Calculation of RF emission brightness temperature of high density plasmas clouds in Sun-terrestrial interplanetary space

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Abstract. In this paper, bremsstrahlung, the dominating RF emission mechanism of high density plasmas clouds in sun-terrestrial interplanetary space, is studied. The bremsstrahlung brightness temperature of the plasmas clouds from 0.47 AU to 1 AU are calculated according to the data that recorded by Mariner 10. The calculating results show that the RF emission brightness temperature of high density clouds can be identified as compared to those plasmas clouds in times of quiet sun by radiometer with 2 K temperature resolution. Therefore, forecast of disastrous space weather can be obtained in time according to the variation of emission brightness temperature of the plasmas clouds.

Index Terms. Brightness temperature, radio emission, interplanetary space, plasmas clouds.

1. Introduction

The Sun is a fixed star which is proximate to Earth of about 1 AU. As a consequence, a wealth of phenomena such as CMEs which occurring through the Sun’s atmosphere are the principal drivers of the space weather and the near-Earth conditions (Raulin and Pacini, 2005; Munro, et al., 1979; Webb and Hundhaunsen, 1987; Cyr and Webb, 1991). For examples, they often drive interplanetary shocks and cause geomagnetic storms. Therefore, space operations and satellite communication and surveillance systems will be disturbed. (Jadav et al., 2005). High density plasmas clouds are the basic nature of CMEs as they propagating into interplanetary space. In Fig. 1, the LASCO C3 solar observatory satellite recorded a major, long duration, proton ejection event from the sun. We can see that high density plasmas cloud is generated as the ejection entered the interplanetary space. Therefore, bremsstrahlung as the mainly radio emission mechanism of the plasmas cloud will be intensified undoubtedly.

In this paper, we calculate the RF emission brightness temperature of high density plasmas cloud that induced by ICMEs by use of the scientific data which recorded by Mariner 10. The calculating results show that the emission brightness temperatures of the plasmas clouds are approximately a few decuple of those plasmas clouds in times of quiet sun. The variation of emission brightness temperatures can be identified by radiometer with 2 K temperature resolution. We can predict how serious the CMEs will be by analyzing the variation of the brightness temperature.

2. Bremsstrahlung theory

The basis for incoherent radio emission in low density medium like the solar corona is the emission from free accelerated particles. The dominating RF emission mechanism of high density plasmas clouds, which are induced by the propagation of CMEs in the interplanetary space, is bremsstrahlung. Moreover, cyclotron emission and recombination emission do a little contribution to RF emission (Sun and Wu, 2005). In this paper, we focus on the calculation of bremsstrahlung brightness temperature.

Fig. 1. CME recorded by LASCO.
Bremsstrahlung is caused by Coulomb collisions between charged particles in plasmas. In Fig. 2, an example of a binary collision between an electron with velocity \( v \) and an ion with charge \( Z_i \) is shown. \( b \) is impact parameter.

Consider a cloud of plasmas with electrons temperature \( T \), number density of the electrons \( N_e \), number density of the ions \( N_i \), and electrons thermal velocity \( v \). The velocity distribution of the electrons in this cloud is given by the Maxwell distribution:

\[
f(v) = N_e \left( \frac{m_e}{2\pi kT} \right)^{3/2} \frac{m_ev^2}{2\pi} e^{-\frac{m_v^2}{2kT}}.
\]

The emission coefficient of bremsstrahlung is:

\[
f_f = 1.501 \times 10^{-39} \frac{NN_iZ^2}{T^2} [17.72 + \ln \left( \frac{T}{fZ} \right)].
\]

where \( f \) is the emission frequency and \( Z \) is the serial number of atomic nucleus. The unit of it is erg cm\(^{-3}\) sr\(^{-1}\) sec\(^{-1}\) Hz\(^{-1}\).

The corresponding absorption coefficient is:

\[
\alpha_f = 9.78 \times 10^{-3} \frac{NN_iZ^2}{T^2 f^2} [17.72 + \ln \left( \frac{T}{fZ} \right)].
\]

The unit of absorption coefficient is cm\(^{-1}\). The source function of bremsstrahlung is:

\[
S_f = \frac{f_f}{n_e^2 \alpha_f}.
\]

Where \( n_r = [1 - \left( \frac{f_{pe}}{f} \right)^2]^{-1} \) is refractive index of the plasmas cloud. The plasma frequency \( f_{pe} \) is approximately equal to \( 10^4 \sqrt{N} \) (Rybicki and Lightman, 1979). When Eqs. (2) and (3) are substituted into Eq. (4), we also obtain:

\[
S_f = 1.534 \times 10^{-37} \frac{Tf^2}{1 - \left( \frac{f_{pe}}{f} \right)^2}.
\]

If there is no initially outer emission, the emission intensity is (G. Bekefi, 1966):

\[
I_f = S_f [1 - e^{-\frac{L}{\alpha_f} ds}].
\]

Where \( \int_0^L \alpha_f ds \) is optical depth, \( L \) is the thickness of the medium. \( \tau_f \) is equal to \( \alpha_f L \) if the plasmas is homogeneous. The unit of it is erg sec\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\). Thus, the emission intensity is

\[
I_f = S_f [1 - e^{-\alpha_f/L}].
\]

When Eqs. (3) and (5) are substituted into Eq. (7), the following equation for \( I_f \) is obtained:

\[
I_f = 1.53 \times 10^{-37} \frac{T_f^2}{1 - \left( \frac{f_{pe}}{f} \right)^2} [1 - e^{-\alpha_f/L}].
\]

The low-frequency portion of the radiation spectrum is well approximated by the relation (Bekefi, 1966):

\[
I_f \approx \frac{2kT_B f^2}{c^2}.
\]

Therefore, the brightness temperature \( T_B \) is:

\[
T_B = \frac{c^2 I_f}{2\alpha f^2}.
\]

When Eq. (8) and the value of \( c, \alpha \) are substituted into Eq. (10), the following equation for \( T_B \) is obtained:

\[
T_B = 0.5 \frac{[1 - e^{-\alpha_f/L}] T}{1 - \left( \frac{f_{pe}}{f} \right)^2}.
\]

The unit of \( T_B \) is K.

3. Calculating results

The bremsstrahlung brightness temperature of high density plasma clouds between 0.47 AU and 1 AU are calculated by using the data that recorded by Mariner 10. The electrons temperature of plasmas clouds have relation to their density, which is shown in the empirical equation (Sittler, Jr. and Scudder, 1980):

\[
T_e \approx 5.5 \times 10^4 \times n_e^{0.175}.
\]

Correspondingly, we obtain the expression of electron density \( n_e \):

\[
n_e \approx 0.175 \sqrt{T_e} \times 10^{-4} / 5.5.
\]

The electrons density \( n_e = 7.1 \) when the heliocentric distance is approximately equal to 1 AU (M. G. Kivelson and C. T. Russell, 1995). Therefore, the corresponding electrons...
temperature $T_e = 0.775 \times 10^5$. By use of the data (Feldman et al., 1979) recorded by Mariner 10 and according to equation (13), we obtain the corresponding electrons density, which is shown in Table 1.

<table>
<thead>
<tr>
<th>$R$ (AU)</th>
<th>$T_e$ (10$^5$K)</th>
<th>$n_e$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.775</td>
<td>7.1</td>
</tr>
<tr>
<td>0.75</td>
<td>0.79±0.04</td>
<td>7.92</td>
</tr>
<tr>
<td>0.69</td>
<td>0.80±0.03</td>
<td>8.51</td>
</tr>
<tr>
<td>0.62</td>
<td>0.85±0.03</td>
<td>12.03</td>
</tr>
<tr>
<td>0.53</td>
<td>0.98±0.07</td>
<td>27.13</td>
</tr>
<tr>
<td>0.47</td>
<td>1.04±0.04</td>
<td>38.10</td>
</tr>
</tbody>
</table>

It can be seen in Fig. 1 that high density plasmas clouds emerge after CMEs ejected into interplanetary space. The densities of them decrease sharply as heliocentric distance increasing. The fluctuation range of electrons density is from 0.3 cm$^{-3}$ to 33.6 cm$^{-3}$ near 1 AU (Sun and Wu, 2005). Moreover, the fluctuation range of electrons temperature $T_e$ is from 6201K to 402019 K near 1 AU (Sun and Wu, 2005). Namely, the electrons density and temperature can reach 4.73 multiple of those in times of quiet sun. In this paper, we conservatively estimate electrons density of the high plasmas cloud by multiply the initial values in Table 1 by $2^{n/2} \times 4.73$, $n=1, 2, 3, 4, 5$. The corresponding electrons temperatures of them are calculated according to equation (12). The calculating results are shown in Table 2.

<table>
<thead>
<tr>
<th>$R$ (AU)</th>
<th>$T_e$ (10$^5$K)</th>
<th>$n_e$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.02</td>
<td>33.6</td>
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<tr>
<td>0.75</td>
<td>1.10</td>
<td>52.98</td>
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<td>0.69</td>
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<td>513.30</td>
</tr>
<tr>
<td>0.47</td>
<td>1.85</td>
<td>1019.43</td>
</tr>
</tbody>
</table>

From equation (3), (11), $Z = 1$, $L = 3 \times 10^{10}$ cm and the value of $N_e$, $T_e$ that in Table 2, we thus obtain the calculating results: brightness temperature of the high density plasmas clouds near 1 AU, 0.75 AU, 0.69 AU, 0.53 AU and 0.47 AU as emission frequency are equal to $10^3$ KHz approach 1.2 K, 3.0 K, 6.5 K, 25 K, 230 K, 850 K, respectively. Moreover, the brightness temperature decreases about two magnitudes if emission frequency increases one magnitude with identical heliocentric distance. We give the detailed results in Fig. 3.

It can be seen in Fig. 3 that: (a) the brightness temperature curves take on the look of semi-parabolic waveform; (b) the brightness temperature with identical emission frequency decrease sharply as heliocentric distance increase.

4. Summary

In this paper, brightness temperatures of mainly RF emission mechanism of the high density plasmas clouds in interplanetary space are calculated. The calculating results presents in this paper are approximately a few decuple of those in times of quiet sun period. Namely, the variation of RF emission brightness temperature of plasmas clouds in times of quiet sun and of the high density clouds can be identified by radiometer with 2 K temperature resolution and appropriate detective frequency. Therefore, according to the variation of emission brightness temperature of the plasmas clouds, forecast of disastrous space weather can be obtained in time by use of radiometer.

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References


