A search for X-ray emission from Saturn, Uranus and Neptune

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Abstract. We present an analysis of X-ray observations of the trans-Jovian planets Saturn, Uranus and Neptune with the ROSAT PSPC in comparison with X-ray observations of Jupiter. For the first time a marginal X-ray detection of Saturn was found and 95% confidence upper limits for Uranus and Neptune were obtained. These upper limits show that Jupiter-like X-ray luminosities can be excluded for all three planets, while they are consistent assuming intrinsic Saturn-like X-ray luminosities. Similar X-ray production mechanisms on all trans-Jovian planets can therefore not be ruled out, and spectral shape and total luminosity observed from Saturn are consistent with thick-target bremsstrahlung caused by electron precipitation as occurring in auroral emission from the Earth.

Key words: planets and satellites: general – planets and satellites: individual: Neptune – planets and satellites: individual: Saturn – planets and satellites: individual: Uranus – X-rays: general

1. Introduction

X-ray emission from solar system objects has so far been detected from the Earth (Rugge et al. 1979; Fink et al. 1988), from the Moon (Schmitt et al. 1991), from several comets (e.g., Lisse et al. 1996; Mumma et al. 1997) and from Jupiter (e.g., Metzger et al. 1983). The observed X-ray emission seems to have different physical origins in the different objects. The principal X-ray production mechanism for Moon and Earth is reflection of solar X-rays; auroral X-ray emission has been found from the Earth and from Jupiter, and similar emission from the outer planets is anticipated.

Aurorae on Earth and Jupiter are generated by charged particles precipitating into the atmosphere along the magnetic field lines. While at Earth the precipitating flux consists of solar wind electrons, there is strong evidence from the *Einstein* observations (e.g., Metzger et al. 1983) that the Jovian X-rays are caused by heavy ion precipitation. Assuming energetic electron precipitation an input power of $\sim 10^{15}$ to $\sim 10^{16}$ W was estimated which seemed to be unreasonably large compared with

both the auroral input power calculated on the basis of the *Voyager* observations of the UV aurora ($\sim 10^{13} - 10^{14}$ W) and with the power estimated to be available in the magnetosphere through mass loading in the torus or pitch-angle scattering induced by wave-particle interactions. From this and from a direct observation of heavy ions in Jupiter's magnetosphere with the *Voyager* spacecraft, Metzger et al. (1983) concluded that heavy ion precipitation is a reasonable X-ray production process (for references, see Metzger et al. 1983). With the *Einstein Observatory* Imaging Proportional Counter (IPC) pulse height spectrum, both a continuous spectrum resulting from bremsstrahlung and a characteristic line emission spectrum from heavy ions, especially from oxygen and sulfur, are consistent. Because of this inability of the IPC to distinguish between continuous emission and line emission, the possibility that the Jovian X-ray emission is due to bremsstrahlung could not be ruled out, but a comparison of ROSAT observations in the soft X-ray spectrum with model-generated bremsstrahlung and line emission spectra strengthened the case for heavy ion precipitation (Waite et al. 1994).

X-ray emission from the other outer planets and especially from Saturn is expected because of the discovery of magnetospheres by the *Voyager* spacecraft (e.g. Opp 1980; Sandel et al. 1982) and the observation of auroral ultraviolet emission from Saturn at high latitude regions (Broadfoot et al. 1981), from Uranus (Herbert & Sandel 1989) near the poles and from Neptune (Broadfoot et al. 1989). Broadfoot et al. (1981) conclude from their UV observations that magnetotail activity on Saturn is more Earth-like and quite different from the dominant Io plasma torus mechanism on Jupiter. If energetic particles are responsible for the observed UV emission, associated X-ray emission is also expected.

On 1979 December 17 Saturn was observed with the *Einstein Observatory* IPC for 10,850 seconds, but no X-ray emission was detected, leading Gilman et al. (1986) to the conclusion that bremsstrahlung was the more likely X-ray production mechanism for Saturn. From this spectral assumption they calculated from the IPC observation a 3σ upper limit for the Saturnian X-ray flux at Earth of 1.7×10^{-13} erg cm^{-2} s^{-1}. This value has to be compared with an expected energy flux at Earth of 8×10^{-16} erg cm^{-2} s^{-1}, obtained from a model calculation (Gilman et al. 1986) based on UV observations (Sandel et al.

Table 1. Observational details for the outer planets

	Saturn	**Uranus**	**Neptune**	**Jupiter**
Obs_req_ID	900160	900130	900132	900013
Start_date	30Apr1992	04Apr1991	03Apr1991	23Apr1991
elapsed time[sec]	288960	867377	113915	189971
Obs_time[sec]	5349	10571	17563	5042
OBIs	3	7	8	8
Ang. diameter	$17''$	$3''$	$2''$	$38''$
distance from Earth[AU]	9.9	19.4	30.2	5.2
apparent motion	$8.8'$	$5.12'$	$39.7''$	$10.5'$
results				
soft band				
source counts+background	22	20	45	211
cts expected from backgr	7.6	21.6	41.4	8.32
probability for no source	1.7×10^{-5}	0.66	0.31	0
energy flux [erg cm^{-2} s^{-1}]	1.9×10^{-14}	–	–	2.9×10^{-13}
95% confidence upper limit				
[cts]	13	30	53	14
[erg cm^{-2} s^{-1}]	–	5.7×10^{-15}	4.7×10^{-15}	–
extrapolation from Jupiter				
[erg cm^{-2} s^{-1}]	8.0×10^{-14}	2.1×10^{-14}	8.6×10^{-15}	–
extrapolation from Saturn				
[erg cm^{-2} s^{-1}]	–	5.0×10^{-15}	2.1×10^{-15}	–
hard band				
source counts+background	4	25	18	49
cts expected from backgr	2.4	19.4	21.6	1.6
probability for no source	0.22	0.13	0.81	0
energy flux [erg cm^{-2} s^{-1}]	–	–	–	1.9×10^{-13}
95% confidence upper limit				
[cts]	6	28	30	5
[erg cm^{-2} s^{-1}]	1.3×10^{-14}	1.6×10^{-14}	1.4×10^{-14}	–

1982) and the assumption of thick-target bremsstrahlung at high latitudes.

With the ROSAT position sensitive proportional counter (PSPC) a more sensitive soft X-Ray observation of Saturn as well as the first X-ray observations of Uranus and Neptune have been carried out. The purpose of this paper is to present and to analyze these data.

2. Observation and analysis

The outer planets Saturn, Uranus and Neptune were observed with the ROSAT PSPC in the pointing mode. Details of the observations such as date, elapsed time, ROSAT sequence numbers, number of observation intervals (OBI), apparent angular size, distance from Earth and other relevant items are summarized in Table 1; for purposes of comparison we also analyzed and list a ROSAT PSPC observation of Jupiter, discussed in detail by Waite et al. (1994).

As can be seen from Table 1, the largest of the planets targeted in these observations, Saturn, had an apparent size of $17''$ at the time of the observation. Since this is still small compared to the ROSAT PSPC point spread function (50% encircled energy is contained within radius of $22''$ for angles up to

$10'$ with respect to the optical axis), we will treat the data as emission from point sources. As can be further seen from Table 1, the elapsed time of the PSPC observations was quite long leading to significant motions of the planets during that period. The ROSAT standard data processing provides the position of each recorded photon with respect to a fixed reference frame. Since the PSPC is photon counting, we know the arrival time for each recorded photon. The planet ephemeris are also known as a function of time, and therefore, we can calculate the position shifts $\Delta\alpha$ and $\Delta\delta$ to all photons required to correct for the planetary motion. This procedure combines all planetary photons into a point source, while photons from sources with fixed celestial positions will yield multiple sources reflecting the planetary motions. The thus transformed images were analyzed in the soft energy range taking counts in the amplitude channel range from channel 10 to 60 ($\sim 0.1 - 0.55$ keV) and in the hard energy range with channels from 61 to 160($\sim 0.55 - 1.6$ keV). From the count rate we calculated the energy flux using a conversion factor of 6×10^{-12} erg cm^{-2} cts^{-1} for the soft band and 2×10^{-11} erg cm^{-2} cts^{-1} for the hard band. The analysis was carried out in two different ways. The first method simply consists of placing a square box on the planet's position and comparing the source box counts with the background counts

determined from a much larger box placed in the vicinity of the source box but containing no sources. For practical purposes we treat Saturn as a point source, since resolving $17''$ requires an extremely high signal to noise ratio. In order to pick up as many source counts as possible while keeping the background low, we choose a box size of $1.5' \times 1.5'$. For the soft X-ray range this source box contains 83.6% of all source photons. This was empirically determined from the supersoft white dwarf HZ43; the energy fluxes given in Table 1 for the soft energy range are corrected by this value. In the soft energy range we thus have an expected source box count of 7.6 ± 0.1 at the position of Saturn from background alone, but we find 22 counts, concentrated towards the center of the source box as expected for a point-like source. The probability of measuring 22 counts or more with only 7.6 counts are expected is 1.7×10^{-5}, assuming Poisson statistics. The corresponding numbers in the hard energy range are 2.4 ± 0.1 expected counts with 4 counts actually recorded. The probability for measuring at least four counts assuming no source is 22%. Clearly, the signal recorded in the hard band is consistent with a background fluctuation, while in the soft band a significant excess is seen. These numbers are recorded in Table 1 for all target planets (as well as Jupiter) for both the soft and hard energy band.

Our second approach consists of applying the maximum likelihood detection technique described by Cruddace et al. (1988) to the transformed images. This procedure results in a source existence maximum likelihood of 3.1 at Saturn's position for the soft energy range and again no detection in the hard energy range. Clearly, the source existence likelihood is low. In judging the significance level one must however keep in mind that X-ray emission was searched for at only one position. A confirmation of this detection by another satellite measurement thus is highly desirable. Accepting for the time being the ROSAT detection of Saturn as real, we find a count rate of 2.7×10^{-3} cts/s which corresponds to an incident energy flux of 1.9×10^{-14} erg cm^{-2} s^{-1}.

It is obvious from Table 1 that no detections of Uranus nor Neptune have been obtained. From the computed 95% confidence count upper limits we calculated flux upper limits in the soft and hard energy bands, which are also listed in Table 1.

3. Discussion

Our analysis of the ROSAT PSPC data on trans-Jovian planets yields a marginal X-ray detection of Saturn, while only upper limits could be obtained for Uranus and Neptune. These upper limits are sensitive in the sense that X-ray emission at the level of Jupiter from Uranus and Neptune would have been detected. However, the upper limits are consistent assuming intrinsic Saturn-like X-ray luminosities for Uranus and Neptune. Therefore, similar X-ray production mechanisms on all trans-Jovian planets can certainly not be ruled out from the currently available observations. On the other hand, it also appears that Jupiter is rather unique with regard to its X-ray luminosity (Gilman et al. 1986; Waite et al. 1994). A possible explanation for the X-ray production on the trans-Jovian planets is thick-

Table 2. Comparison of *Einstein* and ROSAT observations of Saturn

	Flux [erg cm^{-2} s^{-1}]
Einstein observation	
3σ upper limit for	
Bremsstrahlung mechanism	1.7×10^{-13}
same process as Jupiter	5×10^{-13}
model calculation by	
Gilman et al. (1986)	8×10^{-16}
our result from ROSAT	1.9×10^{-14}

target bremsstrahlung caused by electron precipitation, i.e., the process which is also responsible for the generation of aurorae on the Earth. Gilman et al. (1986) (cf. Table 2) expect an X-ray flux from Saturn of 8×10^{-16} erg cm^{-2} s^{-1} from thick-target bremsstrahlung, based on the observed UV-flux and the assumption of a power-law electron distribution function. An even lower value is however obtained from the measured electron flux in Saturn's outer magnetosphere with the *Voyager* spacecraft, assuming, at high energies, an exponential in electron speed (Barbosa 1990). Saturn's energy flux obtained from our PSPC observation exceeds these expected fluxes by more than one order of magnitude. This might be either due to an elevated electron flux at the time of the observation or to other X-ray production mechanisms in addition to bremsstrahlung. Since the Saturnian system does not contain a volcanically active moon like Io, for example, it is unclear how heavy ions can be efficiently inserted into Saturn's magnetosphere.

Support for the assumption of thick-target bremsstrahlung comes from the observed spectral signatures of the X-ray detection of Saturn, which was detected only in the soft energy band (cf. Table 1) as well as from a comparison of aurorae on Earth observed with the very same instrument, i.e., the ROSAT PSPC, with which Saturn was observed and analyzed also in the soft energy band. Freyberg (1994) discusses a number of PSPC observations which show a strong enhancement in the diffuse background count rate and which can be traced back to auroral activity and/or geomagnetic storms. The relevant data are summarized in Table 3. A specific example is the ROSAT observation CA150057, which showed a significantly enhanced background (almost exclusively in the soft energy band) in one observation interval when ROSAT traversed the region south of Greenland. This elevation in count rate is interpreted as auroral X-ray emission due to bremsstrahlung at the Earth's atmosphere near the northern radiation belt. An even more extreme case is the ROSAT PSPC observation WG700232 during which an intense geomagnetic storm took place. In the 27th observation interval of this specific data set the PSPC count rate rose up to a value of more than 2300 counts per second when the PSPC was turned off and went in safe mode; also in this case the count rate was highly time variable and consisted of very soft photons. In both cases we can determine the observed PSPC intensity (in units of counts/sec/arcsec^2) by subtracting the observed background from observation intervals unaffected by auroral emission; the results are listed in Table 3.

Table 3. Comparison of auroral X-ray emission from Earth (Freyberg 1994) and from Saturn (soft band).

	CA150057	WG700232	Saturn
Countrate+backgr [cts sec^{-1}]	75.11	>2300	$4.1 \cdot 10^{-3}$
backgr [cts sec^{-1}]	13.58	28	$1.4 \cdot 10^{-3}$
area [arcsec^2]	$4.1 \cdot 10^7$	$4.1 \cdot 10^7$	227
intensity [cts sec^{-1} arcsec^{-2}]	$1.5 \cdot 10^{-6}$	$> 5.6 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$

A comparison of the observed PSPC intensities of aurorae on Earth in the soft energy band with that of Saturn shows that the former reach values that can easily account for the observed emission from Saturn. Note in particular that the X-ray emission during a geomagnetic storm may be much higher. If therefore – as appears likely – the X-ray emission from Saturn is restricted to its auroral belts, the resulting X-ray intensities may still be in the range of X-ray intensities observed in geomagnetic storms on Earth.

In summary, we can state that Jupiter's X-ray emission among the solar system planets appears unique in terms of total luminosity and possibly also in terms of spectral shape. No other planet has an intrinsic X-ray luminosity as high as Jupiter, and furthermore, Waite et al. (1994) suggest that its X-ray emission seems to be dominated by lines rather than continuum emission. The obtained X-ray detection of Saturn appears to be consistent both in strength and spectral shape with thick-target bremsstrahlung as occurring in auroral emission on Earth, but the observed luminosity implies rather high electron fluxes. It is clearly highly desirable to obtain a high angular resolution X-ray image of Saturn in order to confirm, first, the X-ray detection obtained with the ROSAT PSPC and, second, to study the spatial distribution of the X-ray emission on Saturn's surface, which is expected to be concentrated in Saturn's auroral belts.

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