COMPARISON BETWEEN EUV AND RADIO OBSERVATIONS: A POWERFUL DIAGNOSTIC FOR THE UPPER SOLAR ATMOSPHERE

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ABSTRACT

Using the intensity of several EUV lines observed by SOHO-CDS in an equatorial Coronal Hole, the DEM function $\text{DEM}(T) = N^2 dh/dT$ is derived in the temperature range $10^4 - 10^6$ K. Above the temperature where no more lines are detected, the DEM can be either truncated or arbitrarily extrapolated to a very low value at a very high temperature. The DEM derived with both assumptions reproduce very well the observed line intensities, but are unable to reproduce the observed radio brightness temperature $T_b$. It is shown that the observed radio $T_b$ can be obtained only by postulating the presence of an isothermal Corona above the region where the truncated DEM is defined.

From the fit of the $T_b$, observed by the Nancay Radioheliograph in the same hole at four frequencies between 164 and 410 MHz, a full model of the coronal hole is derived which fits also the EUV line intensities.

The electron density, derived from the coronal emission measure in the hydrostatic equilibrium assumption, disagrees with that derived from density sensitive line ratio: the reason of this discrepancy is discussed.

1. INTRODUCTION

The diagnostic of the low Solar Corona as well as of the Chromosphere-Corona Transition Region is mostly based on the analysis of EUV lines and Radio Emission: the constraints on the parameters of this portion of the solar atmosphere becomes very stringent if these two types of observations are matched together.

In the present work we compare radio and EUV observations of an equatorial coronal hole, observed on October 18 and 19, 1996 during its central meridian transit. The hole was observed by the CDS and EIT instruments onboard SOHO and by the Radioheliograph of Nancay (France) at four radiofrequencies between 169 and 410 MHz. EUV and Radio observations will be described in the next Section, the analysis of EUV lines observed by CDS, the method for the determination of the Differential Emission Measure ($\text{DEM} = N^2 dh/dT$) and the radio brightness temperature determination are presented in Section ?? In Section ?? we present the comparison between EUV and radio results, performed using the DEM in the TR up to a certain temperature determined, together with the pressure at the basis of the corona, from the best fit of radio data. The best fitting models are then checked by computing the EUV line intensities. A general discussion and the conclusions are given in Section ??

2. OBSERVATIONS

2.1. EUV Observations

The EUV spectra in the coronal hole were taken, on October 18, with the Normal Incidence Spectrometer (NIS) of the Coronal Diagnostic Spectrometer (CDS) on board of the SOHO satellite.

The NIS operates in two spectral windows covering the 307-379 Å and 513-633 Å spectral range. Of the whole NIS spectral band, only selected portions have been observed, thus reducing the total observing time. The selected spectral windows allow to detect lines formed in the range of temperatures between $10^4$ K to $10^6$ K, the whole range of temperature between chromosphere and corona.

The total field of view observed by CDS is $122'' \times 450''$ and covers the central portion of the coronal hole. The hole region has been selected where the Mg x line intensity $I_{924,94} < 10$ phot cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$: the intensity of each line has been averaged within this area.

2.2. RADIO OBSERVATIONS

Radio observations of the Coronal Hole were performed on October 19, 1996, by the Nancay Radioheliograph (NRH) (see Kerdraon & Delouis 1997) at the following frequencies: 164 MHz, 236 MHz, 327 MHz and 410 MHz.

in handling the radio data.

3. DATA ANALYSIS

3.1. DEM analysis with CDS

From the average values of the line intensities, the coronal hole DEM, defined as

$$\varphi(T) = N_e^2 \frac{d\text{li}}{dT}$$

(1)

has been determined using the iterative method described by Landi & Landini 1997. Element abundances have been taken from Feldman et al. 1992 (coronal values). Ion fractions come from Arnaud & Raymond 1992 (Fe ions) and Arnaud & Rothenfus 1985 (other ions).

The DEM curve is usually defined in a temperature range including plasma from chromospheric to coronal conditions; above the temperature where no more lines are detected by the instruments, the DEM function is very often extrapolated to a very low value at a very high temperature (~10^6 K). This causes the DEM to have a sharp maximum around the coronal temperature, implying an increase of the temperature gradient $\frac{dT}{dr}$, which would produce a physically unacceptable high temperature. Landi & Landini 1998 have criticized this assumption and proposed to truncate the DEM at a maximum temperature $T_{\text{max}}$ beyond which the DEM is not defined.

In this paper we will use the DEM, derived from the observed EUV line intensities using both methods, to calculate radio brightness temperature and compare it with the observations. The upper limit of the truncated DEM is $T_{\text{max}} = 10^6$ K.

The DEM fits are displayed in Figure ?? together with the data points. In the DEM analysis the Fe, Mg and Si abundances from Feldman 1992 have been lowered by a factors ranging from 3.4 to 4.0, getting a good agreement with the Grevesse & Anders 1991 photospheric values.

3.2. Radio brightness temperature

The radio brightness temperature $T_b$ is related to the plasma parameters through the transfer equation:

$$T_b = \int_0^{r_{\text{max}}} T e^{-\tau} \, dr$$

(2)

where

$$d\tau = -\frac{0.2N_e^2 dr}{\nu^2 n T^{3/2}}$$

(3)

is the differential radio optical depth. In this Equation $l$ is the coordinate along the ray path and $n$ is the refraction index:

$$n = \sqrt{1 - (N_e/N_{\text{cr}})}$$

(4)

where $N_{\text{cr}} = 1.24 \times 10^{-8}$ $\nu^2$ is the critical density. Since the coronal hole is located near the disk center,
the ray path is a straight line, $N_e^2 dl \simeq N_e^2 dh$ and Eq. (5) may be re-written as

$$d\tau = -\frac{0.2\nu(T)}{\nu^2 n T^{3/2}} dT$$

where $\tau_{max}$ is the optical depth of the level where $N_e = N_{e\nu}$ and $T = T_{\nu e}$. In order to take into account the refraction index $n$ in Eq. (5), we must know the electron density profile in the upper part of the solar atmosphere. This has been done in the two following ways:

- (a) from the simple assumption of a constant pressure in the TR (hereafter defined as $p = N_e T$), getting $N_e(T) = p_0/T$

- (b) by combining the DEM profile with the assumption of hydrostatic equilibrium, getting:

$$N_e^2(T) = T^{-2} \times \left( C - 2\alpha \int_{T_0}^T T \varphi(T) dT \right)$$

where $\alpha = \frac{\mu m_p}{k_B} \simeq 1.98 \times 10^{-4} \text{ K m}^{-1}$ and $C$ is an integration constant: $C = p_0(T_0)$.

The lower temperature in the above integral has been arbitrarily set $T_0 = 5 \times 10^4 \text{ K}$: this value does not affect the calculations since all considered radio frequencies have their critical level at a temperature $T_{cr} \gg T_0$ and therefore the integral of the transfer equation stops at higher temperature.

For every value of $T_{max}$, use as an upper limit of the integral in Eq. (6), the minimum allowed value of the pressure is:

$$p^2_{\text{min}} = 2\alpha \int_{T_0}^{T_{max}} T \varphi(T) dT$$

Pressure values lower than $p_{\text{min}}$ would give $N_e^2 < 0$ at $T \leq T_{max}$.

4. COMPARISON BETWEEN EUV AND RADIO OBSERVATIONS

The radio brightness temperatures have been computed from Eqs. (4) and (5), and using $N_e(T)$, derived from the assumptions (a) and (b) mentioned above, in Eq. (6). Both the DEM functions displayed in Figure 1 have been used in the calculation.

No substantial difference is found between the results obtained using the two density profiles (a) and (b) mentioned above. This is because the electron density only enters the refraction index. In the following we will therefore show only the results obtained using the hydrostatic equilibrium assumption, mentioning the other ones when necessary.

Figure 2 displays the radio brightness temperatures calculated using both the DEM curves reported in Figure 1 and three values of the pressure $p_0$. The results obtained using the Landi & Landini 1998 DEM show a very bad fit of the observations all along the frequency range. Those obtained using the standard DEM definition show a rather good agreement with the observations at high frequencies, where the curves are almost independent of $p_0$, while they exceed the observed $T_s$ at low frequencies. Moreover, they present a cut-off, present also in the other set of curves, at a frequency decreasing with decreasing pressure. However a lower pressure $p_0$, which at first sight could appear to provide a better fit of the observations, cannot be adopted, since $p_0 = 3 \times 10^{14} \text{ cm}^{-3} \text{ K}^{-1}$, corresponds to $p_{\text{min}}$ for $T_{max} = 10^8 \text{ K}$.

It must be pointed out that, if one assumes this same DEM function, but performs the integral of the radio transfer equation between $T_{cr}$ and an upper limit $T_s < 10^8$, finds the following results: for $T_{cr} = 10^8 \text{ K}$, the curves are very similar to those shown in Figure 1 (bottom). For $10^6 < T_s < 1.5 \times 10^6$, the computed $T_b$ increases rapidly and for any $T_s > 1.5 \times 10^6$ they remain identical to those shown in Figure 1 (top).
The reason of this disagreement is due, in our opinion, to having neglected the presence of an isothermal corona at the top of the TR. In the derivation of the DEM from EUV line intensities, the presence of the corona is in fact not properly considered as the coronal contribution to the intensity of EUV lines formed at temperatures close to $T_{\text{max}}$ is included in the DEM.

The density profiles derived from the DEM, irrespective to the adopted assumption on the pressure trend, are therefore abruptly truncated at $T = T_{\text{max}}$. If the value of the electron density at $T = T_{\text{max}}$, which depends on the assumed value of pressure, turns out to be larger than the critical density at a given frequency $\nu$, no contribution to the $T_0$ will be given by the atmosphere at all frequencies $\nu \leq \nu_0$, thus producing the sharp cut-off noticed in both panels of Figure 3.

If, on the contrary, the presence of a nearly isothermal corona is assumed above the level where $T = T_{\text{max}}$, we have still an emitting plasma, whose density slowly decreases with height up to extremely low values, that can provide a non zero $T_0$ at any frequency.

Having this in mind, we have repeated the calculations using the DEM up to $T = T_{\text{max}}$ and adding above this level an isothermal corona at $T_0 = T_{\text{max}}$. If hydrostatic equilibrium is assumed, the coronal radio optical depth $\tau_c$ can be analytically calculated, obtaining a symple function of the temperature, the scale height $H = T_0/\alpha$ and the critical density $N_{\text{cr}}$ or the density at the bottom of the corona $N_c(0)$, depending if the critical level is located in the corona or below it.

The pressure $p_0$ and the coronal temperature $T_c = T_{\text{max}}$ are left as free parameters to be determined from the fit of radio data.

The fit of the radio spectrum has been done for three values of the coronal temperature, $T_c = 7.9 \times 10^5, 8.9 \times 10^5$ and $1 \times 10^6$ K and several values of the pressure in the TR spanning from $2 \times 10^{14}$ to $5 \times 10^{14}$ cm$^{-3}$ K. The results, obtained assuming the hydrostatic equilibrium in the whole considered portion of the atmosphere (assumption (b)) are compared with the observations in Figure 3.

Unfortunately the lack of resolution at 164 MHz does not allow a precise determination of the coronal temperature, but only an upper limit, $T_0 \sim 9 \times 10^5$ K. Very good fits are obtained for coronal temperatures $T_0 \leq 8.9 \times 10^5$ K assuming a value of the pressure $p_0 = (3 \div 3.5) \times 10^{14}$ cm$^{-3}$ K at $T_0 = 5 \times 10^4$ K.

Identical results are obtained if a constant pressure (assumption (a)) is assumed in the TR with $p_0 = (2.5 \div 3) \times 10^{14}$ cm$^{-3}$ K. It must be pointed out that a pressure $3 (3.5) \times 10^{14}$ cm$^{-3}$ K at $T_0 = 5 \times 10^4$ K, in the hydrostatic equilibrium assumption, leads to pressure values of $2.5 (3) \times 10^{14}$ cm$^{-3}$ K at $T = 8.9 \times 10^5$ K, thus indicating that the parameter affecting the radio data is the pressure at bottom of the corona and not its trend in the TR.

4.1. Synthetic EUV spectra

The three models used to fit the radio data shown in Figure 3 have been then used to compute theoretical EUV line intensities: the resulting $I_{\text{calc}}/I_{\text{obs}}$ ratios are plotted in Figure 3 as a function of wavelength.

Figure 3 shows that the best agreement between theoretical and observed intensities is reached at $T_c = 8.9 \times 10^5$ K, which is consistent with the results obtained from radio data. Moreover, the top panel in Figure 3 shows also that the EUV line intensities computed assuming $T_c = 7.9 \times 10^5$ K are too low, thus providing a lower limit of the coronal temperature in the hole. We recall that, due to the low resolution at $\nu = 164$ MHz, only an upper limit of $T_0$ was deduced from radio data. It must be pointed out that the computed line intensities using both the DEM curves shown in Figure 3, without the coronal contribution are also in very good agreement with
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Figure 4. Comparison between computed and observed radio brightness temperature, in the assumption of hydrostatic equilibrium.

the observations, being the curves derived from the best fit of the observed line intensities. This indicates that, contrary to what we found for radio data, EUV line intensities can be equally well reproduced by an atmosphere with or without an isothermal corona, provided that the upper limit of the DEM definition is properly set.

5. CORONAL DENSITY

From the values of the best fitting pressure the following electron densities are derived at the base of the corona: $\log N_e(0) \simeq 8.48 \pm 0.04 \text{ cm}^{-3}$ ($T_e = 8.9 \times 10^{5} \text{ K}$) and $\log N_e(0) = 8.53 \pm 0.04 \text{ cm}^{-3}$ ($T_e = 7.9 \times 10^{5} \text{ K}$).

These density values are larger by about a factor 2.5 than those derived from the density sensitive Si IX line ratio ($\log N_e = 8.1 \pm 0.1$ and 8.2 $\pm$ 0.1 respectively). The theoretical Si IX $341.9/\left(349.8+349.9\right)$ line ratio has been calculated using the CHIANTI database (Dere et al. 1997, Landi et al. 1999), taking into account the effects of photoexcitation from photospheric radiation.

The density values at the basis of the corona, determined from the fit of radio data also exceed the average values ($\log N_e = 8.2 \div 8.35$) in polar coronal holes, reported by Fludra et al. 1999a, 1999b but they agree very well with those determined from Si IX line ratio by Del Zanna & Bromage 1997 in this same coronal hole (the elephant trunk hole), observed two rotations before. It must be noticed however that Del Zanna & Bromage 1997 and Fludra et al. 1999a, 1999b did not include photoexcitation from photospheric background radiation as a populating mechanism for the Si IX ground levels. Neglecting this process leads to slightly overestimate the electron density.

The discrepancy between the electron density inferred from Si IX and that derived from the fit of radio data can be, at least in part, ascribed to one of the following reasons: (i) the regions of the coronal hole where EUV line intensities and radio brightness temperature have been averaged are not the same, and (ii) the scarce angular resolution of low frequencies overestimates the electron density in the corona. The most serious physical reason of the overestimation of the electron density derived from radio data will be discussed in the next Section.

6. DISCUSSION AND CONCLUSIONS

The joint analysis of EUV and radio observations of an equatorial coronal hole at its central merid-
ian transit, has shown the very powerful diagnostic provided by these two types of observations, when combined together.

It has been shown that EUV line intensities can be equally well reproduced by an atmosphere with or without an isothermal corona, by properly changing the top temperature in the DEM, while radio data can’t.

From this analysis a coronal emission measure \( EM = 2.7 \times 10^{32} \text{ cm}^{-3} \) and a temperature \( T_e = 8.9 \times 10^8 \text{ K} \) are derived. The EM agrees with Yohkoh observations of coronal holes in X-ray, which however require a much higher temperature (Hara et al. 1994 and reference therein). Low values of the temperature were instead recently determined by other analysis of coronal holes using CDS (Del Zanna and Bromage 1997; David et al. 1998; Fludra et al. 1999a, 1999b), thus removing a long-standing discrepancy between the coronal hole temperature required by the radio and EUV observations (Chiuderi Drago et al. 1977).

A rather strong discrepancy has been found, between radio and EUV data, in the density value at the basis of the Corona (EUV line intensity ratios indicate much lower densities than radio \( T_e \)): it must be pointed out however, that the coronal contribution to the radio brightness temperature (and also to coronal line intensities) depends on the temperature and on the emission measure, \( EM = \int N_e^2 dh \) rather than on the electron density itself. In our case the electron density at the basis of the corona was derived from the best fit of radio data having assumed that in hydrostatic equilibrium and getting therefore: \( EM = N_e(0)^2 H/2 \) with the scale height given by \( H = T_e/\alpha \).

According to Kohl et al. 1998 and Sheeley et al. 1997, deviation from the hydrostatic equilibrium are important only above 1.5 \( R_\odot \). Therefore, since the coronal contribution to the radio brightness temperature at the considered frequencies, as well as that to the EUV line intensities, comes from the deepest layers of the solar corona (\( R < 1.05 R_\odot \)), this assumption is fully justified.

On the contrary, the consequences of having assumed the temperature derived from the fit of radio data to determine the coronal scale height are important. In fact the radio emission of the quiet corona is due to thermal bremsstrahlung and the corresponding temperature is the electron temperature, while that entering the scale height is an average plasma temperature.

Recent SOHO and Ulysses observations have indicated that the proton and the electron kinetic temperatures are quite different, mostly in coronal holes, the latter being much lower than the former. According to Fludra et al. 1999b, the average density profile of several polar coronal holes suggest that \( T_p > 2 T_e \). A larger average coronal temperature would therefore imply a larger scale height with the consequence of getting a lower \( N_e(0) \) from the required EM.

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