X-Ray Emission from the Terrestrial Magnetosheath

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Abstract. X–rays are generated throughout the terrestrial magnetosheath as a consequence of charge transfer collisions between heavy solar wind ions and geocoronal neutrals. The solar wind ions resulting from these collisions are left in highly excited states and emit extreme ultraviolet or soft X–ray photons. A model has been created to simulate this X–ray radiation. Published terrestrial exospheric hydrogen distributions and solar wind speed, density and temperature distributions were used in this model. Simulated images were created as seen from an observation point outside the geocorona. The locations of the bow shock and magnetopause are evident in these images. Perhaps this X–ray emission can be used to remotely sense the solar wind flow around the magnetosphere. Since similar X–rays are produced in the heliosphere, the challenge will be, however, to eliminate this background emission.

1. Introduction

X–ray emission from comet Hyakutake was discovered in 1996 [*Lisse et al.*, 1996]. Subsequently, X–ray emission from a number of other comets, planets, interstellar gas throughout the heliosphere and even the moon has been observed [*Dennerl et al.*, 1997; *Lisse et al.*, 1999a, 1999b; *Cravens*, 2002a, 2002b; *Krasnopolsky and Mumma*, 2001]. *Cravens* [1997] proposed that this X–ray emission could be produced by charge exchange between heavy solar wind ions and cometary neutrals. In these charge exchange collisions, an electron is transferred from a neutral to a high charge state heavy solar wind ion. The heavy ion is left in an excited state and consequently emits a photon in the extreme ultraviolet or soft X–ray region of the spectrum. Recent higher resolution spectra of the cometary X–rays by Chandra [*Lisse et al.*, 2001] and of the extreme ultraviolet emission (EUV) by the EUVE satellite [*Krasnopolsky and Mumma*, 2001] show individual spectral lines, which has confirmed that the solar wind charge exchange (SWCX) mechanism was the main source of these emissions.

Cox [1998] suggested that the SWCX mechanism applied to interstellar neutrals and neutrals in the Earth's geocorona could account for part of the observed soft X–ray background. He also suggested [1998] that the same mechanism could explain some of the temporal variations in the soft X–ray background, and in particular the Long Term Enhancements (LTE) as seen by ROSAT [*Snowden et al.*, 1994]. *Freyberg* [1998] also attributed the LTE to variations

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in the solar wind and speculated that the SWCX mechanism applied to the vicinity of Earth might be responsible.

Cravens [2000] constructed a simple model of heliospheric X–ray emission from charge exchange between the solar wind and interstellar helium and hydrogen. A comparison of the LTE part of the ROSAT X–ray background for the 1/4 keV channel with the solar wind proton flux proved promising [*Cravens et al.*, 2001; *Robertson et al.*, 2001]. Daily averages of measured solar wind proton fluxes were compared with ROSAT LTE data for all days for which both data types were available, and a correlation coefficient of $R = 0.71$ was found. A model of the X–ray emission was used to show that the time variations came from the SWCX mechanism for both the interstellar helium and geocoronal hydrogen. The geocoronal hydrogen density outside the magnetopause was assumed to vary as $n_H = n_{Ho}(10R_E/r)^3$, and the solar wind flow outside the magnetopause was assumed to be uniform. We now report on a more elaborate model of the geocoronal SWCX X–ray contribution. In particular, simulated X–ray images of the magnetosheath are generated. In a similar study, *Holmström et al.* [2001] predicted X–ray intensities and simulated images associated with the solar wind interacting with exospheric neutrals at Mars. Remote observations of the magnetosheath have also been made by the LENA instrument on the IMAGE spacecraft using low energy neutral hydrogen atoms produced by the charge transfer of solar wind protons with geocoronal hydrogen [*Collier et al.*, 2001].

2. The Model

The following expression, similar to the expression originally applied to comets by *Cravens* [1997], is used to obtain the EUV and soft X–ray power density in the Earth's geocorona:

$$P_{X-ray} = \alpha n_{sw} < g > n_H \qquad (\text{eV cm}^{-3}\text{s}^{-1}) \qquad (1)$$

where α contains all the detailed atomic cross sections, transition information, and solar wind heavy ion composition, etc. The neutral geocoronal hydrogen density is denoted by n_H, the solar wind density is n_{sw} and the average ion–neutral collision speed is denoted as $< g >$. *Cravens et al.* [2001] actually used $\alpha = 1.5 \times 10^{-15}$ eV cm^2, although 6×10^{-16} was stated. $\alpha \approx 6 \times 10^{-16}$ eV cm^2 is probably a better choice for the SWCX efficiency factor, although this is still quite uncertain and depends on solar wind conditions [*Schwadron and Cravens*, 2000; *Kharchenko and Dalgarno*, 2000].

The unperturbed upstream solar wind density is assumed to be $n_{sw0} = 7$ cm^{-3} and the unperturbed solar wind speed is set at $u_{sw0} = 400$ km/s. As the solar wind crosses the bow shock and enters the magnetosheath, however, the density and speed change drastically. The solar wind density, speed and temperature inside the magnetosheath are predicted by the numerical global hydrodynamic model of *Spreiter et al.* [1966]. We use the Spreiter contour plots for these parameters inside the magnetosheath. Our spatial grid is crude ($\Delta r \approx 0.57 R_E$), but is sufficient for this initial exploratory study. Some solar wind plasma also certainly enters the magnetosphere through the cusps [*Reiff et al.*, 1977], but we neglect this effect in our current study. The solar wind density jump across the subsolar bow shock is about a factor of

4. The bulk velocity, however, decreases to about a tenth of the unperturbed velocity just outside the nose of the magnetosphere, and the temperature increases by as much as a factor of 22 in the subsolar region. Spreiter's results were for a solar wind with Mach number 8 and a γ of 5/3. A reasonable magnetopause distance for "average" solar wind parameters is 9.5 R_E.

The speed in equation (1) is the average relative speed between ions and neutrals and is calculated as follows. The heavy ion thermal speed is assumed to be the same as the proton thermal speed and is given by:

$$\nu_{thermal} = \sqrt{3k_B T/m} \tag{2}$$

and the total relative speed is given by

$$< g > \cong \sqrt{u_{sw}^2 + \nu_{thermal}^2} \tag{3}$$

T is the temperature, k_B is Boltzmann's constant, m is the proton mass, and u_{sw} is the bulk flow speed. The geocoronal hydrogen densities used in the model were taken from the Monte Carlo model of *Hodges* [1994]. The resulting hydrogen densities were tabulated at the end of his paper. We used the results for equinox conditions and for an $F_{10.7}$ solar flux of 180. Beyond 12 R_E, the outer boundary of the model, we adopted a $1/R^3$ radial variation for the hydrogen density.

The X–ray intensity in a given direction is obtained by integrating the volume emission rate from equation (1) over an appropriate path length s.

3. The Results – X–Ray Images

Figure 1 shows soft X–ray volume emission rates in the x-z plane. The Earth is located at the origin. The x and R axis scales are in units of D, the subsolar distance to the magnetopause. The resolution is rather low (101 data points in both the x and z directions of the graph); however, it can clearly be seen that the maximum production rate is in the subsolar region. The boundaries of the magnetopause and shock are well–defined. Spreiter's plots provided no information for distances greater than 3 D downwind; consequently, our magnetosheath in the tailward direction is abruptly discontinued at that distance.

The volume emission rates were integrated along parallel paths of 100 R_E length for each of the 101 $\times$ 101 pixels in our simulated images (Figure 2). As expected, the sharp demarcation lines of the magnetopause and bow shock, apparent in Figure 1, are smoothed out in Figure 2, although they are still clearly discernible. Figure 2 also shows that X–ray emission can extend far out into the solar wind, but that the magnetosheath region has the greatest intensities. It is also evident from Figure 2 that the soft X–ray appearance of the magnetosheath depends on viewing angle.

4. Results – Variable X–Ray Emission

We now consider time variations of the geocoronal X–ray emission due to solar wind variations. The geocoronal X–ray intensities from the SWCX mechanism should scale with solar wind flux (see equation (1)) as predicted by *Cravens et al.* [2001] and *Robertson et al.* [2001], if the magnetopause stays fixed. However, an increasing solar wind dynamic pressure moves the magnetopause closer to the Earth, allowing the solar wind to enter regions with higher hydrogen densities. This effect was not included by *Cravens et al.* [2001] and *Robertson et al.* [2001]. According to the Chapman–Ferraro theory [cf. *Chapman and Ferraro*, 1931a, b] the relationship between the location of the magnetopause and the solar wind dynamic pressure ($\rho_{sw} u_{sw}^2$, where the mass density is $\rho_{sw} \cong n_{sw} m_p$), is:

$$\frac{R_{mp}}{R_E} = \left(\frac{B_E^2}{2\mu_o \rho_{sw} u_{sw}^2} \right)^{1/6} \tag{4}$$

B_E is the equatorial magnetic field at the Earth's surface, μ_o is the permeability of free space, R_{mp} is the subsolar magnetopause distance, and R_E is an Earth radius.

We numerically determined X–ray intensities for a variety of solar wind densities ranging from $0.3 \leq \rho_{sw}/\rho_{sw0} \leq 10$, and for a view direction through the magnetospheric flank (corresponding with the most probable ROSAT look direction). We divided each X–ray intensity by the upstream proton flux used and normalized the result with respect to the reference flux $\rho_{sw0} u_{sw0}$. The ratio of X–ray intensity corrected for magnetopause distance and the "linear intensity" was found to vary as $(\rho_{sw} u_{sw}^2 / \rho_{sw0} u_{sw0}^2)^{1/3}$, which is just the functional dependence one expects from equation (4), and a geocoronal H density which varies as R^{-3}.

Figure 3 is a more accurate recalculation of the heliospheric X–ray intensities with interstellar helium and hydrogen contributions, using an updated heliospheric neutral model, a smaller α for He (50% of H), and the X–ray emission for geocoronal hydrogen (as discussed in the current paper). Note that Figure 3 includes the non–linear magnetopause effect. The interstellar H contribution exhibits little variability due to its large (many AU) emitting volume (see *Cravens et al.* [2001]).

Figure 4 is an expanded view of a portion of Figure 3. Most of the time there is only a slight difference between the intensities with and without the non–linear contribution. The greatest difference is in the "higher" peaks, when the solar wind density goes up to as much as 53 cm^{-3} or when the solar wind speed increases to about 780 km/s. The X–ray intensities can then be double what the "linear model" would predict, due to a drastically reduced magnetopause distance.

5. Discussion

Is it possible to actually observe the X–rays emitted from the geocorona, and consequently to remotely image the location of the magnetopause and bow shock in the soft X–rays? The geocoronal intensities are small ($\approx$ 25%) compared to the X–ray emission from the heliosphere or interstellar medium, but they exhibit dramatic time variability compared to the other sources, and perhaps this could be used to "filter out" the steady part of the background.

The observation of the time–variable part of the soft X–ray background from ROSAT (i.e., the LTEs) [*Snowden et al.*, 1994] is a clear indication that a time variable signal can be detected with suitable techniques, although the LTEs are the (mainly) geocoronal emission seen from inside the magnetosphere and the images are this emission seen from the outside. Consider the following possible observing strategy for an X–ray telescope located at a distance of $\approx 20\ R_E$

and with about 100 pixels, each subtending a solid angle of $3^\circ \times 3^\circ$. The minimum total counts (photons detected) in a suitable time period would need to exceed ≈ 100 counts in order to extract 20–50 counts of magnetosheath signal from the total signal (carried out by subtraction from a pointing direction well away from the target or from another time period with very different solar wind flux). Using a typical soft X–ray background intensity and a time/integration interval of ≈ 2 hours, the effective detector area (for all pixels) would need to be ≈ 10 cm^2. For comparison, the effective area for the Röntgen satellite (ROSAT) PSPC instrument 1/4 keV channel was ≈ 50 cm^2 but with a much smaller solid angle per pixel.

Efficiencies for the SWCX mechanism (e.g., the α in equation (1)) are currently being re–examined (cf. *Cravens*, 2002a, b). Recently measured charge transfer cross sections for high charge state oxygen ions are about a factor of 2 to 3 less for helium targets than for other neutral targets [*Greenwood et al.*, 2002]. Consequently, we now adopt an alpha value for helium that is a factor of 2 less than the value for H, although this will require further study.

Charge transfer of high charge state heavy solar wind ions produces soft X–rays, but charge transfer of solar wind alpha particles produces He^+ 30.4 nm emission in the EUV part of the spectrum: $He^{++} + H \rightarrow He^{+*} + H^+$, where the excited He^{+*} produces 30.4 nm photons [*Gruntman*, 2001]. The equivalent of equation (1) for this process can be determined using the fractional abundance of He^{++} in the solar wind ($f \approx .05$) and the cross section for charge exchange leading to 30.4 nm emission (2.5×10^{-16} cm^2 at 1 keV/amu ($u_{sw} \approx$ 400 km/s) and 4.5×10^{-16} cm^2 at 2 keV/amu ($u_{sw} \approx 600$ km/s) [cf. *Gruntman*, 2001]). Our estimate of the α for the 30.4 nm emission is $\alpha \cong 1.3 \times 10^{-18}$ cm^2. By scaling this α value with the earlier one for soft X–ray emission, one can immediately convert soft X–ray intensities into He^+ 30.4 nm intensities (photons/cm^3/s) for all the images and figures shown.

As discussed by *Gruntman* [2001], a number of sources of other "background" 30.4 nm (or very nearby) emission exist, including SWCX of He^{++} with interstellar H, solar wind pickup ion glow, and emission from interstellar plasma. Our results indicate that the geocoronal contribution will be comparable to this other emission (few milli–Rayleigh intensities) during enhanced solar wind conditions. However, the other sources will be rather steady and the geocoronal 30.4 nm emission highly variable. Another difference is that the geocoronal 30.4 nm emission should be highly Doppler–shifted ($\Delta\lambda \approx \pm 0.03$ nm) due to the high He^{++} thermal speed in the magnetosheath.

6. Conclusions

This paper made predictions of soft X–ray emission from the terrestrial magnetosheath due to charge transfer of solar wind ions with geocoronal atomic hydrogen. Simulated images were generated in which bow shock and magnetopause locations were clearly evident. Simple estimates indicate that it should be possible to extract the magnetosheath signal from the soft X–ray background emission, in which case soft X–ray observations could potentially provide a powerful means of remotely imaging the magnetosheath.

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Figure captions:

Figure 1. X–ray production rate in the x–z plane. Rates are in eV cm^{-3} s^{-1}. R is the distance from the X–axis in this figure, and D is the radial distance to the subsolar magnetopause. Bow shock and magnetosphere positions are indicated.

Figure 2. Image of the X–ray intensity as observed from the Earth's flanks (left panel), and from an observation point 45° from the Earth–Sun axis (right panel), in the equatorial plane. Units are keV cm^{-2} s^{-1} sr^{-1}. R and X are coordinates in the image plane. Bow shock and magnetosphere positions are again indicated.

Figure 3. Heliospheric X–ray intensities similar to those in *Cravens et al.* [2001] but using an improved interstellar neutral model and a different α. The look direction is north of the ecliptic plane. A look direction in the plane would increase the linear intensities by a factor of 1.4 [*Hodges*, 1994]. Day numbers start at Jan. 1, 1996.

Figure 4. Close up of the spiked region of the geocoronal X–ray intensities in Figure 3. The total intensity differs dramatically from the linear intensity due to a much larger solar wind flux which compresses the magnetosphere.