CORONAL EUV AND RADIO VARIABILITY AND HEATING

S. Krucker1, A.O.. Benz1, J.-P. Delaboudinière2

1Institute of Astronomy, ETH Zurich, CH-8092 Zurich, Switzerland
2Institut d’Astrophysique Spatiale, Université Paris, F-91405 Orsay Cedex, France

ABSTRACT

We present sensitive coronal line (Fe IX and Fe XII) observations by the Extreme ultraviolet Imaging Telescope (EIT) onboard the SOHO satellite. The thermal emission of the quiet corona is detected to fluctuate in time and space, presumably the result of localized heat inputs. Significant fluctuations are found in 85% of all pixels. The more prominent enhancements are identified with previously reported X-ray network flares above the magnetic network of the quiet Sun chromosphere. In coronal EUV lines they are amenable to detailed analysis suggesting that the brightenings are caused by additional, dense plasma injected from below and heated to slightly higher temperature than the preexisting corona. An associated radio enhancement at 3.6 or 6 cm wavelength is found in most cases. About half of them show decreasing spectra indicating gyrosynchrotron radiation. Such radio signature is suggestive of non-thermal electrons well-known as an important constituent of regular flares. Therefore we propose that these enhancements are indeed microflares produced by a reconnection process in the corona. Assuming that these findings apply to all observed EUV enhancements, their energy input would correspond to one fifth of the heating requirement of the quiet corona. These observations give convincing evidence for the first time that microflare heating is a significant process.

Key words: quiet Sun; coronal EUV lines; radio emission; coronal heating.

1. INTRODUCTION

The heating of the corona is one of the persisting enigmas of the Sun. Although several explanations for the million degree outer atmosphere have been proposed, none has been confirmed (e.g. reviews in Ulmschneider et al. 1991). The high temperature of the solar corona was originally interpreted by the dissipation of various kinds of waves originating at lower layers. More than a decade ago heating by a myriad of small flares releasing magnetic energy by reconnection has been proposed (Levine 1974; Priest 1981; Parker 1983). However, the suggested microflares or nanoflares have not yet been identified. In the "quiet" corona (excluding active regions and coronal holes) radiative losses are significant (Withbroe & Noyes 1977). Enhanced emission in coronal EUV lines and soft X-rays thus is related to increased heating or a microflare event.

In low-temperature EUV lines originating in the transition region high-velocity jets and turbulent events at a rate of about 800 s⁻¹ over the whole Sun have been discovered (Brueckner & Bartoe 1983). These brightenings lie on neutral lines of small bipoles (Porter et al. 1987). However, their relation to coronal processes is not clear (Moses et al. 1994).

Up in the corona, recent X-ray continuum observations by Yohkoh/SXT have revealed enhanced emission and thus intense heating above the magnetic network (Benz et al. 1997). In addition, frequent flaring above network elements in the quiet Sun at a rate of 0.3 per second over the whole Sun has been reported by Krucker et al. (1997). Much more intense "X-ray bright points" originating above the magnetic network at a rate of one per hour on the whole Sun are well-known. They have been reported to be associated with thermal radio emission (Habbal et al. 1986), but non-thermal emissions have also been noted (Kundu et al. 1995).

2. OBSERVATIONS

Here we report on very sensitive, high-time resolution observations with SOHO/EIT (Delaboudinière et al. 1995). The normal-incidence, multilayered mirror instrument observed a 7°×7° area of the quiet Sun on July 12, 1996. The observing run lasted 42 minutes and had a time resolution of 127.8 s. Two wavelength bands, 171 Å and 195 Å, have been imaged alternatively. They include lines of Fe IX-X and Fe XII, respectively, sensitive to temperatures in the range of 1.1-1.9×10⁶ K. These parts of the EUV spectrum are dominated by the coronal plasma, and the large photon fluxes provide higher sensitivity than previous X-ray observations.

The raw data were corrected for cosmic rays, missing data, and the grid pattern. Using the two bands, emission measure and temperature have been determined for each pixel and at each time. The mean statistical error per pixel and measurement is typically 2% in emission measure and 0.4% in temperature. In reality, the error introduced by the uncertainty in abundance, filling factor and inhomogeneity is larger, but unknown. The derived parameters are therefore to be taken as formal values. In particular, the temperature represented by one value for the whole pixel area is an average and a rough approximation.

Simultaneous observations at the Very Large Array (VLA) at 3.6 and 6 cm were made from the same quiet
Figure 1. Power spectra of the temporal variability of the coronal emission measure in EUV lines observed by SOHO/EIT. The units are cm$^{-10}$ Hz$^{-1}$. Solid: average of all 23716 pixels; dashed: the brightest 2000 pixels; dotted: the faintest 2000 pixels.

Sun region. The VLA recorded continuum emission in with a bandwidth of 50 MHz at each wavelength. The resolution (FWHP) was 7.5$\times$6.9 and 13.2$\times$11.8, respectively for the two wavelengths. The observing wavelength was switched every minute, resulting in a similar time resolution as in EUV.

3. RESULTS

3.1. Coronal EIT Observations

The temporal evolution of the 23716 individual pixels with each an area of 2.5$\times$2.5 has first been analyzed statistically. In general, the time series in emission measure of each pixel was found to fluctuate much more than expected from Poisson statistics on photon counts. Only 15% of the pixels do not show significant variations in time. The power spectrum (Fig. 1) is not white, but shows a partial power-law distribution ($\Psi(\nu) \sim \nu^{-q}$). The exponent is $q=2.0\pm0.14$ for the brightest 2000 pixels (10%), and $q=1.44\pm0.16$ for the average and 2000 darkest pixels.

Most surprising in Fig. 1 is that even intra-network pixels with minimal emission measure fluctuate. Their spectrum becomes flatter at large frequencies due to noise. Note that the difference in average emission measure between the 10% brightest and the 10% dimmest pixels is only a factor of 1.7. The spectral power of the brighter pixels, however, is 3.8 times stronger. Thus, the network

Figure 3. The time profiles of the event shown in Fig. 2. Top: formal temperature (average over the area of enhanced EUV intensity); second: total emission measure; third: radio flux density observed by the Very Large Array at 6 and 3.6 cm wavelength at the location of the 6 cm peak; bottom: radio flux density observed by the Very Large Array at 6 and 3.6 cm wavelength at the location of the 3.6 cm peak.
pixels fluctuate more (even in relative terms) than the intra-network pixels.

Figure 2 displays the time series of one of the most intense events. To heat the additional emission measure from a chromospheric temperature to the formal value derived from the ratio of the two EUV channels, an energy of $2 \times 10^{26}$ erg is needed. The accuracy of the energy estimate is better than the temperature value, which is a spatial average. The difference images in Fig. 2 indicate a motion of the centroid between 14:45:40 and 14:51:04 UT. If the event is interpreted as hot plasma propagating in a loop, its projected length is $9.5 \times 10^6$ cm, and the source velocity is approximately 50 km/s. Thus the loop reaches a height of about 5000 km.

3.2. Radio Observations

The VLA images are also displayed in Fig. 2 using the same pixel size as EIT. There is clearly a radio enhancement associated, but the peaks occur at slightly different locations in the two wavelengths. It indicates that the spectrum of the two radiating locations was different.

In Fig. 3 the time profiles of the EUV and radio emissions of the same event are presented. The emission measure and temperature have been derived from the observations of the coronal EUV lines (cf. Section 2). In the event of Fig. 3 the temperature clearly increases by only a small amount, which is however not well defined due to the reasons mentioned. The maximum temperature precedes the peak of emission measure by 200 seconds. In regular flares a thousand times more powerful, this is a well-known property.

The temperature peak coincides with the maximum radio emission at 6 cm. The time profiles of the radio emission in Fig. 3 is shown for two positions: the first is taken at the centroid position of the 6 cm emission and includes the area of the radio beams. The emission at 3.6 cm is not significantly enhanced at the location of the 6 cm source and vice versa.

3.3. Case Studies of Large Enhancements

Events in EUV emission measure exceeding 12 standard deviations from the pixel average have been selected for detailed analysis. During most of the prominent EUV enhancements the temperature was observed to increase. Occasionally, the opposite, a "cold flare" has been noticed, where the heating mechanism apparently did not operate up to the temperature of the pre-existing plasma. The temperature maximum was found in the rise phase in 14 of the 23 selected events, 8 peaked simultaneously, and in only one case the temperature maximum was later. The observed temperature evolution suggests an impulsive and rapid heating early in the event.

In all selected events except one, an associated increase in radio emission was noted. All associated radio emissions except one peaked at the time of the EUV event or before.

The two radio channels characterize the emission process. In 8 of 18 cases with good coverage at both wavelengths the spectral slope decreased, suggesting non-thermal emission. The same number of events showed an increasing spectrum, compatible with optically thick thermal emission of chromospheric origin. Two spectra were flat and could be caused either by non-thermal emission, optically thin thermal radiation or a mixture.

The observed preceeding of the radio emission is consistent with the interpretations as gyrosynchrotron and thermal radiations. The former case is reminiscent of the Neupert effect of large flares (Neupert 1968), where non-thermal electrons are accelerated in the corona and radiate before collisionally losing their energy by precipitation into the chromosphere. In the second case the radio emission originates in the chromosphere heated by particle impact.

3.4. Statistics of all Fluctuations

The relation between fluctuations in EUV and radio emission has also been studied by the cross-correlation of the...
The time profiles of the emission measure in coronal EUV lines were cross-correlated with radio observations at 6 cm in each picture element. The pixel size and the observing times of the former were adjusted to the radio beam and time. The observed values are presented with crosses and connected with lines. A spline interpolation is shown dotted.

In the 6 cm data the average cross-correlation at zero time lag is only 0.053 (Fig. 4), but significant. The interpolated curve peaks at 18 s delay of EUV relative to radio emission. At 3.6 cm only the dimmer EUV pixels show significant cross-correlation.

4. DISCUSSION AND CONCLUSIONS

The radio observations suggest that about half of the more prominent fluctuations are accompanied by non-thermal radiation. This associated radio emission has the typical characteristics of coronal gyro-synchrotron emission by relativistic electrons in regular flares. The radiation is apparently missing in the other network flares. The low cross-correlation coefficient indicates furthermore that the weaker EUV and radio fluctuations are not well associated. Many reasons could be responsible why gyro-synchrotron emission is seemingly missing, including free-free absorption, low magnetic fields, or the sensitivity limit of the radio observations.

In conclusion, there is clear evidence that some of the network flares reported earlier are miniature flares characterized by the acceleration of energetic electrons early in the event. They constitute only 6% of the sum over all observed EUV enhancements excluding the photon noise. It is not clear whether these smaller fluctuations are the continuation of the network flares to smaller events. Under the assumption that they are all caused by additional plasma heated and injected from the chromosphere, the total energy input observed at time scales from 4 to 42 minutes can be determined. It amounts to $9 \times 10^8 (h/5000 \text{ km})^{1/2} \text{ erg s}^{-1} \text{ cm}^{-2}$, where $h$ is the density scale height. It is close to the observed radiation loss of the quiet corona in the field of view evaluated with the SPEX code and amounting to $4.5 \times 10^5 \text{ erg s}^{-1} \text{ cm}^{-2}$. The effective heating requirement may be even larger due to conductive losses towards the chromosphere below. They have been estimated to be of equal amount as the radiative losses (Withbroe & Noyes 1977), but may be reduced by constraining magnetic fields. In any case, these coronal EUV observations strongly suggest that microflares considerably contribute to the heating of the quiet corona.

ACKNOWLEDGMENTS

We thank Tim S. Bastian and Barbara J. Thompson for help with the observations. The Very Large Baseline Array and the Very Large Array are operated by Associated Universities, Inc. under contract with the National Science Foundation. The work at ETH Zurich is financially supported by the Swiss National Science Foundation (grant No. 20-046836.96).

REFERENCES