Auroral Processes in the Solar System
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Abstract

Studies of the aurora constitute a fundamental component of geophysical research. The observational, theoretical, and modeling advances achieved in understanding terrestrial auroral activity mark a high point in space science and, in particular, in defining linkages between energetics, dynamics, and coupling within the solar wind-magnetospheric-atmospheric system. One of the major achievements of space age technology has been the detection of auroral emissions on other solar system bodies. While the mechanisms responsible for auroral structure on other worlds involve the same basic physics operating on Earth, the settings are of vastly different scale and with sources often unique to each site. Defining an aurora as any optical manifestation of the interaction of extra-atmospheric energetic electrons, ions, and neutrals with an atmosphere, we review the observational inventory of aurora in the solar system and discuss the different steps used for modeling auroral processes. Aurora offers us a unique and extremely valuable remote sensing of magnetic field configuration and is a tracer of plasma interactions. It is an indicator of the atmospheric composition and energy source and can be used for remote sensing of the characteristics of the incident energetic particles. The diversity of magnetic field geometries, plasma interactions, energy sources, and atmospheric constituents, all make comparative auroral studies a rich field, which should lead us to further understanding of interactions taking place at different solar system bodies.

1. INTRODUCTION

Since the dawn of human history, the aurora has stirred human imagination, curiosity, and fear, creating a mixture of conflicting emotions. Seen as huge green curtains of light beating under a ghostwind, or red veils firing the nightsky, auroral displays have always fascinated human minds [e.g., *Eather*, 1980]. Eskimos in Alaska described the aurora borealis as the dancing souls of their favorite animals; for the Inuits in southern Canada the aurora had the power to decapitate people.

Auroral emissions are not restricted to the Earth. With improved observation capabilities over the last decades we have discovered aurorae on other bodies of the solar system, such as on the Jovian moon Ganymede. On Earth alone auroral emissions span the entire optical wavelength band. Temporal variabilities are observed from few milliseconds to over several hours, and the spatial structures extend from a meter to hundreds of kilometers.

The definition we propose for aurora is any optical manifestation of the interaction of extra-atmospheric energetic electrons, ions, and neutrals, with an atmosphere. The spectral range includes γ-rays [about 0.001-1 pm], soft X-rays [1-10 nm], Extreme UltraViolet (EUV) [10-90 nm], Far-UltraViolet (FUV) [90-200 nm], Near-UltraViolet (NUV) [200-300 nm], visible [300-800 nm], near-InfraRed (IR) [0.8-15 μm], far-InfraRed [15-200 μm]. The shorter wavelength emissions are produced by incident particles with higher energy penetrating deeper in the atmosphere. We choose to focus on optical emissions, even though radio emissions [above 0.2 mm] have been observed in the auroral regions of the Earth and the giant planets [*Zarka*, 1998]. The interaction of the energetic particles with the atmosphere can be direct - the excitation and subsequent light emission are the result of the impact of an energetic particle with an atmospheric species. It can also be indirect, when the excitation results from a chain of reactions initiated by energetic particles. It has to be distinguished from airglow, which is the result of chemical reactions initiated by solar photons [see *Chap I.5 and IV.5*]. For emissions to be called aurora, we propose that the energetic particles have to be extra-atmospheric. Photo-electrons, electrons produced by interaction of the solar photons with an atmosphere, are excluded as energy source of an aurora. The energetic particles at the source of aurora have a large variety of origins, including the solar wind, sputtering of Saturnian rings and icy moon surfaces by magnetospheric ions, Io's volcanic plumes, or the planetary magnetosphere. The particles can be accelerated by magnetospheric convection, diffusion, wave-particle interaction, pick-up (e.g., in the Venusian upper atmosphere), or induced by rotation of the planet (e.g., at Jupiter). The energetic particles can be part of an open flow, precipitating from a magnetosphere, or of solar wind origin. They also can be part of a field-aligned current closing within the ionosphere, as in the current system that exists between the Jovian ionosphere and its moon Io. Heat flux is excluded as it is conduction, not particle transport. It is assumed that the energetic particles impact only on an atmosphere. Even though partly ionized, the dense atmospheres encountered around solar system bodies are dominated by neutral constituents.

The interaction of an energetic particle with an ambient neutral can lead to the excitation of the atmospheric species. During de-excitation, the excess energy is re-emitted as a photon whose wavelength is precisely governed by the same quantum rules which dictate the available energy levels surrounding a given nucleus [e.g., *Chamberlain*, 1995]. The auroral emissions can also be produced by the energetic particle itself. For instance, energetic protons precipitating into an atmosphere can capture an electron (charge-exchange) and become hydrogen atoms in an excited state. As a result, doppler-shifted H emissions are produced, such as Lyman α (121.6 nm) and the Balmer lines, Hα (656.3 nm) and Hβ (486.1 nm). Sometimes for heavy ions such as oxygen, K-shell lines arise as the energetic ions are nearly stripped of electrons and then are either directly excited or charge exchanged into an excited state, which subsequently emits an X-ray photon. As for electrons, bremsstrahlung continuum X-rays are produced when the suprathermal electron is scattered by Coulomb interactions with an atmospheric nuclei and electrons. Auroral IR radiations can be produced by cooling processes in an atmosphere heated by energetic particles. Hydrocarbons are efficient coolers in the giant planets, and NO, He, and CO_2 in the terrestrial thermosphere.

Auroral emissions have been extensively observed and studied. We do not pretend to provide a comprehensive review of the aurora. Detailed reviews can be found in the works by *Fox* [1986] and *Bhardwaj and Gladstone* [2000a]. We would like, rather, to give some insights on the diversity of auroral emissions encountered in our solar system, on the modeling of auroral processes, on the relevance of auroral studies,

and the comparative approach.

2. OBSERVATIONS OF AURORAL EMISSIONS IN THE SOLAR SYSTEM

Auroral emissions have been observed throughout the solar system. To cover the large range of wavelengths, different instruments from ground-based to Earth orbiting observatories have been used. Visible and IR observations are usually performed from the ground. At Mauna Kea, Hawaii, the Keck telescope has been used to observe Ganymede in the red window, and the Canada-France-Hawaii Telescope (CFHT) and Infrared Telescope Facility (IRTF) have observed Jupiter in the IR. The terrestrial atmosphere has been extensively observed from ground with photometers and spectrometers at visible wavelengths. Since UV and X-rays radiation is absorbed in the Earth's atmosphere, the instruments operating in these wavelengths are all space-based. The Polar spacecraft has instruments covering a large spectral range: the UltraViolet Imager (UVI), the Visible Imaging System (VIS), and the Polar Ionospheric X-ray Imaging Experiment (PIXIE). Polar as well as Dynamics Explorer (DE) and the recent Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite have provided crucial global images of the Earth's auroral ovals. The International Ultraviolet Explorer (IUE) satellite at geo-synchronous orbit from 1978 to 1996 and the Extreme UltraViolet Explorer (EUVE) observatory operating at about 430 km from 1992 to January 2001 provided precious data about the giant planets and comets. The Goddard High Resolution Spectrograph (GHRS), onboard the Hubble Space Telescope (HST) orbiting at 600 km, operated until 1997 and was then replaced by the Space Telescope Imaging Spectrograph (STIS) for imaging from UV to near-IR. Also aboard the HST, the Faint Object Camera (FOC), operating in visible and UV wavelengths, and the Wide Field Planetary Camera (WFPC), operating from UV to near-IR, have been extensively used for observations of Saturn, Jupiter, and its Galilean moons, Ganymede, Io, and Europa. The Rossi X-ray Timing Explorer (XTE), the Röntgen satellite (ROSAT), the High Energy Astronomical Observatory 2 (Einstein), and the recent Chandra X-ray Observatory (CXO) have been crucial in the detection of X-rays at comets, Jupiter, and Saturn.

For distant bodies with faint emission or fine spatial structure, spacecraft flybys provide data that near Earth observatories cannot. The UltraViolet Spectrometer (UVS) onboard Pionner Venus Orbiter (PVO) and UVS onboard the Voyager 1 and 2 spacecrafts have recorded auroral emissions on Venus and on the giant planets, respectively. The Solid State Imaging (SSI) instrument on Galileo observing the visible nighttime Jovian aurora gave us images with unprecedented spatial resolution. Over December 2000 - January 2001 (Jupiter Millennium Campaign), the Cassini swing-by of Jupiter along with Galileo and HST observations offered us the first comprehensive, coordinated set of data of the Jupiter's atmosphere and environment [*Clarke*, 2001].

2.1. Earth

On the Earth, the aurora has been studied scientifically for a long time (see for example, *Mairan* [1733] and other historical references listed in *Chamberlain* [1995]). Many reviews have summarized auroral studies with different emphases (see *Vallance Jones* [1974], *Gordiets* [1986], *Rees* [1989], *Meng et al.* [1991], *Stadsnes et al.* [1997], and *Chakrabarti* [1998]). Terrestrial aurorae have been observed from gamma rays associated to MeV protons [*Share and Murphy*, 2001] to radio [e.g., *Liou et al.*, 2000]. Recent advances include multi-spectral and multi-point observations of aurora, from space and ground-based platforms. In this section, we will discuss some of the results not covered in the reviews listed above.

UV observations have opened up a capability that is unavailable to visible and IR - the ability to observe sunlit aurora. Rocket and satellite borne spectroscopic observations [*Vallance Jones*, 1991, and references therein] established the spectral content which has been refined by satellite observations. These observations have shown the auroral spectrum is rich even shortward of 90 nm where it is dominated by O^+ emissions, while the spectral region between 90 and 200 nm contains a large number of emission features due to H, O, N, O^+, N^+, H_2, and N_2. There were reports of argon emissions [*Christensen et al.*, 1977] and O^{++} [*Paresce et al.*, 1983], but they have not been independently validated. Spectroscopic studies of UV aurora have used emission intensity ratios to characterize the particle energies in the sunlit cusp, polar cap, and nightside aurora [e.g., *Chakrabarti*, 1986].

More recently, global imaging in the visible (e.g., DMSP), UV (e.g., DE, Viking and Polar/UVI, IMAGE) and X-rays (e.g., Polar/PIXIE) are being used for a better understanding of auroral processes. For

example, the size of the auroral oval derived from global images has been related to solar wind parameters [*Siscoe*, 1991]. Evolution of the global aurora has been examined to understand the substorm onset and poleward expansion [e.g., *Craven and Frank*, 1987].

Balloons were used to study X-ray emissions from the aurora as early as 1957 [*Winckler et al.*, 1958; *Anderson*, 1965]. X-ray spectrum of an aurora has been related to the energy spectrum of the incident electrons [*Vij et al.*, 1975] and have since been used in conjunction with visible [*Mizera et al.*, 1978; *Stadsnes et al.*, 1997], UV [*Østgaard et al.*, 2000; *Anderson et al.*, 2000] and particle measurements [*Sharber et al.*, 1993]. These studies on the role of auroral X-rays in atmospheric ionization found a peak observed hemispheric power input of 40 GW and an ionization rate that exceeds solar UV and X-ray ionization rate by 2 - 3 orders of magnitude [*Chenette et al.*, 1993]. With improved technology, we now have global X-ray imagers, which have allowed a statistical classification of X-ray flux according to Kp [*Petrinec et al.*, 1999]. Simulation studies have been used to explain the X-ray darkness observed in the postnoon sector [*Chenette et al.*, 1999] in terms of attenuation of drifting plasmasheet electrons [*Chen and Schulz*, 2001].

In low latitude region, a factor of two increase in emission ratios of selected UV lines at geomagnetically disturbed times was attributed to energetic neutral atoms (ENAs) [*Abreu et al.*, 1986]. Subsequently, *Ishimoto et al.* [1992] examined enhancement of several UV emissions during the main phase of a geomagnetic substorm and concluded that they were caused by precipitating energetic oxygen neutrals of ring current origin. Similar enhancement in the low-latitude nighttime N_2^+ (1N) intensities was attributed to ENAs [*Tinsley et al.*, 1994]. Recently, this increase in UV emission intensities in low latitudes due to ENAs has been extended to dayglow [*Stephan et al.*, 2000; 2001].

In a short review it is not possible to highlight all aspects of terrestrial auroral research. So, we note some recent works, which could be used to find other relevant works. *Doe et al.* [1993] observed F region plasma depletion in red line images and were able to attribute it to downward field-aligned current. Using Polar UVI and Wind's solar wind and IMF data, *Liou et al.* [1998] conclude that solar wind parameters (density, speed, and dynamic pressure) have minimal effect on the afternoon aurora. *Kozlovsky and Kangas* [2001] found a correlation of the equatorward drifting arcs with IMF B_z. The authors noted a lag of about 30 minutes of the increase of equatorward drifting of

the arcs located in the region of convection shear. *Sandholt and Farrugia* [2001] studied the substorm intensification process through observations of bursty bulk flows. They were able to relate impulsive injection of electrons at geostationary altitude and brightening of the aurora. Using high spatial and temporal resolutions, *Knudsen et al.* [2001] studied the width of auroral arcs and found them to be 18 ± 9 km, which is consistent with those of *Stenbaek-Nielsen et al.* [1998].

In spite of tremendous progress in auroral studies, there is a lamentable lack of spectral imaging studies on the Earth. The spectacular global auroral images taken by DE, Viking, Polar, and IMAGE all use narrow-band filters, thereby requiring some assumptions on the spectral content within their passband. All our knowledge of optical aurora on other planets come from spectral imaging. Until we conduct a similar observation on the Earth, our understanding of comparative auroral studies will remain incomplete.

2.2. Bodies with a significant intrinsic magnetosphere

In addition to the Earth, five solar system bodies, Jupiter, Saturn, Uranus, Neptune, and the Jovian moon Ganymede, are known to have both an atmosphere and a significant intrinsic magnetosphere, conditions conducive to aurora. Although their magnetic geometries are very different, the giant planets have upper atmospheres with common features. The major species are hydrogen atoms and molecules whose emission lines and bands are the dominant UV and visible auroral radiations. Below the homopause is a hydrocarbon layer that absorbs most of the UV and visible emissions but radiates in IR. X-rays are produced by the energetic particles themselves, mainly by the heavy ions on Jupiter and probably by the electrons on Saturn. For a comprehensive survey of auroral processes on the giant planets, see *Bhardwaj and Gladstone* [2000a, 2000b] and *Chapter II.2*. Consequently, only few major characteristics of aurora on the giant planets are presented here.

Jovian auroral emissions have been observed in the X-rays, UV, visible, and IR ranges [*Waite et al.*, 2000]. The Jovian aurora is not as strongly coupled to the solar wind as the Earth is due to Jupiter's strong magnetic field [*Dessler*, 1983] (although observations with higher spatial and temporal resolution seem to disagree with this conclusion) [see *Chap II.2*]. The main ovals are driven primarily by the rapid rotation of the jovian ionosphere. X-ray auroral emissions are

observed at high latitudes [*Waite et al.*, 1994], and at low latitudes [*Waite et al.*, 1997]. If the major source seems to be heavy ions, it should be noted that recent data from the Jupiter Millennium campaign opens up the possibility that electrons may be important for some of the X-ray emissions [*Gladstone et al.*, 2001]. The visible aurora has not been seen on the dayside - the only hemisphere seen from Earth - due to the strong albedo. Voyager [*Smith et al.*, 1979] and Galileo [*Ingersoll et al.*, 1998] have observed the nightside visible aurora. IR observations revealed the presence of H_3^+ in the Jovian auroral regions [*Drossart et al.*, 1989] and the variability of the thermal IR emissions from hydrocarbons in high latitude suggests that they are driven by auroral processes [*Caldwell et al.*, 1980; *Kim et al.*, 1985]. The H_2 near-IR emissions in the auroral oval are a direct consequence of electron precipitation [*Kim and Maguire*, 1986]. The most peculiar auroral feature encountered on Jupiter is the emissions related to the magnetic flux tube footprint of Io observed in IR [*Connerney et al.*, 1993], UV [*Prangé et al.*, 1996; *Clarke et al.*, 1998], and visible [*Vasavada et al.*, 1999]. Magnetic footprints of Ganymede and Europa were also discovered in UV with HST/ STIS [*Clarke et al.*, 2001]. The detection of these emissions proves the generation of a field-aligned current system between the Jovian ionosphere and the Galilean moons [see *Chap II.2*].

Saturn's aurora has been observed in UV [*Trauger et al.*, 1998], IR [*Geballe et al.*, 1993], and X-rays [*Ness and Schmitt*, 2000]. While Saturn is similar in size and composition to Jupiter, its magnetic field is similar in surface strength to the Earth's. As a result, auroral emission brightnesses on Saturn are much more modest than on Jupiter, with about 10^3 and 100 times less emitted power in UV and IR, respectively. The high latitude auroral ovals located at about 80° latitude are very stable as a result of the alignment of the rotation and magnetic dipole axis. As a consequence of its modest magnetic field (compared to Jupiter), the auroral emission features on Saturn indicate that the local time effects play an important role in the auroral morphology [*Trauger et al.*, 1998]. The detection of IR emissions in auroral regions is associated with the excitation of H_3^+ but the low brightness observed has not yet been fully explained [*Bhardwaj and Gladstone*, 2000a].

The first indication of the presence of auroral activity on Uranus was based on bright and variable H Lyman α emission observed through IUE for several years [*Clarke*, 1982; *Clarke et al.*, 1986]. These emissions were too intense to be attributed to resonant scattering of solar Ly α and no correlation was found with the solar Ly α or the solar wind conditions. Voyager 2 flyby clearly showed emissions associated with the nightside southern magnetic pole [*Broadfoot et al.*, 1986] and confirmed the presence of a strong magnetic field but with a very unusual and complex configuration [*Connerney et al.*, 1987]. The angle between the magnetic and rotation axes and the offset of the dipole are very large, 58.6° and 30°, respectively. Keeping also in mind the large inclination of the Uranian equator toward the orbit (98°), the magnetotail of Uranus rotates about an axis oriented towards the Sun. Dipole, quadrupole, and octapole models have been developed for modeling the magnetic field and explaining the origin of the UV emissions [*Gao et al.*, 1998]. The main auroral features follow a circumpolar oval, even though not complete, at magnetic latitude of 60° for the northern oval and 65° for the southern oval corresponding to very low L shell values (around 4) [*Herbert and Sandel*, 1994]. The brightest auroral emission at each magnetic pole is confined to a range of 90° of magnetic longitude region centered on the magnetotail direction. The low apparent L suggests less than 10 keV energy for the precipitating particles. Even though IR H_3^+ emission has been observed on Uranus, the lack of spatial information makes it hard to interpret or conclude that these emissions are auroral in nature [*Trafton et al.*, 1999].

The UVS instrument onboard Voyager 2 revealed, for the first time, H_2 emissions on nightside of Neptune [*Broadfoot et al.*, 1989; *Sandel et al.*, 1990]. These emissions are 2 to 3 orders of magnitude weaker than the Uranian auroral emissions, largely because Neptune's magnetosphere is emptied of plasma each rotation. Two distinct types of emissions were observed. The first one is a latitudinally broad region extending from 55° South to 50° North. The second feature, seen near the south pole, is brighter and more localized in both longitude and latitude. The orientation of Neptune's spin axis (28.8° obliquity) along with the large magnetic tilt angle of 47° induces a variable geometry for Neptune's magnetosphere, changing every half-rotation (8 hours), from an "Earth-like" magnetosphere to a "pole-on" magnetosphere with only one polar cusp [*Sandel et al.*, 1990; *Bishop et al.*, 1995]. As a result of the ill-known, complex magnetic configuration, there is some controversy about the mechanisms causing each type of emission. The diffuse emissions are attributed to precipitation of conjugate photoelectrons coming from

the sunlit side of the planet [*Sandel et al.*, 1990] or to trapped electrons precipitating in the region of anomalously low surface magnetic field [*Paranicas and Cheng*, 1994]. The brightest emission region seems more clearly to be auroral, but the acceleration mechanism for the charged particles is not yet unanimously accepted [*Bhardwaj and Gladstone*, 2000a]. A suggestion is that this southern aurora extracts its power from Neptune's rotational energy through the electrodynamic coupling of the ionosphere with Triton's plasma arcs [*Broadfoot et al.*, 1989; *Sandel et al.*, 1990].

Ganymede, the only moon known to have a significant intrinsic magnetic field [*Kivelson et al.*, 1996], is by far the most striking case with its double aurora. First, UV observations of the sunlit side, recorded by HST/GHRS [*Hall et al.*, 1998] and then confirmed by HST/ STIS [*Feldman et al.*, 2000] showed oxygen line emissions concentrated at the poles of the satellite. After removing the contribution of the reflected sunlight on Ganymede and of airglow emissions from Earth, they found the brightness to be up to 300 R for OI 135.6 nm. This reveals the presence of a thin oxygen atmosphere around Ganymede, most probably produced by surface sputtering and decomposition of ice from the impact of Io plasma torus ions - a process also called radiolysis - and by photolysis of ice [see *Chap III.3*]. The ratio of OI 135.6 nm to 130.4 nm lines suggests that the main excitation mechanism is electron impact on O_2 with a possible smaller contribution from electron impact on O [*Hall et al.*, 1998]. The temporal variability over a Jovian rotation and the spatial distribution of the oxygen lines observed at geographic latitudes above 40° tend to support the auroral nature of these emissions. The Galileo magnetometer data indicate that Jovian magnetic field lines linked to Ganymede's atmosphere only at high latitudes [*Kivelson et al.*, 1997]. Low energy particles coming from the Jovian magnetospheric plasma can reach the polar atmosphere of Ganymede. The variability of both the brightness and the relative intensity between north and south hemispheres can be explained by the changing Jovian plasma environment at Ganymede. However, this explanation remains controversial today. Local acceleration of electrons induced by the interaction of the Jovian co-rotating plasma with Ganymede's magnetosphere has also been invoked [*Eviatar et al.*, 2001]. The longitudinal nonuniformity in the emission brightness and the lack of a pronounced limb, suggesting that emissions are produced close to the surface, remain unexplained. In addition to the UV polar emission, equatorial nightside aurora in OI 630.0 and 636.3 nm was revealed on Ganymede by the Keck I telescope [*Brown and Bouchez*, 1999]. These visible emissions are concentrated over a region protected by the moon's intrinsic magnetic field from direct bombardment from the Jovian magnetosphere. The excitation is likely to be induced by low energy electrons trapped in the inner magnetosphere of Ganymede [*Eviatar et al.*, 2000]. The absence of red line emissions at poles is still not yet understood.

2.3. Bodies with an induced magnetic environment

Auroral emissions have been observed around bodies which do not generate any significant magnetosphere. These bodies are typically embedded in a magnetic environment of external origin, a source of energetic particles. The induced magnetic environment results from the interaction of the atmospheric body with the solar wind, such as in the case of Venus and comets, or with the mother-planet, as for the Galilean moons, Io and Europa.

Venus has a significant dayside ionosphere, which, as a result of its lack of planetary magnetic field and its dense atmosphere, slows down the solar wind. The interplanetary magnetic field is deflected and drapes back to form a magnetotail [see *Chap II.3*]. Consequently, energetic ions - of solar wind origin or from the sunlit Venusian atmosphere, picked up by the solar wind, and accelerated - and electrons can bombard the nightside atmosphere of Venus [*Brace et al.*, 1987]. Nevertheless, it was still a surprise when the PVO/UVS instrument showed continuous but highly variable emissions at 130.4 nm on the nightside of Venus [*Phillips et al.*, 1986; *Luhmann et al.*, 1994]. The emissions appear as patches and occasionally cover the entire disk. They have typical brightness in the 10-20 R range, but spots sometimes reached intensities exceeding 100 R. The morphology and variability of these emissions suggest an auroral origin. The analysis by *Fox and Stewart* [1991] corroborates this conclusion. The 130.4 to 135.6 nm brightness ratio precludes radiative recombination of O^+ with electrons as the dominant mechanism. The observed intensities are consistent with soft electron precipitation of few tens of eV - derived from PVO particle data - impacting the atmospheric oxygen atoms. No systematic correlations between auroral brightness and the solar wind fluid parameters have been found. However, the periods of brightest emissions seem to be

associated with the passage of interplanetary shocks and its bulk of energetic solar particles [*Phillips et al.*, 1986].

Another unexpected case of aurora is the soft X-ray emissions observed from comets. The first observations were from the comet Hyakutake and was a very surprising and puzzling discovery [*Lisse et al.*, 1996]. These observations, obtained by ROSAT and XTE, showed a very broad emitting region, extending well beyond cometocentric distances of 200,000 km and elongated in the direction perpendicular to the Sun-comet line. The X-ray variability had two components, one slow and the other more impulsive with a factor of 4 of increase and a time scale of one to two hours. *Dennerl et al.* [1997] found that the luminosity varies with heliocentric distance and with cometary gas production rate. Since this discovery EUV and soft X-ray emissions have been observed around more than ten comets, including comet Hale-Bopp [e.g., *Dennerl et al.*, 1997; *Mumma et al.*, 1997; *Krasnopolsky et al.*, 1997; *Lisse et al.*, 1999, 2000]. X-ray emissions seem to be a general property of comets.

Various mechanisms have been invoked to explain the X-ray emissions from comets, including scattering and fluorescence of solar X-rays by cometary dust and gas, excitation by solar wind electrons and protons and by high-energy cometary ions, electron bremsstrahlung from gas and dust, and electron capture of the solar wind ions [*Cravens*, 1997; *Krasnopolosky*, 1997]. The lack of correlation found between the X-ray emission from comet Hyakutake and the solar X-ray flux suggest that the scattering of the solar X-rays by very small (10^{-18} g) dust particles is unlikely the dominant source for this comet [*Neugebauer et al.*, 2000]. However, this conclusion does not preclude significant contributions of this process for producing X-ray emissions from very dusty comets, like Hale-Bopp [*Owens et al.*, 1998]. Note that such contributions are of non-auroral origin. Even though the fraction of heavy ions (Z>2) in the solar wind is only of the order of 0.1 % to the total ion content, electron capture of high charge state solar wind minor ions (e.g., O^{6+}, C^{5+}, N^{5+}, and Si^{10+}) with cometary neutrals (mainly H_2O, OH, and O) is the dominant mechanism for producing X-rays at several comets, in particular at Hyakutake. The modeling of this process provides a total X-ray luminosity and a spatial morphology in relatively good agreement with observations [e.g., *Cravens*, 1997; *Wegmann et al.*, 1998; *Kharchenko and Dalgarno*, 2000]. Using Solar and Heliospheric Observatory (SOHO) particle observa-

tions, *Neugebauer et al.* [2000] demonstrated that the X-ray variability around comet Hyakutake can be explained on the basis of variability in oxygen ion flux.

A critical test for the X-ray excitation mechanism is provided by spectroscopy. Early low spectral resolution observations showed a continuous spectra, which can be reproduced by the electron capture mechanism [*Wegmann et al.*, 1998]. Recently, O^{4+}, O^{5+}, C^{4+}, and Ne^{7+} emission lines were detected by EUVE observations during a close passage of the comet Hyakutake at 0.1 AU [*Krasnopolsky and Mumma*, 2000] and from CXO observations of comet Linear [*Lisse et al.*, 2000]. These detections are the first direct evidence of the production of cometary X-rays by the interaction of solar wind heavy ions with cometary gas and, therefore, of the presence of auroral emissions at some comets. The variability of cometary X-ray emission induced by solar wind was discussed by *Kharchenko and Dalgarno* [2001].

Auroral emissions have also been discovered around the Jovian moon Io. The volcanic activity on Io provides a tenuous atmosphere rich in SO_2 gas and its dissociative products (SO, S, and O). Clorine and sodium, also detected in the atmosphere, are probably produced in the lava. Sublimation and surface sputtering by heavy ions are other sources of the atmosphere [see *Chap III.3*]. Io does not seem to have a significant intrinsic magnetic field. A plasma torus produced by pick up of the iogenic newly-born ions by the Jovian magnetic field surrounds Io's orbit and co-rotates with Jupiter's magnetosphere. Its interaction with Io's atmosphere is expected to produce aurora. It is then not surprising that oxygen, sulfur, and chlorine emissions from Io's atmosphere have been imaged in UV with HST/STIS [*Roesler et al.*, 1999; *Retherford et al.*, 2000a] and in the visible, with Io in eclipse, by Galileo SSI [*Geissler et al.*, 1999] and by HST/STIS with the OI 630.0 nm filter [*Retherford et al.*, 1999].

The most striking auroral features of Io are the bright regions close to Io's equator, called "equatorial spots". The brightness of these spots reaches values up to 2.5 kR for OI 135.6 nm. The emission is brightest at about 200 km above Io's surface and extends several hundred kilometers above that height. *Retherford et al.* [2000b] conducted a comprehensive analysis of these equatorial spots, based on UV HST/STIS images. The spot location is correlated with the orientation of the Jovian magnetic field lines near Io, attesting to the interaction of the Jovian magnetosphere and Io's atmosphere. Models suggest that

the emission location near the magnetic equator - defined as the place perpendicular to the local Jovian magnetic field - is caused by the strong divergence of the corotating plasma flow in the vicinity of the Io's highly conductive ionosphere [*Saur et al.*, 2000]. The brightness is correlated with Io's magnetic longitude, decreasing when Io is further away from the plasma torus' centrifugal equator, which is the densest part of the torus. This indicates that the plasma torus must control these atomic oxygen, sulfur, and chlorine emissions. Some features remain unexplained, such as the location of the anti-Jovian equatorial spots which are, on the average, closer to Io's equator than the magnetic field line tangent points.

Finally, another Jovian moon, Europa, also demonstrates auroral display. Using the HST/GHRS instrument in Earth's shadow, *Hall et al.* [1995] detected OI UV emissions. After removing the solar reflected component on Europa's surface, the OI 130.4 nm and OI 135.6 nm brightnesses were found to be of about 40 R and 70 R, respectively, with an emission region probably within less than 200 km of Europa's solid surface. Photo-excitation processes and resonance scattering of solar OI 130.4 nm photons by oxygen atoms cannot alone explained these brightnesses. *Hall et al.* [1998] showed that the most likely excitation process is electron impact on atmospheric species. The relative intensities of the two OI spectral features favors electron impact dissociation of O_2. Since Europa orbits deep within the Jovian magnetosphere and resides in the outer regions of the plasma torus roughly centered on the orbit of Io, it is likely that magnetospheric electrons of few tens of eV, as observed by Voyager 1 Plasma Science Experiment [*Bagenal*, 1994], are reaching and interacting with Europa's atmosphere.

The existence and stability of an oxygen atmosphere around Europa has been confirmed by HST/GHRS observations [*Hall et al.*, 1998] and by HST/STIS FUV images showing limb-brightening at Europa [*McGrath et al.*, 2000]. Similar to Ganymede, the major source of the atmospheric oxygen is sputtering of the icy surface and decomposition of ice by Io plasma torus ions [see *Chap III.3*]. The particle bombardment is expected to be continuous and intense at Europa's orbit. The HST/STIS images suggest that, unlike Io and Ganymede, Europa does not exhibit obvious concentration of emissions at the equator or the poles. Temporal and spatial variations do not seem to be correlated with the orientation of the Jovian magnetic field relative to Europa. The interaction of

Europa's atmosphere with the ambient plasma environment is not yet fully understood and needs to be further investigated.

3. MODELING OF AURORAL PROCESSES

The first step for modeling auroral processes is to describe how the energetic extra-atmospheric electrons, ions, and neutrals lose their energy and are redistributed in angle through collisions (sections 3.1 and 3.2). The collisional interaction can lead to an excitation of the incident energetic particle or of the ambient target species. The excited state may also be produced by, or be lost through, chemical reactions between atmospheric constituents (section 3.3). Finally, the photon emitted by de-activation of the excited state may be lost by absorption by ambient species or undergo multiple scattering before a possible escape from the atmosphere (section 3.4). The different steps for modeling auroral processes are summarized in Figure 1.

3.1. Kinetic Electron Transport Model

Throughout the solar system the major source of energetic particles is suprathermal electron population. Electrons represent 85% of the energy carried by particles precipitating over the terrestrial auroral ovals [*Hardy et al.*, 1989], and more than half of the energy precipitating over the Saturnian auroral ovals [*Barbosa*, 1990]. In these magnetized planets, energetic electrons precipitate from the planetary magnetosphere. Energetic electrons have also been observed in the vicinity of non-magnetized bodies, such as Venus. Suprathermal electrons - believed to be shocked solar wind electrons moving into the magnetized ionosphere from the tail region during high solar wind dynamic pressure - have been measured in the Venus nightside ionosphere [*Gringauz et al.*, 1979; *Spenner et al.*, 1981]. Energetic electrons have been measured in the magnetotail and plasma sheet of Mars by the Phobos 2 mission [*Verigin et al.*, 1991].

In addition to numerous collisions with the ambient neutrals (elastic scattering, excitation, ionization, and dissociation), suprathermal electrons transfer energy to the ambient thermal electron population through Coulomb collisions and wave excitation [*Rees*, 1989]. Sometimes this process is neglected [*Onda et al.*, 1999]. However, it must be taken into consideration when modeling the electron temperature of an ionosphere perturbed by electron precipita-

tion [e.g., *Stamnes and Rees*, 1983; *Gan et al.*, 1990]. It has been shown that the wave-electron interactions could play a significant role in the electron energetics of the ionosphere of Venus [*Cravens et al.*, 1990]. Usually the electric field acceleration, magnetic field curvature, and gravity are neglected, as they have negligible effect. By neglecting all these processes, electrons are confined to spiral along the magnetic field lines with only collisional energy and angular redistributions. The electrons produced by ionization due to the precipitating energetic electrons are called secondary electrons. For many auroral emissions they are the main excitation source. It is therefore crucial to take their contributions into account [e.g., *Strickland et al.*, 1993].

To describe the transport of suprathermal electrons in an atmosphere, one of the following methods is commonly used: The Continuous Slowing Down Approximation (CSDA) method, the Monte-Carlo (MC) simulation, and the direct solution of the Boltzmann equation (SBE). The simulated electron population is usually considered to have energies above few eV. The upper limit of the energy range is between a few hundreds of eV to few tens of MeV. For dayside studies, the transport of the photoelectrons produced by interaction of the solar photons with the atmosphere is described by the same models. The inputs to the models are the incident energetic electron flux at the top of the atmosphere, the density profiles of the atmospheric neutrals, and the collision cross sections between the energetic electrons and the ambient neutrals. When the heating of ambient electrons is considered, electron density and temperature are used as input parameters. The electron transport models yield the electron flux at different "altitudes" along the magnetic field line, energies, and pitch angles (defined as the angle between the magnetic field line and the electron velocity). Integrated quantities, such as the altitude profiles of the electron production rate or of the excitation rates of ambient species can be derived from the electron flux, the neutral densities and the ionization or excitation cross sections.

The CSDA method is based on the equation stating that the variation in altitude of the electron energy is equal to the negative of the product of the neutral density and the energy loss [e.g., *Rees*, 1989]. This method is relatively simple to implement. Angular redistribution can be included [*Régo et al.*, 1994]. Primary and secondary electron population can be computed self-consistently using the approach of *Rees et al.* [1969]. The drawback of the CSDA method rests

on its concept of continuous energy degradation. Such an assumption is not always warranted for low energy electrons and a discrete energy loss treatment is more appropriate [*Fox and Stewart*, 1991]. In addition, the equation to solve can only be integrated if the composition of the atmosphere is taken as constant over the entire atmosphere, or in several layers of different compositions, [e.g., *Singhal et al.*, 1992] or if the energy losses of the different neutral species are assumed proportional [*Régo et al.*, 1994].

The MC approach is a stochastic method based on the collision-by-collision algorithm [e.g., *Onda et al.*, 1999]. A large number of particles are considered and followed in the simulated atmosphere. The MC approach avoids the use of an energy grid. This can be of great interest for problems with electron energies ranging over five orders of magnitude, as it is the case in the high latitude terrestrial atmosphere [*Solomon*, 1993]. The drawback of the MC method is that it is computationally expensive, since it requires a large number of particles to reduce the statistical noise.

Among those presented, the most accurate method is to explicitly solve the Boltzmann equation, using two-stream or multi-stream approaches. In the former, only two pitch angles - up and down along the magnetic field lines - are considered which drastically simplifies the solution. However, for strongly anisotropic incident flux, a multi-stream approach is more suitable [*Lummerzheim et al.*, 1989]. The Boltzmann equation is applied to suprathermal electrons using the guiding center approximation [*Rees*, 1989]. The collisions between electrons and ambient neutrals are treated as discrete energy loss, whereas the energy transfer to thermal ambient electrons is considered continuous and thus introduced as a dissipative force [*Stamnes and Rees*, 1983]. Because the electron aurora on Earth is often relatively stable over several minutes and the collisional frequencies are of the order of 1-100 s^{-1}, the steady-state situation is commonly assumed. One exception is the application to flickering aurora as described by *Peticolas and Lummerzheim* [2000].

The SBE approach has been widely used in planetary studies. Examples of the two-stream approach include applications to the nightside ionosphere of Venus [*Cravens et al.*, 1983], the Venus ionopause boundary layer [*Gan et al.*, 1990], the ionosphere of Mars [*Haider et al.*, 1992], the Jovian atmosphere [*Grodent et al.*, 2001], and the atmosphere of Titan [*Gan et al.*, 1992]. The multi-stream approach has been applied to the terrestrial high-latitude [*Strick-*

land et al., 1989; *Lummerzheim et al.*, 1989] and low-latitude [*Rassoul et al.*, 1993] ionosphere, the Jovian ionosphere [*Perry et al.*, 1999] and the atmosphere of Titan [*Galand et al.*, 1999].

Validation of these models can be performed by ensuring particle and energy conservation and by comparison with other models [*Lummerzheim and Lilensten*, 1994; *Solomon*, 1993]. Comparison with laboratory measurements allows one step further in the validation process, with the checking of the cross section accuracy [*Lummerzheim and Lilensten*, 1994]. Terrestrial *in situ* observations of the particle flux by rocket experiments is a further step for electron transport validation [*Lummerzheim et al.*, 1989].

The geometry of the magnetic field line needs to be taken into account in the models, as the electron trajectory is bounded to it. Magnetic field lines are usually considered vertical or slanted by the dip angle for the terrestrial auroral regions. However, on Venus, the magnetic field lines are assumed parallel to the dayside ionopause [*Gan et al.*, 1990]. On the nightside, the magnetic field lines are considered horizontal in the magnetized ionosphere of Venus, assuming strong solar wind dynamic pressure conditions [*Cravens et al.*, 1983]. Another interesting example is Titan, whose ionosphere interacts with the corotating Saturnian plasma in which the magnetic field is frozen. Simple configurations have been adopted, like those proposed by *Gan et al.* [1992] and *Galand et al.* [1999]. The most appropriate approach for such a complicated case is to use MagnetoHydro-Dynamic (MHD) models [*Keller et al.*, 1994; *Ledvina and Cravens*, 1998]. Examples of such models applied to several solar system bodies are presented in *Chapters II.3 and II.4*.

The electron transport model provides the volume excitation rate associated with any excited state of the atmospheric species. If no additional atmospheric production or loss of the excited state occurs, the computation of the volume emission rate can be performed directly. That is usually the case for prompt auroral emissions, such as the 130.4 nm and 135.6 nm OI emission lines produced in the nightside ionosphere of Venus. Using an electron transport code and comparing the PVO/UVS data with the simulated brightness ratio of these lines, *Fox and Stewart* [1991] showed strong evidence for direct excitation of the OI lines by impact of low energy electrons on atomic oxygen. On the other hand, an electron transport code alone cannot model the terrestrial mid-latitude aurora where the oxygen lines are induced by precipitation of

O^+ and O from the ring current [*Ishimoto et al.*, 1994; *Tinsley et al.*, 1994]. An auroral emission unique to electron precipitation is the continuum X-ray radiation produced via bremsstrahlung by the energetic electrons themselves, as illustrated by *Østgaard et al.* [1998] for the Earth and by *Singhal et al.* [1992] for Jupiter. In both cases, for the computation of the column-integrated emission rate, not only the electron transport but also the photon transport need to be described (see Section 3.4).

3.2. Kinetic Ion/Neutral Transport Model

Energetic protons, as well as heavier ions and neutrals, have been measured throughout the solar system. Their origins are as diverse as the solar wind, the planetary ionosphere, or the rings and satellites. Energetic protons and oxygen ions near Venus are most likely produced by photoionization of Venusian upper atmospheric H and O accelerated by solar wind pickup process to few eV [*Luhmann et al.*, 1994]. Pickup processes have also been invoked for the Martian atmosphere to explain the production of energetic protons and oxygen ions, with Phobos as a partial source of neutral water molecules. Model calculations have shown that a substantial number of the pickup ions re-impact both Venus and Mars [*Luhmann and Kozyra*, 1991]. At Mars, the re-entering flux undergoes significant neutralization, which can lead to an escape or a loss in the atmosphere. Modeling also shows that charge-exchange between solar wind protons and the Martian upper atmosphere (H, H_2, O) in the subsolar region yields suprathermal H atoms with energies less than 1 keV [*Kallio et al.*, 1997]. On the Earth, protons of both solar and ionospheric origin and oxygen ions of ionospheric origin have been measured over the auroral ovals in the keV range [*Hardy et al.*, 1989; *Rees*, 1989]. MeV protons are a major energy source over the polar cap during solar particle events [*Patterson et al.*, 2001]. At mid-latitudes energetic protons and oxygen ions precipitate from the ring current and, below 20° in latitude the precipitating population is solely hydrogen and oxygen atoms produced by neutralization of the ring current ions [*Rassoul et al.*, 1993; *Ishimoto et al.*, 1994; *Bauske et al.*, 1997]. Due to the presence of an extended corona observed on Saturn and Uranus by Voyager, similar processes yielding H atom precipitation are expected in these giant planets [*Bhardwaj*, 1997]. Heavy ions, mainly oxygen and sulfur ions, but also sodium and carbon ions, have been detected in the magnetosphere of Jupiter by Ulysses [*Lanzerotti*

et al., 1992]. These ions are thought to have escaped as neutrals from the Io plasma torus but were photoionized before they could entirely escape Jupiter's magnetosphere and gain energy as they diffuse in toward Jupiter [*Eviatar and Barbosa*, 1984]. Energetic oxygen ions are also thought to originate from the icy moons by surface sputtering induced by energetic particles precipitating from the planet's magnetosphere. In the case of Saturn, rings are suggested to be another source of oxygen ions. Finally nitrogen ions observed in the magnetospheres of Saturn and Neptune are most likely Titanogenic and Tritonogenic, respectively.

Energetic ions and neutrals interact primarily with the atmospheric neutral species through ionization, excitation, dissociation, charge-changing reactions, and scattering. In dense plasma regions, ions also interact with the ambient plasma through Coulomb collisions leading to heating [e.g., *Kozyra et al.*, 1997]. However, each type of energetic particles interact differently with the atmosphere. For example, for the terrestrial atmosphere, an incident proton beam loses more than 90% of its energy to electron and ion production, whereas about 50% and 2% of the incident energy flux goes into ionization when He^+ and O^+ are the precipitating ions, respectively [*Ishimoto and Torr*, 1987]. Similar models are used to describe their transport in an atmosphere. The three types of approaches, CSDA, SBE, and MC, introduced for electron transport in section 3.1 are also found in the literature on ion/neutral transport modeling [*Decker et al.*, 1996].

The major difference between electron and ion/ neutral transport models come from the many ways ions/ neutrals experiences charge-changing reactions. These include capture (also called charge exchange or charge transfer) and stripping of an electron, which are not components of electron transport codes. For the CSDA models, the composition of the beam needs to be fixed and it is usually assumed that the beam is at charge equilibrium, as illustrated by *Singh* [1991] for hydrogen transport in the Jovian and Saturnian atmospheres or by *Cravens et al.* [1995] for oxygen transport in the Jovian atmosphere. The validity of the assumption of charge equilibrium is discussed by *Régo et al.* [1994; 1999] and by *Kharchenko et al.* [1998]. For hydrogen transport, when the incident particles have energies less than few keV, the equilibrium fraction favors the neutral state and a pure H atom beam can be assumed. That is the case for the ring current H atom precipitation on Saturn

and Uranus [*Bhardwaj*, 1997]. For the solution of the Bolztmann equations, two coupled equations need to be solved, one for the charge state and the other for the neutral state [e.g., *Galand et al.*, 1997]. Due to the complexity of this system, only one charge state can be taken into account. The CSDA and MC methods are more appropriate to X-ray emission simulations where one must consider all charge states from heavy neutral atom up to fully stripped particle [*Cravens et al.*, 1995; *Kharchenko et al.*, 1998].

For SBE and CSDA methods, the spreading of the beam - due to the neutral paths independent of the magnetic field lines - is neglected or considered via an attenuation coefficient applied to the center of the beam [*Jasperse and Basu*, 1982]. The space variables are reduced to one coordinate taken along the magnetic field line. Such an approach is justified if the incident beam is assumed to be sufficiently broad. It is definitily not appropriate for transport of incident neutral atoms as their mean free path can be very large, or for ions with very large gyroradii like those around Titan [*Galand et al.*, 1999] or Mars [*Brecht*, 1997]. In these cases a two or three spatial dimensional approach is needed. MC simulations can easily accomodate this as was illustrated by *Kallio and Barabash* [2001] for the Martian atmosphere bombarded by energetic H atoms. Note that for ring current particles, the time dependence needs to be included due to the ring current decay [*Bauske et al.*, 1997]. Finally, the effect of the magnetic field on the pitch angles of the energetic ions and neutrals is discussed for the case of proton aurora on Earth by *Galand and Richmond* [1999].

The magnetic field configuration is a concern for ion transport and needs to be properly accounted [e.g., *Luhmann and Kozyra*, 1991]. However, for low energy H atoms, like those precipitating into the Martian atmosphere [*Kallio and Barabash*, 2001], one need not consider the magnetic field geometry. Finally, the validation of the ion/neutral transport models [*Decker et al.*, 1996; *Galand et al.*, 1997] is performed in the same way as for electron transport codes (section 3.1).

Inside an energetic ion/neutral beam, the particles themselves can be excited by the interaction with the atmosphere. An example of such emissions is the Doppler-shifted H emissions produced by the energetic H atoms through electron capture of protons and through direct excitation. H Lyman α, H_α, and H_β Doppler-shifted emissions in the terrestrial auroral atmosphere are unique signatures of proton precipi-

tation [e.g., *Lummerzheim and Galand*, 2001; *Burch et al.*, 2001]. Such a signature is more difficult to observe for the giant planets as their atmosphere is mainly composed of H_2 and H. Another emission produced directly by the energetic particles is the X-ray emission coming from the excitation of the energetic heavy ions (K-shell lines). Using a CSDA transport model applied to the Jovian atmosphere, *Cravens et al.* [1995] estimated the X-ray emissions induced by highly charged excited MeV oxygen and sulfur ions. Comparisons of their simulations with ROSAT data support the assertion that the Jovian X-ray emissions are produced primarily by heavy ion precipitation.

The ion/neutral transport models are not sufficient to study other auroral emissions induced by an incident ion or neutral beam. Under proton precipitation, the H_2 Lyman and Werner bands in the Jovian atmosphere are primarily induced by the secondary electrons produced through ionization and electron stripping [*Régo et al.*, 1994]. Secondaries are also responsible for the $O(^1D)$ excited state yielding the red line in proton aurora in the terrestrial atmosphere [*Lummerzheim et al.*, 2001].

3.3. Atmospheric Model

Excitation of atmospheric species is produced by impact of energetic particles with ambient neutrals. The excited state can also be produced by reactions between atmospheric species, such as dissociative recombination and, at dayside, by the solar photons and induced photoelectrons. Photons are emitted when there is radiative decay to lower excited states. If the lifetime of the excited state is large, various other loss processes, such as collisional deactivation (quenching), can become dominant. Cascading from one excited state to a lower one, energy transfer between atmospheric constituents, radiative recombination, reaction with ambient thermal electrons, and atom-atom or ion-atom interchange reaction are sources of production or loss of the excited state. These processes involve atmospheric species, which can undergo diffusion and transport by neutral winds, or minor neutral or ionospheric species, whose density is perturbed by the particle precipitation. The atmosphere is also heated by interaction with the energetic particles yielding thermal IR emissions, like in the hydrocarbon layer of Jupiter [*Kim*, 1988]. For these cases, one needs a comprehensive atmospheric model, which solves the conservation equations or the first moments of the Boltzmann equations to infer the emission rate of the auroral emis-

sions. The first 5 moments solve the density, momentum, and energy equations. Fluid models including chemical, hydrodynamic, and MHD models, are described in detail in *Chap I.3* for the ionospheric species. Global three-dimensional models, such as the General Circulation Model (GCM), have been developed for terrestrial planets [see *Chap IV.1*], for Jupiter [see *Chap IV.2*], and for moons with significant atmosphere [see *Chap IV.4*], A coupling of these models with a kinetic transport code is usually too time consuming and fast computational schemes must be developed to account for precipitating particles as source of excitation, ionization, or heating [e.g., *Roble and Ridley*, 1987].

Often chemical equilibrium is assumed for the excited state when computing the excited state density, n^*. The emission rate η is derived from: $\eta = A\,n^*$, with A being the Einstein coefficient for spontaneous radiative transition in s^{-1} [e.g., *Rees*, 1989]. Note that the computation of the total emission rate may require one to consider the contribution of additional emission sources, such as chemiluminescent reactions, which occur when fragments or ions produced by dissociation or ionization recombine and emit, as illustrated for the Venusian nightglow by *Fox* [1992].

An example of the computation of the nightside aurora requiring the use of a chemical atmospheric model is proposed by *Haider et al.* [1992] for the red line OI (630.0 nm) in the Martian atmosphere. A kinetic electron transport code is used to compute the $O(^1D)$ production rate induced by the precipitating electrons as well as the ion production rates. The incident electron flux was derived from the Phobos 2 data for the magnetotail and for the plasma sheet. Assuming chemical equilibrium, the ion densities, especially O_2^+, CO_2^+, and O^+, were determined and the excitation rate of the red line associated with the dissociative recombination of O_2^+ was derived. The authors reproduced the red line emission including quenching of the excited state $O(^1D)$ by O and CO_2. A brightness of 35 R and 20 R were obtained for the magnetotail and the plasma sheet, respectively. As a result of lower incident electron flux, these values are very small compared with the brightness of the red line in the terrestrial auroral oval, whose value reaches several kR for active magnetic conditions [*Rees and Roble*, 1986]. *Haider et al.* [1992] also showed that in the Martian nighttime atmosphere the red line is dominantely airglow [see *Chap I.5*]. The $O(^1D)$ is mainly produced by recombination of O_2^+, whereas in the terrestrial auroral regions the impact by ener-

getic electrons is the dominant source of excitation [*Solomon et al.*, 1988].

Another example of auroral emissions is the IR radiation produced by vibrationally excited H_3^+ in the Jovian atmosphere. Analysis of the 2 μm and 4 μm IR region emissions can provide some insight into this species (abundance, temperature). In order to simulate the IR radiations produced by H_3^+ in the dayside auroral Jovian ionosphere, *Kim et al.* [1992] used an electron transport code and an ionospheric model solving the continuity equation for H^+, H_2^+, several vibrational levels of H_3^+ and H. Hydrogen atom and electron densities were self-consistently computed through several iterations between the kinetic code and the atmospheric model. A significant source of H_3^+ is the charge transfer from H^+ to vibrationally excited H_2 producing H_2^+, which quickly reacts with H_2. Molecular diffusion is important at high altitudes and the momentum equation for several vibrational levels of H_2 was also solved. The theoretical ionospheric calculations were coupled with the vibrationally excited H_2 calculations in a self-consistent manner. *Kim et al.* [1992] showed that precipitation of 10 keV electrons with a flux of 1 erg cm^{-2} s^{-1} produced vibrational distribution of H_2 and H_3^+ that are consistent with the IR emissions observed in Jovian auroral regions.

3.4. Photon transport model

Photons produced in aurora can undergo multiple scatterings before being absorbed in the atmosphere or escaping through its lower or upper boundary. If the kinetic atmospheric temperature is sufficiently high, the spectral line is Doppler broadened. If the neutral winds are significant, the line is Doppler shifted. For emissions by energetic particles, the line is both Doppler shifted and broadened. The last step for deriving the spectral profile and the brightness of an emergent auroral emission, that is, its column integrated volume emission rate, is the description of the transport of photons in the atmosphere, also called radiative transfer.

At first, we consider the case of atmospheric absorption with negligible scattering (true absorption). The absorption by atmospheric constituents of a photon of wavelength λ, emitted at an altitude z_0 is evaluated through the optical thickness τ_λ of the atmosphere, also called absorption optical depth. For observations along the nadir, τ_λ is defined as the product of the absorption cross section and the density of the absorbing gas integrated between z_0 and the altitude

of the observer. The medium is said to be optically thin to radiation of wavelength λ if $\tau_\lambda \ll 1$; Otherwise it is optically thick and the atmospheric absorption is significant and needs to be taken into account. The transport of photons emitted at a given altitude z_0 is described by the Beer-Lambert absorption law:

$$\frac{dI_\lambda^{z_0}}{d\tau_\lambda} = -I_\lambda^{z_0} \qquad (1)$$

where $I_\lambda^{z_0}$ is the brightness associated with the emission at λ and z_0 and is a function of τ_λ, which, in turn, is a function of z. The total auroral brightness, I_λ, of the emergent emission at the top of the atmosphere (z=z$_\infty$) is expressed as:

$$I_\lambda = \frac{1}{\cos \alpha} \int_0^{z_\infty} exp(-\tau_\lambda(z_0, z_\infty)) \, \eta_\lambda(z_0) \, dz_0 \qquad (2)$$

where α is the viewing angle from the vertical, η_λ is the emission rate at λ, and z$_\infty$ is the altitude of the top of the atmosphere. Because of inherent field-aligned structure the observations are usually field-aligned and α is the angle between the magnetic field and the vertical.

In the Jovian atmosphere the absorption of the auroral emissions by the hydrocarbon layer can be exploited to derive the characteristics of the precipitating particles [*Yung et al.*, 1982]. The H_2 Lyman and Werner bands (90-170 nm) induced by electrons and protons with energies of several tens of keV are produced at or below the hydrocarbon layer and thus undergo atmospheric absorption before escaping the atmosphere. As the absorption by hydrocarbon takes place mainly at wavelengths shorter than 145 nm, the brightness ratio in two different wavelength bands on either sides of 145 nm, also called the color ratio, is an indicator of the CH_4 abundance above the auroral source. This also infers the penetration depth of the particles and thus the energy of the incident particles at the origin of the aurora [*Régo et al.*, 1999]. Similarly, in the Earth's auroral atmosphere, the absorption by Schumann-Runge bands of O_2 is used to derive the mean energy of incident precipitating electrons [see *Chap II.2*].

In addition to true absorption by atmospheric constituents, the emitted photons can be temporarily absorbed by an atmospheric atom or molecule and immediately re-emitted (scattering). Resonance scattering consists of the absorption of a photon causing a transition to a higher electronic state of the absorber, followed by the emission of a photon as the state decays back to the original lower state. The

wavelength of the emitted radiation is nearly the same as the wavelength of the radiation absorbed, but the directional behavior is changed. An example is the OI(130.4 nm) in the Venusian, Martian, and Earth's atmospheres. Another example is the H Lyman α emission in the outer planets. In fluorescent scattering, photons of a given wavelength are absorbed by the atoms of a medium followed by the emission of photons at a wavelength longer than the one of the absorbed photons. Upon each scattering, the upper states can decay to any of a number of lower states other than the ground state, which is called radiative cascade. Both resonance and fluorescence scatterings are limited to transitions that are dipole allowed, whereas energetic particle impact processes can produce excited states that are connected to the ground state by dipole forbidden transitions. Unlike resonance and fluorescence scatterings, Rayleigh scattering is a non-selective scattering process. In the Earth's atmosphere, it occurs over the whole visible range with a $1/\lambda^4$ dependence. The well known consequence of this scattering is the blue color of the sky and the red color of the rising or setting Sun.

In presence of multiple scattering, modeling the emergent auroral emissions at the top of the atmosphere requires one to solve the radiative transfer equation [*Meier*, 1991]:

$$\mu \frac{dI}{d\tau_\lambda} = -I + S \qquad (3)$$

where I is the intensity of the photons, in photons cm^{-2} s^{-1} sr^{-1}, in the direction arccos μ defined from the vertical axis. I is a function of the position, propagation direction, wavelength and, in case of multiplet resonance scattering, of line component. In a scattering event, a photon may be emitted in any of the lines of the multiplet sharing a common upper state following the branching ratio. τ_λ is the vertical extinction optical depth, composed of the extinction due to scattering and true absorption. The source function, S, has several components. The photons are produced within the atmosphere by particle impact excitation, chemical excitation, and multiple scattering, and, at dayside, by the solar radiation incident at the top of the atmosphere. Through multiple scattering, S depends on the intensity I at different location or wavelength. Several approaches can be adopted to solve the radiative transfer equation (3). The general one considers the angle-dependent partial redistribution function (PFR). It is required when scattering occurs outside the Doppler core of

the line. The photons retain a memory of their pre-scattered frequency. On the other hand, when incident photons with frequencies in the Doppler core of the line are mostly scattered by atoms with velocities near the thermal speed, one can assume that there is complete incoherence of frequency in the scattering process. This is known as complete frequency redistribution (CFR). It can be applied when the opacity of the scattering atmosphere (usually defined as the vertical optical depth from the top of the atmosphere down to an altitude where scattering is no longer important or where extinction dominates) is less than a few hundred [*Meier*, 1991]. When the scale height is of the order of the planet or satellite's radius, a spherical geometry needs to be considered [*Bush and Chakrabarti*, 1995].

Gladstone [1992] used a radiative transfer model to simulate the resonance scattering of OI (130.4 nm) triplet emission in the terrestrial atmosphere. Because the width of an aurora can be much smaller than the scale height for atomic oxygen in the auroral region, typically in the 25-50 km range, the radiative transfer of OI resonance emissions are distinctly non-plane-parallel in most aurorae. *Gladstone* [1992] for the first time used a two-dimensional radiative transfer code in a realistic way to simulate auroral resonance lines. A plane-parallel approximation in such a case yields a significant over-estimation of the line brightness. On the Earth, a two-dimensional simulations approach the plane-parallel brightness only when the auroral widths are several hundred to several thousand kilometers. Such an analysis can provide new insights about both the structure of the auroral atmosphere and the nature of the aurora itself.

Another example of multiple scattering deals with the H Lyman α line produced in the Jovian aurora, as proposed by *Régo et al.* [1999]. The Ly α photons produced by excitation of the atmospheric H and H_2 by precipitating electrons and protons are emitted at the rest wavelength and thus are strongly resonantly scattered due to the large abundance of atomic hydrogen in the upper atmosphere of Jupiter. The use of a radiative transfer model, along with an electron and a proton transport models (here CSDA), is required to compute the Ly α profile in the Jovian aurora produced by the atmospheric species. The simulation shows a strong reversal of the line, resulting from the absorption of the H Ly α photons by atomic hydrogen becoming resonant near the rest (or center) wavelength. After getting absorbed, the photons are partly reemitted according to the frequency redistri-

bution function at a different wavelength in the wings of the line, where the atmosphere is optically thin. Such a conclusion corroborates earlier finding inferred from HST observations with the GHRS [*Prangé et al.*, 1997]. The width and depth of the reversal are reliable measures of the H column density along the line of sight to the emission source altitude, which is a function of the mean energy of precipitating particles. As the energy of the incident particles increases, the H column density above the emitting layer increases, the emission becomes fainter, and the line profile broadens. For a given penetration depth, the emergent line profile is comparable for proton and electron excitations. However, the analysis can be used for diagnostic of the incident energy, especially in the low energy range where traditional methods using the hydrocarbon absorption signatures in the H_2 spectra [*Régo et al.*, 1999] become inefficient.

4. CONCLUSION AND DISCUSSION

In Section 2 we offered a survey of the auroral emissions which have been observed in the solar system. The origin of these emissions is, in general, common, which allows us to develop similar models presented in Section 3. As a result, models developed for a relatively well-known atmosphere where validation is possible (e.g., the Earth) are often exported to other solar system bodies. On the other hand, the diversity of the plasma sources and atmospheres, and, therefore, of the auroral emissions, illustrated in Table 1, makes it ideal for comparative auroral studies. As discussed in Section 2, the magnetic environment can be intrinsic or induced and a large diversity of magnetospheric geometries is encountered. Auroral emissions give us unique remote sensing of magnetic field configurations and are a tracer of plasma interactions. The aurora at Io's footprint in the Jovian atmosphere further constraints the source region of the Jovian main oval within the current sheet and thereby Jupiter's magnetic field configuration [*Connerney et al.*, 1998]. X-ray emissions from certain comets attest to the interaction of the solar wind heavy ions with the cometary gas [*Lisse et al.*, 2000].

Auroral emissions are an indicator of the source of energetic particles and can be used for remote sensing of the characteristics of the incident particles (type, energy, flux). The OI 135.6 nm auroral emission observed around Io is prompt and is not resonantly scattered. It can be used as a valuable probe of the Jovian

plasma conditions at Io, where the auroral brightness increases with the density of plasma torus at Io's location [*Retherford et al.*, 2000b]. The analysis of O and CO emissions on the nightside of Venus has shown evidence of precipitation of soft electrons [*Fox and Stewart*, 1991]. On the Earth, auroral emissions observed from ground are used to investigate proton and electron dynamics during magnetospheric substorms [e.g., *Deehr and Lummerzheim*, 2001]. From space, the entire auroral oval has been imaged by Polar in UV and X-rays for estimating the characteristics of the incident soft and hard electron populations, a crucial information for space weather applications [see *Chap II.2*].

The aurora is also a fingerprint of the atmospheric composition. Analysis of UV spectroscopic observations revealed the presence of an O_2 atmosphere on Europa [*Hall et al.*, 1995]. Recently, chlorine was detected in the auroral equatorial spots at Io [*Retherford et al.*, 2000a]. The detection of H_3^+ in the Jovian atmosphere through IR observations in the auroral regions was the first astronomical spectroscopic identification of these spectral bands in the universe [*Drossart et al.*, 1989]. From spectroscopic analysis of the IR lines produced in the Jovian atmosphere, not only the abundance of emitting constituents was derived, but also the temperature of the ionosphere from H_3^+ emissions [*Drossart et al.*, 1993a] and of the stratosphere from the hydrocarbons emissions [*Drossart et al.*, 1993b].

Diverse magnetic configurations and origins, energetic particle sources and their energy ranges, and differing atmospheric constituents, all contribute to make comparative auroral study a rich field. If we consider X-ray emissions for instance, they are produced by electron capture of heavy solar wind ions with ambient neutrals at some comets [*Lisse et al.*, 2000]; by magnetospheric heavy oxygen and sulfur ions precipitating from the $L = 8 - 12$ region of Jupiter to high latitude ionosphere [*Bhardwaj and Gladstone*, 2000a]; by heavy ions precipitating from the inner Jovian magnetosphere (with a significant non-auroral contribution from reflected or fluoresced solar X rays) [*Gladstone et al.*, 1998]; by energetic electrons through bremsstrahlung emissions in the high latitude regions of Earth [*Østgaard et al.*, 2000] and probably at Saturn [*Ness and Schmitt*, 2000]. The known processes producing X-rays at certain comets are also expected to occur at Venus and Mars, offering a remote sensing of the interaction of the solar wind with these non-(or at least low) magnetized

planets [*Cravens*, 2000; *Holmström et al.*, 2001]. It is interesting to note that the emitted X-ray power within the 0.1-2. keV band for the comet Hyakutake (4×10^8 W) [*Lisse et al.*, 1996] and the one for Jupiter (10^9 W) [*Waite et al.*, 1994] are similar. The brightness near Hyakutake is weak, of the order of 0.01 R [*Mumma et al.*, 1997], whereas in the auroral region of Jupiter it is larger than 0.1 R [*Waite et al.*, 1997]. However, the emission area around the comet is very wide, extending well beyond cometocentric distances of 200,000 km [*Lisse et al.*, 1996]. The incident energy of the particles is also very different, of the order of 1 keV/amu (atomic mass unit) for the solar wind high-charged state, heavy ions interacting with the cometary neutrals [*Cravens*, 1997], while it is about 1 MeV nucleon^{-1} or more for the oxygen and sulfur ions precipitating into the auroral region of Jupiter [*Waite et al.*, 1994]. As a result, the spectra emitted around a comet are quite different from those emitted in Jupiter's atmosphere. So, despite a similar mechanism of production of X-rays by interaction of heavy ions with a neutral gas, different characteristics are found between auroral emissions on comet Hyakutake and on Jupiter.

Another interesting emission for comparative auroral study is the OI 135.6 nm line observed around several bodies of the solar system. In the terrestrial high latitude regions, the oxygen line is produced over the auroral ovals by keV particles and its brightness is on the order of kR. On the nightside of Venus, the oxygen emissions appear as patches, with a typical brightness of 1 R above the background [*Fox and Stewart*, 1991]. On the Galilean moons the OI 135.6 nm brightness varies from up to several kR on Io [*Roesler et al.*, 1999] down to 250 R on Ganymede [*Feldman et al.*, 2000] and to less than 100 R on Europa [*Hall et al.*, 1995]. On Europa the OI UV aurora is diffuse, whereas it is seen at the equator of Io and at the poles of Ganymede. This provides a clear example of the different interactions of the planetary magnetospheric plasma with moons. The intrinsic magnetic field of Ganymede prevents the Jovian plasma to reach low latitude regions, whereas a complex current system occurs at the highly conductive Io and less strong interaction takes place at Europa.

If aurora offers us a unique and extremely valuable probe of our solar system, its analysis and modeling can encounter challenges. To estimate the auroral brightness from observations is not always easy. In addition to auroral origin, the observed signal can be terrestrial airglow or solar scattering occurring in the dayside atmosphere or on cometary dust. The signal could be due to solar reflection on a surface like at Europa, or emissions photo-chemically produced or associated with the volcanic plumes of Io. A careful estimation of these other sources is a critical step in the auroral analysis. As for modeling, although the basic equations are similar, the uncertainties on many parameters can prevent retrieval of information, such as on the energetic particle source, from the analysis of auroral emissions. Some knowledge of, or assumptions regarding, the atmospheric densities and the incident energetic particles is required. Uncertainties in cross sections or in reaction rates are limiting factors for the analysis. If the emissions undergo resonance scattering it is difficult to track the location of the source. In the presence of energetic neutral particles or for limb observations, the analysis is complicated by the likely contribution of multiple sources of different characteristics. For incident energetic electrons or ions, the configuration of the magnetic field lines needs to be known. MHD and hybrid particle models of the plasma environment are crucial tools for answering this concern [see *Chapters II.3 and II.4*].

Finally, the definition we propose for aurora can be debated. Some would consider it to be too inclusive, others too exclusive. Having taken the task of investigating aurora in our solar system, which offers such diverse emissions and having concern for clarity and consistency, we propose this definition, with its limitations, and try to follow it as closely as possible throughout the paper. Choosing to focus on optical emissions, we have excluded radio emissions, which are observed in the auroral regions of Earth and of the giant planets. Even though energetically negligible, they are the only means to determine the rotation rate of the giant planet interiors [*Zarka*, 1998]. In our definition we assume the energetic particles interact with an atmosphere. We could extend it to the surface of planets and moons. Soft X-ray observations with ROSAT have revealed an unexpected emission at the dark side of the moon [*Schmitt et al.*, 1991]. This emission probably results from energetic solar-wind electrons striking the moon's surface. Another body deprived of a significant atmosphere is Mercury, where time variable high-latitude enhancements of visible sodium radiations from the exosphere have been seen [*Killen et al.*, 1990; *Killen and Ip*, 1999]. One proposed explanation is that, during magnetic substorms, sputtering of surface minerals by precipitating ions releases sodium vapor in the polar regions [*Potter and Morgan*, 1990]. The observed emission

is sunlight scattered at the sodium resonance lines. With the absence of limb brightnening, the polar aurora at Ganymede could be the result of a similar interaction of energetic particles with its surface. On the Earth, Stable Auroral Red (SAR) arcs seen in mid-latitude night sky are sub-visual emissions from oxygen at 630.0 nm. They reflect the slow energy loss from the ring current ions, but the exact sequence of physical processes occurring between the energy source and the emission region is a matter of continuing debate [*Kozyra et al.*, 1997]. Heat flux can be one possible energy transfer process down to the ionosphere. If this process is found to be the dominant mechanism, will it be a reason to rename SAR arcs? Our main concern is not how to name the emissions observed at Mercury and in the Earth's mid-latitude. It is their analysis that offers us a unique probe of the solar wind interaction with Mercury's magnetosphere or of the energy loss in the ring current of the Earth.

With improving observational techniques, with new space missions and with more comprehensive modeling tools, investigation of electromagnetic radiations, in particular multispectral observations of aurora, along with complementary measurements (plasma, neutral atmosphere), is expected to provide a wealth of precious information on our solar system and to lead us to further understanding of interactions taking place at solar system bodies, such as planets, moons, and comets.

References

Abreu, V.J., R.W. Eastes, J.H. Yee, S.C. Solomon, and S. Chakrabarti, UV nightglow production near the magnetic equator by neutral particle precipitation, *J. Geophys. Res.*, *91*, 11,365-11,368, 1986.

Anderson, K., Balloon measurements of X-rays in the auroral zone, in *Auroral phenomena*, M. Walt ed., 46, Stanford University Press, 1965.

Anderson, P.C., D.L. McKenzie, M. Brittnacher, M. Chen, M. Hairston and M.F. Thomsen, Global storm time auroral X-ray morphology and timing and comparison with UV measurements, *J. Geo-phys. Res.*, *105*, 15,757, 2000.

Bagenal, F., Empirical model of the Io plasma torus: Voyager measurements, *J. Geophys. Res.*, *99*, 11,043, 1994.

Barbosa, D.D., Auroral precipitation flux of ions and electrons in Saturn's outer magnetosphere, *Planet. Space Sci.*, *38*, 1295-1304, 1990.

Bauske, R., S. Noël, and G.W. Prölss, Ionospheric storm effects in the nighttime E region caused by neutralized ring current particles, *Ann. Geophys.*, *15*, 300-305, 1997.

Bhardwaj, A., Ring current H atom precipitation on the outer planets, *Adv. Space Res.*, *20*, 233-237, 1997.

Bhardwaj, A., and G.R. Gladstone, Auroral emissions of the giant planets, *Rev. Geophys.*, *38*, 295-353, 2000a.

Bhardwaj, A., and G.R. Gladstone, Auroras on Saturn, Uranus, and Neptune, *Adv. Space Res.*, *26*, 1551, 2000b.

Bishop, J., S.K. Atreya, P.N. Romani, G.S. Orton, B.R. Sandel, and R.V. Yelle, The middle and upper atmosphere of Neptune, in *Neptune and Triton*, edited by D. P. Cruikshank, pp. 427-487, Univ. of Ariz. Press, Tucson, 1995.

Brace, L.H., et al., The ionotail of Venus - Its configuration and evidence for ion escape, *J. Geophys. Res.*, *92*, 15, 1987.

Brecht, S.H., Solar wind proton deposition into the Martian atmosphere, *J. Geophys. Res.*, *102*, 11,287-11,294, 1997.

Broadfoot, A.L., et al., UV spectrometer observations of Uranus, *Science*, *233*, 74-79, 1986.

Broadfoot, A.L., et al., UV spectrometer observations of Neptune and Triton, *Science*, *246*, 1459, 1989.

Brown, M.E., and A. Bouchez, Observations of Ganymede's visible aurorae, *Bull. Am. Astron. Soc./ Div. Planet. Sci. Meet.*, *31*, #70.08, 1999. Note: The emissions appear to the concentrated at the equator, not poles, of the satellite.

Burch, J.L., et al., Views of Earth's magnetosphere with the IMAGE satellite, *Science*, *291*, 619-624, 2001.

Bush, B.C., and S. Chakrabati, A radiative transfer model using spherical geometry and partial frequency redistribution, *J. Geophys. Res.*, *100*, 19627-19642, 1995.

Caldwell, L., F.C. Gillett, and A.T. Tokunaga, Possible IR aurorae on Jupiter, *Icarus*, *44*, 667-675, 1980.

Chakrabarti, S., Extreme and far ultraviolet emis-

sions from the polar cap, *J. Geophys. Res.*, *91*, 8065-8072, 1986.

Chakrabarti, S., Ground-based spectroscopic studies of sunlit airglow and aurora, *J. Atmos. Solar-Terr. Phys.*, *60*, 1403-1423, 1998.

Chamberlain, J.W., Physics of the aurora and airglow, Classics in geophysics, *AGU*, Washington, D.C., 1995.

Chen, M.W., and M. Schulz, Simulations of storm time diffuse aurora with plasmasheet electrons in strong pitch angle diffusion, *J. Geophys. Res.*, *106*, 1873-1886, 2001.

Cheng, A.F., Triton torus and Neptune aurora, *Geophys. Res. Lett.*, *17*, 1669-1672, 1990.

Chenette, D.L., D.W. Datlowe, R.M. Robinson, T.L. Schumaker, R.R. Vondrak, and J.D. Winnimgham, Atmospheric energy input and ionization by energetic electrons during the geomagnetic storm of 8 - 9 November, 1991, *Geophys. Res. Lett.*, *20*, 1323-1326, 1993.

Chenette, D.L., et al., Global energy-resolved X-ray images of northern aurora and their mappings to the equatorial magnetosphere, in *Sun-Earth Plasma Connections*, Geophys. Monog. Ser., *109*, J. Burch ed., p.65, *AGU*, Washington, D.C., 1999.

Christensen, A.B., G.J. Romick, and G.G. Sivjee, Auroral OI (989 Å) and OI (1027 Å) emissions, *J. Geophys. Res.*, *82*, 4997-5003, 1977.

Clarke, J.T., Detection of auroral hydrogen Lyman-α emission from Uranus, *Astrophys. J.*, *263*, L105-L109, 1982.

Clarke, J.T., et al., Continued observations of the H Ly α emission from Uranus, *J. Geophys. Res.*, *91*, 8771, 1986.

Clarke, J.T., et al., Hubble Space Telescope imaging of Jupiter's UV aurora during the Galileo orbiter mission, *J. Geophys. Res.*, *103*, 20,217-20,236, 1998.

Clarke, J.T., HST/Cassini Campaign of Jupiter Auroral Observations, *EOS Trans. AGU*, *82*, S252, 2001.

Connerney, J.E.P., M.H. Acnua, and N.F. Ness, The magnetic field of Uranus, *J. Geophys. Res.*, *92*, 15,329, 1987.

Connerney, J.E.P., R.L. Baron, T. Satoh, and T. Owen, Images of excited H_3^+ at the foot of the Io flux tube in Jupiter's atmosphere, *Science*, *262*, 1035-1038, 1993.

Connerney, J.E.P., M.H. Acuna, N.F. Ness, and T. Satoh, New models of Jupiter's magnetic field constrained by the Io flux tube footprint, *J. Geophys.*

Res., *103*, 11,929, 1998.

Craven, J.D., and L.A. Frank, Latitudinal motions of the aurora during substorms, *J. Geophys. Res.*, *92*, 4565, 1987.

Cravens, T.E., Comet Hyakutake X-ray source: Charge transfer of solar wind heavy ions, *Geophys. Res. Lett.*, *24*, 105-108, 1997.

Cravens, T.E., X-ray emission from comets and planets, *Adv. Space Res.*, *26*, 1443-1451, 2000.

Cravens, T.E., S.L. Crawford, A.F. Nagy, and T.I. Gombosi, A two-dimensional model of the ionosphere of Venus, *J. Geophys. Res.*, *88*, 5595-5606, 1983.

Cravens, T.E., D. Wu, and H. Shinagawa, A two-dimensional kinematic dynamo model of the ionospheric magnetic field at Venus, *Geophys. Res. Lett.*, *17*, 2261-2264, 1990.

Cravens, T.E., E. Howell, J.H. Waite Jr., and G.R. Gladstone, Auroral oxygen precipitation at Jupiter, *J. Geophys. Res.*, *100*, 17,153-17,161, 1995.

Decker, D.T., B.V. Kozelov, B. Basu, J.R. Jasperse, and V.E. Ivanov, Collisional degradation of the proton-H atom fluxes in the atmosphere: A comparison of theoretical techniques, *J. Geophys. Res.*, *101*, 26,947-26,960, 1996.

Deehr, C., and D. Lummerzheim, Ground-based optical observations of hydrogen emission in the auroral substorm, *J. Geophys. Res.*, *106*, 33-44, 2001.

Dennerl, K., J. Englhauser, and J. Trümper, X-ray emissions from comets detected in the Röntgen X-ray satellite all-sky survey, *Science*, *277*, 1625-1630, 1997.

Dessler, A.J., *Physics of the jovian magnetosphere*, Cambridge Univ. Press, New York, 1983.

Doe, R.A., M. Mendillo, J.F. Vickrey, L.J. Zanetti, and R.W. Eastes, Observations of nightside auroral cavities, *J. Geophys. Res.*, *98*, 293-310, 1993.

Drossart, P. et al., Detection of H_3^+ on Jupiter, *Nature*, *340*, 539-541, 1989.

Drossart, P., J.-P. Maillard, J. Caldwell, and J. Rosenqvist, Line-resolved spectroscopy of the Jovian H_3^+ auroral emission at 3.5 micrometers, *Astrophys. J.*, *402*, L25-28, 1993a.

Drossart, P., B. Bezard, S.K. Atreya, J. Bishop, J.H. Waite, Jr., and D. Boice, Thermal profiles in the auroral regions of Jupiter, *J. Geophys. Res.*, *98*, 18,803-18,811, 1993b.

Eather, R.H., Majestic lights, The aurora in science, history, and arts, *Amer. Geophys. Union*, Washington, D.C., 1980.

Eviatar, A., and D.D. Barbosa, Jovian magnetospheric

neutral wind and auroral precipitation flux, *J. Geophys. Res.*, *89*, 7393-7398, 1984.

Eviatar, A., D.J. Williams, C. Paranicas, R.W. McEntire, B. H. Mauk, and M. G. Kivelson, Trapped energetic electrons in the magnetosphere of Ganymede, *J. Geophys. Res.*, *105*, 5547-5553, 2000.

Eviatar, A., D.F. Strobel, B.C. Wolven, P.D. Feldman, M.A. McGrath, and D.J. Williams, Excitation of the Ganymede UV aurora, *Astrophys. J.*, *555*, 1013-1019, 2001.

Feldman, P.D., M.A. McGrath, D.F. Strobel, H.W. Moos, K.D. Retherford, and B.C. Wolven, HST/STIS UV imaging of polar aurora on Ganymede, *Astrophys. J.*, *535*, 1085-1090, 2000.

Fox, J.L., Models for aurora and airglow emissions from other planetary atmospheres, *Can.J.Phys.*, *64*, 1631, 1986.

Fox, J.L., Airglow and aurora in the atmospheres of Venus and Mars, *Venus and Mars: Atmospheres, ionospheres, and solar wind interactions*, Proceedings of the Chapman Conference, Balatonfured, Hungary, June 4-8, 1990, *AGU*, Washington, D.C., 191-222, 1992.

Fox, J.L., and A.I.F. Stewart, The Venus UV aurora - a soft electron source, *J. Goephys. Res.*, *96*, 9821, 1991.

Galand, M., and A.D. Richmond, Magnetic mirroring in an incident proton beam, *J. Geophys. Res.*, *104*, 4447, 1999.

Galand, M., J. Lilensten, W. Kofman, and R.B. Sidje, Proton transport model in the ionosphere 1. Multistream approach of the transport equations, *J. Geophys. Res.*, *102*, 22261-22272, 1997.

Galand, M., J. Lilensten, D. Toublanc, and S. Maurice, The ionosphere of Titan: Ideal diurnal and nocturnal cases, *Icarus*, *140*, 92-105, 1999.

Gan, L., T.E. Cravens, and M. Horanyi, Electrons in the ionopause boundary layer of Venus, *J. Geophys. Res.*, *95*, 19,023-19,035, 1990.

Gan, L., C.N. Keller, and T.E. Cravens, Electrons in the ionosphere of Titan, *J. Geophys. Res.*, *97*, 12,137, 1992.

Gao, S., C.W. Ho, T.S. Huang, and C.J. Alexander, Uranus's magnetic field and particle drifts in its inner magnetosphere, *J. Geophys. Res.*, *103*, 20,257-20,265, 1998.

Geballe, T.R., M.-F. Jagod, and T. Oka, Detection of H_3^+ IR emission lines in Saturn, *Astrophys. J.*, *408*, L109, 1993.

Geissler, P.E., A.S. McEwen, W. Ip, M.J.S. Belton, T.V. Johnson, W.H. Smyth, and A.P. Ingersoll,

Galileo imaging of atmospheric emissions from Io, *Science*, *285*, 870, 1999.

Gladstone, G.R., Auroral resonance line radiative transfer, *J. Geophys. Res.*, *97*, 1377-1387, 1992.

Gladstone, G.R., J.H. Waite Jr., and W.S. Lewis, Secular and local time dependence of Jovian X ray emissions, *J. Geophys. Res.*, *103*, 20,083-20,088, 1998.

Gladstone, G.R., et al., X-ray Emissions from Jupiter, *EOS Trans. AGU*, *82*, S301, 2001.

Gordiets, B., Excitation of vibrational emission bands in aurora and airglow, *Can. J. Phys.*, *64*, 1673-1678, 1986.

Gringauz, K.I., M.I. Verigin, T.K. Breus, and T. Gombosi, The interaction of electrons in the optical umbra of Venus with the planetary atmosphere - The origin of the nigthttime ionosphere, *J. Geophys. Res.*, *84*, 2123-2127, 1979.

Grodent, D., J.H. Waite, Jr., and J.-C. Gerard, A self-consistent model of the Jovian auroral thermal structure, *J. Geophys. Res.*, *106*, 12,933-12,952, 2001.

Haider, S.A., et al., Calculated ionization rates, ion densities, and airglow emission rates due to precipitating electrons in the nightside ionosphere of Mars, *J. Geophys. Res.*, *97*, 10,637, 1992.

Hall, D.T., D.F. Strobel, P.D. Feldman, M.A. McGrath, and H.A. Weaver, Detection of an oxygen atmosphere on Jupiter's moon Europa, *Nature*, *373*, 677-679, 1995.

Hall, D.T., P.D. Feldman, M.A. McGrath, and D.F. Strobel, The FUV oxygen airglow of Europa and Ganymede, *Astrophys. J.*, *499*, 475-481, 1998.

Hardy, D.A., M.S. Gussenhoven, and D. Brautigam, A statistical model of auroral ion precipitation, *J. Geophys. Res.*, *94*, 370-392, 1989.

Herbert, F., and B.R. Sandel, The Uranian aurora and its relationship to the magnetosphere, *J. Geophys. Res.*, *99*, 4143-4160, 1994.

Holmström, M., S. Barabash, and E. Kallio, X-ray imaging of the solar wind - Mars interaction, *Geophys. Res. Lett.*, *28*, 1287-1290, 2001.

Ingersoll, A.P., et al., Imaging Jupiter's aurora at visible wavelengths, *Icarus*, *135*, 251-264, 1998.

Ishimoto, M., and M.R. Torr, Energetic He^+ precipitation in a mid-latitude aurora, *J. Geophys. Res.*, *92*, 3284, 1987.

Ishimoto, M., G.J. Romick, L.J. Paxton, C.-I. Meng, and R.E. Huffman, Night UV spectra (1100 - 2900 Å) at mid and low latitude during a magnetic storm, *Geophys. Res. Lett.*, *19*, 813-816, 1992.

Ishimoto, M., G.J. Romick, and C.-I. Meng, Model calculation of atmospheric emission caused by energetic O$^+$ precipitation, *J. Geophys. Res.*, *99*, 435-447, 1994.

Jasperse, J.R., and B. Basu, Transport theoretic solutions for auroral proton and H atom fluxes and related quantities, *J. Geophys. Res.*, *87*, 811-822, 1982.

Kallio, E., and S. Barabash, Atmospheric effects of precipitating energetic hydrogen atoms on the Martian atmosphere, *J. Geophys. Res.*, *106*, 165-177, 2001.

Kallio, E., J.G. Luhmann, and S. Barabash, Charge exchange near Mars: The solar wind absorption and energetic neutral atom production, *J. Geophys. Res.*, *102*, 22,183-22,197, 1997.

Keller, C.N., T.E. Cravens, and L. Gan, One-dimensional multispecies magnetohydrodynamic models of the ramside ionosphere of Titan, *J. Geophys. Res.*, *99*, 6511, 1994.

Kharchenko, V., W. Liu, and A. Dalgarno, X ray and EUV emission spectra of oxygen ions precipitating into the Jovian atmosphere, *J. Geophys. Res.*, *103*, 26,687, 1998.

Kharchenko, V. and A. Dalgarno, Spectra of cometary X rays induced by solar wind ions, *J. Geophys. Res.*, *105*, 18,351-18,360, 2000.

Kharchenko, V. and A. Dalgarno, Variability of cometary X-ray emission induced by solar wind ions, *Astrophys. J.*, *554*, L99-L102, 2001.

Killen, R.M., A.E. Potter, and T.H. Morgan, Spatial distribution of sodium vapor in the atmosphere of Mercury, *Icarus*, *85*, 145-167, 1990.

Killen, R.M., and W.H. Ip, The surface - bounded atmospheres of Mercury and the moon, *Rev. Geophys.*, 361-406, 1999.

Kim, S.J., Infrared processes in the Jovian auroral zone, *Icarus*, *75*, 399-408, 1988.

Kim, S.J., and W. Maguire, Two micron quadrupole line emission of H$_2$ from the Jovian auroral zone, in *NASA Goddard Inst. for Space Studies The Jovian atmospheres*, p.95-98 (SEE N87-17598 09-91), 1986.

Kim, S.J., J. Caldwell, A.R. Rivolo, R. Wagener, and G.S. Orton, Infrared polar brightening on Jupiter. III- Spectrometry from the Voyager 1 IRIS experiment, *Icarus*, *64*, 233-248, 1985.

Kim, Y.H., J.L. Fox, and H.S. Porter, Densities and vibrational distribution of H$_3^+$ in the Jovian auroral ionosphere, *J. Geophys. Res.*, *97*, 6093-6101, 1992. See Erratum, *J. Geophys. Res.*, *97*, 10,283, 1992.

Kivelson, M.G., et al., Discovery of Ganymede's magnetic field by the Galileo spacecraft, *Nature*, *384*, 537-541, 1996.

Kivelson, M.G., et al., Magnetic field and magnetosphere of Ganymede, *Geophys. Res. Lett.*, *24*, 2155, 1997.

Knudsen, D.J., E.F. Donovan, L.L. Cogger, B. Jackel, and W.D. Shaw, Width and structure of mesoscale optical auroral arcs, *Geophys. Res. Lett.*, *28*, 705-708, 2001.

Kozlovsky, A., and J. Kangas, Characteristics of the postnoon auroras inferred from EISCAT radar measurements, *J. Geophys. Res.*, *106*, 1817-1834, 2001.

Kozyra, J.U., A.F. Nagy, and D.W. Slater, High-altitude energy source(s) for stable auroral red arcs, *Rev. Geophys.*, *35*, 155-190, 1997.

Krasnopolsky, V., On the nature of soft X-ray radiation in comets, *Icarus*, *128*, 368-385, 1997.

Krasnopolsky, V.A., and M.J. Mumma, EUVE spectroscopy of comet Hyakutake: First detection of solar wind charge transfer emissions, *Bull. Am. Astron. Soc./ Div. Planet. Sci. Meet.*, *32*, #40.01, 1070, 2000.

Krasnopolsky, V.A., et al., Detection of soft X-rays and a sensitive search for noble gases in comet Hale-Bopp (C/1995 O1), *Science*, *277*, 1488-1491, 1997.

Lanzerotti, L.J., et al., The hot plasma environment at Jupiter - ULYSSES results, *Science*, *257*, 1518, 1992.

Ledvina, S.A., and T.E. Cravens, A three-dimensional MHD model of plasma flow around Titan, *Planet. Space Sci.*, *46*, 1175-1191, 1998.

Liou, K., P.T. Newell, C.-I. Meng, M. Brittnacher, and G. Parks, Characteristics of the solar wind controlled auroral emissions, *J. Geophys. Res.*, *103*, 17,543-17,557, 1998.

Liou, K., C.-I. Meng, A.T.Y. Liu, P.T. Newell, and R.R. Anderson, Auroral kilometric radiation at substorm onset, *J. Geophys. Res.*, *105*, 25,325-25,331, 2000.

Lisse, C.M., et al., Discovery of X-ray and Extreme UV emission from comet C/Hyakutake 1996 B2, *Science*, *274*, 205-209, 1996.

Lisse, C.M., et al., X-ray and extreme UV emission from comet P/Encke 1997, *Icarus*, *141*, 316-330, 1999.

Lisse, C.M., et al., Discovery of charge exchange emission from C/LINEAR 1999 S4, *Bull. Am. Astron. Soc./ Div. Planet. Sci. Meet.*, *32*, #40.02, 1070, 2000.

Luhmann, J.G., and J.U. Kozyra, Dayside pickup oxygen ion precipitation at Venus and Mars - Spatial distributions, energy deposition and consequences, *J. Geophys. Res.*, *96*, 5457-5467, 1991.

Luhmann, J.G., J.B. Pollack, and L. Colin, The Pioneer mission to Venus, *Scientific American*, *270*, 90-97, 1994.

Lummerzheim, D., and J. Lilensten, Electron transport and energy degradation in the ionosphere: Evaluation of the numerical solution, comparison with lab experiments and auroral observations, *Ann. Geophys.*, *12*, 1039-1051, 1994.

Lummerzheim, D., and M. Galand, The profile of the hydrogen Hβ emission line in proton aurora, *J. Geophys. Res.*, *106*, 23-31, 2001.

Lummerzheim, D., M.H. Rees, and H.R. Anderson, Angular dependent transport of auroral electrons in the upper atmophere, *Planet. Space Sci.*, *37*, 109-129, 1989.

Lummerzheim, D., M. Galand, J. Semeter, M.J. Mendillo, M.H. Rees, and F.J. Rich, Emission of OI(630 nm) in proton aurora, *J. Geophys. Res.*, *106*, 141-148, 2001.

Mairan, J.J.D. de, Traité physique et historique de l'aurore boréale, *Imprimerie Royale*, Paris, 1733.

McGrath, M.A., P.D. Feldmann, D.F. Strobel, K. Retherford, B. Wolven, and H.W. Moos, HST/STIS UV imaging of Europa, *Bull. Am. Astron. Soc./ Div. Planet. Sci. Meet.*, *32*, #34.09, 1056, 2000.

Meier, R.R., UV spectroscopy and remote sensing of the upper atmosphere, *Space Sci. Rev.*, *58*, 1-185, 1991.

Meng, C.-I., M.J. Rycroft, and L.A. Frank, Auroral physics, *Cambridge University Press*, Cambridge, 1991.

Mizera, P.F., J.G. Luhmann, W.A. Kolasinski, and J.B. Blake, Correlated observations of auroral arcs, electrons and X-rays from a DMSP satellite, *J. Geophys. Res.*, *83*, 5573-5578, 1978.

Mumma, M.J., V.A. Krasnopolsky, and M.J. Abbott, Soft X-rays from four comets observed with EUVE, *Astrophys. J.*, *491*, L125-L128, 1997.

Neugebauer, M., et al., The relation of temporal variations od soft X-ray emission from comet Hyakutake to variations of ion fluxes in the solar wind, *J. Geophys. Res.*, *105*, 20,949-20,955, 2000.

Ness, J.-U., and J.H.M.M. Schmitt, A serach for X-ray emission from Saturn, Uranus, and Neptune, *Astron. Astrophys.*, *355*, 394-397, 2000.

Onda, K., M. Ejiri, and Y. Itikawa, Analysis of electron auroras based on the Monte Carlo method:

Application to active electron arc auroras observed by the sounding rocket at Syowa Station, *J. Geophys. Res.*, *104*, 27991, 1999.

Østgaard, N., et al., Simultaneous measurements of X-rays and electrons during a pulsating aurora, *Ann. Geophys.*, *16*, 148-160, 1998.

Østgaard, N., et al., Global X-ray emission during an isolated substorm - a case study, *J. Atmos. Solar-Terr. Phys.*, *62*, 889-900, 2000.

Owens, A., et al., Evidence for dust-related X ray emission from comet C/1995 O1 (Hale-Bopp), *Astrophys. J.*, *493*, L47-L51, 1998.

Paranicas, C., and A.F. Cheng, Drift shells and aurora computed using the O8 magnetic field model for Neptune, *J. Geophys. Res.*, *99*, 19,433-19,440, 1994.

Paresce, F., S. Chakrabarti, R. Kimble, and S. Bowyer, The 300 to 900 Åspectrum of nightside aurora, *J. Geophys. Res.*, *82*, 10,247-10,252, 1983.

Patterson, J.D., T.P. Armstrong, C.M. Laird, D.L. Detrick, and A.T. Weatherwax, Correlation of solar energetic protons and polar cap absorption, *J. Geophys. Res.*, *106*, 149-163, 2001.

Perry, J.J., Y.H. Kim, J.L. Fox, and H.S. Porter, Chemistry of the Jovian auroral atmosphere, *J. Geophys. Res.*, *104*, 16,451, 1999.

Peticolas, L., and D. Lummerzheim, Time-dependent transport of field-aligned bursts of electrons in flickering aurora, *J. Geophys. Res.*, *105*, 12,895-12,906, 2000.

Petrinec, S.M., F. Fenrich, J. Mobilia, D.L. Chenette, M.A. Rinaldi, and W.L. Imhof, The positions of the auroral energetic electron precipitation region obtained from PIXIE global X-ray observations, *Adv. Space Res.*, *23*, 1735, 1999.

Phillips, J.L., J.G. Luhmann, and A.I.F. Stewart, The Venus UV aurora - Observations at 130.4 nm, *Geophys. Res. Lett.*, *13*, 1047-1050, 1986.

Potter, A.E., and T.H. Morgan, Evidence for magnetospheric effects on the sodium atmosphere of Mercury, *Science*, *248*, 835-838, 1990.

Prangé, R., D. Régo, D. Southwood, P. Zarka, S. Miller, and W. Ip, Rapid energy dissipation and variability of the Io-Jupiter electrodynamic circuit, *Nature*, *379*, 323-325, 1996.

Prangé, R., et al., Detection of self-reversed Ly α lines from the Jovian aurorae with the Hubble Space Telescope, *Astrophys. J.*, *484*, L169-L173, 1997.

Rassoul, H.K., R.P. Rohrbaugh, B.A. Tinsley, and D.W. Slater, Spectrometric and photometric observations of low-latitude aurorae, *J. Geophys. Res.*,

98, 7695, 1993.

Régo, D., R. Prangé, and J.-C. Gérard, Auroral Lyman α and H_2 bands from the giant planets: 1. Excitation by proton precipitation in the Jovian atmosphere, *J. Geophys. Res.*, *99*, 17,075-17,094, 1994.

Régo, D., R. Prangé and L. Ben Jaffel, Auroral Lyman α and H_2 bands from the giant planets 3. Ly α spectral profile including charge exchange and radiative transfer effects and H_2 color ratios, *J. Geophys. Res.*, *104*, 5939, 1999.

Rees, M.H., *Physics and Chemistry of the Upper Atmosphere*, *Cambridge Atmos. Space Sci. Ser.*, Cambridge Univ. Press, New York, 1989.

Rees, M.H., and R.G. Roble, Excitation of $O(^1D)$ atoms in aurorae and emission of the forbidden OI 6300-Åline, *Can. J. Phys.*, *64*, 1608-1613, 1986.

Rees, M.H., A.I. Stewart, and J.C.G. Walker, Secondary electrons in aurora, *Planet. Space Sci.*, *17*, 1997, 1969.

Retherford, K.D., et al., HST-Galileo Io campaign: Images of sodium and oxygen emissions in eclipse *EOS Trans. AGU*, *80*(40), F612, 1999.

Retherford, K.D., et al., Io's UV aurora: Detection of neutral hydrogen and neutral chlorine, *Bull. Am. Astron. Soc./ Div. Planet. Sci. Meet.*, *32*, #34.06, 1055, 2000a.

Retherford, K.D., H.W. Moos, D.F. Strobel, and B.C. Wolven, Io's equatorial spots: Morphology of neutral UV emissions, *J. Geophys. Res.*, *105*, 27,157-27,165, 2000b.

Roble, R.G., and E.C. Ridley, An auroral model for the NCAR thermospheric general circulation model (TGCM), *Ann. Geophys.*, *5*, 369-382, 1987.

Roesler, F.L., et al., FUV imaging spectroscopy of Io's atmosphere with HST/STIS, *Science*, *283*, 353, 1999.

Sandel, B.R., F. Herbert, A.J. Dessler, and T.W. Hill, Aurora and airglow on the night side of Neptune, *Geophys. Res. Lett.*, *17*, 1693-1696, 1990.

Sandholt, P.E., and C.J. Farrugia, Multipoint observations of substorm intensifications: The high-latitude aurora and electron injections in the inner equatorial plasma sheet, *Geophys. Res. Lett.*, *28*, 483-486, 2001.

Saur, J., F.M. Neubauer, D.F. Strobel, and M.E. Summers, Io's UV aurora: Remote sensing Io's interaction, *Geophys. Res. Lett.*, *27*, 2893-2896, 2000.

Schmitt, J. H. M. M., S. L. Snowden, B. Aschenbach, G. Hasinger, E. Pfeffermann, P. Predehl, and J. Trumper, A soft X-ray image of the moon, *Nature*,

349, 583-587, 1991.

Sharber, J.R., et al., Observations of the UARS Particle Environment Monitor and computation of ionization rates in the middle and upper atmosphere during a geomagnetic storm, *Geophys. Res. Lett.*, *20*, 1319-1322, 1993.

Share, G.H., and R.J. Murphy, Atmospheric gamma rays from solar energetic particles and cosmic rays penetrating the magnetosphere, *J. Geophys. Res.*, *106*, 77-92, 2001.

Singh, V., Proton energy deposition and EUV emission in the Jovian and the Saturnian atmospheres, *Indian J. Radio Space Phys.*, *20*, 140-149, 1991.

Singhal, R.P., S. Chakravarty, A. Bhardwaj, and B. Prasad, Energetic electron precipitation in Jupiter's upper atmosphere, *J. Geophys. Res.*, *97*, 18,245-18,256, 1992.

Siscoe, G., What determines the size of the auroral oval?, in Auroral physics, p.159, *Cambridge University Press*, Cambridge, 1991.

Smith, B.A., et al., The Galiean satellites and Jupiter - Voyager 2 imaging science results, *Science*, *206*, 927-950, 1979.

Solomon, S.C., Auroral electron transport using the Monte Carlo method, *Geophys. Res. Lett.*, *20*, 185-188, 1993.

Solomon, S.C., P.B. Hays, and V.J. Abreu, The auroral 6300 Å emission - Observations and modeling, *J. Geophys. Res.*, *93*, 9867-9882, 1988.

Spenner, K., W.C. Knudsen, R.C. Whitten, P.F. Michelson, K.L. Miller, and V. Novak, On the maintenance of the Venus nightside ionosphere - Electron precipitation and plasma transport, *J. Geophys. Res.*, *86*, 9170-9178, 1981.

Stadsnes, J., K. Aarsnes, and J. Bjordal, X-ray imaging of the aurora, *Adv. Space Sci.*, *20*, 1043-1054, 1997.

Stamnes, K., and M.H. Rees, Inelastic scattering effects on photoelectron spectra and ionospheric electron temperature, *J. Geophys. Res.*, *88*, 6301-6309, 1983.

Stenbaek-Nielsen, H.C., et al., Aircraft observations conjugate to FAST: Auroral arc thicknesses, *Geophys. Res. Lett.*, *25*, 2073-2076, 1998.

Stephan, A.W., S. Chakrabarti, and D.M. Cotton, Evidence of ENA precipitation in the EUV dayglow, *Geophys. Res. Lett.*, *27*, 2865-2868, 2000.

Stephan, A.W., S. Chakrabarti, K. Dymond, S. Budzein, S. Thonnard, and R. McCoy, FUV equatorial aurora during geomagnetic storms as observed by LORAAS, *J. Geophys. Res.*, In Press, 2001.

Strickland, D.J., R.R. Meier, J.H. Hecht, and A.B. Christensen, Deducing composition and incident electron spectra from ground-based auroral optical measurements. I - Theory and model results. II - A study of auroral red line processes. III - Variations in oxygen density, *J. Geophys. Res.*, *94*, 13,527-13,563, 1989.

Strickland, D.J., R.E. Daniell, Jr., J.R. Jasperse, and B. Basu, Transport-theoretic model for the electron-proton-hydrogen atom aurora. 2: Model results, *J. Geophys. Res.*, *98*, 21,533-21,548, 1993.

Tinsley, B., R. Rohrbaugh, M. Ishimoto, M. Torr and D. Torr, Middle- and low-latitude emissions from energetic neutral atom precipitation seen from AT-LAS1 under quiet geomagnetic conditions, *J. Geophys. Res.*, *99*, 19577, 1994.

Trafton, L.M., S. Miller, T.R. Geballe, J. Tennyson, and G.E. Ballester, H_2 quadrupole and H_3^+ emission from Uranus: The Uranian thermosphere, ionosphere, and aurora, *Atrophys. J.*, *524*, 1059-1083, 1999.

Trauger, J.T., et al., Saturn's hydrogen aurora: Wide field and planetary camera 2 imaging from the Hubble Space Telescope, *J. Geophys. Res.*, *103*, 20,237-20,244, 1998.

Vallance Jones, A., *Aurora, D. Reidel publising company*, Dordrecht, Holland, 1974.

Vallance Jones, A., et al., The Aries auroral modelling campaign - Characterization and modelling of an evening auroral arc observed from a rocket and a ground-based line of meridian scanners, *Planet. Space Sci.*, *39*, 1677, 1991.

Vasavada, A.R., A.H. Bouchez, A.P. Ingersoll, B. Little, C.D. Anger, and the Galileo SSI Team, Jupiter's visible aurora and Io footprint, *J. Geophys. Res.*, *104*, 27,133-27,142, 1999.

Verigin, M.I., et al., On the possible source of the ionization in the nigthttime Martian ionosphere. I - PHOBOS 2 HARP electron spectrometer measurements, *J. Geophys. Res.*, *96*, 19,307-19,313, 1991.

Vij, K.K., D. Venkatesan, W.R. Sheldon, J.W. Kern, J.R. Benbrook, and B.A. Whalen, Simultaneous investigation of parent electrons and bremsstrahlung X-rays by rocket-borne detectors, *J. Geophys. Res.*, *80*, 2869-2875, 1975.

Waite, J.H., Jr., et al., ROSAT observations of the Jupiter aurora, *J. Geophys. Res.*, *99*, 14,799-14,809, 1994.

Waite, J.H., et al., Equatorial X-ray emissions: Implications for Jupiter's high exospheric temperatures, *Science*, *276*, 104-108, 1997.

Waite, J.H., et al., Multispectral observations of Jupiter's aurora, *Adv. Space Res.*, *26*, 1453-1475, 2000.

Wegmann, R., H.U. Schmidt, C.M. Lisse, K. Dennerl, and J. Englhauser, X-rays from comets generated by energetic solar wind particles, *Planet. Space Sci.*, *46*, 603-612, 1998.

Winckler, J.R., L. Peterson, R. Arnoldy, and R. Hoffman, X-rays from visible aurorae at Minneapolis, *Phys. Rev.*, *110*, 1221, 1958.

Yung, Y.L., G.R. Gladstone, K.M. Chang, J.M. Ajello, and S.K. Srivastava, H_2 fluorescence spectrum from 1200 to 1700 Å by electron impact - Lab study and application to Jovian aurora, *Astrophys. J.*, *254*, L65-L69, 1982.

Zarka, P., Auroral radio emissions at the outer planets: Observations and theories, *J. Geophys. Res.*, *103*, 20,159-20,194, 1998.

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Figure 1. Diagram illustrating the modeling of auroral processes.

Table 1. Characteristics of solar system bodies around which auroral emissions have been observed.

Body	DM/DT($^\circ$)[a]	Excitation source[b]	CD (cm^{-2})[c]	Atmosph. species[d]	Auroral emissions
Venus	<0.0004 /?	e$^-$,H$^+$,He^{++}(sw); H$^+$, O$^+$, He$^+$, C$^+$ (atm)	2 10^{27}	CO$_2$, N$_2$, O, CO	UV (OI)
Earth	1/10.8°	e$^-$, H$^+$, He$^+$(sw); H$^+$/H, O$^+$/O (atm)	2 10^{25}	N$_2$, O$_2$, O	γ, X, UV, visible, IR
Jupiter	20,000 /9.6°	e$^-$,H$^+$ (sw, atm); O ions (icy moons) S/O/Na ions (Io, Europa	-	H$_2$, H, hydrocarbons	X(ions), UV(H$_2$,HI), visible (H), IR (H$_3^+$,H$_2$, hydrocarbons)
Io	?	From Io torus and Jovian magnetosph.	Variable	SO$_2$(volcano), SO, S, O, Na, Cl	UV (OI,ClI, SO, SO$_2$), visible
Ganymede	?/10°	From magnetosph. of Ganym. & Jupit.	~5 10^{14} for O$_2$	O$_2$, O$_3$, O	UV at poles (OI), visible at equat.(OI)
Europa	-	From Io plasma torus and Jovian magnetosphere	~10^{15} for O$_2$	O$_2$, O$_3$, O, Na	UV (OI)
Saturn	600/<1°	e$^-$, H$^+$ (sw, atm); O$^+$(icy moons, rings); N$^+$, N$_2^+$, H$^+$(Titan)	-	H$_2$, H, hydrocarbons	X (e$^-$), UV (H$_2$, H) IR (H$_3^+$)
Uranus	50/58.6°	sw, atm	-	H$_2$, H, CH$_4$	X(?), UV (H$_2$,H)
Neptune	25/47°	N$^+$, H$^+$ (Triton)	-	H$_2$, H, CH$_4$	X(?), UV (H$_2$)
Comets	-	heavy ions (sw)	Variable	H$_2$O, CO, CO$_2$	Soft X-rays

[a] Dipole moment (Earth = 1) / Dipole tilt.

[b] The list is not exhaustive. "sw" and "atm" stand for solar wind and atmospheric origin, respectively.

[c] Column density from surface.

[d] The atmospheric species given here are the major constituents in the region of energy deposition.