VLA Observations of Radio Variability of ER Vulpeculae in 1995

SLAVEK M. RUCINSKI
Canada-France-Hawaii Telescope Co., P. O. Box 1597, Kamuela, HI 96743; rucinski@cfht.hawaii.edu

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ABSTRACT. VLA continuous monitoring of the close, short-period binary ER Vul during two 11.5 hr sessions in 1995 September in the radio continuum at 3.6 cm (X band) showed a variation pattern similar to that observed in 1990 and 1991, but at a lower mean flux level and with no evidence for a phase dependence, contrary to reports in an earlier paper. Simultaneous observations with the Extreme Ultraviolet Explorer in the 70–140 Å band did not show any significant EUV flaring which would correlate with the radio emission.

1. INTRODUCTION

ER Vulpeculae (HD 200391) is a very close, short-period (0.7 day), detached binary system consisting of two almost identical solar-type stars locked in synchronous rotation with the rotation rate some 40 times faster than the Sun. The stars are—as expected—very active and show many signatures of magnetic activity, manifested by strong chromospheric and coronal emissions as well as rapidly evolving, dark photospheric spots. The system was subject to several analyses of its activity, usually in studies that included other, similar, very active, strongly spotted, short-period binary systems. One of the most recent photometric analyses specifically of this system was by Olah et al. (1994); this paper should be consulted for a complete review of the previous literature. An extensive spectroscopic study of the system was presented by Hill, Fisher, & Holmgren (1990).

Of all signatures of activity in active stars, radio emission and its variability are the least explored owing to very low observed fluxes and the implied necessity of using large radio telescopes. In the case of ER Vul, about $10^{-6}$ of the bolometric luminosity is converted into the radio emission (Rucinski 1992, hereafter R92). Although this bolometric-to-radio flux conversion is some $10^5$ times larger than for the solar case and the system is very active and radio bright, the observed fluxes are low; for the distance of ER Vul, the flux levels are typically 1–10 mJy. Because of these low fluxes, studies of rapid variability require application of a 100 m class radio telescope, such as the VLA.1

ER Vul was observed before with the VLA radio telescope system in 1990 and 1991 in a variability-monitoring program described in R92. This reference should be consulted for earlier literature on the subject and for several details that are omitted in the current paper. The continuum spectral bands were 20 cm (L band) and 6 cm (C band) in 1990, whereas most of the 1991 observations were at 3.6 cm (X band) with only single flux-level checks at 6 cm. Each time, about 23 hr of monitoring were used, in two continuous runs. During each run, the star showed a complex variability pattern, apparently a mixture of short flares typically lasting minutes and continuous variations with timescales of hours. The latter seemed to be partly related to the orbital phases and thus possibly due to optical depth effects in a complex magnetosphere surrounding both stars. The fluxes at 3.6 and 6 cm were very similar in 1991, which suggests a flat radio spectrum. A drop in the overall radio activity level was noted between 1990 and 1991.

This paper describes 3.6 cm VLA observations of ER Vul in 1995 conducted in a very similar way as in 1990 and 1991. However, in contrast to the previous VLA runs, which did not have any simultaneous support, the 1995 run was scheduled during an Extreme Ultraviolet Explorer (EUVE) program that lasted 1 week (Rucinski 1998) and provided extreme-ultraviolet spectra of the star. During these observations, the photometric Deep Sky Survey channel (70–140 Å) was activated, which provided an opportunity of seeking correlations between variabilities in thermal (EUV) and nonthermal (radio) components of the coronal emission. The results are described in § 3 following § 2, which describes the observations.

2. VLA OBSERVATIONS

The 1995 observations reported in this paper were done almost exactly in the same way as in 1991; that is, only at 3.6 cm (X band) and during two 11.5 hr continuous runs. The standard VLA continuum frequencies centered at 8.415 and 8.465 GHz with bandwidths of 50 MHz were used. The main differences relative to the 1991 run were twofold: (1) because of the VLA and the EUVE satellite scheduling constraints, the two sessions were not on consecutive days, but were separated by 3 days; (2) the planned, single, 6 cm (C band) observations

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1 The Very Large Array is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
to check the X-band/C-band relative fluxes were inadvertently omitted precluding verification that the C- and X-band fluxes were again comparable in 1995, as they had been in 1991.

The observations were made in equal time intervals of about 15 minutes with the calibration of the scans against the same phase calibrator 2113+293. Individual scans, about 11±12 minutes long, were analyzed using the AIPS. Cleaned radio maps were obtained for all scans; then radio emission fluxes were extracted from the maps assuming a point source at the position of ER Vul. Two different two-dimensional Gaussian fitting routines, JMFIT and IMFIT, were used for the flux extraction. The data in the two 50 MHz spectral bands were handled separately to obtain quasi-external estimates of the flux errors. The reason for this approach was the unrealistically small flux errors given by the two Gaussian fitting routines (R92). Estimation of the errors in this way led to a conclusion that the peak flux errors provided by the JMFIT were internally consistent, but required an upward scaling by a factor of 4.0 times for the first run and 4.5 times for the second run. The fluxes tabulated in Table 1 are the average values from both 50 MHz data sets. They are plotted in the upper panels of Figures 1 and 2. The data were not analyzed for circular polarization owing to the low flux levels. The previous observations (R92) did not show any polarization of the signal.

The times given for the scan midpoints in Table 1 are the heliocentric Julian Days based on the International Atomic Time scale (IAT). To correlate the stellar variability with the orbital orientation of ER Vul, the time shown in Figures 1 and 2 was also expressed in orbital phases counted from the same initial epoch as for the EUVE observations (Rucinski 1998). The ephemeris for the primary (deeper) eclipses was that of Hill et al. (1990): JD(hel) = 2,446,328.9837 + 0.698095E, which is apparently still valid, as had been verified 1 yr before our observations by Zeinali, Edalati, & Mirtorabi (1995). For consistency with the EUVE observations, the epoch $E =$

### Table 1: 3.6 Centimeter VLA Observations of ER Vul in 1995

| JD (IAT) - 2,449,980 | Flux (mJy) | JD (IAT) - 2,449,980 | Flux (mJy) | JD (IAT) - 2,449,980 | Flux (mJy) |
|----------------------|-----------|----------------------|-----------|----------------------|-----------|
| 4.404                | 0.31      | 4.757                | 1.70      | 7.572                | -0.21     |
| 4.414                | 0.25      | 4.767                | 1.57      | 7.582                | 0.06      |
| 4.424                | 0.05      | 4.778                | 1.51      | 7.594                | 0.19      |
| 4.435                | 0.26      | 4.788                | 1.54      | 7.605                | 0.19      |
| 4.445                | 0.30      | 4.799                | 1.48      | 7.615                | 0.22      |
| 4.456                | 0.32      | 4.810                | 1.70      | 7.625                | 0.23      |
| 4.466                | 0.36      | 4.821                | 1.85      | 7.636                | -0.19     |
| 4.476                | 0.02      | 4.831                | 2.25      | 7.646                | 0.04      |
| 4.487                | -0.13     | 4.841                | 2.30      | 7.657                | 0.27      |
| 4.497                | 0.24      | 4.852                | 2.45      | 7.667                | 0.15      |
| 4.508                | 0.56      | 4.862                | 2.82      | 7.677                | 0.22      |
| 4.518                | 0.41      | 4.873                | 2.71      | 7.688                | 0.16      |
| 4.528                | 0.36      | 4.883                | 2.98      | 7.698                | 0.16      |
| 4.539                | 0.21      | 4.893                | 3.42      | 7.709                | -0.03     |
| 4.549                | 0.39      | 4.904                | 2.86      | 7.719                | -0.15     |
| 4.559                | 0.35      | 4.914                | 2.80      | 7.729                | 0.16      |
| 4.570                | 0.39      | 4.924                | 2.44      | 7.740                | 0.38      |
| 4.580                | 0.18      | 7.392                | 0.28      | 7.750                | 0.27      |
| 4.591                | 0.20      | 7.405                | 0.04      | 7.760                | 0.05      |
| 4.601                | 0.27      | 7.416                | 0.07      | 7.771                | -0.04     |
| 4.611                | 0.03      | 7.427                | 0.00      | 7.781                | -0.16     |
| 4.622                | 0.32      | 7.437                | 0.42      | 7.792                | -0.01     |
| 4.632                | 0.50      | 7.447                | 0.74      | 7.802                | 0.23      |
| 4.643                | 0.72      | 7.458                | 0.36      | 7.812                | 0.30      |
| 4.653                | 0.84      | 7.468                | 0.03      | 7.823                | 0.26      |
| 4.664                | 0.90      | 7.479                | 0.39      | 7.833                | 0.23      |
| 4.674                | 0.97      | 7.489                | -0.02     | 7.844                | 0.35      |
| 4.684                | 1.36      | 7.499                | 0.25      | 7.854                | 0.38      |
| 4.695                | 1.78      | 7.510                | 0.24      | 7.864                | 0.31      |
| 4.705                | 1.84      | 7.520                | 0.46      | 7.875                | 0.67      |
| 4.715                | 1.99      | 7.530                | 0.01      | 7.885                | 0.64      |
| 4.726                | 1.94      | 7.541                | 0.03      | 7.895                | 1.26      |
| 4.736                | 2.04      | 7.551                | 0.24      | 7.906                | 1.78      |
| 4.746                | 2.03      | 7.562                | 0.42      | 7.916                | 1.78      |

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1 Astronomical Image Processing System (AIPS) is a data reduction software packages developed by National Radio Astronomy Observatory.
Fig. 1.—Changes of the 3.6 cm continuum flux of ER Vul are shown in the upper panel. The time on the lower horizontal axis is expressed in orbital phases counted from an assumed epoch of the primary eclipse, as described in the text. The upper horizontal axis gives the time in days since 00:00 UT on 1995 September 23. The lower panel shows EUVE observations in the 70–140 Å band, binned in 100 s intervals and expressed as count rates per second. The line segments connect the mean count rate values in groups of data points for each orbital visibility period of EUVE. The error bars in both panels have lengths equal to two standard errors.

Fig. 2.—Same as in Fig. 1, but for 1995 September 26.

5230 was used as the start of the phase count in Figures 1 and 2.

3. RESULTS

The pattern of variability seen during the first run on 1995 September 23/24 was very similar to that seen in the 1990 and 1991 observations, with changes taking place in an hourly timescale, that is in about 0.1–0.2 of the orbital period. The flux levels were very low, close to the typical measurement errors (at or below about 0.3 mJy) at the beginning of the run but then climbed to about 3 mJy at the end of this run, which coincided with the primary eclipse of the binary system. Three days later, on 1997 September 26/27, practically no emission was observed for a long period of time at the orbital phases around the primary eclipse; then, a slight increase was observed at the very end of this day. Thus, during this series of observations, practically no relation to the orbital phases was seen, contrary to what had been observed in 1990 and 1991.

The DSS data in the 70–140 Å continuum that were obtained during the radio observations are shown in the lower panels of Figures 1 and 2. The sampling interval used for the DSS photon accumulation was 100 s. Such intervals were grouped together by the satellite orbital visibility periods. The short line segments in the figures connect mean values for such groups in an attempt to accentuate any hourly timescale variability in the DSS count rate. Although small EUV flares were observed during the whole EUVE run, no significant variability was detected during the portion that overlapped with the radio observations. The DSS data turned out to be consistent with a steady count rate of about 0.14 counts s\(^{-1}\). Apparently, ER Vul was observed during a time at which its magnetic activity was generally at a low state.

We note that the DSS light curve obtained during the whole duration of the EUVE run (Rucinski 1998) showed a mild increase in the quiescent level in the phase interval between the primary and secondary eclipses (phases around the first quadrature at phase 0.25), with a few localized, flarelike increases toward the end of the other half of the orbital period. Higher activity during the first half of the DSS light curve
could be related to the highly variable optical light curve in the same phase interval, as observed by Olah et al. (1994) in 1990–1992 and possibly also by Zeinali et al. (1995) 1 yr before the VLA observations. We see nothing unusual in this phase interval in the 1995 VLA observations. To the contrary, the radio flux was the lowest in the phase interval between the primary and secondary eclipses.

Concerning the radio flux levels in different years, it is obviously risky to assume that radio emission observed during 23 hr long runs in 1990, 1991, and 1995 may be taken to represent typical flux levels for each season. However, if we assume that risk and analyze the observed flux levels in the form of histograms, as in Figure 3, we see a systematic drop over those 6 yr. In terms of the global averages for each program, the mean flux levels were 4.86, 1.16, and 0.74 mJy, while the median flux levels were 4.80, 1.05, and 0.32 mJy. Unfortunately, we have no other data on activity of ER Vul with which to correlate these numbers and to check if the decrease in the radio emission was accompanied by similar decreases in spot, chromospheric, or coronal activities in 1995.

4. CONCLUSIONS

Radio observations of ER Vul in 1995 in the continuum at 3.6 cm gave a very similar picture to those seen during the programs conducted in 1990 and 1991 (R92). A similar type of variability was detected with the dominant slow, hourly timescale variations at the flux levels between nondetection and about 3 mJy. However, this time, the average radio flux levels were the lowest so far observed, and no traces of any phase dependence were seen in the data. The contemporaneous EUV continuum (70–140 Å) observations did not show any flaring variability that would correlate with the radio flux variations. While the new observations do not bring any changes to the previous picture established by the more extensive program (R92), they will contribute to future studies of long-term radio variability in ER Vul.

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