Coordinated *Chandra* HETGS and VLA Radio Observations of the Active Coronae on the Short-Period Binary ER Vul (G0 V + G5 V)


*Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389, USA*

Edward Guinan

*Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085*

**Abstract.** We present results from a long (114 ksec) *Chandra* HETGS observation of the short period (P$_{\text{orb}} =$ 0.69 d) active binary ER Vul, which consists of two solar-like dwarfs with rotation rates $\sim$ 40 times that of the Sun. X-ray spectra were obtained on 2001 March 29-30 along with 10.5 hours of simultaneous VLA monitoring at 3.6 and 20 cm. The *Chandra* Medium Energy Grating (MEG) covers the wavelength range 1.8 - 40 Å in first order, while the High Energy Grating (HEG) covers 1.8-18 Å. These spectra show hot, multi-temperature coronal emission with emission lines ranging in temperature from O VII (2 MK) to Fe XXIV (30 MK). ER Vul showed continuous low-level variability throughout the observation with the largest flare peaking at slightly more than twice the "quiescent" level. Contrary to the behaviour of most longer period active binaries, no large, long-duration flares were detected, consistent with previous X-ray observations of this binary. The largest flare detected has a duration of only $\sim$ 30 minutes, and appears to be very "solar-like". Unfortunately this flare was not observed in the radio, because the VLA observation had not yet started. The 20 cm radio emission shows a highly polarized (LCP) flare that has at best only a weak X-ray response. No evidence for eclipses was seen in either the X-ray or radio emission.

1. **Introduction**

Active binary systems possess outer atmospheres that display extreme stellar activity, because of their tidally-induced rapid rotation. Their coronae, transition regions, and chromospheres are being powered at close to the maximum activity level that stars seem able to maintain (Vilhu and Walter 1987). The study of such extreme coronal and transition region (TR) activity provides important clues to the physical processes powering these regions that may not be obvious in less active stars like the Sun. Flares occur frequently on active binary stars (Osten & Brown, 2000) with most systems spending 30-40% of the time flaring. Consequently, analysis of cool star coronal spectra must involve identification
of quiescent and flaring intervals with independent modelling of these different plasma conditions. While most RS CVn systems contain at least one star that has evolved significantly off the main sequence to become a subgiant or giant star, there are a few systems that contain two main sequence dwarfs; well known examples include $\sigma^2$ CrB (F6 V + G0 V, $P_{\text{orb}} = 1.14$ d) and $\xi$ UMa B (G5 V + G5 V, $P_{\text{orb}} = 3.98$ d). The most extreme examples of dwarf systems are the short-period ($P_{\text{orb}} < 1$ d) active binaries and in this paper we concentrate on the brightest of these systems, ER Vul.

ER Vul (HD200391, $V = 7.3$, $d = 50$ pc) consists of two solar-like (G0 V + G5 V) stars in a short-period ($P_{\text{orb}} = 0.694$ d = 59.96 ksec) detached binary system. Due to tidal effects both stars are rapid rotators with rotational velocities of 81 and 71 km s$^{-1}$ (Hill et al. 1990). Thus these stars are just like the Sun but are rotating at $\sim 40$ times the solar rate and consequently show extremely strong stellar activity. The stellar radii are slightly larger than 1 $R_{\odot}$ and the stellar surfaces are separated by only 2 $R_{\odot}$. Gunn and Doyle (1997) show definitively that ER Vul is near the activity saturation limit and that despite the small separation there is no evidence for significant amounts of circumbinary material. The inclination is $67^\circ$ (Hill et al. 1990; Olah et al. 1994) and the system is partially eclipsing with an eclipse depth of $\sim 0.2$ mag in V. The eclipse depth changes due to varying rotational modulation by large starspots that cover roughly a quarter of the stellar surfaces (Olah et al. 1994 and references therein). However, in X-rays and the EUV no eclipses have been seen.

The coronal emission from ER Vul has an X-ray luminosity of $\sim 10^{30.7}$ erg s$^{-1}$ (Dempsey et al. 1993a: corrected to the Hipparcos distance), a high level given that two dwarf stars are involved. The quiescent ROSAT PSPC count rate was $2.9$ ct s$^{-1}$ (Dempsey et al. 1993a) with ER Vul being the brightest of the short-period RS CVNs. White et al. (1987) found 10-20% variability but no eclipses in a 27 hr EXOSAT observation and derived coronal temperatures of 6 and 40 MK. The ROSAT PSPC data of Dempsey et al. (1993b) gave a two-temperature (2T) parameterisation of 2 and 13 MK, consistent with the softer response of the PSPC. Extreme Ultraviolet Explorer (EUVE) data spanning 7.5 days shows plenty of low level variability but no flares or eclipses (Rucinski 1998a). In October 1999 we observed ER Vul in a 85 ksec (27 days duration) ASCA observation: Once again continuous small-scale variability was seen but no discrete flares (Osten, Brown, Wood, & Brady 2002). The ASCA data were fitted both with a 2T parameterisation (8 and 19 MK) and with a continuous differential emission measure (DEM) distribution, that showed substantial emission measure between 7 and 24 MK.

Previous observations have shown that ER Vul is a bright, highly variable, nonthermal radio source with 6 cm flux densities in the range 3 to 8 mJy (Drake et al. 1986, Morris & Mutel 1988). Rucinski (1992, 1998b) monitored the 3.6 and 6 cm radio emission from ER Vul and detected many radio flares (unlike the situation in X-rays). The 3.6 cm radio emission varied by a factor of six during these observations. When significant radio flares occurred the contemporaneous EUVE DSS light curve showed no flare response in the EUV.
Figure 1. Light curves from *Chandra* MEG and HEG spectrometers. The data have been filtered for bad times intervals and to remove background photons. The signals from the two spectrometers provide an excellent check on the reality of coronal variability. Each bin represents 5 minutes of data. A flare with an enhancement at peak of twice the non-flaring count rate is clearly detected.

2. Observations

Simultaneous multiwavelength observations of stellar flares and other coronal variability offer an extremely powerful technique to determine the physical processes controlling thermal and nonthermal coronal plasmas. We observed ER Vul with *Chandra* for 114 ksec on 2001 March 29-30. The observations were made using the High Energy Transmission Grating Spectrometer (HETGS) in conjunction with the ACIS-S detector array. The HETGS disperses photons through two concentric sets of transmission gratings: the Medium Energy Grating (MEG) covers the wavelength range 1.7-40 Å in first order, while the High Energy Grating (HEG) covers the wavelength range 1.7-20 Å in first order, with almost twice the spectral resolution of the MEG in the regions of overlap. The observation utilized the Timed Exposure mode, in which the CCD events are accumulated over a frametime of 3.2 seconds before being read out.
Figure 2. A comparison of the MEG X-ray light curve and the VLA 3cm variability. An X-ray rise starting at March 29.5 is mirrored by a similar increase at 3 cm. Both light curves are shown binned to 5 minute intervals.

We processed the data using CIAO “threads” to eliminate bad aspect times, filter events based on energy and event grades, and eliminate “streak” events. The data were resolved into spectral events using region filtering and order separation. We generated light curves of the data by binning the MEG and HEG events in five minute time intervals. Because the intrinsic background is so low, no explicit background subtraction has been performed; the 1 σ error bars were calculated using Poisson statistics. The light curves from the MEG and HEG data are shown in Fig. 1. One moderate flare, starting at March 29.4, occurred during the Chandra observation, along with a few possible smaller enhancements.

The X-ray pointing was coordinated with a 10.5 hour (~ 0.4 day) VLA observation to study the effects of flaring on both the thermal and nonthermal coronal electron populations. The VLA was in B array and was operated as two subarrays providing simultaneous observations at 3.6 and 20 cm. The VLA data were calibrated and analysed using AIPS. 3C286 was used as the primary flux calibrator and the phase calibrator was 2115+295, which is located just over 3° away from ER Vul. Radio light curves were generated using the DFTPL routine, after extragalactic sources had been subtracted from the uv visibility data. The 3.6 cm radio light curve is compared with the X-ray variability in Fig. 2. The VLA started observing just after the flare seen in the HETG light curves; it is
not clear if any remnant radio flaring is still ongoing in the first few minutes of 3.6 cm observing. The 3.6 cm and 20 cm variability are compared in Fig. 3. The VLA recorded a large 20 cm radio outburst near the end of the observation.

3. Results

The *Chandra* spectra show a strong, multi-temperature spectrum with emission lines ranging in temperature from O VII (2 MK) to Fe XXIV (30 MK). The integrated MEG and HEG spectra are shown in Fig. 4. Emission lines seen in both spectra include the hydrogen- and helium-like lines of O, Ne, Mg, Al, Si, and S. Numerous iron lines are present spanning the ionization stages Fe XVII to Fe XXIV. Not enough counts are available during the short flaring interval to derive a useful flare spectrum.

For the first time, a definite X-ray flare has been observed on ER Vul. This flare is much more “solar-like”, with a simple morphology and only a 30 min duration, than the longer-duration outbursts seen on other RS CVn systems. Why might large flares, such as those regularly seen on $\sigma^2$ CrB (Osten et al. 2000), be absent on ER Vul? Perhaps the non-synchronous rotation leads to continuous suppression of large-scale magnetic structures.

Because the *Chandra* observation spans nearly two orbital periods of the binary system, we searched in the data for any evidence of eclipses or phase-
related variability. Primary eclipses occurred at March 29.713 and 30.411, while the relevant secondary eclipses were at March 29.364 and 30.062, based on the ephemeris of Hill, Fisher, & Holmgren (1990). No eclipses are seen in either X-rays or the radio. The coronal emitting regions must be large enough to make eclipses of the high-activity poles undetectable in both X-rays and radio. The coronal emission is clearly coming from regions significantly larger than the stellar disks and, given the small separation, the coronae of the two stars must be continuously interacting.

The 3.6 cm radio emission from active binaries is normally due to nonthermal gyrosynchrotron emission. Thus the 3.6 cm light curve of ER Vul should be showing changes in its nonthermal electron population. These changes are fairly mild with the flux density increasing slowly by roughly a factor of three over 10 hours. The 20cm emission is generally a mix of nonthermal gyrosynchrotron and coherent emission. For most of the observation the 20 cm emission is fairly steady. A coherent, highly-polarised 20 cm radio flare was detected during the last 90 minutes of the observation. This flare is 100% left circularly-polarised and is presumably due to plasma emission. A weak delayed response is seen at 3.6 cm towards the end of the 20 cm outburst. No counterpart to the radio flare is seen in the Chandra X-ray light curve.
Acknowledgments. This work was supported by Chandra X-ray Observatory General Observer grant GO1-2016X, and NASA grants NGT5-50241 and NAG5-3226 to the University of Colorado. This paper is based on observations obtained using the Chandra X-ray Observatory and the Very Large Array: The Very Large Array is part of the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

References

The bluster at Noordwijk beach sometimes exceeded that at the sessions