CHANDRA OBSERVATION OF V426 OPHIUCHI: WEIGHING THE EVIDENCE FOR A MAGNETIC WHITE DWARF

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ABSTRACT

We report the results of a 45 ks Chandra observation of the cataclysmic variable (CV) V426 Ophiuchus. The high-resolution spectrum from the high-energy transmission grating spectrometer is most consistent with a cooling flow model, placing V426 Oph among the group of CVs including U Gem and EX Hya. An uninterrupted light curve was also constructed, in which we detect a significant 4.2 hr modulation together with its first harmonic at 2.1 hr. Reanalysis of archival Ginga and ROSAT X-ray light curves also reveals modulations at periods consistent with 4.2 and/or 2.1 hr. Furthermore, optical photometry in V, simultaneous with the Chandra observation, indicates a modulation antcorrelated with the X-ray, and later more extensive R-band photometry finds a signal at ~2.1 hr. The earlier reported X-ray periods at ~0.5 and 1 hr appear to be only transient and quasi-periodic in nature. In contrast, the 4.2 hr period or its harmonic is stable and persistent in X-ray/optical data from 1988 to 2003. This periodicity is clearly distinct from the 6.85 hr orbit and could be due to the spin of the white dwarf. If this is the case, V426 Oph would be the first long-period intermediate polar with a ratio \( \frac{P_{\text{spin}}}{P_{\text{orb}}} \) of 0.6. However, this interpretation requires unreasonable values of magnetic field strength and mass accretion rate.

Subject headings: accretion, accretion disks — novae, cataclysmic variables — stars: individual (V426 Ophiuchi) — X-rays: binaries — X-rays: stars — white dwarfs

On-line material: color figures

1. INTRODUCTION

The cataclysmic variable (CV) V426 Oph has proven to be somewhat enigmatic, even though it is a bright (\( V = 11.5-13.4 \)) system that has been studied for a number of years since its discovery as a nova-like CV with an emission-line spectrum (Herbig 1960). A detailed spectroscopic study by Hessman (1988) revealed a K3 dwarf secondary in a 6.85 hr orbit with a white dwarf, with an inclination of 53° and at a distance of 200 pc. He concluded that this was a Z Cam type of dwarf nova with outbursts approximately every 22 days and some standstills in the light curve occurring about 1 mag fainter than the outburst brightness. This interpretation would indicate that V426 Oph is a system with such a high rate of mass transfer that it is very close to the upper limit for dwarf novae outbursts (Osaki 1996).

However, there are several observational clues that V426 Oph might also harbor a magnetic white dwarf. IUE observations show an unusually flat flux distribution in the UV, possibly indicating the truncation of a hot inner disk by a magnetic white dwarf (i.e., an intermediate polar [IP]), while the X-ray flux at quiescence is larger than for typical dwarf novae (Sz kody 1986). The emission lines show flaring activity and a phase shift from a location near the white dwarf (Hessman 1988). Most importantly, quasi-periodic variability has been seen in the optical and X-ray at a period near 30 minutes at a brightness comparable to standstill (Sz kody et al. 1990) and near 1, 2.5, or 4.5 hr in the X-ray at quiescent brightness (Sz kody 1986; Rosen et al. 1994; but see Hellier et al. 1990). While none of these periods could be positively identified as that of the rotation of the white dwarf to confirm the identification as an IP, the different brightness states combined with the lack of a long stretch of continuous observation have hampered attempts to resolve the origins of the observed periodicities.

With the advent of Chandra, high-resolution X-ray spectroscopy can be combined with uninterrupted long light curves to obtain much better information on the accreting regions of CVs. Results are now available for the dwarf novae U Gem (Sz kody et al. 2002) and WX Hya (Perna et al. 2003) and the IP EX Hya (Mauche et al. 2001), along with five other CVs (Mukai et al. 2003). One of the surprising results is how
similar the spectrum of the low-mass accretion disk system U Gem is to that of the IP EX Hya. Mukai et al. (2003) have found that the seven systems can be divided into two groups. The first group, which includes U Gem and EX Hya, shows a bremsstrahlung continuum with strong H and He-like ion emission, as well as ions from Fe xvi to Fe xxiv. The other group shows a harder X-ray continuum and little Fe L-shell emission. They suggest that the differences in these two groups may be due to differences in the accretion rate per unit area. In the first group, the energy is released as optically thin radiation in a steady state cooling flow. In the second, the line emission arises from a plasma photoionized by the hard continuum. To further explore these ideas and to try to resolve the nature of the accretion in V426 Oph, we obtained a Chandra observation at quiescence, together with simultaneous optical photometry and a single optical spectrum. We also obtained additional optical photometry (in quiescence) at a later date.

2. OBSERVATIONS

The Chandra observation of V426 Oph started at 21:40 UT on 2002 May 30 and ended at 11:02 UT the following day, with 45.15 ks of good exposure time on the source.

Differential photometry with respect to comparison star 1 in Misselt (1996) was accomplished with the Braeside Observatory (BO) 0.4 m reflector using an SITe 512 CCD camera and a Bessell V filter on 2002 May 31 UT. Integrations of 50 s duration for 4.4 hr provided simultaneous overlap of 3.5 hr with the Chandra data. Additional contemporaneous photometry was taken by the YALO 1 m telescope at Cerro Tololo Inter-American Observatory (CTIO). Using comparison stars 13, 14, and 15 (Henden & Honeycutt 1997), the V magnitude of V426 Oph was determined to be 12.79 ± 0.15 (YALO), and using star 1, it was determined to be between 12.7 and 12.9 (BO), consistent with a quiescent state. Observations on the AAVSO and VSNET Web sites show that the previous outburst (V ~ 11) occurred on May 13–14.

On 2003 July 25 and 28 UT longer duration differential photometry in Harris R (4.0 hr) and I (6.3 hr) was obtained at Manastash Ridge Observatory (MRO), with its 0.75 m reflector. The exposure times were 30 and 10 s, respectively.

A single low-resolution optical spectrum (6 Å) was also obtained during the Chandra observation, using the Double Imaging Spectrograph (DIS) on the 3.5 m Apache Point Observatory (APO) telescope, providing spectral coverage from 3800 to 5200 Å and from 6000 to 8000 Å (Fig. 1). This spectrum also confirms that V426 Oph was at a quiescent state, exhibiting characteristic broad Balmer emission lines. All the observations are summarized in Table 1.

3. X-RAY SPECTRAL ANALYSES AND RESULTS

We reprocessed our data starting from the level 1.5 event file, as advised by the Chandra X-Ray Center. To check for intervals of high background, we constructed an off-source light curve, but as none were found, we were able to use the standard good time intervals as supplied. We chose to remove afterglow detection, as for these data it may have led to exclusion of good events. We applied destreaking to the S4 chip, to produce a clean level 2 event file, at the same time restricting our energy range to 0.3–10.0 keV, where calibrations are most reliable. We used tigextract to derive the type II pulse-height analyzer (PHA) file. To achieve maximum signal-to-noise ratio (S/N), we opted to add +1 and −1 grating orders, for both the medium- (MEG) and high-energy (HEG) grating spectra, creating type I PHA files. The script add_grating_orders also generated the appropriate grating response files for these co-added spectra. For high-resolution spectra it is generally advised to include the systematic variations

| UT Date | Observation | UT Time | Comments         |
|---------|-------------|---------|------------------|
| 2002 May 30, 31 | Chandra: ACIS-S/HETGS | 21:40–11:02 | 45.15 ks good time |
| 2002 May 31 | BO | 07:04–11:30 | V filter photometry |
| 2002 May 30 | CTIO: YALO | 08:17–09:34 | V filter photometry |
| 2002 May 31 | APO: DIS | 06:20–06:25 | Spectrum |
| 2003 Jul 25 | MRO | 06:00–10:04 | R filter photometry |
| 2003 Jul 28 | MRO | 04:35–10:51 | I filter photometry |
sensitivity degradation of the ACIS chips (due to a buildup of absorbing material) as an independent model component. However, we found that our S/N was insufficient to constrain the individual elemental abundances of the material. Instead, we corrected the ancillary response files (ARFs) for the expected absorption at the time of observation, based on the nominal elemental composition. The HEG and MEG spectra are shown in Figure 2.

3.1. Cooling Flow Fits

First, in order to compare to earlier work, we fitted a limited, mostly line-free section of our spectrum from 2.0 to 5.0 keV with a simple thermal bremsstrahlung plus absorption model. Our best fit yielded a poorly constrained column of \( N_H = (0.57 \pm 0.54) \times 10^{22} \) cm\(^{-2}\) and \( kT_{br} = 20 \pm 12 \) keV, with a reduced \( \chi^2 \) of 0.51 for 827 degrees of freedom (dof). From both this and simple inspection of the spectra we can see that V426 Oph belongs to the first group of CVs identified by Mukai et al. (2003), namely, those best fitted by a cooling flow model, with a maximum temperature nearer 20 than 80 keV.

We therefore proceeded to attempt a global cooling flow fit to our high-resolution spectra, using XSPEC\(^1\) with the same model as Mukai et al. (2003). A suitable background file was obtained with the CIAO\(^2\) _tg_bkg script. We used the FTOOL (see footnote 1) _grpPHA to associate the appropriate redistribution matrix file (RMF), ARF, and background files with the co-added first-order grating PHA files. We also used _grpPHA to group the spectra both simply binning by 4, then with binning to give \( \geq 10 \) counts bin\(^{-1}\). The S/N of our spectra is such that we opted to use the \( \geq 10 \) counts bin\(^{-1}\) and used \( \chi^2 \) statistics for fitting.

In order to attain the best constraints possible, we performed joint fits to both the HEG and MEG spectra, over wavelength ranges of 1.7–15 and 2.2–20 Å, respectively, where counts are most adequate for fitting. Initially, we constrained the column to the \( N_H = 0.7 \times 10^{22}, 1.6 \times 10^{22}, \) and \( 0.28 \times 10^{22} \) cm\(^{-2}\)

\(^1\) The X-ray software packages XSPEC (spectral) and FTOOLS (general) are both available from http://heasarc.gsfc.nasa.gov/docs/software/lheasoft.

\(^2\) The Chandra data analysis software, CIAO, is available from http://asc.harvard.edu/ciao.
found by EXOSAT, Ginga, and ROSAT observations, respectively (Szksody 1986; Szksody et al. 1990; Rosen et al. 1994). The intermediate column from the EXOSAT spectrum gave the best fit, with $\chi^2 = 0.55$. Indeed, with the column left free we achieved a best fit for $N_{HI} = 1.0 \times 10^{22}$ cm$^{-2}$, giving a $\chi^2 = 0.47$ for 1718 dof. The parameters for these four fits along with the corresponding 2–10 keV fluxes are summarized in Table 2, and the best model fit is overplotted in Figure 2. As found for WX Hya (Perna et al. 2003), we still find that our best-fit model fails to fit any of the prominent lines at $\geq 13$ Å, notably O viii. Even setting low $T = 0.08$ keV, the minimum allowed in XSPEC, did not enhance these line fluxes noticeably.

Hence, we also experimented with several variations on the cooling flow model using a radiative shock wave code (Raymond 1979). We chose a shock speed of 4250 km s$^{-1}$, to give a desired temperature of 22 keV, and complete electron-ion thermal equilibration. In this case, we compared the model results to specific line fluxes and ratios. IDL routines were used to extract background-subtracted and binned data in wavelength and flux units for both HEG and MEG. To estimate line fluxes for the stronger lines, we used the IRAF$^3$ splot task to sum the flux over the width of the line above a continuum estimated by hand. For the weaker lines, important for line diagnostics (see next section), we instead used Gaussian fits to short segments of the MEG spectrum using binning with $S/N \geq 2$ bin$^{-1}$, constraining the line widths to be the same. The various line measurements are presented in Table 3.

The shock code allows us to examine the effects of photoionization. We can also make the flow nearly isobaric or nearly isochoric by adjusting the assumed magnetic field. These experiments showed that the line ratios are essentially independent of whether the flow is isobaric or isochoric, as expected, except that photoionization is relatively more important in the constant-density case. Radiation from the cooling gas does affect the ionization state at the lower temperatures, but even for constant-density cooling the effects are only 10%–20% reductions in ratios such as O viii/Fe xxv. A comparison of line intensities (Table 3) indicates that $N_{HI} = 0.28 \times 10^{22}$ cm$^{-2}$ best matches the O viii intensity, while $N_{HI} = 0.57 \times 10^{22}$ cm$^{-2}$ does better for Ne x, Mg xii, and Fe xvii. Within the restriction of the cooling flow model either value of $N_{HI}$ provides an adequate fit.

We also examined the effects of thermal conduction. As found by Perna et al. (2003) for the case of WX Hya, thermal conduction transports energy to the cooler part of the flow, drastically increasing the strength of lines such as O viii and Ne x. Even saturated thermal conduction (Cowie & McKee 1977) yields large ratios of low-$T$ to high-$T$ lines unless the conduction is strongly suppressed.

### Table 2

**Critical Parameters for Cooling Flow Fits**

| $N_{HI}$ (10$^{22}$ cm$^{-2}$) | Low $T$ (keV) | High $T$ (keV) | Line Width at 6 keV $\sigma_v$ (km s$^{-1}$) | $M$ (M$_{\odot}$ yr$^{-1}$) | $\chi^2$ | 2–10 keV Flux (10$^{-11}$ ergs cm$^{-2}$ s$^{-1}$) |
|-----------------------|--------------|----------------|---------------------------------|------------------------------|--------|-------------------------------|
| 0.28*………………… | 0.9 ± 1.0   | 24.0 ± 0.9     | 600 ± 100                       | (9.6 ± 0.8) x 10$^{-12}$     | 0.95   | 1.8 ± 0.2                     |
| 0.7*………………….. | 1.1 ± 1.0   | 24.2 ± 0.9     | 500 ± 100                       | (1.3 ± 0.2) x 10$^{-11}$     | 0.55   | 2.6 ± 0.4                     |
| 1.6*…………………. | 1.1 ± 2.4   | 20.0 ± 1.1     | 600 ± 400                       | (1.9 ± 0.5) x 10$^{-11}$     | 0.60   | 3.6 ± 0.9                     |
| 1.0 ± 0.1………….. | 1.0 ± 0.2   | 24.2 ± 0.4     | 600 ± 100                       | (1.6 ± 0.2) x 10$^{-11}$     | 0.47   | 3.0 ± 0.3                     |

* Parameter values without uncertainties are fixed.

### Table 3

**Line Summary**

| LINE      | REST $\lambda$ (Å) | MEG FLUX (10$^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | HEG FLUX (10$^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | $N_{HI} = 0.28 \times 10^{22}$ cm$^{-2}$ | $N_{HI} = 0.57 \times 10^{22}$ cm$^{-2}$ |
|-----------|--------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Fe xxiv   | 1.783              | …                              | 166                             | 128                             | 127                             |
| Fe xxv    | 1.850              | …                              | 191                             | 216                             | 214                             |
| S xvi     | 4.729              | 1616                           | 20                              | 26.2                            | 24.6                            |
| Si xiv    | 6.180, 6.187       | 1311                           | 11                              | 30.2                            | 26.6                            |
| Si xiii   | 6.647–6.688        | 6.89                           | 9                               | 17.7                            | 15.2                            |
| Mg xii    | 8.419, 8.424       | 3.53                           | 3.4                             | 7.31                            | 5.52                            |
| Fe xxv    | 10.620–10.662      | 3.1                            | 8.7                             | 23.2*                           | 15.1*                           |
| Fe xxiv   | 11.014             | …                              | 3.2                             | 8.27                            | 5.10                            |
| Fe xxv    | 11.172, 11.189     | 2.2                            | 4.4                             | 27.0                            | 14.8                            |
| Fe xxv    | 11.429             | 2.3                            | 1.5                             | 10.0                            | 5.33                            |
| Fe xxvii  | 11.740             | 1.6                            | …                               | 13.7                            | 6.86                            |
| Fe xxii   | 11.771             | 0.3                            | …                               | 6.41                            | 3.20                            |
| Ne x      | 12.128             | 3.1                            | …                               | 12.4                            | 6.18                            |
| Fe xv     | 15.012             | 4.2                            | …                               | 7.5                             | 2.88                            |
| Fe xvii   | 16.774             | 2.8                            | …                               | 3.35                            | 0.73                            |
| Fe xvii   | 17.051             | 3.4                            | …                               | 3.51                            | 0.72                            |
| Fe xvii   | 17.098             | <2.8                           | …                               | 2.66                            | 0.56                            |
| O viii    | 18.970             | 5.9                            | …                               | 17.7                            | 3.29                            |

* Models are with the blend of Fe xxiv 1210.620, 10.662.
3.2. Line Diagnostics

Mauche et al. (2001, 2004) have shown that the ratios of various Fe ion species can be a useful diagnostic for the density of the line-emitting plasma. Using our Gaussian line fits, we have calculated these ratios, which are presented alongside those of the Sun and EX Hya (from Mauche et al. 2001) in Table 4. Unfortunately, with our low S/N, the ratios for V426 Oph are only upper limits, which are consistent with EX Hya, and only differ with the Sun in the ratios involving the 17.10 Å line. Thus, they do not provide useful diagnostics for the plasma densities or temperatures.

### Table 4

| Ratio       | Sun   | EX Hya | V426 Oph |
|-------------|-------|--------|----------|
| 11.92/11.77 | 1.06  | <2     |
| 15.01/16.78 | 1.23  | <3.9   |
| 15.26/16.78 | 0.50  | <2.0   |
| 15.45/16.78 | 0.05  | <0.16  |
| 17.05/16.78 | 1.65  | 1.8    |
| 17.10/16.78 | 0.08  | <1.0   |
| 15.26/15.01 | 0.41  | <0.8   |
| 17.10/17.05 | 0.05  | <0.8   |

4. TEMPORAL ANALYSES AND RESULTS

4.1. Chandra plus Archival ROSAT and Ginga Data

The core of the Chandra zeroth-order image is significantly piled up (~50%); hence, this could not be used to construct a broadband light curve. Instead, an event file was created from our reprocessed level 2 file, selecting only events in the 1.5–9.0 keV range, which corresponds to the peak of the source spectrum, hence minimizing background contributions. Extraction apertures were chosen to include only the wings of the zeroth-order image point-spread function (PSF), plus the brightest parts of the first-order spectrum landing on the S3 and S4 chips; the areas close to chip boundaries were specifically excluded, since they have a reduced exposure fraction due to the spacecraft dither. As a cross-check, a lower S/N light curve using solely the PSF wings was subjected to the same analysis; fully consistent results were found. The CIAO lightcurve tool was used to extract a light curve with 200 s bins, with background subtraction based on corresponding regions on each side of the dispersed spectra; this is plotted in the top panel of Figure 3.

To search for periodicities in the light curve, both a Lomb-Scargle (Scargle 1982) and phase dispersion minimization (Stellingwerf 1978) periodogram were calculated; the former is most sensitive to sinusoid modulations, while the latter is better for periodic signals with more irregular morphology. Significant peaks (>99.99% level) were found at two frequencies corresponding to 2.13 and 4.31 hr, as shown in the bottom left panel of Figure 3. We then directly fitted the light curve with two sinusoids plus a second-order polynomial to take into account any longer term trends. The 2.1 hr period is close enough to being the first harmonic of the 4.3 hr that we also constrained the periods to these values, leading to period determinations of 4.23 ± 0.05 and 2.12 ± 0.02 hr. Indeed, the latter periods do produce a good fit to the data (see Fig. 3, top panel), with a reduced χ² = 3.03 as compared to χ² = 3.01 for the unconstrained. The total peak-to-peak amplitude is large at 65% ± 5%. Interestingly, these two periods are close
to two of the candidate periods found by Rosen et al. (1994) in their ROSAT light curve. However, we note that we found no evidence for signals at either of the putative short periods, \( /C24 60 \) or \( /C24 30 \) minutes (Szkody 1986; Szkody et al. 1990), the binary orbit at 6.85 hr (Hessman 1988), nor the 1.25 hr ROSAT candidate. Neither did we find signals at either of the spacecraft dither periods of 16.67 or 11.78 minutes, implying that we successfully excluded regions of reduced exposure fraction.

To compare directly to the ROSAT data, we extracted the archival 200 s binned PSPC light curve from the HEASARC. The seven spectral bands were co-added to give us maximal S/N. We examined whether these data could also be fitted by the periods we found in the high-S/N uninterrupted Chandra light curve. A free fit found a period of \( 4.43 \pm 0.08 \) hr with \( \chi^2 = 3.24 \), consistent with that found by Rosen et al. (1994), while if we constrained the period to 4.23 hr, the fit was not significantly worse with \( \chi^2 = 3.49 \). We also attempted a double-sinusoid fit, as for the morphology seen in the Chandra data, but here the better fit is with the single sinusoid. Both single-sinusoid fits are shown overlaid on the data in Figure 4.

The Ginga data have a long time base (72 hr) but, like ROSAT, interrupted sampling due to Earth occultations. We obtained 64 s binned light curves from the HEASARC, for the 2–6 keV range (where the spectrum peaks and S/N is best), and then applied a quadratic detrend to remove longer term variations. The periodograms revealed evidence of significant flickering, but peaks close to the 4.2 hr and its harmonic were by far the most significant. Once again a constrained double-sinusoid fit yielded periods of \( 2.105 \pm 0.005 \) and \( 4.210 \pm 0.010 \) hr, consistent with the Chandra data. However, the fit has \( \chi^2 = 15 \) for the 863 dof, probably as a result of the extensive flickering, but also the morphology of the profile. In Figure 5 we show folded and phase-binned data, where the binning should average out the effects of flickering. Although the modulation is modulated primarily at the harmonic (2.1 hr), the differing morphology of the two humps in the lower fold accounts for the significance of the 4.2 hr signal.

Hellier et al. (1990) reexamined the EXOSAT data in which Szkody (1986) detected a \( \sim 60 \) minute periodicity and suggested an IP classification for V426 Oph. They concluded that

the modulation was not in fact statistically significant. Moreover, they noted that the modulation on the white dwarf’s spin should be greatest at low energies, since it is due to absorption effects. Hence, the hardness ratio (hard/soft flux) should be anticorrelated with the total flux. We have investigated the energy dependence of our significant 4.23 hr modulation. We extracted 800 s binned light curves in two energy bands, 0.3–2.5 keV for the soft and 2.5–6.0 keV for the hard, which approximately splits the counts evenly. In both bands the modulation is apparent, and indeed the signals are significant at \( \geq 99.95\% \) confidence level. Although the percentage amplitudes are different, with a hard-band peak-to-peak amplitude of \( 59\% \pm 5\% \) versus \( 73\% \pm 6\% \) in the soft, the hardness ratio values are consistent with a constant, the signal at 4.23 hr being merely 5% confidence. We also applied a Spearman rank correlation test comparing the hardness ratio with the full-band light curve. This yielded the expected anticorrelation although only at the 2 \( \sigma \) level.

4.2. Optical Results

We succeeded in obtaining optical photometry that overlaps the Chandra X-ray by 3.5 hr at the end of the observation.
This light curve is plotted for ease of comparison in the top panel of Figure 3. Although the simultaneous coverage is limited, it is clear that the optical variability is in general anti-correlated with the X-ray and that it also exhibits a 4.2 hr periodicity. A Spearman rank correlation test yields an anticorrelation at the 3.7 σ level.

Further quiescent light curves were obtained in 2003 July; the light curves, Lomb-Scargle periodograms, and folded and phase-binned data are presented in Figures 6 and 7. Once again fitting sinusoids, we find a modulation in the R data at a period consistent with the first harmonic of the 4.2 hr in the X-ray, 2.18 ± 0.06 hr. The power spectrum also shows a number of significant peaks in the 20–50 minute range, indicative of flickering. In the I band, the best-fit period is 3.10 ± 0.03 hr, similar to half that of the orbit, as expected for an ellipsoidal modulation. Indeed, adding a second sinusoid at double the period does improve the fit. However, in neither case are the periods formally consistent with those derived by Hessman (1988). On the other hand, the light curve does not quite span a full orbit, and together with the irregular/quasi-periodic flickering, this may well account for the discrepancy. Finally, removing the 3.1 hr sinusoid from the I data, we find that a significant modulation (>99.0% confidence) remains at 28.5 ± 0.1 minutes, which is in agreement with the X-ray (from Ginga) and optical periods presented by Szkody et al. (1990). Subdividing the light curve into four parts, we find that the amplitudes are comparable at both the minima and maxima of the 3.10 hr cycle, although the frequency does shift, indicating that this too is most likely only quasi-periodic flickering.

5. EVIDENCE FOR A MAGNETIC WHITE DWARF

5.1. Temporal

The classic signature of an IP is the presence of two or more coherent periodic modulations corresponding to the binary orbit, white dwarf spin, and possibly their beat. In Table 5 we summarize all the periods reported for V426 Oph in the literature and from our own (re)analyses. The orbital period was definitively measured by Hessman (1988), whereas the existence of a second periodicity, the spin period, has been reported, revised, and disputed over time (see Szkody 1986; Hellier et al. 1990; Szkody et al. 1990; Rosen et al. 1994). The candidates (at ~0.5 and 1 hr) are not, however, present in our long, uninterrupted Chandra data set. We have found such periodicities in consecutive nights of optical photometry, but neither the modulation nor period is stable, the latter differing by ~20% from one night to the next. It seems most likely that these short periods are transient quasi-periodic behavior, possibly fairly stable flickering.

Instead, we have now found another, stronger candidate for the white dwarf spin period, at a surprisingly long period of ~4.2 hr. A similar periodicity (4.5 hr) was first reported in the ROSAT observation, although this data set has rather sparse sampling. In our Chandra light curve we have found a prominent modulation at 4.23 hr, with a probable first harmonic at
While a white dwarf spin is the easiest explanation for the 2.12 hr, essentially consistent with the ROSAT result. Our reanalysis of the Ginga data set has also uncovered the same period (to within the larger Chandra ~1% uncertainties), with the first harmonic dominating. Hence, in X-rays either the 4.2 hr or its first harmonic appear persistently in observations from 1988 to 2002. Furthermore, the same periodicities are present in the optical ($V$ and $R$ bands), in both 2002 (simultaneous with the Chandra observations) and 2003. From the simultaneous observation we found a $180^\circ$ phase offset between X-ray and optical modulations on the 4.23 hr period (note that a similar result was evident in the 28 minute modulation observed in simultaneous Ginga and optical data; Szkody et al. 1990); this is consistent with the effects of a reprocessed beam. Unfortunately, none of the X-ray data have sufficient S/N to test conclusively whether the modulation exhibits the expected energy dependence, but neither do they exclude that possibility. We should also note that the 4.2 hr signal is not apparent in a reanalysis of the 1988 optical spectroscopy (R. Hessman 2004, private communication). However, in at least one other case, EX Hya during outburst (Hellier et al. 1989), it appears that any signal on the white dwarf spin, emitted from the magnetic disruption/corotation radius, is washed out by the line emission from the outer disk.

While a white dwarf spin is the easiest explanation for the 4.2 hr period, the physical origin of this long $P_{\text{spin}}$ is problematic. First, if we assume that V426 Oph possesses a fairly typical field for an IP (1–10 MG) and mass transfer rate of $10^{-9}$ to $10^{-10} M_\odot$ yr$^{-1}$, then the Alfvén radius is $\sim 2 \times 10^{10}$ cm for spherical accretion, or half that in the disk case. Depending on the actual values used, this radius could easily be smaller than both the radius of closest approach of the stream from the secondary and that of the initial ring that would form; hence, formation of a disk is certainly possible (Warner 1995, p. 57). However, if we also assume that the corotation radius is similar, one requires a $P_{\text{spin}} \approx 10$ minutes, while $P_{\text{spin}} = 4.23$ hr would place the corotation radius outside the Roche lobe ($R_{\text{co}} \geq 9.0 \times 10^{10}$ cm as compared to the white dwarf–$L_1$ point separation $b \geq 7.8 \times 10^{10}$ cm). Even taking $P_{\text{spin}} = 2.1$ hr, which is in itself difficult to reconcile with the data, leads to a corotation radius comparable to the size of a typical disk; hence, the entire disk would be non-Keplerian and in a transitional state to full magnetic dominance. In addition, for diskless accretion the size of the magnetic moment and in turn the surface field are unreasonable; even taking $P_{\text{spin}} = 2.1$ hr, we estimate $B_1 = 850 (M/10^{-9} M_\odot$ yr$^{-1}$) MG.

An alternate model was put forward by King & Wynn (1999) to account for the spin-orbit equilibrium at $P_{\text{spin}}/P_{\text{orb}} = 0.68$ of the short-period IP EX Hya. In this instance, the magnetic moment is such that the corotation radius is in fact comparable with the distance to the $L_1$ point. Norton et al. (2004) have more recently extended this work in an attempt to explain
the entire range of spin-orbit equilibria seen for IPs. From their Figure 2, we see that at $P_{\text{orb}} \equiv 7$ hr and $P_{\text{spin}}/P_{\text{orb}} = 0.6$, we are within the uncertainties of the model (which does assume $M_1 = 0.7 M_\odot$ in any case) in obtaining a suitable equilibrium. However, a longer period (larger) system like V426 Oph requires $\mu \sim 10^{35}$ G cm$^{-3}$, or equivalently $B_1 \sim 300$ MG, comparable to the most magnetic polars.

An alternative nonmagnetic origin for the 4.23 hr modulation could be stream overflow, which brightens a particular region of the disk. From Tables 3 and 4 in Hessman (1988), the Keplerian period at the outer radius of the disk $r_J$ is $P_{\text{Kep}}(r_J)/P_{\text{orb}} = (1 + q)(r_J/a)^{3/2} = 0.07$, which is much too small. Conversely, to obtain a ratio of 0.62 would require $q \sim 0.007$, again highly implausible.

A final possibility is that we could be seeing V426 Oph in a nonequilibrium state, where $M$ was greatly reduced on Myr timescales compared to what we now observe. However, this is an ad hoc assumption that has no satisfactory explanation.

### 5.2. Spectral

It is instructive to compare our spectral results on V426 Oph with those of previous X-ray observations and Chandra results on other CVs. Given its Z Cam classification, the mass transfer rate for V426 Oph should be high. Instead, the value $\sim 2 \times 10^{-11}$ $M_\odot$ yr$^{-1}$ places it in the middle of the five CVs that Mukai et al. (2003) fit with cooling flows. Moreover, we may compare this to an estimate of the mass accretion rate from the X-ray luminosity, $L_X (2-10$ keV) $= 8 \times 10^{33}$ ergs s$^{-1}$, which yields $M = 7 \times 10^{-12} M_\odot$ yr$^{-1}$, assuming that half of the energy is released as X-rays. But as Perna et al. (2003) comment in the case of WX Hyi (where the cooling flow yields $M$ a factor of 5 less than obtained from fits to the UV continuum), these X-ray fits give $M$ in the outer disk, which may well not be accreting during quiescence, as the disk builds up for the next outburst.

As previously noted, for a thermal bremsstrahlung fit ($N_{\text{H}} = 0.7 \times 10^{22}$ cm$^{-2}$, $kT_{\text{br}} = 32$ keV), the EXOSAT data yielded a high $2-10$ keV flux of $(8-8.4) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, suggesting a magnetic system. For a thermal spectrum plus Fe line at 6.8 keV, the Ginga data gave a flux value a factor of 2 lower, together with an even higher column ($1.6 \times 10^{22}$ cm$^{-2}$) and a lower temperature ($kT_{\text{br}} = 14$ keV). However, at the time of the Ginga observation V426 Oph was in a standstill state, close to outburst; hence, the lower flux and higher column can be expected. Our Chandra observation provides another look at the quiescent state, but we have found a column and temperature intermediate between EXOSAT and Ginga, $1.0 \times 10^{22}$ cm$^{-2}$ and $\sim 20$ keV, respectively. Moreover, the flux given by the best cooling flow fit, $\sim 3 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ (2–10 keV), is much lower than either of the past satellite observations. Thus, it appears difficult to directly compare data taken at different outburst states and with different instrument sensitivities.

If V426 Oph contains a magnetic white dwarf, the X-rays should arise from a cooling region behind the accretion shock, and a shock model for the emission lines is appropriate. Mukai et al. (2003) found that polar spectra were better fitted by models of photoionized plasma. Both polars and IPs must have emission from both the cooling zone behind the accretion shock and the photoionized gas upstream. The difference may be that polars have much narrower accretion columns and higher densities, and the recombination radiation from the photoionized accretion stream scales as the density squared. The emission per unit accreted mass from the shock,
on the other hand, is independent of density. Ratios of lines from 3s and 3d levels of iron ions are a good diagnostic for photoionized plasmas (Liedahl et al. 1990), and the ratios of the Fe xvii lines and ratios of Fe xxiv lines confirm that the emission from V426 Oph originates in a collisionally ionized plasma.

The match between observed fluxes and the shock model is far from perfect, but it is close enough to indicate that the shock structure is basically correct. In particular, thermal conduction would tend to produce overly strong O viii and Fe xvii lines unless it is suppressed by magnetic fields or turbulence. It is probably not advisable to make too much of the differences between the shock model and the observations at present because accretion shocks are thermally unstable (Langer et al. 1982; Imamura et al. 1984). The instability and secondary shocks can modify the emission-line spectrum at the factor of 2 level (Innes 1992).

6. CONCLUSIONS

Our analysis of a long uninterrupted Chandra X-ray light curve of V426 Oph, together with optical photometry and reanalysis of archival X-ray data, has revealed a persistent period at 4.2 hr, unrelated to the known orbit. In contrast, we find that previous candidate spin periods seen in past X-ray studies at ~0.5 and 1 hr are most likely nonpersistent quasi-periodic oscillations (QPOs). Our simultaneous X-ray/optical photometry shows that the modulations are anticorrelated and therefore the variations must arise from different parts of the system, possibly as a result of the reprocessing of beamed X-radiation. Indeed, the period of 4.2 hr is easiest to interpret as the rotation of the white dwarf, implying that V426 Oph is, after all, an IP and making it the first long-period IP with a similar spin-orbit equilibrium to EX Hya, \( P_{\text{spin}}/P_{\text{orb}} \approx 0.6 \). However, this interpretation leads to problems with the magnetic field strengths and mass accretion rates that are typical for IPs.

The high-resolution spectrum places V426 Oph as a member of the group of CVs, including U Gem and EX Hya, where the X-rays are emitted from a cooling flow. Indeed, more detailed modeling of the line fluxes for such a shock model lends further support to the magnetic CV interpretation.

With the death of Bob Fried on November 13 2003, the CV community has lost an active and dedicated observer. We gratefully acknowledge his years of collaboration.

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REFERENCES

Cowie, L. L., & McKee, C. F. 1977, ApJ, 211, 135
Hellier, C., Mason, K. O., Smale, A. P., Corbet, R. H. D., O’Donoghue, D.,
Barrett, P. E., & Warner, B. 1989, MNRAS, 238, 1107
Hellier, C., O’Donoghue, D., Buckley, D., & Norton, A. 1990, MNRAS, 242, 329
Henden, A. A., & Honeycutt, R. K. 1997, PASP, 109, 441
Herbig, G. H. 1960, ApJ, 131, 632
Hessman, F. V. 1988, A&AS, 72, 515
Imamura, J., Wolff, M., & Durisen, R. 1984, ApJ, 276, 667
Innes, D. 1992, A&A, 256, 660
King, A. R., & Wynn, G. A. 1999, MNRAS, 310, 203
Langer, S., Channugam, C., & Shaviv, G. 1982, ApJ, 258, 289
Liedahl, D., Kahn, S., Osterheld, A., & Goldstein, W. 1990, ApJ, 350, L37
Mauche, C. W., Liedahl, D. A., & Fournier, K. B. 2001, ApJ, 560, 992
———. 2004, in IAU Colloq. 190, Magnetic Cataclysmic Variables, ed. M.
Cropper & S. Vrielmann (ASP Conf. Ser. 315; San Francisco: ASP), in press
Misselt, K. A. 1996, PASP, 108, 146
Mukai, K., Kinkhabwala, A., Peterson, J. R., Kahn, S. M., & Paerels, F. 2003,
ApJ, 586, L77
Norton, A., Somerscales, R., & Wynn, G. 2004, in IAU Colloq. 190, Magnetic
Cataclysmic Variables, ed. M. Cropper & S. Vrielmann (ASP Conf. Ser. 315;
San Francisco: ASP), in press
Osaki, Y. 1996, PASP, 108, 39
Perna, R., McDowell, J., Menou, K., Raymond, J., & Medvedev, M. V. 2003,
ApJ, 598, 545
Raymond, J. C. 1979, ApJS, 39, 1
Rosen, S. R., Clayton, K. L., Osborne, J. P., & McGale, P. A. 1994, MNRAS,
269, 913
Scargle, J. D. 1982, ApJ, 263, 835
Stellingwerf, R. F. 1978, ApJ, 224, 953
Szkody, P. 1986, ApJ, 301, L29
Szkody, P., Kii, T., & Osaki, Y. 1990, AJ, 100, 546
Szkody, P., Nishikida, K., Raymond, J. C., Seth, A., Hoard, D. W., Long, K. S.,
& Sion, E. M. 2002, ApJ, 574, 942
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ.
Press)