Four Years of Multi-Wavelength Observations of the RS CVn System HR 1099 (V711 Tau)

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Abstract. We report on four years of multi-wavelength observations of the RS CVn binary HR 1099 (V711 Tau) from 1993, 1994, 1996, and 1998. In total, EUVE observed the system for a duration of 2.4 megaseconds (Ms) in these four years. The campaigns consist of a core of EUVE and radio observations for all four years, plus ultraviolet (IUE + HST) and X-ray (ASCA, RXTE, and BeppoSAX) coverage. We report on the changing activity of the system as recorded in the EUV: in 1993, 1994, and 1996, the system spent > 75% of the duration of the EUVE observations in a flaring state, while in 1998 > 90% of the observation appeared to be non-flaring. Radio, UV, EUV, and X-ray flares generally are well-correlated, with radio bursts preceding higher energy flares. This multi-wavelength flare behavior is in general accord with trends seen during solar flares.

1. Introduction

HR 1099 is a binary composed of a G5 subgiant and a K1 subgiant, whose 2.8 day orbital and rotational periods are tidally synchronized (Fekel 1983). As a bright and variable system in almost all wavelength regions, HR 1099 has been the subject of numerous past observations from radio to X-ray wavelengths. The system is remarkable for its prodigious output of chromospheric, transition region, and coronal emissions, as well as its propensity for frequent flaring. RS CVn binaries are important because the high rotation rates allow for the study of solar-like activity phenomena in a far from solar regime. Optical studies reveal the presence of long-lived large, cool photospheric spots, reminiscent of sunspots but covering a much larger fraction of the stellar disk and tending to occur at high latitudes (Vogt et al. 1999). RS CVn systems spend about 40% of the time in a flaring state (Osten & Brown 1999), with energetic releases up to one million times that of the most energetic solar flare.

Because of the temperature structure of cool star atmospheres, observations in multiple wavelength regions effectively allow us to observe the characteristics and dynamics of plasma at different vertical heights in the atmosphere. Such an approach is especially useful in stellar flare studies, where correlated dynamics gives a clue to the underlying physical processes at work during a flare. Solar
flares produce radiation from \( \gamma \)-rays to meter wavelength radio waves, implying that a range of different emission mechanisms operate during a flare. Multi-wavelength studies of stellar flares are limited to those wavelength ranges where the emission is strong enough to be detected with available instrumentation. In practice, the main frequency bands of use are the microwave, optical/infrared, ultraviolet (UV), far ultraviolet and extreme ultraviolet (EUV), and soft X-ray (SXR). Recently, there have been a few detections of hard X-ray (HXR) emission during stellar flares (see the review by Pallavicini 2001).

Extensive studies of solar flares have revealed numerous spatial and temporal correlations between emission in different wavelength regions. Centimeter, soft X-ray, and hard X-ray emission from solar flares are both temporally and spatially well-correlated (Kundu et al. 1994), with the centimeter and hard X-ray emission “bursts” occurring during the rise phase of the soft X-ray flare emission. There also is known to be a temporal correlation between UV and HXR bursts (Cheng, Tandberg-Hanssen, & Orwig 1984). A general picture of an impulsive solar flare as gleaned from multi-wavelength observations is discussed in Dennis & Schwartz (1989). Briefly, the radio emission arises from gyrosynchrotron radiation as accelerated electrons gyrate down field lines from the corona into the lower atmosphere, and these electrons produce hard X-ray bremsstrahlung emission when they impinge on the dense lower atmosphere and are collisionally braked. Subsequent heating of chromospheric material ablates this plasma into the corona, where it radiates thermal emission in the soft X-ray region.

Since HR 1099 is one of the brightest RS CVns in the radio, UV, EUV, and X-ray, and because it flares frequently, a series of campaigns was undertaken to investigate the nature of flares on this active binary system. The Extreme Ultraviolet Explorer (EUV) proved to be vital in these campaigns because of its long look times, which are well-matched to the long duration flares that occur frequently on active binary systems (Osten & Brown 1999), which can last for days. Flares that occur on faster timescales are more difficult to study because of the poor orbital efficiency of the EUVE satellite. Small flares also tend to show less enhancement over the “quiescent” emission in the EUV, as compared with observations in harder energy bandpasses. The low spectral sensitivity precludes a detailed temporal-spectral analysis, but the Deep Survey light curves at least indicate changing coronal activity. Combined with observations in other spectral ranges, this is a powerful method for investigating whether the solar analogy in multi-wavelength form applies to large stellar flares. We know already that there are numerous disparities between solar and stellar flares: in the energetics (stellar flares can release up to \( 10^6 \) times more energy than the largest solar flares); the durations (stellar flares can last for several days, while the longest solar flares are several hours at most); and the coronal temperatures (active binary systems achieve typical solar flare temperatures of \( \sim 25 \) MK in quiescence, and the stellar flaring temperatures generally are a factor of two or three greater). We present here a preliminary discussion of four separate multi-wavelength campaigns on HR 1099 that took place in 1993, 1994, 1996, and 1998. A detailed discussion of the large body of data which encompasses these campaigns is in preparation.
2. Observations

HR 1099 was observed in four different years with EUVE as part of multi-wavelength campaigns to record coronal variability on this active binary system. The total elapsed time of these four observations by EUVE amount to 2.4 megaseconds, or almost one month, giving us an unprecedented view of the changing coronal activity state of the system. Figure 1 summarizes the light curves from the four EUVE observations from these campaigns. The first three years of observations caught the system in very active states, as gleaned from variations in the EUV (Figure 1). Totalling the elapsed time the system appeared to be in a flaring state from the EUVE light curves, in 1993 and 1994 > 90% of the time the system was flaring. In 1996, ~77% of the observation duration showed HR 1099 to be flaring, while in 1998 only one short flare was observed; amounting to ~8% of the pointing.

![EUVE light curves](image)

Figure 1. Summary of EUVE light curves of HR 1099 from the four years of the campaign. A remarkable degree of coronal variability is present in the four different recordings – the observation in 1993 showed two large flares, compared with only one small burst in 1998. Each point represents one EUVE orbit.

A summary of the observations, wavelength coverage, and participating telescopes is given in Table 1. During the four different campaigns, there is core
coverage by EUVE in the extreme ultraviolet, and the Very Large Array (VLA) and Australia Telescope Compact Array (ATCA) in the radio, supplemented by X-ray and ultraviolet observations. Numerous flares were detected in all the wavelength regions. Figures 2, 3, and 4 detail the overlapping multiwavelength observations from 1993, 1994, 1996, and 1998.

<table>
<thead>
<tr>
<th>Year</th>
<th>Radio</th>
<th>UV</th>
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<tbody>
<tr>
<td>1993</td>
<td>VLA, ATCA</td>
<td>IUE, HST/GHRS</td>
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<tr>
<td>1994</td>
<td>VLA, ATCA, Sept. 13.6-18.4, Sept. 14.5-17.9</td>
<td>Sept. 16.4-19.2, Sept. 15.0-19.7</td>
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<tr>
<td>1996</td>
<td>VLA, ATCA, Aug. 25.3-28.6, Aug. 23.7-27.0</td>
<td>Aug. 23.5-28.7</td>
</tr>
<tr>
<td>1998</td>
<td>VLA, ATCA, Sept. 2.3-7.7, Sept. 2.6-7.0</td>
<td>...</td>
</tr>
<tr>
<td>1993</td>
<td>EUVE, Sept. 16.4-21.6</td>
<td>X-ray</td>
</tr>
<tr>
<td>1994</td>
<td>EUVE, Aug. 24.0-28.0</td>
<td>ASCA</td>
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<td>1996</td>
<td>EUVE</td>
<td>RXTE</td>
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<tr>
<td>1998</td>
<td>EUVE, Sept. 1.5-11.1</td>
<td>SAX, RXTE</td>
</tr>
<tr>
<td>1998</td>
<td>EUVE, Sept. 3.0-11.7</td>
<td>SAX, RXTE</td>
</tr>
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Interpretation of the large body of data collected during these four campaigns is complicated by the non-uniform data sampling and coverage offered by the different data sets. Nevertheless, some outstanding trends are noticeable. Where UV observations occur during a flare seen in the EUV or X-ray, the C IV flux appears to increase during the rise of the high energy flare. In two cases (shown in the left panel of Figure 2 and the left panel of Figure 3) the C IV fluxes peak before the EUV flare has peaked. In the second case, the peak of the C IV flux appears to coincide with the maximum of the radio burst. Solar research has shown temporal correlations between UV and HXR bursts; since the HXR emission is spatially and temporally correlated with microwave emission, one expects to see a correlation between the radio and UV emission if the solar analogy holds.

There does appear to be evidence of correlation between EUV/SXR emission and radio emission in these flares in accord with the temporal relationship expected from the solar analogy. During the rise of the small flare seen with EUVE and ASCA on 1994 August 25 (right panel of Fig. 2) there is a transient burst of radio emission at 3 cm, and some evidence of a rise in the C IV flux. During the rise of another EUV flare on 1994 August 26 (left panel Fig. 3), a microwave flare also is seen. Likewise, the large double EUV flare seen starting 1996 August 7 corresponds to two fast flares at 3 cm (left panel Fig. 4). The situation earlier in this campaign in 1996 is complicated by the number of small EUV flares and discontinuous radio observations (right panel Fig. 3). A large radio flare on 1996 September 3 shows no correlation with EUV/X-ray flares. A flare seen with EUVE on 1996 September 5 has no corresponding radio increase;
Figure 2. (left) Variation of EUV, UV, and radio emission during the 1993 campaign. Dashed line indicates peak of EUV light curve during this flare; dotted line indicates peak of UV emission. The UV flux appears to peak during the rise of a flare in the EUV. Radio observations were not simultaneous with UV data at the time of UV peak emission. A large radio flare at the start of the observation appears to be unrelated to the subsequent EUV and UV variations. (right) Variation of X-ray, EUV, UV, and radio emission on August 25, 1994. The C IV flux increases as the radio emission increases. A burst of microwave radiation occurs during the onset of a small flare in the SXR and EUV.

however there was a gap in radio observations immediately prior to the EUV flare. Also confounding is the moderately large flare seen in 1998 with RXTE, BeppoSAX, and weakly with EUVE, but shows no response in the radio (right panel Fig. 4). The one discernible flare seen with EUVE in 1998 on 6 September unfortunately occurred before the other telescopes in the campaign started taking data.
Figure 3.  **(left)** Variation of EUV, UV, and radio radiation later in the 1994 campaign. Dashed line indicates the peak of the EUV flare; dotted lines indicate peaks of microwave emission. The first radio burst coincides with the onset of the flare rise in the EUV and also with a peak in C IV emission. The second radio burst occurs near a break in the rise of the EUV flare. The third radio flare happens during the decay of the EUV flare, but may be related to the small “hump” in the EUV light curve just prior to the radio burst. **(right)** Variation of the X-ray, EUV, and radio observations during four days in 1996. Numerous X-ray and EUV flares are visible, along with several radio peaks. The complexity of the observations makes interpretation more difficult. The first enhancement seen by RXTE is not mirrored in the EUV light curve and has no corresponding signature in the radio. A radio burst on 3 September appears to have no correspondence in EUV/X-ray emission. The large flare seen with RXTE on 4 September shows only a modest increase in the EUV light curve, and may be accompanied by a small radio burst. Another larger flare in the EUVE light curve has no radio counterpart; this may be due to the lack of radio observations directly preceding the EUV flare.
Figure 4. (left) Light curves of EUV and radio variability during four days in 1996. Dashed lines indicate approximate time of peak emission in the EUV flare; the two flares seen here appear to sustain a constant level of emission after a rise to maximum, making the identification of the “flare peak” tentative. Dotted lines indicate times of peak radio emission during two bursts, both of which occurred while the rise of the EUV flare was commencing. Due to the lack of continued radio observations during the large EUV flare, we cannot follow the evolution of the radio emission during the double flare in the EUV. (right) Light curves from RXTE, BeppoSAX, EUVE, and of 3 cm microwave emission in 1998. A moderate flare is visible with BeppoSAX and RXTE, and barely visible in the EUVE light curve (without the aid of the higher energy emissions, such a bump would undoubtedly be relegated to “quiescent emission” in the EUV). There is no apparent response in the microwaves to this flare.

The pattern of correlations seen on HR 1099 are in the right sense to invoke the solar analogy as an explanation of the events seen here, when a definite correlation is seen. This invites the question of whether such flares are in fact scaled-up versions of solar flares. Whereas the temporal correlations observed during flares on the Sun in these wavelength regions occur on typical timescales of ~ seconds or less, the observed time delays between the microwave bursts and peak of the EUV/SXR emission here can range anywhere from just under one hour to several hours, or possibly as much as 1.2 days. There is a similar discontinuity in the flare durations – on the Sun, long duration flares last for several hours to a day at most, whereas on RS CVn systems, flares lasting several days are common (Osten & Brown 1999). The radiant energy release rate differs widely as well. For a solar flare releasing \( \approx 10^{32} \) ergs in the SXR in \( \sim 10^3 \) seconds, the energy release rate is \( \sim 10^{29} \) erg s\(^{-1}\). Using the details of the flare observed with ASCA in these campaigns, the net flare energy from 0.6 - 10
keV is $8 \times 10^{34}$ ergs after subtracting an estimate of the quiescent emission during the flare duration of 10.5 hours. This results in a sustained energy release of $2 \times 10^{30}$ ergs s$^{-1}$, an order of magnitude higher than in the solar case. We have already mentioned several other discrepancies between solar and stellar flares in temperature, density, and energy.

Multi-wavelength studies of flares on M dwarfs reveal a similar pattern as seen here for the evolved binaries. Hawley et al. (1995) used EUVE observations as a probe of the thermal corona, and optical measurements to diagnose the response of the lower atmosphere to nonthermal energy input, and found that the integrated impulsive phase radiation closely matched the instantaneous thermal emission. (See also the review by Hawley in this proceedings). This pattern, the Neupert effect, has also been observed in the SXR and radio (Güdel et al. 1996) for another M dwarf, and shows the applicability of solar flare evaporation scenarios in stellar environs.

The legacy of EUVE for stellar flare studies has been its capability of observing stars for long enough that the long duration flares could be identified and characterized. Combining this unique capability of EUVE with observations in other wavelength ranges has allowed us to expand the study of stellar flares to probe the interrelated dynamics of the stellar atmosphere during a violent coronal outburst. Preliminary results seem to indicate that the solar analogy holds, despite the severe disconnection between solar and stellar flare parameters.

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**References**


Dennis, B. R., & Schwartz, R. A. 1989 Solar Physics, 121, 75


Part 4

EUV Missions:
Past, Present, Future