Identifying the Main Driver of Active Region Outflows

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Abstract. Hinode’s EUV Imaging Spectrometer (EIS) has discovered ubiquitous outflows of a few to 50 km s\(^{-1}\) from active regions (ARs). The characteristics of these outflows are very curious in that they are most prominent at the AR boundary and appear over monopolar magnetic areas. They are linked to strong non-thermal line broadening and are stronger in hotter EUV lines. The outflows persist for at least several days. Whereas red-shifted down flows observed in AR closed loops are well understood, to date there is no general consensus for the mechanism(s) driving blue-shifted AR-related outflows. We use Hinode EIS and X-Ray Telescope observations of AR 10942 coupled with magnetic modeling to demonstrate for the first time that the outflows originate from specific locations of the magnetic topology where field lines display strong gradients of magnetic connectivity, namely quasi-separatrix layers (QSLs), or in the limit of infinitely thin QSLs, separatrices. The strongest AR outflows were found to be in the vicinity of QSL sections located over areas of strong magnetic field. We argue that magnetic reconnection at QSLs, separating closed field lines of the AR and either large-scale externally connected or ‘open’ field lines, is a viable mechanism for driving AR outflows which are potentially sources of the slow solar wind. In fact, magnetic reconnection along QSLs (including separatrices) is the first theory to explain the most puzzling characteristics of the outflows, namely their occurrence over monopolar areas at the periphery of ARs and their longevity.

1. Observations

AR 10942 was observed by the Hinode satellite at various times between February 19 and 26. Here we concentrate on EIS (Culhane \& et al. 2007) observations on February 20 when the raster scan fully covered the eastern polarity of the AR (Fig. 1). All data reduction was carried out using standard SolarSoft procedures. EIS Doppler velocities were determined by fitting a single Gaussian function to the calibrated spectra and instrumental effects were removed. EIS and XRT data were coaligned with SOHO/MDI magnetograms.
Figure 1. Left - EIS Fe xii emission line intensity maps of AR 10942. Middle - EIS Fe xii emission line velocity maps overlaid with ± 50 G MDI magnetic contours. White/black is positive/negative polarity. Right - photospheric trace of QSLs (thick red lines) and field lines originating in the QSLs are overlaid on a grayscale EIS Fe xii emission line velocity map. (Lines with circles leave the computational box and are considered to be ‘open’ or large extended loops). The overlay image clearly shows strong AR outflows along field lines computed from the QSLs.

Figure 2. Left panel - Global linear force-free magnetic field model of AR 10942 over Hinode XRT image. There is a global agreement between the coronal magnetic field model and the XRT observations. Obvious QSLs are indicated where there are sharp gradients in magnetic connectivity over both polarities. Right panel - Photospheric trace of dominant QSLs (thick red lines) in AR 10942 with SOHO/MDI magnetic field contours.
2. Modeling

To compute the magnetic field topology of AR 10942, we first modeled the coronal field using a linear force-free field (LFFF) extrapolation to the corona ($\vec{\nabla} \times \vec{B} = \alpha \vec{B}$, where $\vec{B}$ is the magnetic field and $\alpha$ is a constant). We then determined the locations of QSLs from observed magnetic data using the Quasi-Separatrix Layers Method (Démoulin et al. 1996) computing the squashing degree $Q$ (see Titov et al. (2002) and Aulanier et al. (2005) for a definition and properties of $Q$). QSLs corresponding to the highest values of $Q$ ($\log_{10} Q$ above $\approx 10$) are defined as dominant QSLs for AR 10942. The magnetic models and the locations of the photospheric traces of dominant QSLs are shown in Fig. 2. For a complete discussion of the modeling techniques and limitations, see Baker et al. (2009).

3. Results

The most extended QSL trace, labeled $a$ in the right panel of Fig. 2, is located over the positive/eastern polarity of the AR where we observe the strongest outflows in the EIS Fe xii velocity map (Fig. 1 - middle panel). Another major QSL trace, $d$ in Fig. 2, is found over the negative/western polarity and is associated with outflows (not shown - see Baker et al. (2009)). Blue-shifted outflows occur in the vicinity of the dominant QSLs at the periphery of the AR over its monopolar magnetic field concentrations.

Though the precise 3D velocity structure cannot be determined from 2D maps, the projection of the expected outflow locations can be compared with the EIS velocity maps, and for velocities observed in hot coronal lines, it is the spatial extension of the 'open'/large-scale field lines which is the most appropriate to compare with the spatial distribution of the observed outflows. We found that such a set of field lines greatly spreads out from the QSL photospheric trace and fills a spatial region that is comparable to the observed outflows from 10942. The outflows originate in the vicinity of QSLs and fan out with height. (See Baker et al. (2009) for a discussion of outflows across a range of coronal temperatures).

4. Discussion

Outflows are not observed over all QSLs. In order to drive outflows we need a QSL separating 'open' or large-scale field lines from closed ones. Moreover, an evolution of the magnetic configuration is required to build up significant currents along the QSL and the current layer thickness must become small enough to induce magnetic reconnection. Further, for a section of a QSL to become flow active, a strong magnetic field is also required to provide enough magnetic energy. This was shown to be the case for flare ribbon-QSL association (e.g. Démoulin 2007) and, indeed, the strongest outflows occur in the vicinity of the QSL sections that overlie the strongest magnetic field in the case of AR 10942.

To date, none of the proposed mechanisms for driving AR outflows adequately explain their long duration at specific locations at the periphery of ARs over monopolar magnetic field concentrations. However, we propose that magnetic reconnection along QSLs is a plausible driver of AR outflows that can fully account for all of the observed characteristics of AR outflows. First of all, by definition, QSLs (including separatrices)
divide drastically different connectivities over a magnetic polarity therefore they are naturally present over monopolar areas. Second, the strongest outflows are seen at the periphery of ARs where there are sharp boundaries that mark the change in magnetic topology from ‘open’ or large-scale externally connected to closed field i.e. a natural location for strong gradient in magnetic field connectivity. Finally, outflows persist at approximately the same locations for time scales of at least several days. This can be explained by the very nature of QSLs since they are defined by the global properties of the magnetic configuration which evolves slowly. More precisely, they are dominantly defined by the photospheric magnetic flux distribution.

QSLs are locations where reconnection takes place as ideal MHD breaks down. QSL reconnection is rarely fast unless the current layer thickness is small enough and/or there is a strong driving force such as an ideal instability of the magnetic field. In 3D, reconnection occurs simultaneously at multiple locations along the length of a QSL involving many field lines over an extended region so outflows appear smooth and extended. Small-scale events with low reconnection rates are also expected to happen along QSLs, especially where they are initially broad. In such cases the accumulation of magnetic stress is needed to build a thin enough current layer to later start reconnection impulsively with a sufficiently fast rate. We suggest that the reconnection-driven plasma flows are the result of the spatial and temporal superposition of nearly-continuous reconnection together with many small-scale events. These reconnections are driven by the almost permanent shuffling of footpoints. We consider that there are at least four reconnection-related mechanisms that can drive AR outflows at QSLs: 1. impact of accelerated particles in denser lower layers leading to gentle chromospheric evaporation; 2. pressure gradient generated after the reconnection of two loops; 3. small-scale reconnection jet-like outflows; and, 4. siphon flows along closed loops.

In summary, we found that AR outflows occur in the vicinity of QSLs and by their very nature QSLs occur: 1. at the periphery of ARs where there are natural strong gradients in magnetic connectivity, and 2. over monopolar regions of strong magnetic field. The persistent outflows originating at the flow-active sections of QSLs are driven by the slow, continuous reconnection of the global magnetic topology. Magnetic reconnection along QSLs is the first theory to explain the most puzzling characteristics of the ubiquitous AR outflows without contradicting other proposed drivers including coronal plasma circulation, impulsive heating at AR loop footpoints, chromospheric evaporation, expansion of large-scale reconnecting loops, continual AR expansion, and waves. (See Baker et al. (2009) and references therein).

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