All ionospheres are not alike: Reports from other planets

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Introduction

Gauss, Lord Kelvin and Stewart Balfour suggested the existence of an electrically conducting region in the terrestrial upper atmosphere already in the last century. The first direct verification of the existence of such a region came when Marconi succeeded in sending radio signals across the Atlantic. The name ionosphere was coined by R. A. Watson-Watt in 1926. No uniform definition of the ionosphere exists; a rather broad definition might be *"the ionosphere is that region of the atmosphere (or gaseous envelope) surrounding a solar system body where significant numbers of low energy, free electrons and ions are present."* The first direct evidence for an ionosphere at a planet other than Earth came from the radio occultation measurements of electron densities by Mariner 5, as it flew by Venus on October 19, 1967. Since then spacecraft have visited all planets, except Pluto. As a minimum, radio occultation measurements of the electron densities have been obtained at all, but Mercury. However, ground-based optical observations indicate that Mercury has a significant exosphere; thus an ionosphere, in its broad definition, must also be present. Also for Pluto, optical measurements have established the presence of an atmosphere, implying it too has an ionosphere.

Venus' ionosphere has been explored the most, except for the terrestrial one. The majority of this information comes from instruments carried on the Pioneer Venus Orbiter (PVO). Earlier, Mariners 5 and 10 and some of the Veneras provided useful data. Pioneer Venus went into orbit around Venus in December 1978 where it remained until October 1992 when it entered the atmosphere and burned up. In Section II this review presents a selective summary of new observations obtained during the entry period, and highlights of recent theoretical studies of the Venus ionosphere.

The major development in the investigation of the ionospheres of the outer planets during the last qua-

drennium has been the use of bright 2-4μm (micrometer) emissions from vibrationally excited H_3^+ to probe the bulk ionospheres of Jupiter, Saturn and Uranus from ground-based observatories. Section III summarizes these observations as well as the results of recent ionospheric modeling studies.

The Giotto flybys of comets Halley and Grigg-Skjellerup provided a unique data base on the plasma environment of comets, which led to significant advances in our understanding of cometary ionospheres. Similarly, the Voyager flyby of Titan and the planned Cassini mission to Saturn and Titan prompted the development of new ionospheric models. Section IV outlines the new work on the ionospheres of comets and Titan.

Venus and Mars

The periapsis (the lowest altitude in the orbit) of PVO was maintained near an altitude of 150 km until 1980, when the onboard fuel supply was just about exhausted. Solar tides then pushed the periapsis to higher altitudes until it reached about 2300 km in 1986, after which the periapsis began to drop. During this period of high periapsis no in situ ionospheric measurements were possible, although radio occultation observations provided electron density profiles throughout the life of PVO. Beginning around early 1992 the periapsis of PVO was again inside the ionosphere allowing direct measurements in the nightside of Venus. The small amount of remaining fuel was used to keep the periapsis around 140 km, but it was finally exhausted before the orbit precessed to the dayside and PVO entered the atmosphere. Most of the results from the entry phase portion of the PVO mission were published together in the December 14, 1993 issue of *Geophysical Research Letters*. It should be noted that the bulk of the entry phase ionospheric measurements were restricted to nightside observations.

The retrograde rotation of Venus results in a very long nighttime period ($\approx$ 58 earth days); therefore it was first thought that the absence of solar ionizing (extreme ultraviolet, EUV) radiation for such a long pe-

riod would virtually eliminate the ionosphere. The detection of a robust nightside ionosphere by Mariner 5 was thus a surprise. To explain this observed nightside ionosphere became a major research objective. Two competing mechanisms responsible for the maintenance of the nightside ionosphere were proposed (i) plasma transport from the dayside and (ii) ionization by precipitating low-energy ($\approx$ 40-200 eV) electrons. Model calculations and PVO data prior to that obtained from the entry phase seemed to indicate that day-to-night plasma transport is the main source during solar maximum conditions and impact ionization becomes the dominant mechanism during solar minimum. The early phase of the PVO data base, 1978-1981, corresponds to high solar activity ($F_{10.7} \approx 200$), while the entry phase data corresponds to low solar activity ($F_{10.7} \approx 120$). The 10.7 cm radio emission, $F_{10.7}$, monitored at the surface of the Earth, has been used as a proxy indicator of solar EUV emissions. The observed mean nightside electron densities, at the higher altitudes, are significantly lower during moderate than at high solar activity; however, the solar cycle differences are small near the density peak [*Theis and Brace*, 1993]. These observations support the results of model calculations [*Cravens et al.*, 1983; *Fox*, 1992; *Brannon et al.*, 1993; *Dobe et al.*, 1995], which indicated that day to night plasma transport is responsible for most of the plasma during high solar activity, but that during solar cycle minimum conditions the decrease in ionopause altitude chokes off the flow and precipitation becomes the dominant ionization source. The latter is sufficient to maintain a peak electron density close to the solar maximum value (within maybe a factor of about two), but results in significant decreases at the higher altitudes. This behavior is due to the fact that the impact ionization rate peaks near 140 km and drops off rapidly with the neutral density at higher altitudes. The observed solar cycle dependence of the nighttime electron temperature is more puzzling. *Theis and Brace* [1993] argue that the temperature increase at higher altitudes during low solar activity might be due to a combination of decreased densities and a "better" thermal connection to the hot sheath plasma, while the decrease at the lower altitude is caused by a reduction in the thermal coupling to the dayside. The observed large decrease in electron densities and only limited increase in plasma temperatures above about 160 km during low solar activity results in the dominance of the magnetic pressure over the kinetic pressure in the upper nighttime ionosphere [*Russell et al.*, 1993]; this is a change from solar cycle maximum behavior when the kinetic pressure is the dominant one throughout the ionosphere.

Ion composition measurements made during low solar cycle activity [*Cloutier et al.*, 1993; *Grebowsky et al.*, 1993] helps to elucidate further the sources of nightside ionization. These observations show that the relative abundance of atomic ions (e.g., O^+ and H^+) decrease significantly compared to molecular ones (e.g., O_2^+). More than a decade ago *Cravens et al.* [1983], and more recently *Brannon et al.* [1993] and *Dobe et al.*

[1995], showed that electron impact ionization can produce molecular ion densities near 140 km comparable to those resulting from day to night transport, but produce much smaller O^+ densities above the ionization peak. The recent model calculations of *Brannon et al.* [1993], *Kar et al.* [1994] and *Dobe et al.* [1995] show quantitatively that using precipitating low energy electron flux values, consistent with the limited observational constraints, can reproduce most of the ion densities observed during the PVO entry phase; however, the presence of a much reduced day-to-night transport source cannot be excluded. In summary, the new, nighttime, in situ ionospheric data, obtained during the PVO entry phase, helped to elucidate the processes responsible for the maintenance of the nightside Venus ionosphere during conditions of both moderate and high solar activity.

Recently model studies have also explored the question of which mechanism or mechanisms maintain the nightside ionosphere of Mars. *Haider et al.* [1992] and *Fox et al.* [1993] looked at the potential electron precipitation source; *Fox et al.* [1993] also studied plasma transport from the dayside. These two potential source mechanisms are not inconsistent with the limited observational constraints set by radio occultation measurements of electron densities [e.g., *Zhang et al.*, 1990]; however, more information (e.g., ion composition measurements) is needed to establish what the major sources of the nightside ionosphere are.

The question whether Mars has an intrinsic magnetic field is still not resolved. Building on earlier studies, *Shinigawa and Cravens* [1992] used their ionospheric MHD (magneto-hydrodynamic) model to consider the effects of different orientations of a weak horizontal intrinsic field on the dayside ionosphere of Mars and concluded that such a field would have to be less than about 50 nT (nanoTesla) in order for its effects on the ionospheric electron density structure to be evident. *Zhang and Luhmann* [1992], based on the examination of peak ionospheric pressures at Venus and Mars, also concluded that any intrinsic magnetic field at Mars must be very small.

The relative importance of different potential energy sources and transport mechanisms of the dayside ionospheres of Venus and Mars has been debated for about two decades [cf. *Nagy et al.*, 1983], ever since it became obvious that solar EUV heating and classical thermal heat conduction lead to electron and ion temperatures significantly smaller than the measured values. Model calculations lead to temperature values consistent with the observed ones if either an ad-hoc topside heat inflow into an unmagnetized ionosphere is assumed and/or the electron thermal conductivity is reduced from its classical value. There have been a number of reasonable suggestions for sources and mechanisms of a heat inflow [*Taylor et al.*, 1979; *Gan et al.*, 1990; *Szego et al.*, 1991] and the observed presence of fluctuating and small steady magnetic fields in the ionosphere is consistent with reduced thermal conductivity. However, the data base has been insufficient to establish the rela-

tive importance of these two mechanisms. It was hoped that further in situ data from the dayside ionosphere would be obtained from PVO during its entry phase. Unfortunately, atmospheric entry and burnup occurred before any meaningful dayside data could be obtained. This led *Dobe et al.* [1993] to reexamine the old PVO database. They concluded that elevated temperatures at Venus are most likely the result of reduced thermal conductivity, but no definitive conclusions can be made without further information. No new missions are planned to explore Venus further, but the great similarities between the ionospheres of Venus and Mars mean that data from the upcoming Mars 96 and Planet B missions may not only help us to advance our understanding of the ionosphere of Mars, but also help to answer some of the remaining questions concerning Venus.

Finally, it should be mentioned that ionospheric processes, such as dissociative recombination of molecular ions (e.g., O_2^+, N_2^+), are among the most important mechanisms responsible for atmospheric escape at Venus and Mars. Theoretical calculations by *Fox* [1993] indicate that, assuming an initial CO_2 pressure of 2 bars at Mars, an exponential loss of the atmosphere, with a time constant of 700 m.y., is consistent with the observed isotope ratio of atomic nitrogen. Different isotopes of a given atom have different atomic masses and thus have different escape rates. In another theoretical study *Zhang et al.* [1993] examined the loss of oxygen from Mars, which is thought to be an indicator of the loss of water, via ionospheric processes. They concluded that given their assumptions (e.g., changing solar EUV intensities), these ionospheric processes may have been responsible for the loss to space of about 30 meters of water on an evolutionary time scale. This calculated escape rate is higher than the escape rate due to O^+ and O_2^+ ions in the tail of Mars, as observed by one of the ion mass spectrometers on Phobos-2 [*Lundin et al.*, 1990]. The measured escape rate was of the order of 10^{24} ions/sec, which corresponds to a loss of water of only about 1 meter over Mars' history.

Outer Planets

The ionospheres of the four gas giants—Jupiter, Saturn, Uranus, and Neptune—are composed principally of H^+ and H_3^+, produced through ionization of the dominant neutral atmospheric constituent H_2. Hydrocarbon and metallic ions are expected at lower altitudes. These outer planet ionospheres are created and maintained through photoionization by solar EUV radiation and impact ionization by energetic particle precipitation and are subject to modification by a variety of influences, such as the infall of water from rings and icy satellites. Unlike the terrestrial ionosphere, or even that of Venus, we have a very limited observational data base on the ionospheres of Jupiter, Saturn, Uranus, and Neptune. Until recently, our understanding of them was based solely on simple photochemical models and on the limited set of electron density profiles from the Pioneer and Voyager radio science experiments: 8 profiles for Jupiter (Pioneer 10 and 11, Voyager 1 and 2), 6 for Saturn (Pioneer 11, Voyager 1 and 2), 2 for Uranus (Voyager 2), and 2 for Neptune (Voyager 2). There are some uncertainties in the radio occultation data, and the data are limited in local time coverage. Further, discrepancies exist between the model calculations and the measured density profiles. (For a review of our knowledge of the outer planet ionospheres at the start of the 1987-1990 quadrennium, see *Waite and Cravens* [1987]). These discrepancies are not likely to be resolved, nor is a fuller understanding of outer planet ionospheres likely to be achieved, until the Galileo and Cassini orbiters begin sending back data from the Jupiter and Saturn systems in 1995 and 2004, respectively. In the meantime, as will be discussed below, the detection of vibrationally excited H_3^+ in the ionospheres of Jupiter, Saturn, and Uranus has given researchers a powerful new tool for routinely probing outer planet ionospheres from ground-based observatories.

Radio occultation measurements indicate that the ionospheres of Jupiter, Saturn, and Uranus have a complex, multilayered structure, with a primary density peak and several secondary peaks at lower altitudes. Twenty years ago, prior to the first Pioneer flyby, *Atreya et al.* [1974] suggested that metallic ions resulting from meteor ablation or Iogenic Na^+ could produce secondary ionization layers at Jupiter (see also *Atreya* [1986]). Such layers may also be made up of ionized hydrocarbons, as has been shown by *Kim and Fox* [1991; 1995], who find that photons penetrating below the methane homopause can create a hydrocarbon layer above the ammonia cloud tops in the ionospheric E region of Jupiter. The hydrocarbon ions produced initially by this process then react with neutral hydrocarbons to form more complex hydrocarbon ions. Similar hydrocarbon layers are expected at Saturn and Neptune, but may be absent at Uranus [*Kim and Fox*, 1995].

As noted above, there are discrepancies between the electron density profiles measured by the Pioneer and Voyager radio science experiments and those calculated with existing ionospheric models: models predict much higher densities than have been measured and place the density peaks at lower altitudes than have been observed [*Waite and Cravens*, 1987]. Using a one-dimensional chemical-diffusive model, *Majeed and McConnell* [1991] sought to address these discrepancies and found that, for Jupiter and Saturn, reasonable fits between modeled and measured profiles could be obtained by invoking upward plasma drifts along field lines, together with increased ion loss through interaction with vibrationally excited H_2, and, in the case of Saturn, increased ion loss resulting from the influx of water from the rings. The discrepancy between predicted and observed electron densities was also addressed by *Cravens and Eisenhower* [1992], who investigated the effects of oxygen ion precipitation on the Jovian auroral ionosphere. The inclusion in their numerical model of odd oxygen ($O + OH + H_2O$) chemistry initiated by the influx of oxygen ions yielded a lower electron density

(through the removal of H^+); the resulting calculated density was still substantially higher than the measured density, however, suggesting either that there are other sources of odd oxygen than auroral ions or that other loss mechanisms must be invoked. As a sequel to this study, *Cravens* [1994] modeled the effects of the injection of large amounts of water into Jupiter's ionosphere by the impacting fragments of comet Shoemaker-Levy 9. Predicted effects were reductions in ionospheric electron and H_3^+ densities and the temporary appearance of H_3O^+ as the major ionospheric ion species.

The bulk of the research on outer planet ionospheres undertaken during the last four years has centered on the detection and interpretation of near-infrared (2-4 μm) emissions from rotationally-vibrationally excited H_3^+ ions. The possible importance of the molecular ion H_3^+ in hydrogen atmospheres was proposed on the basis of photochemical theory over 30 years ago [*Martin et al.*, 1961]. Recent ionospheric model calculations indicate that H_3^+ is a major ion in the ionospheres of the outer planets. It was not until 1989, however, that the first astronomical spectroscopic detection of this ion—in Jupiter's auroral ionosphere —was reported [*Drossart et al.*, 1989; *Trafton et al.*, 1989]. Subsequent confirming measurements [*Oka and Geballe*, 1990; *Maillard et al.*, 1990; *Miller et al.*, 1990] provided additional information about the ion's rotational temperature, vibrational levels, and the temporal variability of the emissions. H_3^+ emission features have also been detected in the ionospheres of Uranus [*Trafton et al.*, 1993] and Saturn [*Geballe et al.*, 1993]. Because of the strength of the H_3^+ emissions and their high contrast with background emissions, and because emissions in the 2-4 μm range are easily observed from the ground, the detection of H_3^+ in the ionospheres of the outer planets has, to paraphrase *Trafton et al.* [1993], opened a new "window" into the bulk ionospheres of the outer planets above the methane homopause.

At the beginning of the 1991-1994 quadrennium, Jovian auroral H_3^+ emissions were successfully imaged with the infrared camera ProtoCAM at NASA's Infrared Telescope Facility (IRTF) in Hawaii [*Kim et al.*, 1991; *Baron et al.*, 1991] (see Plate 1). Together with spectral measurements, such images have made it possible to investigate the morphology of the H_3^+ auroral emissions and to begin to relate these emissions to auroral emissions at other wavelengths. For example, the IRTF images show bright emission features at high latitudes that generally track the rotation-dependent intensity patterns of the ultraviolet emissions; however, the H_3^+ emissions appear to be characterized in both the northern and southern auroral zones by twin, longitudinally fixed emission peaks that may or may not be present in the ultraviolet aurora [*Drossart et al.*, 1992; *Livengood et al.*, 1992]. An especially exciting example of the value of the IRTF H_3^+ images in the elucidation of Jovian auroral processes was the detection by *Connerney et al.* [1993] of a bright emission $8°$-$10°$ equatorward of the main H_3^+ aurora (see Plate 2). Clearly associated with the ionospheric foot of the Io

flux tube, this emission provides direct evidence of the coupling between Io and the Jovian ionosphere and establishes an unambiguous "fiducial" mark for mapping auroral emissions onto L-shells.

Although the most intense Jovian H_3^+ emissions occur in the auroral zones, H_3^+ emission features have also been observed at other latitudes across the disk of the planet [*Ballester et al.*, 1994]. These nonauroral emissions occur in two mid-high latitude bands in the northern and southern hemisphere, where the column densities are high and the temperatures are relatively low, and in an equatorial region, where the density is low but the temperatures are high (1000-1250 K).

While most of the observational work on outer planet H_3^+ emissions during the last four years has focused on Jupiter, successful searches were undertaken for H_3^+ emission features at Saturn and Uranus as well. *Trafton et al.* [1993] detected emissions at Uranus that are, in intensity and computed column abundance, a few percent of the Jovian emissions. The emissions observed at Saturn by *Geballe et al.* [1993] appear to be weaker than the Uranian ones. This is puzzling in view of the level of UV auroral activity at Saturn and in view of the fact that the H_3^+ emission intensity seems to be a function of the distance from the Sun [*Geballe et al.*, 1993], suggesting that the Saturnian emissions should be less intense than those from Jupiter, but stronger than the Uranian emissions. The solution to this puzzle, and more accurate information about the temperature, column abundance, spatial distribution, and temporal behavior of the H_3^+ emissions at Saturn and Uranus must await further observations.

In addition to the observational studies of H_3^+ emissions, the last quadrennium has seen significant theoretical and laboratory work on the chemical and quantum mechanical behavior of H_3^+ that is relevant to the interpretation of the observed emission features and the associated ionospheric conditions and processes [*Kao et al.*, 1991; *Bates et al.*, 1993; *Dinelli et al.*, 1994; *Smith and Spanel*, 1993; *Sundström et al.*, 1994]. Of particular importance are the studies by Sundström et al. and Bates et al. of the H_3^+ dissociative recombination rate, which has been a subject of controversy and for which a wide range of values have been proposed. Dissociative recombination is the principal loss process for H_3^+ in the ionospheres of the outer planets, and the rate at which this process occurs determines the column density and relative abundance of this ion. Accurate knowledge of the dissociative recombination rate is thus required for the development of accurate ionospheric models. The paper by Bates et al. and the laboratory study by Sundström et al. provide strong theoretical and experimental support for a recombination rate ($\sim 1.5 \times 10^{-7} cm^{-3} s^{-1}$ at $300°K$) faster than that assumed in some recent ionospheric studies (e.g., *Majeed and McConnell*, [1991]).

Satellites and Comets

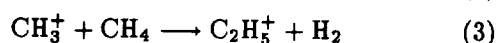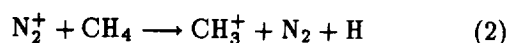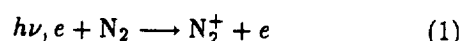Saturn's largest satellite, Titan, possesses an atmosphere with a surface pressure greater than Earth's!
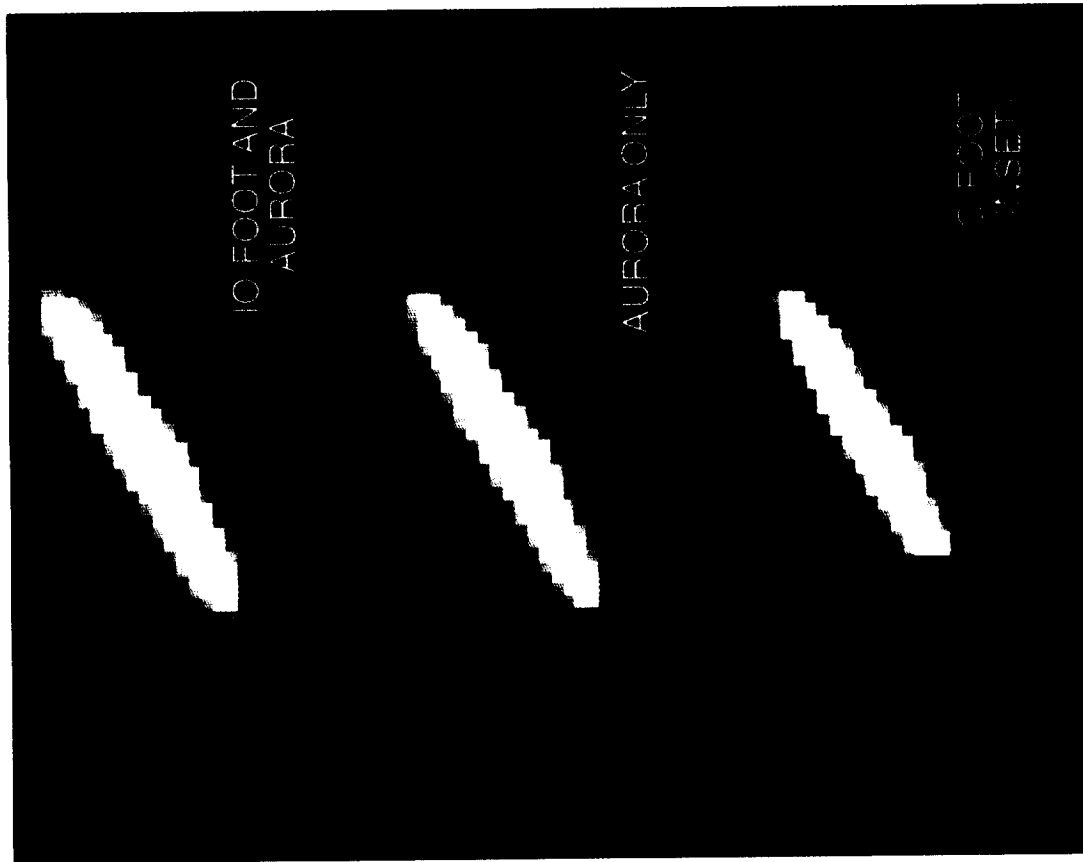
Plate 2. A ProtoCAM image of H_3^+ emissions from Jupiter's south polar region. The faint emission feature equatorward of the auroral oval (bottom panel, inset) is associated with the ionospheric foot of the Io flux tube (the magnetic field lines linking Jupiter's ionosphere with the Io plasma torus) and is produced by the impact of changed particles accelerated downward into the ionosphere by the elcytrody-namic interaction of Io with the Jovian magnetosphere. (Reprinted with permission from *Connerney et al.* [1993]. Copyright 1993 American Association for the Advancement of Science.)
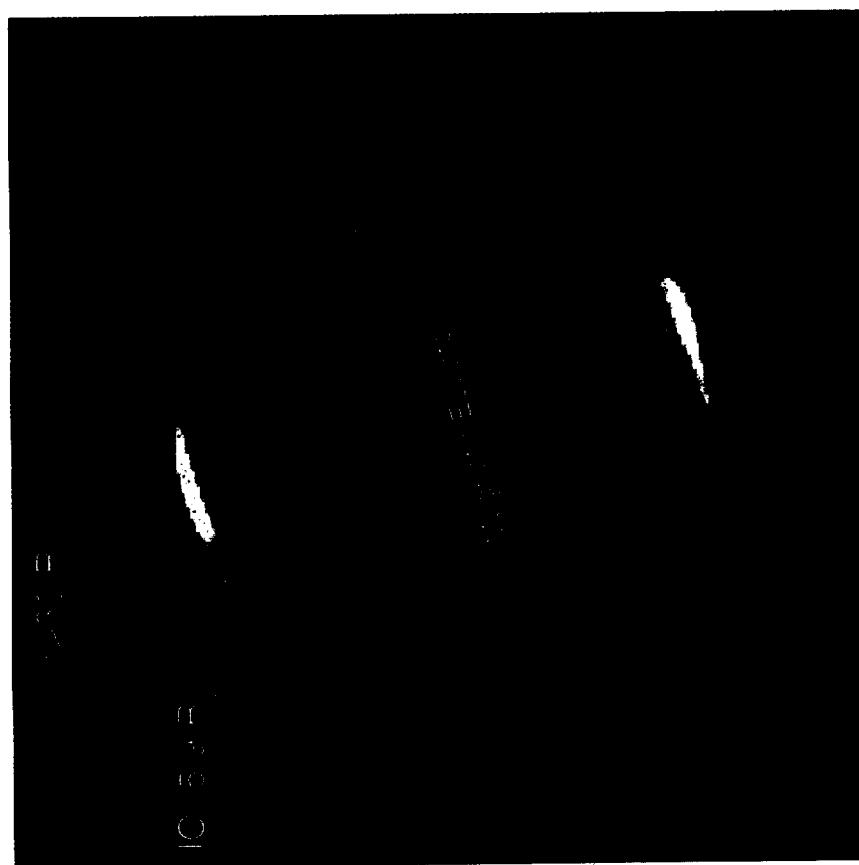
Plate 1. Jovian Auroral H_3^+ emissions at 3.40 μm imaged with the ProtoCAM infared camera at NASA's Infrared Telescope Facility at the Mauna Kea Observatory in Hawaii. Magnetic field lines linking Jupiter's upper atmosphere to the outer magnetosphere (beyond 30 R_J) and to the Io plasma torus have been superimposed on this mosaic of nine ProtoCAM images. First detected in 1989, such emissions from ro-vibrationally excited H_3^+ have provided researchers during the 1991-1994 quadrennium with valuable diagnostic information about Jupiter's bulk ionosphere above the methane homopause. (Reprinted with permission from *Connerney et al.* [1993]. Copyright 1993 American Association for the Advancement of Science.)

Voyager 1 flew through the plasma wake of Titan at a distance of about 2.5 Titan radii on November 12, 1980 and made in situ plasma and field measurements [e.g., *Hartle et al.*, 1982; *Neubauer et al.*, 1984] as well as remote measurements of the atmosphere. We learned from ultraviolet spectrometer measurements [*Broadfoot et al.*, 1981; *Hunten*, 1984] that molecular nitrogen is the major atmospheric constituent, although the abundances of methane and other hydrocarbon species are also high. The Voyager radio occultation experiment only set upper limits on the peak ionospheric electron densities—about 3000 cm^{-3} on the dawnside and about 5000 cm^{-3} on the duskside [*Lindal et al.*, 1983; *Neubauer et al.*, 1984]. Theoretical models predict a substantial ionosphere with densities not much less than these upper limits [e.g., *Atreya*, 1986; *Ip*, 1990; *Keller et al.*, 1992]. A number of recent theoretical studies of the ionosphere of Titan have been undertaken, motivated by NASA's Cassini mission, now in the construction stage. Instruments on the Cassini spacecraft will be able to make both remote and in situ measurements of the upper atmosphere and ionosphere of Titan.

The photochemical ionospheric model of *Keller et al.* [1992] confirmed earlier theoretical expectations of very complex ion chemistry and that the major ion species is undoubtedly H$_2$CN$^+$, which is produced by a chain of reactions involving CH$_4$ and HCN:

$$h\nu, e + N_2 \longrightarrow N_2^+ + e \qquad (1)$$

$$N_2^+ + CH_4 \longrightarrow CH_3^+ + N_2 + H \qquad (2)$$

$$CH_3^+ + CH_4 \longrightarrow C_2H_5^+ + H_2 \qquad (3)$$

$$C_2H_5^+ + HCN \longrightarrow H_2CN^+ + C_2H_4 \qquad (4)$$

The H$_2$CN$^+$ ions recombine dissociatively. Other predicted ion species include CH$_5^+$, C$_2$H$_5^+$ and other hydrocarbon ion species such as C$_3$H$_6^+$. The production mechanisms for the ionosphere are thought to be both photoionization by solar radiation and electron impact ionization due to magnetospheric electrons [*Gan et al.*, 1992]. The ionosphere of Titan is likely to be dynamically complex and should look very different on the ramside, which faces the corotating Saturnian magnetospheric plasma flow, than it does on the wakeside. The ramside ionosphere was studied by *Keller et al.* [1994] with a one-dimensional, multispecies, magnetohydrodynamic (MHD) model and by *Ip* [1990] with a single fluid MHD model. Both these models predict an ionosphere permeated with an induced magnetic field and downward ion flow speeds of a few m/s. On the other hand, a one-dimensional, hydrodynamical model of the wakeside ionosphere [*Keller and Cravens*, 1994] predicts upward ion flow speeds in the wakeside as high as a few km/s. The flow speeds depend both on the wakeside field geometry and on the plasma energetics. Both *Gan et al.* [1992] and *Roboz and Nagy* [1994] constructed models of the ionospheric energetics of Titan, which predict plasma temperatures of about 700°K on the ramside. As the Cassini mission gets underway over

the next few years, we can expect that in anticipation of new data, increasingly sophisticated models of Titan's ionosphere and plasma environment will be developed.

Cometary atmospheres and ionospheres are very different from their planetary, or satellite, counterparts in that they are not gravitationally bound. The neutral atoms and molecules in the coma are ionized by solar radiation, thus producing cometary plasma. In the denser cometary atmosphere within a few thousand kilometers of the nucleus, for an active comet like Halley, the cometary ion density can exceed 10^{4}cm^{-3} and the plasma is cold and slow moving. This region can be called the cometary ionosphere. The ion chemistry in this region is quite complex [e.g., *Huebner*, 1985; *Keller and Cravens*, 1990], but the most abundantly produced ion is H$_2O^+$ which reacts with water to produce the major ion, H$_3O^+$. Some other ions, such as CO$^+$ are also present in the cometary ionosphere and in the plasma tail.

The Giotto spacecraft launched by the European Space Agency flew by Comet Halley in March of 1986, and the ion mass spectrometer onboard that spacecraft measured the ionospheric plasma in the inner coma [*Balsiger*, 1986]. Soviet and Japanese spacecraft also visited Comet Halley, but did not get close enough to make ionospheric measurements. The Giotto measurements demonstrated that there was a cometary ionosphere with a high plasma density (up to 10^{4}cm^{-3}) and that the major ion species was indeed H$_3O^+$. Many other ion species were also detected. The magnetometer on board Giotto measured a significant magnetic field throughout most of the cometary ionosphere although it also observed a field-free cavity within a distance from the nucleus of about 4500 km [*Neubauer*, 1986]. The cavity is thought to be formed by the frictional force that the outwardly moving neutrals exert on the cometary ions "attached" to the magnetic field lines [cf. *Cravens*, 1991]. NASA's ICE spacecraft visited Comet Giacobini-Zinner in 1985 and also made plasma measurements. The review paper of *Cravens* [1991] summarizes much of what we have learned about plasmas in the inner coma of a comet (i.e., the ionosphere) since 1986.

During the past 4 years the pace of work on cometary ionospheres has slowed considerably, although much of the data remains uninterpreted. *Lindgren and Cravens* [1993] constructed a two-dimensional, two species, MHD model of comet Halley with a variable radial bin size; *Gombosi et al.* [1994] have developed an MHD model on an adaptively refined grid. *Flammer* [1993] has continued her work on the structure of the diamagnetic cavity boundary layer; she has compared the results of a hybrid simulation with the earlier results of a fluid MHD code [*Cravens*, 1989]. The two types of models differ in how the width of the boundary layer varies with the flow speed, or Mach number, of the incident ionospheric plasma. Another issue that remains unresolved is the degree to which the plasma in the inner coma is actually thermalized. *Puhl et al.* [1993] determined the evolution of the cometary ion distribu-

tion function as the plasma convects inward towards the nucleus using a numerical solution of the Fokker-Planck equation, including both Coulomb and charge-transfer collisions. They demonstrated for Comet Halley that the cometary ion distribution function is transformed from the shell-like distribution function, expected for isotropized pick-up ions, into a Maxwellian distribution at a cometocentric distance of the 15,000 km for Comet Halley, a distance which is within the region one could call the ionosphere.

On July 10, 1992, the Giotto spacecraft flew by Comet Grigg-Skjellerup. This was a comet with a weak gas production rate of only about $7 \times 10^{27} s^{-1}$ (the Comet Halley gas production rate was about $10^{30} s^{-1}$). The region with cold ionospheric type plasma for such a comet is expected to be confined very close to the nucleus [*Flammer and Mendis*, 1993]. In fact, the diamagnetic cavity has been predicted to exist at cometocentric distances of less than 100 km. The Giotto spacecraft's closest approach distance was approximately 200 km [*Flammer and Mendis*, 1993] but clearly not within the diamagnetic cavity. This conclusion is supported by the fact that magnetometer data showed the spacecraft passing through a magnetic pileup region, with a maximum field strength of about 65 nT, but never passing through a field-free region [*Glassmeier and Neubauer*, 1993].

Summary

Our understanding of planetary ionospheres made some progress during the last four years. Most of this progress was due to new and/or improved theoretical models, although some new data were also obtained by direct and remote sensing observations. The very basic processes such as ionization, chemical transformations and diffusive as well as convective transports are analogous in all ionospheres; the major differences are the result of factors such as different neutral atmospheres, intrinsic magnetic field strength, distance from the Sun, etc. Improving our understanding of any of the ionospheres in our solar system helps in elucidating the controlling physical and chemical processes in all of them. New measurements are needed to provide new impetus, as well as guidance, in advancing our understanding and we look forward to such information in the years ahead.

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