SURFACE STRUCTURES AND FLARES ON RS CVn SYSTEMS

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1. Introduction

I describe the scientific background and rationale for the third program in the December 1989 *MUSICOS* campaign – multi-site observations of HR 1099. I do not intend to present a comprehensive review of magnetic activity on RS CVn stars or of past multi-site observing campaigns. Rather, I will provide a summary of the evidence for these phenomena (surface structures and flares) and describe why we need multi-site observations to study them.

1.1 RS CVn Stars

Let me begin by reminding you what RS CVn stars are. Although many of the individual stars in this class had been observed for many years, RS CVn stars were first "officially" defined *as a class* by Hall (1976). His original list of 24 stars shared the following defining characteristics:

- spectroscopic binary systems
- period $\sim$ 1–14 days
- enhanced Ca II H and K line emission
- the hotter star is spectral type F or G, luminosity class IV or V

Hall (1976) also listed 15 other "non-defining" characteristics, shared by most, but not all of the stars on his list. These included

- CaII emission from cooler star or from both stars
- wave-like visible light photometric curve; migrating phase of minimum light
- detached binary; mass ratio near 1

Later reviews (Hall 1981, Bopp 1983, Vogt 1983, Catalano 1983, Linsky 1983) attempted to put these characteristics on a more physical basis. For example, Linsky (1983) suggested that the defining period range should be limited on the one end by synchronization of the orbital and rotational periods (about 20 days), and on the other by the requirement that the system be detached. Strassmeier *et al.* (1988) cataloged 168 spectroscopic binary systems with Ca II emission. Their catalog therefore contains all the known RS CVn stars, but it also contains systems that are physically distinct from the RS CVn stars.

1.2 Magnetic Activity

RS CVn stars are perhaps the most active late-type stars. By "active" I refer to the presence of magnetic phenomena such as starspots, chromospheres, and coronae. The Ca II H+K and Hα emission lines, the far-ultraviolet emission lines, and x-ray emission indicate the presence chromospheres and coronae. More rapidly rotating late-type stars tend to have a higher level of emission from these activity indicators. Because RS CVn stars are converting orbital angular momentum into rotational angular momentum, they tend to rotate very rapidly and thus have a very high level of such emission.

1.3 Surface Structure

Not only do RS CVn stars show the highest level of activity among the late-type stars, they also show the highest degree of *variability.* Some of this variation is attributable to rotational modulation caused by a very non-uniformly bright atmosphere, i.e. photospheric spots and chromospheric plages. Some of the variation is on timescales of minutes to hours ("flares"), and some of the variation is due to long-term evolution of the surface structure or perhaps cyclic variability in the stellar magnetic configuration, analogous to sunspot cycles.

1.4 Key Physical Questions

- Are spots and plages "real"? Are they a likely interpretation? Are they even a possible interpretation?
- What produces and maintains their structure? how?
- How can images and maps of spots help us to understand: system or component evolution? binary interaction? energy transfer within the atmosphere? the global magnetosphere?
- What is the three-dimensional structure of the atmosphere? What are the physical parameters within the various regions?
- What can a knowledge of the three-dimensional structure tell us about global stellar parameters? stellar interiors? stellar atmospheres?
- Are binaries different in any respect than single stars (e.g. active regions "locked" to orbital phase)?

2. Evidence For Photospheric Activity and Spatial Structure

2.1 Visible Photometry

Early interest in RS CVn stars was spurned by the irregular but pronounced variability of their visible light. As the observations accumulated, most explanations for this variability were ruled out. The usual explanation is dark "spotted" regions in the photospheres of RS CVn stars. These regions are presumed to be analagous to sunspots, which are centers of magnetic activity and cooler than the surrounding photosphere.

In order to produce the observed variability (typically $\sim$0.1 magnitude), these spotted regions must be large and their distribution on the surface must be highly non-uniform (see Figure 1). In the most extreme cases, the spot area must be greater than 50% of the visible hemisphere to explain the amplitude (see Doyle *et al.* 1989). Typically, the minimum spot area is 5 to 20%.

Figure 1: The observed light curve (a) of HR 1099 in late 1981 (filled squares). Phases of light minimum and maximum are marked with arrows. The fit through the observations was generated by a two-spot model (b and c). See Rodonò *et al.* 1986 for details.

Photometry provides no information on sizes, locations, or homogeneity of individual spots. On the other hand, it does provide a measurement of the uniformity of the overall spot distribution and the relative spot area over the stellar surface. Changes in amplitude, mean level, and the phase of minimum light provide important and unique insight into stellar cycles and spot evolution. More observational constraints are needed to solve independently for other unknowns such as absolute area, temperature, size, shape, locations, and distribution of actual spot regions. In order to advance our understanding of spots, it therefore is necessary to seek out spectroscopic indicators, which provide an entirely new *dimension* of observational constraints.

2.2 TiO Absorption Bands

An ideal indicator of spots is one that is formed **only** in the spots, not in the unspotted photosphere. Several interesting candidates can be found by comparing sunspot spectra with those of the quiet Sun. Perhaps the most promising candidates are the TiO absorption bands. TiO is dissociated in the warmer photospheres of G and early K stars, but they are strong features in M star spectra and in sunspot spectra.

Ramsey and Nations (1980) showed that the 8860 Å bandhead of TiO from HR 1099 is quite strong, in spite of its relatively early spectral type. The very presence of TiO absorption in these spectra implied that a substantial fraction of the photosphere must be spotted. The strength of this absorption is strongly dependent on spot *area* and somewhat dependent on spot *temperature*. The relative strength of the 8860 Å band with a band formed at a different temperature sensitivity (e.g. the bandheads around 7110 Å) is *sensitive primarily to temperature.*

Along with Steve Saar (CfA), I am carrying out a program at the McMath telescope (NOAO/NSO) to measure in this way spot areas and temperatures of G and K dwarfs and a few RS CVn stars. Our procedure (see Figure 2) is briefly outlined by Saar and Neff (1990). We have completed observations at both 7110 Å and 8860 Å of a grid of "inactive" G and K comparison stars and a sample of M star spectra, representing different spot temperatures.

Figure 2: The 7110 Å (a) and 8860 Å (b) spectral regions of the target star (upper solid curves), the photospheric proxy (dashed curves), and the starspot proxy (lower solid curves). Note the excess absorption in the target star spectra at the wavelengths of the TiO bands (which are clearly visible in the starspot proxy spectra).

Our sample of active stars has been observed primarily as a survey, but we plan to continue observations to study rotational modulation and long-term cycles.

2.3 Doppler Imaging

The line profiles of the most rapidly rotating stars provide a new constraint for determining the spatial brightness distribution. To the extent that the line width is dominated by rotation, spectral position on a line profile maps directly to a specific region on the star's surface (see Figure 3). A single spectrum provides only a one-dimensional mapping. Combining spectra obtained at many different viewing angles (i.e. rotational phases), a two-dimensional map can be built up.

The spatial resolution of the map depends on several extrinsic factors, including the ratio of $v \sin i$ to the intrinsic line width, the completeness and uniformity of the phase coverage, as well as on the quality of the observed profiles. Vogt and Penrod (1983) first applied this principle to late-type stars (see Figure 4). Vogt, Penrod, and Hatzes (1987) further developed the method, and several other groups have now developed successful algorithms based on the same principles. While the competing methods use slightly different assumptions, they appear to produce comparable results. However, very few actual images have been published to date (Vogt and Penrod 1983; Vogt 1988; Piskunov, Tuominen, and Vilhu 1990; Strassmeier 1990), so a direct comparison is difficult.

A crucial point to understand about these procedures is that they involve mathematical inversions, which can render the solutions non-unique. For the problems to be well-constrained, all of the physical properties of the various atmospheric regions, as well as the physics of line-profile formation, must be known *a priori* in order to map the geometry. For photospheric imaging, this probably is not a serious limitation. For a more complete discussion of the physical and mathematical implications involved, see Neff (1990a; 1988), Piskunov *et al.* (1990), Rice, Wehlau, and Khoklova (1989), and Vogt *et al.* (1987).

2.4 Summary

Doppler imaging is a powerful, robust technique to map the photospheric brightness distribution of rapidly-rotating, late-type stars. The technique requires full, uniform, and repeated coverage of the rotational cycle. The S/N and resolution requirements are substantial.

A complete solution, however, requires additional input regarding total spot area and temperature. The ideal program to study spatial structure must include coordinated Doppler imaging, TiO, and photometric observations. For more slowly rotating stars, only the latter two methods are available. Neither photometry nor Doppler imaging, taken alone, provides a complete solution of the imaging problem or satisfactory understanding of the photospheric brightness distribution.

3. Evidence For Activity and Structure in Outer Atmospheres

3.1 Rotational Modulation of Line Fluxes

Rodonò *et al.* (1987) presented the now-famous anti-correlation between the integrated fluxes of far-ultaviolet emission lines and the V-band magnitude for II Peg in 1981 (Figure 5). This suggested a strong spatial correlation between chromospheric activity and photospheric spots. Further observations of this and other RS CVn-type systems have not shown such a striking correlation, and sometimes there is no correlation at all.

The variation of ultraviolet line fluxes due to the rotation of stars with a non-uniform brightness distribution is far more pronounced than the V-band variation, because the contrast between active and inactive regions is much higher, and because there is little photospheric contribution. On the other hand, space-based observations are required, so it is difficult to obtain the full phase coverage required to see rotational modulation. In order to separate spatially-induced variations from transient effects – which are far more common in the outer atmosphere than in the photosphere – observations must be obtained over several orbits. This has been done for only a few cases.

Rotational modulation of ultraviolet line fluxes has the same implicit limitations for studying spatial structure as visible photometric methods. One major advantage is that one can obtain height information by studying lines formed at different temperatures in the chromosphere and transition region.

3.2 Line Profile Variations: Ultraviolet Spectral Imaging

In order to map the spatial structure of the outer atmospheres of stars, we should be able to use high-dispersion ultraviolet spectra and apply the basic principles of Doppler imaging. Ultraviolet spectral imaging has several noteworthy advantages over photospheric imaging:

- The contrast between active and inactive regions is much higher in the outer atmospheres, and there is very little far-ultraviolet emission from the photospheres of RS CVn-type stars. Therefore, the S/N requirements are much lower.

- Rapid rotation makes the chromospheric emission line profiles brighter and broader, whereas photospheric absorption line profiles get shallower and "washed out".

- Chromospheric active regions should be larger than photospheric spot regions, because the magnetic fields tend to flare out higher in the atmosphere.

- From high-earth orbit, one can observe a star continuously, without day-night cycles and weather problems.

On the other hand, there are some disadvantages:

- The atmospheric structure and line formation physics are poorly understood, if at all. Therefore, we cannot use the inversion techniques developed for photospheric imaging.
- Available spectra are at much lower S/N and resolution than ground-based spectra.
- Space-based observations are required. Furthermore, they should be continuous for two or more orbital cycles (4 to 8 days).
- Temporal variability (i.e. flares – see Section 4) is more frequent and the effect is larger than for photospheric observations.

In order to extract spatial information from a series of high-resolution ultraviolet spectra, a different approach than that developed for photospheric Doppler imaging must be adopted. I developed an algorithm using a series of 8 spectra of AR Lac obtained with IUE in 1983 (Walter *et al.* 1987) and applied it to a more complete series of 18 spectra of AR Lac obtained in 1985 (Neff *et al.* 1989). The analysis procedure is based on the assumption that a spatially **uniform** star will produce a **symmetric** emission line profile *centered* at the radial velocity of the star. Phase-dependent departures from this symmetry are then interpreted as emission from discrete regions of enhanced brightness in the chromosphere (i.e. "plages"). Plage position and size can be determined using the entire series of spectra. The net result is a spatially-resolved map the the Mg II k (2800 Å) surface flux at all observed phases (see Neff *et al.* 1989).

4. Stable Spatial Structures v. Flares

Figure 6 shows a pole-on schematic of the chromospheric and coronal brightness distribution of AR Lac in 1983 and 1985. The relative sizes and positions of the structures seen in 1983 and 1985 are similar, but the 1985 features are approximately 60° ahead in longitude. There is no way to be certain whether they are the same features, stable but migrating in longitude. In fact, the data at each epoch were inadequate to demonstrate conclusively that they are spatial structures at all, because in each case the data were obtained in a single orbital cycle.

In 1987, AR Lac was observed again with IUE, but htis time the observations covered two full cycles (4 days). The line profile asymmetries were the same in both orbits, so they must be due to the *spatial* brightness distribution, not to flares. The only other data set covering two full cycles was of EI Eri in 1988. The behavior of the line profiles and fluxes from EI Eri was radically different from one orbit to the next, implying that it is <u>not</u> due to stable spatial structures. It is therefore critical to observe for at least two cycles. Those features that repeat are due to spatial structures; those that don't are sporadic, temporal phenomena. Both are of interest, and both require the full, multi-orbit orbserving program to study.

Roughly once per rotational/orbital cycle, the RS CV'ns that have been studied with IUE in this fashion have been seen to "flare". A flare is difficult to define (see Neff 1990b for my best attempt to do so and for a complete review of ultraviolet flares from RS CVn-type systems). These flares can be a million times more energetic than solar flares (see Figure 7).

By comparing the flare-peak line profiles with profiles obtained before and after the flare (or better still with the profile at the same phase in a subsequent orbit), it is possible to measure the flaring region profile (see Figure 8). High-resolution flare speectra permit studies of flare *dynamics* (see Linsky *et al.* 1989). If several spectra are obtained during the flare decay, as for AR Lac in 1985 (see Neff *et al.* 1989), the flare location and size can be mapped out with the spectral imaging techniques.

In summary, RS CVn-type systems show chromospheric structure that is stable, at least over two orbits, and flares that rise in minutes and decay for 2 to 12 hours. A series of high-resolution, ultraviolet line profiles obtained over two orbital cycles permits us to study the structure, energetics, and dynamics of these regions individually. Observations obtained at many epochs are permitting us to probe the *evolution* of these individual regions and their motion on the stellar surface.

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Figure 3: This figure illustrates the correspondence between surface location and line profile position. Note that the observed effect of a dark region on the surface is an emission "bump" in the absorption profile. This bump transits the profile from blue to red as the star rotates. From Vogt and Penrod (1983).

Figure 4: The observed line profiles of HR 1099 in 1981 (a) used to construct the first "Doppler images" (b) of the photosphere of a late-type star. From Vogt and Penrod (1983).

Figure 5: The integrated line fluxes in the far-ultraviolet emission lines (upper panel) from II Peg in 1981 varied 180° out of phase with the V-band variations (upper panel). Rodonò *et al.* (1987) interpreted this modulation as due to the passage of a large spot/plage complex across the visible hemisphere.

Figure 6: The 1985 system model of AR Lac overlaid on the 1983 model and the x-ray results of Walter *et al.* (1983). Three plage regions, labelled A, B, and C, were seen on the K star in 1985. A dark patch and a flare were seen on the G star. The two plage regions seen on the K star in 1983 share roughly the same relative position and size as plages A and B in 1985, but there is no way to tell if they are the same regions. The coronal distribution was inferred from modelling the x-ray eclipse light curve.

Figure 7: The 1 January 1979 flare on UX Ari, observed with IUE. The Mg II k lines are shown here during the flare (upper histogram) and at a similar phase but at a later epoch. The dots are the flare spectrum (flare minus non-flare). The flare enhancement is very broad and redshifted by more than $v \sin i$.

Figure 8: The Mg II k profile of HR 1099 observed during a flare (histogram). The global emission profiles of the G and K stars and the interstellar medium were constrained in this fit to be their mean non-flaring value, and the exess emission was fit with a fourth gaussian (labelled F), which is due to the flare alone. Notice that the flare emission is again broad and redshifted.