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ON MARTELL AND KAITCHUCK'S MODEL FOR THE INTERMEDIATE POLAR FO AQUARII

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ABSTRACT

Martell and Kaitchuck have proposed that FO Aqr is a low-inclination system, rather than an eclipsing system, as recently claimed; and that the dominant periodicity (21 minutes) is the beat period rather than the white dwarf spin period, as is commonly supposed. We show that both proposals make it harder to understand the observations of this star, while there is no substantive evidence in their favor.

Subject headings: binaries: general — stars: individual (FO Aquarii)

1. INTRODUCTION

The intermediate polar class of magnetic cataclysmic variables is characterized by a coherent X-ray periodicity shorter than the orbital period of the binary. Although X-ray modulations may also be seen at the orbital and beat periods, it has previously been regarded as axiomatic that the dominant X-ray modulation reveals the spin period of the magnetic white dwarf.

This picture has recently been challenged by Martell & Kaitchuck (1991, hereafter MK) in a paper reporting optical spectroscopy of FO Aquarii. Although this star possesses the largest-amplitude X-ray modulation of any intermediate polar (at 21 minutes), they claim that this modulation is at the beat period between the orbital and spin periods, and that the X-ray modulation at the spin period is much weaker.

MK arrive at their conclusion from a consideration of optical spectroscopy. They conclude that emission-line changes over the 21 minute cycle are best explained by reprocessing of X-ray flux by a wind arising from near the secondary star, fixed in the binary frame. Hence, they claim, the 21 minute period must be the beat period, with the illuminating X-ray flux varying with a spin period of 19.5 minutes. Since this period is not seen directly in the X-ray light curves, they conclude that the X-ray beam must be confined to the orbital plane and that the system must be seen face-on. To sustain this model, they attempt to refute the claim by Hellier, Mason & Cropper (1989, hereafter HMC89) that the secondary eclipses part of the accretion disk, which would imply a system inclination of $\sim 70°$.

Since eclipsing systems provide valuable diagnostics, this is an important issue, particularly in FO Aqr, where the eclipse bears on several issues of current debate. First, several papers have questioned whether intermediate polars possess accretion disks (e.g., Hameury, King, & Lasota 1986; King & Lasota 1991), and the eclipse of the accretion flow provides a direct test (see Hellier 1991). Second, a possible, but disputed, cause of the X-ray orbital modulation seen in FO Aqr (Norton et al. 1990) is obscuration of the white dwarf by disk structure. Since this would require a high system inclination, the presence or absence of an eclipse is crucial. Last, the eclipse locates the phase of the secondary, determining the phasing of the orbital and beat period modulations, which is vital in deducing their origin (e.g., Osborne & Mukai 1989). In view of this importance, we give a detailed response to the MK arguments for doubting the reality of the eclipse and then proceed to their reasons for regarding the 21 minute period as the beat period in this system.

2. COMPARISON OF DATA

Since MK base their conclusions on their extensive optical spectroscopy, the most relevant comparison is with HMC89 and the more comprehensive analysis of the same data reported in Hellier, Mason, & Cropper (1990, hereafter HMC90—we refer to both papers collectively as HMC). Having studied the reports of HMC and MK, particularly the gray-scale representations, we judge that there are few significant differences between the two data sets. The difference between MK, on the one hand, and HMC and this paper, on the other, is one of interpretation of the data, not of the results obtained.

We do note, however, that the HMC data have superior spectral and temporal resolution. First, the spectral resolution of the HMC data is 1.2 Å (~ 75 km s^{-1} at Hβ) versus 2.5 Å (~ 150 km s^{-1}) for MK; compare this to the small amplitude ($K < 50$ km s^{-1}) of the radial velocity modulations under discussion. Second, MK used 200 s exposures (or one-sixth of the 21 minute cycle) for individual spectra. Such long integration times will smear out the radial velocity modulations. In comparison, HMC used 60 s exposures (1/21 of the cycle) and so were better able to resolve the variations (see § 4).

3. IS THERE AN ECLIPSE?

HMC89 reported features of the emission lines in FO Aqr which they explained as an eclipse of the accretion disk by the secondary star. When the optical orbital modulation is at minimum (which commonly occurs at the inferior conjunction of the secondary in these stars), the V/R ratio of the lines changes rapidly. First the line becomes redder, and then it rapidly becomes bluer—a "rotational disturbance" considered indicative of an eclipse of rotating material. HMC89 also noted some evidence for an eclipse in the optical continuum light curves.

In their report, HMC89 concentrated on the He II λ4686 line, which showed the effect most clearly. This line is dominated by an *s*-wave resulting from the impact of the accretion stream with the disk (see HMC90, Plate 1). Hence, in this line, the changes in the line profile are due primarily to the eclipse of the hot spot, and only secondarily to the eclipse of the underlying disk (which is a weak He II λ4686 emitter and which is only partially eclipsed). Similar distortions of the rotational disturbance are seen whenever a strong *s*-wave is present (see examples in Honeycutt, Kaitchuck, & Schlegel 1987). Unfortunately, the role of the hot spot was not emphasized in HMC89; if it had been, the following misunderstanding might not have arisen.

MK see the same changes in the He II λ4686 line profile; however, they conclude that they are not caused by an eclipse (see their § II*e*), for the following reasons: (1) the disturbance occurs 180° out of phase with respect to the line motion, if this motion is orbital; (2) if this motion were *s*-wave rather than orbital, then the eclipse of the disk components would be weak and difficult to detect; and (3) the disturbance is unlike that of a disk since it is very asymmetrical, having a much greater blueward excursion than redward excursion.

We accept all three points but argue that they are exactly as expected in a line dominated by an *s*-wave. The phasing is correct, since the motion is due to an *s*-wave; the contribution due to the disk is indeed weak; and the asymmetry arises from the eclipse of the hot spot—since it will be redshifted during eclipse, its disappearance produces a large blueward excursion.

The other point raised by MK is more interesting. They have looked at the rotational disturbance in He II λ4686 in two halves of their data, one accumulated near the maximum of the 21 minute cycle and the other near the 21 minute minimum. They find that the change in radial velocity during the disturbance is prominent only in the 21 minute maximum data set and is much reduced in the 21 minute minimum data set. MK claim that this shows that the disturbance cannot be an eclipse, since the existence of an accretion disk cannot depend on the phase of the 21 minute cycle.

However, we can explain their result straightforwardly within the model of HMC. According to HMC, the He II λ4686 flux arises from two locations. Emission from the hot spot at the edge of the disk produces the orbital cycle s-wave. This emission dominates the line except when it is eclipsed by the secondary, which occurs when the s-wave is redshifted (see HMC 90, Plate 1). He II λ4686 emission also arises from "accretion curtains" near the white dwarf (where it would escape eclipse). This emission is modulated in velocity with the 21 minute (spin) cycle in the sense that it is blueshifted at spin maximum and redshifted at spin minimum (note that identical behavior is seen in other intermediate polars, e.g., AO Psc, as reported in Hellier, Cropper, & Mason 1991). Hence, during eclipse, looking at data from spin minimum only, the redshifted emission from near the white dwarf will fill in the line profile where the s-wave would have been, resulting in no net velocity shift. At spin maximum, however, the blueshifted emission from near the white dwarf adds to the line profile on the opposite side to where the s-wave would have been, resulting in the very marked velocity shift seen. The 21 minute modulated component filling in the line profiles can be seen directly in Figure 23 of MK.

Hence, the MK analysis of the rotational disturbance, which they claim refutes the eclipse, is in fact entirely consistent with the HMC proposal. Additionally, it is difficult to sustain any model for such rapid profile changes (see HMC89, Fig. 1) at a low inclination. Thus, we conclude that a high inclination with an eclipse by the secondary is the most natural explanation for the rotational disturbance and that there is currently no reason to doubt this proposal.

4. THE ORIGIN OF THE 21 MINUTE PERIOD

MK propose that the 21 minute period in FO Aqr, which dominates both the X-ray and optical light curves, is the beat period between the orbital and spin periods, and that the spin period is therefore 19.5 minutes. We first discuss the implications of this idea and then examine the evidence in its favor.

4.1. *Consideration of the MK Model*

4.1.1. *Why Is a Prominent* 22.5 minute *Peak Seen?*

The best quality power spectrum of the X-ray light curve of FO Aqr is presented by Norton et al. (1990). At the low-frequency end, this spectrum shows an orbital modulation and its first harmonic. In addition, there is a dominant 21 minute peak accompanied by both first and second orbital sidebands on both sides (i.e., the 24.4, 22.5, 19.5, and 18.3 minute sidebands). Power at these frequencies can result from amplitude modulation of the 21 minute peak at the orbital and twice-orbital frequencies (this is a straightforward extension of the therory of Warner 1986). However, this Fourier transform also shows that the power at 22.5 minutes is much greater than that at the other sidebands, so the amplitude of this modulation is approximately half that of the main 21 minute peak. This is readily explained if the 21 minute period is the spin period, since any interaction between the spin pulse and orbitally fixed structure produces such a modulation. However, in the MK proposal that the real spin period is 19.5 minutes, no intrinsic variation at the 22.5 minute period would occur—only that due to the orbital modulation of the 21 minute period, which would produce a variation of equal intensity at the opposite sidelobe.

A similar argument can be made from the optical light curves. The Fourier transform of Patterson & Steiner (1983) clearly shows power at the 21 minute and 22.5 minute periods, but, again, intrinsic power at 22.5 minutes is not expected if the spin period is 19.5 minutes.

Thus, both X-ray and optical photometry of FO Aqr strongly support identifying the 21 minute and 22.5 minute periods as the spin and beat periods.

4.1.2. *Why Is the* 19.5 minute *Period Not Seen?*

As discussed above, there is no evidence in either the X-ray or optical light curves for an intrinsic modulation at the 19.5 minute period. If the MK proposal were correct, FO Aqr would be a unique intermediate polar in showing little sign of a spin period modulation. MK propose that the 21 minute pulse is caused by reprocessing of the direct beam by a wind near the secondary. Since the reprocessing efficiency (limited by the solid-angle of the wind) would be at most 10%, the direct beam must be at least one order of magnitude more intense than the observed 21 minute beam. Since up to 80% of the observed X-ray emission is pulsed with the 21 minute period (Norton et al. 1990), this sets an upper limit of $\sim$2% to any direct X-rays emitted towards Earth as compared to those emitted toward the reprocessing region. MK propose that the direct beam is not seen because it is constrained to the disk plane. They therefore require a large X-ray optical depth out of the plane, which they suggest results from magnetically entrained gas. Note that for this model to work, the gas must be optically thick to hard X-rays ($\sim$25 keV), implying that electron scattering must be the dominant source of opacity and that it must obscure the direct beam at all spin phases. However, this picture is not supported by the studies of the accretion geometry in intermediate polars (e.g., King & Shaviv 1984; Rosen, Mason, & Córdova 1988). The material is too diffuse to block more than a small proportion of the hard X-rays, and it will do so only if the accreting pole area is very small. In any case the geometry of the obscuring material is highly dependent on spin phase, and so the X-ray beam would not be occulted at all spin phases. In addition, in any magnetic dipole geometry where material is accreted from the disk plane, the amount of obscuring material in a direction along the disk plane is greater than the amount in a direction perpendicular to the plane—the opposite to the requirement of the MK model. We can also question why, if the direct beam is so heavily obscured at all times in FO Aqr, it is so readily visible in all other intermediate polars. Finally, we note that the MK proposal to hide the spin pulse also requires a low system inclination, whereas in § 3 we concluded in favor of FO Aqr being an eclipsing system.

4.1.3. *The Reprocessing Model for the* 21 minute *Pulse*

MK argue that the 21 minute X-ray modulation is the result of reprocessing the direct (19.5 minute) X-ray beam in a wind. Since the 21 minute modulation extends to high energies (at least 25 keV), this model requires a high optical depth ($\tau \sim 1$) to Thomson scattering. This implies an electron column density of $N_e \sim 2 \times 10^{24}$ cm^{-2}. The wind must cover a large area to present a large enough solid angle to the direct beam. If we assume that it has the dimensions of the secondary ($\sim 6 \times 10^{10}$ cm wide) and a typical velocity of 200 km s^{-1} (the wind velocity derived by MK), then we estimate the wind mass-loss rate of $\sim 4 \times 10^{18}$ g s^{-1}. This rate is substantially greater than the *mass accretion rate* typical for cataclysmic variables above the period gap ($\sim 10^{17}$ g s^{-1}) and is far greater than could be driven by irradiation by an X-ray luminosity of less than the 10^{34} ergs s^{-1} that is feasible in a cataclysmic variable. Even in neutron-star accreting binaries, where the X-ray luminosity can approach the Eddington limit ($\sim 10^{38}$ ergs s^{-1}), such intense winds are found to be difficult to maintain by X-ray irradiation alone (see, e.g., the study of Cyg X-3 by Tavani, Ruderman, & Shaham 1989). The MK model is therefore physically unrealistic.

4.2. *Evidence for the MK Model*

We have shown above that the MK model leads to severe difficulties in understanding the observations of FO Aqr, sufficiently so that it should be considered only if supported by strong evidence. The only evidence for their model put forward by MK is at the beginning of § 4 where, considering the He II λ4686 line, they say:

> "The lack of any obvious radial velocity variations on the 21 minute cycle makes it unlikely that they originate in gas that is entrained in the magnetic field of the white dwarf. This combined with their strong blueshifts, strongly suggests a wind origin."

And so, since a wind origin implies reprocessing, they associate the 21 minute period with the beat period.

Our response is simply that there *is* obvious radial velocity motion of He II λ4686 on the 21 minute cycle. This is clear from the HMC90 analysis of the V/R ratios (their Figs. 2 and 5) and is also easily seen directly in the line profiles (e.g., Plate 2 of HMC90). Furthermore, Figures 9, 14, and 27 presented by MK all seem to us to show clear radial velocity motion of emission lines on the 21 minute cycle. Indeed, when discussing their Figure 14, showing radial velocities of the He II λ4686 derived from a Gaussian fit, MK actually state, "there is a low-amplitude radial velocity modulation . . ." on the 21 minute cycle.

However, MK prefer to interpret these apparent radial velocity changes on the 21 minute cycle as the result of two fixed-velocity components whose intensities vary. This interpretation is certainly consistent with their data; however, they do not give reasons for favoring this over the simpler, one-component, variable-velocity interpretation (as adopted by HMC90). Moreover, it is clear that the higher quality gray scales presented by HMC90 (Plate 2) cannot be interpreted as the result of two stationary components. It may well be that the inferior spectral and temporal resolution of the MK data (§ 2) permit the alternative interpretation which the HMC data exclude. Since all parts of an intermediate polar binary are in rapid motion, it seems natural to regard apparent radial velocity motion as real motion unless compelling reasons otherwise are found, which MK do not provide.

In this regard it is worth remarking that the profile variations on the 21 minute cycle of He II λ4686 in FO Aqr are very similar to the variations of He II λ4686 on the spin period in AO Psc (Hellier et al. 1991). In AO Psc there is little room to doubt the identification of the spin period, since the dominant optical modulation is at the orbital sideband of the X-ray period; this alone strongly supports the identification of the 21 minute period with the spin period in FO Aqr.

5. CONCLUSIONS

Having considered the arguments of MK, we conclude that FO Aqr is most likely a high-inclination system in which the secondary eclipses part of the accretion flow. There is no substantial evidence that the 21 minute period in FO Aqr is the beat period and strong evidence that it is the rotation period of the white dwarf.

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