Asymmetric Magnetic Field Distribution in Active Regions

Gianna Cauzzi
Osservatorio Astronomico di Capodimonte,
via Moiariello 16, I-80131 Napoli, Italy

Lidia van Driel - Gesztelyi
Observatoire de Paris, DASOP, F-92195 Meudon Cedex, France
Konkoly Observatory, Budapest, Pf. 67, H-1525, Hungary

Abstract. We analyze several years of vector magnetograms acquired with the Haleakala Stokes Polarimeter (HSP) at the Mees Solar Observatory. We find that the magnetic field distribution within the active regions is asymmetric, in the sense that the magnetic neutral line appears, on average, closer to the main following polarity ($F$) spots than to the main preceding ($P$) ones. This is consistent with previous studies, and with numerical simulations of magnetic flux tubes emerging through the solar convection zone, that predict an asymmetric shape of the loops. We also find that the asymmetry in the field distribution does not change sensibly with the progressing of the solar cycle, while it depends on other parameters such as age and magnetic flux of the regions.

1. Introduction

Long-term observations of solar active regions (ARs) have been instrumental in defining general properties of solar magnetism, for example to model the solar dynamo mechanism. Beside the obvious advantage of deriving the time-dependence of active regions' characteristics, long term observations taken with the same instrumental setup have provided large datasets of consistent quality, from which to extract average properties, not readily visible in smaller samples. Some of the most interesting characteristics of solar active regions, such as the tilt of the main bipole axis with respect to the equator, its dependence on the latitude of emergence and on the polarity separation, have been derived in this way. For a summary of active region properties, we refer the reader to the paper by Wang & Sheeley (1989), that analyzed Kitt Peak magnetograms covering all of cycle 21, or to the series of papers written by Howard (see e.g. the reviews of 1994 and 1996), using the wealth of data acquired at Mt. Wilson.

In the last few years, many of these observed characteristics have started to be understood as the results of the rise of thin magnetic flux tubes, anchored at the bottom of the convection zone and emerging through it under the effect of magnetic buoyancy. The detailed 3-D numerical simulations developed by several groups (D'Silva & Choudhuri 1993; Fan et al. 1993 1994; Caligari et al.
1995) provided in general a good agreement with a variety of observed properties of solar ARs (for recent reviews see, e.g., Moreno-Insertis 1994; 1997).

An interesting property of the developing ARs was pointed out by Caligari et al. (1995): as the flux tubes rise throughout the convection zone, they develop an asymmetry in field line inclination, namely, the following (F) wing remains more vertical than the preceding (P) one during the whole emergence process. Their simulations predict also that this asymmetry should be more pronounced for ARs with higher magnetic flux values. As a general consideration, they also remark that since the numerical simulations of thin flux tubes are carried out up to the emergence at the surface (or shortly before it), this and other predictions should be compared preferably with observations of the early phases of development of the ARs.

Earlier work on this subject has been conducted by van Driel-Gesztelyi and Petrovay (1990, hereafter VDGP), that showed how the distribution of the photospheric magnetic fields in ARs can be used to derive information on the inclination of the subsurface loops. Analyzing about 5 years of longitudinal magnetic field maps published by the Okayama Observatory, they concluded that, on average, the distribution of the magnetic field is asymmetric, in the sense that the magnetic neutral line is closer to the main following spots than to the main preceding ones. This is consistent with the idea of an asymmetric flux tube emerging from the convection zone, whose follower wing is more vertical with respect to the solar surface than the preceding wing. VDGP didn't find any dependence of the magnetic field distribution asymmetry with the phase of the solar cycle, suggesting that the emerging mechanism works essentially in the same way regardless of the latitude at which the flux tubes start their journey. Finally, they found an ascending trend of the asymmetry with the age of the regions.

In the present paper, we follow the approach of VDGP, and analyze a completely independent set of data, i.e. vector magnetograms acquired at Mees Solar Observatory during the years 1991-95. Beside the importance of having an independent confirmation (or a lack of) to the results obtained earlier, we also improve on their method by using full vector magnetographic information, instead of only longitudinal maps. This will allow us to correct for projection effects, which start being relevant at some distance from disk center, and to obtain magnetic flux measurements for the ARs, i.e. to probe another prediction of the numerical simulations.

2. Data Analysis

We used a sample of vector magnetograms acquired with the Hawaii Stokes Polarimeter (HSP, Mickey 1985) at Mees Solar Observatory, from October 1991, to June 1995. The HSP has been into operation since the late 80’s, and in standard mode it acquires at least one magnetic map per AR per day. This allowed the collection of a large and consistent dataset, of great utility for statistical studies.

We analyzed a total of 132 regions, for a grand total of 539 magnetograms. For each of the regions we had observations at least on the day of their maximum development, in order to define a unique value of magnetic flux. Many regions were however observed several times over the course of their development. The
projection effects were corrected making use of the full vector magnetic field components (Canfield et al. 1993), i.e. obtaining the 3 components of the magnetic field at the solar surface ($B_x$, $B_y$ and $B_z$). In the following, only $B_z$ will be used for our study.

Several parameters were calculated for each region: latitude and longitude of emergence, axial tilt with respect to the equator; magnetic flux; etc. We ran many tests using these parameters, following essentially the outline of the work by Wang & Sheeley (1989), in order to check whether our sample represented an “average” set of regions. Apart from the obvious smaller size of our sample, we didn’t find any significant deviation from the average properties reported by Wang & Sheeley.

Finally, we defined the parameter “asymmetry” of the magnetic field distribution as described in Fig. 1: given the segment connecting the main $P$ and $F$ spots, we call $X_P$ the distance between the main $P$ spot and the magnetic neutral line along this segment, and $X_F$ the distance between the main $F$ spot and the neutral line. The “asymmetry” parameter is then defined as $A = X_P/(X_P + X_F)$. A value of $A$ greater than 0.5 implies that the magnetic neutral line lies closer to the $F$ polarity, and is consistent with the model of a flux tube whose $F$ wing is more vertical than its $P$ wing, as mentioned in the Introduction.

Figure 1. Contours of vertical component $B_z$, outlining the preceding (dashed) and following (solid) polarity of region NOAA 7117. The distances of the $P$ and $F$ spots from the magnetic neutral line (thick contour) define the asymmetry of the magnetic field distribution.
3. Results

Fig. 2 shows the histogram of the asymmetry values calculated over the whole sample, considering each magnetogram independently. The asymmetry parameter varies over a great range, from $\sim 0.2$ (magnetic neutral very close to the main $P$ spot) to $\sim 0.8$ (neutral line very close to the main $F$ spot), but the peak of the distribution is for values somewhat greater than 0.5, and the average is at $0.562 \pm 0.002$. This result is in agreement with the results of VDGP, that found an average asymmetry value of $0.574 \pm 0.014$.

The average value remains nearly the same if we consider only one value of asymmetry per region, taken as the average of the asymmetries for each magnetogram obtained for that region.

To check for a possible variation of the asymmetry with the phase of the solar cycle, we divided the sample of magnetograms in subsets corresponding to each one of the years analyzed. The number of regions in the subsets were 10, 40, 41, 31, 10 for the years 1991, 92, 93, 94, 95, respectively. We don’t find any clear trend of the asymmetry within these years. The same result was found by VDGP, in their analysis of years 1983-87.

As mentioned in Section 2, we measured the magnetic flux of the active regions, as the total absolute value of the vertical component of the magnetic field, $B_z$. The smallest values of magnetic flux that we could measure are $\sim 5 \times 10^{21}$ Mx, essentially due to the coarse spatial resolution of the HSP data (2.8″ or 5.6″ per pixel). The flux was computed only on the day of maximum development of each region, in order to define a unique value of flux for each of them. Fig. 3 shows a scatter plot of the average asymmetry values for each active region, versus their magnetic flux; the straight line represents the fit to the data, obtained with a robust least absolute deviation technique. The asymmetry of the magnetic field distribution is positively correlated with the magnetic flux of the
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Figure 3. Scatter plot of average asymmetries versus the magnetic flux of each region, expressed in Mx

active region; this is a new result, that agrees qualitatively with the prediction of the numerical simulations.

Finally, we took into consideration the possible dependence of the asymmetry parameter with the age of the region. We chose to use as a measure of age the number of days from maximum development, essentially for two reasons: a) since about half of the regions were not born on the disk, we couldn’t define their absolute age, and the choice of this latter parameter would have greatly reduced the available sample; b) this definition has the advantage of clearly discriminate between growing and decaying regions, hence adding further information to the analysis. Fig. 4 shows the average values of asymmetry calculated on regions with the same “age”, versus the age itself. There is a clear negative trend of asymmetry versus age, with a smooth transition between growing and decaying active regions. The slope of the least-squares fit line is -0.011, when the age is expressed in days.

This last result is opposite to the findings of VDGP, that derived a growing dependence of asymmetry with the absolute age of the regions. This is somewhat surprising, giving the general agreement between our and their results. A possible cause for this discrepancy could lie in the projection effects that influence the maps of longitudinal magnetic fields used in the analysis of VDGP. A bias in the positioning of the magnetic neutral line could translate from an “hemispheric” (East or West) dependence, typical of a geometrical effect, to an “age” effect, since older regions are found more frequently on the western part, and younger ones on the eastern part of the solar disk. To clarify this issue, we measured again the asymmetry of the magnetic field distribution, but using the $B_{long}$ maps instead of the $B_z$ ones, and finally plotted the average values versus the age indicator. We found a growing trend, with a slope comparable to the one found by VDGP. We hence conclude that the earlier finding of growing asymmetry with age of the regions was due to an incorrect assessment of the position of the neutral line, due to projection effects. However, it must be remarked that
the average values of asymmetry obtained by VDGP are still reliable, since the opposite effects on both hemisphere would cancel in a statistical sense.

4. Discussion and Conclusions

We have analyzed a set of vector magnetograms acquired with the Haleakala Stokes Polarimeter (Mickey 1985) at Mees Solar Observatory, in the years 1991-95. We studied the distribution of the magnetic field in active regions, using an “asymmetry” parameter that measures the position of the magnetic neutral line with respect to the main $P$ and $F$ spots.

We find that the average value of the asymmetry, computed over more than 500 magnetograms, is $0.562 \pm 0.002$, i.e. the neutral line is on average closer to the main $F$ part of the region. This is in agreement with the results of van Driel-Gesztelyi and Petrovay (VDGP, 1990), obtained on a completely different dataset. The range of values displayed by the asymmetry parameter is broad, but the large sample of magnetograms, all of consistent quality, allowed us to retrieve an average property of active regions that is related to their subsurface configuration. In fact, as shown by VDGP, and noted by Caligari et al. (1995), this asymmetry in the magnetic field distribution is consistent with the model of an asymmetric flux tube emerging from the convection zone, whose $F$ wing is more vertical than the $P$ one.

A coarse inspection of the asymmetry dependence with time didn’t provide any clear trend: the asymmetry parameter seems to be unrelated to the phase of the cycle. The total span analyzed in our work is less than 5 years, during the declining phase of the cycle; a better assessment of the temporal behavior of the asymmetry will have to come from the analysis of a longer period. However, the same basic conclusion was derived by VDGP, that studied the years 1983-87, i.e. the years centered around the minimum. A tentative conclusion is that the process of emergence of the magnetic flux tubes from the depth of the convection zone, responsible for the creation of the asymmetry, does not depend on the solar cycle, i.e. on the underlying dynamo mechanism.
We found a relationship between the asymmetry and the magnetic flux of each region: regions with higher magnetic flux display higher values of asymmetry. This is a novel result, and is again qualitatively consistent with the predictions of the numerical simulation of Caligari et al. (1995). A quantitative comparison between the model and the observations is not yet viable, since the numerical simulations do not provide any "measure" of the asymmetry in the magnetic field distribution.

Finally, we find that the asymmetry decreases with the age of the region. Lower values of asymmetry for older regions could be due to "surface effects", disturbing the loops' configuration once the region has emerged in the completely different environment of the solar atmosphere. In particular, the high buoyancy of magnetic elements at the surface might somehow alter the field distribution. Although the basic property remains visible (the magnetic field distribution is on average asymmetric), its signature gets weaker as the regions age and surface effects become the more important. Another possibility is that lower portions of the emerging flux tube, visible in the later stages of an active region development, display a smaller asymmetry than the higher portions. Even if not present in the numerical simulations, such an effect seems to be consistent with information derived from the analysis of proper motions in active regions (van Driel-Gesztelyi & Petrovay 1990).

References


Group Discussion

**Penn:** Using full vector field measurement, can you confirm the inclination you see with your technique? (Currently the noise in $B_x$ and $B_y$ is too high).

**Cauzzi:** I measured the field inclination using the full magnetic field vector. In high field regions, such as spot umbrae, the field lines are essentially vertical,
with no difference between P and F polarity. In lower field regions the noise in the Bx and By component is too high to give a definite answer.

van Ballegooijen: The present models of rising flux tubes show very wide $\Omega$-loops with large longitudinal extent. Once such loops emerge through the photosphere, they will probably exhibit rapid forward motion of the leading sunspots and large asymmetry between leading and following polarity flux, in contradiction with your observations. To reproduce your observations, the models of $\Omega$-loops probably need to have longitudinal extent not much more than 200 Mm.

Cauzzi: I agree with your remark on the longitudinal extent of the rising $\Omega$-loops. However, the present models do stop about $10^4$ km below the surface, and it is not clear to me how much the final stage of emergence can affect (or change) the loops’ properties. Recent observations of a young and developing active regions (Strous et al. 1996) show very high values of forward motion of the leading spots, of the order of 500 m s$^{-1}$, that are not in contradiction with the model of an inclined loop. The asymmetries in magnetic field distribution that I showed are obtained with an instrument that has a moderate spatial resolution, hence observations of the very early stages of active region development – when presumably the asymmetry could be higher – are not usually possible.

Ruzmaikin: The asymmetry of emerging magnetic loops and their tilts, discussed by R. Howard, are caused by the Coriolis force on different components of the loop speed inside the convection zone. Are a combination of the asymmetry and tilts observations a good diagnostics of these speeds?

Cauzzi: The different velocity components for an emerging loop are an intrinsic property of the models used to represent them. The comparison should hence be done between observables such as the tilt and the asymmetry and the whole class of models (with different initial field strength, flux, latitude of initial rise, etc.) to see which holds the best fit.