Auroral Ion Precipitation and Acceleration at the Outer Planets

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Jupiter's aurora is a powerful source of radio, IR, visible, UV, and X-ray emission. An UV aurora has also been observed on Saturn. Jovian X-ray emissions with a total power of about 1 GW were observed by the Einstein Observatory, the Roentgen satellite (ROSAT), Chandra X-ray Observatory, and XMM-Newton Observatory. Most of the X-ray power is in soft X-ray emission from the polar caps, but some harder X-ray emission from the main auroral oval was also observed and is probably due to electron bremsstrahlung emission. X-ray emission provides the main evidence that auroral energetic ion acceleration and precipitation is taking place on Jupiter. Two possible mechanisms have been suggested for the soft X-ray emission: (1) cusp entry and precipitation of solar wind heavy ions and (2) acceleration and subsequent precipitation of ions from the outer magnetosphere. Models of ion precipitation and observations of spectra containing oxygen and sulfur lines from high-charge state ions support the second mechanism. Acceleration by field-aligned potentials of about 10 MV is required for the X-ray production. Significant downward parallel currents linking the polar cap to the magnetopause region are associated with this ion precipitation.

1. INTRODUCTION

Auroral emission has been observed from many planets and satellites (e.g., Titan) [*Cravens et al.*, 2005] in the solar system and is due mainly to charged particle precipitation into the upper atmospheres of these bodies from either their magnetospheres or the solar wind [cf. *Galand and Chakrabarti*, 2002]. Auroral emission on Earth is mainly due to energetic electron precipitation, including discrete emissions associated with substorm activity, and is caused by electron acceleration by field-aligned electrical potentials and diffuse aurora in the polar cap (see the many chapters in this monograph). The topic of the current chapter is auroral ion precipitation on Jupiter and Saturn, which produces (or does not for Saturn) X-ray emission.

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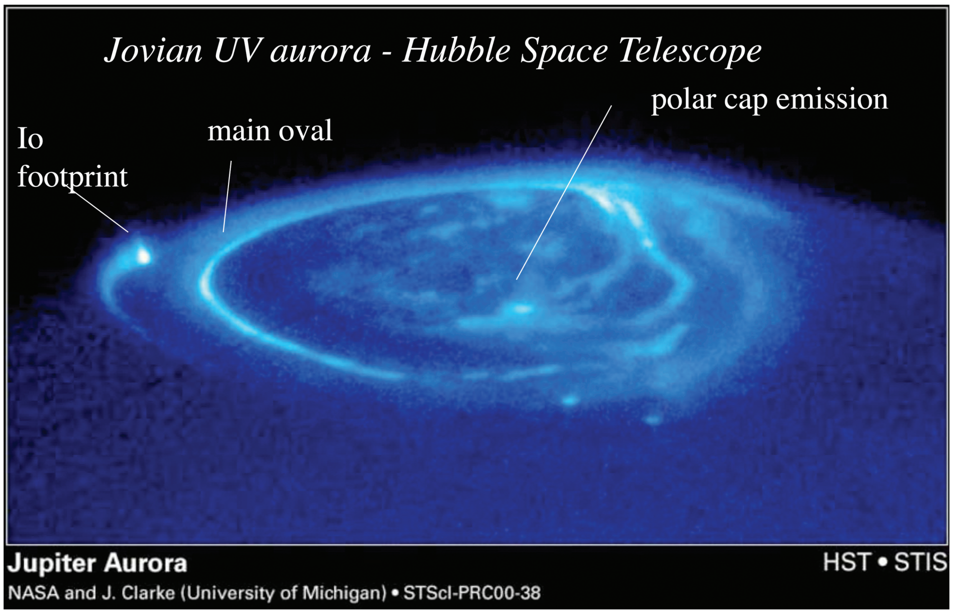
The most intense emission in Jupiter's aurora is in the UV part of the spectrum due to the Lyman and Werner bands of H_2 and Lyman alpha emission from atomic hydrogen with a total power of 10^{13}–10^{14} W [cf. *Clarke et al.*, 1998; *Grodent et al.*, 2001]. The main UV auroral oval is located near 65°–70° latitude, as shown in Figure 1 [*Clarke et al.*, 1998] and generates the highest intensities. Polar cap UV emissions and UV spots associated with the magnetic footprints of Io and the other Galilean satellites are also evident in this, and similar, images. Our current understanding is that the main oval emission is caused by upward field-aligned currents linking with the middle magnetosphere (radial distances averaging about $r \approx 30\ R_J$). These currents are associated with co-rotation lag of the outwardly diffusing plasma, which has been loaded down with sulfur and oxygen ions from the Io plasma torus [cf. *Hill*, 2001; *Cowley and Bunce*, 2001]. The UV spectra suggest that the electrons are accelerated to energies of 50–100 keV [e.g., *Clark et al.*, 2004]. The polar cap UV emissions are not well understood, unlike the main oval emissions, and the polar emissions can be very time variable and flare-like [*Waite et al.*, 2001].



Q2 **Figure 1.** UV image of the Jovian northern hemisphere aurora with different regions indicated. Image courtesy of J. T. Clarke.

Q1 ## 2. BRIEF HISTORY OF EARLIER WORK ON X-RAY EMISSION ON JUPITER

X-ray emission was discovered on Jupiter in 1979 by the Einstein Observatory [*Metzger et al.*, 1983; see *Bhardwaj*, 2006], and about a decade later, many important observations were subsequently made with the Roentgen satellite (ROSAT) [e.g., *Waite et al.*, 1994]. The sulfur and oxygen fluxes measured by Voyager in the middle magnetosphere led *Gehrels and Stone* [1983] to suggest that such ions could be precipitating into the auroral atmosphere. *Horanyi et al.* [1988] modeled energetic (up to MeV) oxygen ion precipitation and the aeronomical effects (i.e., ionization rates, UV emission rates. . .) of this ion aurora.

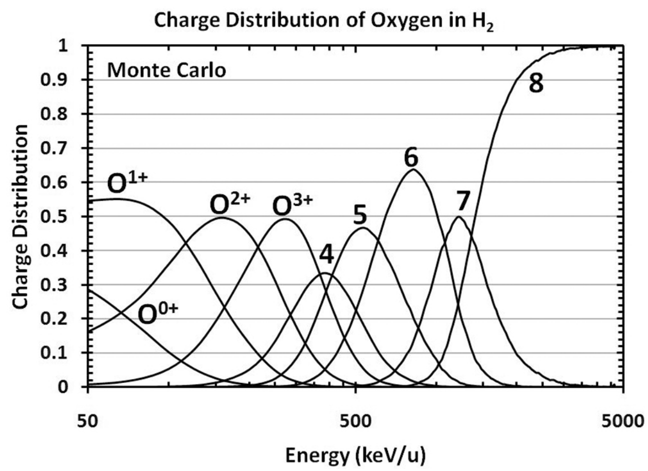
The spectral resolution of the ROSAT X-ray observations [e.g., *Waite et al.*, 1994] was good enough to indicate that the X-ray emission was "soft," with photon energies between about 0.1 and 1 keV, but not good enough to clearly distinguish between a continuum-like source (as suggested by *Barbosa* [1990]) and a line-emission source, although the line model did seem to provide a somewhat better spectral fit [*Waite et al.*, 1994; *Cravens et al.*, 1995]. Recent Chandra X-ray Observatory (CXO) observations show that most of the X-ray power is due to line emission below 1 keV but that a few percent of the power, particularly above 1 keV, could be from electron bremsstrahlung [*Branduardi-Raymont et al.*, 2008].

ROSAT had poor spatial resolution but still indicated that X-ray emission came both from high latitudes (i.e., auroral, but the latitude range was large) and lower latitudes. Both the low and high latitude emissions were attributed by *Waite et al.* [1997] to ion precipitation. *Maurellis et al.* [2000] made the alternative suggestion for the lower-latitude X-ray emission that seemed to account for the spatial morphology and lower-latitude luminosity (like the auroral X-rays, about 1 GW), scattering of solar X-ray photons from Jupiter's upper atmosphere, and also *K* shell fluorescence from the carbon in atmospheric methane. Later work on disk emission from Jupiter and Saturn confirmed this suggestion [e.g., *Cravens et al.*, 2005; *Bhardwaj et al.*, 2005a, 2005b].

The next step in understanding why ion precipitation could generate X-ray emission was the recognition that X-rays are produced by charge exchange collisions of highly charged heavy ions with neutrals because the product ions are left in states with high principle quantum numbers that emit in the X-ray part of the spectrum [*Cravens et al.*, 1995; *Liu and Schultz*, 1999; *Kharchenko et al.*, 1998]. *Cravens et al.* [1995] explained that the low-charge state ions (mostly O^+ and S^+ with some O^{++}, S^{++}. . .) [*Mauk et al.*, 2002] found in the Jovian magnetosphere undergo electron stripping (or removal) collisions with atmospheric H_2 for high energies (MeV per nucleon) resulting in higher-charge state ions. For oxygen, O^{7+} and O^{6+} ions will produce soft X-rays. The key reactions for O^{6+} can be written as

$$O^{6+} + H_2 \rightarrow O^{7+} + H_2 + e$$

$$O^{7+} + H_2 \rightarrow O^{6+*} + H_2^+.$$



Q3 **Figure 2.** Equilibrium fraction for oxygen charge states in H_2 versus ion energy and very similar to results from the work of *Cravens et al.* [1995]. From the work of *Ozak et al.* [2010].

The O^{6+*} ion is excited and emits soft X-rays. In addition to these processes, collisional ionization and excitation of the atmospheric target gases also take place. Cravens et al. used charge exchange (CX) and stripping cross sections for O^{q+} (q = 0 up to 8) collisions with H_2 to calculate an equilibrium fraction versus energy (i.e., fraction of ion beam in each charge state), as shown in Figure 2. Note that the O^{6+} and
Q4 O^{7+} ions are found near energies of ≈ 1 MeV u^{-1}. These models assumed that the ions came from the middle magnetosphere with the necessary energies.

Q5 3. CHANDRA X-RAY OBSERVATORY AND XMM-NEWTON OBSERVATIONS

Some CXO and XMM-Newton observations are briefly reviewed. See *Branduardi-Raymont et al.* [2009] for a more detailed review. Key CXO observations of Jupiter were made by *Gladstone et al.* [2002], and the high-resolution camera images clearly showed two types of soft X-ray emission: (1) evenly distributed disk emission with a total power of about 1 GW and (2) auroral emission from latitudes clearly more poleward than the main oval (also about 1 GW). The image shown in Figure 3 from CXO [*Elsner et al.*, 2005] illustrates this. The polar cap location of the emission strongly suggested that the responsible particle populations originate either in the outer magnetosphere or even on open field lines.

The measured time history of the X-ray power [*Gladstone et al.*, 2002] showed a 40 min period. That is, the X-ray emission was "pulsating." However, the periodicities in later observations were not so clear [e.g., *Elsner et al.*, 2005; *Branduardi-Raymont et al.*, 2004]. Other Jovian phenomena show ~ 40 min periodicities, including ion fluxes both inside and outside the Jovian magnetosphere [*Anagnostopoulos et al.*, 1998] and radio emissions, called QP-40 emissions [*MacDowall et al.*, 1993].

Oxygen lines are evident in CXO spectra of Jupiter's aurora (Figure 4). The spectral region near 500–800 eV is where O^{6+} (helium-like transitions) and O^{7+} (hydrogen-like transitions) emission lines are located as predicted [e.g., *Kharchenko et al.*, 1998]. Any continuum emission (i.e., bremsstrahlung) is relatively weak. The region near 300–
400 eV contains sulfur lines [see *Elsner et al.*, 2005, Table 2]; Q6
Kharchenko et al., 2006]. A cometary X-ray spectrum shown in the bottom panel of Figure 4 has similar oxygen lines, but unlike the Jovian spectrum, this spectrum has features near 400 eV due to solar wind carbon.

Branduardi-Raymont et al. [2008] displayed the locations on a polar map of both low-energy (E < 2 keV) and high-energy (E > 2 keV) photons using different symbols. Soft X-ray photons (line emission from charge exchange) were found mainly in the polar cap, and harder X-rays were mostly found near the main oval. The harder X-rays were interpreted as being electron bremsstrahlung photons.

Spectra measured by XMM-Newton also indicated the presence of high-charge state oxygen and sulfur lines, but with a different sulfur to oxygen ratio from CXO spectral fits [*Branduardi-Raymont et al.*, 2004, 2008]. An XMM-Newton grating spectrum was also obtained, but the auroral and disk emissions were mixed, complicating the interpretation [*Branduardi-Raymont et al.*, 2007]. Nonetheless, distinct O^{6+} and O^{7+} oxygen lines were seen, and some components had broad spectral widths consistent with fast oxygen (i.e., speeds of about 5000 km s^{-1} or energies of ≈ 1 MeV u^{-1}).

4. INTERPRETATION OF INITIAL CXO AND XMM AURORAL OBSERVATIONS

Cravens et al. [2003] noted that the location of the X-ray emission poleward of the main oval implied that the source particle populations were not in the middle magnetosphere as originally thought, but were on open field lines and/or in the outer magnetosphere. Two possible sources were suggested, both involving high-charge state heavy ions (e.g., oxygen): (1) a solar wind ion source and (2) a magnetospheric ion source. For the first, solar wind ions precipitate on open field lines associated with the polar cap and magnetospheric cusp. Solar wind heavy ions are already highly charged and produce X-rays following charge exchange collisions, which is the basis for the solar wind charge exchange (SWCX) mechanism for producing cometary X-rays [*Cravens*, 1997, 2002]. *Cravens et al.* [2003] estimated that to make the SWCX mechanism work for the Jovian X-ray aurora, field-aligned acceleration through a 200 kV or so electrical potential drop

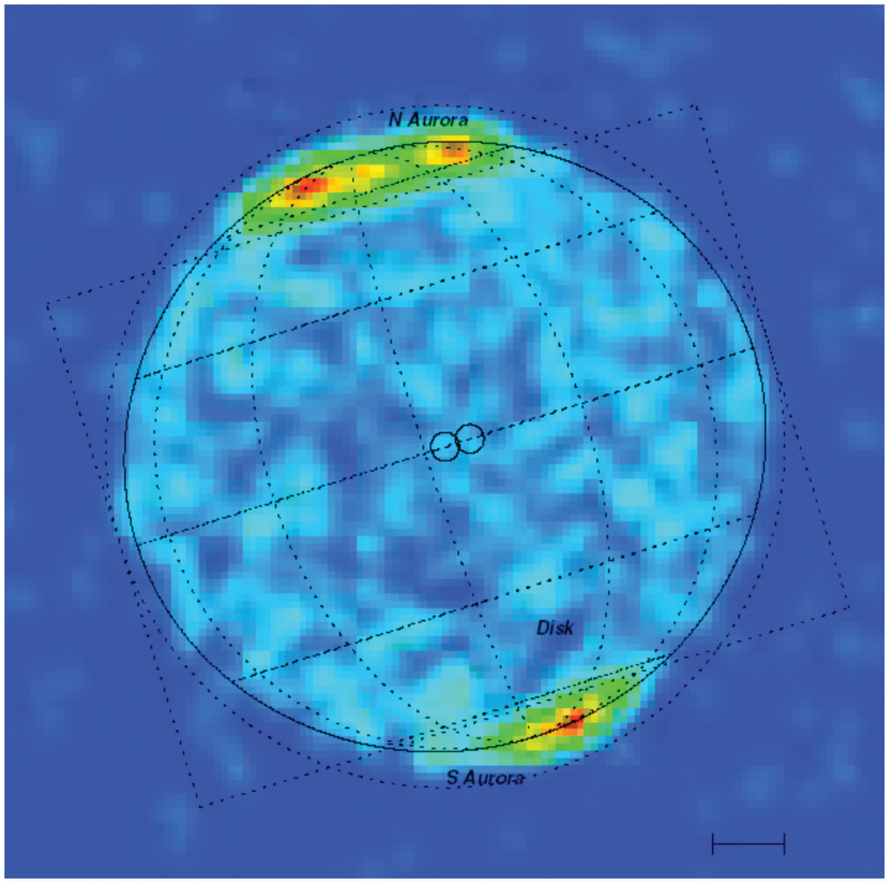


Figure 3. Chandra X-Ray Observatory (CXO) image of Jupiter. Note the disk and the auroral emission regions. From the work of *Elsner et al.* [2005].

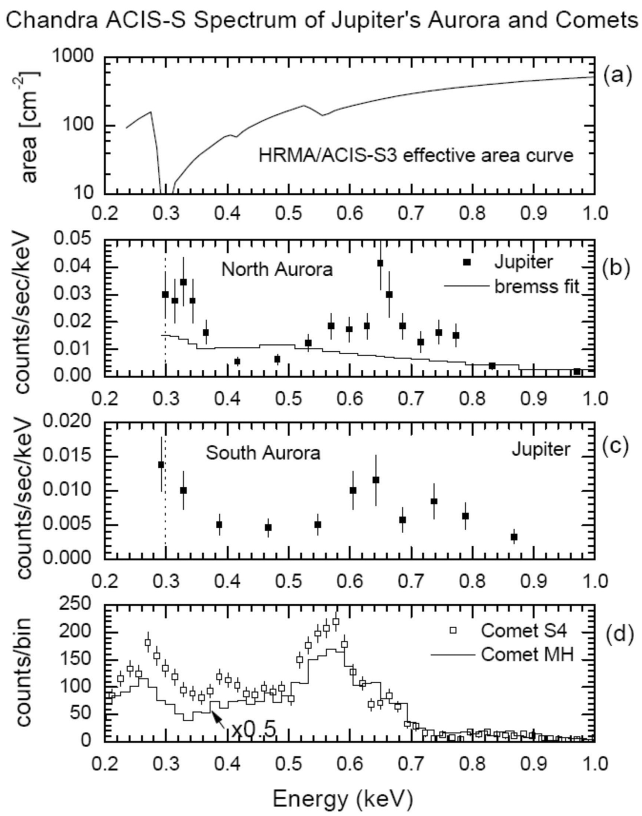
would be needed (via the Knight mechanism) [*Knight*, 1973; *Lyons*, 1981], not to produce the highly charged ions but to boost the flux sufficiently to provide the observed 1 GW X-ray power. It was pointed out that the solar wind protons would also be accelerated to high energies, and the associated UV emissions have not been observed (to our knowledge).

For the second mechanism, S and O ions in the outer magnetosphere are the source, but these magnetospheric ions have average energies of only 50 keV or so [*Mauk et al.*, 2002] and would be insufficient to produce the X-ray aurora.
Q7 *Cravens* suggested that acceleration by several MV field-aligned potentials would allow the ions to produce X-rays, as discussed earlier. The ion fluxes are also boosted by such a field-aligned acceleration process via the Knight mechanism. The same mechanism has been invoked (in different forms)
Q8 for auroral electron acceleration on Earth (e.g., review and this monograph) or on Jupiter [*Hill*, 2001]. *Cravens* suggested that the heavy ion precipitation was associated with the downward "return current" (into the planet) of the main current system. Electrons that are accelerated upward to several MeV could be responsible for the observed QP-40 radio bursts [*MacDowell et al.*, 1993; *Elsner et al.*, 2005].

Bunce et al. [2004] proposed that the field-aligned potentials and associated field-aligned currents needed for the
X-ray aurora are caused by pulsating reconnections at the Q9
dayside magnetopause. They estimated that, at least for fast solar wind conditions, the potentials (i.e., ion energies) and fluxes would be sufficient to generate the required X-ray aurora.

5. RECENT WORK ON THE JOVIAN X-RAY AURORA

Kharchenko et al. [2006, 2008] introduced sulfur as well as oxygen precipitation (using the relevant cross sections) in their model, given that the magnetosphere contains both species. Significant quenching effects were found for the $^3P^0$–^1S and ^3S–^1S n = 2 transitions of O^{6+} (i.e., the intercombination and forbidden transitions, respectively) and



Q10 **Figure 4.** (middle) CXO ACIS spectra of the north and south aurorae. (top) The instrument response function. (bottom) Cometary X-ray spectra. From the work of *Elsner et al.* [2005].

particularly for the ^3S–^1S transition [*Kharchenko et al.*, 2008; *Ozak et al.*, 2010]. Updated cross sections for energetic sulfur and oxygen ion electron removal, charge exchange, and ionization were used for a wide range of charge states [*Kharchenko et al.*, 2008; *Hui et al.*, 2010; *Ozak et al.*, 2010]. State-specific charge exchange cross sections were also used to improve the accuracy of the predicted spectra, and Monte Carlo methods were used to determine ion charge state distributions versus altitude in the atmosphere. The Ozak et al. Monte Carlo model additionally considered the altitude dependence of the energy deposition and X-ray volume production rate, which helped with the quenching rate determination, as well as allowing opacity effects for outgoing X-ray photons to be taken into account.

Hui et al. [2010] used a detailed ion precipitation model that included not just S and O ions of various charge states, but also carbon ions, and at lower energies (200 keV or so) as well as at MeV energies in order to see if this species could contribute to the observed X-ray spectrum. They concluded that carbon lines are not making a significant contribution to

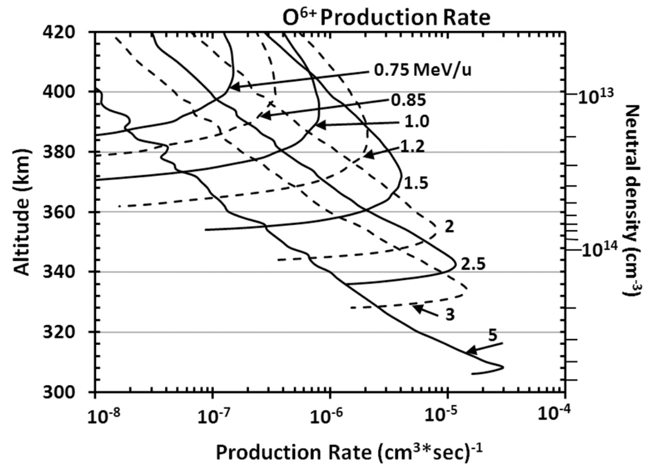


Figure 5. Production rate versus altitude for several incident oxygen energies of O^{6+} ions from charge exchange. The O^{6+} production is proportional to the X-ray emission from this species. From the work of *Ozak et al.* [2010]. Q11

the observed Jovian X-ray spectra, thus indicating that the solar wind source is probably not important.

Ozak et al. [2010] adopted neutral upper atmosphere density profiles versus altitude based on Galileo entry probe data [*Seiff et al.*, 1996] and used the *Hui et al.* [2010] detailed X-ray transition probabilities. Figure 5 shows the production rate of O^{6+} ions created in high principle quantum number states versus altitude for a range of incident ion energies. O^{6+} accounts for a large fraction of the total X-ray volume emission rate. As expected, with higher incident ion energies, the ions penetrate deeper into the atmosphere. For example, the

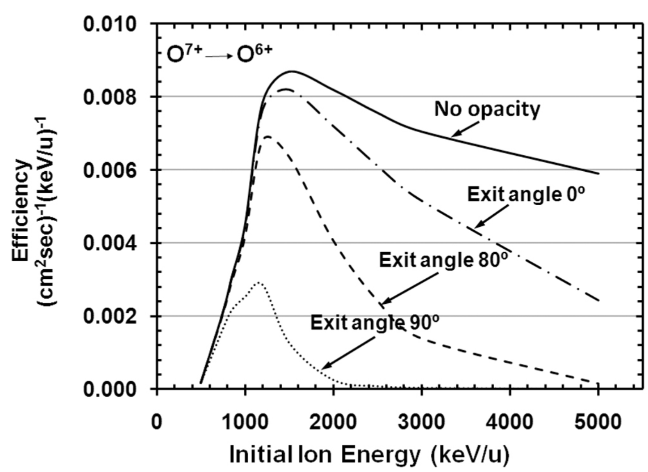


Figure 6. X-ray power efficiency for all transitions for different incident oxygen energies and for different photon exit geometries. Opacity effects were included for some curves. From the work of *Ozak et al.* [2010].

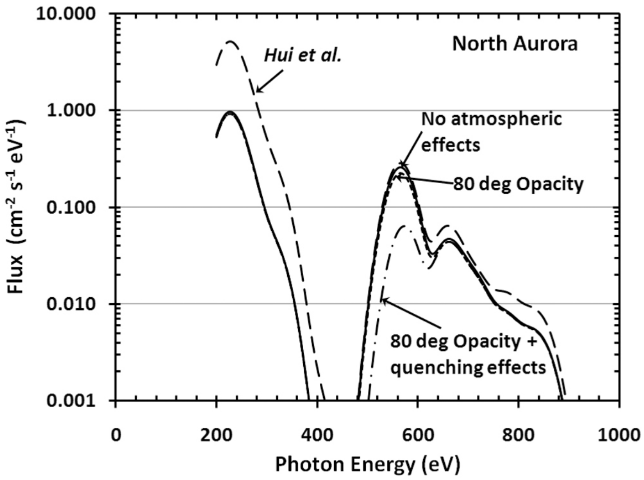


Figure 7. X-ray intensity versus photon energy from the *Ozak et al.* [2010] and *Hui et al.* [2010] models. The *Hui et al.* [2010] spectrum is a proxy for the CXO-measured spectrum.

peak production rate for O^{6+} is at an altitude z = 390 km for a 1 MeV u^{-1} ion. For a 2 MeV u^{-1} ion, the peak is at z = 354 km. The homopause is near 400 km, so that 2 MeV u^{-1} (and higher energy) ions are penetrating into the mixed atmosphere containing relatively abundant methane (a good UV and soft X-ray absorber). Production rate profiles for several S and O charge states and integrated over altitude were used to determine X-ray volume emission rates and to give predicted intensities (and spectra). The effect on outgoing radiation of the soft X-ray opacity of the atmosphere was investigated.

Ozak et al. [2010] found emission efficiencies by dividing total intensity over all directions ($4\pi I$) by the value of the initial ion energy. For example, the X-ray efficiency for oxygen charge state O^{6+} is shown in Figure 6, and the most efficient production occurs for incident ions with energies of about 1.5 MeV u^{-1}. For O^{7+} ions (not shown here), the peak efficiency is for initial energies of 2.5 MeV u^{-1}. Incident sulfur ions with energies of about 1 MeV u^{-1} are most efficient in producing S^{8+}. Opacity effects for outgoing photon angles of 0° (dash-dotted line), 80° (dashed line), and 90° (dotted line) are shown. Opacity effects become significant for incident ion energies higher than 2 MeV u^{-1} for O^{7+} ions, 1.2 MeV u^{-1} for O^{6+} ions, and 1 MeV u^{-1} for S^{8+} ions. For energies higher than 5 MeV u^{-1}, the atmosphere becomes extremely opaque at the large exit angles relevant for the auroral regions.

One of the *Ozak et al.* [2010] X-ray spectra is shown in Figure 7. The higher energy emission is due to oxygen and the lower energy emission to sulfur. The *Hui et al.* [2010] curve in Figure 7 is for a model case with the best fit (varying incident ion energy and sulfur to oxygen ratio) to the CXO data. Clearly, the opacity affects the spectra and affects any deductions of the S to O ratios and energies. More work is still needed on this topic.

6. MAGNETOSPHERE-IONOSPHERE COUPLING ON JUPITER: IMPLICATIONS OF X-RAY AND THE ABSENCE OF A SATURNIAN X-RAY AURORA Q12

Oxygen ions in the outer magnetosphere must be accelerated by field-aligned potentials of about 10 MV in order to produce X-ray emission. *Bunce et al.* [2004] suggested that magnetic reconnection at the dayside magnetopause of Jupiter should be able to accomplish this task for fast solar wind conditions. On the other hand, on Saturn, although disk and possibly ring X-rays were observed, an X-ray aurora was not detected. *Branduardi-Raymont et al.* [2009] set an upper limit of about 40 MW on the auroral X-ray power. *Hui et al.* [2010] modeled heavy ion precipitation on Saturn and concluded that magnetosphere-ionosphere coupling at Saturn is such that any field-aligned potential must be well below a few MV. They also concluded that no significant cusp entry and precipitation of solar wind ions is taking place on Saturn.

7. FUTURE WORK

Much work remains to be done to improve our understanding of ion precipitation and X-ray production on Jupiter, including a detailed assessment of field-aligned currents and the effects of this aurora on the atmosphere (e.g., heating, ionization UV emissions, ...). In particular, why do 10 MV field-aligned potentials develop (evidently) in the Jovian magnetosphere at high latitudes but not on Saturn?

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