The Emergence of a Solar Active Region

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Abstract. In July 1996 a major active region emerged abruptly close to disk center. We present radio and magnetic field observations of the development of this active region. The magnetic data clearly show how new flux interacts with a pre-existing bipole. The radio data trace the effect of reconnection of rapidly emerging flux concentrations and the changes in coronal density associated with emergence.

1. Introduction

The way in which magnetic flux generated in the solar convection zone rises to the photosphere and forms solar active regions is an important topic in solar physics. There have been many studies of active-region emergence, but ground-based studies are often incomplete due to gaps in observing coverage. Studies of the response of the corona to the emergence of an active region are generally more difficult than studies of the magnetic development at the photosphere. Emission from fully-developed active regions dominates the appearance of the Sun at wavelengths sensitive to coronal emission (EUV, X-rays and radio) due to the high densities of hot plasma trapped on closed magnetic field lines, but the exact nature of the link between the emergence of field lines into the corona and the production of high densities on those field lines is not well understood. Even less well understood is the development of coronal magnetic field strengths. Radio observations presently provide the only means for measuring coronal field strengths, but since the Very Large Array (VLA), which provides the most sensitive and highest resolution radio observations of the Sun, is not solar-dedicated we need to be lucky in order to obtain suitable data on an emerging region. In June 1996 we were lucky to observe the very rapid emergence of AR 7978 with the VLA. AR 7978 has been described as “the last, best old-cycle region” (Hudson et al. 1997). It drew attention by producing the first GOES class-X soft X-ray flare for three years. As we will show, this region emerged with remarkable abruptness and is therefore ideal for study. Within 2 days, the region spanned many heliographic degrees and contained a fully-developed delta spot at its center. Of the wealth of data available for this region, here we present and briefly discuss the SOHO/MDI magnetograms and the radio observations of the very first stages of flux emergence.
2. Magnetic Flux Emergence at the Photosphere

The photospheric magnetic field data are shown in Figure 1. They are taken from sequences of magnetograms acquired every 96 minutes by the Michelson Doppler Imager (MDI; Scherrer et al. 1995) telescope on the SOHO spacecraft.
The images have 2" resolution, and in Figure 1 we have removed solar rotation. The time sequence runs from top to bottom in each column.

The first two columns show the early development of the active region on July 6 – 7. The first few panels show a simple bipole which existed and was quite stable for at least a day prior to the emergence of AR 7978: it had moved to this position gradually from the north–west. In Figure 1, the first sign of new flux is a weak positive feature which appears to the south–west of the original negative pore at 16:04 UT. This feature is also faintly visible at 14:28 with higher contrast, when the average field strength is less than 20 G. By 17:40, the new positive feature has grown and a corresponding negative feature has appeared just to the north–east of it. In subsequent images these features rapidly grow and separate, with the negative feature moving to the east while the positive feature remains stationary (in heliographic coordinates) and eventually is to become a delta spot.

The first sign of interaction with the pre–existing bipole occurs at 22:28 UT, when a new weak positive feature, weakly connected to the new positive flux to the south, appears just to the east of the original negative–polarity pore. In the next few hours the new positive feature and the old negative feature seem to cancel each other out (whether by flux “annihilation” or by reconnection followed by submergence of the flux bundle is not clear). At the same time as the original negative pole is destroyed, the original positive pole begins to move rapidly to the west and eventually becomes the positive leading spot of the region. As can be seen from careful inspection of Figure 1, the original positive pole shows no motion until the original negative pole disappears, as if it was originally held in place by field lines which connected the two poles until the emergence of the new positive feature, when the original field lines were severed and released the positive pole.

The last column in Figure 1 shows magnetograms every 384 min during the period when the delta spot develops in the center of the region. Although it is not very evident from these figures, the overall pattern for flux emergence in this region was for discrete positive flux features to appear near the positive central spot and then to move rapidly westwards to pile up at the leading spot: this produces the long “bridge” of positive polarity between the leading spot and the delta spot which may be clearly seen after 06:28 on July 8. The delta configuration in the central spot starts to develop early on July 8. The X flare took place on July 9, and thereafter the central spot rapidly vanished.

In summary, the initial emergence of this region shows a number of interesting features, particularly in its interaction with the pre–existing weak bipole: the negative pole is rapidly subsumed, and once this happens the positive pole goes into rapid motion and becomes the strong leading spot in the region. The location where new flux first emerges is exactly where the delta spot forms 2 days later.

3. The Coronal Response to Magnetic Flux Emergence

Figure 2 shows radio images during the initial period of emergence on July 6. We were fortunate to be observing this location prior to the emergence of AR 7978 because there was a small dark pore associated, we believe, with the
Figure 2. VLA 8 GHz images of the evolution of the radio emission as AR 7978 emerged on 1996 July 6. The time is labelled in each panel, and in panels corresponding to the times of MDI magnetograms, the magnetogram is also shown. The field of view is approximately $160'' \times 100''$. Contours are plotted at brightness temperature multiples $\pm 3,4,6,8,12,16,24,32,40,48,56,64 \times 2000$ K. The beam size is 9''.

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original negative pole which was the only "spot" of any description reported by NOAA the previous day. Both bremsstrahlung and gyroresonance emission can contribute to radio opacity at the wavelength shown. Based on the sub-coronal brightness temperatures ($\approx 10^5$ K) and the lack of circularly-polarized emission features, we believe that all the radio emission observed on July 6 was optically-thin bremsstrahlung from heated plasma in coronal loops, and the Yohkoh/SXT images available agree with this conclusion. In general the radio observations are sensitive to material somewhat cooler than seen by SXT. The lack of significant gyroresonance opacity can be used to place an upper
limit on the coronal field strengths present during initial emergence on July 6: if coronal field strengths reached 600 G, we would expect to have detected optically thick and highly polarized emission at brightness temperatures of order $10^6$ K. The observed brightness temperature would be diluted somewhat if the area of strong field in the corona is small, but the gyroresonant opacity depends directly on field strength, not magnetic flux, and consequently we expect that even a feature much smaller than the beam would be detectable through its polarization signature as long as sufficiently strong fields were present. No such signature was seen, implying that, the emerging flux tubes do not contain fields stronger than several hundred gauss in, e.g., highly sheared cores which could not expand due to the field twist.

There is no detectable radio emission associated with the newly-emerging flux until 18 UT, when a feature appears at the location of the new flux. This rapidly becomes the brightest radio feature, and Figure 2 shows how it brightens and grows. Initially it appears to be a set of loops connecting the new positive and negative polarities. For some time, there appear to be separate radio sources associated with the old and new flux, although the source associated with the old flux definitely brightens (e.g., 19:33 UT) even before we see any clear signs of interaction with the new flux. We noted that reconnection between new positive polarity and the old negative polarity seems to take place staring at around 22:30, based on the magnetograms. The radio images show distinct morphological changes consistent with a connection between the original bipole and the new flux also starting at about this time and there is a peak in the radio emission at 23:24 which could feasibly be linked to this process. We are still working to improve the overlays between radio and magnetic field data in order to look at this association more carefully.

The radio emission is produced by dense coronal plasma, and indicates that such plasma is present in the corona on new magnetic field lines associated with the newly-emerging flux within a few hours of its appearance. The new radio emission does not appear instantly with the new magnetic flux: there seems to be a delay, indicating that the mechanism by which the new flux produces dense heated coronal plasma does take some time to develop. The most commonly discussed mechanism is chromospheric evaporation produced by a heat flux into the chromosphere from the corona; the heat flux is presumably a consequence of enhanced heating in the corona from the new magnetic fields. This region, by virtue of the rapidity of its emergence and the availability of excellent data, promises to illuminate many aspects of this process.

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References

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