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2011 J. Phys.: Conf. Ser. 271 012007

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Properties of Near-surface Flows around Active Regions from Helioseismic Holography

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Abstract. A variety of local-helioseismic analyses have shown ~ 50 m/s flows converging on active regions (ARs). We have examined the average properties of both the 75 strongest converging and 75 strongest diverging flows present in Carrington rotation CR1988 within the uppermost 3 Mm of the Sun. The flows, averaged over 5 days, were deduced from calibrated helioseismic holography measurements applied to MDI observations of CR1988. Inflows associated with ARs typically have maximum speed of between 20 and 60 m/s at about 3 heliocentric degrees from their centers and fall to zero by a radius of 7 degrees. Similar converging flows, however, are prevalent in the quiet Sun. Outflows of similar spatial extent, but significantly larger speeds, are present diverging from sunspots (i.e. the moat flows). Many of the converging flows in ARs appear to simply mark the boundaries of the moats while others converge on plage regions. In general, large ARs containing sunspots contain a complex mixture of both inflows and outflows which, aside from sunspot moats, also appear similar in property to convective components of the quiet Sun.

1. Introduction

Shallow converging flows, on the order of ~ 50 m/s and centered on solar active regions (ARs), are a significant finding of local helioseismology [1] [2]. They are believed to extend down to 10 Mm below the photosphere and appear to lie above deeper diverging flows [3]. However, few systematic studies have been done to date of their general properties (a notable exception is [4]). Here we quantify the magnitude and horizontal extent of both near-surface inflows and outflows present over one solar rotation and obtained by applying helioseismic holography to Doppler observations obtained with MDI/SOHO [5]. We are particularly interested in addressing the following questions: 1) how do flows around ARs differ from quiet-Sun flows and 2) how do the properties of inflows compare with those of outflows (for example, moat flows around sunspots). Answering these questions is critical to deriving and interpreting models of these flows [6]. For this study we selected the time period 2000 Mar 29-Apr 26 (corresponding to Carrington rotation CR1988), a period close to the peak of solar cycle 23 and with almost 50 NOAA numbered ARs visible on the solar disk.

2. Methods and Results

Lateral-vantage helioseismic holography [7] [8] [9] is applied to one month of MDI observations spanning the Carrington rotation (CR1988) under study. Briefly, considering waves propagating down to a focus depth of 3 Mm, we measure acoustic (p -mode) travel times between opposite quadrants of an annular pupil. The difference in the travel times, between waves propagating

from one quadrant to its opposite and the travel times of waves propagating in the reverse direction, is sensitive to horizontal flows near the focus [8] [9].

The travel-time differences between the east and west quadrants, τ_{we} , and the differences between the north and south quadrants, τ_{ns} , are calibrated into eastward and northward vector components of a horizontal flow by applying different tracking rates to the same region of the Sun (the Carrington rotation rate and the Carrington rate plus a constant offset). The shift in τ_{we} between the two sets of measurements, divided by the known tracking offset rate, provides a calibration factor relating the travel time differences and the flow averaged over some (sensitivity) function of depth. The sensitivity function, computed under the Born approximation, for lateral-vantage holography at a 3 Mm focus-depth shows a strong peak within 1 Mm below the photosphere as well as somewhat weaker contributions at depths between approximately 2 and 5 Mm below the photosphere [9].

For each 15° span of longitude, daily maps of the horizontal flow (\mathbf{v}_h) are averaged over 5 days around the central-meridian passage to produce a synoptic flow map (e.g. see Fig. 4 of [8]). Supergranulation dominates the flow maps (even over 5 days), making the identification of AR-scale flows challenging. To do this, we find the local maxima and minima (hereafter “extrema”) of maps of the horizontal component of the flow divergence smeared with a 2D Gaussian with FWHM of 7.5° . In heliographic coordinates (L, B), the horizontal component of the flow divergence is given by

$$\nabla_h \cdot \mathbf{v}_h = (1/\cos B) [\partial(v_B \cos B)/\partial B + \partial v_L/\partial L], \quad (1)$$

where $\mathbf{v}_h = (v_L, v_B)$. For this study, we only consider centers of inflows or outflows within latitudes B between -40° and $+40^\circ$.

To look for correlations of the flows with solar activity, we use MDI magnetograms to assess the total (unsigned line-of-sight) magnetic flux within an angular distance of 7.5° (hereafter defined as “nearby”) of each identified flow location. Fig. 1 shows a scatter plot of the flow divergence at the extrema against the nearby flux. It is apparent that there is a weak correlation of inflow (negative-divergence) strength with magnetic flux. A stronger correlation is observed for outflows, with the sunspot moats dominating the correlation at high flux and flow divergence values. We select for further study the strongest 75 inflows and outflows, using cutoffs in $\nabla_h \cdot \mathbf{v}_h$ indicated by the vertical lines in Fig. 1.

Fig. 2 shows probability distribution functions of the nearby magnetic flux for the strongest 75 inflows and outflows as well as a set of random locations within the same latitude range ($\pm 40^\circ$). Inflows have a significantly higher probability over chance of having nearby flux levels of between 3 and 10×10^{21} Mx. On the other hand, outflows have a higher probability than chance to be near the highest flux values. Somewhat surprising, however, is the large number of strong flows, of both types, in the quiet Sun. Thus, it is worth examining how flows associated with strong nearby magnetic flux differ from those associated with weaker nearby flux.

To explore further the dependence of the properties of the flows on solar activity, we define three subgroups of each of the sets of 75 strongest inflows and outflows based on the nearby magnetic flux (the horizontal lines in Fig. 1 separate these subgroups). First, we split the inflows into three subgroups of 25 members each (denoted $A-$, $B-$, and $C-$). The first 17 outflows, ranked by flux, are clearly identified with sunspot moats and define group $A+$. Assigning the 25 outflows with the weakest nearby flux to group $C+$ (as for the inflow subgroup $C-$) leaves 33 outflows associated with intermediate flux values ($B+$). The subgroups $C-$ and $C+$ are essentially associated with quiet-Sun.

For each of the 75 inflows and 75 outflows, the original (unsmeared) vector flow fields are projected onto Postel coordinates centered on the extrema of the divergence signal. A “radial velocity” is defined to be the component of the horizontal flow along a great circle passing through the center of the projection. Fig. 3 shows the averages of the radial velocity over

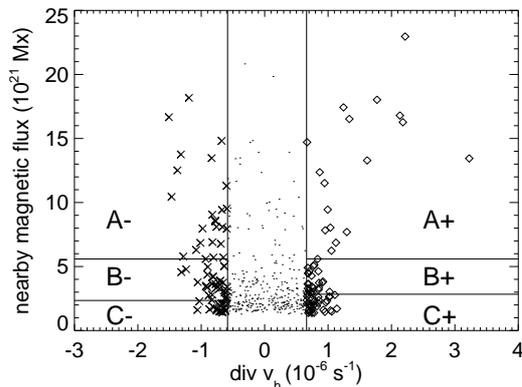


Figure 1. Scatter plot of the horizontal component of the flow divergence for each local maximum or minimum of a (Gaussian-smearred) synoptic map against the total unsigned magnetic flux within 7.5° of the given divergence extremum. The vertical solid lines isolate the 75 strongest divergence extrema, with inflows denoted by Xs and outflows by diamonds, from the weaker divergence extrema denoted by points. The horizontal lines separate six inflow or outflow subgroups (see text).

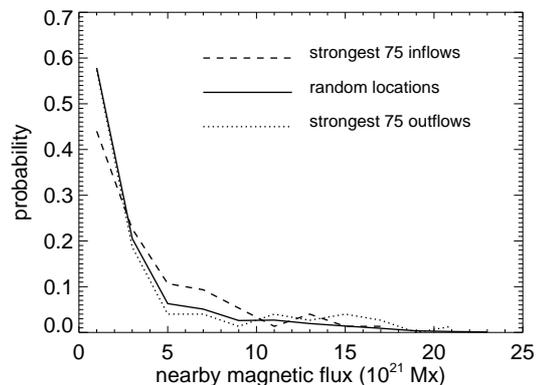


Figure 2. Probability distribution of the magnetic flux (in 2×10^{21} Mx bins) near the 75 strongest inflows (dashed line) and 75 strongest outflows (dotted line) compared with the probability distribution for random locations (solid line). Taken together, this and the preceding plot demonstrate that the association of inflows with active regions, while significant, is not an especially strong one considering the large number of similar flows in the quiet Sun.

the perpendicular (azimuthal) coordinate in the Postel projection for the inflows and outflows associated with the strongest nearby flux (left panels) as well as the quiet Sun (right panels). Plots of the same quantities for the intermediate flux groups $B-$ and $B+$ (not shown) are similar to those for $C-$ and $C+$. It is clear that the inflows all have similar properties, regardless of their proximity to active regions. Thus, inflows clearly associated with ARs appear to be quantitatively and qualitatively similar to those found in the quiet Sun. These inflows are significantly more compact (i.e. extending no more than about 7° from their centers) than previously noted [1]. The azimuthally-averaged flows peak at around 40 m/s. An examination of individual flows in group $A-$ shows that the inflows near ARs generally fall into two types: those that are centered near plage ($\sim 40\%$), and those that coincide with the edge of a sunspot moat flow ($\sim 60\%$). Outflows around sunspots (i.e. the moat flows) are substantially stronger than those outflows not associated with spots. Nevertheless, all inflows and outflows are similarly compact.

3. Conclusions

While occurring more often near ARs than expected by chance (Fig. 2) the inflows examined here are similar to those found in quiet Sun and thus may not require specialized physics [6], particularly those which may simply mark the boundaries of the sunspot moats. For the inflows centered on plage, there remains a “chicken and egg” question: do converging flows form because of some physical influence of the magnetic fields, or does field collect in the center of existing inflows? But by far the strongest AR-related near-surface flows seen (at least in CR1988) are associated with the diverging moat flows which, while having no significant counterpart in the quiet Sun, are an important component of the dynamics of ARs. More systematic studies of helioseismically-inferred flows [4] are needed.

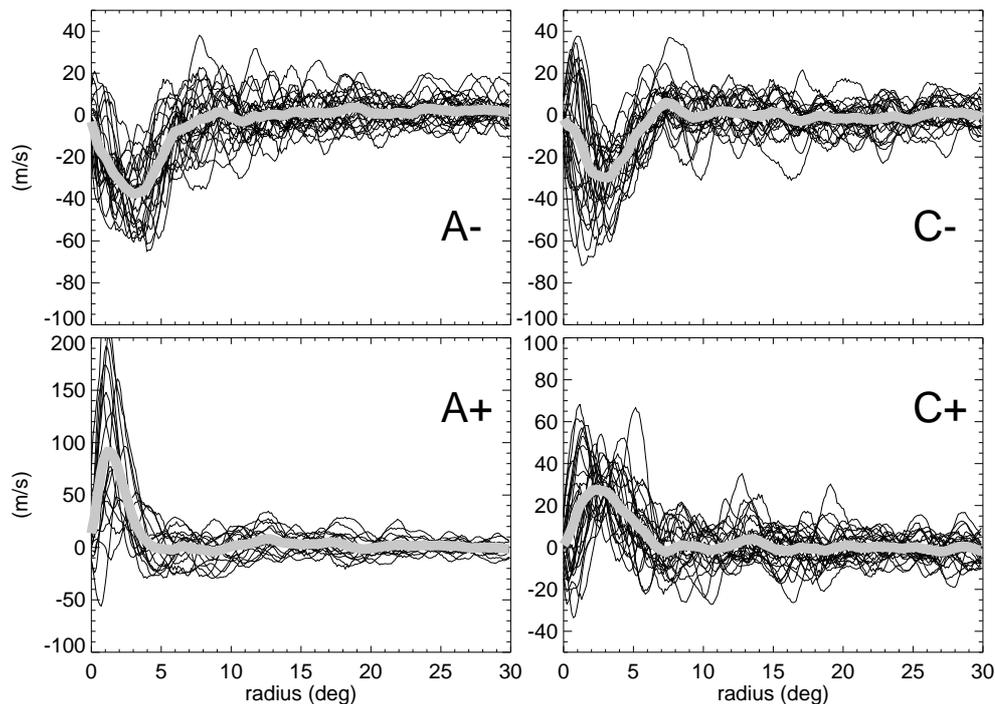


Figure 3. Azimuthal averages of the radial velocity component of the flows for four subgroups. The thin black lines indicate the radial velocities for each of the subgroup members (to give some indication of the variation within each group), while the thick grey line indicates the mean of the radial velocities over the entire subgroup. The left panels indicate the inflows (top) and outflows (bottom) associated with the strongest nearby flux, while the right panels indicate the inflows (top) and outflows (bottom) present in quiet Sun. Note the change in the vertical scale for group A+ (the sunspot moats).

Acknowledgments

This work is supported by the Astronomical Division of the NSF (AST-0406225)

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