Towards Magnetic Images of Rapidly Rotating Late-type Stars

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Abstract: We present the first magnetic detections using Zeeman-Doppler Imaging (ZDI) in the two bright rapidly rotating RS CVn systems HR 1099 and σ^2 CrB, and discuss their compatibility with various recent results on magnetic activity in cool stars.

1. Introduction

In a large number of late-type stars, activity indicators are found to be essentially similar to those observed in the sun despite the different strengths and time scales: this common phenomenology is usually attributed to the dynamo mechanism. Solar physicists have long known that the major parameter in the study of activity is the magnetic field. However, stellar magnetic geometries are very difficult to derive since the star itself is unresolved. In the last 10 years, the first direct estimates of magnetic field strengths B and filling factors f_B have been obtained for slowly rotating cool stars from Zeeman broadening measurements of unpolarized profiles. Recent studies (e.g. Saar, 1990) report that the field intensity correlates with the surface pressure, while the magnetic flux $f_B B$ correlates with both rotation rate and inverse Rossby number. However, the study of the origin and evolution of activity processes in cool stars still remains elusive, partly due to the lack of spatial information on the magnetic structures. The direct study of individual magnetic starspots should lead to a more informative solar-like way of studying activity.

A breakthrough may come from the recent developments of indirect imaging techniques. Using the correspondence between wavelength position of a rotationally Doppler-broadened spectral line and spatial position across a stellar disk, it becomes in principle possible to derive 2D images of a rapidly rotating star in terms of surface brightness inhomogeneities. ZDI (which can be roughly described as Stokes V Doppler Imaging) should similarly help unravel the spatial structure of the field.

We present here new magnetic measurements for the bright RS CVn systems HR 1099 and σ^2 CrB, using ZDI. For both of them a field is detected. In HR 1099, the rotational modulation of the Zeeman signature is briefly interpreted in terms of the distribution of magnetic field. The implications of these results for photospheric activity are discussed.

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2. Deriving spatial magnetic information

Polarization in line profiles is an unambiguous signature of magnetic field. In particular, the circularly polarized light is related to the longitudinal component of the field. Because the shape of spectral lines from a rapidly spinning star is dominated by rotational broadening, a high resolution spectrum becomes essentially a 1D image of the star (Vogt, 1988): for such stars, the heterogeneous structure of photospheric magnetic fields may be resolved from the rotational modulation of the circular polarization profile $V(\Delta\lambda)$ (Semel, 1989).

Let $F(\Delta\lambda)$ denote the Doppler-resolved distribution of the longitudinal component of the stellar magnetic field and w the equivalent width of the local profile f. In the weak field approximation, the convolution of $F(\Delta\lambda)$ with the *normalized* local profile $f_N(\Delta\lambda) = f(\Delta\lambda)/w$ is proportional to the indefinite integral of $V(\Delta\lambda)$ (Donati and Semel, 1990):

$$F * f_N(\Delta\lambda) = \frac{1}{g'w}\int^{\Delta\lambda} V(u)\,du$$

in which g' denotes the "reduced" Landé factor of the transition, equal to $4.67\times10^{-13}\lambda^2 g_{eff}$ Å/G. Note that the magnetic distributions derived are in principle almost independent of the line used, so that averaging the results from many different lines may significantly increase S/N.

From the time modulation of these 1D magnetic distributions, a complete map may be recovered: the first results of a maximum entropy code applied to the recovery of synthetic magnetic structures are presented in Brown and Donati (1990). Like all other methods (e.g. Saar, 1990), ZDI detects the magnetic field in plages rather than in cool spots, due to the very low relative contribution of dark regions to stellar profiles.

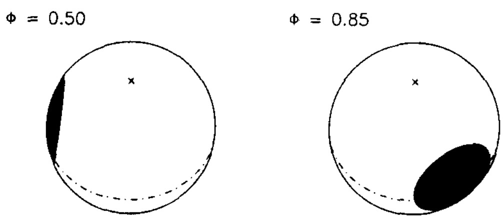
From the formal expression for the photon noise level in the magnetic distribution (Donati *et al.*, 1989), we find that $S/N = 900$ per 80 mÅ pixel is needed to detect a 1000 G field over 10% of the stellar surface in a star with $v\sin i = 38$ kms^{-1}, with a confidence level of 10σ, if one uses a single $g_{eff} = 2$ line at 5500 Å with $w = 180$ mÅ. To satisfy these stringent requirements, we use the special observation and reduction procedure described in Donati *et al.* (1990).

3. Results for HR 1099 and σ^2 CrB

HR 1099 = V711 Tau (K1IV + G5V) and σ^2 CrB (F6V + G0V) are very bright RS CVn binary systems, the cool components of which show manifestations of intense activity. Both are well suited to ZDI. Three magnetically sensitive Fe I lines ($g_{eff} \simeq 2$) around 5500 Å were simultaneously used in the analysis.

The complete results of a 2 day observing campaign at the Anglo-Australian Telescope on the active primary star of HR 1099 are reported in detail in Donati *et al.* (1990). Phases 0.50 and 0.85 were observed. In the two corresponding distributions, the only feature exceeding the 5σ level is a large positive redshifted bump at phase 0.85. With the rough approximation of a radial field (of constant strength B) inside a circular region, we can try to mimic the two observed distributions and infer basic information on the field structure. For a spot latitude l greater than 10°, the amplitude of the feature generated in $F * f_N(\Delta\lambda)$ at phase 0.50

would be too high to go undetected. The magnetic field should also be lower than the equipartition "pressure-balancing" magnetic field B_{eq} (Saar, 1990), equal to 1060 G in the particular case of HR 1099, so that l must be larger than 0°.



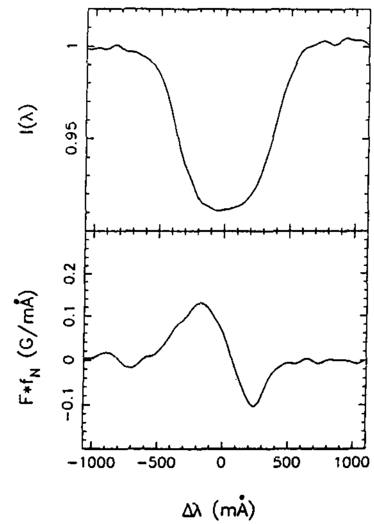


Fig. 1. a) HR 1099 in two observed phases with the detected magnetic region (up) b) Simultaneously measured intensity profile (upper curve) and magnetic distribution (lower curve) for σ^2 CrB around phase 0.25.

The final parameters are $B = 985 \pm 270$ G, $L = 86 \pm 4°$, $l = 5 \pm 5°$ and $r = 0.53 \pm 0.08$, where L and r denote the spot longitude and fractional radius. The region therefore covers $f_{ph} = 8 \pm 2\%$ of the total stellar surface [note the mistake in Donati *et al.* (1990)] and $f_B = 14 \pm 4\%$ of the visible hemisphere at phase 0.85. The geometrical configuration of the star with the detected magnetic region on its surface is shown in Fig. 1 a) for both observed phases. This region is found to be largely monopolar and may coincide with a hot region if associated with a brightness inhomogeneity (Donati *et al.*, 1990).

The very new data on σ^2 CrB were obtained in April 1990 at the Canada-France-Hawaii Telescope and the system was observed around phase 0.25. At that particular phase, a bipolar magnetic field is unambiguously detected for the first time on the G0 secondary component, and nothing is seen on the F6 primary star. The lower curve of Fig. 1 b) shows the 1D magnetic distribution of the secondary star around first quadrature. More than only one of these distributions is required to obtain spatial information on the field structure, such as we derived for HR 1099.

4. Discussion

It is now possible to derive spatial information on the magnetic structure of rapid rotators: this may be especially interesting for the study of stellar activity given the various correlations already reported between rotation rate and magnetic flux for slow rotators (Saar, 1990). The size of the monopolar magnetic region detected on the primary star of HR 1099 is similar to that of the cool spots derived with spectroscopy (Vogt, 1988). The typical horizontal size scale of the field distribution is therefore also much larger than in the sun. As a result, a large rotational modulation of the 1D magnetic flux distribution is noticed between the two observed phases. Similar huge magnetic regions may also be responsible for the high magnetic variability of the cool G8 dwarf ξ Boo A (Saar, 1990). Conversely, some other cool stars (like ϵ Eri) show little magnetic variability along the rotational phase (Saar, 1990): there the photospheric field structure may consist of many small regions (flux tubes) for which the integrated filling factors and average field modulus over the visible hemisphere are almost independent of rotational phase. Different emerging modes of the magnetic field may be associated with different horizontal size scales in the magnetic distribution and to different values of the stellar parameters (rotation rate, convective zone thickness, age...).

Extrapolating the linear correlation reported by Saar between magnetic flux $f_B B$ and rotation rate in single slowly rotating late-type stars would imply $B \simeq 4$ kG and $f_B \simeq 1$ for a star with $\Omega = 0.35$ day^{-1} like HR 1099. Our estimate of the magnetic flux $f_B B$ for this star is at least 25 times lower, with approximate values of 150 G at phase 0.85 and ≤ 50 G at phase 0.50. Part of this difference may be attributed to tiny dipoles undetected in circular polarization (bipolar structure smaller than the local line width) but they would need then to be very strong and to almost cover the entire stellar surface, which is somewhat unlikely. Our $f_B B$ value is also 20 times lower than the magnetic flux in some of Saar's most rapid rotators, so that the saturation regime that his relation probably reaches for high rotation rates does not explain everything. Saar's stellar sample contains main sequence stars almost exclusively: his relation may not be valid for subgiants and giants. In particular, other parameters than the rotation rate alone may be invoked to explain stellar activity levels in these RS CVn stars.

At the moment, very few magnetic measurements are available on rapid active rotators ($\Omega \geq 0.17$ day^{-1}) and ours is the only one in such a spotted RS CVn system. Some more data are needed for this particular stellar class to study how magnetic flux correlates with rotation at high rotation rates. Zeeman-Doppler images of late-type stars will be soon available (Brown and Donati, 1990) to provide this type of information.

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