SF2A 2015
F. Martins, S. Boissier, V. Buat, L. Cambrésy and P. Petit (eds)

SPECTROPOLARIMETRIC STUDY OF THE COOL RV TAURI STAR R SCUTI

B. Tessore[1], A. Lèbre[1] and J. Morin[1]

Abstract.
With the spectropolarimeter Narval at TBL we have initiated in spring 2015 a 2-year campaign dedicated to a sample of cool and evolved stars including pulsating RV Tauri stars. We monitor net circular and linear polarisation in the spectral lines of R Scuti, the brightest of such variable targets. Our aim is to study the surface magnetic field and the linear polarisation associated with specific spectral lines. We confirm a definite detection of the surface magnetic field of R Sct, with an average longitudinal component $B_\ell = 0.9 \pm 0.5$ G. We also unveil our first results on linear polarisation.

Keywords: stars: late-type, stars: R Sct, stars: magnetic field, line: profiles, polarisation

1 Introduction

Magnetic fields of cool evolved stars, have previously been detected with radio observations in circumstellar envelopes (Vlemmings 2012), but still, little is known on the surface magnetic field. Surface magnetic fields in evolved stars are often invoked (Pascoli & Lahoche 2008) to explain the mass loss and the shaping of the circumstellar envelope in the Asymptotic Giant Branch (AGB) phase and beyond. Recently, magnetic field at the surface of the radially pulsating AGB Mira star, χ Cygni has been detected by Lèbre et al. (2014). The latter, point out a relation between this detection and the radiative shock waves known to propagate periodically through the stellar atmosphere.
Like Mira stars, RV Tauri stars are pulsating variable targets but they present a succession of deep and shallow minima in their light curve. R Sct is the brightest RV Tauri star and it is suspected to be in a post-AGB evolutionary stage (van Winckel 2003). Radiative shock waves are also known to propagate through its atmosphere (Lebre & Gillet 1991). It is therefore possible to follow and to detect the presence of a shock wave, through high resolution spectroscopy. Indeed atomic lines present typical signature tracing the presence of shock waves such as strong emission in Balmer lines and doubling of photospheric lines (Lebre & Gillet 1992). In R Sct, the radiative shock waves may also enhance the surface magnetic field and ease its detection. In order to provide new observational constraints on magnetic field - shock waves interaction, R Sct is monitored with spectropolarimetry along its pulsation period. Observations of R Sct in all Stokes parameters (I, U, Q, V) are performed with the new generation spectropolarimeter Narval at TBL (Pic du Midi). Figure 1 shows the light curve of R Sct and the observation dates. The star is preferentially observed around its maxima of luminosity, so as to optimise the signal-to-noise ratio (S/N) and to avoid molecular blending occurring at low temperature.
The surface magnetic field is measured from polarisation in spectral lines induced by the Zeeman effect.
Circular polarisation (Stokes V), as well as linear polarisation (Stokes U and Q), are analysed with the Least-Square Deconvolution (LSD) method (Donati et al. 1997). To detect very weak polarisation signals (down to $10^{-5} \times I_c$), the LSD technique combines polarimetric signatures present in thousands of spectral lines to compute for each Stokes parameter an average line profile with enhanced S/N. A numeric mask, gathering atomic data extracted from the VALD database (Kupka et al. 1999) and optimised for the stellar parameters ($T_{\rm eff}$ and log g) of R Sct is used for the LSD analysis (Sabin et al. 2015).

[1] LUPM, Université de Montpellier, CNRS, Place Eugène Bataillon, 34095, France

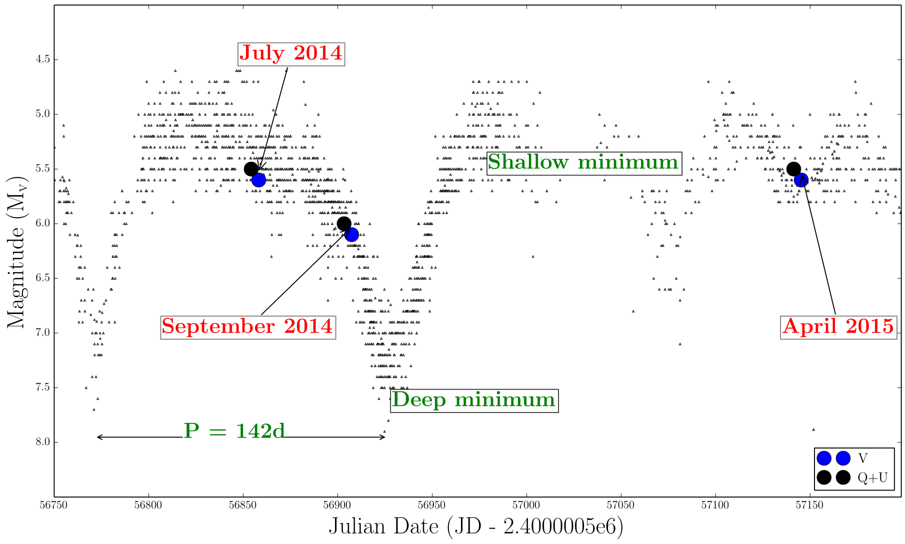

Fig. 1. Observations of R Sct along its pulsation period (P = 142 d). The light curve comes from the American Association of Variable Star Observers database (`https://www.aavso.org/`).

2 Circular polarisation: surface magnetic field

Figure 2 presents the Stokes V profiles at different epochs after analysis with the LSD method. Stokes V profiles are shown in the left panel of Fig.2. The same optimised mask for R Sct was used for all epochs.
From a mean LSD Stokes V profile, the mean longitudinal component of a surface magnetic field can be computed using the first moment method (Rees & Semel 1979):

$$B_\ell = -2.14 \times 10^{11} \frac{\int vV(v)\ dv}{\lambda gc \int [I_c(v) - I(v)]\ dv}$$

where I, I_c, V, g, λ, v and c are respectively, intensity, continuum intensity, circular polarisation, Landé factor, wavelength (nm), velocity (km/s) and celerity of light in vacuum (km/s), and B_ℓ is the projection of magnetic field along the line-of-sight (in Gauss). The magnetic field at the surface of cool evolved stars is expected to be at the Gauss level, according to the measurement of magnetic field in their circumstellar envelopes (Vlemmings 2012). Moreover, from spectropolarimetric facilities, Aurière et al. (2010) confirm that trend in the Red SuperGiant (RSG) star Betelgeuse, where a longitudinal magnetic field of approximately 1 G is measured. Lèbre et al. (2014) also measure a Gauss-level magnetic field in the AGB star χ Cygni. Sabin et al. (2015) report a longitudinal magnetic field $B_\ell = 0.6 \pm 0.6$ Gauss in R Sct from the Narval observations of 21-23 July 2014. This first detection of a surface field in RV Tauri star needs to be confirmed and further investigated. Our own investigations confirm this definite detection – according to a standard statistical criterion based on Donati et al. (1997) – only for the 21-23 July 2014, but not for other epochs. Right panel of Fig. 2 shows that the Zeeman signature (detected in Stokes V profile) is centered with the blue component of the Stokes I line profile. We therefore consider that a more physically meaningful value of $B_\ell = 0.9 \pm 0.5$ G is obtained by considering only the blue component of the intensity in its computation with the first moment method. The double-component structure in the mean intensity line, is indeed typical of a shock wave presence in the photospheric region. The blue component is therefore related to the material moving upward with the passage of the wave. We note that for the April 2015 observations no magnetic field is detected, whereas the pulsation phase ($\phi = 0.56$) is close to that of 21-23 July 2014 ($\phi = 0.62$). However the shape of the cycles of 2014 and 2015 look different, pointing out different physical conditions and the non-rigorous reproducibility of the cycles. This is confirmed by the fact that the mean intensity profile of April 2014 does not exhibit the typical double-component. All these observations strengthen our idea that a shock wave may enhance the magnetic field and hence may ease its detection.

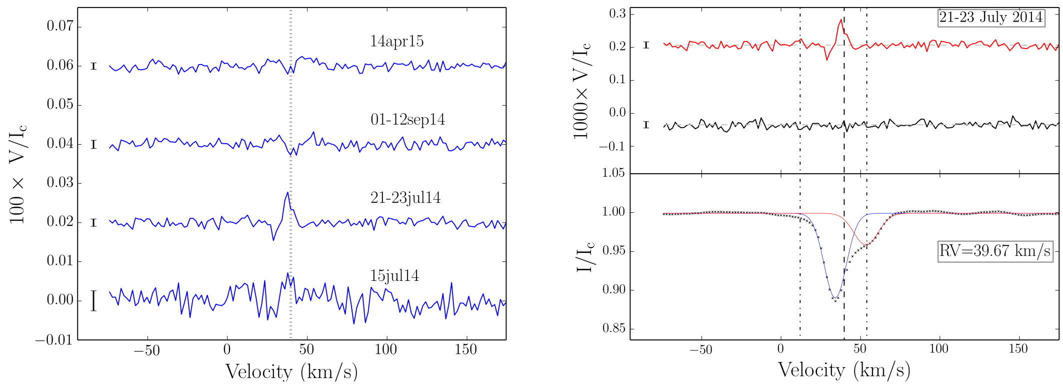

Fig. 2. Left: Circular polarised spectra of R Sct at different phases along its pulsation period. These data are collected with the spectropolarimeter Narval. The S-shape of the 21-23 July detection is typical of a weak dipole field. The gray dashed line shows the central radial velocity of the star. **Right:** The resulting LSD profile for the detection of July. Top panel: Stokes V in red, Null polarisation in black. Bottom panel: intensity profile. The blue and red components of the intensity profile are shown so as to highlight the connection between surface magnetic field and shock waves. The dashed and the dot-dashed are respectively, the central radial velocity of the star (RV = 39.67 km/s) and the bounds used for the first moment method (12 − 57 km/s).

3 Linear polarisation: from LSD profiles to individual lines view

In the weak field approximation – which is perfectly valid as we deal with Gauss and sub-Gauss level for the surface magnetic field strength – the circular polarisation amplitude is about one order greater than the linear polarisation one. In the cool evolved stars which present strong net linear polarisation, on the contrary, the measured amplitude of Stokes Q and U are systematically one order of magnitude larger than Stokes V. We can therefore rule out the Zeeman effect as a major contributor to the observed linear polarisation structures. Other contributions to linear polarisation are related to anisotropies of the radiation field. In this context, linear polarisation is compared with what we know about the solar case. In that case the linear polarisation has two contributions: (i) depolarisation of the continuum by absorption and scattering lines and (ii) intrinsic polarisation of lines. For the Sun, the anisotropy of the radiation field is related to center-to-limb variation (Stenflo & Keller 1997) which is a centro-symmetric effect. Thus the disk-integrated linear polarisation would be zero. Therefore, on spatially unresolved stars, the detection of net linear polarisation traces the presence of surface inhomogeneities. Recently, (Aurière et al. in prep.) have discovered linear polarisation in the spectrum of the RSG star Betelgeuse. For this case, the proposed main contributor to the observed linear polarisation is the depolarisation of continuum by lines through Rayleigh scattering due to photospheric spots. Lèbre et al. (2015) have also measured net linear polarisation in the spectral lines of the variable Mira star χ Cygni; however no linear polarisation signals were found in spectral lines of non-pulsating AGB stars hosting surface magnetic field. Figure 3 displays Stokes Q and U LSD profiles of R Sct. Strong signatures are detected for all epochs except 15 July 2014. In the right panel of Fig. 3, linear polarisation is represented in terms of linear polarisation rate $P_\ell = \sqrt{Q^2 + U^2}/I_c$. Time variation of P_ℓ is observed with an increasing amplitude toward minimum luminosity. Linear polarisation in the spectral lines of R Sct is so strong – at the level of a percent of the unpolarised continuum – that it can be measured in individual lines. Figure 4 depicts the linearly polarised spectrum of R Sct around the strontium I line at 460.7 nm. This spectral line – known to show strong polarisation in the second solar spectrum – is clearly detected in linear polarisation for R Sct. Comparing the behaviour of polarised lines in the spectrum of R Sct with the second solar spectrum will help us to improve our understanding of the origin of linear polarisation in R Sct.

4 Summary

We have initiated a large campaign of observations over two years with the spectropolarimeter Narval. We aim to detect magnetic field at the surface of cool evolved stars, to highlight the nature of the interaction between magnetic field and shock waves for a sample of variable stars and to determine the origin of linear polarisation.

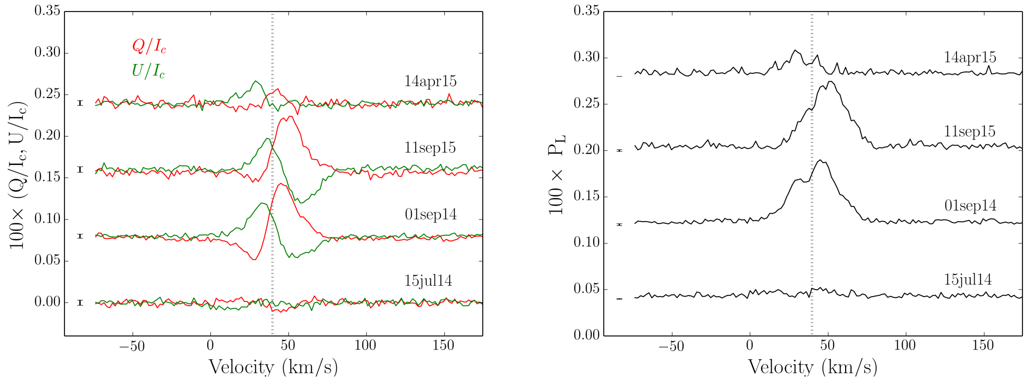

Fig. 3. Left: Linear polarisation profiles, Stokes Q and U. **right:** Linear polarisation rate.

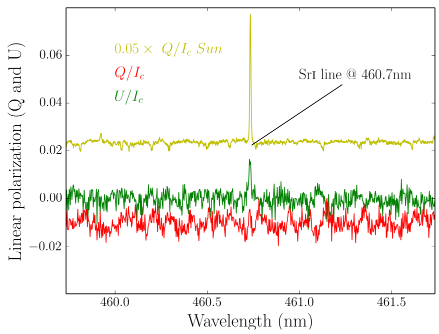

Fig. 4. The linearly polarised spectrum of R Sct around the SrI line at 460.7 *nm*. A clear polarisation is detected. The second solar spectrum (yellow) is shown for comparison (Stenflo 2014).

The main results we have obtained so far are: 1) Zeeman signature in net circular polarisation seems to be related to the atmospheric dynamics, 2) considering 1) we report a better estimation of $B_\ell = 0.9 \pm 0.5$ G and 3) non-Zeeman net linear polarisation is very strong and could be related to surface inhomogeneities.

Ongoing observations with Narval and ESPaDOnS (CFHT, Hawaii) will help us to confirm the systematic connection between surface magnetic field and photospheric dynamics and to study the physical origin of linear polarisation in RV Tauri stars and AGB stars.

We acknowledge financial support from "Programme National de Physique Stellaire" (PNPS) of CNRS/INSU, France, and the "Société Française d'Astronomie et d'Astrophysique" (SF2A).

References

Aurière, M., Donati, J.-F., Konstantinova-Antova, R., et al. 2010, A&A, 516, L2

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, MNRAS, 291, 658

Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119

Lèbre, A., Aurière, M., Fabas, N., et al. 2014, in IAU Symposium, Vol. 302, IAU Symposium, ed. P. Petit, M. Jardine, & H. C. Spruit, 385–388

Lèbre, A., Aurière, M., Fabas, N., et al. 2015, in IAU Symposium, Vol. 305, IAU Symposium, 47–52

Lebre, A. & Gillet, D. 1991, A&A, 251, 549

Lebre, A. & Gillet, D. 1992, A&A, 255, 221

Pascoli, G. & Lahoche, L. 2008, PASP, 120, 1267

Rees, D. E. & Semel, M. D. 1979, A&A, 74, 1

Sabin, L., Wade, G. A., & Lèbre, A. 2015, MNRAS, 446, 1988

Stenflo, J. O. & Keller, C. U. 1997, A&A, 321, 927
van Winckel, H. 2003, ARA&A, 41, 391
Vlemmings, W. 2012, in IAU Symposium, Vol. 283, IAU Symposium, 176–179