FUSE and IUE Spectroscopy of the Prototype Dwarf Nova ER Ursa Majoris During Quiescence

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Abstract
ER Ursae Majoris is the prototype for a subset of SU UMa-type dwarf novae characterized by short cycle times between outburst, high outburst frequency, and negative superhumps. It suffers superoutbursts every 43 days, lasting 20 days, normal outbursts every 4 days, and has an outburst amplitude of 3 mag. We have carried out a far-ultraviolet (FUV) spectral analysis of ER UMa in quiescence, by fitting Far Ultraviolet Spectroscopic Explorer and International Ultraviolet Explorer spectra with model accretion disks and high-gravity photosphere models. Using the Gaia parallax distance and an orbital inclination of 50°, we find that during the brief quiescence of only four days, the accretion rate is 7.3 × 10^{-11} M_{⊙} yr^{-1}, with the ER UMa white dwarf contributing 55% of the FUV flux and the accretion disk contributing the remaining 45% of the flux. The white dwarf in ER UMa is marked by hotter (32,000 K) than the other white dwarfs in dwarf novae below the cataclysmic variable (CV) period gap, which have typical temperatures of ~15,000 K. For higher inclinations of 60°–75°, the accretion rates that we derive are roughly an order of magnitude higher, (1–3) × 10^{-10} M_{⊙} yr^{-1}.

Key words: stars: dwarf novae – novae, cataclysmic variables

1. Introduction
ER Ursae Majoris is the prototype system of a subclass of SU UMa-type dwarf novae. Like SU UMa systems they exhibit two types of outbursts: normal and superoutbursts. These superoutbursts show superhumps that are ruled by tidal instabilities. In the canonical view of the cataclysmic variables superoutbursts show superhumps that are ruled by tidal instabilities. Yet, there were some systems that challenged the traditional SU UMa classification due to their frequency of outbursts, superoutbursts, and suspected unusually high mass-transfer rates for the dwarf novae below the CV period gap. Once ER UMa was discovered in the Palomar Sky Survey as an ultraviolet-excess object (Green et al. 1986), along with a handful of similar systems, it was clear that they belonged to a new subclass of SU UMa systems (e.g., Iida 1994; Kato et al. 1999). After the observation of dwarf nova outbursts in the system (Iida 1994), it was seen that ER UMa is characterized by an extremely high outburst frequency and short supercycles (Kato et al. 1999), suggesting a higher mass-transfer rate than other SU UMa systems. During a superoutburst, ER UMa was confirmed to have negative superhumps, a behavior observed since the 1990s. Negative superhumps are a dynamic behavior of the system in which the superhumps have a shorter period than the orbital period, and displayed retrograde precession (Harvey et al. 1995; Patterson et al. 1997; Patterson 1999; Skillman et al. 1999; Wood & Burke 2007; Montgomery 2012). This is thought to be due to an eccentric tilted disk. Some theories suggest that ER UMa is simply an evolutionary stage of classical novae, through studies of the recently subclassified ER UMa system, BK Lyncis (Patterson et al. 2012).

The published orbital and physical parameters of ER UMa are given in Table 1 along with the literature references. Dubus et al. (2018) take an inclination of 45° ± 10° for ER UMa, but the observation of sharp absorption lines in the optical may indicate that the system may have a low inclination (Szkody et al. 1996). The correct orbital inclination of ER UMa is unknown. Szkody et al. (1996) cite the line widths, small equivalent widths, and low radial velocity amplitude of ER UMa as indicating a low inclination. On the other hand, Thorstensen et al. (1997) found, using the double convolution method, that the separation of the Gaussian peaks is 1260 km s^{-1} and the radial velocity of the white dwarf (WD) is 48 km s^{-1}. If one assumes 1 M_{⊙} for the WD and 0.1 M_{⊙} for the secondary star and applies Kepler’s third law, the corresponding inclination is i ~ 50°. However, the uncertainties in this inclination value are large. First, the H$_{α}$ radial velocity curve of the WD obtained over four nights shows a large scatter. Thorstensen et al. (1997) caution that, in cases where there is an independent check on the gamma velocity and radial velocity semi-amplitude K of the WD, these two quantities rarely reflect the true dynamical motion of the WD. Furthermore, different emission lines may form in different parts of the accretion disk and thus it cannot be assumed that they manifest the true dynamical motion of the WD. Therefore, in view of the lack of a truly reliable value for the inclination, we carry out here an analysis of ER UMa far-ultraviolet (FUV) spectra for a range of values of the inclination, namely i = 18°, 41°, 65°, and 70°.

In Section 2, we present the FUV spectroscopic observations. In Section 3, we present the details of our accretion disk and high-gravity photospheric models, and we describe our analysis and model fitting results. Finally in Section 4, we summarize our conclusions.

2. Far-ultraviolet Spectroscopic Observations
In 1995, ER UMa was observed with the International Ultraviolet Explorer (IUE) and seven spectra were obtained during its 43-day supercycle (Szkody et al. 1996). The data
show large flux changes through the cycle with corresponding large spectral lines changes. The IUE spectrum presented here was obtained during quiescence on April 17 and exhibits

Figure 1. FUSE spectrum of ER UMa (flux vs. wavelength) obtained during quiescence. The sharp emission lines (H I and He II) are all due to daylight reflected inside the telescope, and only the broad emission lines of O VI (1032 and 1038 Å) and C III (1175 Å) are positively identified as originating from the source. Interstellar medium (ISM) absorption lines have been marked with tick marks in the middle of each panel and consist mostly of molecular hydrogen. Additional ISM absorption lines of N I, C II, Si II, Fe II, and Ar I have also been marked. The S IV, Si III and IV and C III absorption lines are from ER UMa. The airglow emission lines have been annotated above each panel with a cross inside a circle, and correspond mainly to the Lyman hydrogen series which have been annotated below each panel. FPN is a detector fixed pattern noise artifact.

Table 1
Orbital and Physical Parameters of ER UMa

| Parameter | Value | References |
|-----------|-------|------------|
| $P$       | 0.06366 day | Thorstensen et al. (1997) |
| $d$       | 374 pc     | Gaia       |
| $i$       | 18°–50°    | Szkody et al. (1996), Dubus et al. (2018) |
| $E(B - V)$ | 0.01      |            |
| $M_{\text{red}}$ | 1.0 ± 0.2$M_\odot$ | This paper |
| $M_2$     | 0.10$M_\odot$ | Dubus et al. (2018) |
| $q$       | 0.100     | Oshima et al. (2014) |

Table 2
Observation Log

| Telescope | Data ID | Date (UG) | Time (UT) | Exp. Time |
|-----------|---------|-----------|-----------|-----------|
| IUE       | SWP54455| 1995 Apr 17 | 22:04:26 | 8700      |
| FUSE      | D90514002 | 2004 Jan 15 | 08:56:38 | 806       |
| FUSE      | D90514003 | 2004 Jan 15 | 09:42:18 | 2249      |
| FUSE      | D90514004 | 2004 Jan 15 | 10:38:29 | 1169      |
| FUSE      | D90514005 | 2004 Jan 15 | 11:30:07 | 3615      |
| FUSE      | D90514006 | 2004 Jan 15 | 13:06:43 | 4119      |
| FUSE      | D90514007 | 2004 Jan 15 | 14:43:52 | 4204      |
| FUSE      | D90514008 | 2004 Jan 15 | 16:24:22 | 4178      |
| FUSE      | D90514009 | 2004 Jan 15 | 18:02:43 | 4274      |
| FUSE      | D90514011 | 2004 Jan 15 | 19:57:13 | 3161      |
| FUSE      | D90514012 | 2004 Jan 15 | 21:45:09 | 2910      |
mainly emission lines. The data were collected through the large aperture, low dispersion, short wavelength camera: SWP54455. No data were collected through the long wavelength camera, hence we do not have long wavelength coverage of the quiescent state of ER UMa. The \textit{IUE} spectrum of ER UMa in quiescence has a wavelength coverage of $\sim$1150–2000 Å. The exposure time is 8700 s, or about $\sim$1.6 orbital periods. The \textit{IUE} observation log for the SWP54455 data is in Table 2.

On 2004 January 15, ER UMa was observed in quiescence with the \textit{For Ultraviolet Spectroscopic Explorer} (\textit{FUSE}; Froning et al. 2012) with the low-resolution (LWRS; 30") aperture for 15 consecutive \textit{FUSE} orbits. However, only 10 exposures had valid data. The \textit{FUSE} spectrum presented here consists of the coadded 10 good exposures, totalling 30,625 s of good exposure time. The total (raw) \textit{FUSE} observation time was 13.5 hr, or about $\sim$8.8 orbital periods. The \textit{FUSE} observation log for the 10 exposures is in Table 2.

All spectral data were retrieved from the online Mikulski Archive for Space Telescopes (MAST) and were all processed and calibrated by the pipelines. For the \textit{FUSE} observations we used our suite of IRAF procedures, FORTRAN programs, and Linux shell scripts to post-process the data from the eight series (see Godon et al. 2012; e.g., taking care of the "worm"), with a wavelength coverage of 904–1188 Å. Due to the hydrogen cutoff (Lyman series/jump) the spectrum starts around 914 Å.

The \textit{FUSE} and \textit{IUE} spectra were dereddened assuming $E(B-V) = 0.01$ and using the extinction curve of Fitzpatrick & Massa (2007).

In Figures 1 and 2, we display the dereddened \textit{FUSE} and \textit{IUE} spectra, respectively, the continuum fluxes levels in both spectra matched up in the wavelengths region where they overlap between 1170 and 1180. Thus, the two spectra combined together cover a broader wavelength range than the \textit{FUSE} or \textit{IUE} spectrum alone. This wider wavelength coverage samples more of the spectral energy distribution (SED) of ER UMa which helps to achieve more accurate model fits. Figures 1 and 2 show the strongest lines identified for both spectra.

Table 3 highlights the characteristics of the identified lines in the \textit{FUSE} spectrum intrinsic to CVs, and the lines due to the ISM have been labeled as such (e.g., Godon et al. 2012). Some characteristic lines are not clearly identifiable in the spectral plot and therefore are not included in the table.

All the sharp emission lines (H I and He II) in the \textit{FUSE} spectrum of ER UMa are all likely due to daylight reflected inside the telescope (more than 50% of the observation took place during the daytime of the \textit{FUSE} telescope, i.e., when it is not in the shade of the Earth). The very broad emission lines of O VI (1032 and 1038 Å) and C III (1175 Å) are from the hottest...
component of the system located in the inner disk and exhibit a strong Keplerian broadening. There are possibly additional broad emission lines (e.g., C III 977 Å), especially in the very short wavelength region ($\lambda < 950$ Å, higher ionization species such as S VI, N IV), which might be broad enough to merge together to form the continuum observed in the range of $\sim 920 - 945$ Å. The spectrum displays many sharp and shallow ISM absorption lines mostly from molecular hydrogen (rotational and vibrational energy levels) and from some metals such as N I, C II, Si II, Fe II, and Ar I. The S IV, Si III and IV and C III absorption lines are from ER UMa as they are not as sharp. Taking into account that the FUSE spectrum was obtained over a period of time of the order of several binary orbital periods, the fact that we do see narrow absorption lines from the source (but not as narrow as the ISM lines) is an additional argument in favor of the low inclination.

Table 4 shows the identifiable lines from the IUE spectrum. The very strong S IV emission doublet is due to the high temperature of the hot component in the system. C IV is in emission too, and could be associated with a disk corona or the boundary layer. Finally, there is also a distinct blend of Al III lines, which, because of their apparent strength, could be due to a suprasolar abundance of Al III, perhaps accumulated from the thermonuclear ashes of previous novae that are either being fed back to the WD or are brought to the surface of the WD from below by a process such as radiative acceleration or forced (shear) convective mixing during outburst.

3. Synthetic Spectral Modeling and Analysis

The dereddened spectra were fitted with both disk and photosphere models in order to extract certain values for analysis such as WD mass, accretion rate, and inclination angle. The model accretion disks were implemented from the optically thick, steady state, disk model grid for solar composition better known as the standard disk model (Wade & Hubeny 1998). For these models, the accretion disk’s outermost radius, $R_{\text{out}}$, is chosen in
Figure 4. Same as in Figure 3 displaying the IUE spectral range.

Figure 5. Best-fit accretion disk model to the dereddened FUSE spectrum (alone) of ER UMa in quiescence. The solid blue line is the disk model with $M_{wd} = 1.03M_\odot$, inclination angle of $75^\circ$, and an accretion rate of $\dot{M} = 3.0 \times 10^{-10}M_\odot$ yr$^{-1}$, giving a scaled distance of 340 pc.
such a way that the effective temperature is around 10,000 K. Disk annuli beyond $R_{\text{out}}$ are neglected because they contain cooler zones with very little contribution to UV flux in the FUSE and IUE Short-wavelength Prime Camera (SWP) spectral range.

The Wade & Hubeny DISK models cover the following combination of inclination angle $i$, WD mass $M_{\text{wd}}$, and mass accretion rate $\dot{M}$: $i = 18^\circ$, $41^\circ$, $60^\circ$, $75^\circ$, and $81^\circ$; $M_{\text{wd}} = 0.35$, $0.55$, $0.80$, $1.03$, $1.21 M_\odot$. $\log(M) = -8.0$, $-8.5$, $-9.0$, $-9.5$, $-10.0$, $-10.5 M_\odot$ yr$^{-1}$. For the photosphere models, we used TLUSTY (Hubeny 1988) and SYNSPEC (Hubeny & Lanz 1995) to construct a solar composition, WD, stellar photospheres grid. The temperatures range from 12,000 to 60,000 K in 1000 to 5000 K step sizes. The stellar surface gravity is set to agree with the WD mass accretion disk models above. The projected stellar rotation rate is varied from 50 to 500 km s$^{-1}$, in steps of 50 km s$^{-1}$.

3.1. Low Inclination Models

Our disk and photosphere modeling starts with the parameters listed in Table 1. Having the Gaia distance removes one free parameter. Optical spectroscopic observations (Szkody et al. 1996; Thorstensen et al. 1997) reveal narrow line widths and low radial velocities in ER UMa ($K_1 \sim 50$ km s$^{-1}$), which may be indicating that the system orbital inclination may be low. Therefore, we first restricted the range of disk inclination angles in our disk modeling to be 18$^\circ$. The mass ratio $q = 0.10$ was taken from the study of the period of Stage A (positive) superhumps by Ohshima et al. (2014). We included a WD component in the model fits described below, not only to assess its flux contribution in quiescence relative to an accretion disk but also because its inclusion should help improve the fits to the observed absorption lines that are unaccounted for in the disk model itself.
With the Gaia distance of \( d = 374 \) pc, a disk inclination angle of \( i = 18^\circ \), we fit the observed combined FUSE + IUE spectrum with a WD mass of \( M_{\text{wd}} \approx 1.0 \pm 0.2 M_\odot \), with a temperature of \( T_{\text{wd}} = 30,000 \pm 5000 \) K, and a disk with a mass accretion rate of \( \dot{M} = 10^{-10.5} - 10^{-10} M_\odot \text{yr}^{-1} \). Fitting the FUSE and IUE spectra alone gives the same results.

In Figures 3 and 4 we display the best-fit accretion disk + WD model to the combined FUSE + IUE spectrum of ER UMa. For convenience the FUSE spectral range is shown in Figure 3 and the IUE spectral range is shown in Figure 4. This model has a WD mass of \( M_{\text{wd}} = 1.03 M_\odot \), a mass accretion rate of \( \dot{M} = 3.26 \times 10^{-11} M_\odot \text{yr}^{-1} \) and a WD surface temperature of \( T_{\text{wd}} = 32,000 \) K. The WD, with a radius of 5611 km (\( \log(g) = 8.6377 \)), which contributes 55% of the FUV flux and the accretion disk contributes 45%. To fit the absorption lines, the projected stellar rotational velocity, \( V_{\text{rot}} \sin i \), was set to 100 km s\(^{-1}\).

In the very short wavelengths of the FUSE range, Figure 3, the model has too little flux to fit the observed continuum flux level. Models with a higher WD temperature and/or higher mass accretion rate provide an adequate flux level there, but the distance obtained is far too large and the models steep slope do not agree with the IUE slope of the spectrum. These models also generate different absorption lines that were not observed. These models had to be discarded. Instead, it is more likely that the flux continuum in the very short wavelengths of FUSE is due to broad emission lines of N IV (\( \sim 923 \) Å), S VI (933 and 945 Å) merged together.

### 3.2. High Inclination Models

In Figure 5, we display the best-fit model accretion disk to the FUSE spectra of ER UMa. This model has a WD mass of \( M_{\text{wd}} = 1.03 M_\odot \), an inclination angle of 75°, and yields an accretion rate of \( \dot{M} = 3 \times 10^{-10} M_\odot \text{yr}^{-1} \). The scale-factor-derived distance
(344 pc) is well within the error bars of the Gaia parallax distance. Next we sought the best-fit models to the combined FUSE + IUE spectrum. This led to a best-fit disk model to the entire FUSE + IUE SWP spectrum displayed in Figure 6 where again the WD mass is $M_{\text{wd}} = 1.03M_\odot$, but now the disk inclination is 60°, the accretion rate is $M = 1 \times 10^{-10} M_\odot$ yr$^{-1}$, and the scale-factor-derived distance is 370 pc. In Figure 7, the combined spectrum is best fitted with a disk model having $M_{\text{wd}} = 1.03M_\odot$, a disk inclination angle of 75°, and an accretion rate of $M = 3 \times 10^{-10} M_\odot$ yr$^{-1}$, corresponding to a scale-factor-derived distance of 378 pc. In both of the best fits to the combined spectra, the flux contribution of a WD, although a minor contributor to the continuum flux, does help to improve the accuracy of the fit by accounting for the observed absorption lines. We note also that the best fits to the combined (FUSE + IUE) spectrum give essentially the same accretion rate as that derived for the FUSE-only spectrum in Figure 5. We also point out that Zemko et al. (2014), using optical observations, obtained an accretion rate for ER UMa in quiescence in agreement with the higher values given in Table 5.

### 4. Summary and Conclusion

In Table 5, we tabulate the best-fit accretion disk models for the two cases of high and low inclination. For an intermediate inclination of $i = 50^\circ$, we ran models with $i = 41^\circ$ and $60^\circ$ which nicely bracket 50°. Interpolating between the 41° disk model and the 60° disk model, we estimate that the accretion rate of ER UMa in quiescence is $7.3 \times 10^{-11} M_\odot$ yr$^{-1}$ for a disk inclination angle of 50°, 1.0$M_\odot$ WD, and the Gaia distance of 374 pc.

With a distance of 374 pc, and for a WD mass range of $M_{\text{wd}} \approx 1.0 - 1.2M_\odot$, we find that during the brief quiescence of only four days, the accretion rate has dropped to $10^{-10.5} - 10^{-10} M_\odot$ yr$^{-1}$, while the WD has a temperature of $30,000 \pm 5000$ K. This accretion rate agrees with dwarf novae quiescent mass accretion rates, however, the WD in ER UMa is much hotter ($\sim 30,000$ K) than other WDs in dwarf novae below the CV period gap which have typical temperatures $\sim 15,000$ K.

If the WD in ER UMa is heated by compressional heating alone, then the surface temperature during quiescence with an accretion rate of $2.1 \times 10^{-5}$ g s$^{-1}$ is given by $T_{\text{eff}} = 1.7 \times 10^7$ K ($\langle M \rangle /10^{-10.25} [M_{\text{wd}} / 0.9])$.

Thus, the WD should have $T_{\text{eff}} = 14,272$ K, a factor of two smaller than from our modeling of ER UMa’s FUV spectra in quiescence. For both the low inclination disk models and high inclination disk models, our estimates of the WD surface temperature are a factor of two hotter than the average WD temperature of the WDs in SU UMa systems below the period gap.

The WD during quiescent accretion might be heated not only by compression due to the weight of the accreted gas but also by the boundary layer. If, as expected for low mass accretion rates, the boundary layer is optically thin, then it advects energy directly into the outer layers of the WD and especially in its equatorial region. The broad strong emission lines of C III (977 and 1175 Å), O VI (1131.9 and 1137.6 Å), and also possibly of N IV (921.46–924.91 Å), S V (933.4 and 944.5 Å) are all indicative of the presence of a very hot component, namely the boundary layer.

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### Table 5: Synthetic Spectra Model Fit Results

| # | $M_{\text{wd}}$ | $T_{\text{eff}}$ | $M$ | $i$ | $d$ | Fig |
|---|---|---|---|---|---|---|
| 1 | 1.03 | 32 | $3.26 \times 10^{-11}$ | 18 | 374 | 3, 4 |
| 2 | 1.03 | ... | $7.0 \times 10^{-10}$ | 41 | 381 | ... |
| 3 | 1.03 | 32 | $4.5 \times 10^{-11}$ | 41 | 367 | ... |
| 4 | 1.03 | 30 | $1.0 \times 10^{-10}$ | 60 | 370 | 6 |
| 5 | 1.03 | ... | $3.0 \times 10^{-10}$ | 75 | 344 | 5 |
| 6 | 1.03 | 22 | $3.0 \times 10^{-10}$ | 75 | 378 | 7 |