CONTINUOUS COVERAGE OF HR 1099 WITH IUE DURING THE MUSICOS 1992 CAMPAIGN

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Abstract. Using the International Ultraviolet Explorer, we observed the bright RS CVn-type system HR 1099 (V711 Tau) continuously for two contiguous orbital/rotational cycles (Period$\sim$2.83 days) in December 1992. We are thus able to discriminate changes in the ultraviolet line fluxes and line profiles that are induced by stellar rotation from those that are sporadic (e.g. flares). These observations were coordinated with the 1992 campaign for Multi-Site Continuous Spectroscopy (MUSICOS). Supporting photometric and radio observations also were obtained simultaneously. We discuss the success of the observing campaign and present preliminary results from the ultraviolet spectroscopy. Our observations constrain the rise and decay phases of five flares, their energetics, and the dynamics within the flaring plasma. There was no rotational modulation of the ultraviolet emission line fluxes, but the Mg II line wings were variable.

1 Introduction

One of the outstanding questions in stellar astrophysics is the cause and nature of chromosphere and coronae about late-type stars. The "activity" is clearly related to magnetic fields, which confine the plasma in outer stellar atmospheres and which permit the transfer of energy from the convection zone into these tenuous layers. On the Sun, and presumably on other stars, these processes occur in localized "active regions". In order to arrive at any detailed understanding, it is necessary to *spatially resolve* those regions and to model the active atmosphere independently from the inactive atmosphere. Furthermore, we have seen that magnetic activity can be highly variable.

By obtaining a series of high-resolution line profiles from rapidly rotating stars, it is possible to spatially map their surfaces. Any stable, asymmetric distribution of active regions will induce phase-dependent asymmetries in the line profiles. The photosphere can thus be mapped using visual-band absorption lines (Vogt, Hatzes, Penrod 1987), while the chromosphere can be mapped using ultraviolet emission lines (Neff et al. 1989). The observations must be uniformly spaced, preferable continuously, throughout two or more subsequent rotational cycles of the star. This is readily done for the ultraviolet lines using the space-based International Ultraviolet Explorer (IUE). *Only the MUSICOS network is able to obtain this sort of coverage from the ground.*

In December 1992, we observed the RS CVn binary system HR 1099 (V711 Tau; HD 22468) both with the MUSICOS network (to spatially resolve the stellar photospheres) and with IUE (to spatially resolve their chromospheres). Ted Simon (Hawaii) was the Principal Investigator for the MUSICOS campaign. HR 1099 is a non-eclipsing ($i \sim 33°$) binary, and the synchronized orbital/rotational period is 2.83774 days. The $v \sin i$ of the primary (G5 IV) is 13 km s^{-1}, and for the secondary (K1 IV) it is 38 km s^{-1}. HR 1099 is an ideal system for a MUSICOS campaign because it is bright (V$\sim$5.7), and it lies on the celestial equator.

2 The Observations

2.1 International Ultraviolet Explorer

During the 6-day interval from 12 to 18 December 1992, we observed HR 1099 nearly continuously (with only two short gaps in our coverage) with the IUE satellite. This probably represents the longest continuous pointing at a single target ever made with IUE. We obtained 78 SWP low-resolution and 78 LWP high-resolution spectra, and we monitored the visual magnitude using the FES. The data were all calibrated with standard IUESIPS software and then measured using the ICUR package of one-dimensional spectroscopic analysis tools (Neff et al. 1989).

The scattered solar-light anomaly severely complicates the analysis of the visual light curve obtained with the FES. It also affected the LWP flux calibration, causing periodic "drop outs" as the scattered light background peaked each day. Scattered light did not affect the SWP images.

2.2 The MUSICOS Network Observations

The objective of the MUSICOS network was to obtain high resolution ($R > 30,000$), high signal-to-noise ($S/N > 400$), spectra of the Fe I (6430 Å) and Ca I (6439Å) lines continuously for approximately 3 days, with time resolution $t_{exp} < 60$ minutes. Table 1 lists the facilities used in this campaign. Nearly 100% phase coverage was obtained over one orbital cycle (16-19 December). These data will be used (see

Table 1: The MUSICOS 92 Doppler Imaging Core Campaign

Site	Institution	Telescope	# Clear Nights	Spectrograph
Mauna Kea	Univ. Hawaii	2.2 m	2.5 of 4	MUSICOS
Kitt Peak	NSO McMath-Pierce	1.5 m	0.5 of 4	solar-stellar
OHP	Obs. Haute Provence	1.5 m	2 of 4	Aurelie
Xinglong	Beijing Astron. Obs.	2.2 m	5 of 5	ISIS
AAT	Anglo-Australian Obs.	3.0 m	3 of 5	Zeeman-Doppler

Jankov and Donati; these proceedings) to construct an image of the photospheric starspot distribution to be compared with the chromospheric image to be derived from the high-resolution IUE observations.

2.3 Supporting Observations

In addition to the IUE and MUSICOS observations, a great deal of supporting observations were obtained. We have tried to summarize these in Table 2, but we might have inadvertantly omitted some. Where possible, we acquired imaging-quality data of the Fe I and Ca I lines before and after the campaign. Nearly 100% continuous phase coverage during the MUSICOS campaign was obtained for moderate-resolution Hα observations. Photometric observations were obtained throughout the season, with a special intensity during the campaign (and continuously using the IUE FES). Radio observations were obtained during the campaign from NOTO (Sicily) and from the VLA. There was a VLBI observation of HR 1099 scheduled for 19 December. We have assimilated most of the Hα observations. Cutispoto (these proceedings) is assimilating the photometric observations.

3 Preliminary IUE Results

3.1 Visual Photometry

We were able to obtain visual photometry of HR 1099 throughout the period of the IUE observations using the Fine Error Sensors on IUE (see Figure 1). We made every effort to obtain accurate photometry, recording the focus and temperature and making measurements before every spectroscopic exposure. Unfortunately, the background scattered light severely plagued the observations. The behavior of this background was roughly periodic with IUE's geosynchronous orbit. This is shown (on an arbitrary scale) along with the corrected visual light curve in Figure 1. Because we also obtained background ("sky") counts with each measurement, we were able to correct for this. Because the background rises rapidly, and because the sky

Table 2: Supporting Observations During MUSICOS92 HR 1099 Campaign

Observatory	Telescope	Dates	Observer	Comments
		Visual Spectroscopy		
Lick	3m	Sep - Nov	Hatzes, Vogt	Doppler imaging data
Lick	3m	1 Dec	Hawley	
Kitt Peak	Coude Feed	6-19 Nov	Welty, Hall	
Kitt Peak	Coude Feed	1-10 Dec	Huenemoerder	
Kitt Peak	McMath-Pierce	16-21 Dec	Saar	
Kitt Peak	2.1m	31 Dec - 2 Jan	Walter	
Lowell	SSS	Dec	Hall	bad weather; no data
Ritter	1m	Dec	Bopp	bad weather; no data
Penn State	1.6m	Jul-Dec	Neff	
Penn State	1.6m	15-31 Dec	Welty	bad weather; no data
ESO	1m CAT	7-18 Dec	Char	CaHK
ESO	1m CAT	19 Nov	Strassmeier	
Serra La Nave		13-16 Dec	Pagano	Hα
Bappu		12-14 Dec	Ghosh	Hα
Xinglong		15 Dec	Foing	Hα
Mt. Stromlo	1.9m	30 Nov	Butler	Hα; Doppler imaging
		Visual Photometry		
		(see Cutispoto et al. for a complete description)		
IUE	FES	12-18 Dec	Neff, Rodonò	continuous coverage
Villanova		Oct - Nov	Guinan	
Beijing		Nov - Dec	Zhang Xiaobin	
		Radio Observations		
VLA		8-16 Dec	Mutel	3.6, 6, and 20cm
NOTO		12-18 Dec	Umana, Trigilio	6cm

and star measurements are not obtained in precisely the same fashion, this correction is still not perfect. Nevertheless, it is virtually impossible to obtain this kind of continuous photometric coverage from the ground.

3.2 Rotational Modulation of Line Fluxes

The IUE spectra contain emission lines formed over the temperature range characteristic of HR 1099's chromosphere and transition region. A low-resolution SWP spectrum thus provide a spatially-averaged map of the temperature structure as a function of height. The rotational modulation of line fluxes can be combined with Doppler imaging results to piece together a three-dimensional atmospheric model (Walter et al. 1987). Unfortunately, very little rotational modulation was seen. Instead, the system was undergoing a period of extreme flaring activity. Five separate flares are easily seen in the ultraviolet light curve (Figure 2).

The most intense flare (at $\Phi = 1.56$) was saturated in several lines, so the actual enhancement could be arbitrarily higher. This was the brightest ultraviolet flare ever seen from an RS CVn system. The corresponding visual light enhancement (Figure 1) suggests that the bolometric output of the flare likely was also a record setter. At the beginning of the observing window, the system was undergoing the decay from what must have been an even larger flare.

The Mg II h integrated emission line fluxes, shown in Figure 2 show periodic dropouts, roughly corresponding to the times of high background. It is not clear why the background would affect the flux calibration. Because of the frequent flaring and flux dropouts, we could not determine whether the Mg II flux is rotationally modulated.

3.3 Mg II Line Profiles

The primary purpose of this observing campaign was to obtain a large number of high-resolution spectra of the Mg II lines (k: 2795 Å and h: 2803 Å). Any non-uniformly distributed chromospheric surface structure would manifest itself in phase-dependent asymmetries in these emission lines. The line cores are only marginally asymmetric at any phase. The line wings, on the other hand, frequently show large and variable asymmetries.

While in the process of analyzing these spectra, new data were obtained with the Hubble Space Telescope by Dempsey et al. (1994). These spectra were of far higher signal-to-noise and resolution. The line wings are far more detailed than we had supposed after inspecting the IUE data, so we have deferred a complete analysis pending the results of the HST program. The HST data have now been analyzed, and the results are in preparation. We will return to the December 1992 IUE data set, as well as all of the archival data of HR 1099, to probe the long-term behavior of the chromospheric structure and of the line wings.

3.4 Chromospheric/Transition-Region Flares

HR 1099 was undergoing an episode of frequent, but not steady, flaring in December 1992. Five dramatic flares are visible in the far-ultraviolet "light curve" (Figure 2). Integrated line fluxes have been used to measure the rise and decay timescales, relative flux and density enhancements, and the total energy loss due to the flares. In Table 3 we list the non-flare mean flux for several bright emission lines and for a density-sensitive line ratio. We then give the peak flux enhancement (lower limits) for each of the five flares.

During the most intense flare (14 December; $\Phi = 1.56$), the ultraviolet emission lines were extremely broad. At flare peak, the FWHM of the C IV line (derived by fitting a gaussian emission line to the unsaturated parts of the line) was 8.6 Å, compared to a non-flare mean given by the instrumental resolution (FWHM=7Å).

Table 3: Flare Peak ÷ Non-Flare Mean (10^{-13} erg s^{-1} cm^{-2}) Flux

DATE:	(NON-)	12 DEC	12 DEC	13 DEC	14 DEC	18 DEC
PEAK UT:	(FLARE)	1056	1810	1023	1117	0442
PEAK PHASE:	(MEAN)	0.87	0.96	1.20	1.56	2.87
N V 1240	2.1	2.2	2.2	2.2	8.4	2.1
Si IV 1394+1403	7.7	2.5	5.3	4.2	14.4	1.7
C IV 1549	29.1	2.9	4.3	3.3	8.8	3.2
C II 1335	17.7	2.4	2.3	2.2	4.7	2.0
Si II 1808+1817	12.9	1.5	1.0	1.3	2.6	1.5
O I 1304	12.2	1.6	1.9	1.5	4.0	1.6
Si III]^{1892}/C III]^{1909}	1.2	1.0	1.3	2.3	4.9	2.8
Mg II k 2795	>190	—	—	—	> 3.0	—
Mg II h 2803	150	—	—	—	2.2	—

The high-resolution LWP spectra (Figure 4) showed symmetric line wings with a gaussian FWHM of 8.5 Å for the k line and 3.48 Å for the h line, corresponding to velocity widths (with instrumental profile deconvolved) of 914 km s^{-1} and 362 km s^{-1}, respectively. The (saturated) k core width was >1.3 Å, compared to its non-flare value of 1.1 Å.

We have not yet determined the location or size of the flaring regions, but we should be able to derive this information using the techniques described by Linsky et al. (1989). The 14 December flare was the most intense and peculiar ultraviolet flare ever observed (see Neff 1991 for a review). The continuum flux was measurably enhanced even at the shortest wavelengths. Only one other flare (UX Ari in 1979) produced similarly broad line wings, but they were asymmetric (Simon, Linsky, and Schiffer 1980). We also clearly detect the subordinate Mg II lines at 2791 and 2799 Å. A more detailed analysis of these flares is in preparation.

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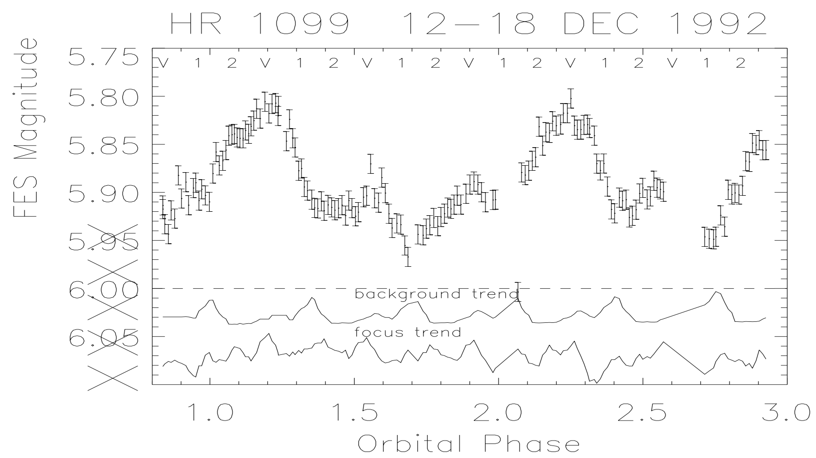

Figure 1: The IUE/FES permitted us to monitor the photospheric brightness of HR 1099 continuously for two continguous orbits. The background flared up periodically throughout the 6-day observing cycle, seriously affecting the FES magnitude. This figure includes a first-order correction that we applied to the raw counts.

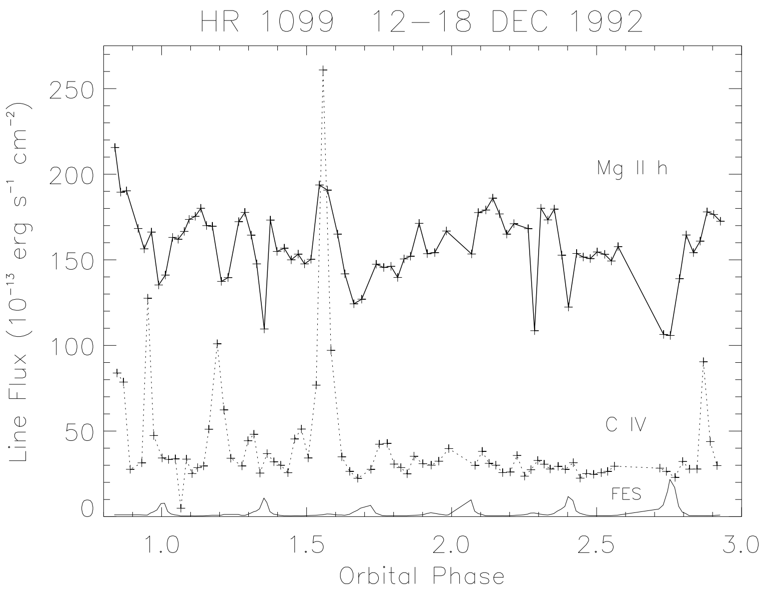

Figure 2: The ultraviolet emission line "light curve" of HR 1099. The integrated Mg II h (2802 Å) flux (corrected for interstellar absorption) is shown by the thick solid line, and the C IV (1550 Å) flux is shown with the dotted line. The C IV line flux most clearly demonstrates the times and durations of the 5 flares, including the flare decay seen at the beginning of the observing window. Periodic dropouts in the Mg II h flux calibration are related to the daily increase in the scattered light background, shown (not to scale) in the bottom (FES) curve.

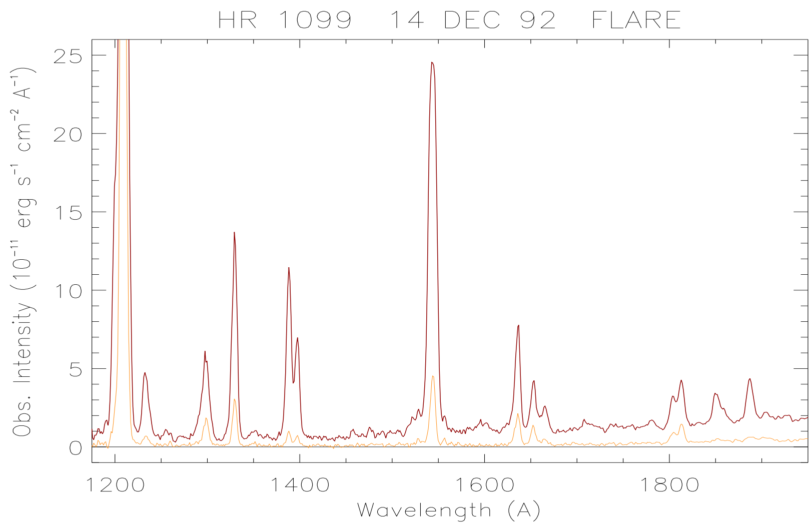

Figure 3: The far-ultraviolet spectrum obtained at the peak of the flare at $\Phi \sim 1.6$ on 14 December (solid) is compared to the spectrum obtained exactly one stellar rotation period later (dashed). As expected, the enhancement is greatest in the lines of the most highly-ionized species (e.g. N V 1240 Å; Si IV ∼1400 Å; C IV; Si III 1893 Å). Si II (∼1800 Å), on the other hand, was enhanced ver little. There is continuum emission from the flare throughout the entire bandpass.

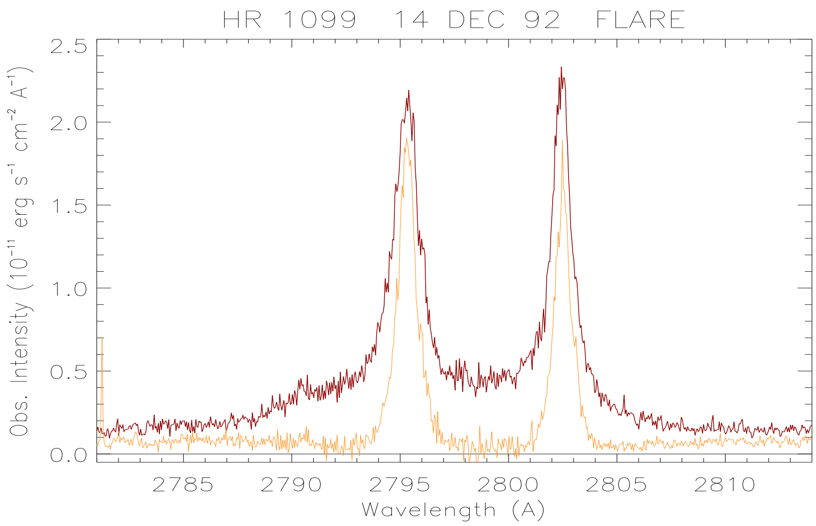

Figure 4: The 14 December flare had a dramatic effect on the Mg II line profiles (solid line). Approximately symmetric wings extend to nearly 1000 km s^{-1} from line center, and the continuum is enhanced. The non-flare spectrum (dashed line) was obtained at the same orbital phase but one rotation later.