MULTIWAVELENGTH OBSERVATIONS OF A PARTIALLY OCCULTED SOLAR FLARE.

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ABSTRACT

The GOES class X3.3 flare which occurred on the 20th of July 2002 was a partially occulted event which was partially observed by RHESSI and OWSA. The fully unocculted flare was observed by Ulysses, then behind the Sun. Comparison of these observations shows that a significant fraction of the HXR emission above 25keV occurred in the high corona. Examination of the RHESSI images shows that the Hard X-ray emission is increasingly confined to the looptops.

The flaring loops quickly became rather dense ($\approx 10^{11}\text{cm}^{-3}$) with around $10^{32}$ electrons accelerated in a magnetic field of $\approx 80G$.

1. INTRODUCTION

Coronal hard x-ray sources were first observed in occulted flares in the 1970's (1); (2) using data from the OSO 5 and OSO7 satellites. The earliest imaging observations (3) found coronal emission at 3.5-16keV extending to a height of 30,000km into the corona. Observations with Hinotori extended the energy range up to 25keV (4). The $10^{30}$/HXT instrument provided further evidence for coronal HXR sources during the 990's and since the launch of RHESSI in 2002 a number of coronal sources have been observed at energies up to 200keV.

Several theoretical interpretations have been suggested for the occurrence of an impulsive coronal HXR source. Tsuneta et. al. (5) suggested that Fermi acceleration of particles at the fast mode shock of a reconnection outflow impacting on a dense static loop system below could account for particles of up to 100keV. Alternate explanations are that coronal sources are the signature of the current sheet itself (6) or particles trapped and accelerated in the field below a reconnecting coronal structure (7). Recent observations with RHESSI and GOES have suggested that the X-ray emission is due to thick target bremsstrahlung from non-thermal particles stopped in a dense region of the corona (8).

2. OBSERVATIONS

2.1. Hard X-ray observations

The RHESSI satellite was launched in 2002. It's primary objectives is the study of the evolution of energy release and particle acceleration in solar flares with high spectral and temporal cadence. It has an energy range of 3keV-17MeV and a best imaging resolution of 2 arcsec (9).

The lightcurves from RHESSI and GOES show that the flare was a gradual, long duration event, which had the GOES classification of X3.3 (Fig.1). It was observed on the south east limb of the Sun. The flare occurred in AR 0039 which was occulted, the occultation height estimated to be 11 000km (10). The unocculted portion of the flare was observed by RHESSI. A fully unocculted view of the flare was obtained by the Cosmic Ray and Solar Particle Instrument which returns summed lightcurves between 25-150keV on board the Ulysses spacecraft, then behind the Sun. Comparing the summed count rate of the two instruments demonstrates that a significant fraction of the total HXR emission occurred in the unocculted part of the flare which was observed by RHESSI.

The RHESSI image reconstruction was carried out using the PIXON image reconstruction algorithm, which provides high quality, excellent noise suppression and photometrically accurate images, but which has the disadvantage of being extremely computationally intensive (11). The RHESSI observations show a distinctive arcade of loops in the lowest energy observation (20-30keV), but as the energy increases we see that the emission is increasingly confined to the looptop (Fig. 2). The looptop emission is observable to 200keV. The high resolution spectra from RHESSI was fitted using two thermal components and a non thermal component as well as line emission at 93keV. The two thermal components consist of a moderately high temperature (26MK), high emission measure $7.0 \times 10^{33}\text{cm}^{-3}$ component and a very high temperature (63MK), low emission measure($5.0 \times 10^{34}\text{cm}^{-3}$) component. The non thermal component has a steep $\gamma = 2.25$ photon spectral index (Fig. 3).
Figure 1. GOES plot showing the rise, peak and cooling phase of the 20th July 2002 long duration event in 0.5-4 and 4-8 bands.

From the GOES satellite we can obtain an estimate of the temperature and emission measure independent of RHESSI, from GOES we obtain a temperature estimate of 24MK and a very large emission measure \(2.8 \times 10^{50} \text{cm}^{-3}\). The emission measure observed by GOES gradually increases in the initial phase of the flare (while RHESSI is still in eclipse) followed by a rapid increase at the onset of the impulsive phase.

2.2. Radio observations

The Owens Valley Solar Radio Array (OVSA) consists of 2x27m dishes and 5x2m. It observes between 1 and 18GHz and is tunable to any harmonic of 200MHz within this range. It observes left and right circular polarisation and linear polarisation. The radio spectra can provide information on the energy distribution, magnetic field, density and non thermal power law distribution of the microwave emitting electrons. Here we use the radio emission as a diagnostic of magnetic field strength and electron number.

We can see from the dynamic spectrum (Fig.4) that there are several distinct peaks in the microwave emission, the first near the onset of the flare at 21:05 and the second two, in rapid succession around 21:30. If we examine the spectrum at the last and most powerful of these peaks (Fig.4), we see that the peak of the spectra occurs at 7.4GHz, with a maximum power of 10 076 SFU (1SFU = 1 \times 10^{-19} \text{ergs}). The spectrum is fitted with the function (12):

\[
S = A\nu^\alpha (1 - e^{-B\nu^{-\beta}})
\]  

Where \(\alpha\) and \(\alpha - \beta\) are respectively the optically thick, low frequency slope and the optically thin, high frequency slope. We find for the high frequency slope \(\alpha - \beta = -1.7\). Using (13):

\[
\alpha - \beta = 1.22 - 0.9\delta
\]  

We obtain a value for the electron spectral index of \(\delta = 3.2\).

3. PARAMETERS DERIVED FROM THE OBSERVATIONS

3.1. X-ray parameters

Where the photon spectrum can be approximated to a power law \(I(\epsilon) = A\epsilon^{\gamma}\) the instantaneous number of electrons in the flaring system can be determined using (14))

\[
N(E)V = (5.67 \times 10^{41}/n_i)(\gamma - 1)^2
\]

\[
B[\gamma - \left(\frac{1}{2}\right) - \frac{1}{2}]AE^{-\gamma + \frac{1}{2}}
\]

\approx 6.7 \times 10^{32} \text{electrons}

Where we integrated over energy to obtain the number of electrons above 10keV From GOES and RHESSI we can obtain estimates of the density in the loop. From the RHESSI images, we estimate the total flaring volume observed to be \(6.98 \times 10^{26} \text{cm}^3\). The emission measure, \(EM = n^2V\), therefore we can say that \(n\) is \(1 \times 10^{11} - 2 \times 10^{11} \text{cm}^{-3}\). This allows us to estimate the
Figure 2. PIXON reconstruction of RHESSI images in 20-30, 30-50, 50-100, and 100-200keV. With increasing energy the emission becomes increasingly confined to the looptop.
Figure 3. RHESSI spectrum displaying the two fitted thermal components (25 & 63MK and the non thermal power law component. There is also a line component fitted at $\approx 93\text{keV}$.

Figure 4. OVSA radio spectrum from 1-18GHZ during the last and most powerful spike in the microwave emission and OVSA. OVSA dynamic spectrum showing three distinct microwave bursts.
energy of particles which we would expect to be stopped fully in the loop by collisional bremsstrahlung (15);

\[ E = \sqrt{3}KN \approx 8.8\sqrt{N_{19}} \approx 28 - 41 \text{ keV} \]  
(4)

3.2. Radio parameters

The magnetic field strength can be determined from the degree of circular polarisation \( r_c \). During the peak of this flare (21:30) \( r_c = 0.15 \). Using the numerical formula (16);

\[ r_c = 1.26 \times 10^{0.035 \delta} 10^{-0.071 \cos \theta} \left( \frac{\nu}{\nu_B} \right)^{-0.782 + 0.545 \cos \theta} \]  
(5)

and estimating a line of sight angle of 80° we find \( \nu/\nu_B = 31 \). Since \( \nu_B = 2.8 \times 10^8 B \), the magnetic field is estimated to be 80G. The source function is given by (13);

\[ S_{\nu} = \frac{kT_{\nu} \nu^2}{c^2} \Delta \Omega \]  
(6)

Since \( T_b = T_{\text{eff}} \tau_{\nu} \) in the optically thin limit and

\[ T_{\text{eff}} \approx 2.2 \times 10^{9} 10^{-0.031 \delta} \]
\( \left( \sin \theta \right)^{-0.36 + 0.06 \delta} \left( \frac{\nu}{\nu_B} \right)^{0.5 + 0.085 \delta} \]

\[ \tau_{\nu} = k_{\nu} \approx 1.4 \times 10^{-9} 10^{-0.22 \delta} \]
\( \left( \sin \theta \right)^{-0.09 + 0.72 \delta} \left( \frac{\nu}{\nu_B} \right)^{-1.330 - 0.98 \delta} \].

(7)

(8)

substituting equations 7 and 8 into equation 6 we can obtain a value for the number of electrons in the flaring system emitting in the radio. We find; \( NV = 5.3 \times 10^{32} \) electrons. Which is in good agreement with the number derived from the X-ray observations.

4. DISCUSSION AND CONCLUSIONS

We have established from observations that the flare on 20th July 2002 was a large flare in which a substantial fraction of the total HXR emission occurs high in the corona. The plasma in the flaring loops rapidly become dense, allowing electrons with energy less than 40keV to be stopped fully in the upper corona. These electrons dump their energy in the corona, allowing very efficient heating of the plasma, possibly accounting for the rather high temperatures observed by RHESSI.

The magnetic field derived from the radio emission is \( \approx 80G \), this is consistent with the observed emission occurring high in the corona. Although much lower than measured photospheric fields, it is significantly larger than coronal fields measured from coronal seismology in ‘quiet’ coronal fields. This is probably to be expected due to the significantly larger magnetic flux in active regions.

What cannot be explained by this coronal thick target model is the high flux of photons of energies > 50keV observed by RHESSI, and their confinement to the loop-top. We suggest the occurrence of a local acceleration and/or mechanism in the loop-top, which while allowing some fraction of the electrons to escape along the loop to the footpoints, keeps a significant fraction confined. This may be due to particles trapped in the reconnection region (7) or due to some shock acceleration (5), however further qualitative modelling is necessary.

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REFERENCES


