X-RAY EMISSION FROM PLANETS AND COMETS: RELATIONSHIP WITH SOLAR X-RAYS AND SOLAR WIND

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Scattering of solar X-ray radiation mainly produces the non-auroral X-ray emissions from Jupiter, Saturn, and Earth, those from the disk of Mars, Venus, and Moon, and from the rings of Saturn. Recently X-ray flares are observed from the low-latitude disk of giant planets Jupiter and Saturn in the energy range of 0.2-2 keV. These flares are found to occur in tandem with the occurrence of solar X-ray flare, when light travel time delay is accounted, suggesting that X-rays from these planets can be used to study flaring on the hemisphere of the Sun invisible to near-Earth space weather satellites. Also by proper modeling of the observed planetary X-rays the solar soft X-ray flux can be derived. X-ray flares are also observed recently from Mars in direct response to solar flares. The X-ray emission from comets, the heliosphere, the geocorona, and the Martian and Venusian halo are all largely driven by charge exchange collision between highly ionized minor heavy ions in the solar wind and gaseous neutral species in the bodies' atmosphere or exosphere – a process known as solar wind charge exchange (SWCX). In particular, the cometary X-ray spectrum can be used to derive abundances of high-charge state ions of O, C, Ne as well as the speed of the solar wind. Thus cometary X-rays can provide a diagnostic of the solar wind properties even at far off distances from the Earth. This paper provides a brief overview of X-rays from some of the solar system bodies and their connection with solar X-rays and solar wind, and how planetary and cometary X-rays can be used to study the solar X-ray radiation and solar wind properties.

1. INTRODUCTION

X-rays are generally associated with high temperature phenomena, such as hot plasmas of 1-100 million degree K and above in solar and stellar coronae and other astrophysical objects. However, in the solar system, other than the Sun, we observe X-rays from bodies that are much colder (temperatures below 1000 K). This makes the field of planetary X-rays an interesting discipline, where X-rays are produced from a wide variety of phenomena and under a broad range of conditions (Bhardwaj et al., 2007, Bhardwaj and Lisse, 2007).

With the advent of sophisticated X-ray observatories, viz., Chandra and XMM-Newton, the field of planetary X-ray astronomy is advancing at a faster pace. Several new solar system objects are now known to shine in X-rays at energies generally below 2 keV. Apart from the Sun, the known X-ray emitters now include the planets – Venus, Earth, Mars, Jupiter, and Saturn; the planetary satellites – Moon, Io, Europa, and Ganymede; all active comets, the Io plasma torus, the rings of Saturn, corona (exosphere) of Earth, Mars and Venus, and the heliosphere.

In this paper we will briefly describe, using examples, how planetary X-rays are directly related to electromagnetic radiation and particle flux from the Sun (i.e., solar X-rays and solar wind) and what we can learn about solar radiation using X-rays from the solar system bodies.

2. JUPITER

X-ray emission from Jupiter is the brightest among planetary bodies in the solar system (Bhardwaj and Gladstone, 2000; Bhardwaj et al., 2002, 2007). Jovian X-rays are basically of two types: 1) the "auroral" emissions, which are confined to high-latitudes (~>60°) in both polar regions, and 2) the "dayglow" emissions, which are from the low-latitude

(~<50°) regions of the disk (Bhardwaj, 2006). (Henceforth, we define X-rays from the low-latitude regions of planet as "disk" emissions.)

During November 26 to 29, 2003, XMM-Newton observed soft (0.2–2 keV) X-ray emissions from Jupiter for 59 hours (6 Jupiter rotations). Bhardwaj et al. (2005a) found that the day-to-day variability in Jovian low-latitude disk X-rays was synchronized with solar X-ray emissions measured by the Earth-orbiting TIMED/SEE and GOES satellites. A moderate (C4-class) solar X-ray flare occurring on the Jupiter-facing side of the Sun was found to have a corresponding time-matching feature in the Jovian disk X-rays (cf. Fig. 1), after accounting for photon travel time delays. This is the *first* direct evidence that demonstrated that the Sun controls the X-ray emission from Jupiter's disk.

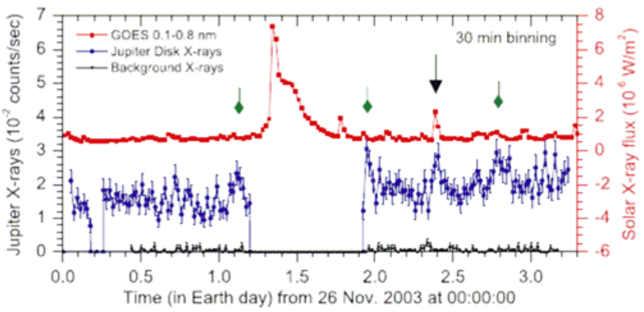

Fig. 1. Comparison of 30-min binned Jupiter disk X rays (blue curve) with GOES 10 0.1–0.8 nm solar X-ray data (red curve). The light curve of background X-rays is shown in black. The Jovian X-ray time is shifted by -4948 s to account for light travel time delay between Sun-Jupiter-Earth and Sun-Earth. The small gap at ~0.2 days is due to a loss of telemetry from XMM-Newton, and the gap between 1.2 and 1.9 days is caused by the satellite perigee passage. The black arrow (at 2.4 days) refers to the time of the largest solar flare visible from both, Earth and Jupiter, during the XMM-Newton observation, which has a clear matching peak in the Jovian light curve. The green arrows represent times when the Jupiter light curve shows peaks, which we suggest correspond to solar flares that occurred on the western (Earth-hidden) side of the Sun. The phase angle (Sun-Jupiter-Earth angle) of the observations was 10.3°, and the solar elongation (Sun-Earth-Jupiter angle) was between 76.7° and 79.8° during the observation. [From Bhardwaj et al., 2005a].

The XMM-Newton's EPIC soft (0.2–2.0 keV) X-ray image of Jupiter shows a relatively uniform intensity disk that is consistent with that expected for scattered solar X-rays and is in agreement with Chandra observations (Bhardwaj et al., 2006). The EPIC-measured disk X-ray brightness is 0.08 R, which is in agreement with the model calculations based on scattering of solar X rays from Jupiter's upper atmosphere (Cravens et al. 2006). This study suggests that Jupiter's upper atmosphere acts like a "cloudy-mirror" for solar X-rays – scattering back one in few thousand solar photons – enabling Jupiter's disk to shine in soft X-rays.

The correlation between Jupiter disk X-rays and solar X-rays, first found in the XMM-Newton Nov. 2003 observations, have also been seen in Chandra observations of Jupiter during Dec. 2000 and Feb 2003 (Bhardwaj et al., 2006). Thus, Chandra observations further strengthen the finding first reported by XMM-Newton observations (Bhardwaj et al. 2005a).

3. SATURN

The X-ray emission from Saturn was unambiguously detected by XMM-Newton in October 2002 and by Chandra in April 2003 (Ness et al., 2004). X-rays were detected mainly from the low-latitude disk and no clear indication of auroral X-rays was observed (Bhardwaj et al., 2005b, 2007; Bhardwaj, 2006).

In January 2004, Saturn was observed by the Advanced CCD Imaging Spectrometer (ACIS) of the Chandra X-Ray Observatory in two exposures, 00:06–11:00 UT on January 20 and 14:32 UT on January 26 to 01:13 UT on January 27. Bhardwaj et al. (2005b) detected the *first* X-ray flare from Saturn's non-auroral (low-latitude) disk in the energy range 0.2–2.0 keV, which is seen in direct response to an M6-class flare emanating from a sunspot that was clearly visible from both Saturn and Earth (cf. Fig. 2). Saturn's disk X-ray emissions are found to be variable on time scales of hours to weeks to months. This study establishes that disk X-ray emissions from Saturn are directly regulated by processes happening on the Sun. But unlike Jupiter, X-rays from Saturn's polar (auroral) region appear to have characteristics similar to those from its low-latitude disk and they vary in brightness inversely to the FUV aurora observed by the Hubble Space Telescope (Bhardwaj et al., 2005b).

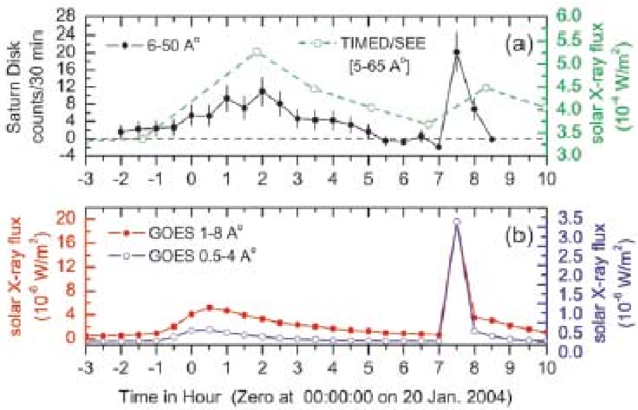

Fig. 2. Light curve of X-rays from Saturn and the Sun on 20 January 2004. All data are binned in 30 minute increments, except for the TIMED/SEE data, which are 3 minute observation-averaged fluxes obtained every orbit (~12 measurements per day). **(a)** Background-subtracted low-latitude (non-auroral) Saturn disk X-rays (0.24–2.0 keV) observed by Chandra ACIS, plotted in black (after shifting by -2.236 hr to account for the light-travel time difference between Sun-Saturn-Earth and Sun-Earth). The solar 0.2–2.5 keV fluxes measured by TIMED/SEE are denoted by open green circles and are joined by the green dashed line for visualization purpose. **(b)** Solar X-ray flux in the 1.6–12.4 and 3.1–24.8 keV bands measured by the Earth-orbiting GOES-12 satellite. A sharp peak in the light curve of Saturn's disk X-ray flux—an X-ray flare—is observed at about 7.5 hr, which corresponds in time and magnitude with an X-ray solar flare. In addition, the temporal variation in Saturn's disk X-ray flux during the time period prior to the flare is similar to that seen in the solar X-ray flux. [From Bhardwaj et al., 2005b].

These observations suggest that Saturn's disk X-ray emissions, like those at Jupiter (Bhardwaj et al. 2005a), are solar X-rays scattered and fluoresced from the planet's upper atmosphere. However, not all the incident solar X-rays in the 6–50 Å band are scattered: the calculated X-ray albedo of Saturn over this wavelength band is ~7 x 10^{-4}. The observationally derived albedo of Saturn is slightly larger than that of Jupiter (Bhardwaj et al. 2005a). This is consistent with the model of Cravens et al. (2006) and is due to higher abundance of He on Jupiter relative to that on Saturn (the He absorption cross section exceeds the hydrogen absorption cross section).

A further demonstration of a relationship between X-rays from Saturn and the solar radiation can be seen in Figure 3 where the emitted power in X-rays by Saturn's entire disk for all the observations, whose results are reported so far, is plotted as a function of solar 10.7 cm fluxes at 1 AU. X-ray fluxes measured by Chandra, XMM-Newton, and ROSAT X-ray observatories are converted to emitted power (cf. Bhardwaj et al. 2005b for details). The solar 10.7 cm flux has been used as a proxy for the activity of the Sun. The linear relationship between these two parameters adds credence to the conclusion that the Sun directly controls and regulates the X-ray emissions from Saturn.

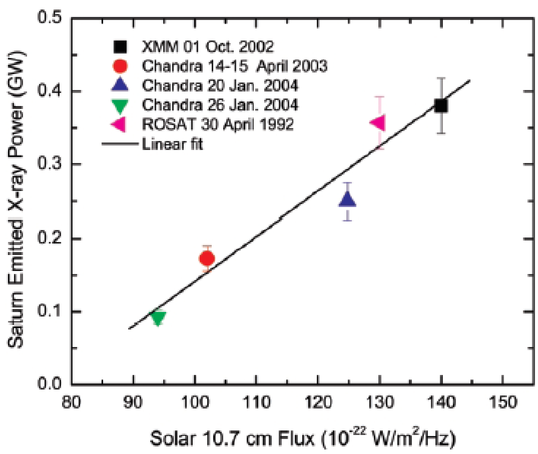

Fig. 3. X-ray power emitted from Saturn's disk plotted against the value of the solar 10.7 cm flux on the day of observation. X-ray fluxes measured by Chandra, XMM-Newton, and ROSAT X-ray observatories are converted to emitted power (see Bhardwaj et al. 2005b). A uniform 10% error bar is shown for all observations. The energy fluxes for Chandra and XMM-Newton observations are for a similar energy range of ~0.2–2.0 keV, while for the *ROSAT* observation it is 0.1–0.55 keV. The solid black line shows a linear fit to the emitted power. The correlation in the X-ray power emitted from Saturn's disk with the solar 10.7 cm flux suggests that the two parameters are closely related and implies that X-ray emission from the Saturn disk is primarily controlled by solar radiation. [From Bhardwaj et al., 2005b].

4. COMETS

The discovery of high-energy X-ray emission in 1996 from comet C/1996 B2 Hyakutake has created a new class of X-ray emitting objects (Lisse et al. 1996). Observations since 1996 have shown that the very soft (E < 1 keV) emission is due to an interaction between the solar wind and the comet's atmosphere, and that X-ray emission is a fundamental property of comets. Theoretical and observational work has demonstrated that a charge exchange collision of highly charged solar wind ions with cometary neutral species is the best explanation for the emission. Now a rapidly changing and expanding field, the study of cometary X-ray emission appears to be able to lead us to a better understanding of a number of physical phenomena: the nature of the cometary coma, other sources of X-ray emission in the solar system, the structure of the solar wind in the heliosphere, and the source of the local soft X-ray background (Bhardwaj et al., 2007).

Fig. 4 demonstrates the strong correlation found between the time histories of the solar wind proton flux (a proxy for the solar wind minor ion flux), the solar wind magnetic field intensity, and a comet’s X-ray emission, for the case of comet 2P/Encke 1997 (Lisse et al. 1999). Neugebauer et al. (2000) compared the ROSAT and EUVE luminosity of C/1996 B2 (Hyakutake) with time histories of the solar wind proton flux, oxygen ion flux, and solar X-ray flux, as measured by spacecraft residing in the solar wind. They found the strongest correlation between the cometary emission and the solar wind oxygen ion flux, a good correlation between the comet’s emission and the solar wind proton flux, but no correlation between the cometary emission and the solar X-ray flux.

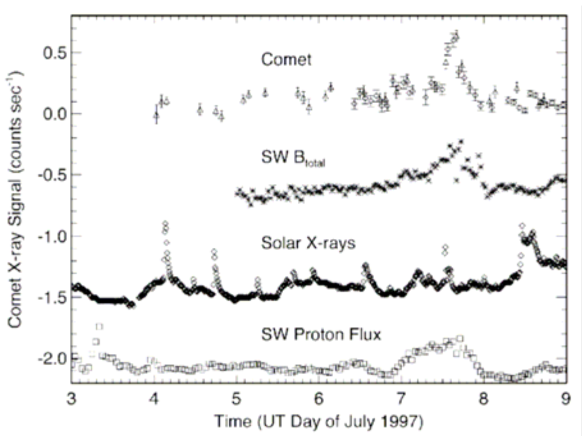

Fig 4. Temporal trends of the cometary X-ray emission. Lightcurves of solar wind magnetic field strength, solar wind proton flux, and solar X-ray emission for comet 2P/Encke 1997 on 4 to 9 July 1997 UT. All error bars are ± 1σ. Δ - HRI light curve, 4 to 8 July 1997. ◊ - EUVE scanner Lexan B light curve 6 to 8 July 1997 UT, taken contemporaneously with the HRI observations, and scaled by a factor of 1.2. Also plotted are the WIND total magnetic field B_{total} (*), the SOHO CELIAS/SEM 1.0-500 Å solar X-ray flux (◊), and the SOHO CELIAS solar wind proton flux (boxes). There is a strong correlation between the solar wind magnetic field/density and the comet's emission. There is no direct correlation between outbursts of solar X-rays and the comet's outbursts. [From Lisse et al., 1997].

For the 4 comets for which extended X-ray lightcurves were obtained during quiet Sun conditions, the time delay between the solar wind proton flux and the comet's X-ray impulse was well predicted by assuming a simple latitude independent solar wind flow, a quadrupole solar magnetic field, and propagation of the sector boundaries radially at the speed of the solar wind, and azimuthally with period one half of the solar rotation period of 28 days (Lisse et al. 1997, 1999; Neugebauer et al. 2000). From a recent observation of comet 2P/Encke 2003, which was a relatively low-activity comet, the X-ray lightcurve has provided the rotation period of the comet nucleus (Lisse et al., 2005).

5. MARS

X-rays from Mars were detected for the first time on 4 July 2001 (Dennerl, 2002). The observation was performed with the ACIS-I detector onboard Chandra. The computer simulations by Dennerl (2002) showed that scattering of solar X-rays is most efficient between 110 km (along the subsolar direction) and 136 km (along the terminator). This behaviour is similar to Venus, where the volume emissivity was found to peak between 122 km and 135 km (Dennerl et al. 2002). The most exciting feature about X-rays from Mars, however, is the gradual decrease of the X-ray surface brightness between 1 and ~3 Mars radii. The statistical significance of this halo (exospheric) emission, however, was based on an excess of only 35 photons relative to the background and thus the inference was only marginal.

The situation improved considerably with the first observation of Mars with XMM-Newton during November 19-21, 2003. This observation definitively confirmed the presence of the Martian X-ray halo and made a detailed analysis of its spectral, spatial, and temporal properties possible. High resolution spectroscopy of the halo with the Reflection Grating Spectrometer (RGS) (Dennerl et al., 2006) revealed the presence of numerous (~12) emission lines at the positions expected for de-excitation of highly ionized C, N, O, and Ne atoms, strongly resembling a cometary X-ray spectrum. The He-like O^{6+} multiplet was resolved and found to be dominated by the spin–forbidden magnetic dipole transition $2\ ^3S_1 \rightarrow 1\ ^1S_0$, confirming charge exchange as the origin of the emission. Thus, this was the *first* definite detection of charge exchange induced X-ray emission from the exosphere of another planet, providing a direct link to cometary X-ray emission.

In addition to these new results about the Martian X-ray halo emission, the XMM–Newton observation confirmed that the X-ray radiation from Mars itself is mainly caused by fluorescent scattering of solar X-rays: close to Mars, the RGS spectrum was dominated by fluorescence from CO_2. Fluorescence from N_2 was also observed. XMM–Newton RGS resolved fine structure in the oxygen fluorescence, which was found to consist of two components of similar flux, resulting from a superposition of several electron transitions in the CO_2 molecule (Dennerl et al., 2006). Further support for the interpretation that the X-rays from Mars itself are caused by fluorescent scattering of solar X-rays comes from the fact that the temporal behaviour of this radiation is well correlated with the solar X-ray flux (Dennerl et al., 2007). Also the Martian X–ray halo exhibited pronounced variability, but, as expected for solar wind interactions, the variability of the halo did not show any correlation with the solar X-ray flux (Dennerl et al., 2007).

6. EARTH

The non-auroral X-ray background above 2 keV from the Earth is almost completely negligible except for brief periods during major solar flares (Petrinec et al., 2000). However, at energies below 2 keV soft X-rays from the sunlit Earth's atmosphere have been observed even during quite (non-flaring) Sun conditions (e.g., McKenzie et al., 1982; Fink et al., 1988; Snowden and Freyberg, 1993). The two primary mechanisms for the production of X-rays from the sunlit atmosphere are: 1) the Thomson (coherent) scattering of solar X-rays from the electrons in the atomic and molecular constituents of the atmosphere, and 2) the absorption of incident solar X-rays followed by the emission of characteristic K lines of Nitrogen, Oxygen, and Argon.

Figure 5 shows images of the Earth taken from the PIXIE (Polar Ionospheric X-ray Imaging Experiment) instrument on board the NASA/GGS Polar spacecraft, demonstrating X-ray (2.9-10 keV) production in the sunlit atmosphere during solar flares on August 17 and November 23, 1998. During flares, solar X-rays light up the sunlit side of the Earth by Thomson scattering, as well as by fluorescence of atmospheric Ar to produce characteristic X-rays at 3 keV, which can be observed by the PIXIE camera.

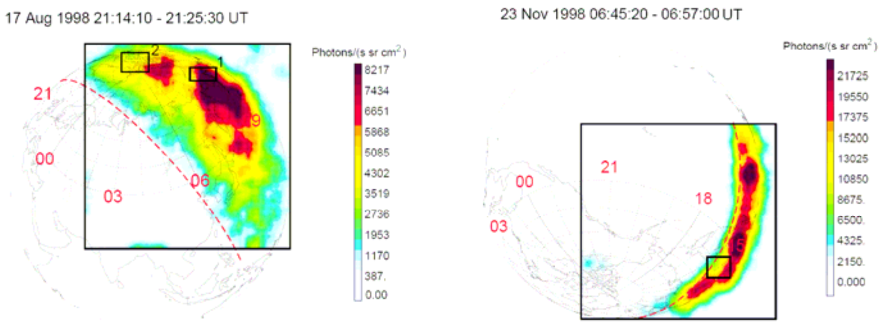

Fig. 5. X-ray images of Earth from the Polar PIXIE instrument for energy range 2.9-10.1 keV obtained on August 17, 1998 (left) and Nov. 23, 1998 (right), showing the dayside X rays during a solar X-ray flare. The grid in the picture is in corrected geomagnetic coordinates, and the numbers shown in red are magnetic local time. The terminator at the surface of the Earth is shown as a red dashed line. [From Petrinec et al., 2000].

Figure 6 shows the lightcurves of solar X-rays as observed by GOES and Earth sunlit X-rays as observed by PIXIE/Polar. A sharp rise in the Earth X-ray emission at the time of the occurrence of a strong solar

X-ray flare (X-class) is clearly seen from this figure. The X-ray brightness can be comparable to that of a moderate aurora. Petrinec et al. (2000) examined the X-ray spectra from PIXIE for two solar flare events during 1998. They showed that the shape of the measured X-ray spectra was in fairly good agreement with modeled spectra of solar X-rays subject to Thomson scattering and Argon fluorescence in the Earth's atmosphere.

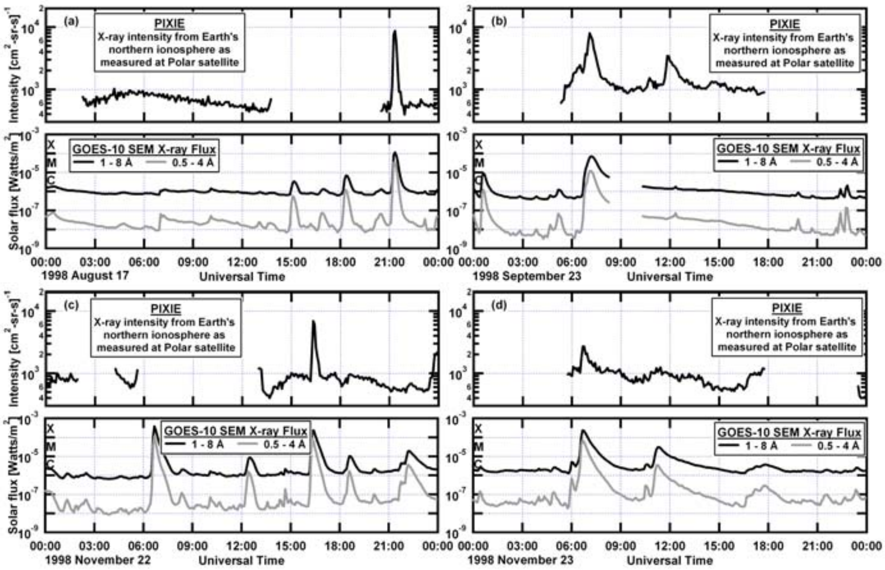

Fig. 6. **(a)** 17 August 1998. A sudden increase and subsequent decrease in X-ray intensity was observed shortly after 21 UT while the PIXIE instrument was observing the Earth's northern hemisphere. This spike in X-ray intensity coincided with an X1 solar X-ray flare, as measured by GOES-10. **(b)** 23 September 1998. The occurrence of an M7 solar flare at ~07 UT resulted in a sudden increase and decrease in X-ray albedo at the Earth. A later increase in X-ray emissions from the Earth's ionosphere (shortly before 12 UT) was due to increased auroral activity. **(c)** 22 November 1998. A solar flare (X2) occurring shortly after 16 UT resulted in increased X-ray emissions from the Earth's ionosphere. **(d)** 23 November 1998. An X2 solar flare occurring after 06 UT was coincident with an increase in ionospheric X-rays as measured by PIXIE. There is not a strong correlation between the magnitude of the solar flare and the magnitude of X-ray emissions from Earth's ionosphere between events in part because the different viewing

angles of PIXIE on the polar orbiting Polar spacecraft places a constraint on the amount of sunlit ionosphere observed.

6. SUMMARY

The recent observations of Jupiter and Saturn, described above, demonstrate that the upper atmospheres of the giant planets Saturn and Jupiter act as “diffuse mirrors” that backscatter solar X-rays. Thus, these planets might be used as potential remote-sensing tools to monitor X-ray flaring on portions of the hemisphere of the Sun facing away from near-Earth space weather satellites. Such a solar flare monitoring instrument does not require the high spatial resolution of Chandra; it needs to only resolve Saturn. It will also work well for Jupiter, resolving its auroral and low-latitude disk X-rays, since Jupiter is about twice the size of Saturn, and auroral X-rays at Jupiter are located at high latitudes (Gladstone et al. 2002; Elsner et al. 2005; Branduardi-Raymont et al., 2007). Moreover, unlike XMM-Newton and Chandra, such an instrument could be a single-channel camera sensitive in the spectral band 0.1 to 1.0 keV. Essentially, a modest experiment can work for space weather studies. On Earth X-rays have been observed since a long time and it is known that the sunlit atmosphere of Earth brightens whenever a large solar flare happens on the Sun’s hemisphere facing the Earth.

Mainly driven by the solar wind, cometary X-rays provide an observable link between the solar corona, where the solar wind originates, and the solar wind where the comet resides. Once we have understood the solar wind charge exchange mechanism’s behavior in cometary comae in sufficient detail, we will be able to use comets as probes to measure the solar wind throughout the heliosphere. This will be especially useful in monitoring the solar wind in places hard to reach with spacecraft – such as over the solar poles, at large distances above and below the ecliptic plane, and at heliocentric distances greater than a few AU (Lisse et al., 1996, 2001, Krasnopolsky et al. 2004). For example, ~1/3 of the observed soft X-ray emission is found in the 530-700 eV oxygen O^{+7} and O^{+6} lines; observing photons of this energy will facilitate studies of the oxygen ion charge ratio of the solar wind, which is predicted to vary significantly between the slow and fast solar winds

(Neugebauer et al., 2000; Schwadron and Cravens, 2000; Kharchenko and Dalgarno, 2001) (cf. Fig. 7).

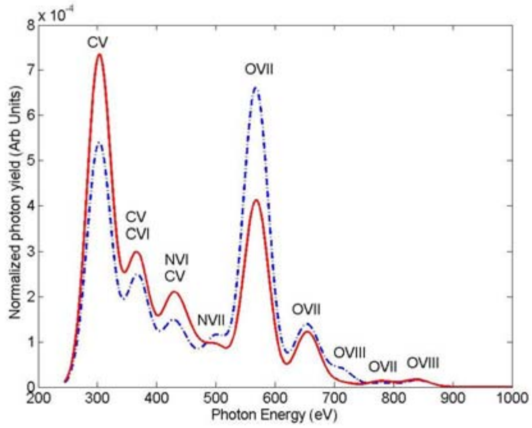

Fig. 7. X-ray spectra for comet Encke for two different solar wind speeds, assuming a resolution of 60 eV, for the collisionally thin case. Blue curve: The 200 km s^{-1} solar wind speed. Red curve: The 600 km s^{-1} solar wind speed. The largest changes in the spectra occur near 350, 500, 650, and 820 eV. [From Lisse et al., 2005].

Mars is an interesting object in the sense that X-rays from its atmosphere (disk) and exosphere (corona) are mainly produced by two different mechanisms. While Martian disk X-rays are mainly fluorescently scattered solar X-rays, the Martian halo X-rays are produced by the solar wind charge exchange mechanism (similar to cometary X-rays). Thus Martian halo X-rays provides another probe to study solar wind properties. Holmström and Kallio (2004) noted that since crustal magnetizations at Mars are asymmetrically distributed, they will also introduce asymmetries in the solar wind flow around the planet and thus in the X-ray emission. Also due to the considerable size of the ion gyroradii (~0.3 Martian radii), kinetic effects are very pronounced. Due to its sensitive dependence on so many parameters, the X-ray emission of the Martian halo contains a wealth of valuable information. Recently, observation of Venus by Chandra in March 2006 (Dennerl, 2008) has shown the presence of the Venusian halo X-rays produced by the solar wind charge exchange mechanism (similar to Martian halo X-rays).

The field of planetary X-ray astronomy is now a very dynamic and at the forefront of planetary research. With the discovery of several types of X-ray objects in the solar system (see Bhardwaj et al., 2007 for review), the field of comparative planetary disk X-rays, auroral X-rays, exospheric X-rays, and surface X-rays, is emerging as a unique field and it will get a boost with newer results that are expected to come soon in the near future.

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