Jovian X-ray Emission from Solar X-ray Scattering

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Abstract. Soft x-ray emissions with brightnesses of about 0.01–0.2 Rayleighs have been observed from both the equatorial and auroral regions of Jupiter. It has been proposed that the equatorial emission, like the auroral emission, may be largely due to precipitation of energetic heavy ions into the atmosphere [Waite et al., 1997]. In this paper we model two alternative mechanisms for low-latitude x-ray emission: (1) elastic scattering of solar x-rays by atmospheric neutrals, (2) fluorescent scattering of carbon K-shell x-rays from methane molecules located below the jovian homopause. Our modeled brightnesses agree, up to a factor of two, with the bulk of low-latitude ROSAT measurements. This suggests that solar photon scattering (approximately 90% elastic scattering) may act in conjunction with energetic heavy ion precipitation to generate jovian equatorial x-ray emission.

Introduction

Energetic heavy ion precipitation as a result of pitch angle scattering from the inner magnetosphere was originally proposed to explain x-ray line emissions from the jovian aurorae [Metzger et al., 1983; Waite et al., 1994; Cravens et al., 1995]. More recently, data from the high-resolution imager (HRI) on ROSAT has been used to explain jovian exospheric heating and to identify a correlation of equatorial x-ray emission with System III longitude [Waite et al., 1997]. In particular, x-ray intensities appear to be inversely proportional to surface magnetic field strength [Gladstone et al., 1998] which supports an ion precipitation source. However there also appears to be a significant correlation of the x-ray limb with the bright visible limb as well as a correlation of the disc-integrated emission with the solar F10.7 proxy. The latter correlations suggest a solar-driven process. In this letter we model the x-ray emission expected from Jupiter due to scattering as well as carbon K-shell fluorescence of soft solar x-ray photons (with energies less than a few hundred eV). The notion that K-shell fluorescence of solar x-rays might give rise to measurable x-ray emission from planetary atmospheres was first suggested almost thirty years ago [Aiken, 1970]. Apart from models of solar x-ray fluorescence and scattering by Earth’s atmosphere [Fink et al., 1988; Snowden & Freyberg, 1993] and a study of ionospheric formation in Titan’s atmosphere, we know of no other studies in which planetary x-ray emissions have been modeled, in particular, using real-time solar data.

Model Inputs

Solar Irradiances

ROSAT measured x-ray emission from the jovian disc during the periods July 13–22, 1994, March 21-25, 1996 and September 25-28, 1996 over a bandpass of about 0.1–2.1 keV (Gladstone et al., 1998). We model solar x-ray irradiances for the above dates using the EUV97 solar proxy model [Tobiska & Eparsier, 1997] for wavelengths from 3–12 nm. We employ 4-hour averages of Yohkoh satellite x-ray spectral irradiances in order to capture the high degree of variability of solar x-ray fluxes for wavelengths in the range 0.2-3 nm. The latter were computed using Yohkoh-derived coronal color temperature [Acton et al., 1999] based on modeled synthetic spectra [Meue et al., 1985; Meue and van den Oord, 1986]. The combined irradiiances were adjusted by the distance of Jupiter from the sun (5.42, 5.24 and 5.17 AU for each observational epoch). Figure 1 shows expected photon fluxes at a distance of 1 AU from the sun at 0h00 UT on July 15, 1994.

Cross-sections

Atomic attenuation and scattering cross-sections at x-ray wavelengths have been taken from NIST tabulations for atomic hydrogen, helium and carbon [Chantler, 1995]. Cross-sections for H2, CH4 are obtained by adding the cross-sections of their atomic constituents. The NIST tables also provide a separate cross-section for the contribution of the

Figure 1. Solar irradiance spectrum at 1 AU.
Plate 1. Modeled volume emission rates for the subsolar point assuming a solar spectrum as in Figure 1. Left panel: contribution due to H$_2$ scattering. Center panel: contribution due to CH$_4$ scattering and fluorescence. Right panel: total volume emission rate.

K-shell to the carbon total absorption spectrum. We assume a yield for carbon K-shell fluorescent emission of $2 \times 10^{-3}$ [Krause, 1979] and a Thomson-scattering angular dependence for both scattering and fluorescence cross-sections.

Atmospheric Model

Altitude profiles of jovian atmospheric constituents are required in order to determine atmospheric attenuation as well as emission rates. To this end we used a double-sided Bates temperature profile $T = T_1 - (T_1 - T_n) \exp^{-\frac{z}{z_n}}$ for $z > z_n$ and $T = T_0 + (T_n - T_0) \exp^{-\frac{z}{z_n}}$ for $z < z_n$ (1).

Figure 2. Unit optical depth contour for four solar zenith angles ($c = 0°, c = 30°, c = 60°, c = 90°$).

Figure 3. Expected top-of-the-atmosphere x-ray brightness spectrum for the subsolar point at the same time of observation as in Figure 1.
to data returned by the Galileo probe [Steff et al., 1997]. We use an exospheric temperature of $T_{\infty} = 940$ K and obtain best-fit parameters $T_0 = 160$ K, $T_n = 300$ K, $z_n = 300$ km, $\sigma_0 = 52.5$ km, $\sigma_{\infty} = 240$ km. We assume that eddy diffusion dominates below the homopause and use mixing ratio data from the Galileo Probe’s quadrupole mass spectrometer [Niemann et al., 1996] at a pressure of 0.5 bar to solve upwards, for atmospheric constituents other than atomic hydrogen, until the homopause is reached (at about 350 km). Above this point we solve for the neutral densities assuming hydrostatic equilibrium. Methane profiles thus obtained are consistent with other atmospheric models [Gladstone et al., 1996] and recent observations [Sada et al., 1998]. We ignore the scattering effects of atomic H since it has a column density of about $3 \times 10^{17}$ cm$^{-2}$ [Ben Jaffe et al., 1993] which is much lower than the columns of H$_2$ ($1.2 \times 10^{22}$ cm$^{-2}$), CH$_4$ ($3.1 \times 10^{19}$ cm$^{-2}$) and He ($1.9 \times 10^{21}$ cm$^{-2}$) predicted by our model for the altitude range 200–3000 km above the 1-bar level.

Figure 2 gives an indication of the optical depth resulting from the atmospheric model for different solar zenith angles at x-ray wavelengths. Although optical depth is largely controlled by the considerable number density of H$_2$, the unit optical depth contour reaches well below the homopause for most of the wavelength range which means that many photons reach the methane component of the atmosphere.

**Scattering Model and Results**

We assume that the volume emission rate for single-scattering is given by

$$\eta_{sc}(z, \lambda) = \sum_i \pi F \ exp(-\tau_{in}) \ \frac{d\sigma_{sc}^{(i)}}{d\Omega} \ n_i , \hspace{1cm} (2)$$

where $F(\lambda)$ is the solar irradiance at Jupiter, $\tau_{in}(z, \lambda, \chi)$ is the optical depth due to all atmospheric species at altitude $z$, wavelength $\lambda$ and solar zenith angle $\chi$, $n_i(z)$ denotes the number densities of scattering species and $d\sigma_{sc}^{(i)}/d\Omega$ represents the differential cross-section for Thomson scattering in a direction $\theta$. The summation is over species H$_2$, He and CH$_4$. We take into account the ROSAT-Jupiter-Sun angle which was approximately $10^\circ$ for all measurements.

The volume emission rate for carbon K-shell fluorescence at the K-shell $\lambda_K(\approx 4.1$ nm) is given by

$$\eta_K(z) = \int_{\lambda<\lambda_K} d\lambda \ \pi F \ \exp(-\tau_{in}) \ \omega_K \ \frac{d\sigma_K}{d\Omega} \ n_C . \hspace{1cm} (3)$$

Here $d\sigma_K/d\Omega$ is the differential cross-section for carbon K-shell absorption and $\omega_K$ is the fluorescence yield.

In plate 1 we show the contributions to the volume emission rate of H$_2$ (term $i = H_2$) and CH$_4$ (term $i = CH_4$ in equation 2 plus the contribution of equation 3) along with the total volume emission rate due to all three modeled atmospheric species resulting from the spectrum in figure 1. The contribution of the carbon K-shell to total emission (see bright spike in middle panel at approximately 4 nm) may vary between 8 % and 12 %, depending on solar activity. Clearly, the bulk of the emission occurs in the optically thin region at altitudes below the homopause and for wavelengths less than 5 nm.

We determine intensities out of the top of the atmosphere using

$$I_{sc}(\lambda) = \int dz \ \exp(-\tau_{out}(z, \lambda, \xi)) \ \eta_{sc}(z, \lambda) \hspace{1cm} (4)$$

$$I_K(\lambda_K) = \int dz \ \exp(-\tau_{out}(z, \lambda_K, \xi)) \ \eta_K(z) \hspace{1cm} (5)$$

**Figure 4.** X-ray brightness (equation 6) from modeling (dots) compared with ROSAT observations (stars with error bars) integrated over latitudes of absolute value less than 45°. The four dashed curves are simply linear fits to individual groups of ROSAT data (before and after Shoemaker-Levy 9 impact in the case of the left panel).
where $\tau_{\text{out}}$ is the optical depth for the outgoing radiation at observer zenith angle $\xi$, and the integral is carried out over the altitude range of the atmospheric model. The top-of-atmosphere brightness spectrum for a single point on the visible disc in Rayleighs $^1$ using solar x-rays [Banaszkiewicz & Zarnecki, 1999] is then

$$B(\lambda) = 4\pi \times 10^{-6} [I_{sc}(\lambda) + I_K(\lambda_K)\delta(\lambda - \lambda_K)] .$$

(6)

Figure 3 shows the brightness spectrum corresponding to plate 1.

Discussion

We have computed x-ray intensities across the visible disc for three periods during which ROSAT observed Jupiter. Figure 4 shows the modeled 4-hour integrated brightnesses due to solar x-rays as well as the results of the ROSAT observations. The modeled and observed brightnesses are integrated across the disc for latitudes of absolute value less than 45°. Solar photon-driven emission arises primarily out of H₂ scattering (which is the major atmospheric species) and from carbon K-shell fluorescence (an effect of 8–12%). We note that the model produces the largest x-ray brightnesses at the sub-solar point with values as high as 0.03 R. A solar source might thus explain the correlation of peak x-ray emission with the bright visible limb [Gladstone et al., 1998] and with modeled solar activity (figure 4). However, the model predicts non-auroal luminosities of at most $3 \times 10^{10}$ W which are approximately an order of magnitude less than the power output derived from the observations. This model also cannot explain any dependence of the emissions on System III longitude. We conclude that solar x-ray scattering and fluorescence play a role complementary to that of high-energy ion precipitation in generating jovian non-auroal x-ray emission. In figure 3 we provide a typical spectrum for the solar-driven emission which may be tested against results from forthcoming CHANDRA observations.

Acknowledgments. ANM acknowledges the assistance of Rüdiger Lang and the hospitality of the Atmospheric Physics Kruislaan 71-591, 1995.


Acknowledgments. ANM acknowledges the assistance of Rüdiger Lang and the hospitality of the Atmospheric Photochemistry Group at FOM-Institute AMOLF. TEC acknowledges NASA Planetary Atmospheres grant NAG5-4358. The work of LWA has been supported by NASA contracts NAS8-37334 and NAS8-40801 with Marshall Space Flight Center.

References


\(^1\text{Rayleigh} = 10^6 \text{ ph cm}^{-2} \text{ s}^{-1} (4 \text{ sr})^{-1}.$