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Can star spots mimic differential rotation?

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Abstract. The search for stellar differential rotation in Fourier-transformed profiles utilizes subtle deviations from the standard rotation profile. We investigate the influence of stellar spots on the results obtained with the Fourier Transform Method. Different spot configurations, especially polar spots, are examined, and their influence on Fourier-transformed line profiles studied. We found that polar spots cannot mimic solar-like differential rotation and are thus not critical for the use of the Fourier Transform Method. Although not indicated by Doppler imaging, other configurations may occur on stellar surfaces and their influence on the analysis is discussed. A symmetric distribution of spots in an activity belt leads – in a small region of the parameter space – to line profiles that are very similar to the signatures produced by differential rotation.

Key words. starspots – stars: rotation

1. Introduction

The solar rotation law and its applicability to stars other than the Sun play a key role in our understanding of the solar/stellar dynamo and activity. Evidence for the differential rotation of the Sun comes from long-term observations of solar spots and from helioseismology (Howard 1984; Schou et al. 1998). Rotation laws on other stars cannot be observed directly and different approaches have been developed. One method is to search for effects of differential rotation in the line profiles, that was first discussed by Huang (1961). The usefulness of the Fourier transform in this context was realized by Gray (1977), and the effects of differential rotation on Fourier-transformed line profiles were studied in detail by Reiners et al. (2002). They specifically show that the Fourier Transform Method (FTM) is capable of detecting stellar differential rotation under certain circumstances.

The Fourier-transformed line profile of a rotating star shows a characteristic shape (Fig. 1), that is dominated by a "main lobe" at low frequencies, followed by smaller "sidelobes" at higher frequencies. Reiners et al. (2002) studied the location of the zeros (q_1, q_2 etc.) separating the lobes for differentially rotating stars, assuming rotation laws similar to that observed on the Sun:

$$\omega(l) = \omega_0(1 - \alpha \sin^2 l), \tag{1}$$

with l the latitude and ω_0 the angular velocity at the equator. $\alpha = 0$ implies solid body rotation, $\alpha > 0$ equatorial acceleration (solar-like differential rotation; $\alpha_\odot = 0.20$) and $\alpha < 0$ polar acceleration.

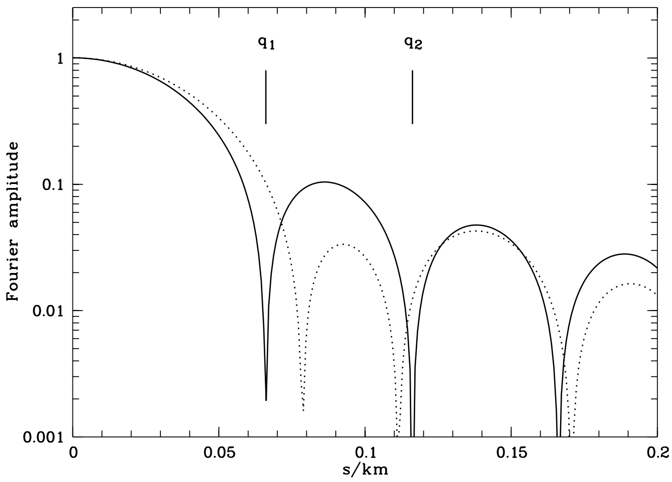

Fig. 1. Normalized Fourier transforms of rotationally broadened line profiles with $v_{\rm rot} = 10\,{\rm km\,s^{-1}}$ ($i = 90°$); rigid rotation ($\alpha = 0.0$; solid line) and differential rotation ($\alpha = 0.5$; dashed line) are shown. Zero positions q_1 and q_2 of the solid line are marked.

Reiners et al. (2002) specifically showed that the ratio q_2/q_1 can be used to determine the value of α. In Fig. 2 the dependence of q_2/q_1 on α and on the inclination angle i is plotted in grayscale (from black to white, values of q_2/q_1 from 1.3 to 2.0 are shown). In the considered case a linear limb darkening law with a limb darkening parameter $\epsilon = 0.6$ was used. The correct choice for ϵ is only poorly known and three lines of constant q_2/q_1 according to different values of ϵ but constant $\alpha = 0.0$ are overplotted. The dashed line represents q_2/q_1 for $\epsilon = 0.6$, the value expected for the Sun; solid lines indicate the values due to extreme ($\epsilon = 1.0; q_2/q_1 = 1.83$, left line) and no limb darkening ($\epsilon = 0.0; q_2/q_1 = 1.72$, right line).

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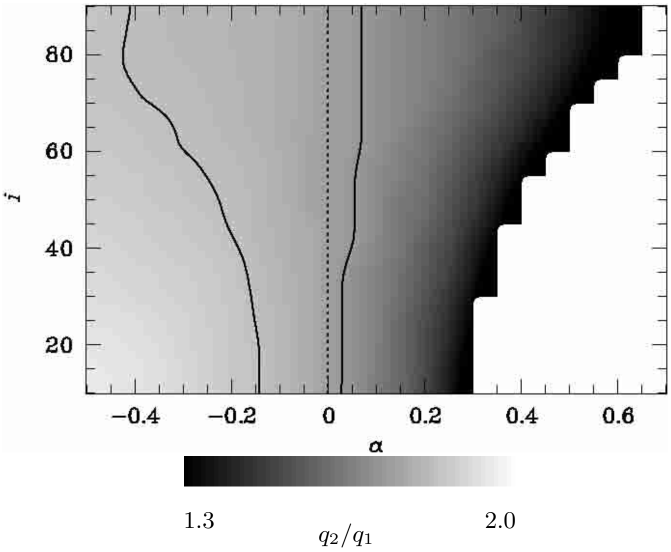

Fig. 2. Dependence of the measured ratio q_2/q_1, which is sensitive to differential rotation, on the inclination angle i and the amount of differential rotation (α). q_2/q_1 is greyscaled with values from 1.3 (black) to 2.0 (white). Three lines at constant q_2/q_1 are plotted for $\alpha = 0.0$; solid lines show $q_2/q_1 = 1.83$ ($\epsilon = 1.0$), $q_2/q_1 = 1.72$ ($\epsilon = 0.0$), the dashed line has constant q_2/q_1 at $\epsilon = 0.6$ (see text).

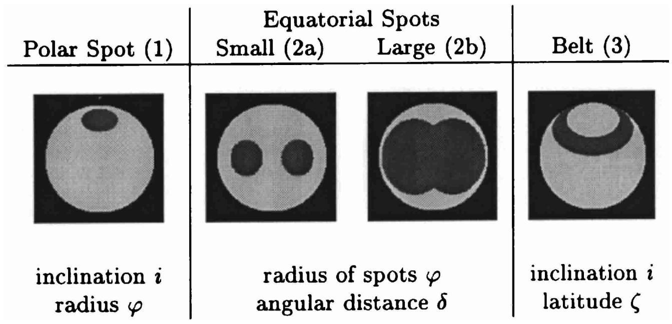

Fig. 3. The geometries of stellar spot distributions considered in this study and the varied parameters. (1) polar spot; (2) two spots on the equator seen under inclination $i = 90°$, the phase is chosen to obtain a symmetrical distribution; (3) a belt around the pole, thickness $h = 20°$.

Thus the region in between the solid lines is occupied by values that can be obtained by varying the limb darkening parameter ϵ of a rigidly rotating star ($\alpha = 0.0$), as well as by varying the differential rotation parameter α while leaving ϵ constant. As a consequence, this implies that values of q_2/q_1 outside the region bordered by the solid lines cannot be due to an undisturbed rigidly rotating stellar surface, regardless of the choice of ϵ.

In summary, measurements of $q_2/q_1 < 1.72$ indicate solar-like differential rotation ($\alpha > 0.0$), $q_2/q_1 > 1.83$ indicate anti-solar-like differential rotation ($\alpha < 0.0$). A value of $q_2/q_1 = 1.65 \pm 0.01$ was determined for ψ Cap (F5V) by Reiners et al. (2002), which has been interpreted as solar-like differential rotation ($\alpha = 0.15 \pm 0.1$). For a fast rotator like ψ Cap ($v \sin i = 42 \pm 1\,\mathrm{km\,s^{-1}}$) no differential effect of this strength would be expected and the question arises whether there are additional effects influencing the shape of the spectral lines and mimicking differential rotation. An obvious candidate are star spots. Star spots can be quite large in active stars and can change the gross features of the line profile. Rapid rotators in which differential rotation is least difficult to detect tend to be active stars and active stars tend to have spots. The purpose of this paper is therefore to investigate whether star spots can mimic differential rotation effects in Fourier transformed line profiles.

2. Configurations of active regions

In any discussion of the influence of stellar surface structures on line profiles, two different cases must be distinguished from the observer's point of view; the projected configuration of spots on the stellar surface with respect to the axis of rotation is a) symmetric, or, b) it is asymmetric. In high quality spectra, asymmetric surface configurations lead to asymmetries in the line profiles. These asymmetries can easily be found by mirroring the profile at its center and comparing the original with the mirrored profile. Because the Fourier Transform Method (FTM) explained in Sect. 1 is only applicable to symmetric profiles, we must disregard any asymmetric profiles. This implies that the FTM is not suitable for stars showing asymmetric projections of the distributions of surface spots (that are large enough to affect the line profiles).

For the symmetric line profiles three different scenarios with spots are possible; 1) polar spots, 2) incidentally symmetric distributions of spots, 3) activity belts. Stellar surfaces with polar spots are often found in Doppler images, and their influence on the FTM will be discussed in Sect. 2.1. Incidentally, symmetric distributions include principally any spotted stellar surface that happens to yield to a symmetric projection towards the observer. These cases are considered in Sect. 2.2. Another symmetric configuration can occur if many spots are ordered on a belt around the rotational pole. This geometry is investigated in Sect. 2.3.

2.1. Polar spots

Indications for polar spots on the photospheres of cool stars have been found in a series of studies. Particularly, the Doppler imaging technique indicates that polar spots are quite frequent on the surfaces of G- and K-type stars (for an overview see e.g. Strassmeier 2001). Line profiles from stars with polar spots are affected in the line center. The surface configuration does not change with rotation and no modulation of the light curve can be seen either. Thus polar spots cannot be ruled out by the use of photometric or spectroscopic time series, and the only way to detect them is to compare the spectra with model profiles from unspotted stars.

It is not obvious whether polar spots affect line profiles and especially the Fourier transform in a similar way to

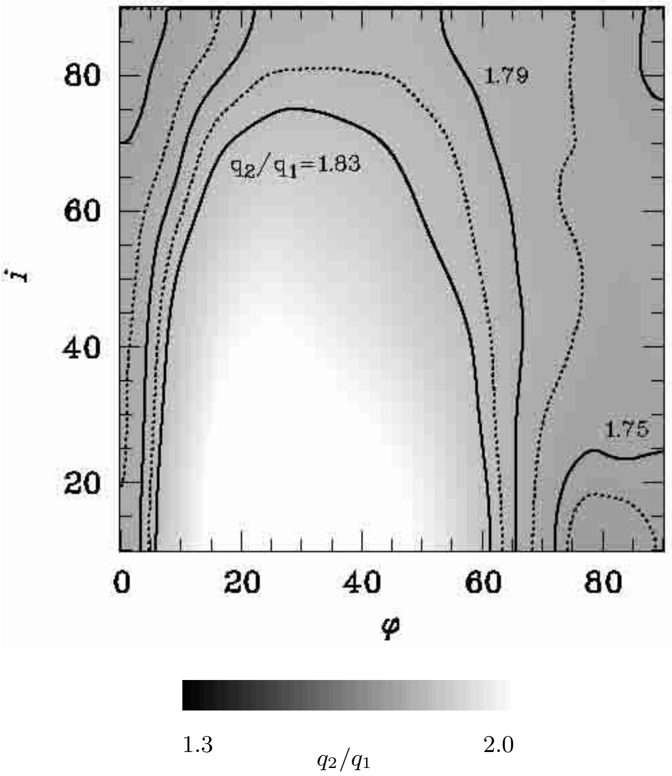

Fig. 4. Map of grayscaled q_2/q_1 according to a star with a cool polar spot of radius φ (in degrees), observed under inclination i. Grayscale of q_2/q_1 is the same as in Fig. 2. Contours indicate constant q_2/q_1 for $1.83 \geq q_2/q_1 \geq 1.75$ in steps of 0.02, the dashed line in the lower right corner is the same as in Fig. 2 (q_2/q_1 at $\alpha = 0.0$ and $\epsilon = 0.6$). Note that the line at $q_2/q_1 = 1.72$ does not appear; $q_2/q_1 > 1.72$ for all cases.

differential rotation. We therefore modelled a rigidly rotating star with one circular spot at the visible pole using the same modeling and transformation technique discussed in Reiners et al. (2001). The temperature of our model star is 5700 K, and we used a spot temperature of 4200 K, comparable to an average sunspot. Two parameters are varied in our study; a) the inclination i of the rotational axis to the observer's line of sight, b) the radius φ of the spot; φ is expressed in degree, i.e., a spot with a radius of $\varphi = 90°$ covers half the star (cf. Fig. 3).

An analysis identical to that discussed in Sect. 1 was carried out for the spotted star's spectra. We found that the shape of the Fourier transform does not fundamentally change by the introduction of a polar spot, and that the characteristic sidelobe structure can be found in the Fourier transformed profiles of all of our model stars. The ratio q_2/q_1 was calculated and the results are shown in Fig. 4. The same lines of constant q_2/q_1 as used in Fig. 2 appear, and some additional contours are also plotted for readability. It appears that the dashed line, which represents that value of q_2/q_1 which is expected from a rigidly rotating star with a limb darkening parameter $\epsilon = 0.6$ without any spots, spans only a small part of the considered parameter space (lower right part in Fig. 4). A large part of the parameter space is covered by values of q_2/q_1 larger than 1.83 (which is marked with a solid line), the highest ratio q_2/q_1 that can be caused by limb darkening effects. The line at $q_2/q_1 = 1.72$ does not appear in Fig. 4, i.e. q_2/q_1 is always larger than 1.72.

Since the criterion for the detection of solar-like differential rotation in a Fourier transformed line profile is $q_2/q_1 < 1.72$, we conclude that polar spots cannot mimic solar-like differential rotation. Therefore polar spots cannot invalidate any search for solar-like differential rotation using FTM. On the other hand we found that a large region of the parameter space yields values of q_2/q_1 larger than 1.83. These values can also be due to anti-solar-like differential rotation (pole rotates faster than equator), but cannot be obtained from the spectrum of an unspotted rigidly rotating star. For rigidly rotating stars believed to occupy that region in Fig. 4, $q_2/q_1 > 1.83$ is a necessary condition for the existence of the polar spot. Thus it is possible in some cases to check the geometries suggested from Doppler Imaging.

2.2. Incidentally symmetric spot distributions

We can in principle not exclude the case that the observed characteristics of line profiles are due to incidental combinations of the spots' temperatures and spatial distributions. Almost arbitrary spot distributions on the stellar surface observed at a suitable phase of rotation might cause symmetric projections towards an observer.

Whether the symmetry of an observed stellar surface is due to a symmetric surface geometry or is only due to the projection at the time of observation can be tested by more observations. Observations at different rotational phases will vary if the surface distribution is asymmetric and thus these cases can be ruled out.

We carried out simulations for the case of two circular spots with identical sizes φ (in degrees), and with a distance $\delta < 180°$, describing an asymmetric geometry, but with the observational phase chosen to obtain a symmetric projection of this geometry (cf. Fig. 3). We varied the parameters φ and δ and calculated q_2/q_1 from the Fourier spectrum. The inclination angle is always set to $i = 90°$. Configurations with spot radii $\varphi \gtrsim 30°$ (case 2b in Fig. 3) have spot filling factors of >30% of the visible surface. Such large filling factors are unlikely due to spots. On the other hand such geometries would be comparable to hot spots at the poles, which are not considered here.

Some configurations implying spots with $\varphi \lesssim 30°$ do indeed lead to values of $q_2/q_1 < 1.72$ and thus mimic solar-like differential rotation (e.g., case 2a in Fig. 3 has $q_2/q_1 = 1.71$). For all of those models the distance between the two spots is $40° < \delta < 90°$, which means that two noticeable bumps emerge in the spectrum. Our calculations showed that perturbations of the undisturbed (rigidly or differentially) rotation profile, which are due to such spots, will be significant, if the signal to noise ratio is as high as needed for the detection of differential rotation.

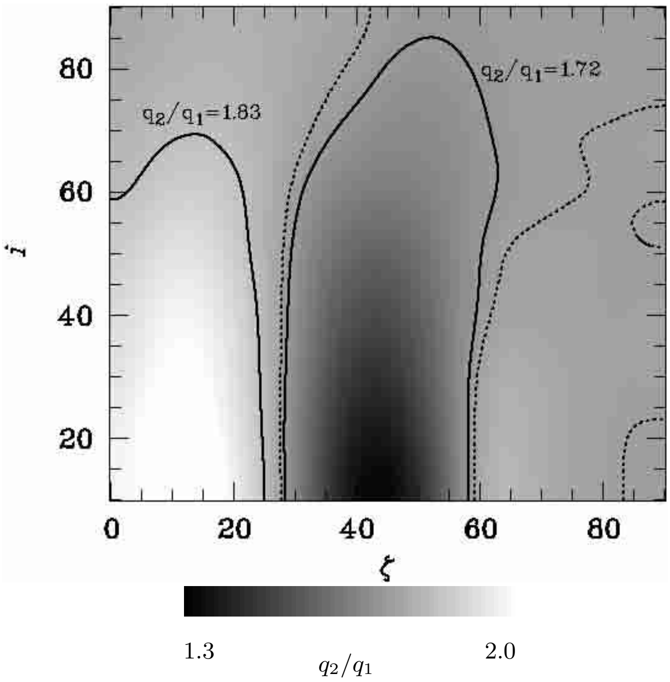

Fig. 5. Map of grayscaled q_2/q_1 according to a star with a cool belt of 20° width at latitude ζ (in degree), observed under inclination i. Grayscale of q_2/q_1 and overplotted lines of constant q_2/q_1 are the same as in Fig. 2.

Thus those "small" spots contained in the profile cannot be misinterpreted as differential rotation.

2.3. Activity belts

Besides polar spots there is a second symmetric distribution of active regions that one should consider. If in analogy to the solar case, active regions are placed at certain latitudes, one also can think of stars where these latitudes are to a high degree populated by spots. In these cases the spots might apparently merge to a belt of active regions around the star. We computed this configuration using a thickness of the belt of $h = 20°$ (cf. Fig. 3, case 3). The belt latitude ζ is varied between 0° (which is equivalent to a polar spot) and 90° (a belt around the rotational equator). The rotational axis is inclined under an arbitrary inclination angle i ($0° < i \leq 90°$). We show the q_2/q_1-map of this geometry in Fig. 5. The bright region at small values of ζ is comparable to the case of polar spots, because the belt is almost closed around the pole. For values of $30° < \zeta < 60°$, there is a region where $q_2/q_1 < 1.72$.

Taking a look at the Fourier transforms of the line profiles with $\zeta \gtrsim 50°$, it emerges that their shape differs strongly from shapes due to rigid or differential rotation. Those profiles would in practice not be attributed to differential rotation. On the other hand, activity belts with $30° < \zeta < 50°$ lead to profiles that can hardly be distinguished from rotational profiles. If additionaly the inclination angle has a value leading to $q_2/q_1 < 1.72$ (Fig. 5), such cases can mimic solar-like differential rotation using FTM.

3. Discussion and conclusions

A study on the influence of geometrical distributions of stellar spots on the search for solar-like differential rotation using FTM has been carried out. It is impossible to attribute small values of q_2/q_1 to a polar spot, a stellar surface feature that can be found on many Doppler images. Furthermore, the signature of a polar spot in stellar line profiles is similar to anti-solar-like differential rotation. Since we do not expect an anti-solar-like rotation law (i.e., an accelerated pole) for solar-like stars, it is possible to test the results from Doppler-imaged polar spots.

Our study of the influence of equatorial spots showed that with a signal-to-noise ratio needed for the detection of differential rotation, spots that might influence the Fourier transform will be detected directly in the line profile. Thus significant asymmetric spot distributions can be discerned, and they will not mimic an unspotted differentially rotating surface.

For the symmetric distributions a handful of configurations remain which indeed can mimic solar-like differential rotation. Since the incidental symmetric distributions are rather implausible, the only probable geometry is a large number of spots occupying a region along a certain latitude in a belt. At latitudes $30° < \zeta < 50°$ and certain inclination angles i (cf. Fig. 5) q_2/q_1 becomes smaller than 1.72, which is the indication of solar-like differential rotation. On the Sun a typical filling-factor of 0.2% is reached at the maximum of activity. The desired configurations have filling-factors of ∼8%. For the faster rotators that can be investigated with FTM this might not be unrealistic. In these cases time-series can be helpful; if the value of q_2/q_1 was dominated by a belt, and if we assume that those objects underly activity cycles similar to the Sun, q_2/q_1 in turn will change during a stellar cycle.

However, although indications for spots situated along activity belts do indeed exist (e.g., Barnes et al. 2001), the configurations are not sufficiently continuous to mimic an unspotted differentially rotating star. Thus we conclude that observed q_2/q_1 values cannot be attributed to surface spots and that the most probable interpretation of $q_2/q_1 < 1.72$ is that of solar-like differential rotation.

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References

Barnes, J. R., Collier Cameron, A., James, D. J., & Steeghs, D. 2001, MNRAS, 326, 1057
Gray, D. F. 1977, ApJ, 211, 198
Howard, R. 1984, ARA&A, 22, 131
Huang, S.-S. 1961, ApJ, 133, 130
Reiners, A., Schmitt, J. H. M. M., & Kürster, M. 2001, A&A, 376, L13
Reiners, A., & Schmitt, J. H. M. M. 2002, A&A, 384, 155
Schou, J., Antia, H. M., Basu, S., et al. 1998, ApJ, 505, 390
Strassmeier, K. G. 2001, 11th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ed. R. J. García López, R. Rebolo, & M. R. Zapatero Osorio, ASP Conf. Ser., 223, 271