Bull. Astr. Soc. India (2003) **31**, 159–166

X-ray Emissions from the Jovian System

Anil Bhardwaj*
Space Physics Laboratory, Vikram Sarabhai Space Center, Trivandrum 695 022

Abstract. X-ray emissions from Jupiter, discovered by Eisnsten observatory and followed up by ROSAT, have been thought to be excited by energetic and highly charged sulphur and oxygen ions precipitating from the inner magnetosphere into the planet's polar regions. However, recent observations by Chandra telescope have revealed surprising new results, including mysterious pulsating (period ~45 minutes) x-ray hot spot in the northern polar regions of Jupiter, that have called into question our understainding of Jovian auroral x-rays. Further, x-rays from the moons of Jupiter - Io, Europea, and probably Ganymede and from the Io plasma torus have been discovered by the Chandra observatory. This paper presents a brief review of the x-ray emissions from the Jupiter, the Galilean satellites and the Io plasma torus.

1. Introduction

Emissions from Jupiter, the largest planet of our solar system, have been studied at wide range of wavelengths, from x-rays to UV, visible, IR, and radio (e.g., Bhardwaj and Gladstone 2000, Bhardwaj 1997, Galand and Chakrabarti 2002; Waite and Lummerzheim 2002, Bhardwaj et al. 2002). The emissions at different wavelengths provide unique and complementary information about the key physical processes operating in the atmospheric and magnetospheric regions where they originate. In this paper we present an overview on the recent x-ray observations of the Jovian system, which include Jupiter, Galilean satellites, and Io plasma torus, and discuss the proposed emission production mechanisms.

2. Jupiter

Although the search for x-rays from Jupiter started in early 1960's (cf. Bhardwaj and Gladstone 2000), the first detection was made in 1979 by the satellite-based Einstein observatory (Metzger et al. 1983). The emissions were detected in the 0.2-3.0 keV energy range from both poles of

---

*email:bhardwaj_spl@yahoo.com

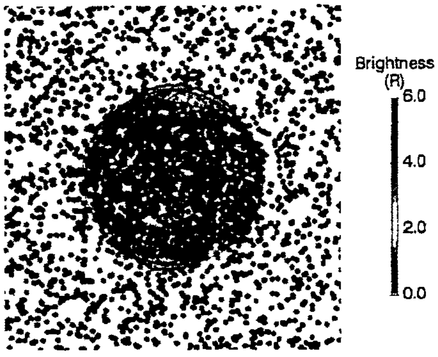

Figure 1. Chandra x-ray image of Jupiter on 18 December 2000 generated from 10 hours of continuous observations. A jovicentric graticule with 30° intervals is overplotted, along with the $L = 5.9$ and $L = 30$ footprints of the magnetic field model. The image shows strong auroral x-ray emissions from high latitudes and rather uniform emissions from the disk. [from Gladstone et al. 2002].

Jupiter. Analogous to the processes on Earth, it was expected that Jupiter's x-rays might originate as bremsstrahlung by precipitating electrons (Barbosa 1990). However, the power requirement for producing the observed emission with this mechanism (10^{15}–10^{16} W) is more than two orders of magnitude larger than the input auroral power available as derived from Voyager and IUE observations of the ultraviolet aurora (cf. Bhardwaj and Gladstone 2000). Metzger et al. (1983) suggested a mechanism implying K-shell line emissions from precipitating energetic sulfur and oxygen ions from the inner magnetosphere, with energies in the 0.3-4.0 MeV/nucleon range. The heavy ions are thought to emit x-rays by first charge stripping to a highly ionized state, followed by charge exchange and excitation through collisions with H_2. The bremsstrahlung process was further ruled out by theoretical models (Waite 1991, Singhal et al. 1992) showing that primary and secondary precipitating electrons in the 10-100 keV energy range are inefficient at producing the observed x-ray emissions (Bhardwaj et al. 2002).

Furthermore, during its Jovian flyby, the Ulysses spacecraft did not detect significant emissions in the 27-48 keV energy range (Hurley et al. 1993) as would have been the case if electron bremsstrahlung was a major process. Observations of Jupiter x-ray emissions by ROSAT (Waite et al. 1994) supported the suggestion of Metzger et al. (1983) and the model calculations (Waite 1991, Singhal et al. 1992) that precipitating energetic (> 700 keV per nucleion) S and O ions are most probably responsible for the x-ray emissions from Jupiter. A detailed modeling of the x-ray production (Cravens et al. 1995, Kharchenko et al. 1998, Lui and Shultz 1999) suggests that recombination lines from highly charged precipitating O and S ions mainly contribute to the soft x-rays detected by ROSAT.

Recent high-spatial resolution observations of Jupiter (Fig. 1) with the Chandra X-ray Observatory (CXO) (Gladstone et al. 2002) have revealed that most of Jupiter's northern auroral x-rays come from a 'hot spot' located significantly poleward of the latitudes connected to the inner magnetosphere (cf. Fig. 2). The hot spot is fixed in magnetic latitude (60-70°) and longitude (160-180°) and occurs in a region where anomalous infrared and ultraviolet emissions (the so-called "flares") have also been observed. Its location must connect along magnetic field lines to regions in the Jovian magnetosphere well in excess of 30 Jovian radii from the planent (cf. Fig. 1), a region where there are insufficient S and O ions to account for the hot spot (Gladstone et al. 2002). More surprising, the hot spot x-rays pulsate with an approximately 45-min period, similar to that reported for high-latitude radio and energetic electron bursts observed by near-Jupiter spacecraft (Gladstone et al. 2002).

These new and surprising results invalidate the idea that Jovian auroral x-ray emissions are mainly excited by steady precipitation of heavy energetic ions from the inner magnetosphere. Instead, the x-rays seem to result from currently unexplained processes in the outer magnetosphere that produce highly localized and highly variable emissions over an extemely wide range of wavelengths. In any case, the power needed to produce the brightest ultraviolet "flares" seen in the same polar cap regions as the x-ray hot spot is a few tens of TW, much less than the estimated power of a few PW needed to produce the observed x-rays by electron bremsstrahlung. Thus, electron bremsstrahlung still seems to fail in explaining the observed Jovian x-rays hot spot. One possible source of Jovian x-rays production is via charge-exchange of solar wind ions that penetrate down the atmosphere in the magnetic cusp region. But in this case the solar wind ions would have to be accelerated to much higher energies (100s of keV), probably by parallel electric field or wave particle interactions, to generate sufficient luminosity to account for the observations. In summary, at the present time the origin of the Jovian auroral x-rays and its source is still an open issue (Bhardwaj et al., 2002).

2.1 Non-Auroral Emissions

Soft x-ray emissions with brightnesses of about 0.01-0.2 Rayleighs were observed from the equatorial regions of Jupiter using the ROSAT/HRI (Waite et al. 1997). It was proposed that the equatorial emission, like the auroral emission, may be largely due to the precipitation energetic (> 300 keV/amu) sulfur or oxygen ions into the atmosphere from the radiation belts. Further evidence for a correlation between regions of low magnetic field strength and enhanced emission (Gladstone et al. 1998) lent additional support to this mechanism, since it can be assumed that the loss cone for precipitating particles is wider in regions of weak surface magnetic field. However, Maurellis et al. (2000) showed that two alternative mechanisms should not be overlooked in the search for a complete explanation of low-latitude x-ray emission, namely elastic scattering of solar x-rays by atmospheric neutrals and fluorescent scattering of carbon K-shell x-rays from methane molecules located below the Jovian homopause. Modeled brightnesses agree, up to a factor of two, with the bulk of low-latitude ROSAT/PSPC measurements that suggests that solar photon scattering (~90% elastic scattering) may act in conjunction with energetic heavy ion precipitation to generate Jovian non-auroral x-ray emission. The solar x-ray scattering mechanisms is also suggested from the correlations of Jovian emissions with the F10.7 solar flux and of the x-ray limb with the bright visible limb (Gladstone et al. 1998). During the Decenber 2000 observations by Chandra HRC-I, the disk-averaged emitted x-ray power was about 2 GW (Gladstone et al. 2002), but the

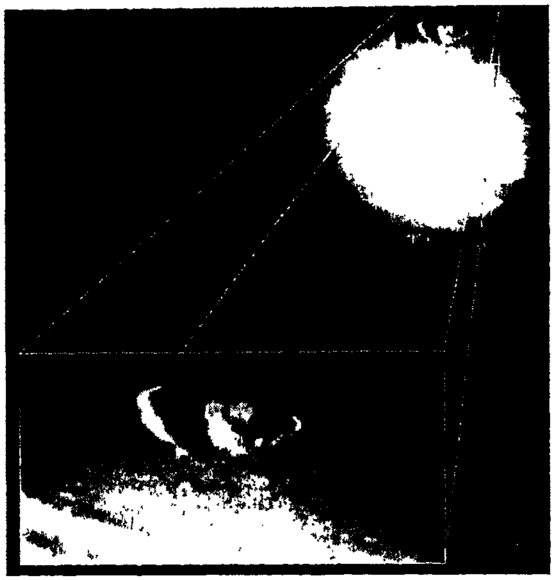

Figure 2. This composite image displays x-ray data from Chandra and ultraviolet data from Hubble Space Telescope overlaid on an optical image of Jupiter. While Chandra observed Jupiter for an entire 10-hour rotation period on December 18, 2000, this image shows a 'snapshot' of a single 45-minute X-ray pulse. [from http://chandra.harvard.edu/photo/2002/0001/ 0001_xray_opt_uv_zoom.jpeg].

signal-to-noise ratio of the disk emission was not adequate to show the limb brightening expected by solar photon-driven x-ray emission (Bhardwaj et al. 2002).

3. Galilean Satellites

Jupiter and its satellites constitute a miniature solar system. The inner four satellites - called Galilean satellites - are important among them. Recenlty the CXO has discovered (Elsner et al. 2002) x-ray emission from the Galilean satellites (cf. Fig. 3). The CXO observations of the Jovian system were made on 25-26 November 1999 for 86.4 ks with the ACIS-S instrument and on 18 Decenber 2000 for 36 ks with the HRC-I instruments. The time tagged nature of the CXO data makes it possible to correct for varying satellite motions, and with ACIS it is also possible to filter the data by energy for optimum sensitivity. During the ACIS-S observation, Io and Europa were detected with a high degree of confidence, and Ganymede at a lesser degree of confidence. Io was also detected with high confidence during the shorter HRC-I observation. Over the nominal energies of 300-1890 eV range detected by ACIS-S, the x-ray events show a clustering between 500 and 700 eV, probably dominated by the oxygen K_α line at 525 eV. The estimated energy fluxes at the telescope and power emitted are 4×10^{-16} erg cm^{-2} s^{-1} and 2.0

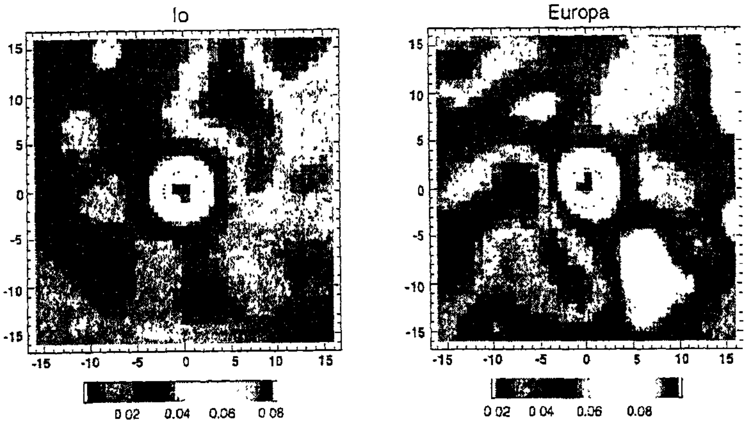

Figure 3. Chandra ACIS-I image (0.2-2 keV) of Io and Europa obtained on November 25-26, 1999. The solid circle shows the size of the satellite (the radii of Io and Europa are 1820 km and 1560 km, respectively), and the dotted circle the size of the detect cell. The axes are labeled in arcsec (1 arcsec ≈ 2995 km) and the scale bar is in units of smoothened counts per image pixel (0.492 by 0.492 arcsec). [from Elsner et al. 2002].

MW for Io, and 3×10^{-16} erg cm^{-2} s^{-1} and 1.5 MW for Europa. Ganymede was roughtly a third as luminous as Io. Callisto was not detected in either set of data.

The most plausible emission mechanism is inner (K shell) ionization of the surface (and perhaps incoming magnetospheric) atoms followed by prompt x-ray emission. Oxygen should be the dominant emitting atom in either a silicate or SO_2 surface (Io) or in an icy one (the outer Galilean satellites). It is also the most common heavy ion in the Jovian magnetosphere. The extremely tenuous atmospheres of the satellites are transparent to x-ray photons with these energies, and also to much of the energy range of the incoming particles (Michael and Bhardwaj, 2000). However, oxygen absorption of the 525 eV line is such that the x-rays must originate in the top ~10 microns of the surface in order to escape. Simple estimates suggest that excitation by incoming ions dominates over electrons and that the x-ray flux produced is sufficient to account for the observations.

Detailed models are required for verifying this picture and also for predicting the strengths of K_α lines for elements other than oxygen, especially heavier ones such as Na, Mg, Al, Si, and S. Within this framework, it is possible to constrain the surface composition of these moons from x-ray obsevations, but this requires a greater signal-to-noise ratio than provided by the Chandra observations. The detection of x-ray emission from the Galilean satellites thus provides a direct measure of the interactions of magnetosphere of Jupiter with the satellite surfaces.

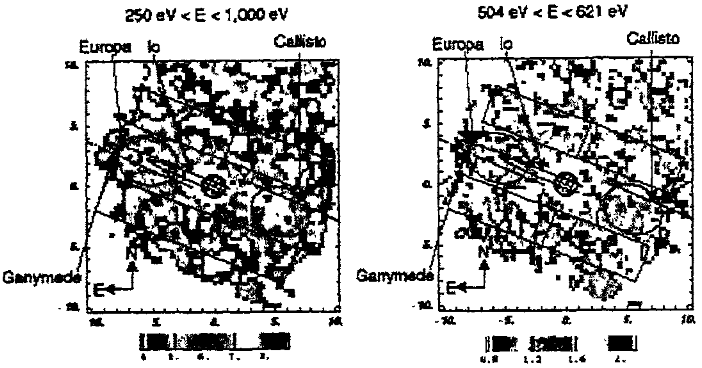

Figure 4. Chandra ACIS-I image of Io plasma torus obtained on November 25-26, 1999. The axes are labelled in units of Jupiter's radius, R_J and the scale bar is in units of smoothed counts per image pixel (7.38 by 7.38 arcsec). For this observation, Jupiter's radius corresponds to 23.8 arcsec. The paths traced by Io, Europa, Ganymede, and Callisto are marked on the image. The regions bounded by rectangles were used to determine background. The regions bounded by ellipses were defined as x-ray source regions. [from Elsner et al. 2002].

4. Io Plasma Torus

The Io Plasma Torus (IPT) is known to emit at EUV energies and below (e.g., Hall et al., 1994; Woodward et al., 1997; Gladstone and Hall, 1998), but it was a surprise when CXO discovered (Fig. 4) that it was also a soft x-ray source (Elsner et al. 2002). The Jovian system has so far been observed with Chandra using the ACIS-S high-spatial-resolution imaging camera, which also has modest energy resolution, for two Jovian rotations in November 1999, and using the HRC-I high-spatial-resolution camera, with essentially no energy resolution, for one rotation in December 2000. X-ray emission from the IPT is present in both observations. The ACIS-S spectrum was consistent with a steep power-law continuum (photon index 6.8) plus a gaussian line (complex) centered at ~569 eV, consistent with K_α emission from various charge species of oxygen. Essentially no x-rays were observed above this specral feature, consistent with the steepness of the power-law continuum. The 250-1000 eV energy flux at the telescope aperture was 2.4×10^{-14} erg cm^{-2} s^{-1}, corresponding to a luminosity of 0.12 GW, and was approximately evenly divided between the dawn and dusk side of Jupiter. However, the line emission originated predominantly on the dawn side. During the ACIS-S observation (cf. Fig. 4), Io Europa, and Ganymede were on the dawn side, while Callisto was on the dusk side. For the HRC-I obsevation, the x-ray emission was stronger on the dusk side, approximately twice that observed on the dawn side. During the HRC-I observation, Io, Europa, and Ganymede were on the dusk side, while Callisto was on the dawn side.

The physical origin of the x-ray emission from the IPT is not yet fully understood. According to the estimates given in Elsner et al. (2002), fluorescent x-ray emission excited by solar x-rays, even during flares from the active Sun, charge-exchange processes, previously invoked to explain Jupiter's x-ray aurora (e.g., Bhardwaj and Gladstone 2000, Cravens et al. 1995) and cometary x-ray emission (e.g., Cravens 2002), and ion stripping by dust grains fail to account for the observed emission. Assuming bremsstrahlung emission of soft x-rays by non-thermal electrons in the few hundred to few thousand eV range, with a kappa, or generalized Lorentzian, distribution with a temperature of 10 eV and an index of $\kappa = 2.4$ (Meyer-Vernet et al. 1995), which is consistent with the in-situ Ulysses observations, Elsner et al. (2002) estimated an IPT soft x-ray luminosity of 0.03 GW. This falls short of but is a significant fraction of the observed luminosity of 0.12 GW.

5. Summary

Observation of x-rays from planetary bodies is a useful diagnostic tool for remotely probing the physical conditions on them. From the discussion presented in previous sections it is clear that processes responsible for the production of x-rays from different objects in the Jovian system are yet to be delineated. Recent Jupiter x-ray observations carried out by our group in February 2003 using CXO's both HRC and ACIS instruments will help further in understand the physics of generation of x-rays on Jupiter. Moreover, observation of Saturn by Chandra and XMM-Newton would aid in appreciating the x-rays production mechanism on magnetic planets.

Acknowledgements

I thank my collaborators, in particular, Randy Gladstone, Ron Elsner, Hunter Waite, Martin Weisskopf, Denis Grodent, Tariq Majeed, John Clarke, Tom Cravens, Bob Howell, Al Metzger, Nick Ostgaard, Achil Maurellis, Bob Johnson, for keeping my enthusiasm in the area of planetary x-ray astronomy, and R. Sridharan for encouragement and support.

References

Barbosa, D.D. 1990, *J. Geophys. Res.*, 95, 14, 969.

Bhardwaj, A. 1997, Scientific Report SPL-SR-01-97, 65pp, SPL, VSS, Trivandrum.

Bhardwaj, A., and Gladstone, G.R. 2000, *Rev. Geophys.*, 38, 295.

Bhardwaj, A., Gladstone, G.R., Elsner, R.F., Waite, J.H., Grodent, D., Cravens, T.E., Howell, R.R., Metzger, A.E., Ostgaard, N., Maurellis, A.N., Johnson, R.E., Weisskopf, M.C., Majeed, T., Ford, P.G., Tennant, A.F., Clarke, J.T., Lewis, W.S., Hurley, K.C., Crary, F.J., Feigelson, E.D., Garmire, G.P., Young, D.T., Dougherty, M.K., Espinosa, S.A., Jahn, J.-M. 2002, *ESA SP-514*, 215.

Bhardwaj, A., Gladstone, R.G. and Zarka, P. 2001, *Adv. Space Res.*, 27, 1915.

Cravens, T.E. 2002, *Science*, 296, 1042.

Elsner, R.F., Gladstone, G.R., Waite, J.H., Jr., Crary, F.J., Howell, R.R., Johnson, R.E., Ford, P.G., Metzger, A.E., Hurley, K.C., Feigelson, E.D., Garmire, G.P., Bhardwaj, A., Grodent, D., Majeed, T., Tennant, A.F., Weisskopf, M.C. 2002, *Astrophys. J.*, 572, 1077.

Galand, M. and Chakrabarti, S. 2002, in *Atmospheres in the Solar Systems: Comparative Aeronomy, AGU Geophysical Monograph 130*, Eds. M. Mendillo et al., p. 115-139, AGU, Washington, DC.

Gladstone, G.R. and Hall, D.T. 1998, *J. Geophys. Res.*, 103, 19927.

Gladstone, G.R., Waite, J.H., Jr. and Lewis, W.S. 1998, *J. Geophys. Res.*, 103, 20083.

Gladstone, G.R., Waite, J.H., Jr. Grodent, D, Lewis, W.S., Crary, F.J., Elsner, R.F., Weisskopf, M.C., Majeed, T., Jahn, J.-M., Bhardwaj, A., Clarke, J.T., Young, D.T., Dougherty, M.K., Espinosa, S.A. and Cravens, T.E. 2002, *Nature*, 415, 1000.

Hall, D.T., et al. 1994, *Astrophys. J.*, 426, L51.

Hurley, K.C., Sommer, M. and Waite, J.H., Jr. 1993, *J. Geophys. Res.*, 98, 21217.

Kharchenko, V., Liu, W.H. and Dalgarno, A. 1998, *J. Geophys. Res.*, 103, 26687.

Lui, W. and Shultz, D.R., 1999, *Astrophys. J.*, 526, 538.

Maurellis, A.N., Cravens, T.W., Gladstone, G.R., Waite, J.H., Jr. and Acton, L. 2000, *Geophys. Res. Lett.*, 27, 1339.

Metzger, A.E., Gilman, D.A., Luthey, J.L., Hurley, K.C., Schnopper, H.W., Seward, F.D. and Sullivan, J.D. 1983, *J. Geophys. Res.*, 88, 7731.

Meyer-Vernet, N., Moncuquet, M. and Hoang, S. 1995, *Icarus*, 116, 202.

Michael, M. and Bhardwaj, A. 2000, *Geophys. Res. Letts.*, 27, 3137.

Singhal, R.P., Chakravarty, S.C., Bhardwaj, A. and Prasad, B. 1992, *J. Geophys. Res.*, 97, 18245.

Waite, J.H., Jr., Bagenal, F., Seward, F., Na, C., Gladstone, G.R., Cravens, T.E., Hurley, K.C., Clarke, J.T., Elsner, R. and Stern, S.A. 1994, *J. Geophys. Res.*, 99, 14799.

Waite, J.H., Jr. 1991, *J. Geophys. Res.*, 96, 19529.

Waite, J.H., Jr. Gladstone, G.R., Lewis, W.S., Drossart, P., Cravens, T.E., Maurellis, A.N., Mauk, B.H. and Miller, S. 1997, *Science*, 276, 104.

Waite, J.H., Jr., and Lummerzheim, D. 2002, in *Atmospheres in the Solar System: Comparative Aeronomy, AGU Geophysical Monograph 130*, Eds. M. Mendillo et al., p.115-139, AGU, Washington, DC.

Woodward, R.C., Scherb, F. and Roesler, F.L. 1997, *Astrophys. J.*, 479, 984.