LONG-TERM EVOLUTION OF THE EMISSIVITY AND HEATING IN A SOLAR ACTIVE REGION

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ABSTRACT

We study the evolution of the emissivity and heating correlated with magnetic observables of an active region (AR) from its birth throughout its decay during six solar rotations (July-Nov. 1996). Taking one “snapshot” per rotation at each consecutive central meridian passage (CMP) of the AR, outside the time of flares, we analyse multi-wavelength and multi-instrument data obtained from SOHO (MDI and SUMER), Yohkoh (SXT), GOES and 10.7 cm radio data from DRAO, Canada. We find that the magnetic flux density emitted by active regions follow a power-law with exponents which appear to depend on the formation temperature (height) of the emission.

Key words: solar activity, active region evolution

1. INTRODUCTION

The evolution of active regions in each and every detail reflects the evolution of the magnetic field which emerges from below, interacts with its magnetic environment, gets dispersed by persistent large-scale flows and more rapidly evolving supergranular and granular convective flows, and furthermore, gets sheared by the differential rotation. It is a generally accepted idea that magnetic field plays an important role in heating the solar atmosphere, thus its evolution must influence the amount of radiation emitted by active regions.

At least two major recent papers dealt with the relations between radiative output and magnetic observables of solar active regions. Fisher et al. (1998), using a great combined sample of Yohkoh/SXT images and HSP (Hawaii) vector magnetograms, analysed the relationship between different magnetic observables and soft X-ray emission. They found that the X-ray luminosity is best correlated with the total unsigned magnetic flux of a given AR. Harvey and White (1999) analysed Ca II images and Kitt Peak magnetograms and found that the Ca II K (residual) intensity is proportional to the half-power of the magnetic flux density. However, none of these important works dealt explicitly with the evolutionary aspect of active regions. This is what we aim to explore in the present paper.

During the second half of 1996, solar activity was dominated by a single active region on the southern hemisphere, which was identified as NOAA AR 7978 when it emerged in July. This “last best region” of the cycle (Harvey and Hudson, 1997) provided a rare opportunity for various studies, mainly, because of the lack of other active regions on the Sun its evolution was relatively undisturbed and even one-dimensional datasets could be analysed in a meaningful way (Orlando et al. 1999). Strong and smooth rotational modulation of the coronal emission made this period ideal for stellar modelling studies (Oláh et al. 1999).

In former papers (van Driel-Gesztelyi et al. 1999, Mandrini et al. 1999) we studied the long-term evolution of the magnetic field and the coronal non-potentiality combined with flare and CME activity of this AR. In the present paper we analyse the evolution of the heating and emissivity of NOAA 7978 from its birth throughout its decay between July and December 1996. Using multi-wavelength and multi-instrument data we derive physical parameters like intensity (flux), temperature and emission measure of the entire AR versus time, total magnetic flux and magnetic flux density and make an attempt to formulate their relationship.

2. DATA

During the period of August-October NOAA 7978 was practically the only sizable AR on the Sun, which allowed us the use of one-dimensional datasets like...
GOES soft X-ray and DRAO 10.8 cm radio data besides the two-dimensional SOHO (MDI and SUMER) and Yohkoh/SXT images.

MDI (Michelson Doppler Imager) is one of the twelve experiments on board SOHO, which measures the photospheric manifestation of solar oscillation (Scherrer et al., 1995). Besides the dopplergrams it records the line-of-sight magnetic field, making full-disk magnetograms every 96 minutes. For this analysis we use level-1.5 5-minute averaged data.

SUMER (Solar Ultraviolet Measurements of Emitted Radiation, Wilhelm et al., 1995) performs high-resolution spectral imaging of the Sun at several EUV emission lines. For the present study we use full-disk scans taken in the S VIa 933 Å and SVIb 944 Å lines \((T \approx 2 \times 10^5 \text{ K})\), which are recorded on different parts of detector A: S VIa on KBr, S VIb on MCP bare. Intensities are calibrated.

The grazing incidence soft X-ray telescope (SXT, Tsuneta et al., 1991) on board of Yohkoh provides images in the 3-60 Å wavelength range. The use of pairs of thin metal filters permits temperature and emission measure analysis of the corona. For this study, we used the thin Al (Al.1) and the aluminium-magnesium sandwich (AlMg) filters.

Geostationary Orbiting Environmental Satellites (GOES) provide soft X-ray irradiance measurements in the 1-8 Å flux range in Wm\(^{-2}\). For our analysis we use low-channel data of the X-ray Sensors (XRS) on board the GOES-9 satellite.

Daily 10.7 cm solar radio flux measurements were recorded at the Dominion Radio Astrophysical Observatory (DRAO) at Penticton, Canada (Tapping and Charrois, 1994). The daily flux was measured at 17:00, 20:00 and 23:00 UT. The data is given in solar flux units \((10^{22} \text{ Wm}^{-2}\text{Hz}^{-1})\) or \(10^{4}\) Jansky. Note that both the DRAO and the GOES data were calibrated to 1 AU distance.

3. METHOD

Using the images we measured the magnetic flux and the emitted radiation of the active region during the emergence and six more consecutive central meridian passages. We drew the magnetic boundary of the AR "by hand", relying on the detection by the human eye of the steep magnetic field gradient at the boundary using magnetic maps displayed in the same dynamic range (Figs. 1 and 2). We admit that such method brings in some subjective errors, but after carrying out several series of measurements, we did not find greater than about 10 % scatter for the magnetic area and flux. We also used a rectangular area of about \(1.6 \times 10^{12} \text{ km}^2\) around the AR for magnetic flux measurements in order to follow the interaction of the newly emerging flux with the pre-existing magnetic environment. This area was always adjusted to the changing solar-terrestrial distance during this half-year period.

The emitted radiation, emission measure and temperature were measured inside the magnetic boundaries of the AR in the images taken closest in time to the central meridian passages.
Figure 2. SOHO/MDI magnetic maps show the evolution of NOAA AR 7978 during six solar rotations around the times of central meridian passage. The contours outline the magnetic area of the decaying AR, of which the magnetic flux is getting dispersed. The rectangular area which provided another set of magnetic flux measurements.

4. RESULTS

We find that the magnetic area of the AR increased roughly linearly at a rate of \(1.25 \times 10^4 \pm 500 \text{ km}^2\text{sec}^{-1}\). At the beginning, the X-ray emitting area was larger than the magnetic area, due to interaction of the emerging flux with pre-existing magnetic fields around the AR, i.e. to the formation of bright reconnected loops but it fell behind after the 5th rotation when the magnetic field got very dispersed.

Following the evolution of the magnetic flux in a fixed area of \(1.6 \times 10^{11} \text{ km}^2\) containing the growing AR we find an about 20% flux unbalance, due to the fact that the AR emerged in a dominantly negative polarity environment. The total (unsigned) flux inside the rectangular area increased two-fold due to the emergence of the AR of \(1.5 \times 10^{22} \text{ Mx}\), and it nearly returned to the starting level (i.e. to the total flux in the "box" before the flux emergence) by the fourth rotation (Fig. 3). The increase of the flux in October and after that was due to new flux emergence, i.e. the appearance of minor ARs inside or at the boundary of the decaying AR.

The magnetic flux density (B averaged over the entire AR) reached the highest level (188 Mx cm\(^{-2}\)) by the 4th day of the emergence and decreased steadily after that (Fig. 4).

The soft X-ray irradiance (GOES-9) increased steeply during the flux emergence and decreased during the decay phase (outside of flare times). During the evolution process the emissivity did not seem to correlate closely with the area or the total magnetic flux (Fig. 5). The magnetic flux which emerged to form the AR disappeared relatively slowly, followed by an increase after the 4th rotation (Fig. 3), while the SXR emission showed a steep and more steady decrease. On the other hand, intensity, emission measure and temperature shows a better correlation with
the magnetic flux density in the AR. We find that the magnetic flux density versus intensity, emission measure and temperature $|B|$ vs I, EM and T of the AR relations follow a power law. These log-log curves show a roughly linear dependence with different slopes. The soft X-ray emission appears to be proportional with the 1.1-1.3 power of the magnetic flux density, while the transition region lines seem to have a power smaller than one (Figs. 6-9).

5. DISCUSSION AND CONCLUSIONS

We find that the magnetic flux density versus intensity, emission measure and temperature $|B|$ vs I, EM and T of the AR relations follow a power-law. The log-log curves of these observables are roughly linear with different slopes for coronal and transition line emission. There is even some difference between the slopes of GOES and Yohkoh/SXT data. Though both of these instruments observe in the soft-X-ray domain, the two wavelength ranges are not identical.

The GOES/XRS “window” in the soft channel is between 1-8 Å (Hansen and Sellers 1996, Bornmann et al. 1996), while that of Yohkoh/SXT is in the range 3 - 45 Å at 1% of peak response (Tsuneta et al. 1991). The passbands of the SXT filters used are about ~ 3 - 35 Å (A1.1) and ~ 3 - 30 Å (A1Mg). The shorter the wavelength, the higher the temperature, thus GOES “sees” the hottest, SXT with the A1.1 filter the coolest coronal plasma (although the A1.1 and A1Mg filters have a similar passband). The exponents follow the same trend: we see the highest one in case of GOES ($1.3 \pm 0.1$) and the lowest with the SXT A1.1 filter, though the difference between the two SXT filters may not be significant ($1.07 \pm 0.09$ for the A1.1 filter and $1.13 \pm 0.1$ for the A1Mg filter). When we go to lower temperature and look at the slopes of the $|B|$ versus emission in the SVI lines as observed with SUMER, we find that these transition region lines ($T \approx 2 \times 10^5$ K) have a weaker response to the changing magnetic flux density than the soft X-ray radiation. The scatter is large in the data and there is a difference between the S VIa and the S VIb lines, but the exponents are definitely lower than what we found with the SXR radiation. Though the present analysis does not cover a wide range of spectral lines, our results suggest that the exponent in the power law $I \sim |B|^{22}$ depends on the formation temperature (or altitude) of the emission. The flattest slope ($0.1 \pm 0.01$) was found with the 10.7 cm radio flux, which is of dominantly non-thermal origin.

### Table 1. Exponents of the power-law describing the magnetic flux density - intensity relations

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Temperature</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOES 1-8 Å</td>
<td>5-6 $10^6K$</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>Yohkoh/SXT 3-35 Å</td>
<td>2-4 $10^6K$</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>SUMER S VIa</td>
<td>2 $10^6K$</td>
<td>0.9 ± 0.4</td>
</tr>
<tr>
<td>SUMER S VIb</td>
<td>2 $10^6K$</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>DRAO 10.7 cm radio</td>
<td>~</td>
<td>0.1 ± 0.01</td>
</tr>
</tbody>
</table>

### Table 2. Exponents of the power-law describing the magnetic flux density - emission measure and temperature relations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yohkoh/SXT emission measure</td>
<td>1.32 ± 0.13</td>
</tr>
<tr>
<td>Yohkoh/SXT temperature</td>
<td>0.24 ± 0.03</td>
</tr>
</tbody>
</table>

An interesting result is the power-law relation between the magnetic flux density and the soft X-ray temperature: $T \sim |B|^{0.24\pm0.03}$; thus the coronal temperature of the AR is proportional to the quarter power of the magnetic flux density (Fig. 10). The Yohkoh/SXT emission measure seems to have a strong response to the changing magnetic flux density; we found $E.M \sim |B|^{1.32\pm1}$. 
Our findings seem to contradict results by Fisher et al. (1998), who found that the X-ray luminosity of ARs is best correlated with their total unsigned magnetic flux. However, the latter authors dealt with active regions of the same evolutionary stages: all of them were relatively young, and spotless ARs with dispersed magnetic fields were not represented in their sample. Their results simply show that the greater the magnetic flux content of a young AR, the stronger it emits X-ray radiation. Studying the evolutionary aspect of emissivity after a given magnetic flux emergence provides an extension of their result. The emissivity of a given total magnetic flux shows dependence on how closely the flux is packed. Also, an evolving active region presents a case when both the total magnetic flux and the magnetic flux density are changing.

Recent results by Harvey and White (1999) are in good agreement with our findings and expand the wavelength range studied by us. They found that Ca II K intensity in active regions and plages is proportional to the half-power of the magnetic flux density. The $|B|$ vs I relation in this cool chromospheric line adds another value to the exponent list given in Table 1, and confirm our suggestion that the exponent depends on the formation temperature (or height in the atmosphere) of the emission.

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REFERENCES


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Figure 7. Log-log curves of the magnetic flux density and Yohkoh/SXT DN numbers indicate linearity. The X-ray emission appears to be proportional to the $1.1 \pm 0.1$ power of the magnetic flux density. Note that this value is somewhat lower than that of the same relation for the GOES flux (cf. Fig. 6 and Table 1).

Figure 9. Log-log curve of the 10.7 cm radio emission (DRAO) versus magnetic flux density suggests a power law with $0.1 \pm 0.01$ – a very flat slope. Note that 10.8 cm radio emission is basically non-thermal.

Figure 8. Log-log curves of SUMER S VI line intensities versus magnetic flux density, though the scatter is high for the S VIa line, suggest power laws with exponents of $0.9 \pm 0.4$ and $0.7 \pm 0.2$ for these transition region lines – lower values than in the case of the X-ray emission.

Figure 10. Log-log curve of the Yohkoh/SXT temperature values versus magnetic flux density indicates a power of $0.24 \pm 0.03$, i.e. that the coronal temperature of the AR is proportional to the quarter power of the magnetic flux density.