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Evolution of magnetic fields in the solar atmosphere

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Abstract. The Sun affects the terrestrial climate and weather as well as near Earth space by its high energy radiation and particle emissions. It is now becoming clear that the solar magnetic field, which controls all the physical processes in the solar atmosphere, is the driver for these two processes. In this thesis we have studied the role of the evolution of magnetic fields in the production of enhanced high energy radiation and particle emission from the Sun.

Keywords : Sun: activity – Sun: coronal mass ejections (CMEs) – Sun: oscillations – Sun: magenetic fields

1. Introduction

The Sun is our nearest star. It gives steady warmth and light. It is a source of energy which sustains the life on planet Earth. Apart from these, there are two kinds of processes by which the Sun affects the Earth's climate and weather. These are high energy radiation and particle emission. Observational evidences indicate that the magnetic field controls the production of high energy radiation and particle emission from the Sun. To understand the long term subtle changes in the Earth's climate and to predict the space weather it is very important to study the magnetic field in the solar atmosphere. To start with, one can find empirical relationships between the magnetic field parameters and the intensity of high energy radiation and the kinematics of particle emissions. In this thesis, we have attempted to do the same through the study of production of EUV radiation and Coronal Mass Ejections (CMEs) in relation with the magnetic field evolution.

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2. Results and conclusions

We have used the data from the Extreme ultraviolet Imaging Telescope (EIT), Michelson Doppler Imager (MDI) and Large Angle Spectroscopic Coronagraph (LASCO) on-board the Solar and Heliospheric Observatory (SoHO). We have also used the magnetograms archived by the Kitt Peak observatory (NSO/KP).

2.1 He II λ304 Å network brightening and photospheric magnetic field

In the case of production of high energy radiation, we chose He II λ304 Å emission for our study because it is a line which is brightest in EUV emission next to H I L_α in the solar atmosphere. Because of its short wavelength, it is a dominant source of energy for heating and ionizing the terrestrial upper atmosphere. A good knowledge of He II λ304 Å emission and its variability is essential for the study of photo-chemistry and energy balance of planetary atmospheres. However, one needs to understand the mechanism which can enhance the brightness of the He II λ304 Å emission in the solar atmosphere. The excitation mechanism of the helium and its ion in the solar atmosphere is still an unsolved problem.

A number of suggestions have been offered by many to explain the enhanced intensity in the resonance line of He II at 304 Å. We made an attempt to relate the observed network intensity with the magnetic field strength. Even though, the coronal EUV radiation beyond 228 Å is capable of ionizing the helium ion in the solar atmosphere, it would make the features in the transition region more diffused and broader than the coronal features. Since the observed morphologies are different in He II λ304 Å filtergrams and in corona, we concluded that coronal radiation can not be the source of network brightening observed in He II λ304 Å. We then showed how the morphology of the photospheric line-of-sight magnetic field, absolute value of the magnetic field and gradient of the magnetic field are matched with the He II λ304 Å network morphology. We found that the network brightness occurs at the foot points of the magnetic fields by overlying the contours of the magnetic fields upon the He II λ304 Å images. The scatter plots between the He II λ304 Å intensity and absolute value of the magnetic field showed that the network brightness observed in He II λ304 Å has a linear relationship with the strength of the magnetic field for field strength larger than 10 G (Ravindra and Venkatakrishnan 2003a). We estimated the probable height of formation of the network elements observed in He II λ304 Å. We found that at about 3000 km above the photosphere, the size of the potential extrapolated magnetic network elements matches with the size of the He II λ304 Å network elements. The characteristics of the network cells observed in He II λ304 Å is almost matching the characteristics of extrapolated magnetic network cells rather than the photospheric magnetic network cells (Table 1) (Ravindra and Venkatakrishnan 2003b). Thus, our study indicates that the role of magnetic field is important in the network brightening observed in He II λ304 Å.

Table 1. The average lifetime and size of the network cells and elements.

Network Observed in	Life time (hrs)	Size of the network (km)	Size of the element (km)
He II $\lambda 304$	23-27	25000-30000	12800
Magnetic field (MF)	13-16	12000-15000	5000
Extrapolated MF	>30	$\approx$ 25000	12450

2.2 Magnetic field fluctuations in sunspots

Coronal images exhibit pronounced EUV and X-ray emission in the region that are spatially related to sunspots. These regions have temperatures of 8-20 MK, equivalent to an energy budget of 10^7 erg cm^{-2} s^{-1}. Motivated by the earlier results (Ulrich 1996) that this pronounced EUV and X-ray emission is related to the magnetic field fluctuations in sunspots, we examined the magnetic field fluctuations and their magnitudes in sunspots.

We found using four sets of high resolution ($1''.2$) time sequence of magnetograms of active regions, that there is a 3 mHz oscillation in most of the locations in sunspots. In addition to 3 mHz, there is a 5.5 mHz oscillations in the sunspot umbra. The magnitude of magnetic field fluctuations in the sunspot umbra is 7-14 G. The estimated mechanical energy flux ($\approx 10^9$ erg cm^{-2} s^{-1}) from the magnetic field fluctuations ($\approx$ 10 G) is sufficient to heat the active region corona (Ravindra 2004). Apart from the high frequency fluctuations, we found low frequency magnetic field fluctuations in sunspots. The power spectrum shows that a broad range of low frequency power is present in the magnetic field fluctuations. These low frequency fluctuations may be due to the inward and outward drift of features in sunspots. The inward and outward motion of features can be seen in the space time map and is confirmed by applying Local Correlation Tracking technique on magnetograms. We found that the velocity of the inward moving features is small ($\approx$ 0.1 km s^{-1}) and the velocity of the outward moving features lies in the range of 0.4-0.7 km s^{-1} (Ravindra, Venkatakrishnan and Brajesh Kumar 2004).

2.3 CME velocity and active region magnetic energy

The fastest coronal mass ejections blast out through the corona at a speed greater than 1000 km s^{-1}, driving a bow shock that accelerates protons and other ions to cosmic ray energies of 100 MeV or more. Most of these CMEs originate from the strong magnetic fields in ARs like sunspots. The explosions produce a flare in tandem with the CME. Motivated by the earlier results on the prediction of arrival time of CMEs at the Earth and that the intensity of the geomagnetic severity is well related to the initial velocity of the CME, we proceeded to identify the property of the associated active region (AR) that determines the initial velocity of a CME.

To start with, we used 37 halo CME events with their source regions located within 30° from the disk center. We used the differential rotation technique to compensate for the geometrical foreshortening and we multiplied the line-of-sight field strength by $\cos^{-1}\phi$ to remove the projection effects. We improved the signal to noise ratio by adding five successive magnetograms, thereby reducing the noise in the magnetograms from ±20 G to ±9 G. We used a virial relationship to estimate the volume magnetic energy using the three components of the potential magnetic field of the associated AR. Using all these inputs, for all the selected events we found that the initial speed of of the halo is related to the magnetic energy of the associated AR. Interestingly enough, the expansion velocity of the CME varies as 0.26th power of the magnetic energy (Venkatakrishnan and Ravindra 2003). This power is in close resemblance with the Sedov solution for the spherical blast wave expansion, where the expansion velocity of the spherical blast wave varies as 0.2th power of the injected energy. This resemblance suggests that the magnetic energy of the individual AR is the engine for the CME. Our results shows that the maximum speed of a CME is seen to be proportional to the square root of AR magnetic energy.

Thus, the evolution of magnetic fields in the solar atmosphere shows different phases on different spatial and temporal scales. More clearly, the brightness of the quiet sun network and brightness of the active region chromosphere and corona as well as the kinetic energy carried by the CMEs are different manifestations of the magnetic field dynamics in the solar atmosphere. The small scale dynamics of the magnetic field seems to power the sources of high energy radiation and large scale dynamics seems to power the sources of particle emission. In summary, the evolution of the solar magnetic field on different spatial and temporal scales provides the energy for both high energy radiation and particle emission from the Sun.

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