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Solar equatorial plasma rotation: a comparison of different spectroscopic measurements

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Abstract. We present solar equatorial rotation velocities measured with two different spectral lines (Fe I 557.6 nm and Ni I 676.8 nm) and two different spectrometers at the German Vacuum Tower Telescope (VTT) on Tenerife. The 'classical' sidereal solar equatorial rotation velocity of about 2000 m/s has been confirmed. The results are compared with those from velocity data of the Michelson Doppler Imager (MDI) onboard the Solar Heliospheric Observatory (SOHO) obtained on 10 June 1996 and 27 May 1999. From both data sets of MDI, a rotation velocity about 100 to 200 m/s below the 'classical' value cited above was found. Possible explanations of this discrepancy are discussed.

Key words: Sun: photosphere – Sun: rotation

1. Introduction

The rotation of the solar plasma is most often determined by measuring the Doppler shifts of photospheric spectral lines across the western and eastern solar hemispheres. In the past mainly the magnetically split Fe I 525.02 nm spectral line had been used (e.g. Howard & Harvey 1970; Snodgrass 1984), because in general the main aim was the measurement of the solar large-scale magnetic field. For specific measurements of the solar plasma rotation the magnetically insensitive Fe I 557.61 nm spectral line was chosen, which in addition allowed to use molecular iodine lines as wavelength reference (e.g. Lustig & Wöhl 1989). The main finding was a solar plasma rotation of about 2000 m/s at the equator with a smooth differential rotation towards the solar poles. Typical parameters for the differential rotation of the plasma rotation as compared with solar structures (e.g. sunspots and coronal holes) are summarized by Stix (1989). Typical numerical values of the solar equatorial plasma rotation and their errors are given e.g. by Balthasar (1984): (1971 $\pm$ 3) m/s, Duvall (1984): (1988 $\pm$ 5.6) m/s, and Ulrich & Bertello (1996): (1987 $\pm$ 7) m/s. From a set of Fourier-Transform Spectra obtained at the Kitt Peak National Observatory, Balthasar (1984) claimed that no variation of the solar rotation with depth within the photosphere could be determined. Possible daily changes of the solar equatorial rotation velocity are of the order of a few m/s (Küveler & Wöhl 1983). From several years of their own measurements and comparison with data obtained at two other observatories Lustig & Wöhl (1989) concluded that no significant changes of the equatorial plasma rotation due to changes of the solar activity could be found.

The Ni I 676.8 nm line is used for the determination of Doppler motion in two major programs: the Global Oscillations Network Group (GONG) (Harvey et al. 1996) and the Michelson Doppler Imager (MDI) on SOHO (Scherrer et al. 1995). Both experiments concentrate on the investigation of the gobal solar oscillations, but the data can also be used to determine the solar plasma rotation. Hathaway et al. (1996) report a value of only 1837 m/s for the solar equatorial rotation velocity within the first 6 months of GONG operation in 1995. Schmidt et al. (1999) found a similar result with an equatorial rotation velocity of 1790 m/s from MDI full disk velocity data taken 10 June 1996. This nourished the suspicion that these results could somehow be related with uncertainties in instrument calibrations as well as to properties of the line itself.

We have carried out a comparative observation using the Ni I 676.8 nm line (g=1.5) and the nonmagnetic Fe I 557.6 nm line to measure the equatorial rotation velocity. In addition, and in order to improve the reliability of our findings we have repeated basically the same measurement with two very different focal plane instruments: an Echelle spectrograph and a Fabry-Pérot filter spectrometer.

2. Observations

The observations were carried out at the VTT and its Echelle grating spectrometer (Schröter et al. 1985) as well as its scanning double Fabry-Pérot spectrometer, called TElecentric SOlar Spectrometer (TESOS, see Kentischer et al. 1998) on 27 May 1999 from about 8:30 until 18:30 UT.

Setup for the grating spectrograph: The spectral line positions at the focal plane of the grating spectrometer were recorded simultaneously using two different CCD cameras (AT1 with 1024×1024 pixels and XEDAR with 2048×2048 pixels) with exposure times of 0.8 s each. In order to obtain sufficient coverage of the regions near the east and west limb, the solar image was moved across the spectrograph slit in steps of 10”, starting

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at the limb. The slit width equaled about 0.5”. Five of these stepping cycles each were repeated at heliographic positions of $0°, \pm 15°$, and $\pm 30°$ latitude at both limbs within about one hour.

Setup of the TESOS spectrometer: The Fabry-Pérot interferometer TESOS allows to record up to four spectral lines in sequence. We used 25 wavelength positions for each line with stepwidths of 2.11 pm and 2.56 pm for the Fe and the Ni line, respectively. The exposure times were 0.2 s and the cycle time to obtain the twodimensional spectra was 55 s. The field diameter of the TESOS spectra is 94”, therefore a single image position near the limb was sufficient. The spectra were taken at the same heliographic positions as the short scans taken with the grating spectrograph, as described above.

Although in principle the two spectrometers could have been operated in parallel we preferred not to do so: The beam splitting would reduce the signal-to-noise of the data. The different observing principles with scanning in the case of the grating spectrograph and fixed positions in the case of the Fabry-Pérot spectrometer would have complicated the setup and increased the total amount of time needed to construct an optimum program for parallel observations with both spectrometers. There was also no reason to believe the time difference of a few hours between the two measurements would cause any significant effect. Nevertheless the various measurements with the different instruments could not be exactly cospatial due to rotation and seeing effects.

The main reason to use two completely different instruments was the higher spectral resolution of the grating spectrometer and the capability of simultaneous two-dimensional measurements with the TESOS spectrometer.

3. Data reduction

Data from the grating spectrograph: The reduction of the data obtained with the CCD cameras at the grating spectrometer followed the normal procedure by subtracting dark exposures and correcting for different pixel sensitivity (“flat fielding”). The necessary flat-fielded images had been obtained by averaging spectral images obtained during rapid motion of the telescope. The spectral line positions were determined by fitting second order polynomials through the lower 40% of the spectral profiles. To obtain Doppler shifts the spectral line positions from corresponding positions in the eastern and western hemisphere on the Sun were subtracted. Averages of several arcseconds were taken in the spatial direction as well as from the complete scans mentioned above. The limb distances in arcseconds were converted into heliographic longitude and latitude. These values were used to reconstruct the tangential solar rotation velocities from the measured components at the selected positions. Only 5 of the 10 positions scanned near to the solar limbs were used in the reduction to have the same spatial coverage as the TESOS data.

Data from TESOS: The reduction of data from TESOS is simpler with respect to the solar positions, because the same CCD detector was used for both spectral lines. Its digital images were

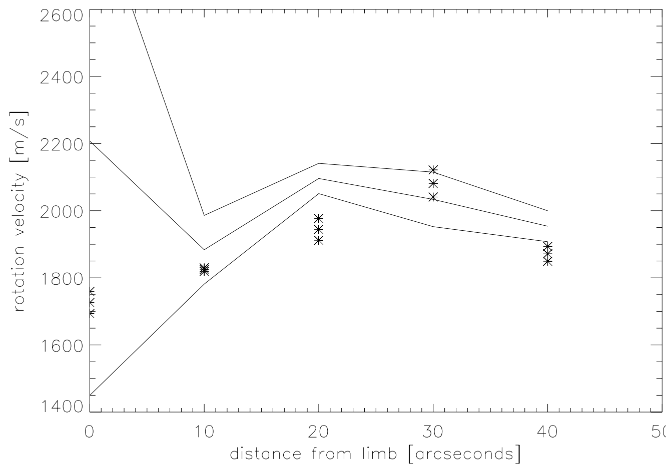

Fig. 1. Rotation velocity from data taken with the grating spectrograph at the solar equator on the east and west limbs. Full lines: Ni I 676.8 nm spectral line data, asterisks: Fe I 557.6 nm data; mean and $\pm 1\sigma$, respectively

reduced in similar steps as those described above. The spectral line positions within each scan were obtained with the same method, i.e. a second order polynomial was fitted to the lower 60% of the spectral line profile around the spectral line minimum, with the minimum of the parabola being the spectral line position.

The method to obtain real solar rotation velocities at the equator was again similar to that described for the grating spectrograph, except that more spatial positions within the shorter total distances of 32” from the limbs towards the disk center were available.

The different depths of the spectral profiles used was forced by the higher noise in the original data from the TESOS spectrometer. We limited the analysis to the equatorial region, because higher latitudes were influenced by magnetic activity. The equatorial belts were free of activity in all data sets.

4. Results

The sidereal solar equatorial rotation velocities from the averaged spectra at the east and west limbs are given in Fig. 1 for the data from the grating spectrometer and in Fig. 2 for the TESOS data. The averaged values are summarized in Table 1, together with the corresponding numbers from the MDI measurements. There are rather large rms fluctuations of the velocities listed in Table 1 ranging from 68 m/s to 125 m/s, but – as can be seen from the figures – these stem mainly from the supergranular velocities measured. They cannot be compared with the errors cited in the introduction, therefore we do not include them in Table 1. The error of the velocity determination is of the order of 20 m/s.

Scattered light: The results of the VTT data listed do not yet include any correction for scattered light. It is well known that scattered light can reduce the velocities derived from Doppler measurements, because a fraction of light from central areas of the solar disk is scattered towards to the limb. A theoretical

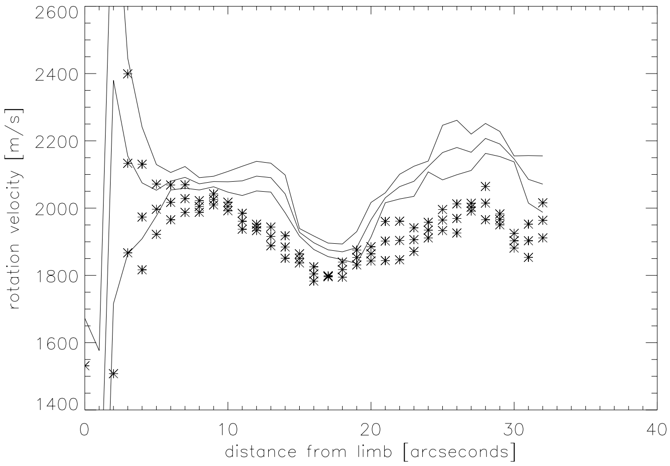

Fig. 2. Rotation velocity from data taken with TESOS at the solar equator on the east and west limbs. Full lines: Ni I 676.8 nm spectral line data, asterisks: Fe I 557.6 nm data; mean and $\pm 1\sigma$, respectively

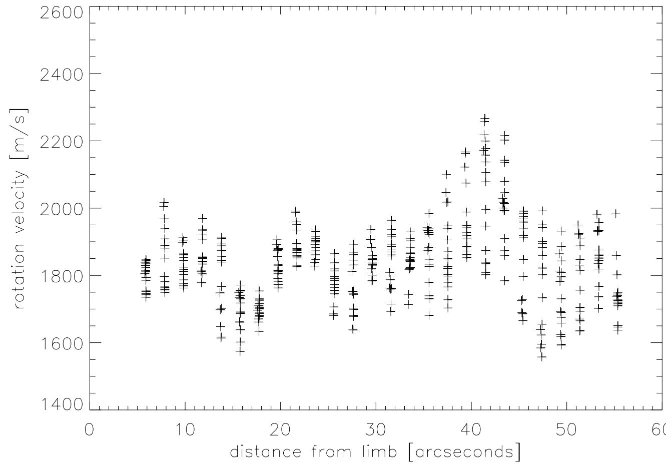

Fig. 3. Rotation velocity from MDI data taken at the solar equator on the east and west limbs on 27 May 1999 at noon. The data are averaged for one hour. All pairs of data points with latitudes less than $\pm 1°$ distance to the solar equator and central distances of more than $70°$ in central meridian distance are used

investigation of the correction for scattered light of the solar equatorial plasma rotation velocity measured in an aureola is given by Albregtsen & Andersen (1985).

One of the CCD cameras used at the Echelle spectrograph (AT1 camera) had a 16 bit digitization and therefore good sampling of low light levels outside the solar disk. From these data the scattered light level at a distance of 120" was extrapolated to be about 0.3% of the disk center intensity. This is in agreement with earlier measurements of Lustig & Wöhl (1993) and indicates corrections of the solar rotation velocity of less than 10 m/s. Since the scattered light is less important for longer wavelengths, the correction for the Ni I 676.8 nm data would be rather negligible i.e. within the accuracy of our measurements and the solar "noise" caused by the large-scale horizontal flow pattern.

5. Comparison with MDI

As already mentioned, the low equatorial rotation velocity found from full disk velocity data of MDI was the motivation for the observations described herein. The instrument, its calibration and data analysis was described by Scherrer et al. (1995). Our results were then compared with the reduced MDI velocity data available at the web site of MDI: There was the old set of data from 10 June 1996 available, which gave a rather low equatorial rotation speed of about 1790 m/s when fitting the hourly mean data with the usual formula for differential rotation (Schmidt et al. 1999). When we learned that old MDI data had been re-reduced in early 1999, we downloaded a sequence of data obtained at noon on 10 June 1996 and a similar sequence obtained at 27 May 1999.

Thanks to the possible averaging of data obtained within one hour with a cadence of one minute, the noise in these data is rather small. Therefore all the data points instead of averages are displayed in Fig. 3. When comparing the spatial structures in Figs. 2 and 3 it seems that the dip near 17" and the rise between 20" and 30" distance to the limb are similar. It remains unclear, whether this is fortuitous or related to the supergranulation.

Table 1. Rotation velocities for 27 May 1999. Comparison between VTT and MDI

Instrument	line	velocity [m/s]
Echelle spectrograph	Fe I 557.6	1965
	Ni I 676.8	2027
Filter spectrometer	Fe I 557.6	1926
	Ni I 676.8	2060
MDI	Ni I 676.8	1842

The average value for the sidereal solar equatorial rotation velocity from all data given in Fig. 3 and included in Table 1 is 1842 m/s. The average from the old data of 10 June 1996 yields a value of 1710 m/s using a similar selection procedure near the solar limbs, while the corrected data of 10 June 1996 give a mean of 1725 m/s. We expect that most of this discrepancy is due to instrumental and/or reduction differences not caused by real solar changes of the rotation velocity.

6. Discussion and conclusion

The determination of the sidereal solar equatorial rotation velocity by the grating spectrometer at the VTT yielded the expected value of about 2000 m/s. There is no significant difference detectable from data reduced from the two spectral lines Ni I 676.8 nm and Fe I 557.6 nm. In Fig. 1 the rotation velocity data from both spectral lines show good agreement in most of the local changes, which are due to horizontal flow components of the supergranulation.

About the same mean value of the rotation velocity was found from data obtained with the scanning Fabry-Pérot spectrometer TESOS. Again, the difference between results from the two spectral lines is not significant.

The results obtained from MDI full disk velocity fields reduced only at the limbs like the VTT spectral data exhibit a sidereal solar equatorial rotation velocity at the same day (27 May 1999) of 1842 m/s. The full disk data from this day yield a rotation velocity of 1900 m/s. These values are 100 m/s to 150 m/s below the 'classical' value given in the literature and verified in the present investigation.

The analysis of the data obtained by MDI on 10 June 1996 showed that the new reduction method of the SOI team raised the results by about 15 m/s. Nevertheless the value obtained is 200 m/s below the 'classical' value. Changes of the solar rotation rate of this amount are very unlikely within 3 years. Since the data have been taken with the same instrument, there might be changes in the instrument itself and/or the reduction procedures that are responsible for these discrepancies.

It should be mentioned that all full disk velocity data from MDI investigated exhibit a gradient of the reconstructed rotation velocity of about -100 m/s from 20° distance to the solar disk center towards the limbs. We thought that scattered light within the MDI instrument is one of the causes for the underestimation of the rotation speed, but MDI experts argue that the level of the scattered light is very low. A wavelength gradient across the field of view (i.e. the solar disk) can not be ruled out. Both GONG and MDI measure the global solar oscillations with high accuracy, but the 'standard' velocity data of MDI are not very useful for solar rotation studies. New calibration methods were suggested by Evans et al. (1998) and Beck et al. (1998) which can be used to correct the MDI velocity data by improved look-up tables. Schou et al. (1998) claim that they were able to fit the solar rotation results derived from solar oscillations at about 0.995 of the solar radius to the solar surface measurements of Ulrich et al. (1988) – at least for data of heliographic latitudes below 80 degrees.

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