EUVE Observations of the Magnetic Cataclysmic Variable QQ Vulpeculae

Kunegunda E. Belle, Steve B. Howell\textsuperscript{1} & Amy Mills

Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071; keb@tana.irastro.uwyo.edu; howell@psi.edu

ABSTRACT

We present simultaneous X-ray ($\lambda_{\text{peak}} \sim 44\text{Å}$) and EUV ($\lambda_{\text{peak}} = 89\text{Å}$) light curves for the magnetic cataclysmic variable QQ Vulpeculae, obtained with the EUVE satellite. We find that the unique shape of the X-ray light curve is different from previously obtained X-ray light curves of QQ Vul and provides evidence for two-pole accretion. Detailed examination of the photometric data indicates that QQ Vul undergoes a stellar eclipse of the X-ray emitting region, indicative of a high binary inclination. We discuss possible implications for the nature of this system given the observed shape of its EUV and X-ray light curves.

Subject headings: accretion — cataclysmic variables — stars: individual (QQ Vul) — ultraviolet: stars — X-rays: stars

1. Introduction

Polars, or AM Her systems, a subset of magnetic cataclysmic variables (CVs), are a unique class of CVs. As with the typical CV, polars contain a white dwarf which accretes matter from a Roche lobe-filling low-mass secondary star. However, unlike a typical CV, the white dwarf in a polar has a magnetic field strength on the order of a few tens of megaGauss (MG). These strong magnetic fields cause the disruption of the accreted material that would otherwise form an accretion disk. Instead, material transfer is routed on to the white dwarf in the form of an accretion stream which follows the path of one or more of the magnetic field lines to impact the surface at one or both of the magnetic poles. As the material approaches the white dwarf, a shock front is created where impact energy is released in the form of extreme ultraviolet (EUV) and X-ray photons. Surface heating, of up to a few hundred thousand degrees Kelvin, and possible penetration of the surface by material blobs completes the accretion region production of high energy flux. Cropper (1990) presents a detailed review of polars.

\textsuperscript{1}Present address: Head, Astrophysics Group, Planetary Science Institute, 620 N. 6th Ave. Tucson, AZ 85705
Since the accretion regions in polars are the site of the majority of high energy emission, we would expect that EUV and X-ray observations would provide a wealth of information about their accretion geometry. This is indeed the case as shown, for example, by Sirk & Howell (1998). Differentiation and study of eclipses of the accretion region by the secondary, the far and near accretion stream, and the white dwarf (a self-eclipse; when the rotation of the CV system causes the accretion pole to pass behind the limb of the white dwarf), allows a number of system parameters to be determined. These include the inclination of the system, the position of the accretion pole on the white dwarf, and if the white dwarf is accreting at one or both of its magnetic poles. With this type of study in mind, one of us (SBH) placed QQ Vul on the target list of the EUVE satellite Right Angle Program (McDonald et al. 1994).

2. Previous Observations of QQ Vul

Serendipitously discovered in a survey of soft X-ray sources (Nugent et al. 1983), QQ Vulpeculae was confirmed as an AM Her binary through detection of circular and linear polarization (Nousek et al. 1982, 1984). QQ Vul has a relatively long orbital period for a polar, $P_{\text{orb}} = 222.5$ min (Nousek et al. 1984), and although the strength of the magnetic field has not been directly measured, it is assumed to be fairly typical, $\sim 20 - 30$ MG (Liebert & Stockman 1985). Blackbody fits to the spectrum of QQ Vul yield a temperature of $T \sim 2 \times 10^5$ K for the X-ray heated accretion regions (Nousek et al. 1984). Mass estimates of $M_1 = 0.58M_\odot$ and $M_2 = 0.35M_\odot$ have been determined for QQ Vul by Mukai & Charles (1987).

The initial multi-wavelength observations of QQ Vul (Nousek et al. 1984) were able to place some constraints on the system geometry. These observations suggested a system with a magnetic pole tilted $\sim 75^\circ - 85^\circ$ from our line of sight during the linear polarization pulse peak, an orbital inclination of $46^\circ < i < 74^\circ$, and a stellar latitude of the accreting magnetic pole in the range $63^\circ < \Delta < 80^\circ$. Circular and linear polarization observations (Nousek et al. 1984) have revealed a weak and diffuse linear polarization pulse centered on maximum light, indicating that the near field accretion column is always in sight, although the pole does graze the limb during a self-eclipse (Cropper 1998). The polarization data also suggest that there is non-radial accretion flow (McCarthy, Bowyer, & Clarke 1986; Cropper 1998) implying a “kink” in the accretion stream which flows to the magnetic pole.

Throughout its history of observations, QQ Vul has repeatedly shown a complex and varying X-ray light curve. Studies undertaken with the use of *Einstein* (Nousek et al. 1984), *ROSAT* (Beardmore et al. 1995), and *EXOSAT* (Osborne et al. 1986, 1987) have all shown the complexities apparent in the X-ray component of QQ Vul. Osborne et al. (1987) found that the soft X-ray count rate had doubled within a period of two years and that the shape of the light curve they observed was indeed quite different from the initial X-ray light curve of QQ Vul (Nousek et al. 1984). Figure 1 in Osborne et al. (1987) provides a comparison of the different X-ray light curves previously obtained for QQ Vul.
There has been conflicting evidence for whether or not QQ Vul possesses two accreting poles. While the double peaked nature of the soft X-ray light curves of Osborne et al. (1986, 1987) might lead one to interpret it as two-pole accretion, it is noted there that the second pole is not evident in the optical light curve. Other observations (Beardmore et al. 1995) detected soft X-ray spectral variations as a function of orbital phase which could be modeled by an extended multi-temperature accreting region or by two accreting poles with slightly different temperatures. However, all of these previous observations do agree that if two-pole accretion is taking place, the primary accreting pole is a weaker source in soft X-rays. Recent polarization data seem to strongly suggest that QQ Vul is undergoing two-pole accretion. Optical polarization data from Schwope (1991) cannot be explained by one-pole accretion and a second linear polarization peak, seen in the data of Cropper (1998), requires a second accreting region to be in view at certain binary phases.

### 3. EUVE Observations and Data Analysis

The EUV photometric data were obtained with the EUVE satellite using the right-angle pointing Scanner Telescopes A and B. Scanner A imaged QQ Vul through a Lexan/Boron filter (\(\lambda_{\text{peak}} = 89\) Å), sensitive in the bandpass 50 – 180 Å while Scanner B data were obtained in an Al/Ti/C filter (\(\lambda_{\text{peak}} = 171\) Å), sensitive in the bandpass 160 – 240 Å. Details of the photometric properties of the imaging telescopes on board the EUVE may be found in Sirk et al. (1997).

Our observations of QQ Vul began on 1996 Aug 11 (GMT) and continued through 1996 Aug 16 (GMT), spanning \(\sim 1.5 \times 10^5\) s, or a total of \(\sim 11P_{\text{orb}}\). The data were passed through EUVE standard processing and delivered to us in compressed format on CD-ROM. We then extracted the scanner observations using the standard EUVE data analysis software packages within IRAF. Photometry was performed using an aperture with a seven pixel radius centered on the coordinates of the source and a background annulus having a radius of twenty pixels also centered on the object. Due to the large difference in signal-to-noise obtained in the two data sets, every 100 data points (photon events) were binned together for the raw data from Scanner A, and every 30 data points were binned together for the raw data from Scanner B. An IDL program (written by M. Sirk) was then used to produce light curve data files that were phased according to the ephemeris of the inferior conjunction of the secondary star in QQ Vul, HJD 2448446.4710(5) + 0.15452011(11)E (Schwope et al. 1998a). Finally, our resultant light curves, in both Scanner A (Lexan/B) and Scanner B (Al/Ti/C), were rebinned to 0.005 in phase.

Figures 1 and 2 present our obtained EUVE light curves phased on the Schwope et al. (1998a) ephemeris. Convolving the mean EUV count rate of 0.01 counts/second with the effective area as a function of wavelength for the Lexan/B filter (Sirk 1999), we find that the observed EUV flux is \(4.74 \times 10^{-14}\) ergs s\(^{-1}\)cm\(^{-2}\). It is interesting to note that Scanner B, viewing QQ Vul through the Al/Ti/C filter, detected anything at all. At a wavelength of 171 Å, and a hydrogen column density of \(N_H \sim 10^{20}\) cm\(^{-2}\) (Osborne et al. 1986) for a distance to QQ Vul of 215 pc (Mukai & Charles 1986), the optical depth is \(\tau \sim 14\). At such a large optical depth, the ISM transmission
of photons from QQ Vul at this wavelength is essentially zero. We would therefore not expect to
detect photons through this filter and indeed no other polar has been detected by EUVE in Scanner
B at these wavelengths. However, the Al/Ti/C filter is known to have an X-ray leak peaking near
44Å (Finley et al. 1988; Vallerga & Sirk 2000), and we conclude that the data collected here with
Scanner B is an X-ray light curve for QQ Vul with a mean effective wavelength of \( \sim 44\text{Å} \). We note
that this is not the first detection of an X-ray leak with the Al/Ti/C filter; X-ray leaks were also
reported in EUVE observations of the nova V1974 Cygni (MacDonald 1996; Stringfellow & Bowyer
1996).

One flaw in our conclusion concerning the X-ray light curve would be if QQ Vul were actually
quite close by in space, say less than 50 pc. We therefore independently re-determined the distance
to QQ Vul using Bailey's method (Bailey 1982) and newly obtained infrared observations. Bailey’s
method relies on the relationship between certain physical parameters of the secondary star in the
CV system and the distance to that system. The relation is:

\[
\log d = \frac{K}{5} + 1 - \frac{S_K}{5} + \log \frac{R_2}{R_\odot}
\]  

(1)

where \( d \) is the distance, \( K \) is the \( K \)-band magnitude of the secondary star, \( S_K \) is the \( K \)-band
surface brightness of the secondary, and \( R_2 \) is the radius of the secondary star.

Using data kindly obtained by M. Huber with the Wyoming Infrared Observatory on 1998 Aug
30 UT (9:30 hours), we find that QQ Vul had a \( K \) magnitude of 14.0\pm0.1 mag. Taking \( S_K = 4.5 \)
(Bailey 1982), and \( R_2 = 0.43R_\odot \) (Nousek et al. 1984), the distance to QQ Vul is determined to
be 342 pc; a value which is in agreement with earlier measurements which suggest a lower limit
of \( \sim 215 \) pc (Mukai & Charles 1986). \( V,R, \) and \( I \) observations of QQ Vul by Mukai, Charles, &
Smale (1988) detected a visual “companion star” to QQ Vul with \( K \sim 14.5 \) (obtained using \( V-K \)
colors derived for \( K \) spectral type stars). If possible contamination from this star in the infrared
(i.e., \( K \) band) is taken into consideration, QQ Vul would be even farther away. Therefore, it seems
highly unlikely that the detected signal in Scanner B is due to 160 – 240Å photons but is instead
the aforementioned X-ray leak.

The effective bandpass of the X-ray leak in the Al/Ti/C filter is roughly triangular in shape
and covers the range of 15Å < \( \lambda \) < 68Å. The peak throughput, at 68Å, is \( \lesssim 2\% \) of the normal filter
transmission near 171Å and has zero sensitivity to photons with a wavelength below 15Å (Sirk
1999). Using the effective area ratio of the Lexan/B filter to the Al/Ti/C filter (Sirk 1999), and the
fact discussed above concerning the total absence of long wavelength photons, we can determine
that the X-rays observed for QQ Vul have wavelengths from 15 – 68Å, with a mean effective central
wavelength near 44Å. Performing an approximate integration under the triangular bandpass and
convolving it with the effective area as a function of wavelength, we find the observed X-ray flux
to be \( 3.60 \times 10^{-10} \) ergs s\(^{-1}\)cm\(^{-2}\). X-ray fluxes ranging from \( 1.5 \times 10^{-12} \) ergs s\(^{-1}\)cm\(^{-2}\) (Osborne
et al. 1987) to \( 2.25 \times 10^{-11} \) ergs s\(^{-1}\)cm\(^{-2}\) (Beardmore et al. 1995) have been reported in previous
studies, which, along with the value determined here, reflect the variability of the source.
We have thus obtained simultaneous time-resolved photometric data in the X-ray ($\lambda \sim 44\AA$) (Figure 2) and EUV ($\lambda_{\text{peak}} = 89\AA$) (Figure 1) wavelength regions which allow us to make a direct comparison of the emitting character of this system in these two wavelength regimes.

4. Discussion and Conclusions

The EUV and X-ray light curves, Figures 1 and 2 respectively, both show a double peak shape with minima occurring near phase 0.2 and phase 0.85 and maxima at phases 0.0 and 0.45. While each light curve reveals similar gross features, we note that there is far less change and detail in the EUV data. This could be due to the fact that QQ Vul has a broader, more diffuse EUV emitting region but a smaller, better defined X-ray emitting region. The modulations of both light curves are uneven in their minima and maxima. The minima alternate between a deep, essentially complete eclipse at phase 0.85 to a less deep and well-defined dip near phase 0.2, while the maxima shift between a narrow peaked one near phase 0.0 to a brighter, broader one covering about 0.4 in phase, centered at 0.45. The two maxima, while showing that the secondary pole is stronger in intensity, are probably nearly equal in phase extent and overall shape, the narrower one being "cut-off" around phase 0.9 by an eclipse of the magnetic pole accretion region by the near-field accretion stream (Sirk & Howell 1998).

Interpreted as a two-pole accretor, the locations of the two poles would have centers near binary phases 0.1 and 0.55, that is, almost directly along the line of centers of the binary. The eclipse by the near-field stream of the accretion region facing the secondary star occurs before phase 0 as is the case in most polars (Sirk & Howell 1998). The magnetic pole on the far side of the white dwarf suffers no eclipse, thus, it is visible in phase for approximately one-half of the orbital period, and its shape is consistent with a spot latitude of $55^\circ - 75^\circ$ (Sirk & Howell 1998) given a binary inclination of $60^\circ - 90^\circ$ (see below).

Figure 3 is a close-up of the X-ray light curve minimum near phase 0.8. It appears that this minima has two components. The first half of the broad dip, starting at phase 0.7, has a slow decline up to phase 0.85 and is likely to be the result of an eclipse by the near-field accretion stream. The remaining part of this dip shows an abrupt drop to near zero counts and appears to be flat bottomed from phase 0.85 to 0.92, with the most likely cause being a stellar eclipse of the X-ray emitting region by the secondary star. If true, this constrains the system inclination to be greater than $60^\circ$.

An interesting feature appearing in the X-ray light curve (Figures 2 and 3), but not seen in the EUV light curve, is the narrow dip which occurs at phase 0.96. Using other polar light curves as a guide, this narrow dip feature is likely to correspond to an eclipse of the accretion region by the far-field accretion stream. It may also be present in the EUV data but the noise level precludes its discovery. While unresolved, the short duration of this narrow feature (0.015 in phase or 3 min) provides strong evidence for the compactness of the hard X-ray emitting region in QQ Vul.
Translating this time in to a size on the white dwarf surface (without correction for latitude and assuming $R_{\text{WD}} = 7000\text{km}$) we find an emitting region diameter of 660 km or, if circular, $f = 0.002$.

Taking the gross ratio of the low EUV count rate to the higher X-ray count rate (even as a leaked signal) one could conclude that the magnetic field strength in QQ Vul is relatively low, possibly less than 10-30 MG (Ramsay et al. 1994). However, while in general a large X-ray to EUV ratio indicates a lower magnetic field strength in polars, this is not always the case with the difference attributed to the structure and size of the accretion region (Sirk & Howell 1998).

Figure 4 presents the hardness ratio (X-ray/EUV) for QQ Vul. Due to the low value of the flux in the EUV light curve, both the X-ray and EUV light curves were re-binned to 0.05 in phase, thereby allowing the hardness ratio to not be dominated by noise spikes due to the low EUV flux values. Figure 4 exhibits an increased hardness near phase 0.25, with a sharp rise near phase 0.3. This peak might indicate the emergence of the second accreting pole.

A comparison of our QQ Vul X-ray light curve with previous high energy observations shows that the continuous orbital variations and temporal changes, noted by Osborne et al. (1987), appear to be persistent. Some similarities, however, do exist between our X-ray light curve and the 1983 Oct and 1985 Jun EXOSAT light curves discussed in Osborne et al. (1986, 1987). For example, the unequal minima and maxima and even the presence of a narrow dip, probably due to an eclipse of the accretion region by the far-field accretion stream. This narrow dip feature occurs near phase 0.03 in the 1983 Oct EXOSAT light curve and 0.08 in the 1985 Jun EXOSAT light curve, compared with phase 0.96 seen in our light curve [according to the ephemeris of Schwipe et al. (1998a)]. The 1985 Sep EXOSAT light curve (Osborne et al. 1987), is very different from our present data as it exhibits a much different shape with nearly equal maxima and yet again a narrow dip but one which appears at yet another phase (phase 0.71) within the light curve. The fact that the narrow dip is always present but changes phase indicates a movement, within the binary, of the far-field accretion stream similar to that observed in HU Aqr (Schwipe et al. 1998b).

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Fig. 1.— EUV light curve for QQ Vul observed by EUVE/Scanner A with the Lexan/B filter ($\lambda_{\text{peak}} = 89\text{Å}$). The data are folded on the orbital period of 222.5 min according to the ephemeris of Schwpo et al. (1998a). Each point represents 0.005 in phase and the data cover nearly 11 consecutive binary orbits of QQ Vul. The error bars are 1σ values in the count rate for each phase bin.
Fig. 2.— X-ray light curve for QQ Vul observed by EUVE/Scanner B with the Al/Ti/C filter. These data represent an X-ray leak in the Al/Ti/C filter and have a mean effective wavelength near 44Å. This is the first X-ray detection of a polar with the EUVE satellite. The data are folded on the orbital period of 222.5 min according to the ephemeris of Schwope et al. (1998a). Each point represents 0.005 in phase and the data cover nearly 11 consecutive binary orbits of QQ Vul. The error bars are 1σ values in the count rate for each phase bin.
Fig. 3.— An expanded view of the X-ray minimum in QQ Vul at phase 0.8. One can clearly see the structure in the minimum including the near-field accretion stream absorption and the probable stellar eclipse of the X-ray emitting region by the secondary star (phases 0.85 to 0.92). The narrow dip seen near phase 0.96 is caused by an eclipse of the X-ray emitting region by the far-field accretion stream.
Fig. 4.— The hardness ratio ($\lambda \sim 44\text{Å}/\lambda \sim 89\text{Å}$) for QQ Vul. The X-ray and EUV light curves were re-binned to 0.05 in phase for this plot. The ratio shows a peak near phase 0.3, possibly associated with the appearance of the second accreting pole.