DOPPLER IMAGING OF ECLIPSING BINARIES

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Abstract. We describe the extension of our Doppler imaging technique to the case of eclipsing binary systems. Using numerical experiments, we show that the simultaneous imaging of both components breaks the north-south ambiguity that occurs for single stars with high inclination. Characteristic map distortions can be used to correct errors in the orbital parameters of the binary.

We apply this technique to ER Vul – an active RS CVn type binary. Our preliminary results show the presence of the hot spots on the substellar sides of both components, perhaps due to the reflection effect.

We also discuss application of the same technique to contact binaries, where non-sphericity is significant.

1. Introduction

Since Deutsch (1958) first suggested the use of rotational modulation of line profiles to derive the distribution of chemical elements on Ap-stars, Doppler Imaging (DI) has evolved into an important tool for studying stellar surface structure. With improvemed mathematical methods and numerical techniques, application area of DI is becoming more wide. Today DI is routinely used for chemical analysis of Ap-stars (see e.g. Rice and Wehlau 1990) and temperature imaging of late-type stars (see e.g. Piskunov et al. 1990). A few years ago, Semel (1989) introduced Magnetic Doppler Imaging and used it to measure magnetic fields on active late-type stars (Donati et al. 1992). O'Neal et al. (1995) supplemented the conventional DI with TiO bands – temperature diagnostics that are very sensitive below 4000 K.

Many active late-type stars are part of binary systems (Strassmeier et al. 1988) and a significant fraction of them shows eclipses. The eclipse causes some loss of phase information, and its presence often results in the north-south ambiguity of the DI maps due to the high inclination of the orbit.

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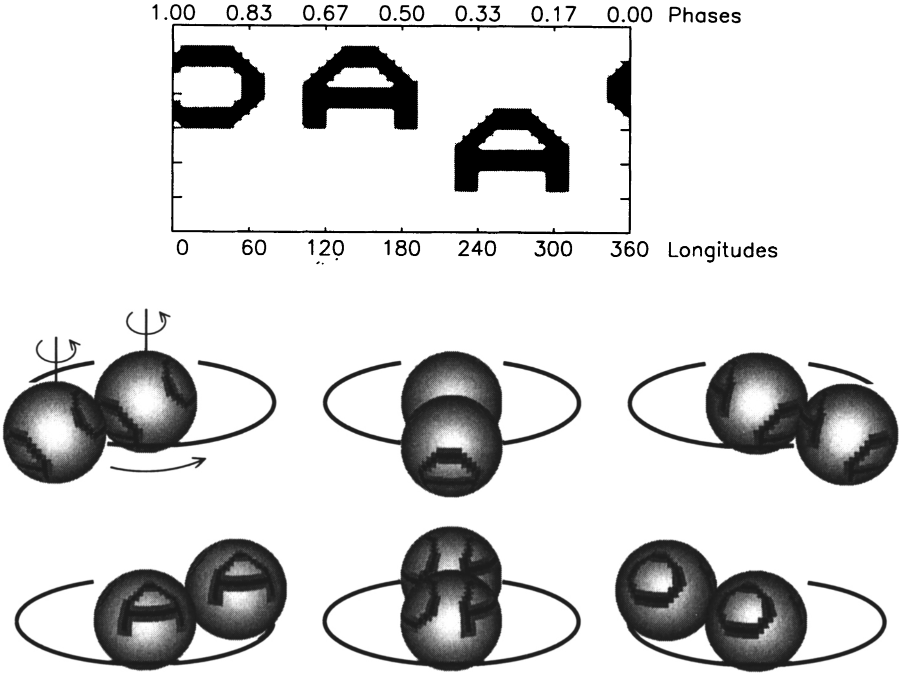

Figure 1. Test pattern for numerical experiments (Vincent et al. 1990).

Recently, Vincent et al. (1993) demonstrated that it is possible to apply DI to eclipsing binary systems and successfully reconstruct the temperature distribution on both components. In this paper we summarize the results of our numerical experiments for eclipsing and contact binaries in order to prove that DI can produce reliable maps of such objects, even for high inclination angles.

2. Techniques

The imaging of eclipsing binaries is based on the same principles as the conventional DI (Piskunov et al. 1990). The presence of a spot on the stellar surface distorts the profiles of spectral lines. The Doppler shift of the distortion is determined by the longitude of the spot, while the information about its latitude can be extracted from the amplitude of the Doppler shift of the distortion and its visibility time (the fraction of the period during which the spot is visible). For an eclipsing binary star, the Doppler shift of the spot also includes the orbital motion of the component, and the visibility time may be reduced by the eclipse.

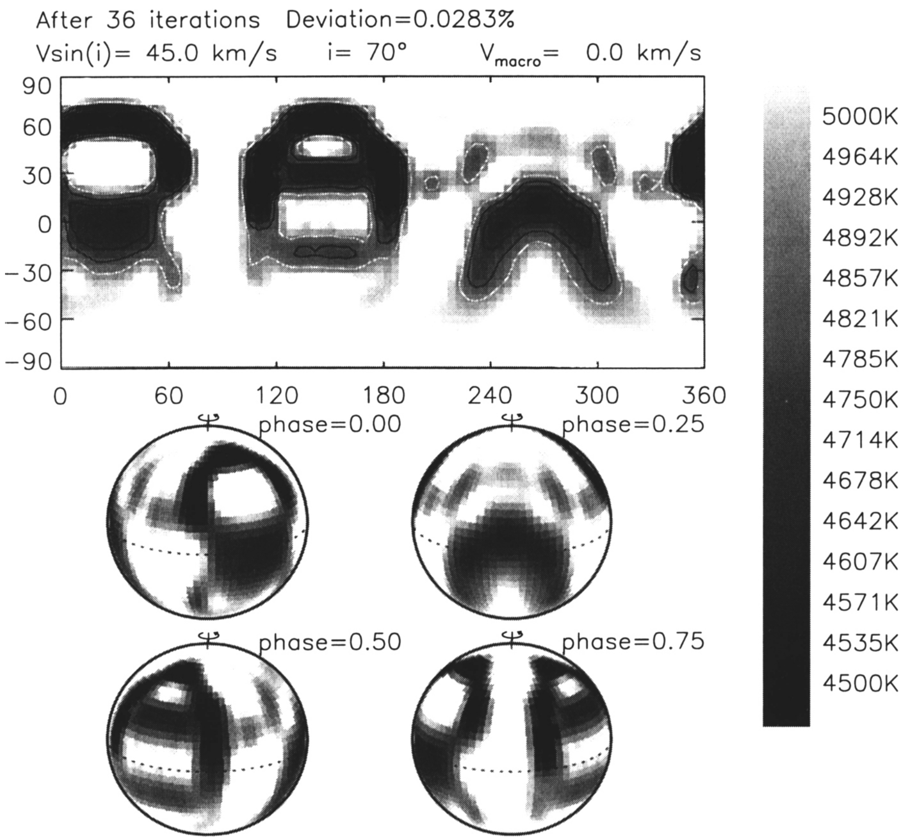

Figure 2. The reconstruction of the OA_A pattern for a single star (Vincent et al. 1990).

The formulation of the inverse problem for an eclipsing binary is very similar to the case of a single star: we minimize the deviation of the spectral synthesis from the observed line profiles by adjusting the surface structure. The adjustment procedure is constrained by a regularization function which leads to a unique solution. However, the spectral synthesis calculation is significantly different. We assume to know the elements of the orbit and the exact shape of the stars. At any given phase we integrate specific intensities over the visible parts of the binary components, taking into account rotational and orbital Doppler shifts. The specific intensities are computed by solving the radiative transfer equation in each surface element of the two components. To save the computing time we precalculate the table of the local line profiles (Piskunov and Rice 1993) and interpolate while integrating the residual fluxes. Two separate tables have to be computed if the components have significantly different temperatures and masses. The explicit solution of the radiative transfer allows us to incorporate blends

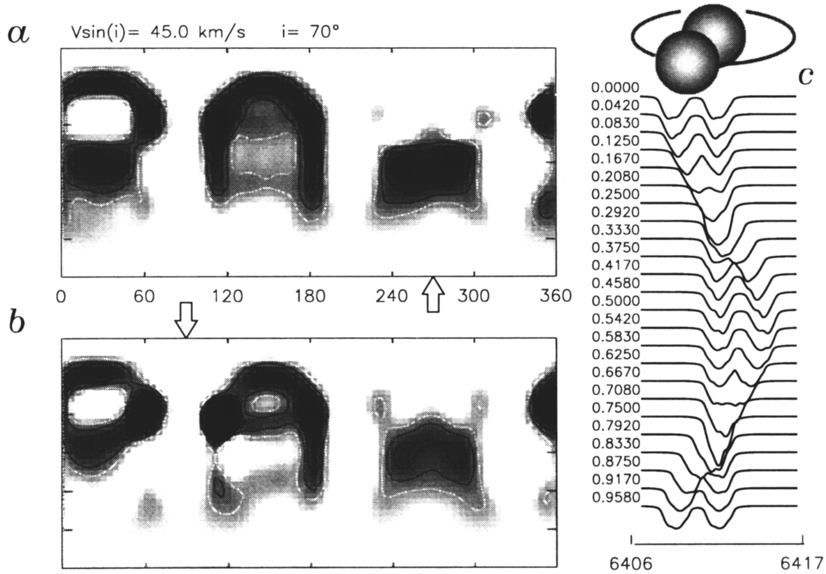

Figure 3. The reconstruction of the OA_A pattern for a binary star (Vincent et al. 1990). The arrows mark the phase of the eclipse for each component.

and the proper temperature behavior of the lines. The latter is crucial for eclipsing binaries because most of them have very large orbital Doppler shifts and therefore we must synthesized wide portions of the spectra for each of the components in order to reproduce the combined spectrum at every phase.

3. Numerical experiments

The numerical experiments with the simulated line profiles for a preset spot pattern allow us to predict the quality of the map for different geometrical configurations and different observational data quality. In our experiments (Vincent et al. 1993) we synthesised the observed spectra for a binary system with cold spots in the shape of letters OA_A (Figure 1). This particular shape provides a very thorough test for the DI procedure because the pattern contains several horizontal and circle–like details. The contrast of the spots is 1000 K and we assume the components to have the same temperature so that both spectra are visible.

Figure 2 shows the reconstruction of OA_A pattern for a single star using the same inclination and 24 rotational phases. One can see "reflections" of the letters to the opposite hemisphere. Figure 3 shows the reconstruction for the model in Figure 1.

A comparison of Fig. 2 and 3 proves that DI for eclipsing binaries can

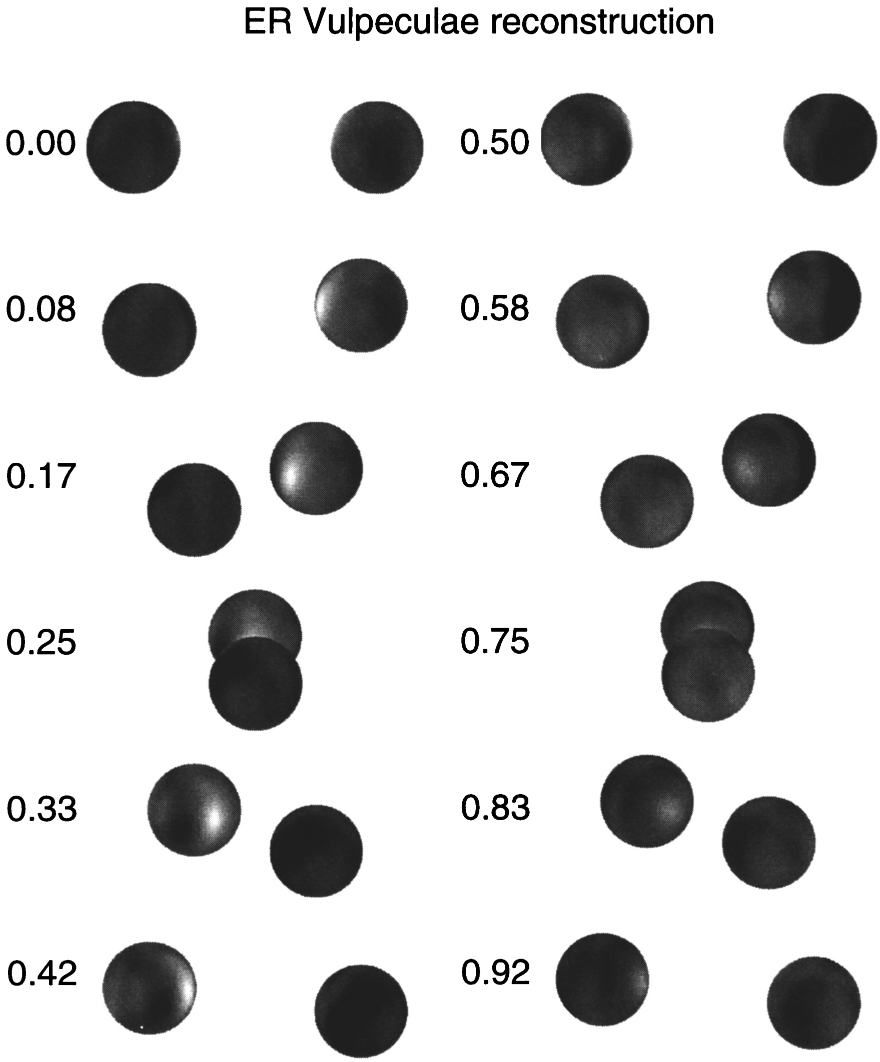

Figure 4. Doppler imaging of the effective temperature distribution on the surface of ER Vul. At phase 0.25 primary is in back. Bright spots at substellar points are probably due to the reflection effect.

produce maps of the same quality as for a single star. Moreover, the observations during the ingress and egress improve the recovery of the latitude information for the eclipsed part of the star (Figure 3) and significantly reduce reflections around near the eclipsed longitudes. Other experiments show that the spatial resolution of the map is higher for the larger and therefore faster rotating component, and that the DI map is very sensitive to the errors in orbital elements, especially the semi-major axis, eccentricity, and inclination of the orbit. The latter can be used to tune the orbital

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elements because even small deviations in these parameters result in a bad fit to the observed spectrum and very characteristic distortions of the map. The important check for the crosstalk effect proves that the method can reliably distinguish between the two spectra and properly attributes spots to the right component.

4. ER Vulpeculae

ER Vulpeculae (HD 200391) is one of the best studied RS CVn type eclipsing binary stars. The components of ER Vul (spectral class G0V and G5V) show synchronized orbital motion with a period of 0.698 days. The orbit is very close to circular with a radius of 3.97 $r_\odot$ and an inclination of 67°, giving rise to a partial eclipse. The identical radii of the components (1.07 $r_\odot$) let us achieve the same spatial resolution on both stars.

The 12 spectra of ER Vul were obtained in June 1993 using the SOFIN spectrograph on the Nordic Optical Telescope at La Palma during 3 consecutive nights. The typical signal-to-noise ratio is 200 and the resolution is 90 000. For DI, we used the spectral region centered on 6440 Å that contains a number of temperature sensitive Ca I and Fe I lines. The resulting distribution of effective temperatures is shown in Figure 5. Both components show large temperature variations around the mean values (5900 K for the primary and 5750 K for the secondary). Hot spots are concentrated around substellar points, presumably due to the reflection effect. The contrast of the hot spots is approximately 1200 K. Cold spots have similar contrast but their distribution does not show any regular pattern. Regular observations would allows us to confirm the presence of the reflection effect and to monitor the evolution of the dark regions.

5. Contact binaries

Recently, we modified our code to allow for non-spherical shape of components and ran a series of numerical experiments for W UMa type eclipsing binaries. We used HD 87079 (Hill 1979) as our prototype. HD 87079 is an F8 type contact binary system with mass ratio 1:2 and an orbital period of 0.42 days. The gravitational darkening parameter, β, was set to 0.08. In addition, we placed a rectangular spot on surface of the primary. The temperature within the spot is 500 K cooler than it would be due to gravitational darkening.

Simulated spectra were generated for the region around 5507 Å, which is dominated by a strong Fe I line (5506.779 Å). In addition to the spectroscopic data, we also simulated B and V band photometry. To account for the brightness of HD 87079 (V=9.9) we reduced the S/N of the simulated spectra to 100. Given the high rotational velocities in the system

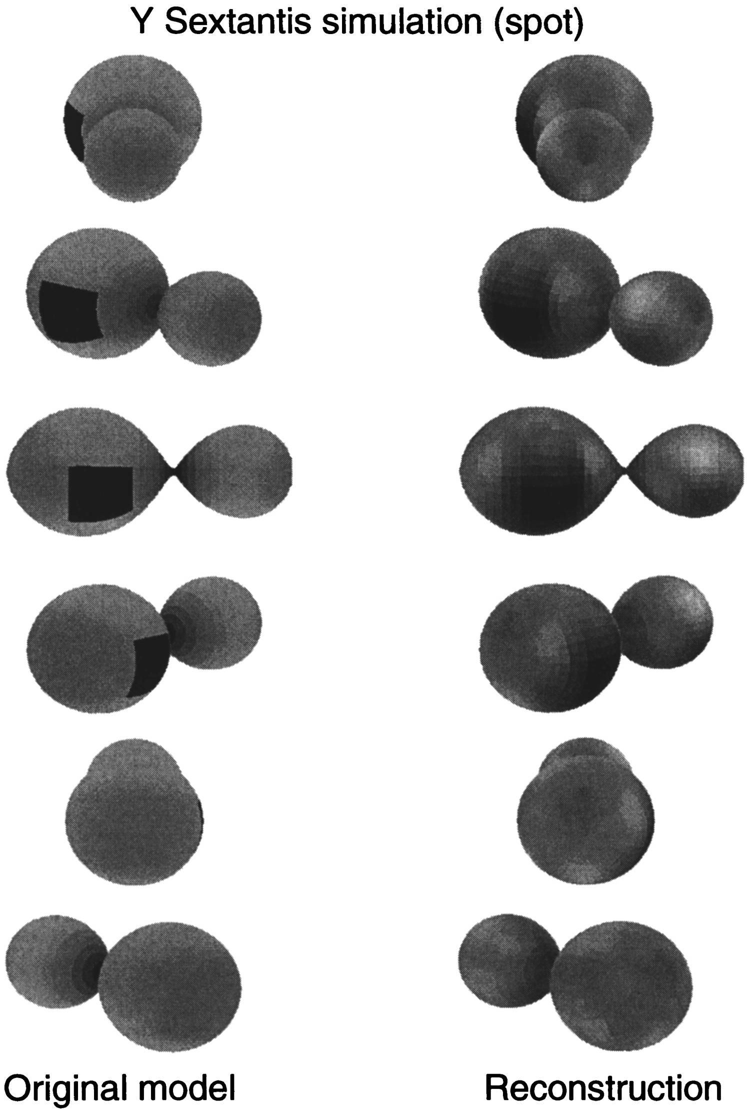

Figure 5. The reconstruction of the model for HD 87079 using Fe I 5506.779 Å line and the 2-band photometry. The spot contrast is 500 K. The spectroscopic S/N was set to 100.

($V \sin i$ ≈180 km/s), this made the reconstruction very difficult. Nevertheless the resulting image (Figure 4) reproduces the general temperature distribution on both stars. The maximum difference from the original model occurs in the "neck" between the components (≈400 K), which has very small Doppler shifts and contributes little to the total flux. The rest of the surface is reproduced to within 50 K. The reproduction of the spot is acceptable although sharp boundaries were lost due to the high level of noise in the data. The quality of the image can be improved by using simultaneous narrow-band photometry.

6. Conclusions

With the help of numerical simulation we show that DI technique can be successfully extended to the case of eclipsing binary systems. The presence of the eclipse provides extra constraints for the imaging procedure and resolves the north-south ambiguity typical for high inclination of the orbit. Our imaging procedure can image both components simultaneously (if both spectra are visible) and the crosstalk effect between the two maps is negligible. The Doppler shifts of the line profiles are very sensitive to the orbital elements and radii of the components, therefore DI can be used to improve the accuracy of these parameters. We can also verify the assumption of the synchronous rotation and spherically shaped components. The image of the temperature distribution allows us to measure the reflection effect, as in the case of ER Vul.

DI of binary systems requires very high quality observations, especially in terms of the signal-to-noise ratio and phase coverage, and a spectral synthesis approach to the calculation of the residual profiles. Single line imaging does not provide enough temperature sensitivity and is influenced by the blending between both spectra that is changing with the orbital phase.

We also find that DI can be applied to W UMa type systems, and the combination of narrow-band photometry and spectroscopic data allows us to distinguish temperature spots over most of the surface of these objects and to measure the gravitational darkening.

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