DOPPLER IMAGING OF STARSPOTS

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ABSTRACT

We discuss a newly-developed technique for spatially resolving starspots on some of the more rapidly rotating RS CVn stars. Basically, the method uses high resolution, very high signal-to-noise spectral line profiles and exploits the Doppler velocity correspondence between position across the stellar disk and wavelength position across a rotationally broadened line profile to synthesize an image of the star, showing the location, sizes, and shapes of its starspots. Though still in a developmental stage, the technique is already yielding information about the structure and general appearance of starspots. Examples of Doppler Imaging observations of HR 1099 will be presented, along with a movie showing the behavior of synthetic line profiles generated from a computer spot model.

1. INTRODUCTION

Photometric variations attributed to starspots are seen in several classes of fast-rotating late-type stars. In principle, these variations contain a great deal of useful information on the sizes, locations, and temperatures of the spot groups. In recent years, a number of attempts to extract this information have been made, with considerable success (Vogt 1981a; Dorren and Guinan 1982; Dorren et al 1981; Bopp and Noah 1980; Eaton and Hall 1979). While the studies have shown that suitably chosen spot distributions can indeed reproduce the observed light curves, all have been relatively unable to handle the problem of solution uniqueness pointed out by Vogt (1981a). The derived solution may well fit the observations, given the modeling assumptions, but a family of often very different solutions may fit just as well.

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In view of these difficulties, we have been pursuing an entirely new line of modeling of the spot distributions which, when combined with simultaneous photometric observations, may largely eliminate the problem of non-uniqueness and reveal important new information on spot shapes and movements. We call this technique Doppler Imaging.

2. TECHNIQUE

The Doppler Imaging technique exploits the fact that, in the spectrum of a rapidly rotating star, there exists a one-to-one correspondence between wavelength position across a spectral line profile and spatial position across the stellar disk. Lines of constant radial velocity are chords across the stellar disk parallel to the star's projected rotation axis. Thus, a unique mapping occurs in one dimension between position across the rotating stellar disk and position across the line profile. Any dark or bright region on the stellar surface will produce an associated bump or depression at the corresponding location in the line profile. As the region is carried across the stellar disk by rotation, the associated bump propagates across the line profile. Such bumps were first noticed by Fekel (1980) as line profile asymmetries in HR 1099 whose shape correlated with the phase of the photometric wave.

Figure 1 illustrates the phenomenon. Here we show a star divided into five zones of equal area, each with a characteristic and approximately constant radial velocity. The star is assumed to be rotating sufficiently rapidly that the rotational broadening is several times the width of the intrinsic profile. The left-hand sequence of Figure 1 shows the formation of a rotationally broadened spectral line on an unspotted star , as the sum of five specific intensity profiles each appropriately shifted by the radial velocity of its corresponding zone. The resultant sum produces a greatly broadened line profile whose width merely reflects the star's projected rotation velocity.

The right-hand sequence of Figure 1 illustrates the formation of a line profile on a rapidly rotating, spotted stellar surface. A black, zero flux spot is assumed to cover half of the area of Zone III. The summation of the specific intensity profiles now produces a normal rotationally broadened profile with an apparent "emission" bump in the center. Obviously, this bump does not represent true emission, but rather a lack of line absorption (in real energy units) at the radial velocity in the spectral line corresponding to the spotted Zone III. This effect is simply a geometric one, and bumps would appear almost identically in all of the star's absorption lines. The spot also produces a lowering of the continuum by 10%, but high dispersion spectroscopists rarely determine absolute continuum fluxes. Rather, they usually normalize to the continuum surrounding the line profile, as shown in the bottom frame of the right-hand sequence of Figure 1.

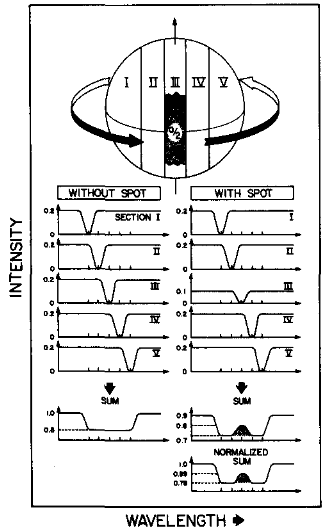

FIGURE 1

In real life, the situation is rather more complex than the idealized case of Figure 1. In general, the continuum flux and line profile from the spot itself must also be included in the computation, along with the center-to-limb dependence of both the line profile and the continuum flux (limb darkening). While these factors complicate the analysis, they can be exploited to yield more detailed spatial and temperature information on the spot groups.

Any single observation provides only one-dimensional spatial information across the disk. A series of observations, with good phase coverage, is necessary to accurately model the true two-dimensional spot distribution. Obviously, a dark spot at the pole will produce an "emission" bump at line center at all observed phases, while spots at progressively lower latitudes will exhibit progressively greater excursions across the line profile, and progressively greater rates of crossing the line profile. In practice, perhaps 6-10 observations uniformly spread across the rotation period of the star are needed to produce a reasonably valid map of the spot distribution.

The effective resolution of the technique is limited more by the rotation velocity of the star and the width of the intrinsic profile than by our instrumental resolution. Our typical instrumental resolution is about 0.15 Å, or 7 km sec^{-1}, while the line intrinsic widths are of order 10 km sec^{-1}. A projected rotation velocity of 40 km sec^{-1} thus yields 7-8 resolution elements across the stellar disk.

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3. MODELING

The actual construction of a spot distribution is an iterative process. A distribution is initially assumed, and a series of theoretical profiles are generated for comparison with the observed profiles. The spot distribution, built up from as many as 50 small circular spots, is then modified until a satisfactory fit is achieved.

The theoretical profiles are generated by program PROFILE. Specific intensity profiles are computed at 30 limb angles for both the immaculate stellar photosphere and the spotted areas, and the stellar disk is divided into a rectangular grid of typically 10,000 zones. Each zone is assigned a radial velocity (a combination of rotation and a random element of radial-tangential macroturbulence) and an appropriate specific intensity profile, which depends both on its limb-angle and whether or not it falls within the boundaries of our spot groups. The shifted profiles are then added to produce the integrated profile, which is then convolved with an instrumental profile to produce the final result. This modeling often fits our high-resolution, very high signal-to-noise spectra to better than 0.5% at all resolution elements.

4. OBSERVATIONS

Most of our observations are obtained with the double-pass echelle spectrograph (Soderblom et al. 1978) and an image-tube image-dissector scanner (Robinson and Wampler 1972) mounted at the coudé focus of the Lick Observatory Shane 3-m telescope. The spectrograph was typically used with an entrance slit of 0.85 arc-second, yielding a spectral resolution of 100 mÅ, each resolution element being over-sampled at 8 points. Since the detector covers only about 6.5 Å of spectrum in the 9th order, generally only one spectral line can be obtained at each setting.

Additional observations are obtained with the Reticon system (Vogt 1981b) and coudé spectrograph of the 3-m telescope. The detector is an 1872 channel unintensified silicon photodiode array, mounted at the focus of the 40" camera. The entrance slit is normally set to 0.75 arc-second, giving an effective spectral resolution of 200 mÅ, with 3 sample points per resolution element. This set-up provides about 140 Å of spectral coverage.

The spectral lines chosen for most of the observations were Fe I 6430.9 and Ca I 6439.2. These lines are relatively unblended even at the high rotation velocities of our double-lined binary program stars, and allow us to exploit the excellent red response of both detectors.

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5. RESULTS

As the spot distributions can change on time scales of a few months, it is vital to obtain observations in a relatively short period of time. The autumn-winter cloud cover at Lick Observatory has made this a most difficult prospect during the last two seasons. Our most convincing data set is a set of 8 phases taken of HR 1099 (V711 Tau) during September-October of 1981, shown in the left-hand panel of Figure 2. This star is a well-known bright RS CVn binary with a 2.838-day orbit (Bopp and Fekel 1976). As previously noted, it was on this star that Fekel (1980) observed asymmetries in all of the stellar line profiles, which led to the development of the Doppler Imaging technique. The inclination of the rotation axis was taken to be 33° (Fekel 1982), while the projected rotation velocity was determined to be 38 km sec^{-1}. The stellar effective temperature was assumed to be 4700 K, appropriate for its K1 IV spectral type, and the spots were assumed to have a temperature of 3500 K (Vogt 1981a).

Our derived spot distribution (preliminary), shown in the right-hand panel of Figure 2, can be characterized as two spot groups. One, which crosses line center at phase 0.55 (determined from the ephemeris J.D. = 2442766.080 + 2.83774E), is centered at +12° latitude and is roughly circular, covering about 6-7% of the observed hemisphere. The second group consists of a large, almost circumpolar clump and a narrow filament which descends to about +30° latitude. This spot group crosses line center at roughly phase 0.25, about 110° in longitude distant from the first group, and covers about 8% of the hemisphere.

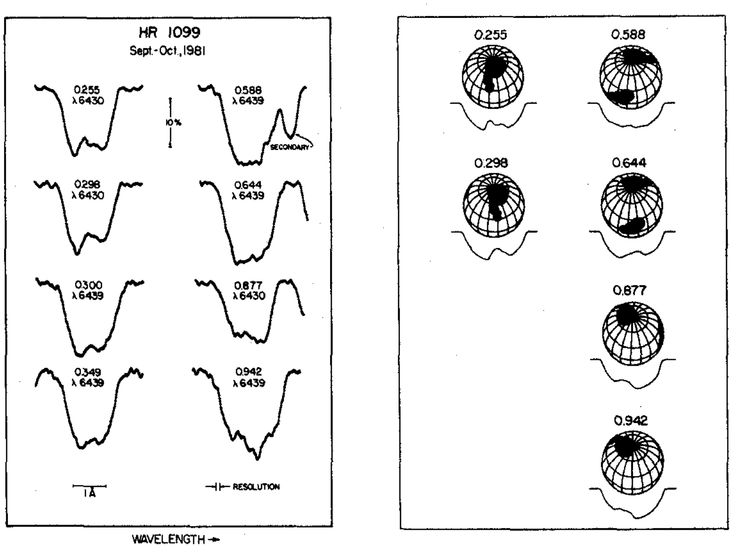

FIGURE 2

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A more convincing representation of this spot distribution can be seen in our movie of the evolution of the line profiles, which will be shown by one of us (SSV) elsewhere during the colloquium. The movie is particularly valuable as a demonstration of the relative ease of finding the spot latitudes from their rates of motion across the line profiles.

6. DISCUSSION

A comparison of our derived spot distribution with photometric observations will be presented more fully elsewhere. The most remarkable result of this work is the derived shape of the polar spot group. Clearly, any sort of circular spot model is a poor approximation of this group. In fact, the shape of this group is remarkably similar to that of solar coronal holes, which are the most visible and spectacular features associated with the solar complexes of activity (Bumba and Howard 1965). Indeed, the similarities of many physical parameters of "starspots" and those of solar complexes are striking. Both exhibit almost rigid-body rotation, along with a slow poleward drift with time. In each case, the activity is largely confined to "active longitudes", although the starspot (starstripe) on HR 1099 is rather narrower than its solar counterpart. A solar complex dies by drifting to the pole and eventually decaying into bright plage regions. This is remarkably similar to the scenario previously suggested by Vogt (1981a) for the disappearance of a spot on BY Draconis.

The great difference between the solar complexes and starspots is the filling factor of dark spot umbrae. Presumably this simply reflects the vastly greater dynamo activity on the rapidly rotating stars. A solar complex typically has a magnetic flux of 10^{23}Mx (Galloway and Weiss 1981). If spot fields scale with photospheric pressure, the maximum spot fields on HR 1099 should be of order 1500 G. A typical spot group would then have a magnetic flux of 2-5 x 10^{25}Mx, hundreds of times the value of its solar analogue.

Hence, we suggest that starspots are analogous more to solar complexes than to either active regions or individual sunspots. Further observations are clearly needed to confirm this suggestion on a broader sample of stars. A more complete discussion of these results (Vogt, Penrod, and Fekel 1982) will be forthcoming in the Astrophysical Journal.

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