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Surface velocity network with anti-solar differential rotation on the active K-giant σ Geminorum

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We demonstrate the power of the local correlation tracking technique on stellar data for the first time. We recover the spot migration pattern of the long-period RS CVn-type binary σ Gem from a set of six Doppler images from 3.6 consecutive rotation cycles. The resulting surface flow map suggests a weak anti-solar differential rotation with $\alpha \approx -0.0022 \pm 0.0016$, and a coherent poleward spot migration with an average velocity of $220 \pm 10\,\mathrm{m\,s^{-1}}$. This result agrees with our recent findings from another study and could also be confirmed theoretically.

1 Time-series Doppler images of σ Gem

σ Geminorum (75 Gem, HR 2973, HD 62044) is a long-period ($P_{\rm rot} \approx 19.6$ d) RS CVn-type system with a K1-giant primary and an unseen companion. In our initial paper (Kővári et al. 2001) six time-series Doppler images were recovered from the Ca I-6439 Å and Fe I-6430 Å lines. The maps cover 3.6 consecutive stellar rotations in 1996/97. Images #1, #3, and #5, as well as #2, #4, and #6 represent contiguous stellar rotations and therefore independent maps (see our extensive study for details). Since there is a reasonable good agreement between the respective Ca and Fe maps, for further use we combine them to decrease statistically the uncertainties of the individual Doppler reconstructions.

2 Local correlation tracking

The local correlation tracking (hereafter LCT) technique, originally developed for tracking different solar surface features, cf., e.g., Sobotka et al. (1999, 2000), Ambrož (2001), and Švanda et al. (2006), is based on the principle of the best match of two image frames that record the tracked surface structures at two different instants. A small correlation window is chosen in the first frame and compared with a somewhat displaced window in the second frame. When the best matching displacement is found, a vector of displacement is recorded, and a new correlation window is chosen by the side of the former one. This pattern is followed until the whole image frame is covered. The resulting vector field is interpreted as the surface flow map over the time lag of the two initial images. For a more detailed description of the method as well as numerical simulations with artificial data, we refer to a forthcoming paper (Švanda et al. 2008).

In our pilot study we apply the LCT technique to the time-series of the six average (Ca+Fe) Doppler images of σ Gem (Kővári et al. 2001). From the six maps we set four correlation pairs: #1–#3, #2–#4, #3–#5 and #4–#6, i.e., we choose the independent consecutive but contiguous maps to minimize the time shift and, thus, the masking effect of individual spot evolution on the flow pattern. Then, for each pair a velocity field map is computed and finally the four maps are averaged.

The resulting average flow map is shown in Fig. 1. In the figure the large-scale flow network is related to the spatially resolved surface structures, which is expected from solar analogy. The amplitude of the velocity vectors of typically several hundreds of $\mathrm{m\,s^{-1}}$ also seem reasonable. Flows of the order of $100\,\mathrm{m\,s^{-1}}$ are observed in the photosphere of the Sun. Figure 1 shows convergent flows towards spotted regions, which is also consistent with the solar case.

In Fig. 2 we plot the zonal and meridional flow components extracted from the LCT map. Despite its large error bars, the latitudinal distribution of the zonal component is in favor of a weak anti-solar differential rotation (DR afterwards). The latitude (β) dependent rotation law is assumed in the usual quadratic form of

$$\Omega(\beta) = \Omega_{\rm eq} - \Delta\Omega \sin^2 \beta\,, \tag{1}$$

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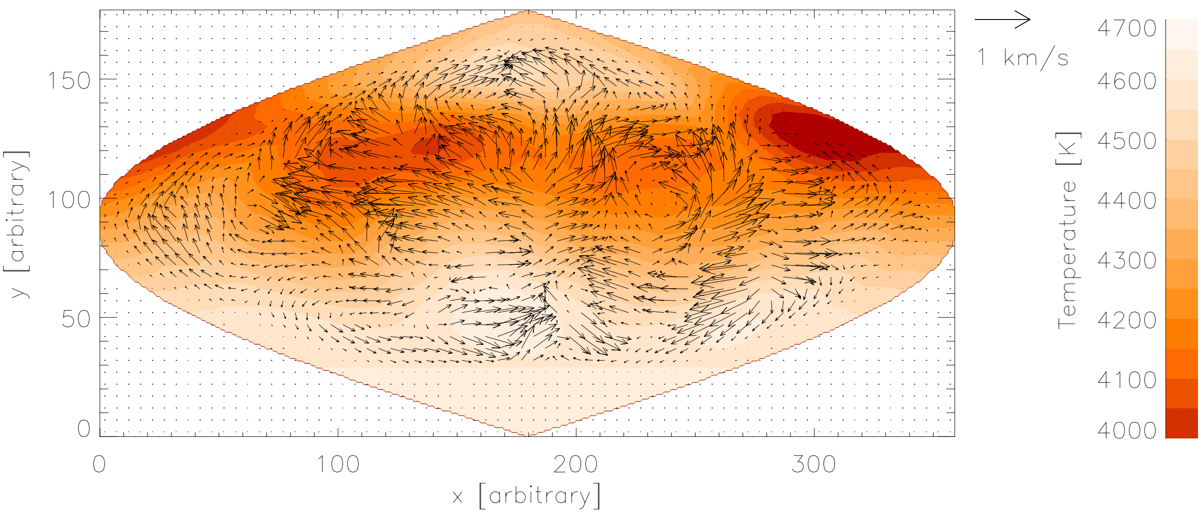

Fig. 1 (online colour at: www.an-journal.org) Surface changes in the photosphere of σ Gem from LCT. As a background we use the average of the six combined (Ca+Fe) time-series Doppler images. Two distinct flow structures can be observed: a complex network of convergent flows around spots and a general poleward trend.

where $\Omega_{\rm eq}$ is the equatorial angular velocity, $\Delta\Omega = \Omega_{\rm eq} - \Omega_{\rm pole}$ is the angular velocity difference between the equator and the pole. The surface shear parameter is defined as $\alpha = \Delta\Omega/\Omega_{\rm eq}$. The best fit gives $\Omega_{\rm eq} = 18.33 \pm 0.01\,°$/day and $\Delta\Omega = -0.04 \pm 0.03\,°$/day which yields $\alpha = -0.0022 \pm 0.0016$, i.e., an almost rigid body rotation. The meridional flow component indicates mostly poleward spot migration. The formal surface-averaged poleward meridional component is $2.5 \pm 0.1°$ over a rotation cycle of ≈20 days, which converts to an average velocity of $\approx 220 \pm 10\,{\rm m\,s^{-1}}$. In the RS CVn-type σ Gem such a meridional flow could be maintained by large-scale thermal inhomogeneities (from large cool spots) and/or by tidal effects from the close binary nature (cf. Kitchatinov & Rüdiger 2004).

3 Cross-correlation results

In this section we compare the LCT results with our recent findings (Kővári et al. 2007b) for the same data by applying the method of 'Average cross-correlation of contiguous Doppler images' (hereafter ACCORD). The method was described and applied to detect surface differential rotation first for LQ Hya in Kővári et al. (2004), and further on has become a powerful tool in analysing time-series Doppler maps (e.g., Kővári, Weber & Strassmeier 2005; Kővári et al. 2007a).

We use again the consecutive but contiguous correlation image pairs (i.e., #1–#3, #2–#4, #3–#5 and #4–#6) and compute four cross-correlation function (ccf) maps. Then we make a linear normalization, since the time baseline of the ccf maps are different. After averaging the normalized maps, we fit the correlation peak for each latitudinal stripe with a Gaussian profile. These Gaussian peaks per latitude are fitted with the usual quadratic form (Eq. 1). The result shown in the upper panel of Fig. 3 suggests an anti-solar type DR law with $\Omega_{\rm eq} = 18.29 \pm 0.05\,°$/day and $\Delta\Omega = -0.38 \pm 0.08\,°$/day and a surface shear of $\alpha \approx -0.021 \pm 0.005$.

Meridional motion of surface features can be derived similarly, by cross-correlating the corresponding longitude stripes along the meridian circles (but restricting only to the more reliable visible hemisphere). The resulting average latitudinal ccf map is plotted in the lower panel of Fig. 3. The best correlating latitudinal shifts suggest a common poleward migration of spots of $\approx 4.1 \pm 0.3\,°$ per rotation cycle, which can be interpreted as a poleward meridional flow with an average velocity of $\approx 350\,{\rm m\,s^{-1}}$.

4 Summary and conclusions

We have demonstrated that LCT technique can be used to map flow fields on stellar surfaces. Applying LCT for time-series Doppler images of σ Gem we reconstruct large-scale surface flows in the order of several hundreds of ${\rm m\,s^{-1}}$ and observe complex network of convergent flows around spots. Zonal flow components suggest rigid-body rotation or anti-solar DR with a very weak surface shear of $\alpha = -0.0022 \pm 0.0016$, while meridional flow components show a coherent poleward spot migration at an average velocity of $220 \pm 10\,{\rm m\,s^{-1}}$. For a more detailed description of the method as well as for numerical tests on artificial data, we refer to a forthcoming paper (Švanda et al. 2008).

Our findings agree well with the results from a recent application of the ACCORD method on the same data (Kővári et al. 2007b). ACCORD resulted also in anti-solar DR law, but with a stronger shear of $\alpha = -0.021 \pm 0.005$.

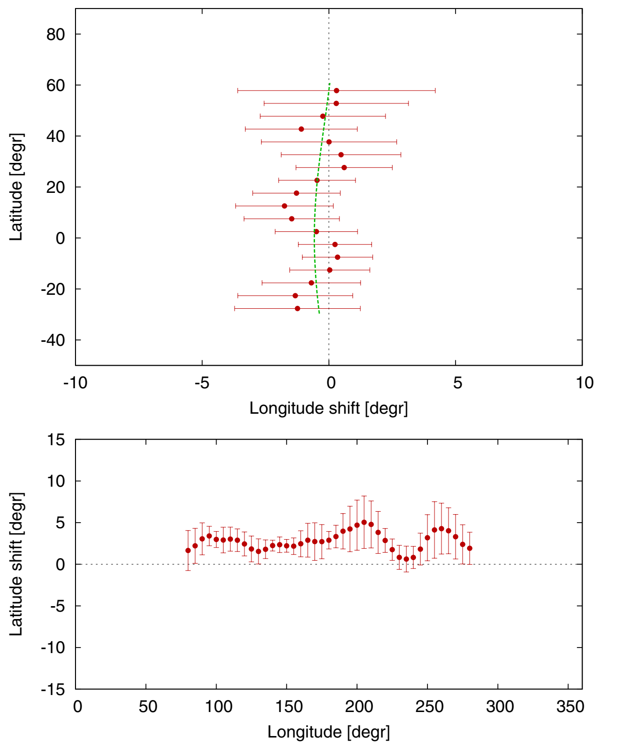

Fig. 2 (online colour at: www.an-journal.org) Zonal (*top*) and meridional (*bottom*) flow components from the LCT method. The zonal distribution may be indicative of anti-solar differential rotation with a shear of $\alpha = -0.0022 \pm 0.0016$. The meridional component shows a coherent poleward flow with an average velocity of $2.5 \pm 0.1°$ over a rotation cycle.

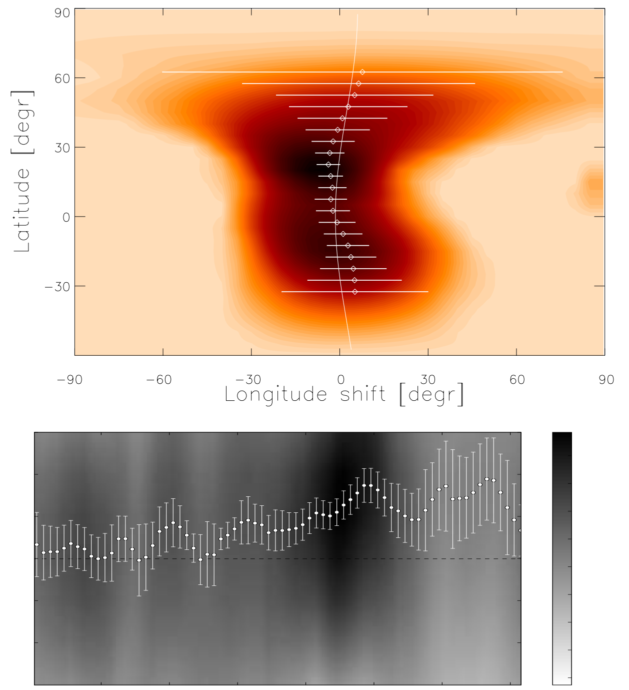

Fig. 3 (online colour at: www.an-journal.org) Latitudinal (*top*) and longitudinal (*bottom*) cross-correlation maps of σ Gem from ACCORD using the average (Ca+Fe) Doppler images from Kővári et al. (2001, 2007b), suggesting anti-solar DR with a coherent poleward migration of spots.

From the latitudinal cross-correlation a coherent poleward flow was derived with a rate of $\approx 350\,\mathrm{m\,s^{-1}}$, which is in qualitative and also in quantitative agreement with the meridional flow component from LCT. The deviation could be originated from the different limitations of the two different approaches.

Sufficiently fast meridional flow can result in anti-solar type DR and the necessary angular momentum transport (i.e., the necessary rate of the meridional flow) can be estimated from Eq. 15 in Kitchatinov & Rüdiger (2004). Taking a turnover time of $\tau = 5.5 \times 10^6$ s with a mixing length l of 7×10^8 m (cf. Gunn, Mitrou & Doyle 1998; Paternò et al. 2002) would yield $\approx 300\,\mathrm{m\,s^{-1}}$, which agrees with our results derived from two different methods. If the poleward surface migration on σ Gem is interpreted due to an underlying meridional circulation, our result could be regarded as a confirmation of the theoretical estimates in Kitchatinov & Rüdiger (2004).

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