KQ MON AND THE NATURE OF THE UX URSA MAJORIS NOVA-LIKE VARIABLES

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ABSTRACT

KQ Mon, a new UX UMa type nova-like variable discovered by H.E. Bond, exhibits optical spectra, UBV and high speed photometric characteristics strongly similar to other members of the UX Ursa Majoris subset. However its ultraviolet spectra when compared with other UX UMa stars shed considerable light on the nature of these objects. Its spectrum is dominated by strong broad highly ionized absorption lines including the NV, SiIV and CIV UV resonance doublets. No emission lines or P Cygni type features are evident and the velocity displacements are smaller suggesting the absence of a hot high velocity wind characterizing other UX UMa stars. A physical interpretation of the UV absorption spectra and optical spectra and their observed temporal variations is presented. Based upon (1) high mass accretion rates derived by fitting the observations with theoretical continuum fluxes from steady accretion disk models by R.E. Williams, (2) the presence of outflowing winds with the determination of corresponding mass loss rates and properties of the theoretical wind models by Cassinelli, Olson and Stalio, and (3) new time independent steady state disk structure computations, a model is suggested to explain the observed properties of the UX UMa stars and their lack of major outbursts.

1. INTRODUCTION

The UX Ursa Majoris stars form a group of nova-like variables with common photometric and spectroscopic properties. The optical characteristics of these objects are thoroughly described by Warner (1976). They appear to be related to the cataclysmic variables but are not known to have undergone major outbursts such as those observed for dwarf novae, recurrent novae, classical novae, or symbiotic variables. In order to understand the still uncertain evolutionary connection between the UX UMa stars, the old novae, the dwarf novae in the outburst or extended high states and other cataclysmic variables as well as the physics of steady state disks, it is fundamentally

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important to know why any outburst behavior is absent in these stars. Critical new information about the UX UMa stars has recently become available from x-ray observations with the Einstein satellite (cf. Cordova, Mason and Nelson 1981) and ultraviolet spectroscopy with the International Ultraviolet Explorer satellite (cf. Greenstein and Oke 1982, Holm, Danek and Schiffer 1982, Guinan and Sion 1982a, 1982b, Sion and Guinan 1982, Wargau et al 1982). A new object, KQ Mon, has been added to our program of study with the IUE satellite. In this paper we discuss its relationship to the other UX UMa stars and suggest a model to explain their observed properties and absence of major outbursts.

2. OBSERVATIONS OF KQ MON

Bond's (1981) optical spectra of KQ Mon revealed very shallow Balmer absorption lines and HeI (λ4471) absorption, while his UBV and high speed photometric observations in 1978 and again in early 1981 revealed no light variations due to possible orbital phase modulation nor was an appreciable brightness change expected given the absence of radial velocity variations in the optical spectra. However, Bond's high speed photometry revealed the presence of low amplitude flickering that when coupled with the appearance of the optical spectrum and KQ Mon's location near the old novae and white dwarfs in the two color diagram, suggested a strong similarity to the UX Ursa Majoris subset of the nova-like variables (Warner 1976).

KQ Mon was observed at low dispersion with the IUE satellite on December 5, 1981 and February 5, 1982. The instrumentation and spacecraft characteristics are described by Boggess et al.(1978). Four spectra with the short wavelength prime (SWP) camera, and four spectra with the long wavelength redundant (LWR) camera were obtained. The exposure times were 35 minutes and 40 minutes respectively, with the large and small aperture and two of the spectra were trailed.

Using the Fine Error Sensor (FES) photometer, visual magnitudes of +13.06 and +12.97 were obtained in December 1981 and February 1982 respectively while Bond obtained V=+13.06 in 1978, indicating that the light level appears reasonably constant. Broad band color indices for KQ Mon were measured by Bond (1982) to be B-V=+0.08, and U-B=-0.72. The U, B and V magnitudes were converted to absolute flux units using the absolute calibration of Hayes (1980).

In figure 1 a single SWP spectrum typical of the others is shown together with labeled identification of the strongest line features. The spectrum is dominated by strong broad absorption lines due to NV, OI + SiIII, SiIV, CIV, HeII and NIV. Possible Lyα absorption is obscured by the strong geocoronal feature. The long wavelength (LWR) spectrum appears essentially featureless. The data was de-reddened using the interstellar extinction law of Nandy et al.(1975) and a value of E(B-V)=0.08 was adopted. In figure 2 we plot the de-reddened satellite continuum fluxes on a log F_λ vs. log λ(Å) scale along with the broad band U B and V fluxes. On the same figure we show, for comparison, theoretical continuum fluxes from model steady state accretion disks calculated by Williams (1981b) assuming a disk inclination angle i=0 (pole-on). The models shown in figure 2 are normalized to the optical V band flux.

3. COMPARISON TO OTHER UX UMA STARS

The UV line spectrum of KQ Mon shows strong broad absorption lines of the resonance doublets and excited species but unlike other members of the UX UMa class (e.g. TT Ari in its high state, LS I 55 8, V 3885 Sgr, RW Sex, UX UMa) they are not appreciably violet-displaced and P Cygni-type emission is entirely absent. Thus a hot wind from the disk driven by X-radiation from the inner disk may be weak or absent in KQ Mon. Moreover, the absorption lines of KQ Mon appear to be marginally broader than those of LS I 55 8, V 3885 Sgr and RW Sex. The strengths and shapes of the CIV, NV and SiIV absorption features show significant variations as a function of time over the longest time baseline of our observations, 130 minutes. Similar line variations were found in other low inclination UX UMa stars (e.g. LS I 55 8, TT Ari, RW Sex) and may arise due to the changing aspect of gas observed against the disk at different orbital phases or possibly may result from disk asymmetry.

The estimates of mass loss rates due to wind outflow in the UX UMa stars give $\dot{M}_{wind} \sim 10^{-2}$ to 10^{-4} $\dot{M}_{acc}$ when $\dot{M}_{acc}$ is the mass accretion rate (cf. Guinan and Sion 1982a, 1982b, Greenstein and Oke 1982). The weakness or absence of an outflowing wind in KQ Mon may be due to (1) a somewhat lower (sub-critical?) $\dot{M}_{acc}$ than other UX UMa stars (2) accreting gas flowing above and/or below the disk plane (3) a weak white dwarf magnetic field preventing disk gas from forming a high pressure zone at the equator which could drive the type of polar wind described by Greenstein and Oke (1982) or (4) a nearly pole-on disk with conical outflow of hot gas in a narrow cone angle.

Like other UX UMa stars, the UV continuum is essentially flat from the UV to the optical and can be fitted quite well with accretion disk fluxes. The disk model fits in figure 2 clearly indicate an accretion rate near $10^{-8} M_\odot yr^{-1}$ for KQ Mon.

4. NATURE OF THE UX URSA MAJORIS STARS

Given the high ionization states of the UV absorption lines and the evidence for mass outflow in most of the UX UMa stars, the following tentative interpretation of the UV line and continuum spectra is suggested based in part on the wind models of Cassinelli Olson and Stalio (1978 cf. section IV, Guinan and Sion 1982). If we assume the X-radiation in these systems emerges from the hot inner disk boundary

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layer region rather than say a "hot spot" at the disk edge (because the disk is too luminous relative to a hot spot) it is likely that the UV resonance doublets such as N V (λ1240), C IV (λ1550) and Si IV (λ1396) arise in an outflowing wind. These high ionization features, seen in combination with a relatively "cool" integrated disk continuum, are similar to the UV spectra of O and B stars with outflowing winds (Cassinelli, Olson and Stalio 1978). A thin hot corona ($\sim 10^6$K) at the base of the flow in the boundary layer region provides the X UV photon source needed for the high ion states. The high ionization stages can be produced by the Auger mechanism, whereby two electrons are removed from C, N and O following K shell absorption of x-rays. Greenstein and Oke (1982) have independently proposed for RW Sex than an outflowing wind from the disk is driven by X-radiation, with the gas in conical geometry at the poles of the degenerate dwarf. They propose a broad cone while Guinan and Sion (1982) did not specify the geometry for V 3885 Sgr. It should be noted that for values of the viscosity parameter between 0.0 and 1 (Bath and Pringle 1981) derived for dwarf novae in outburst, a wind outflow geometry other than spherical would constrain the UX UMa systems to have magnetic fields (Wiita 1982). Indeed one of the UX UMa stars, TT Ari, appears to be an "intermediate polar" (Warner 1982) with a magnetic field strength lower than that associated with the AM Her objects and magnetic white dwarfs but strong enough to funnel a radial accretion flow. In either case the outflowing gas is seen silhouetted against a luminous disk for a large range of orbital inclinations which explains the appearance of the blue-shifted absorption lines and P Cygni-type features observed in a number of UX UMa stars. It is likely that when the accretion rate $\dot{M}$ is high, X UV quanta do not penetrate to the disk edge because the accretion flow is optically thick to that flux region. When the disk luminosity declines (i.e. $\dot{M}$ decreases), it is predicted that mass loss should cease, the absorption lines formed in the wind should disappear, the continuum should fade and the UV line spectrum should go into emission with the high excitation (barely displaced) UV emission lines originating in a "chromosphere" surrounding the inner disk region (cf. TT Ari in its low state; Wargan et al.1982). The site of this "chromosphere" is predicted to be the upper parts of the disk atmosphere more than one scale height from the central plane of the disk. When $\dot{M}$ again increases, the boundary layers' luminosity goes up and the UV spectrum again goes into absorption and an outflowing wind may again be driven.

That UX UMa stars may have higher accretion rates than other types of cataclysmic variables is indicated directly or indirectly by (1) derived accretion rates from continuum fits (e.g. RW Sex, Greenstein and Oke 1982; V 3885 Sgr, Guinan and Sion 1982a; LS I 55 8, Guinan and Sion 1982b; KQ Mon, Sion and Guinan 1982; Wargau et al.1982), (2) the flat continuum of a luminous, thick disk dominating the light from the UV through the optical and IR, (3) the low ratio of L_X/L_{opt} for those UX UMa stars observed with the Einstein satellite (Cordova Mason and Nelson 1981) and (4) the outflowing winds from accretion disks which may manifest a higher boundary layer luminosity or local super Eddington accretion.

We contend here that the accretion rates of the UX UMa stars are higher than, for example, the dwarf novae during quiescence and that the higher accretion rates of the UX UMa stars are responsible for their lack of major outbursts. Based upon the excellent agreement between our observed fluxes and the theoretical disk continuum fluxes of Williams (1981b), steady accretion rates $\gtrsim 10^{-8} M_\odot yr^{-1}$ are implied for the UX Ursa Majoris stars. A higher mass accretion rate implies more massive thicker disks with some mechanism or viscosity source which allows continuous accretion onto the white dwarf thus keeping the system in continuous "outburst" (or extended high state). Time independent steady state disk models with the central plane convection occurring for the high accretion rates associated with the UX UMa stars, have been calculated by Vila (1982). Here central plane convection would be an effective viscosity source allowing accretion onto the white dwarf. However, recent steady disk models by Meyer and Meyer-Hofmeister (1981) have stable radiative structure for $\dot{M}_{acc} \gtrsim 10^{-9.5} M_\odot yr^{-1}$. Since the accretion rates of the UX UMa stars seem to be well above this value, steady state radiative disk structure can be maintained as long as $\dot{M}$ remains high enough for the disk to be in a stable radiative state. Thus these models lead us to suggest that the UX UMa stars possess steady state equilibrium disks due to their high mass accretion rates which would explain the absence of "outbursts." A stable steady state disk may also provide a natural explanation for the observed winds in RW Sex, LS I 55 8, V 3885 Sgr and UX UMa. If the accretion flow is high enough to be super-critical, the wind outflow may result from the response of the disk to re-establish a steady state accretion flow. In this case, KQ Mon may lack an outflowing wind because the accretion flow is just sub-critical. On the other hand, the accretion rate derived for RW Sex by Greenstein and Oke (1982) is super-Eddington for a $1 M_\odot$ white dwarf.

Finally further work is needed on the driving mechanism and structure of the winds in UX UMa systems. Since systemic mass loss appears to be occurring via these winds, the effects of angular momentum loss on the evolution of UX UMa stars should be investigated.

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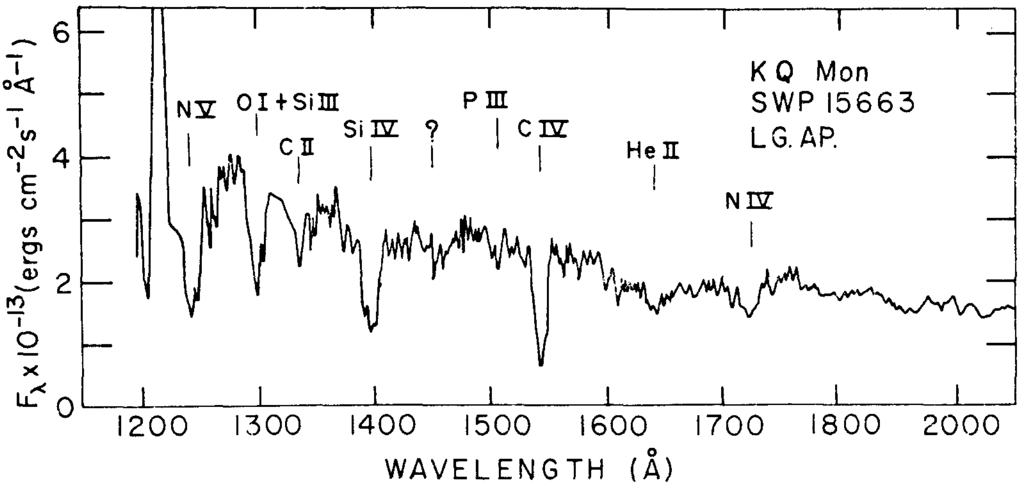

Figure 1: Short Wavelength Prime (SWP) low dispersion IUE spectrum of KQ Mon. The strong off-scale emission line at λ1216 is geocornal Lyman Alpha. The stronger absorption features are identified

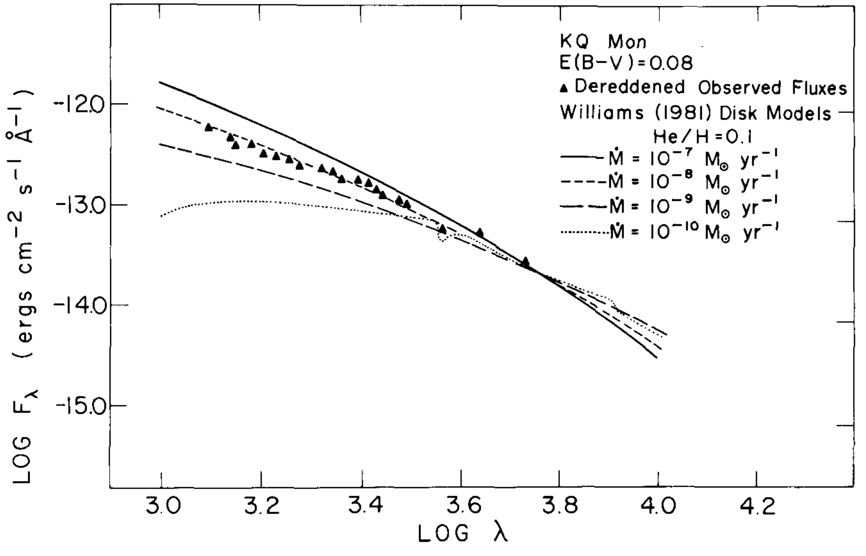

Figure 2: The de-reddened continuum fluxes of KQ Mon, log F_λ versus logλ, compared with three solar composition accretion disk models of Williams (1981b) normalized at the optical V band flux. Optical fluxes are labeled with corresponding bandpass designations.

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DISCUSSION FOLLOWING E. SION'S TALK

WARNER: The wind that you see, is the velocity greater than the escape velocity from the system?

SION: The wind velocities in all but one case are less than the escape velocity from the surface of the white dwarf. In the case of BD-7307 terminal velocities that exceed the escape velocity from a white dwarf are indicated.

WARNER: I am interested in escape from the system, I just wonder whether it is a method of losing angular momentum from the system, from the binary, that is.

SION: We haven't checked that yet.

WARNER: A bit of historical accuracy, the idea that UX Ursa Majoris systems, as they are now called, are systems in permanent outbursts, really goes back to Bob Kraft in about 1965 or so.

ROBINSON: Is there any correlation of the strength of the P Cygni profile with orbital inclination? That is to say, have you looked at UX Ursa Majoris, which has a very high inclination and does it show the P Cygni profiles, evidence of a wind and so forth?

SION: Yes, there is a correlation, the deeper the absorption trough the more nearly pole-on seems to be the system and in UX Ursa Majoris those same absorption features are gone, it is mostly emission in the UV, because you are looking at the gas above, you are seeing the disk edge on.

FRIEDJUNG: First, a reply to Robinson, there is a recent preprint by Cordova and Mason where they say there is a correlation between the intensity of the P Cygni component and the inclination . A second thing, I would like to say about the wind, these winds from accretion disks may not be quite as unusual as they first appear, they may resemble very much winds from normal hot stars and may be something completely different from the winds you get from novae during outburst. An approximate calculation I did, using the most recent form for radiation pressure in the lines, by Abbot, and applying it to the old nova HR Del predicted the mass loss rate to within a factor of two. My impression is that these winds may be driven just by the radiation pressure in the lines as in certain theories for hot star winds.

SION: This is precisely my interpretation.

MEYER: I want just to clarify what continous outburst means, in view of the model that has been suggested by different people and also by us, it would just be the stationary disk, which is not modulated by the nonstationary flows in convective regions. So you don't need a special process to dump matter on the star, but rather you get rid, with your high mass flow rates, of the modulation process.

SION: In TT Ari the disk goes away or seems to shrink and then the luminosity goes down and then goes back up again.

MEYER: As long as you are above the critical mass accretion rate, of course you can have such variations. I would like to add that the velocities in your P Cygni profiles would probably give you information about the distance from the white dwarf from which the main bulk of this flow originates.

WILLIAMS: I was going to say that the fact that the velocities of outflow deduced from the resonance lines, are less than the escape velocity from the surface, requires that the mass loss is coming from further out, from the accretion disk. This is consistent with Friedjung's point that you would in fact expect mass loss from accretion disks, particularly in systems where you have heating of the disk by X-rays. One further point, N IV absorption that you identified, I think in KQ Mon that line is forbidden, it is very difficult to get it in absorption, I think you should recheck the identification of that, I think it may be a silicon line.

KING: I would like to support Williams' point. We had some UV spectra of UX UMa and we found that the C IV line was not eclipsed, when the system was eclipsed, which means this region of gas is very large, it must be as big as the shadow the secondary casts.

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