ULTRAVIOLET STUDIES OF NOVA-LIKE VARIABLES
WITH THE IUE

NASA Contract NAG 5-205

Final Report

For the Period 1981 April through 1983 September

Principal Investigator
Edward F. Guinan
September 1983

Prepared for
National Aeronautics and Space Administration
Washington, DC 20546

Villanova University
Villanova, Pennsylvania 19085

The NASA Technical Officer for this contract is Dr. Yogi Kondo,
NASA-Goddard Space Flight Center, Greenbelt, MD 20771
TABLE OF CONTENTS

I. Summary of Completed Research
II. Publications and Presented Papers
III. Copies of the Research Papers
I. Summary of Completed Research

Our investigations of UX Ursae Majoris-type nova-like variables and binaries with degenerate components in the far ultraviolet with the International Ultraviolet Explorer satellite have resulted in a total of five publications and papers. The list of papers are given in Section II and the copies of the papers are given in Section III.

The chief results of this research program are summarized as follows:

1) The discovery of hot, high velocity (~1000 km s^{-1}) winds from the accretion disks of the nova-like stars.

2) We affirm the presence of thick accretion disks centered on the degenerate components of the nova-like variables studied.

3) By fitting theoretical flukes computed by R.E. Williams for steady state accretion disks models, we determined that the accretion rates of \( \dot{M} \approx 10^{-9} \text{M}_\odot \text{yr}^{-1} \). These inferred accretion rates are higher than found for the dwarf novae in quiescence.

4) The steady state disk structure in a stable radiative state thus explains for the first time the "absence of outbursts" for the Nova-like stars.
II. Publications and Papers on Research Completed under Grant NAG 5-205


Advances in Ultraviolet Astronomy: Four Years of IUE Research

Yoji Kondo, Jaylee M. Mead, and Robert D. Chapman, Editors
NASA Goddard Space Flight Center
Greenbelt, Maryland

Proceedings of a symposium held at NASA Goddard Space Flight Center
Greenbelt, Maryland
March 30 - April 1, 1982
THE NOVA-LIKE VARIABLE KQ MON AND THE NATURE OF THE UX URSA MAJORIS STARS

Edward M. Sion and Edward F. Guinan

Astronomy Department, Villanova University

ABSTRACT

KQ Mon is a new UX UMa-type nova-like variable discovered by Howard Bond. Optical spectra taken by Bond in 1978 reveal very shallow Balmer absorption lines and He I (λ4471) absorption. Bond also did UBV and high speed photometry in 1978 and early 1981. There has been no evidence of orbital variations but the appearance of the optical spectrum and the presence of low amplitude flickering suggested a strong similarity to CD-42°14462 (=V3885 Sgr) and other members of the UX UMa class. KQ Mon was observed at low dispersion with the IUE satellite. Six spectra taken with the short wavelength prime (SWP) camera are dominated by strong broad absorption lines due to N V, O I, Si III, Si IV, C IV, He II, N IV, and Al III. There is little evidence of orbital phase modulation over the time baseline of our observations. Unlike UV observations of other UX UMa-type objects, KQ Mon exhibits no emission lines or P Cygni-type profiles and the velocity displacements appear to be smaller, suggesting the absence of a hot, high velocity wind characterizing other UX UMa stars. The relationship of KQ Mon to other UX UMa disk stars is discussed and a model is suggested to explain their observed properties and the lack of major outbursts.

INTRODUCTION

In a continuing investigation of the nature of nova-like variables, a new system, KQ Mon, recently discovered by H.E. Bond (1978) was added to our program of study with the International Ultraviolet Explorer Satellite. Bond's (1981) optical spectra 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 any 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. This observation coupled with the appearance of the optical spectrum and its location near the old novae and white dwarfs in the two color diagram suggested a strong similarity of KQ Mon to the UX Ursa Majoris subset of the nova-like variables (Warner 1976). Analysis of our ultraviolet spectra confirm that KQ Mon shares the UV characteristics of the other UX Ursa Majoris stars.

OBSERVATIONS

KQ Mon has been 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). We obtained four spectra with the short wavelength prime (SWP) camera, and four spectra with the long wavelength redundant (LWR) camera. 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). Since our data tapes from the February 1982 observing run were not available when we went to press, we cannot address here the question of whether line and continuum variations are present due to orbital phase modulation.

In figure 1 a single SWP spectrum typical of the others is shown together with labelled identification of the most important line features. The spectrum is dominated by strong broad absorption lines due to NV, OI + SiIII, SiIV, CIV, HeII and NIV. Possible Lya absorption is obscured by the strong geocoronal feature. The long wavelength (LWR) spectrum appears essentially featureless. No absorption dip is apparent at \( \lambda \) 2200 indicating that interstellar reddening for KQ Mon is probably small. In figure 2 we plot the unreddened satellite continuum fluxes on a \( \log F_\lambda \) vs. \( \log \lambda (\AA) \) 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 B band flux.

**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 LS I 55 8, V 3885 Sgr, RW Sex) 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 somewhat broader than those of LS I 55 8, V 3885 Sgr and RW Sex.

The estimates of mass loss rates due to wind outflow in the UX UMa stars give \( \dot{M}_{\text{wind}} \approx 10^{-2} \) to \( 10^{-4} \dot{M}_{\text{acc}} \) where \( \dot{M}_{\text{acc}} \) is the mass accretion rate (cf. Guinan and Sion 1982, Greenstein and Oke 1982). The weakness or absence of an outflowing wind in KQ Mon may be due either to (1) a somewhat lower \( \dot{M}_{\text{acc}} \) than other UX UMa stars (2) accreting gas flowing above and/or below the disk plane or (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), also Witta (1982).
Like other UX UMa stars, the UV continuum is essentially flat from UV to the optical and can be fitted quite well with accretion disk fluxes (see fig. 2). Reddening corrections would shift the fluxes upward in figure 2 toward a higher accretion rate. The accretion rate of KQ Mon probably lies between $10^{-8} M_\odot$ yr$^{-1}$ and $10^{-10} M_\odot$ yr$^{-1}$.

**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 emerge from the hot inner disk boundary layer region rather than say a "hot spot" at the disk edge it is likely that the UV resonance doublets such as N V ($\lambda$1240), C IV ($\lambda$1550) and Si IV ($\lambda$1396) arise in an outflowing wind. These high ionization features, seen in combination with a relatively "cool" integrated disk continuum, are similar to the UV spectra of O and B stars with outflowing winds (Cassinelli, Olson, and Stalio). A thin hot corona ($\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 that 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. 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 UV emission lines originating in a "chromosphere" surrounding the inner disk region (cf. TT Ari; Krautter et al 1981). 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 1982; TT Ari, Krautter et al 1982), (2) the flat continuum of a luminous, thick disk dominating 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. It is very likely that the accretion rate of UX UMa stars is higher than, for example, the dwarf novae during quiescence.

We suggest here that the higher accretion rates of UX UMa stars are responsible for their lack of major outbursts. The optical spectra of the UX UMa stars resemble the spectra of dwarf novae in outburst (e.g. Warner 1976) and the UV continuum distribution and line spectra of the UX UMa stars also resemble the UV spectra of dwarf novae in outburst (cf. Krautter et al., 1982). H.E. Bond (1978) described V 3885 Sgr as being in continuous outburst since at least 1899 with only very minor changes in brightness in the last eighty-three years. If the UX UMa stars are in a continuous outburst state, we are led to seek a cause of the extended outburst. There is excellent agreement between our observed fluxes and the disk continuum fluxes of Williams (1981b). Thus the disk physical parameters and accretion rates from Williams (1981a) model grid can be adopted with reasonable validity. The higher accretion rates of the UX UMa stars implies more massive thicker disks with a source of viscosity which allows gas to continually accrete onto the white dwarf photosphere. Vila (1982) has calculated steady disks with high mass fluxes which become convective in their central plane. In these models, convective instability increases as the mass accretion rate increases. We argue here that higher \( \dot{M} \) in the UX UMa stars produces disk convection which allows gas to continually dump onto the degenerate dwarf with the release of gravitational potential energy. According to Starrfield (1982) a similar scenario based upon disk calculations in progress is proposed to explain dwarf novae outbursts as due to the transition from an optically thin to an optically thick disk with onset of convection. In summary, we propose that UX UMa stars have higher accretion rates than dwarf novae in quiescence and post-novae and thus are in an extended outburst state until accretion from the companion star ceases or declines to the point that steady disk structure with convection ends.

ACKNOWLEDGEMENTS

It is a pleasure to thank Dr. Robert E. Williams for kindly making available unpublished model accretion disk continuum fluxes for normal and helium-rich compositions. We are very grateful to Dr. Howard Bond for calling our attention to KQ Mon as a possible UX UMa star and providing a finding chart as well as unpublished optical photometry. Useful discussions with Drs. S.G. Starrfield, S.C. Vila and P. Wiita are gratefully acknowledged.

REFERENCES

Figure 1: Short Wavelength Prime (SWP) low dispersion IUE spectrum of KQ Mon. The strong off-scale emission line at \( \lambda 1216 \) Å is geocoronal Lyman Alpha. Strong absorption features are identified.

Figure 2: Flux plot \( \log F_\lambda \) versus \( \log \lambda \) compared with three accretion disk models of Williams (1981b) normalized at the optical V band flux. Optical fluxes are labelled with corresponding bandpass designations and all continuum fluxes are unreddened.
HIGH VELOCITY GAS OUTFLOW FROM THE NOVA-LIKE VARIABLE LSI 55°-8
Edward F. Guinan and Edward M. Sion
Astronomy Department, Villanova University

INTRODUCTION
LSI 55°-8 (α=00h18m10s; δ=+55°26′1:1950) was identified as a possible subluminous, blue object by Haug (1970) from its unusual UBV colors during the Hamburg-Case Survey of Luminous Stars (Hardorp et al. 1959). Palomar spectra of LSI 55°-8 obtained by Greenstein, Sargent and Haug (1970; hereafter GSH) show a blue, nearly smooth continuum with weak, broad Balmer absorption lines having weak emission cores; other weak, broad emission lines of He II λ4686 and C III λ4647 were also reported. From its spectrum and UBV measures (V=+12.79; B−V=+0.07; U−B=−0.79), GSH suspected the object of being an old nova or a cataclysmic variable. High speed photometry was carried out during 1977 by Africano and Quigley (1978), where they monitored the star on 7 nights for a total of 20 hours and found rapid, nonperiodic light variations of up to 0.4 mag. Rapid light variability (flickering) is a common photometric characteristic of many cataclysmic variables and nova-like variables (Robinson 1976) and is believed to be associated either with a hot spot at the impact region of the gas with the accretion disk, or with non-radial oscillations of the disk, driven in the boundary layer region (Hesser, Lasker and Osmer 1972). Since LSI 55°-8 is not known to have undergone a large change in brightness with time like the dwarf novae, Quigley and Africano classified it (correctly) as a nova-like variable. It is generally believed that nova-like variables are either (a) old novae that have undergone outbursts that were unrecorded or (b) dwarf novae that are in very extended high states similar to those observed for the Z Cam systems, but of much longer duration (Warner 1976).

THE OBSERVATIONS
LSI 55°-8 was observed with the IUE satellite on 1981, December 05 as part of a continuing ultraviolet study of nova-like variables. Five low dispersion (λ6A) SWP spectra (λλ1175-1900) and two LWR spectra (λλ2100-3100) were obtained over a 4 hour time interval. In addition, the optical brightness of the star was monitored between the UV exposures using the Fine Error Sensor (FES) onboard the satellite. The FES counts were converted to V magnitudes using the calibration of Holm and Crabb (1979). During the observing interval the range of visual magnitudes was between +12T635V(FES)≤+12T78. These values are close to the value of V=+12.79, measured earlier by Haug, and the short-term variability in light is similar to that found previously by Africano and Quigley.

RESULTS
The far UV spectrum of LSI 55°-8 (SWP 15659S) is shown in Fig.1 where the data reduction was by the standard IUESIPS routines. The identified spectral features are shown in the figure and also
are listed in Table I along with the rest and measured wavelengths, the residual intensities, the line widths at half maximum, and the corresponding Doppler displacement velocities. The LWR spectra of the star are essentially featureless. The UV spectrum of LSI 55-8 is strikingly similar to the nova-like binaries V3885 Sgr (Guinan and Sion 1982) and RW Sex (Greenstein and Oke 1982), which both show strong, blue-shifted absorption lines of such high temperature ions as C IV, NV, Si IV, and He II in their SWP spectra. As can be seen from the table, the high temperature (∼10^5K) ions of C III, C IV, He II, NV, and Si IV have relatively large negative Doppler shifts corresponding to radial velocities between -800 km s^-1 and -1400 km s^-1. Much higher expansion velocities are associated with the broad absorption wings of the lines. The low temperature (∼10^4K) ions of H I (Lyα), O I, Si II, and Si I do not appear to show significant velocity displacements and probably originate from the outer accretion disk, with some contribution from the interstellar medium. In addition, the C IV (λ1549) resonance doublet shows a variable P Cygni-type profile with a blueshifted absorption component. The presence of this feature, along with the blueshifted absorption features of the high temperature ions, indicate the existence of outflowing hot plasma (i.e. a wind). Using the method of Castor, Lutz and Seaton (1981), an upper limit of the mass outflow rate can be made from the short wavelength edge of the C IV absorption which yields M_{max} < 10^{-5}M_⊙/yr. Fig. 2 shows a plot of the normalized C IV profile as a function of time. As shown in this figure, the C IV profile is variable with the largest changes occurring in the relative strength and shape of the emission component. These changes appear to be systematic and may be associated with the changing projection of the outflowing hot plasma against the disk as a function of orbital motion. We have found similar behaviour for the C IV feature of TT Ari, in which the profile appears to change with its orbital motion (Guinan and Sion 1981). Fig. 3 shows the residual line intensities of a few of the stronger spectral features as a function of time; in addition to the C IV variations, it appears that strength of the He II (λ1640) absorption feature is also time dependent. Although at low resolution it is difficult to be certain, it appears that the observed changes in the He II residual intensity are caused by broad emission filling in the bottom of the absorption feature. If this is the case, there appears to be correlation between the observed decrease in the C IV emission line strength with time and the decrease of the He II emission, inferred from the apparent strengthening of the He II absorption line feature with time.

Although LSI 55-8 is not definitely known to be a binary system, it has most of the characteristics (both spectral and photometric) exhibited by the nova-like, UX UMa-type variables, as well as with the dwarf novae in outburst or standstill. These systems are believed to be very short period, close binaries involved in active mass transfer and −5 −7 M⊙ via Roche lobe overflow of gas from a low mass, cool star onto a white dwarf (Robinson 1976). An accretion disk is formed around the white dwarf compon-
ent as a result of the mass transfer mechanism and is predicted by Herter et al. (1979) to dominate the luminosity of the system at all but long wavelengths. Using the interstellar extinction law of Nandy et al. (1975), the data was de-reddened after several trials until no perceptible 'dip' (under-corrected for interstellar extinction) or 'hump' (overcorrected interstellar extinction) appeared at λ2200. A value of E(B-V)=0.30 was adopted and the observations were corrected for interstellar extinction and appear in Fig. 4 as log F vs. logλ. Various steady state, accretion disk model fluxes were tried (Herter et al. (1979); Pacharintanakul and Katz (1980); Williams (1981)) with the model fluxes of Williams yielding the best fit to observations. As shown in the figure, the steady-state accretion disk of Williams with accretion rate of M~10^{-7} M⊙/yr and i=0 fits the data very well. The disk model fluxes of Herter et al. and Pacharintanakul and Katz produce higher than observed fluxes in the far UV relative to the optical wavelength fluxes. Unfortunately the Williams' fluxes are available only for the case in which the disk is seen face-on (i=0). The effect of viewing the disk at higher inclination has been investigated by Herter et al., and produces a decrease in the far UV flux relative to optical wavelengths, as the outer, cooler portion of the disk begins to dominate the observed radiation. From the appearance of its optical and UV spectrum (especially the presence of the blueshifted absorption features of the highly ionized species and C IV P Cygni-type profile), and the lack of significant periodic light variations, it appears that LSI 55-8 is being viewed at a low inclination (i<50°). The high accretion rate of M~10^{-7} M⊙/yr, inferred from fitting the Williams disk model fluxes to our data, would appear to support the hypothesis that LSI 55-8 and related nova-like systems are in a state of prolonged outburst.

A ground-based radial velocity study of the star is needed to confirm the binary nature of the object and to determine its orbital period. The spectral changes observed in our study indicate a period 3h<P<7h. We plan to publish a more thorough investigation of this interesting star in the near future. We wish at this time to thank Dr. Howard Bond for supplying us with an identification chart, and also to thank Dr. Robert Williams for sending unpublished theoretical disk model fluxes.

REFERENCES
Guinan, E.F. and Sion, E.M. 1981, in The Universe at UV Waves,
Hardorp, J., Rohlfs, K. Slettebak, A. and Stock, J 1959, Luminous
Stars in the Northern Milky Way, vol.I Hamburger Sternwarte,
Warner and Swasey Observatories.

467
Fig. 1. The SWP 15659 (small aperture) spectrum of LSI 55°-8 with the stronger spectral features identified.

<table>
<thead>
<tr>
<th>Object</th>
<th>λ(Å)</th>
<th>λ_0(Å)</th>
<th>(λ_0/λ)</th>
<th>Δ(Å)</th>
<th>V_0(km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIV</td>
<td>1549.59</td>
<td>1542</td>
<td>0.44</td>
<td>10</td>
<td>-1565</td>
</tr>
<tr>
<td>NIV</td>
<td>1240.15</td>
<td>1237</td>
<td>0.77</td>
<td>11</td>
<td>-760</td>
</tr>
<tr>
<td>OII+OII</td>
<td>1304</td>
<td>1302</td>
<td>0.21</td>
<td>14</td>
<td>-230</td>
</tr>
<tr>
<td>NIV</td>
<td>1240.15</td>
<td>1237</td>
<td>0.77</td>
<td>11</td>
<td>-760</td>
</tr>
<tr>
<td>SiIV</td>
<td>1402.73</td>
<td>1399</td>
<td>0.32</td>
<td>7</td>
<td>-800</td>
</tr>
<tr>
<td>CIV</td>
<td>1549.59</td>
<td>1542</td>
<td>0.44</td>
<td>10</td>
<td>-1565</td>
</tr>
<tr>
<td>HeII</td>
<td>1660.47</td>
<td>1653</td>
<td>0.23</td>
<td>10</td>
<td>-1565</td>
</tr>
<tr>
<td>SiII</td>
<td>1817.63</td>
<td>1815</td>
<td>0.10</td>
<td>9</td>
<td>-800</td>
</tr>
<tr>
<td>SiII</td>
<td>1817.63</td>
<td>1815</td>
<td>0.10</td>
<td>9</td>
<td>-800</td>
</tr>
</tbody>
</table>

LS 55°-8
SWP 15659 SM
1981 DEC.05UT
Fig. 3. The observed residual intensities of C IV (absorption and emission components), He II(λ1640), and N V(λ1240) as a function of time.

Fig. 4. The de-reddened continuum fluxes of LSI 55°-8 plotted along with the Williams' (1981) accretion disk fluxes. The stellar fluxes for \( T_{\text{eff}} = 22,500 \)K; \( \log g = 4.5 \) from Kurucz (1979) are also plotted for comparison. All of the model fluxes have been normalized to the observed flux near λ5500. (i.e. \( \log F\nu = 14.74 \)).
An Ultraviolet Investigation of the Unusual Eclipsing Binary System FF Aqr

J.D. Dorren(1), E.F. Guinan(2) and E.M. Sion(2)

(1) Department of Astronomy, University of Pennsylvania
(2) Department of Astronomy, Villanova University

Introduction

FF Aqr (BD-3°5357) is an eclipsing binary which consists of a G8 III-IV star and a subdwarf in a 9d.2 orbit. IUE and optical observations of such a system provide a unique opportunity to extract information about the temperature, gravity and composition of the subdwarf as well as about the chromosphere of its giant companion, which is known to have strong Ca II H+K emission and may resemble members of the RS CVn group. A series of 7 low-dispersion IUE exposures in both wavelength regions was obtained on Dec. 6, 1981 during the eclipse of the subdwarf, during egress, and out of eclipse. In Fig. 1 these observations and the binary phase at which they were made are shown on a schematic representation of the V-band light curve obtained in 1975 by Dworetsky et al. (1977). The depth in V is 0.15 mag. The circles are IUE V-magnitudes from FES measures obtained during the observing run. They indicate an eclipse depth some 0.05 mag. lower than expected, possibly due to difficulties with the color term in the FES calibration. In our calculations we assumed the eclipse depths of Dworetsky et al. in U, B and V.

The Subdwarf Component

The smoothed continuum flux of the spectrum LWR 12086 (large aperture) taken during total eclipse was subtracted from the out-of-eclipse spectrum LWR 12088 (large aperture) to yield the UV continuum flux longward of 1900 Å for the subdwarf alone. For the shortwave region, spectrum SWP 15662 yields the subdwarf flux directly since the continuum is essentially zero in the spectrum SWP 15660 taken in eclipse. The calibrated flux from these large-aperture exposures is shown in Fig. 2, and includes the Lyα line. The UV flux was de-reddened adopting $E_B - V = 0.10$, and the interstellar extinction law of Nandy et al. 1975, which is sufficient to fill in the shallow interstellar extinction feature near 2200Å. In principle log $g$ and $T_{eff}$ can now be determined. However suitable model atmospheres for subdwarfs are not readily available. We used the model atmospheres of Kurucz (1979) for stars of solar abundance, and the pure hydrogen models of Wesemael et al. (1979) for high gravity stars. Fits using both models are shown in Fig. 2. The Kurucz model provides a better fit to the UV continuum and the optical U, B, V fluxes, while the Wesemael model gives a much better fit to the Lyα line, and permits a more accurate determination of log $g$. A temperature near 35,000°K and log $g = 6.0$ are suggested. For $E_B - V = 0.10$ the intrinsic color of the giant component is $(B-V)_{0} = +1.00$ which corresponds to a spectral type near G8 III and $T = 4800°K$, hence $m_{bol} = +9.17$. A distance of 320 pc and a radius of 6.1 $R_\odot$ is consistent with the analysis of Dworetsky et al. We derived from our own analysis of $\lambda$ And, which is also a G8 III-IV star, but of known distance (Dorren and Guinan 1982). Masses of 0.5 $M_\odot$ and 2.0 $M_\odot$ for the subdwarf and giant respectively are consistent with the mass function of f(m) = 0.0188 and the inclination of 81° which, following
Dworetsky et al., we adopt. The eclipse duration implies that for $i = 81^\circ$, $R_{\text{ed}} = 0.1 \, R_\odot$ and $\log g \sim 6.1$.

The subdwarf spectrum is shown in Fig. 3 for the short wavelength region, with the identification of the prominent absorption lines. It shows strong C II as well as C IV and Si IV. Note that He II $\lambda 1640$ is relatively weak. Its presence is, however, confirmed by our other spectra. Its weakness can be understood as either representing a low surface abundance due to diffusion or as due to the lower effective temperature range of the subdwarf ($35,000 K < T_e < 40,000$) especially in view of the absence of the middle ultraviolet He II ($3 - n$) series in the LWR spectrum. Thus it is expected that HeII ($\lambda 4686$) would be weak in the optical spectrum and the classification would probably be sdOB. Unfortunately the cool component dominates the light at optical wavelengths making a direct measurement of the He II $\lambda 4686$ feature difficult. On a $\log g / \log T_e$ plot (Fig. 4, from Hunger and Kudritzki, 1981) the subdwarf in FF Aqr appears to the right of the subdwarf group. The approximate boundary between sdB and sdO subdwarfs lies at $\log T_e \sim 4.6$. In the same figure we show for comparison a downward extension to higher gravity and temperature of the Strittmatter and Norris (1971) boundary between the domain of radiation pressure driven mass loss and surface diffusion. Stars to the right of the dashed boundary should generally be weak helium line/metal deficient objects due to downward diffusion. Neglecting the possible effects of accretion, the observed strength of the helium and metal lines in the subdwarf in FF Aquarii may shed light on the evolutionary status of the hot subdwarfs and in particular the possibility of an sdO/sdB evolutionary transition.

THE COOL COMPONENT

The SWP spectrum of the G8 star is shown in Fig. 5 in which the emission lines are identified. The spectrum is generally similar to that of $\lambda$ And (Baliunas and Dupree 1982) with the hot transition region lines of NV, C IV and C II prominent and with weaker Si IV and He II as is found in stars with active chromospheres. In fig. 6 the ratio of line fluxes at Earth to apparent bolometric luminosity (Ayers et al. 1981) are plotted against the same ratio for Mg II (from LWR 12086) and compared with the fluxes from the most active RS CVn stars HR 1099 and UX Ari, with the similar giant component of the RS CVn system $\lambda$ And, and with the unusual rapidly rotating G - giant FK Comae and another member of this interesting small group, HD 199178 (Bopp and Stencel 1981). Relative to Mg II, the star has greater emission in the hot lines in particular than the active RS CVn stars. We note that the observed distortions of the light curve (Dworetsky et al.) may be due to surface activity on the G star (spots?) rather than the reflection effect which should be negligible for this system.

In a separate paper we hope to analyze the subdwarf with more suitable model atmospheres and investigate its evolutionary status. Our own optical photometry from 1977-1978 will also be analyzed to obtain tighter constraints on the parameters of this important system.
REFERENCES


Fig. 1-Orbital phase of the IUE exposures shown on a schematic light curve. The circles are the FES V-magnitudes.

Fig. 2-UV and optical fluxes for the hot subdwarf, assuming $E_{B-V} = 0.10$. Kurucz and Wesemael et al. fits are shown.
Fig. 3 - The subdwarf UV spectrum from 1200-1900 Å with prominent absorption lines identified.

Fig. 4 - Position of the subdwarf on a log g / log $T_{\text{eff}}$ plot. Evolutionary tracks for 0.51 and 0.57 $M_\odot$ stars are shown. The dashed line is discussed in the text. The positions of sdOB stars (o), extreme He-rich (•) and intermediate He-rich stars (e), and central stars of planetary nebulae (+) are shown. (From Hunger and Kudritzki 1981).

Fig. 5 - The spectrum of the G8 III-IV component with prominent emission lines identified.

Fig. 6 - Correlation diagrams for chromospheric and transition region fluxes for late-type giants and dwarfs (solid lines: Ayres et al. 1981). The cool star in FF Aqr (o) compared with FK Com (x), HD 199178 (+), the mean of HR 1099 and UX Ari (o), and $\lambda$ And (Δ) (Bopp and Stencel 1981).
THE HOT DO WHITE DWARF HD 149499 B: EINSTEIN REDSHIFT OF A DB PROGENITOR WITH CARBON FEATURES

EDWARD M. SION AND EDWARD F. GUINAN
Department of Astronomy, Villanova University
Received 1982 July 28; accepted 1982 October 20

ABSTRACT

High-resolution IUE spectra of the hot DO white dwarf HD 149499B have been analyzed. The mass of the white dwarf needed to fit our measured gravitational redshift is $0.5 \pm 0.1 \, M_\odot$ for a degenerate core composed of carbon based upon using a nonzero temperature mass-radius relation. The resonance doublet of C iv ($\lambda 1550$) appears to be photospheric in origin, and two possible explanations for the presence of carbon in a hot DO white dwarf are discussed. The relationship of HD 149499B and other DO white dwarfs to the DB white dwarfs is also considered.

Subject headings: stars: atmospheres — stars: white dwarfs

I. INTRODUCTION

The DO white dwarfs have long been thought to be immediate, hot, helium-rich progenitors of the chemically pure D3 white dwarfs, although, for the derived abundances of DO stars, dilution or expulsion of remaining hydrogen may be still required (see Sion, Guinan, and Wesemael 1982). It now appears that there are three distinctly different classes of DO white dwarfs Wesemael et al. 1983). Members of the hottest temperature class ($T_e \approx 80,000 \, \text{K}$) have ultraviolet photospheric metal lines not unlike the hottest subdwarf O stars; an intermediate temperature class of DO stars ($T_e \approx 50,000-80,000 \, \text{K}$) exhibits photospheric metals with only He ii in the optical, and a "cooler" type ($T_e \approx 50,000-60,000 \, \text{K}$) like Hz 21, Lanning 14, and HD 149499 B, exhibits no positively detected photospheric metal lines from low-dispersion International Ultraviolet Explorer (IUE) spectra.

High-dispersion IUE spectra can provide crucial information on the nature of the hot DO stars by revealing weak photospheric features, narrow, non-local thermodynamic equilibrium (non-LTE) line cores, and evidence for mass outflow and circumstellar gas. HD 149499 B is one of a handful of hot degenerates bright enough to be observed at high resolution with the IUE spacecraft. High-resolution spectra of HD 149499 B were obtained by us in 1979 August. The detailed line profile data from these spectra, along with low-dispersion UV line profiles, IUE, Voyager 2, and optical continuum fluxes, were used to do a detailed spectro-photometric analysis (Sion, Guinan, and Wesemael 1982, thereafter SGW). However, over a dozen positively identified weak line features in the high-resolution spectrum of HD 149499 B are definitely interstellar in origin. The interstellar medium in the directions of HD 149499 B and three other white dwarfs has been thoroughly investigated by Bruhweiler and Kondo (1981, 1982) who analyzed the interstellar absorption lines in high-resolution IUE spectra.

In the present work, we analyze weak noninterstellar line features (C iv $\lambda 1549$ and He ii $\lambda 1640$) first reported by Sion and Guinan (1982), who presented a preliminary gravitational redshift determination. These features were detected only at high resolution and shed further light on the nature of the DO stars. Our objectives in this Letter are to (1) analyze the C iv ($\lambda 1549$) resonance doublet as a test of the effect of radiative accelerations on diffusion time scales as well as theoretical predictions based upon diffusion theory, (2) explore the possible evolutionary implications of having carbon features in the spectrum of a hot DO white dwarf, and (3) determine an Einstein gravitational redshift for the hot white dwarf using the core of the He ii ($\lambda 1640$) absorption feature and a K0 V companion of known radial velocity. To our knowledge, HD 149499 B is the hottest white dwarf for which a gravitational redshift has been determined and thus makes possible the first direct test, for a non-DA white dwarf, of the effect of nonzero temperature on the mass-radius relation for a completely degenerate configuration.

In § II we present our high-resolution observations and discuss the accuracy of our IUE wavelength scale: in § III we describe the Einstein redshift determination and discuss its implications; in § IV we discuss evolutionary implications of the C iv absorption features, and in § V we summarize our conclusions.

II. HIGH-RESOLUTION SPECTRUM

Observations of HD 149499 B were obtained on 1979 August 24 with the high-resolution echelle mode of the
A detailed description of the spacecraft instrumentation is found in Boggess et al. (1978). Two images were obtained with the large aperture, one with the short-wavelength prime camera (SWP 6272) having an exposure time of 90 minutes and one with the long-wavelength redundant camera (LWR 5442) having an exposure time of 75 minutes.

The data reduction for our spectra was carried out at the IUE data reduction facility at the Goddard Space Flight Center. The data were corrected for echelle ripple and background as provided by the IUE Observatory. Wavelength corrections are also required for effects of thermal and temporal variations on the SWP camera. The resulting wavelength calibration yields an absolute wavelength scale accurate to approximately 3 km s⁻¹ (see Bruhweiler and Kondo 1982). A check on our measured wavelengths was made through comparison with those measured by Bruhweiler and Kondo (1982) for several interstellar lines in the spectrum of HD 149499 B. In seven out of eight lowly ionized interstellar features across the SWP region measured by ourselves and Bruhweiler and Kondo (1982), agreement was exact to a hundredth of an angstrom. An independent check on our measured wavelengths was made by comparison with measurements of Dupree and Raymond (1982) for the C iv (λ1549) features and the He II (λ1640) absorption core in their four SWP spectra of HD 149499 B. Again, agreement with our measurements was excellent.

The two strongest features in the SWP spectrum are the stellar absorption features due to Lyα + He i (λ1216) and He II (λ1640). Unlike the low-dispersion spectrum of HD 149499 B, the high-dispersion spectrum reveals a very sharp He II (λ1640) core, which is briefly discussed in SGW, and a strong, sharp resonance doublet of C iv (λ1550). In Figure 1 the sharp He II line core is shown, and in Figure 2 we display the C iv resonance doublet. For comparison, three N i lines which are typical of the interstellar features in the spectrum of HD 149499 B are shown in Figure 3. The observed low-dispersion He II (λ1640) profile has an equivalent width of 4–5 Å (see SGW, Fig. 3), and the expanded wavelength scale of the He II region in the high-resolution spectrum shown in Figure 1 reveals the sharp core but not the entire profile whose wings extend far beyond the scale of Figure 1. The identifications and wavelength displacements of the interstellar lines in the UV spectrum of HD 149499 B are tabulated by Bruhweiler and Kondo (1982) and are not repeated here. However, in the region of Mg ii (λλ2795, 2802), the LWR spectrum is extremely noisy, making it difficult to measure Δλ for the absorption components, which we interpret as interstellar. However, our LWR spectrum reveals emission components of Mg ii whose displacements indicate they arise from the K0 V star HD 149499 A which is the cool component of the visual pair, at a present separation of approximately 1'5.

The sharp core of the He II (λ1640) was measured on the single high-resolution spectrum of SGW and three high-resolution exposures obtained by Dupree and Raymond (1982). In each case, the line center was defined to be the deepest part of the line. The average displacement was found to be Δλ = +0.05 ± 0.02, considerably redshifted relative to the lowly ionized interstellar features. The longward component (λ1550.774) of the C iv (λ1550) resonance doublet, whose displacement is less affected by interstellar contribution, yielded Δλ = +0.06 ± 0.02 for the four combined spectra. Each
component of C iv has an equivalent width of \( \sim 80 \) mA and is redshifted relative to the interstellar features.

We feel that the C iv absorption in the spectrum of HD 149499 B is most likely photospheric rather than interstellar in origin. A photospheric origin is supported by (a) C iv having the same wavelength displacement as He II (\( \lambda 1640 \)), (b) the apparent absence or extreme weakness of N v (\( \lambda 1240 \)) and Si iv (\( \lambda 1400 \)) to the limit of 20 mA which would be present if the C iv were interstellar, (c) the likelihood that C iv ions would be supported by differential radiation pressure force at the effective temperature (~ 55,000 K) of HD 149499 B (Fontaine and Michaud 1979; Vauclair, Vauclair, and Greenstein 1979), and (d) the presence of C iv in the low-dispersion IUE spectra of at least four hotter DO stars (Wesemael et al. 1983). We return to points (c) and (d) in § IV.

III. GRAVITATIONAL REDSHIFT DETERMINATION

Correcting for the motion of the Earth and the IUE spacecraft (+23 km s\(^{-1}\)), the displacement of the He II core yields \( v_r = -14.2 \pm 2.8 \) km s\(^{-1}\) for the heliocentric radial velocity of HD 149499 B. Wegner (1978) measured the heliocentric radial velocity of the KO V component (HD 149499 A) to be \(-31 \pm 3 \) km s\(^{-1}\) from the Na D and Ca I lines. His measurement was made from a red spectrum using a coude spectrograph with a plate factor of 13.6 A mm\(^{-1}\). The errors in Wegner's radial velocity measurement and our IUE measurements are roughly comparable. Using \( v_r = -31 \) km s\(^{-1}\) and our heliocentric radial velocity for the white dwarf yields a velocity displacement due to the Einstein redshift of \(+17 \pm 5 \) km s\(^{-1}\). This value is well below the mean gravitational redshift (+45 km s\(^{-1}\)) of DA stars determined by Greenstein et al. (1977) but is consistent with, for example, the redshift of 40 Eri B (Wegner 1980) and corresponds to a 0.4–0.5 M\(_\odot\) white dwarf composed of carbon based upon the zero-temperature mass-radius and mass-gravity relations of Hamada and Salpeter (1961). Moreover, the relatively low mass (\( \sim 0.45 M_\odot\)) needed to fit our gravitational redshift is not inconsistent with the lower mean mass (0.44 ± 0.01 M\(_\odot\)) derived by Koester, Schulz, and Wegner (1981) from fitting colors and equivalent widths of DB stars. However, such masses are uncomfortably small if they correspond to white dwarfs with cores composed of carbon since they are not much larger than the minimum mass for helium burning.

In interpreting our gravitational redshift, one should be cautioned about effects which would tend to yield a lower redshift value. At a surface temperature of 55,000–60,000 K, the radius of HD 149499 B could be larger than that of a completely degenerate, zero-temperature configuration as in Hamada and Salpeter (1961). However, according to the latest evolutionary models by Winget, Lamb, and Van Horn (1983), using state-of-the-art envelope physics for a cooling carbon white dwarf, release of gravitational energy and the radius correction due to nonzero temperature for a star which has cooled to the temperature of HD 149499 B is too small (\( \leq 35 \) km s\(^{-1}\)) to make a significant difference. If the sharp core of He II (\( \lambda 1640 \)) forms significantly higher in the atmosphere than in the wings, a lower gravitational redshift derived from this line would result. Although one cannot completely rule out this possibility, it is difficult to understand how helium could be supported at a significant fraction of the stellar radius above the photosphere. We prefer to interpret the sharp core as being due to non-LTE effects (see SGW).

If our gravitational redshift is compared to a mass-radius relation defined by the models of Winget, Lamb, and Van Horn (1983), the implied mass is between 0.5 M\(_\odot\) and 0.6 M\(_\odot\), a value higher than that implied using the Hamada-Salpeter (1961) relation. Moreover, the higher implied mass agrees with the radius determination reported in SGW based upon the photometric parallax and temperature determination for HD 149499 B. The recent trigonometric parallax by Ianna, Rohde, and Newell (1982) agrees very closely with the distance used in SGW (31 pc vs. 36 pc) yielding a radius very close to that reported in SGW. Unfortunately, the comparison of our radius with the Winget \textit{et al.} models is possible only for 0.6 M\(_\odot\) until other models become available. For temperatures between 50,000 and 70,000 K, the radius increases over the zero temperature value is 25% or less for a pure carbon model and for a \(^{12}\)C core with a helium layer of \(10^{-4}\) stellar masses and hydrogen layer of \(10^{-15}\) stellar masses.
IV. IMPLICATIONS OF IONIZED CARBON FEATURES

The presence of carbon in the photosphere of HD 149499 B suggests two interesting possibilities. The first one involves the net downward diffusion velocity for a helium-rich white dwarf which depends upon the competition between the downward acceleration due to gravitational plus thermal diffusion $g_{\text{rad}}$ and the radiative acceleration $g_{\text{rad}}$. Vauclair, Vauclair, and Greenstein (1979) have shown that, in helium-rich envelopes, radiative accelerations are larger due to the larger broadening of the lines, whereas saturation effects prevent an enhancement of CNO ions for hydrogen envelopes. For a helium-rich white dwarf with $M = 0.5 M_\odot$ and $T_e = 55,000$ K as in HD 149499 B, $\log g_{\text{rad}} > \log g_{\text{rad}}$ for temperatures greater than $\log T = 4.75$ which corresponds to a mass fraction $\Delta M/M = 5 \times 10^{-14}$ at $T = 1$. Thus, the presence of photospheric carbon in observable amounts in HD 149499 B would appear to confirm the predictions of diffusion theory. However, it should be noted that the theory is still beset with uncertainties in the proper treatment of diffusion at small optical depth. The absence or extreme weakness of observable nitrogen in HD 149499 B would suggest that $g_{\text{rad}}$ is greater on nitrogen than carbon in a helium-rich white dwarf, the nitrogen may have left HD 149499 B earlier in the form of a wind driven by selective radiation pressure.

The other possibility emerges from consideration of dredge-up processes that occur before ejection of a planetary nebula and the possible linkage of these processes with the origin of the DB and DB white dwarf spectral sequences. Iben (1976) has shown that, for stars larger than $3 M_\odot$, inward penetration by envelope convection lifts away nitrogen created from carbon in the CNO shell source during the first ascent of the giant branch and lifts away more nitrogen as well as helium from the helium zone surrounding the inert $^{12}\text{C} = ^{16}\text{O}$ core during the second ascent of the giant branch. Recent evolutionary model calculations by Iben et al. (1983) show that some planetary nebula central stars, cooling in the range from 10 to 100 $L_\odot$, can undergo a late helium-shell flash and retrace their evolutionary path back to the red giant domain as the final thermal pulse causes the core to brighten. Preliminary results indicate that a substantial number of planetary nuclei may undergo the final thermal pulse (Kaler 1982), although dependence upon interior parameters is still unclear.

Models such as these (1) may explain the phenomenon of Abell 30 and Abell 78 (Iben et al. 1983), large high-excitation planetary nebulae that exhibit zones of nearly pure helium near their cores, and (2) may be relevant to the origin of DB white dwarfs. If we suppose that HD 149499 B is a true hot progenitor of DB stars from single star evolution, the presence of carbon and absence of nitrogen may be an artifact of pre-white dwarf evolution and a common characteristic of DB progenitors. This suggestion is strengthened by statistical arguments that the $C_2$ white dwarfs are cooled DB stars (Sion, Fragola, and O'Donnell 1979) and by the recent detection by Wegner (1980) of neutral helium in the optical spectra of two $C_2$ stars. In addition, neutral atomic carbon lines have been detected in several DC white dwarfs known to be helium dominated, in other words, cooled DB stars. It should be noted, however, that carbon in the photosphere of a hot DO star could be explained by mechanisms other than the two we have discussed above. Recently, for example, Wesemael and Truran (1982) have discussed the accretion of grains by slowly rotating, weakly magnetic, helium-rich white dwarfs as a means of explaining metal features in the spectra of objects much cooler than HD 149499 B.

V. SUMMARY OF CONCLUSIONS

From high-resolution IUE spectra of the hot DO white dwarf HD 149499 B, we have used the sharp, non-LTE He II line core to derive a gravitational redshift which, within the observational uncertainties, is fitted by a carbon core with a mass of 0.5 ± 0.1 $M_\odot$. If this star is a true DB white dwarf progenitor, the low mass is not inconsistent with generally lower masses of DB stars derived from model atmosphere fits by the Kiel group in particular.

We argue that the C iv resonance doublet detected in our high-resolution IUE spectrum is photospheric in origin. We suggest that its presence can be attributed to differential radiation pressure force on carbon ions, or an enhanced carbon abundance due to dredge-up processes, or a late shell flash during the pre-white dwarf evolutionary phase, or to all three.

Theoretical C iv line profiles are needed in order to place limits on the carbon abundance in HD 149499 B and other hot helium-rich degenerates. This would enable us to make a study of the carbon abundances that are present in the hottest DO stars down to the coolest DB stars as a function of radiative acceleration and gravitational thermal diffusion time scales.

It is a pleasure to thank Drs. James Kaler, Gary Wegner, John Raymond, and Andrea Dupree for communicating results in advance of publication, and to express our appreciation to Drs. James Liebert, Harry Shipman, and Francois Wesemael for commenting on an earlier draft of this Letter. This research was supported by NASA grant NAG 5-260 for which we are grateful.

REFERENCES


No. 2,
Fontaine, Greenstein, 1977.
Hamada, Ianna, P.
Iben, R. Iben, R., 264, 69
Kaler, J. Koester.
Sion, E.
A.S.P.
of the hotter star was fitted in order to
HD 149499 B


BAD F. GUINAN and EDWARD M. SION: Department of Astronomy, Villanova University, Villanova, PA 19085
KING: Since you have such large line opacities wouldn't it be the case that your ratios will be affected by the deviation from spherical symmetry, so that if it is the secondary, as it moves around, your predicted ratio should change.

METCALF: Yes, definitely, if you talk about Balmer decrement, my prediction is that it should change.

KING: Is the continuum between the lines real continuum or noise?

METCALF: First, you have seen the M giant which was very strong and that was subtracted by another M giant.

KING: So you then have an estimate for the relative energy in all the lines and the continuum.

METCALF: Yes, I do, this comes from other people's observations with the HBE, this relates to my answer about the covering factor of the source is covered by clouds.

KING: And the nature of the UX Ursae Majoris nova-like variables

Edward M. Sion and Edward F. Guinan
Astronomy Department, Villanova University

Abstract

UX Mon, a new UX Uma type nova-like variable discovered by H.E. Bond, exhibits optical spectra, UV, and high speed photometric characteristics strongly similar to other members of the UX Ursae Majoris subset. However its ultraviolet spectra when compared with otherUX Uma stars shed considerable light on the nature of these objects. Its spectrum is dominated by strong, broad, highly ionized absorption lines including the N\textsubscript{V}, Si\textsubscript{IV} and C\textsubscript{IV} 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 Stahl, and (3) the 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 Ursae 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
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. Corson, Mason, and Nelson 1981) and ultraviolet spectroscopy with the International Ultraviolet Explorer satellite (cf. Greenstein and Oke 1965, Hoag, Danek, and Schiffer 1982a, Guinan and Sion 1982a, 1982b, Sion and Guinan 1982b, Morkov et al. 1982). A new object, KQ Mon, has been added to our program of study with the UJE satellite. In this paper we discuss its relationship to 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 He I (λ4471) absorption, while its UV and high speed photometric observations in 1978 and again in early 1981 revealed no light variations due to possible orbital phase modulation and no appreciable brightness changes, 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, KQ Mon’s location near the old nova and white dwarfs in the two color diagram, suggested a strong similarity to the UX Ursae Majoris subset of the nova-like variables (Warner 1976).

KQ Mon was observed at low dispersion with the UJE satellite on December 5, 1981 and February 5, 1982. The instrumentation and space characteristics are described by Bougeres et al. (1976). 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 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 +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 (1960).

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, CI + SiII (1, 1), SiIV, CIV, HeII and IV. Possible Lyman absorption is obscured by the strong geocoronal feature. The long wavelength (LWR) spectrum appears essentially featureless. The data was de-redenred using the interstellar extinction law of Nandy et al. (1975) and a value of (E(B-V))=0.06 was adopted. In Figure 2 we plot the de-redenred satellite continuum fluxes on a log F vs. log λ 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 show 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 B, V 3865 SrI, RW Sex, UX UMa) TVc are not appreciably violet-shifted and P Cygni-type emission is entirely absent. Thus a hot wind from the disk driven by X-radiation is not present in KQ Mon. Moreover, the absorption lines of KQ Mon appear to be marginally broader than those of LS I 55 B, V 3865 SrI 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 B, 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 Mwind=10^-2 to 10^-4 M☉/yr when Macc 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?) Macc than the 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☉/yr for KQ Mon.

4. NATURE OF THE UX URSAE 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 is suggested in part on the wind models of Cassinelli and Stalio (1978) 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
layer region rather than say a "hot spot" as 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 (A1240), C I (A1550) and Si IV (A1396)
arise in an outflowing wind. These high ionization features, seen in
combination with a relatively "cool" continuum disk, are
similar to the UV spectra of and B stars with outflowing winds
(Cassinelli, Olson and Stalle [1970]). A thin hot corona (with a temperature at the
base of the flow in the boundary layer region provides the UV photon
source needed for the high ion states. The high ionization stages can be
produced by the Meyer mechanism, whereby two electrons are removed
from C, N and O following X shell absorption of X-rays. Greenstein
and Oke (1982) have independently proposed for RN 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
RN Sex at 3805 SrY. It should be noted that for values of the viscosity param-
eter between 0.0 and 1 (Bath and Pringle 1981) derived for dwarf
novae in outburst, a wind outflow geometry other than spherical would
construct an outflow system to the disk to be in a bipolar one.
Indeed one of the UX UMa stars, Ti Ari, appears to be an "intermediate polar"
(Warner 1982) with a magnetic field strength lower than that
associated with the RN 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 (e.g. RN Sex, Greenstein and Oke 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 
flow 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
cataclysmic variables is indicated directly or indirectly by
(1) derived accretion rates from continuum fits (e.g. RN Sex, Greenstein
and Oke 1962, RN Sex, Guinan and Sion 1982a; LS I 55 B, Guinan
and Sion 1982b; UX Mon, Sion and Guinan 1982; Wargau et al. 1987),
(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 (Curts et al. 1981)
and (4) the outflowing winds from accretion disks which
may manifest a higher boundary layer luminosity or local super Eddington
accretion.

KU MIN AND THE NATURE OF UX UMA NOVA-LIKE VARIABLES

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 UMs 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 (1981a), steady accretion rates >10^-9 M_\odot yr^-1 are implied for
the UX UMa Majors stars. A higher mass accretion rate implies more
massive chiller 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 (1980)
have stable radiative structure for Macc >10^-9 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 a
magnetic field is present. 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
RN Sex, LS I 55 B, RN Sex 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, KU Min may lack an outflow because the accretion
flow is just sub-critical. On the other hand, the accretion rate
derived for RN Sex by Greenstein and Oke (1982) is super-Eddington for
a white dwarf in a steady state.

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 in the evolution of UX UMa stars should be investigated.

ACKNOWLEDGMENTS

It is a pleasure to thank Dr. Robert E. Williams for kindly making
available unpublished model accretion disk continuum fluxes for normal
and helium-rich compositions. We are very grateful to Dr. Howard Bond
for providing a possible UX UMa star and for a possible UX UMa star
and providing a finding chart as well as unpublished optical photometry.
Useful discussions with Drs. S.G. Starrfield, S.C. Vila and P. Witta
are gratefully acknowledged. This work was supported by the National
Aeronautics and Space Administration under contracts NASA 5375 and
NASA 7349.
Figure 1: Short Wavelength Prime (SWP) low dispersion IUE spectrum of KQ Mon. The strong off-scale emission line at λ1216 is geocoronal Lyman Alpha. The stronger absorption features are identified.

Figure 2: The de-reddened continuum fluxes of KQ Mon, log $F_{\lambda}$ versus log $\lambda$, compared with three solar composition accretion disk models of Williams (1993a) normalized at the optical $V$ band flux. Optical fluxes are labeled with corresponding broadband designations.

REFERENCES


Bond, H.E.: 1981 (private communication).


Wiita, P.: 1982 (private communication).
DISCUSSION FOLLOWING E. SION'S TALK

KANE: 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 RS 303 terminal velocities that exceed the escape velocity from a white dwarf are indicated.

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

SION: We haven't checked that yet.

ROBINSON: 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.

FRATRIG: 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 Abbott, and applying it to the old nova 1985 that 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.

NEYER: I want just to clarify what continuous 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.

NEYER: 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.

KJ MUN AND THE NATURE OF UX URA: NOVA-LIKE VARIABLES

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 Friedman'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 UX UMa 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.

KJ: I would like to support Williams' point. We have 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.