm H}$ ranging between 0.5–7 $\times 10^{21}$ cm^{-2} (within 3 σ errors), consistent with the optical and UV results quoted above.

2.2. *Temporal Analysis*

In order to look for X-ray modulations with the known periods of the binary system, the background-subtracted count rates were determined by a similar procedure used for the spectral analysis. Subsequently, the photon arrival times were corrected to the solar system barycenter, and the X-ray counts were grouped in bins of 440 s to suppress the wobble period of the spacecraft. Most of the periods determined for CP Puppis were within a range of ~600 s. Thus, considering that the data span covered by the observation was about two spectroscopic or photometric periods and the binning procedure resulted in errors of about 440 s, we concluded that distinguishing between the photometric and spectroscopic periods would not be possible. Therefore, we used the spectroscopic period of Bianchini et al. (1990) to fold the X-ray count rates since it had

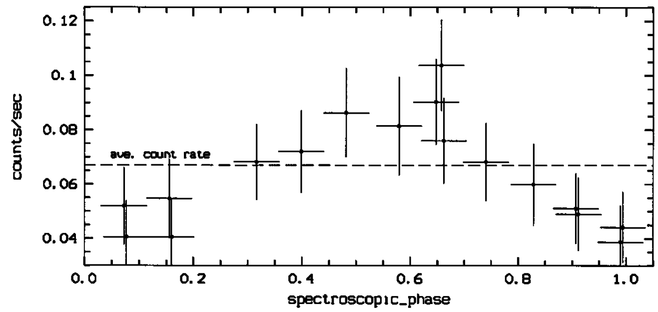

FIG. 3.—The X-ray light curve folded with the spectroscopic period determined by Bianchini et al. (1990). The x-axis shows the spectroscopic phase, where the white dwarf position is farthest away from the line of sight at phase 0.25 and closest to the line of sight at phase 0.75. The light curve is binned in 440 s, and the horizontal dashed line is the average count rate 0.067 counts s^{-1}. Horizontal error bars show the uncertainty caused by the binning procedure and do not include the propagated phase errors of ~0.10.

the most accurately determined ephemeris [T = (JD) 2445322.0180($\pm$ 0.0001) + 0.0613750E($\pm$ 0.0000001)]. As a result, we found modulations in the X-ray count rates with an amplitude variation of about 30%. The significance of the modulations were tested using the phase dispersion method described by Stellingwerf (1978) (F-test statistics for binned data sets) and found to be at the 3 σ confidence level. Figure 3 shows the X-ray light curve folded with this spectroscopic period where the white dwarf position is closest to the line of sight at phase 0.75 and farthest away at 0.25. The propagated phase error was ~0.10, and the error resulting from the binning procedure was ~0.042. A sine curve was fitted to the X-ray light curve, yielding an orbital phase of 0.56 $\pm$ 0.02 for the X-ray maximum with an amplitude 0.023 $\pm$ 0.002 counts s^{-1} above the average count rate. However, we caution that the real phase error of the maximum may be greater, since some of the reported spectroscopic ephemerides of the source are inconsistent with each other (White et al. 1993).

We also searched for hardness variations along the spectroscopic phase by separating the count rates as soft and hard X-rays at about 1 keV. The energy cut was made so that there were equal numbers of events in each light curve. The results did not show significant variation in the hardness ratio on timescales larger than the binning time of 440 s. Also, a power spectrum analysis for other possible amplitude variations did not give meaningful results (i.e., because of instrumental artifacts, the wobble period [~402 s] and its harmonics, etc.).

3. DISCUSSION

Although CP Puppis is a well-studied CV, the nature of the binary system and the magnetic properties of the white dwarf are still unclear. We examined the X-ray characteristics of the system for further evidence that could reveal the accretion geometry of the system.

Intermediate polar systems are observed to have hard X-ray spectra with high temperatures above ~1 keV and no soft X-ray component (Patterson 1994). The results from our spectral analysis (see § 2.1) are consistent with an intermediate polar interpretation. In addition, the spectral fits (see Table 1) imply an emission measure of $\sim 2 \times 10^{55}$ cm^{-3} for the X-ray–emitting region. The emission measure for a hot, totally ionized plasma (i.e., hot postshock regions) can be expressed as $\langle n_e^2 \rangle \times$ volume. Thus, assuming a cylindrical volume for an accretion column with a radius and a height $\sim 10^8$ cm, a simple calculation yields $n_e \sim 2.6 \times 10^{15}$ cm^{-3}, which is consistent with the densities expected in accretion columns (Cropper 1990). Using the relation $L_x \simeq GM\dot{M}/R$ and taking the derived value of the X-ray luminosity $\sim 10^{32}$ ergs s^{-1} for a white dwarf of mass 0.2–0.6 $M_\odot$ and $R \sim 10^9$ cm, the accretion rate $\dot{M}$ is calculated as $\sim 10^{15}$–10^{16} g s^{-1} for the system. The boundary layer theory for nonmagnetic CVs requires $\dot{M} \geq 10^{16}$ g s^{-1} for optically thick soft X-ray or EUV emission and $\dot{M} < 10^{16}$ g s^{-1} for optically thin hard X-ray emission (Patterson & Raymond 1985a, 1985b). The hard X-ray spectrum and the $\dot{M}$ derived for CP Puppis suggests that the X-ray–emitting region can be an optically thin boundary layer. However, several studies have found that there is no significant periodicity in the hard X-ray emission from boundary layers of CVs (Cordova & Mason 1984; Eracleous et al. 1991b). Considering the X-ray modulations detected and the low inclination angle of the system, boundary layer emission is not an attractive explanation for the X-ray emitting region.

In general, if the accretion is via a disk, the white dwarf is fed symmetrically and the primary X-ray emission should be independent of the orbital phase. Detection of X-ray modulations with the spectroscopic period, generally interpreted as the orbital period of the system, suggests that CP Puppis is a magnetic system. The shape of the detected modulation is sinusoidal. In addition, the X-ray count rates decrease by only 30% at the minimum with respect to the average count rate, indicating that either the emitting region is still in the line of sight (i.e., only partially occulted), or that the modulations are the result of absorption of X-rays. Orbital modulations in binary systems commonly result from occultation by the secondary or the disk. However, for low inclination systems such as CP Puppis, this is unlikely. The possibility of absorption by structures in the disk is not an attractive solution, since the hardness ratio does not show significant variation along the spectroscopic phase. Thus, the modulations should result from partial occultation of an X-ray–emitting region ($r \leq 10^9$ cm) by the white dwarf itself. Considering that the X-ray maximum coincides with minimum of the spectroscopic phase (~ 0.56) as in all intermediate polars (Hellier 1992) and that the line widths of He II lines modulate with this period (White et al. 1993), it is possible that the spectroscopic period (i.e., the shortest period determined for the system) is the spin period of the white dwarf itself. Moreover, the radial velocities derived from the spectroscopy result in unreasonable mass estimations for the white dwarf, which indicates that they do not necessarily represent the orbital motion (O'Donoghue et al. 1989; White et al. 1993; Bianchini & Friedjung 1995).

In conclusion, we favor an intermediate polar interpretation for the system, considering the X-ray modulations and the hard X-ray spectrum with unbounded plasma temperatures.

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