Available online at www.sciencedirect.com
ScienceDirect
Planetary and Space Science 55 (2007) 1126–1134
Planetary and Space Science
www.elsevier.com/locate/pss

Latest results on Jovian disk X-rays from *XMM-Newton*

G. Branduardi-Raymont[a,*], A. Bhardwaj[b], R.F. Elsner[c], G.R. Gladstone[d], G. Ramsay[a], P. Rodriguez[e], R. Soria[a], J.H. Waite Jr.[f], T.E. Cravens[g]

[a] *Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK*
[b] *Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum 695022, India*
[c] *NASA Marshall Space Flight Center, NSSTC/XD12, 320 Sparkman Drive, Huntsville, AL 35805, USA*
[d] *Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228, USA*
[e] *XMM-Newton SOC, Apartado 50727, Villafranca, 28080 Madrid, Spain*
[f] *University of Michigan, Space Research Building, 2455 Hayward, Ann Arbor, MI 48109, USA*
[g] *Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA*

Available online 19 January 2007

Abstract

We present the results of a spectral study of the soft X-ray emission (0.2–2.5 keV) from low-latitude ('disk') regions of Jupiter. The data were obtained during two observing campaigns with *XMM-Newton* in April and November 2003. While the level of the emission remained approximately the same between April and the first half of the November observation, the second part of the latter shows an enhancement by about 40% in the 0.2–2.5 keV flux. A very similar, and apparently correlated increase, in time and scale, was observed in the solar X-ray and EUV flux.

The months of October and November 2003 saw a period of particularly intense solar activity, which appears reflected in the behavior of the soft X-rays from Jupiter's disk. The X-ray spectra, from the *XMM-Newton* EPIC CCD cameras, are all well fitted by a coronal model with temperatures in the range 0.4–0.5 keV, with additional line emission from Mg XI (1.35 keV) and Si XIII (1.86 keV): these are characteristic lines of solar X-ray spectra at maximum activity and during flares.

The *XMM-Newton* observations lend further support to the theory that Jupiter's disk X-ray emission is controlled by the Sun, and may be produced in large part by scattering, elastic and fluorescent, of solar X-rays in the upper atmosphere of the planet.

Keywords: Planets; Jupiter; X-rays

1. Introduction

The current generation of X-ray observatories, with their greatly improved spatial resolution (*Chandra*) and sensitivity (*XMM-Newton*), coupled to moderate (CCD) to high (gratings) spectral resolution, have made it feasible for the first time to study solar system objects in detail. X-ray observations of planets, satellites and comets, coupled with solar X-ray studies and solar wind and magnetospheric measurements *in situ*, are being used to extend our understanding of the photon and particle processes taking place all over the solar system, of the interactions between the Sun and solar system bodies, and ultimately of the effects solar activity may have on our own Earth (for a review see Bhardwaj et al., 2006b, this issue).

Jupiter has a particularly complex magnetospheric environment, which is governed by the fast rotation of the giant planet, and by the presence of Io and its dense plasma torus. This made it an interesting target since the earliest attempts of solar system X-ray studies: Jupiter was first detected at X-ray energies with the *Einstein* observatory (Metzger et al., 1983); later studies with *ROSAT* (Waite et al., 1994, 1997) established the presence of two distinct types of X-ray emission from the planet: 'auroral', from regions near the magnetic poles, and 'disk' emission, from lower latitudes. The present paper focuses on the disk emission; recent detailed studies of the Jovian X-ray aurorae can be found in Branduardi-Raymont et al. (2004, 2006a, b) and Elsner et al. (2005), and references therein.

*Corresponding author.
E-mail address: gbr@mssl.ucl.ac.uk (G. Branduardi-Raymont).

0032-0633/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2006.11.017

The first attempt to explain the origin of Jupiter's disk emission (Waite et al., 1997) was based on energetic ion precipitation, the same mechanism invoked to account for the auroral emissions also seen by *ROSAT*. However, a general decrease in the overall X-ray brightness of Jupiter over the years 1994–1996 was found to be coincident with a similar decay in solar activity, as characterized by the solar 10.7 cm flux; the X-ray flux from the Jovian disk also revealed an interesting dependence on local time, with the X-ray bright limb coinciding with the bright visible limb (Gladstone et al., 1998). These two facts combined suggested that the planet's disk emission may be controlled by the Sun to some extent. Indeed, Maurellis et al. (2000) were able to demonstrate that scattering of solar X-rays in Jupiter's atmosphere may well play a role in generating its equatorial emission. They modelled this component of solar origin with a combination of elastic scattering by atmospheric neutrals, and, to a smaller degree, fluorescent scattering of C K-shell X-rays on methane molecules.

Chandra High Resolution Camera (HRC) observations of Jupiter in December 2000 (Gladstone et al., 2002) not only revealed surprising characteristics in its auroral emission, but also gave us the sharpest X-ray view of the planet yet, clearly separating the bright auroral and the essentially uniform disk emissions (see Figure 28 of Bhardwaj et al., 2006b, this issue). However, no information on the spectral characteristics of the emissions could be obtained from the HRC data. Jupiter was observed again in February 2003 with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS), and the HRC, and this time spectra were acquired of both auroral (Elsner et al., 2005) and disk (Bhardwaj et al., 2006a) emissions. Recently, Cravens et al. (2006) have produced calculations of the scattering albedo for soft X-rays from the outer planets and have compared them against the ACIS spectra of Jupiter's disk. The conclusion is that indeed the soft X-ray emissions of Jupiter (and Saturn) can largely be explained by scattering and fluorescence of solar X-rays.

A study of Jupiter's soft X-ray emission from the first *XMM-Newton* observation of the planet in April 2003 (Branduardi-Raymont et al., 2004) clearly demonstrated the different characteristics of the auroral and disk spectra: while charge exchange was found most likely to be responsible for the auroral soft X-ray production, a coronal (i.e. optically thin collisional plasma) model best fitted the disk emission, giving support to the solar X-ray scattering hypothesis. In the following we describe the results of a second *XMM-Newton* observation, carried out in November 2003 (a preliminary account of this can be found in Branduardi-Raymont et al., 2006a), and we compare them with those from a re-analysis of the April 2003 data.

2. *XMM-Newton* observations

XMM-Newton (Jansen et al., 2001) observed Jupiter for two consecutive spacecraft revolutions (0726 and 0727; a total of 245 ks) between 2003 November 25, 23:00 and November 29, 12:00, i.e. for more than twice the duration of the April 2003 observation (110 ks, Branduardi-Raymont et al., 2004). As on that occasion the EPIC-MOS (Turner et al., 2001) and -pn (Strüder et al., 2001) cameras (with a field of view of 30 arcmin diameter) were operated in full frame and large window mode, respectively, and the RGS instrument (den Herder et al., 2001) in spectroscopy. The filter wheel of the OM telescope (Mason et al., 2001) was kept in the blocked position because the optical brightness of Jupiter is above the safe limit for the instrument, so no OM data were collected; also to minimize the risk of optical contamination in the X-ray data the EPIC cameras were used with the thick filter. Jupiter's motion on the sky (11 and 16 arcsec/h in April and November 2003, respectively) required several pointing trims during the long observations so that the target would not move out of the cameras' central CCD chip, and to avoid worsening the RGS spectral resolution. During both observations the planet's path on the sky was roughly along the RGS dispersion direction, so that good separation of the two auroral spectra could be achieved. The planet's disk diameter was 38 arcsec in April and 36 arcsec in November 2003.

The data were processed and analyzed with the *XMM-Newton* Science Analysis Software (SAS) (see SAS User's Guide at http://xmm.vilspa.esa.es/external/xmm_user_support/documentation). Photons collected along Jupiter's path during the pointings were referred to the center of the planet's disk so that images, lightcurves and average spectra could be constructed in the planet's reference system. Exclusion of data affected by high particle background at the end of both spacecraft revolutions in November 2003 leaves a total of 210 ks of good quality data for analysis (this total was 80 ks in April 2003). Fig. 1 displays the 0.2–2.0 keV image of Jupiter obtained combining the November 2003 data for all *XMM-Newton* EPIC CCD cameras.

3. Temporal analysis

Unlike in April 2003 (Branduardi-Raymont et al., 2004), the EPIC lightcurve of X-ray events extracted from the equatorial regions of Jupiter in November 2003 presents evidence for variability, with a smooth visible increase in flux from beginning to end by ~40%. A similar increase is present in the solar EUV and X-ray fluxes over the same period (see Fig. 2, taken from Bhardwaj et al., 2005). Moreover, a large solar X-ray flare taking place on the Jupiter-facing side of the Sun (at 2.4 days into the observation; see Fig. 2, this paper, and Figure 30 of Bhardwaj et al., 2006b, this issue) appears to have a corresponding feature in the Jovian X-rays. Both these facts support the hypothesis that Jupiter's disk emission is predominantly scattered solar X-rays from the planet's upper atmosphere and that it is directly controlled by solar irradiation. It is interesting to note that the months of