The Formation and Lifetime of Outflows in a Solar Active Region

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Abstract

Active regions are thought to be one contributor to the slow solar wind. Upflows in EUV coronal spectral lines are routinely observed at their boundaries, and provide the most direct way for upflowing material to escape into the heliosphere. The mechanisms that form and drive these upflows, however, remain to be fully characterized. It is unclear how quickly they form, or how long they exist during their lifetimes. They could be initiated low in the atmosphere during magnetic flux emergence, or as a response to processes occurring high in the corona when the active region is fully developed. On 2019 March 31 a simple bipolar active region (AR 12737) emerged and upflows developed on each side. We used observations from Hinode, SDO, IRIS, and Parker Solar Probe (PSP) to investigate the formation and development of the upflows from the eastern side. We used the spectroscopic data to detect the upflow, and then used the imaging data to try to trace its signature back to earlier in the active region emergence phase. We find that the upflow forms quickly, low down in the atmosphere, and that its initiation appears associated with a small field-opening eruption and the onset of a radio noise storm detected by PSP. We also confirmed that the upflows existed for the vast majority of the time the active region was observed. These results suggest that the contribution to the solar wind occurs even when the region is small, and continues for most of its lifetime.

Unified Astronomy Thesaurus concepts: Solar physics (1476); Slow solar wind (1873); Solar active regions (1974); Solar energetic particles (1491)

Supporting material: animation

1. Introduction

Outflows from the edges of active regions have become a focus of many studies since they were noted in early observations from Hinode (Kosugi et al. 2007). These outflows are of great interest because of their likely contribution to the slow solar wind (Sakao et al. 2007; Doschek et al. 2008; Harra et al. 2008). Upflows in active regions are most obvious in hot spectral lines formed around 1–2 MK (Del Zanna 2008; Warren et al. 2011), and occur in dark areas where the line intensities are faint, especially at the active region edges (Doschek et al. 2008). They show bulk plasma motions on the order of tens of kilometers per second (Del Zanna 2008). A higher speed component, reaching hundreds of kilometers per second, is also often present in the blue wing of EUV spectral lines (Bryans et al. 2010; Peter 2010; Tian et al. 2011; Brooks & Warren 2012). Plasma composition measurements and simple mass flux estimates have strengthened the idea of a connection to the slow solar wind (Brooks & Warren 2011; Brooks et al. 2015; Brooks & Yardley 2021). Indeed different composition signatures in the outflows may help explain variability in the slow wind (Brooks et al. 2020), and the evolution of the upflows has even been linked to radio noise storms detected close-in to the Sun by Parker Solar Probe (PSP; Harra et al. 2021).

Linking remote sensing and in situ observations is a key goal of both PSP (Fox et al. 2016) and Solar Orbiter (Müller et al. 2020). Detailed recent reviews focusing on active region outflows are given by Hinode Review Team et al. (2019) and Tian et al. (2021), while an extensive review including their contribution to the solar wind was presented by Abbo et al. (2016).

There remain several outstanding issues with our understanding of the upflows/outflows, and these have significant implications for their contribution to the slow solar wind. In particular, it is not clear how early they form in the emergence phase of an active region, nor how long they persist during its lifetime. Do upflows become outflows and contribute to the slow wind all the time they exist, or just for a shorter fraction of the active region lifetime? Clearly active regions are a more significant contributor to the slow wind if (1) the upflows exist longer, and (2) even small regions have upflows.

One of the difficulties in studying the early formation phase is that the spectroscopic instruments used to measure plasma flows around active regions have small fields-of-view (FOV) and slow slit scanning times. This makes it challenging to catch active regions as, or soon after, they emerge. Harra et al. (2010) present observations of emerging flux within an already developed active region that was observed by the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on Hinode. The interaction between newly emerging and preexisting
opposite polarity magnetic field formed a ring of strong upflows at the active region edge. This formed quickly within 12 hr—but we should note that the magnetic topological conditions were very favorable since large-scale upflows were already present in the overlying developed active region. These may already have opened the field surrounding the active region. It is unclear if upflows form as quickly in an isolated active region.

These ideas are closely connected with the upflow formation mechanism itself, which is another unresolved issue. Perhaps the most popular picture is that closed field loops in the active region core are opened by interchange reconnection with the open fields in its surroundings. This can occur at quasi-separatrix layers (Baker et al. 2009; Mandrini et al. 2015), where there are strong gradients in magnetic connectivity, and may be driven by the active region emergence and expansion (Murray et al. 2010; Del Zanna et al. 2011). This process provides a mechanism to transfer the closed (solar wind-like) composition of the hot core loops onto open magnetic fields.

Again, a key question is when and where? If emergence is the driver, this could happen quickly and low down in the atmosphere. Conversely, it could be that even after upflow formation, the parent active region needs to expand and interact with high lying magnetic field before the upflow opens to the heliosphere. Some studies have shown that the upflow magnetic field is not always open (Edwards et al. 2016), while others suggest that some fraction of the upflow mass flux also flows through connections to distant active regions (Boutry et al. 2012).

Another possibility is the direct injection of mass and energy into the upflows by chromospheric jets (De Pontieu et al. 2009). Recently Polito et al. (2020) found signatures of the upflows in chromospheric spectral lines observed by the Interface Region Imaging Spectrometer (IRIS; De Pontieu et al. 2014). Several chromospheric and transition region lines showed different behavior in the upflows compared to the cores of two active regions. It is still unclear, however, if these signatures are evidence of the driving mechanism of the upflows operating at low heights. It is also possible that they are revealing a chromospheric response to the changed coronal environment of open-field regions. Based on the multiwavelength analysis of Hinode/EIS and IRIS data, Barczynski et al. (2021) argue that at least three parallel mechanisms generate the plasma upflow, and that these mechanisms are localized in the chromosphere, transition region, and corona.

AR 12737 emerged on the Earth facing solar disk on 2019 March 31 during the second PSP encounter, and was targeted 1–2 days later by EIS and IRIS. From a case study of AR 12737, we will show evidence that (1) the upflows in this region are formed low down, in the early emergence phase, when it is still relatively small, and (2) once formed, the upflows exist for the entire observed lifetime of the region.

2. Observations

In this work we use several data sets from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). These were downloaded via the web-based interface to the Joint Science Operations Center at Stanford, are calibrated and correspond to level 1.5. We retrieved 193 Å data for two long duration time periods at 156 and 600 s cadence, and a high cadence (12 s) multiwavelength (304, 171, 193, and 211 Å) data set around the time of the upflow onset.

For Doppler velocity maps of the active region corona we use EIS measurements. EIS is a dual spectrograph that observes in the 171–211 Å and 245–291 Å wavelength ranges with a spectral resolution of 22.3 mA. To account for instrumental effects (defective pixels, dark current, cosmic ray hits) we reduced the data using the eis_prep SolarSoftware routine. The observations we analyze are 261″ × 512″ field-of-view (FOV) rasters of AR 12737 using the 2″ slit with coarse scan steps of 3″. The exposure time was 40 s.

To obtain the Doppler velocity maps we fit the strong Fe XII 195.119 Å spectral line. We used a double Gaussian function to take into account the density sensitive Fe XII blend at 195.179 Å. Measured line centroids were converted to velocities after first correcting for spectral motion across the CCD, due to instrumental structure temperature variations around the Hinode orbit, using the artificial neural network model of Kamio et al. (2010). We then calibrated the velocities to a reference wavelength obtained by averaging the top part of the FOV, and finally removed a residual orbital variation that was present following the strategy of Brooks et al. (2020). This last step was necessary since the neural network model uses data from early in the mission that are less applicable to recent observations. The accuracy is on the order of 4–5 km s⁻¹, though we do not use any actual values in this study.

For observations of chromospheric structure and velocities we used IRIS. The IRIS instrument observes two wavelength bands in the far and near-ultraviolet (FUV and NUV) covering 1332–1407 Å and 2783–2835 Å. IRIS has a slit-jaw imager and spectograph. Here we focus on observations in the SiIV 1393 Å, C II 1335 Å, and Mg II 2796 Å spectral lines. These cover the transition region, upper chromosphere, and mid to upper chromosphere, respectively. We use level-2 data, and these are processed to account for instrumental effects (dark current, geometric effects, flat-field, orbital wavelength variation). The observations we analyze are 129″ × 126″ FOV rasters constructed from coarse (2″ step scans) at a spatial resolution of 0.33″–0.4″. The exposure time was 15 s.

Doppler velocity maps of the upper chromosphere and transition region were derived from spectral fits to the C II 1335 Å and Si IV 1393 Å lines. The Si IV 1393 Å velocities are derived from the line peak of a single Gaussian fit. The C II 1335 Å line profiles are complex and can be singly or doubly peaked. The velocities here are derived from the peak if the profile has a single peak, but are computed from the line reversal position if the profile is double peaked. We used the algorithm of Rathore et al. (2015) to identify the profile peaks. We also constructed a map of the Mg II 2796 Å k2 asymmetry i.e., the difference in intensity between the peaks in the red and blue wings of the line profile. A positive asymmetry can imply upflows due to increased absorption in the blue wing, while a negative asymmetry can imply downflows due to increased absorption in the red wing. We analyzed the Mg II spectral profiles using the iris_get_mg_features_lev2 procedure available in the IRIS branch of SolarSoftware (Freeland & Handy 1998).

We also compare our analysis of AIA images with type III radio noise data recorded by the FIELDS (Bale et al. 2016) Radio Frequency Spectrometer (RFS; Pulupa et al. 2017) on PSP. The RFS obtains full Stokes parameters using low- and high-frequency receivers covering a wide range from 10.5 kHz...
to 19.17 MHz. The usual spectral cadence is 7 s. We only use a subset of the RFS encounter 2 data, described in detail by Harra et al. (2021), for illustration. We focus only on the frequency of maximum Stokes intensity. The data were reduced as described in Harra et al. (2021).

3. Analysis Results

3.1. Evolution of the Upflows

AR 12737 was a quiescent active region. Despite its emergence the GOES X-ray flux remained below B-class while it was the sole region on disk. Figure 1 shows AIA 193 Å images to give an overview of its emergence phase. It appears to have evolved from a cusp-shaped loop arcade around 00 UT on March 31. By 10 UT it is clear that a new active region is forming, and this development phase lasts several hours. By 20 UT the typical structure of an active region has formed. In Figure 1 we can see a hot core loop arcade, high lying million degree loops, and dark channels from the active region edge, which often show propagating motions in imaging data. These dark areas at the active region edge typically show upflow signatures when observed by EIS (Doschek et al. 2008). In Section 3.2 we attempt to estimate these time periods more quantitatively.

EIS moved to observe AR 12737 from 15:51 UT on April 1 and tracked the region across the solar disk, making a final slit scan at 06:39 UT on April 9. Figure 2 shows an overview of these observations. EIS spectroscopically confirms the existence of upflows in the dark channels on both the east and west sides of AR 12737 as early as 16 UT on April 1.

Harra et al. (2021) used linear force-free field models to establish the global coronal structure of AR 12737, and discussed the expansion and development of the eastern upflow after April 1 in detail. They show that the area of the blueshifted upflow expands by a factor of 10 between April 1 and April 4, that the region is associated with large-scale magnetic field lines in their model, and that the area associated with these large-scale field lines increases as the AR expands. This seems to be driven by the expansion of closed loops to the southeast of the AR, which appear as redshifted in the EIS velocity map of April 1 (Figure 2, left panel). We show an example of their magnetic field model in Figure 3, overlaid on an EIS Doppler velocity map to highlight the associations between the extrapolated field lines and the active region outflows. Large-scale field lines are clearly seen rooted in the positive polarities at the base of the blueshifted outflow on the east side (around coordinates [−30, 0]). The field lines are a composite from different models and the details are described in Harra et al. (2021).

Figure 2 also shows that the eastern upflow is still clearly visible on April 9. Projection effects, however, mean that we can no longer detect blueshifted emission in the western upflow.

IRIS scanned AR 12737 from 05:17–05:36 UT on April 2 (~13.5 hr after the first EIS scan). Figure 4 shows intensity and velocity diagnostics from the transition region (Si IV 1393 Å).
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3.2. Formation of the Upflows

We have attempted to pinpoint the transition from an emerging flux region to a formed active region with upflows using a combination of time-slice intensity tracking, cross-correlation analysis of images, and simple visual inspection. Without spectroscopic data of the very early emergence phase this is, of course, difficult to confirm, but here we discuss evidence that the upflows may have formed as early as 12–16 UT on March 31.

First, while viewing AIA movies of the emerging active region, we noticed a small eruption from the east side around 10 UT. Figure 5 shows multiwavelength AIA images of the mini-eruption. The figure is linked to a 30 minute animation in the same format. The eruption is best seen in the 304 Å images, and in temperatures below ~2 MK (formation temperature of the 211 Å band). Prior to the eruption the region is bipolar with a closed field cusp-shaped arcade—as was shown in Figure 1, left panel. After the eruption, the loop arcade appears to spread open and rapidly develop. Loops appear to draw back from the location where the upflows are later observed, and start to interact with the closed field to the southeast: a process that seems to be integral to the expansion of the upflows after April 1. Even as early as shortly after the eruption on March 31 it appears that large-scale, open, or distantly connecting long loops develop. The field is predominantly positive in the core of the AR at this time, with only weak scattered negative flux to the north so that field lines from the southeast can only connect far from the region, i.e., the negative polarities that counter-balance the positive field are not nearby. This is the picture we also get from a magnetic field extrapolation we attempted, though unfortunately the AR is too close to the east limb for the model to be convincing and reliable—so we do not include it here.

The features of the small eruption can be seen in the spacetime intensity plot of Figure 6, which shows high cadence (12 s) 304 Å data obtained between 10–12 UT on March 31. The plot is made by stacking intensities extracted along the thin blue line shown in Figure 5. Relatively stable structures, such as the active region itself, appear as broad horizontal trails in the plot, whereas dynamic features that move rapidly along the line appear as streaks. The sky blue arrow P0 points out the streak at the start of the small eruption just after 10 UT (around 60° along the slice line). The fuzzier “W” shaped streaks following P0 are a result of the loops spreading open and then retracting.

To quantitatively show when the active region emerged and infer when the upflows developed, we examined spacetime intensity cuts of the AIA 193 Å data. Figure 7 shows a context image with two slice lines overlaid in sky blue and red. We examined several slice lines but these two illustrate the behavior of the eastern upflow. Note that they are not optimized for the upflows on the western side. The sky blue line runs across the eastern dark lane where EIS later detects upflows. The idea here is to try to trace back, from when we know the dark emission is associated with upflows detected by EIS, to as early as we can in the active region development. The red line runs across the central loop arcade to try to trace the dark emission farther back in time when AR 12737 was small, and the upflows, if formed, would be closer to the core. As the lines run across the upflow and bright core we expect that when they are stacked in time we should see a bright trail across the spacetime plot that represents the core region, and a dark trail below it that represents the area where the upflow is later detected. We used 193 Å data at 156 s cadence for this analysis.

Figure 8 shows the results. The top left panel is the spacetime plot for the sky blue line in Figure 7. We can see the...
emergence of the active region from \( \sim 10-11 \) UT and the development of the bright loop arcade \( \sim 14 \) UT in the center of the spacetime plot, as expected. The loop arcade further brightens and expands thereafter, trailing left to right across the spacetime plot, as expected. The loop arcade further trail with the sky blue arrows.

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Figure 4. IRIS Si IV 1393 Å and C II 1335 Å intensity and velocity maps AR 12737 on April 2. The last two panels show the Mg II 2796 Å \( k_3 \) intensity and asymmetry between the \( k_2 \) and \( k_3 \) peaks. The FOV is shown by the white box in Figure 1.

4. Summary and Discussion

We have studied the formation and lifetime of the eastern upflow from AR 12737 using EUV spectroscopic observations from EIS, NUV, and FUV spectroscopic data from IRIS, images from AIA, and radio data from FIELDS/RFS. Our goal was to understand where and how quickly upflows form in an active region, and how long they might contribute to the slow solar wind during the observed lifetime.

These observations establish the following time line. The active region emerged and developed from a cusp-shaped loop arcade from 8 UT on March 31. A small eruption occurred \( \sim 10 \) UT, and the typical structure of an active region with bright core loops and peripheral dark features (usually associated with upflows) formed from 12–16 UT. Spacetime intensity plots and image-to-image correlation analysis support this picture and show that the active region did not alter appreciably until EIS observed it at 15:50 UT on April 1. At this time, EIS confirmed the presence of blueshifted upflows associated with large-scale field lines connecting out of the AR, from both the east and west edges, in force-free field models (Figure 3). IRIS observed the region \( \sim 13.5 \) hr later, and detected signatures of the upflow in the chromosphere and transition region. The active region grew and the upflow area expanded between April 1–4. The magnetic field modeling is consistent with this expansion, and there is an associated
increase in the number of large-scale (potentially open) field lines (Harra et al. 2001). The eastern upflow was still present when the region was last observed by EIS at 06:39 UT on April 9. The region was observed for 9 days. We conclude that the upflows in AR 12737 formed early in its lifetime (no later than 32 hr after emergence) and persisted for as long as EIS tracked it (85% of the observed lifetime). Any contribution to the slow solar wind is therefore not a short lived phenomenon.

The lack of spectroscopic data within the first 32 hr makes it difficult to confirm the exact time of upflow formation, but our analysis also suggests that it occurred earlier. Based on the spacetime and correlation analysis, the eastern upflow can be traced back to when the typical structure of the active region was formed between 12–16 UT on March 31. That is, the upflow may have formed as little as 4–8 hr after emergence and persisted for 95% of the observed lifetime. The small eruption could have opened the magnetic field on the eastern side before this, and the onset of the radio noise storm detected by FIELDS/RFS occurred at the start of this period. We should add the caveat that the upflow might not contribute to the slow wind all the time it is observed, but magnetic modeling of the region suggests it is associated with large-scale expanding field lines the whole time that it was tracked, so in principle the plasma flows can become outflows and escape to the heliosphere.

The evidence also suggests that the upflow formation occurs low down in the atmosphere. The mini-eruption ejected from

Figure 5. AIA 304, 171, 193, and 211 Å images showing the small eruption at 10 UT on March 31. The blue arrow on the 304 Å image points out the eruption from the solar east side of AR 12737. This image is linked to a 12 s cadence, 30 minutes (09:5–10:24 UT) animation with the same wavelength selection and format in the online version of the manuscript.

(An animation of this figure is available.)

Figure 6. Spacetime analysis showing the mini-eruption in the 304 Å data. The spacetime plot corresponds to the thin blue line in Figure 5. The data were taken at a high cadence of 12 s between 10 and 12 UT on March 31. The sky blue arrow points out the start of the small eruption discussed in the text.

Figure 7. AIA 193 Å context for the spacetime and correlation analysis, taken at 07 UT on April 1. The sky blue line corresponds to the spacetime plot shown in the left panel of Figure 8. The red line corresponds to the spacetime plot shown in the right panel of Figure 8. The white box shows the region used for the correlation analysis in the lower panel of Figure 8.
the base of the cusp loop arcade soon after emergence while the active region was still small. It was also best observed in the AIA filters associated with cooler temperatures, especially 304 Å. Even if we only consider the spectroscopic data, possible signatures of the upflows were observed in the chromosphere and transition region by IRIS on April 2, and the EIS data show that the active region and upflow did not grow to their full extent until April 4. This implies that the upflow formation was well underway before AR 12737 had expanded to interact with high lying magnetic fields. The radio noise storm observed by FIELDS/RFS also showed a frequency drift that can be interpreted as the emission height forming at lower altitudes. Future multi-mission observations, of the earliest stages of active region emergence, will hopefully pin down

Figure 8. Spacetime and correlation analysis. Top left: spacetime plot corresponding to the sky blue line in Figure 7. Top right: spacetime plot corresponding to the red line in Figure 7. Middle panel: image-to-image correlation at 156 s (blue dots) and 600 s (sky blue dots) cadence for the region shown by the white box in Figure 7. The sky blue arrows in the top panels indicate features discussed in the text. Bottom panel: RFS data showing the onset of the type III radio storm detected by PSP. The plot shows the frequency of the peak normalized intensity (red) during the same time interval as the correlation analysis. Data points with frequency above $6 \times 10^7$ Hz are increased in size to visually highlight the noise storm.
more accurately some of the suggestions put forward in this article.

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