Solar-stellar connections - modelling the Sun as an active star

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Abstract. A diagnosis of photometric starspot models is given through modelling active areas on the Sun using softwares originally written for starspot modelling. One-dimensional measurements of the Sun in radio (10.7cm, DRAO, Canada) and in soft X-rays (GOES satellites) were used for the modelling and the results were compared to the contemporaneous direct images of the solar disc made in similar wavelengths at Nobeyama and with the Yohkoh spacecraft.
Conflicting results are found in recovering spot coordinates. The resulting latitudes of the spots are uncertain, artificially high latitude spots appear to account for global brightness changes. The flux ratio between the spotted and undisturbed areas are evolving with the active region, following a power law. The modelled spot areas are close to the reality when this change is taken into account. On a longer time base the flux of the disturbed areas (active nests) comes from co-existing emerging and decaying spots, thus the flux ratio has an almost constant average value. Using this average flux ratio the long-term changes of the spot area could be recovered well. This means, that in starspot modelling, if a well-established spot temperature is found, on a long-term base the resulting changes of spottedness are probably real. However, this is not necessarily true for shorter terms.

1. Introduction

The precise photometric databases are almost three decades long for some well observed active stars (see e.g. Strassmeier et al. 1997). With the general use of automated photometric telescopes (APTs) the databases are continuously growing. It is very important to extract as much information as possible out of those data, that are often used to study the patterns of spottedness using spot modelling codes. It is of crucial importance to test the reliability of the spot modelling results. Since the photometric data have only one dimension and thus have limited information content, simplified assumptions are used: two, or as a maximum, three co-existing spots are assumed. The modelling codes need physical input parameters like the unspotted brightness of the star, the temperature of the spots compared to the quiet photospheric temperature, the inclination angle and the limb darkening coefficients. The stability of spot modelling results (resulted spot locations) and the effects of the physical input parameters were thorougly investigated by Kővári and Bartus (1997).

The ideal test of the reality of any starspot model would be to compare the modelling result with a direct image of the star. This experiment became possible since contemporaneous one-dimensional measurements and images are taken on the Sun every day. This possibility was used first by Catalano et al. (1998) who modelled C II line flux at 133.5 nm and compared the results to direct Hα images, and by Peres et al. (1998) who synthesized solar spectra as if it were measured from a point source (a star) by a satellite (like ROSAT), using Yohkoh images. The opportunity to test photometric starspot modelling arose with the 1996 solar activity minimum when the Sun's activity was very simple, on the other hand, images were taken and one-dimensional flux measurements were gathered each day in several wavelengths.

An important question in starspot modelling is the value of the spot temperature that directly affects the resulting spot area (and through that even the latitude). The long-term databases of the stars do not have sufficient colour information to derive spot temperature for each light curve, therefore usually one constant spot temperature (deduced from recent photometric observations which have V and I colours or for some stars from TiO bands) is used when modelling photometric data. Another question is, how reliable the derived change of spottedness of an active star could be. The existing observations around the solar activity minimum made possible to investigate this problem as well.

2. Method and data

The first step of the work was the modelling of one active region on the Sun. This was possible using the solar data between mid-July and the end of October, 1996, when only one major active region existed on the Sun. Since the amplitude of the flux variability caused by the single active region of the Sun in the radio and X-ray wavelengths was similar to those we observe on stars, we could use these observations to test our spot modelling results. We run our modelling code on the solar one one-dimensional data and compared the results with the direct images (Oláh et al. 1999a, Oláh et al. 1999b, hereafter Paper I).

The second step of the work was modelling an active nest on the Sun. This nest existed between March-December, 1996, including the time when the nest consisted of only one active region. The modelling of the active nest could test how reliable the spot area results could be on a longer time-base.

We used two one-dimensional datasets: daily 10.7cm solar radio flux measurements recorded at DRAO (Dominion Radio Astrophysical Observatory, Tapping and Charrois 1994) Penticton, Canada and soft X-ray irradiance measurements in the 1-8 Å flux range provided by GOES9 (Geostationary Orbiting Environmental Satellites) satellite. Transient (flare) events were removed from the data since we were interested in only the slow flux variability caused by the rotation of the Sun. The GOES9 data were averaged to three datapoints/day; this way the number of data were similiar in the two wavelength range investigated.

The two-dimesional datasets (images) that were used for comparing the modelling results with the reality were full-disc radio images taken with the Nobeyama Radioheliograph at 17GHz (λ = 1.7635cm, Nishio et. al. 1994, Hanaoka et. al. 1994) and soft X-rays full-disc images recorded with the grazing incidence soft X-ray telescope (SXT) onboard Yohkoh (Tsuneta et. al 1991). The same images were also used for direct area measurements.

For modelling the solar radio and X-ray data we used a software package TISMO (*TI*me-series *S*pot *MO*delling, Bartus, 1996) without major modification. In case of stars dark (cool) spots cause the rotational modulation, i.e. the star is fainter when the spot is facing towards us. whereas on the Sun in radio and X-rays we observe bright features. As it was mentioned already the amplitude of the flux variation caused by these bright spots are similar to those we observe on stars caused by dark spots, only the sign of the variability is opposite, i.e., the Sun is brighter in X-rays and radio when the active region is in view. That makes no difference using the spot modelling code. As in most cases of starspot modelling we used one- and two-spot fits. The free parameters were only the spot coordinates and sizes, other physical parameters like inclination, limb-darkening and, in the second step of our work the spot temperature was fixed (about varying spot temperature see the next section).

3. Results

3.1. Models compared to the images

The solar flux measurements together with the two-spot fit are displayed in Figure 1 both in radio and X-ray wavelengths. An example for the comparison between the model and the image is given in Figure 2.

It is well seen from Figure 1 that the rotational modulation given by the one-dimensional data is well approximated by the model. The place and size of the resulting main spot agrees with the image in both wavelengths (Figure 2), where, during the modelling, spot latitudes were fixed to the solar equator.

We made several test runs for the August-October part of the dataset, when only a single active region existed on the Sun. The main task was, as mentioned earlier, to test the reality of photometric starspot modelling. The procedure and the results are given in details in Paper I. We made spot solutions with the code TISMO on solar one-dimensional measurements and compared the results with the direct images made on similar wavelengths. Our most important findings were as follows:

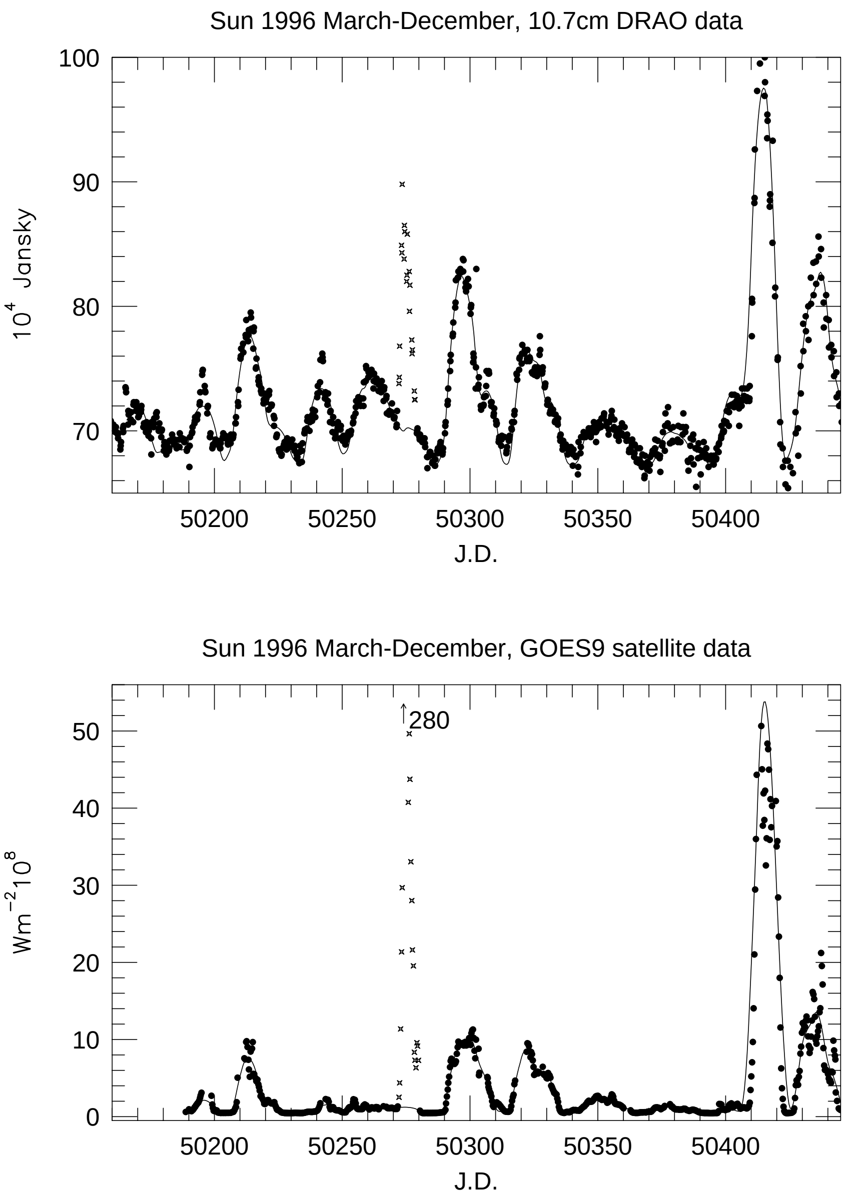

Figure 1: Fitted solar radio (up) and X-rays (bottom) data, March-December 1996. The emergence of the new active region at the beginning of July is plotted by crosses; the latter event was very fast and was not modelled by TISMO.

1. When all the spot coordinates (longitudes and latitudes) and spot sizes were free parameters in the modelling, we found artificially high latitude spot(s) both in the one- and two-spot models. To account for the general (long-term) variability this result is inevitable, since a (changing) spotted area that shows no rotational modulation is necessary, and its proper place is the polar region of a star or of the Sun. (It is noteworthy that the high latitude spots are commonly resulting both in photometric and spectroscopic (Doppler Imaging) starspot modelling. The reality of those results should be strenghtened by independent observations (direct images!) and theoretical considerations.

2. In most cases using two spots is enough to model the deviations from pure sinusoidal light curves (see for more details Kővári and Bartus 1997). However, when a resulting spot is small, it can be put nearly anywhere in the star (with other words

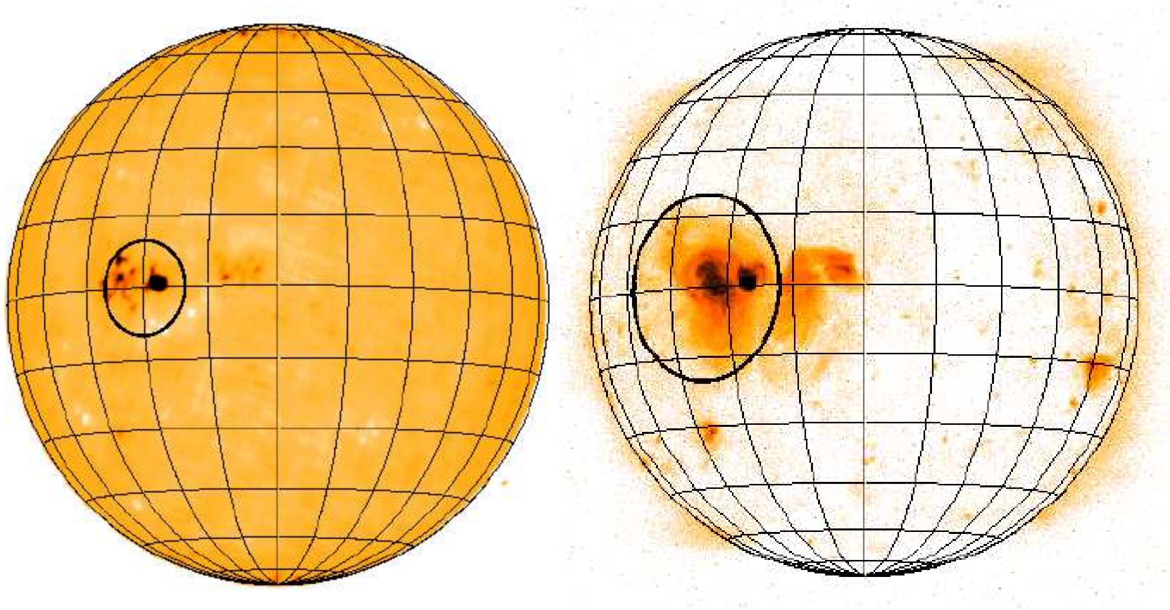

Figure 2: Solar radio (left) and X-ray (right) images overlayed with results of spot modelling on May 11, 1996.

its coordinates are totally unstable), especially in case of high latitudes. These small spots can account for short living spots at different locations on the stars that modify the light curves. Only clearly double-humped light curves caused by two (modelled) spots of similar size suggest two active longitudes with certainty.

3. The spot area could be derived with the highest accuracy using photometric spot modelling. Using the solar one-dimensional data, the modelled spot areas are close to the areas measured on direct images, provided that the intensity of the undisturbed surface and the flux ratio between that and the active region is well known. If we observe systematic changes in spot areas (growing or shrinking spots), that, beside the real area changes, could also mean changes of the flux ratio (warming or cooling active region). The flux ratio and its changes are of crucial importance and is discussed in detail in the next section.

3.2. The flux ratio problem

During the first test runs modelling the August-October dataset, when only one major active region existed on the Sun, we used a constant flux ratio that was calculated using a typical large active region size (5%) and average intensity ratios between the spot and the background given by the measurements. We found that the area of the resulting spot was decreasing in time between August-October. The images, on the contrary, showed that the area of the bright region was growing, as usual, when an acive region is aging. We found that the average temperature difference between the surface and the disturbed area was continuously decreasing, following approximately a hyperbolic function. We then took this change into account and modelled the data with changing flux ratio. The spot area results obtained this way were similar to those we got from direct measurements.

Using constant flux ratios is typical in starspot modelling, since the long datasets usually do not have appropriate colour information to derive spot temperature for each light curve for decades. We saw that the average contrast of a single active region to the background was continuously decreasing. On the other hand, we also know that inside a long-living active nest (or active longitude) the active regions are continuously born and decay. Supposing that during the lifetime of the active nest the temperature changes caused by emerging and decaying active regions were levelling up, we hoped that a constant flux ratio on a longer time-base would give reliable results. To test this hypothesis we modelled the active nest that existed on the Sun between March-December 1996.

We made direct area measurements both in radio and X-ray images on several days during the lifetime of the active nest. Using those areas and the one-dimensional measurements we calculated the flux ratios (FR) using the following expression:

$$\frac{\mathrm{I}}{\mathrm{I}_0} = \frac{FR \times \mathrm{A}_{\mathrm{spot}} + (\mathrm{A}_{\mathrm{disc}} - \mathrm{A}_{\mathrm{spot}})}{\mathrm{A}_{\mathrm{disc}}},$$

where I and I_0 were the spot and background intensities, and $\mathrm{A}_{\mathrm{spot}}$ and $\mathrm{A}_{\mathrm{disc}}$ were the areas of the active region and the solar disc, respectively. The background intensities were derived using the measurements on those days when no active region was visible on the Sun. We formed average flux ratios for the whole investigated time-base and modelled the one-dimensional dataset. Figures 3 and 4 show the results: the determination of the background intensities, the average flux ratios and the modelled area results compared to the direct measurements. The upper panels of Figures 3 and 4 show that the determination of the background intensity of the Sun is not straightforward. Even when no active area is seen on the solar disk, its X-ray and radio intensities are not constant. After the emergence of the large active region in July, an intensity increase was seen even on the other side of the Sun, half a rotation later. Moreover, the DRAO data, at least partly, were uncertain at the end of the year because of the low altitude of the Sun at the latitude of DRAO. The solar minimum occurred in mid-October 1996. Taking all these into account we fixed the unspotted intensity to the values given in Figures 3 and 4.

The flux ratio calculated using the above equation showed strong variability as the active regions emerged and decayed. In Figures 3 and 4 on the left side of the middle panels we also gave the extreme high values of this parameter. The hyperbolic decay of the flux ratio is seen starting around J.D. 50298, when only a large single active region was present on the Sun (for more details see Paper I). We calculated an average flux ratio that we could use in modelling the whole active nest. The highest values corresponding to active regions' emergence were left out of consideration when we made the averages, since extremely high flux ratio values would strongly distort the mean. Additionally, the time-scale of an active region emergence is very short (few days) comparing to the time-scale of the rotational modulation (27 days), and we did not calculate flux ratio values for each day of the observations.

The bottom panels of Figures 3 and 4 show the measured and modelled spot areas in percentages of the total solar surface. We got the modelled spot areas using the average flux ratios. The changes of the modelled spot areas thus follow the changes of the

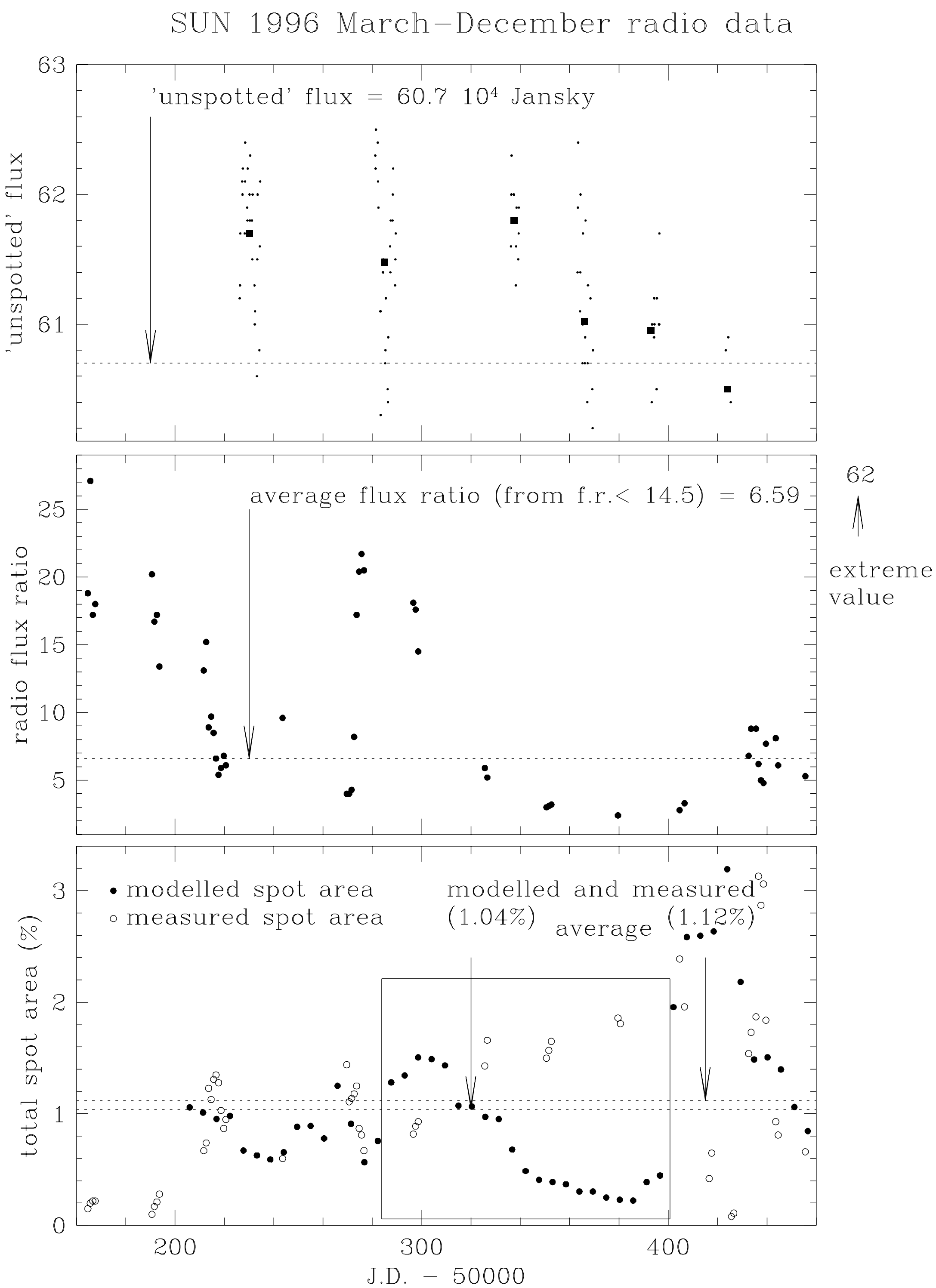

Figure 3: The unspotted flux (top), the flux ratio (middle) and the resulting spot areas in percents of the solar surface (bottom), in radio wavelength. A strong variability of the flux ratio is well seen. The resulted spot area varied following the flux ratio changes, since we used a constant flux ratio during the modelling. The measured and modelled spot areas disagree but their average values are very close to each other.

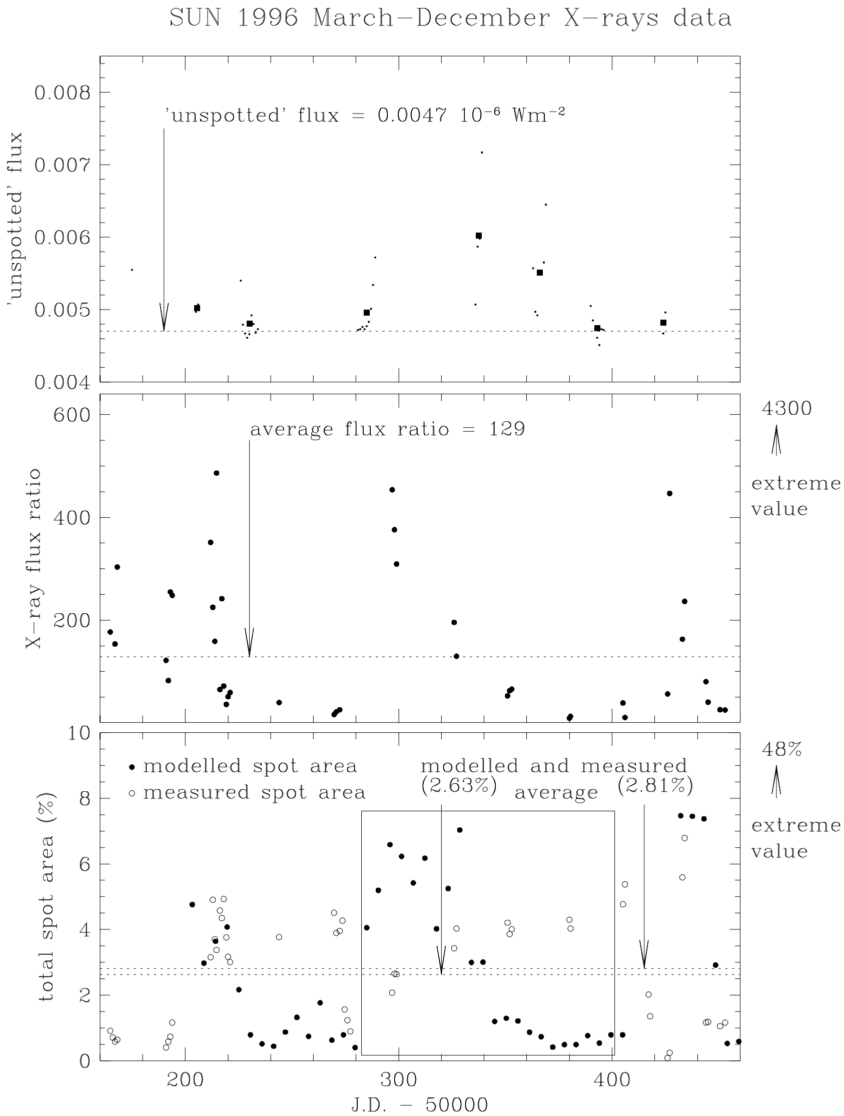

Figure 4: The same as in Figure 3, but in X-ray wavelength.

calculated flux ratios, but the averages of the modelled and measured spot areas between March-December 1996 are in good agreement. On the other hand, on a short time-base, using constant flux ratios, the resulting spot areas do not reflect the reality well. Figure 5 shows the results only for the August-October data that are marked with boxes in the bottom panels of Figures 3 and 4. During this time only a single active region was present on the Sun, and was decaying alone for four rotations. Using a constant flux ratio when modelling this part is grossly in error. If someone wishes to get a reliable spot area value for a single spot (and not for a complex where spots born and die), the variability in the flux ratio should be taken into account in the modelling. This way the spot area could succesfully be recovered (Paper I).

Our hypothesis thus turned out to be true: using constant flux ratios, starspot modelling could give reliable results on a longer time-base, when the changes of the flux ratios caused by the emerging and decaying spots level up each other.

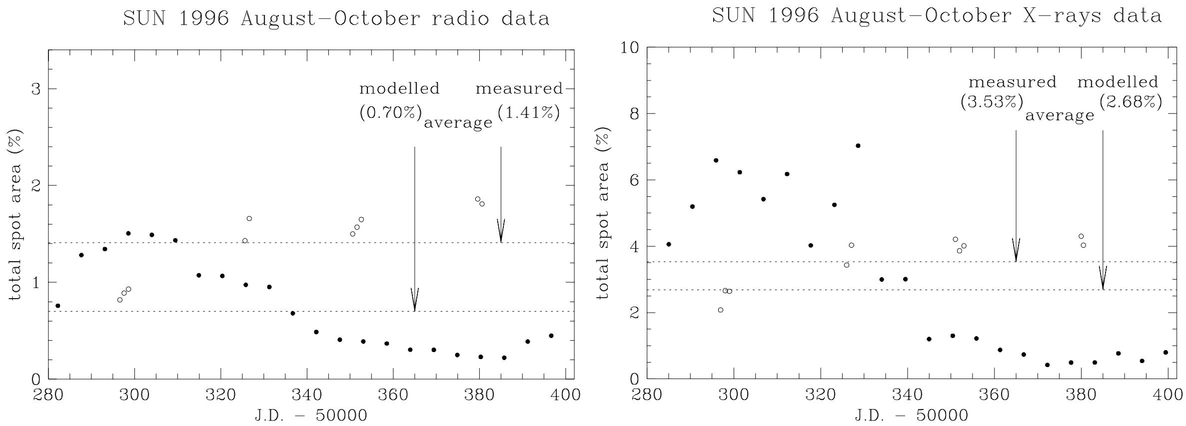

Figure 5: Details from Figures 3 and 4. The measured (open circles) and modelled (dots) spot areas are compared to each other in radio (left) and in X-ray (right) wavelength, only for the August-October 1996 dataset. The mean values of the measured and modelled spot areas disagree.

4. Summary

Using a stellar spot modelling technique on one-dimensional solar measurements and comparing the results with direct images we tested different aspects of photometric starspot modelling.

Recovering spot coordinates we found that long-term overall brightness variations (that are added to the rotational modulation) may result in artificially high latitude spots. The reason of this problem is that the overall brightness change requires spotted areas without rotational modulation, and to obtain this spots are placed to the polar region of the star by the modelling code. In two- or multi-spot models the coordinates of a resulting small spot (beside a big one) is totally unstable, and that can account for short living spots anywhere on the star.

We discussed the validity of using constant flux ratios when calculating photometric spot models of active stars. When we used one dimensional measurements and contemporaneous direct images of the Sun in radio and X-ray wavelengths we found a hyperbolic decrease in the flux ratio between the studied single active region and the undisturbed area (Paper I). On short time-scale the change of the flux ratio must be well known to succesfully recover spot areas. Using constant flux ratio may cause systematic change in spot size that could be partially due to flux ratio changes.

Using a longer dataset we studied the evolution of an active nest, between March-December 1996, as it was reflected in the total soft X-ray and radio emission of the Sun. For both wavelengths we investigated the flux ratios and their variations, and calculated the average flux ratio between the undisturbed background and the active nest as a whole that consists of old and new active regions together, at the same time.

Using the average flux ratio we could succesfully recover the average area of the active nest. Thus, if the stellar spots are analogous with active nests on the Sun, using constant temperature difference in spot modelling may give reliable results on the spot area changes on long time-scales.

Acknowledgements

The author is grateful to Dr. I. Jankovics, the Director, and to the staff of Gothard Observatory for the generous support to take part in the meeting, and who made the whole event unforgottable. I am indebted to Dr. L. van Driel-Gesztelyi, who helped me very much in understanding the solar activity features. She and Drs. Zs. Kővári and B. Szeidl critically read the manuscript. Support from OTKA T-026165 grant is acknowledged. Special thanks are due to the Sun, as the primary target of the present investigation, for performing the most spectacular event, the total eclipse.

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Discussion

L. van Driel: Can we decide merely from stellar spot modelling whether stellar activity is due to one big AR, or a cluster of coming-and-going ARs?

K. Oláh: From photometric starspot modelling we cannot decide whether the light variability is due to one or two big AR('s), or several spots clustering in the stellar surface. Test results show that light curves generated by a lot of spots can well be modelled using two big spots (see Kővári and Bartus, 1997). On the other hand, using Doppler Imaging Technique on high dispersion spectra, details of the stellar surface can be recovered. The results show several spots that are coming and going, but these spots are still much larger than the sunspots. In case of simultaneous photometric and spectroscopic spot modelling the spectroscopic result may give positions of 2-3 activity centers, or clusterings of spots, that the photometric modelling describes by 2-3 single spots.