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magnetosphere The H₃⁺ ion: a remote diagnostic of the jovian

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J. E. P. Connerney and T. Satoh

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$\begin{array}{c} \text{The H}_3^+ \text{ ion} \ \text{the H}_3^+ \text{ ion} \ \text{the ion} \end{array}$ $3¹$ **EXTROLIES**
ion: a remote diagnostic of
iovian magnetosphere H_3^+ ion: a remote diagnostic of the jovian magnetosphere **the jovian magnetosphere**
BY J. E. P. CONNERNEY¹ AND T. SATOH²

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Observations of the jovian system in the near-infrared $(3.4 \text{ }\mu\text{m})$ reveal a wealth of information about Jupiter's magnetic eld, magnetosphere, and magnetospheric Observations of the jovian system in the near-infrared $(3.4 \text{ }\mu\text{m})$ reveal a wealth
of information about Jupiter's magnetic field, magnetosphere, and magnetospheric
dynamics. This wavelength contains a few emission li of information about Jupiter's magnetic field, magnetosphere, and magnetospheric
dynamics. This wavelength contains a few emission lines of the H_3^+ ion *and* it is cen-
tred on a deep methane absorption band. As a res dynamics. This wavelength contains a few emission lines of the H_3^+ ion *and* it is centred on a deep methane absorption band. As a result, one can image Jupiter's ionosphere at this wavelength with extraordinary signa tred on a deep methane absorption band. As a result, one can image Jupiter's iono-
sphere at this wavelength with extraordinary signal-to-noise ratio, against a planet
otherwise darkened by absorption due to methane in its sphere at this wavelength with extraordinary signal-to-noise ratio, against a planet otherwise darkened by absorption due to methane in its atmosphere. High spatial resolution images of the planet's surface provide a synop olution images of the planet's surface provide a synoptic view of the entire magnetoplution images of the planet's surface provide a synoptic view of the entire magneto-
sphere, from the electrodynamics of Io and the torus, to the excitation of auroral dis-
plays at high magnetic latitude. Observations of sphere, from the electrodynamics of Io and the torus, to the excitation of auroral dis-
plays at high magnetic latitude. Observations of the Io Flux Tube footprint have pro-
vided a new magnetic coordinate system for the j plays at high magnetic latitude. Observations of the Io Flux Tube footprint have provided a new magnetic coordinate system for the jovian polar regions and new insight
into the electrodynamic interaction between Jupiter an vided a new magnetic coordinate system for the jovian polar regions and new insight
into the electrodynamic intensity are observed in the IR and are well correlated
variations (days) of auroral intensity are observed in t into the electrodynamic interaction between Jupiter and Io. Short-term temporariations (days) of auroral intensity are observed in the IR and are well correlastions with variations in the solar-wind ram pressure arriving $\frac{1}{3}$ emisvariations (days) of auroral intensity are observed in the IR and are well correlated
with variations in the solar-wind ram pressure arriving at Jupiter. These H_3^+ emissions are thermally excited and are a good proxy with variations in the solar-wind ram pressure arriving at Jupiter. These H_3^+ emissions are thermally excited and are a good proxy for time-averaged energy deposition.
It is now possible to produce detailed maps of en sions are thermally excited and are a good proxy for time-averaged energy deposition.
It is now possible to produce detailed maps of energy deposition from the Io footprint $(L = 6)$ to the pole, in which both system III an

Keywords: infrared; H_3^+ ; magnetosphere; Jupiter; auroral; Io

1. Introduction

Burke & Franklin (1955) detected low-frequency radio emission from Jupiter in 1955 Burke & Franklin (1955) detected low-frequency radio emission from Jupiter in 1955
and initiated an era of remote observation of Jupiter's magnetosphere using radio
telescopes. This occurred before the launch of Sputnik in Burke & Franklin (1955) detected low-frequency radio emission from Jupiter in 1955
and initiated an era of remote observation of Jupiter's magnetosphere using radio
telescopes. This occurred before the launch of Sputnik in and initiated an era of remote observation of Jupiter's magnetosphere using radio
telescopes. This occurred before the launch of Sputnik in 1957 and prior to the
introduction of the term 'magnetosphere' by T. Gold in 1959. telescopes. This occurred before the launch of Sputnik in 1957 and prior to the introduction of the term 'magnetosphere' by T. Gold in 1959. By the time the first space probe arrived at Jupiter in 1973, much was already kn introduction of the term 'magnetosphere' by T. Gold in 1959. By the time the first
space probe arrived at Jupiter in 1973, much was already known about Jupiter's
magnetic field and the enigmatic interaction between it and space probe arrived at Jupiter in 1973, much was already known about Jupiter's magnetic field and the enigmatic interaction between it and the innermost Galilean satellite, Io (see review by Carr *et al.* (1983)). *In situ* field and magnetospheric plasmas confirmed the presence of an Earth-like magnetic satellite, Io (see review by Carr *et al.* (1983)). In situ observations of the magnetic field and magnetospheric plasmas confirmed the presence of an Earth-like magnetic field, with an axis of symmetry tilted by *ca*. 10 field and magnetospheric plasmas confirmed the presence of an Earth-like magnetic
field, with an axis of symmetry tilted by $ca. 10^{\circ}$ with respect to the rotation axis
(reviewed by Acuña *et al.* (1983)). With a magneti field, with an axis of symmetry tilted by $ca. 10^{\circ}$ with respect to the rotation axis (reviewed by Acuña *et al.* (1983)). With a magnetic moment of $ca. 1.5 \times 10^{30}$ G cm³, Jupiter is the most magnetic planet in the (reviewed by Acuña *et al.* (1983)). With a magnetic moment of $ca. 1.5 \times 10^{30}$ G cm³, Jupiter is the most magnetic planet in the solar system. At a distance of 5.2 AU from the sun, it creates a voluminous obstacle to Jupiter is the most magnetic planet in the solar system
the sun, it creates a voluminous obstacle to the solar
sky about three times as large as the Moon or Sun. *Phil. Trans. R. Soc. Lond.* A (2000) 358, 2471-2483

transmittance of the jovian atmosphere at several pressure levels (1 mbar, 10 mbar, 100 mbar).

Like Earth, Jupiter also has an omnipresent and spectacular auroral display, first observed at ultraviolet (UV) wavelengths by the Voyager spacecraft during its 1979 Like Earth, Jupiter also has an omnipresent and spectacular auroral display, first observed at ultraviolet (UV) wavelengths by the Voyager spacecraft during its 1979 flyby (Broadfoot *et al.* 1979). Jovian UV spectra are observed at ultraviolet (UV) wavelengths by the Voyager spacecraft during its 1979
flyby (Broadfoot *et al.* 1979). Jovian UV spectra are dominated by the intense
1216 Å hydrogen Ly α emission line, followed by H₂ Lym flyby (Broadfoot *et al.* 1979). Jovian UV spectra are dominated by the intense
1216 Å hydrogen Ly α emission line, followed by H₂ Lyman and Werner band emis-
sions. Ultraviolet spectrometers aboard the Earth-orbiting 1216 A hydrogen Ly α emission line, followed by H₂ Lyman and Werner band emissions. Ultraviolet spectrometers aboard the Earth-orbiting International Ultraviolet Explorer (IUE) and Hubble Space Telescope (HST) have mo sions. Ultraviolet spectrometers aboard the Earth-orbiting International Ultraviolet
Explorer (IUE) and Hubble Space Telescope (HST) have monitored jovian auroral
activity beginning with the IUE observations of Clarke *et* Explorer (IUE) and Hubble Space Telescope (HST) have monitored jovian auroral activity beginning with the IUE observations of Clarke *et al.* (1980). Direct imaging of the UV aurora became possible with the faint object c activity beginning with the IUE observations of Clarke *et al.* (1980). Direct imaging
of the UV aurora became possible with the faint object camera (FOC) on the HST in
1992 (Caldwell *et al.* 1992; Dols *et al.* 1992; Gér of the UV aurora became possible with the faint object camera (FOC) on the HST in 1992 (Caldwell *et al.* 1992; Dols *et al.* 1992; Gérard *et al.* 1993), and, subsequently, with the wide field planetary camera (WFPC2) on 1992 (Caldwell *et al.* 1992;
with the wide field planeta
1998; Prangé *et al.* 1998).
Infrared emissions due to th the wide field planetary camera (WFPC2) on the HST (Clarke *et al.* 1996, 98; Prangé *et al.* 1998).
Infrared emissions due to the molecular ion H_3^+ were first detected spectroscop-
ally in a 2 um overtone band (Dr

1998; Prangé *et al.* 1998).
Infrared emissions due to the molecular ion H_3^+ were first detected spectroscopically in a 2 μ m overtone band (Drossart *et al.* 1989; Trafton *et al.* 1989; Oka &
Geballe 1990) and sub Infrared emissions due to the molecular ion H_3^+ were first detected spectroscopically in a 2 μ m overtone band (Drossart *et al.* 1989; Trafton *et al.* 1989; Oka & Geballe 1990) and subsequently imaged in the 3-4 ically in a 2 μ m overtone band (Drossart *et al.* 1989; Trafton *et al.* 1989; Oka & Geballe 1990) and subsequently imaged in the 3–4 μ m ν ₂ fundamental band using an IR array camera at NASA's 3 m infrared teles Geballe 1990) and subsequently imaged in the 3–4 μ m ν ₂ fundamental band using an IR array camera at NASA's 3 m infrared telescope facility (IRTF) (Baron *et al.* 1991; Kim *et al.* 1991). H₃⁺ is formed in the IR array camera at NASA's 3 m infrared telescope facility (IRTF) (Baron *et al.* 1991;
Kim *et al.* 1991). H_3^+ is formed in the jovian ionosphere by the rapid ion-molecule
reaction $(H_2^+ + H_2 \rightarrow H_3^+ + H)$ that follows i reaction $(H_2^+ + H_2 \rightarrow H_3^+ + H)$ that follows ionization of molecular H_2 . H_3^+ is
major ionospheric ion between *ca*. 1 and 100 μ bar, with H^+ dominating at hi
altitudes (Waite *et al.* 1997; Kim & Fox 1994; Achi Kim *et al.* 1991). H_3^+ is formed in the jovian ionosphere by the rapid ion-molecule reaction $(H_2^+ + H_2 \rightarrow H_3^+ + H)$ that follows ionization of molecular H_2 . H_3^+ is the major ionospheric ion between *ca*. 1 and altitudes (Waite *et al.* 1997; Kim & Fox 1994; Achilleos *et al.* 1998). H_2^+ emission major ionospheric ion between ca. 1 and 100 μ bar, with H⁺ dominating at higher altitudes (Waite *et al.* 1997; Kim & Fox 1994; Achilleos *et al.* 1998). H₃⁺ emission originates from a critical region of Jupiter's altitudes (Waite *et al.* 1997; Kim & Fox 1994; Achilleos *et al.* 1998). H_3^+ emission originates from a critical region of Jupiter's atmosphere, where the planet electrically couples to its environment, providing a u originates from a critical regionally couples to its environment
magnetospheric phenomena. *Phil. Trans. R. Soc. Lond.* A (2000)

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A remote diagnosticofthejovianmagnetosphere ²⁴⁷³

Figure 2. Image of Jupiter at 3.4 µm obtained at NASA's IRTF at Mauna Kea, Hawaii, using the
NSECAM facility imager. At this wavelength, bright H⁺ emissions appear against a planetary Figure 2. Image of Jupiter at 3.4 μ m obtained at NASA's IRTF at Mauna Kea, Hawaii, using the NSFCAM facility imager. At this wavelength, bright H_3^+ emissions appear against a planetary disc darkened by methane abso NSFCAM facility imager. At this wavelength, bright H_3^+ emissions appear against a planetary disc darkened by methane absorption.

30 *R***^j**

Io - 6 *R***^j**

In the state is the magnetic term in the magnetic state of the spectroscopy of H_3^+ have, thus, emerged as a valuable probe of piter's atmosphere and magnetosphere. We present here results of the imaging Imaging and spectroscopy of H_3^+ have, thus, emerged as a valuable probe of Jupiter's atmosphere and magnetosphere. We present here results of the imaging campaigns and refer to a companion article by Miller *et al.* (Imaging and spectroscopy of H_3^+ have, thus, emerged as a valuable probe of Jupiter's atmosphere and magnetosphere. We present here results of the imaging campaigns and refer to a companion article by Miller *et al*. (Jupiter's atmosphere and magnetosphere. We present here results of the imaging campaigns and refer to a companion article by Miller $et al.$ (this issue) who summarize spectroscopic observations of Jupiter. Imaging and spect campaigns and refer to a companion article by Miller *et al.* (this issue) who summarize spectroscopic observations of Jupiter. Imaging and spectroscopy are highly complementary. Spectroscopy is more diagnostic of the $H_$ marize spectroscopic observations of Jupiter. Imaging and spectroscopy are highly
complementary. Spectroscopy is more diagnostic of the H_3^+ source region, e.g. to infer
temperatures, number densities, and conditions i complementary. Spectroscopy is more diagnostic of the H_3^+ source region, e.g. to infer
temperatures, number densities, and conditions in Jupiter's atmosphere. Imaging is
more diagnostic of Jupiter's magnetic field and temperatures, number densities, and conditions in Jupiter's atmosphere. Imaging is
more diagnostic of Jupiter's magnetic field and magnetosphere, its response to the
solar wind, and satellite interactions. Together they pr more diagnostic of Jupiter's magnet
solar wind, and satellite interactions
state of the jovian magnetosphere.

e.
2. ${\rm H}_3^+$ imagery

2. \textbf{H}_3^+ imagery
A plethora of jovian H_3^+ emission lines is available in the near-infrared, particularly in
the K-band $(2-2.5 \text{ nm})$ and L-band $(3-4 \text{ nm})$ atmospheric windows. To best observe A plethora of jovian H_3^+ emission lines is available in the near-infrared, particularly in the K-band (2-2.5 μ m) and L-band (3-4 μ m) atmospheric windows. To best observe the *K*-band (2–2.5 μ m) and *L*-band (3–4 μ m) atmospheric windows. To best observe
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Jupiter 89° **CML** $\Phi_{10} = 90^{\circ}$

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jovian H_3^+ from terrestrial observatories, such as NASA's IRTF atop Hawaii's Mauna
Kea volcano, we need to satisfy three constraints. We look for a strong H_2^+ emission jovian H_3^+ from terrestrial observatories, such as NASA's IRTF atop Hawaii's Mauna
Kea volcano, we need to satisfy three constraints. We look for a strong H_3^+ emission
line or group of several lines within the ima jovian H_3^+ from terrestrial observatories, such as NASA's IRTF atop Hawaii's Mauna
Kea volcano, we need to satisfy three constraints. We look for a strong H_3^+ emission
line, or group of several lines within the im Kea volcano, we need to satisfy three constraints. We look for a strong H_3^+ emission
line, or group of several lines within the imager bandpass. We need to find emission
lines that coincide with terrestrial 'atmospher line, or group of several lines within the imager bandpass. We need to find emission
lines that coincide with terrestrial 'atmospheric windows', i.e. regions of the spectrum
relatively free of molecular band absorption, sc lines that coincide with terrestrial 'atmospheric windows', i.e. regions of the spectrum
relatively free of molecular band absorption, scattering and extinction due to water
vapour and atmospheric constituents. These firs relatively free of molecular band absorption, scattering and extinction due to water
vapour and atmospheric constituents. These first two constraints can be satisfied
throughout much of the K-band and L-band windows. We c throughout much of the K -band and L -band windows. We choose to image a group throughout much of the K-band and L-band windows. We choose to image a group
of H_3^+ emission lines near 3.4 μ m to take advantage of a deep methane absorption
band (figure 1) that prevents light from deep in Jupiter of H_3^+ emission lines near 3.4 μ m to take advantage of a deep methane absorption
band (figure 1) that prevents light from deep in Jupiter's atmosphere from escaping.
Within this absorption band, Jupiter appears ver band (figure 1) that prevents light from deep in Jupiter's atmosphere from escaping.
Within this absorption band, Jupiter appears very dark, free of reflected sunlight or
other emissions originating below the homopause. Th Within this absorption band, Jupiter appears very dark, free of reflected sunlight or other emissions originating below the homopause. Thus, the high-altitude emissions we are interested in appear with extraordinary signa other emissions originating below the homopause. Thus, the high-altitude emissions
we are interested in appear with extraordinary signal-to-noise (S/N) ratio against
a background darkened by absorption due to methane in t we are interested in appear with extraordinary signal-to-noise
a background darkened by absorption due to methane in the
Jupiter's atmosphere (pressures greater than a few millibars).
Figure 2 is a 3.4 um image of Jupiter a background darkened by absorption due to methane in the well-mixed part of Jupiter's atmosphere (pressures greater than a few millibars).
Figure 2 is a $3.4 \mu m$ image of Jupiter taken with the 256×256 pixel NSFCAM

Jupiter's atmosphere (pressures greater than a few millibars).
Figure 2 is a $3.4 \mu m$ image of Jupiter taken with the 256×256 pixel NSFCAM
infrared array camera and the circular variable filter (CVF) at the IRTF. The Figure 2 is a 3.4 μ m image of Jupiter taken with the 256 \times 256 pixel NSFCAM
infrared array camera and the circular variable filter (CVF) at the IRTF. The figure
is actually a composite of several images, since Jupit infrared array camera and the circular variable filter (CVF) at the IRTF. The figure
is actually a composite of several images, since Jupiter's disc more than fills the field
of view of the telescope. Individual images ar is actually a composite of several images, since Jupiter's disc more than fills the field
of view of the telescope. Individual images are acquired with 20 s integrated exposure
time (e.g. 10 exposures of 2 s each, co-adde of view of the telescope. Individual images are acquired with 20 s integrated exposure
time (e.g. 10 exposures of 2 s each, co-added) with a S/N ratio of more than 100.
These individual images are then cross-correlated and time (e.g. 10 exposures of 2 s each, co-added) with a S/N ratio of more than 100.
These individual images are then cross-correlated and joined to construct full disc
images or co-added to further improve the dynamic rang These individual images are then cross-correlated and joined to construct full disc
images or co-added to further improve the dynamic range. This composite figure
shows H_3^+ emissions that have very different origins, much about Jupiter's ionosphere and magnetosphere. ows H_3^+ emissions that have very different origins, which, once deciphered, reveal
uch about Jupiter's ionosphere and magnetosphere.
The high-latitude emission evident at both poles is the H_3^+ aurora. The greatly

much about Jupiter's ionosphere and magnetosphere.
The high-latitude emission evident at both poles is the H_3^+ aurora. The greatly
increased emission intensity at these latitudes results from the precipitation of ener The high-latitude emission evident at both poles is the H_3^+ aurora. The greatly
increased emission intensity at these latitudes results from the precipitation of ener-
getic charged particles, arriving from the distan increased emission intensity at these latitudes results from the precipitation of energetic charged particles, arriving from the distant magnetosphere along magnetic field
lines crossing the Equator between *ca*. 12 and getic charged particles, arriving from the distant magnetosphere along magnetic field
lines crossing the Equator between *ca*. 12 and $30R_j$ radial distance (Satoh & Conner-
ney 1999*a*; Satoh *et al.* 1996). A less inten lines crossing the Equator between $ca. 12$ and $30R_j$ radial distance (Satoh & Connerney 1999a; Satoh *et al.* 1996). A less intense band of emission extends a few degrees in latitude equatorward from the main oval t ney 1999*a*; Satoh *et al.* 1996). A less intense band of emission extends a few degrees
in latitude equatorward from the main oval to the Io *L*-shell footprint, i.e. those field
lines crossing the Equator at the orbital in latitude equatorward from the main oval to the Io L-shell f
lines crossing the Equator at the orbital distance of Io. A fer-
power are radiated away from the auroral zone by the H_3^+ io.
The view of Juniter's aurora in latitude equatorward from the main oval to the Io L -shell footprint, i.e. those field lines crossing the Equator at the orbital distance of Io. A few million megawatts of es crossing the Equator at the orbital distance of Io. A few million megawatts of wer are radiated away from the auroral zone by the H_3^+ ion alone.
The view of Jupiter's auroral ovals changes dramatically as Jupiter r

power are radiated away from the auroral zone by the H_3^+ ion alone.
The view of Jupiter's auroral ovals changes dramatically as Jupiter rotates, for
an observer on Earth, due to the ca . 10[°] angle between Jupiter's The view of Jupiter's auroral ovals changes dramatically as Jupiter rotates, for
an observer on Earth, due to the $ca. 10^{\circ}$ angle between Jupiter's magnetic and rota-
tion axes (Connerney 1993). In figure 2, obtained at an observer on Earth, due to the $ca. 10^{\circ}$ angle between Jupiter's magnetic and rotation axes (Connerney 1993). In figure 2, obtained at 89° jovian system III longitude (positive west is the convention, i.e. longit tion axes (Connerney 1993). In figure 2, obtained at 89° jovian system III longitude
(positive west is the convention, i.e. longitudes increase with time), the southern
magnetic pole is tilted towards the observer, so the (positive west is the convention, i.e. longitudes increase with time), the southern magnetic pole is tilted towards the observer, so the southern auroral oval is most visible. The variation of auroral intensity with jovia magnetic pole is tilted towards the observer, so the southern auroral oval is most visible. The variation of auroral intensity with jovian system III longitude approximates a sinusoidal variation (Baron *et al.* 1996) that can be analytically related to the position, size and altitude of the auroral ova mates a sinusoidal variation (Baron *et al.* 1996) that can be analytically related to the position, size and altitude of the auroral ovals (Connerney *et al.* 1996). Since one can rarely acquire observations over a full the position, size and altitude of the auroral ovals (Connerney *et al.* 1996). Since one
can rarely acquire observations over a full rotation (10 h) in a single night, this model
is extremely useful in comparing observat can rarely acquire observations over a full rotation (10 h) in a single night, this model
is extremely useful in comparing observations from night to night. The integrated
intensity of the H_3^+ aurora varies by about a is extremely useful in
intensity of the H_3^+ aurobserver's longitude.
In addition to the r Exercisty of the H_3^+ aurora varies by about a factor of two or three depending on the server's longitude.
In addition to the prominent auroral emission, an isolated and distinct emission sture can be seen on the dawn

feature can be seen on the dawn limb just a few degrees equatorward of the auroral feature can be seen on the dawn limb just a few degrees equatorward of the auroral emission. This feature appears at the foot of the magnetic field line linking Jupiter's feature can be seen on the dawn limb just a few degrees equatorward of the auroral
emission. This feature appears at the foot of the magnetic field line linking Jupiter's
ionosphere and the innermost Galilean satellite, Io emission. This feature appears at the foot of the magnetic field line linking Jupiter's ionosphere and the innermost Galilean satellite, Io, orbiting at a radial distance of $5.95R_j$. It is the surface expression of the e of 5.95 R_j . It is the surface expression of the electrodynamic interaction between
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A remote diagnostic of the jovian magnetosphere 2475
Jupiter's magnetic field and the satellite. The feature can be seen in both hemi-
spheres if the viewing geometry allows and moves across Jupiter's disc in concert Jupiter's magnetic field and the satellite. The feature can be seen in both hemispheres, if the viewing geometry allows, and moves across Jupiter's disc in concert with the orbital motion of Io. First detected in the infr Jupiter's magnetic field and the satellite. The feature can be seen in both hemispheres, if the viewing geometry allows, and moves across Jupiter's disc in concert with the orbital motion of Io. First detected in the infra spheres, if the viewing geometry allows, and moves across Jupiter's disc in concert
with the orbital motion of Io. First detected in the infrared (Connerney *et al.* 1993),
it has also been observed in the UV (Clarke *et a* with the orbital motion of Io. First detected in the infrared (Connerney *et al.* 1993), it has also been observed in the UV (Clarke *et al.* 1996, 1998; Prangé *et al.* 1998) with instruments aboard the HST. This feature it has also been observed in the UV (Clarke *et al.* 1996, 1998; Prangé *et al.* 1998) with instruments aboard the HST. This feature provides a fiducial reference mark on the planet's surface, greatly improving the accura with instruments aboard the HST. This feature provides a fiducial reference mark on
the planet's surface, greatly improving the accuracy of jovian magnetic field models
and auroral mapping (Connerney *et al.* 1998). It is the planet's surface, greatly improving the accuracy of jovian magnetic field models and auroral mapping (Connerney et al . 1998). It is also a powerful tool for understanding the detailed nature of the electrodynamic in Io. In anding the detailed nature of the electrodynamic interaction between Jupiter and
The disc of Jupiter can also be seen in figure 2, against a darker background,
it is illuminated by weaker emission from the non-auroral i

Io.
The disc of Jupiter can also be seen in figure 2, against a darker background,
as it is illuminated by weaker emission from the non-auroral ionosphere. While the
disc appears uniformly illuminated in figure 2, if one a The disc of Jupiter can also be seen in figure 2, against a darker background,
as it is illuminated by weaker emission from the non-auroral ionosphere. While the
disc appears uniformly illuminated in figure 2, if one allow as it is illuminated by weaker emission from the non-auroral ionosphere. While the disc appears uniformly illuminated in figure 2, if one allows for limb brightening of the emission, spatial variations of the lower-latitu disc appears uniformly illuminated in figure 2, if one allows for limb brightening
of the emission, spatial variations of the lower-latitude emissions have been mapped
spectroscopically (Miller *et al.* 1997; Lam *et al.* of the emission, spatial variations of the lower-latitude emissions have been mapped
spectroscopically (Miller *et al.* 1997; Lam *et al.* 1997). In our images, the majority of
the non-auroral H_3^+ appears distributed spectroscopically (Miller *et al.* 1997; Lam *et al.* 1997). In our images, the majority of the non-auroral H_3^+ appears distributed as one would expect of an ion formed quickly as a result of solar EUV radiation (Sato the non-auroral H_3^+ appears distributed as one would expect of an ion formed quickly
as a result of solar EUV radiation (Satoh & Connerney 1999b). The observation of
limb brightening and a dark terminator at both dawn as a result of solar EUV radiation (Satoh & Connerney 1999*b*). The observation of
limb brightening and a dark terminator at both dawn and dusk (before and after
opposition) argues for rapid recombination of H_3^+ , i.e. limb brightening and a dark terminator at both dawn and dusk (before and after opposition) argues for rapid recombination of H_3^+ , i.e. the H_3^+ density is substantially depleted during *ca*. 5° of jovian rotation (depleted during $ca.5^{\circ}$ of jovian rotation (500 s). Using a recombination time constant $\rm s^{-1}$ (L pid recombination of H_3^+ , i.e. the H_3^+ density is substantially
jovian rotation (500 s). Using a recombination time constant
(Leu *et al.* 1973), this implies an electron density of 10^4 cm⁻³
 $\frac{1}{2}$ (non-au depleted during ca. 5° of jovian rotation (500 s). Using a recombination time constant
of $\kappa_r = 2 \times 10^{-7}$ cm³ s⁻¹ (Leu *et al.* 1973), this implies an electron density of 10^4 cm⁻³
at the altitude of the H₃⁺ $3¹$ of $\kappa_r = 2 \times 10^{-7}$ cm³ s⁻¹ (Leu *et al.* 1973), this implies an electron density of 10⁴ cm⁻³
at the altitude of the H₃⁺ (non-auroral) disc emissions. This must be well above the
altitude of the peak ionosphe 10^5 cm⁻³) measured by radio occultations at high solar zenith angles (Strobel & altitude of the peak ionospheric electron density (a few times $10⁴$ to a few times altitude of the peak ionospheric electron density (a few times 10^4 to a few times 10^5 cm⁻³) measured by radio occultations at high solar zenith angles (Strobel & Atreya 1983). From the spatial distribution one can 10^5 cm⁻³) measured by radio occultations at high solar zenith angles (Strobel & Atreya 1983). From the spatial distribution one can deduce that the non-auroral H_3^+ emission peaks at an altitude corresponding to Atreya 1983). From the spatial distribution one can deduce mission peaks at an altitude corresponding to *ca*. 5–7 nb.
the detailed numerical model of Achilleos *et al.* (1998). the detailed numerical model of Achilleos *et al.* (1998).
3. Aurora

3. Aurora
There is great interest in using auroral emissions to study the dynamics of Jupiter's
magnetosphere. The entire magnetosphere can be mapped to the surface of Jupiter There is great interest in using auroral emissions to study the dynamics of Jupiter's
magnetosphere. The entire magnetosphere can be mapped to the surface of Jupiter
with a suitable magnetospheric model. Since particles mo magnetosphere. The entire magnetosphere can be mapped to the surface of Jupiter with a suitable magnetospheric model. Since particles move freely along magnetic magnetosphere. The entire magnetosphere can be mapped to the surface of Jupiter
with a suitable magnetospheric model. Since particles move freely along magnetic
field lines, the ionosphere and magnetosphere are tightly cou with a suitable magnetospheric model. Since particles move freely along magnetic
field lines, the ionosphere and magnetosphere are tightly coupled. What we (often)
cannot observe in the distant magnetosphere may have a vis field lines, the ionosphere and magnetosphere are tightly coupled. What we (often)
cannot observe in the distant magnetosphere may have a visible (or infrared) expres-
sion in the ionosphere that we can study. A visiting s cannot observe in the distant magnetosphere may have a visible (or infrared) expression in the ionosphere that we can study. A visiting space probe, such as Galileo or Ulysses, and Voyagers 1 and 2 before them, can sample sion in the ionosphere that we can study. A visiting space probe, such as Galileo
or Ulysses, and Voyagers 1 and 2 before them, can sample a minute fraction of the
magnetosphere. In situ observations of the magnetic field or Ulysses, and Voyagers 1 and 2 before them, can sample a minute fraction of the magnetosphere. In situ observations of the magnetic field and charged-particle environment are much more valuable if we can infer how to globalize our local knowledge. Images of the aurora help us do that, since each imag ronment are much more valuable if we can infer how to globalize our local knowledge.
Images of the aurora help us do that, since each image is a snapshot of the entire
magnetosphere mapped onto the ionosphere.
The ability Images of the aurora help us do that, since each image is a snapshot of the entire

distant magnetosphere depends critically on the accuracy of the magnetic map. The The ability to associate a location in the ionosphere with its counterpart in the distant magnetosphere depends critically on the accuracy of the magnetic map. The map has two parts: the magnetic field of the planet (Acuña distant magnetosphere depends critically on the accuracy of the magnetic map. The map has two parts: the magnetic field of the planet (Acuña *et al.* 1983; Connerney 1993) and that of the magnetospheric ring currents, des map has two parts: the magnetic field of the planet (Acuña *et al.* 1983; Connerney 1993) and that of the magnetospheric ring currents, described by a magnetodisc model (Connerney *et al.* 1981). The position of the aurora 1993) and that of the magnetospheric ring currents, described by a magnetodisc model (Connerney *et al.* 1981). The position of the auroral oval on the surface of the planet is largely dictated by the internal field model model (Connerney *et al.* 1981). The position of the auroral oval on the surface of the planet is largely dictated by the internal field model, whereas the size of the oval, and the mapping between magnetic colatitude and and the mapping between magnetic colatitude and radial distance, is dictated largely

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field model was a serious limitation, leading to uncertainties of $ca.\pm 10^\circ$ latitude in
the predicted position of the Io footprint (e.g. Connerney 1992). This meant that field model was a serious limitation, leading to uncertainties of $ca.\pm 10^{\circ}$ latitude in the predicted position of the Io footprint (e.g. Connerney 1992). This meant that the model position of the auroral ovals was unce field model was a serious limitation, leading to uncertainties of $ca \pm 10^{\circ}$ latitude in
the predicted position of the Io footprint (e.g. Connerney 1992). This meant that
the model position of the auroral ovals was unce the predicted position of the Io footprint (e.g. Connerney 1992). This meant that
the model position of the auroral ovals was uncertain by this amount, leading to
difficulties interpreting the early auroral images (see, fo difficulties interpreting the early auroral images (see, for example, Caldwell *et al.* 1992; Gérard *et al.* 1993, 1994).
The discovery of an emission feature at the instantaneous foot of the Io Flux Tube

1992; Gérard *et al.* 1993, 1994).
The discovery of an emission feature at the instantaneous foot of the Io Flux Tube
(IFT) in images of jovian H_3^+ aurora (Connerney *et al.* 1993) resolved the mapping
problem in larg The discovery of an emission feature at the instantaneous foot of the Io Flux Tube (IFT) in images of jovian H_3^+ aurora (Connerney *et al.* 1993) resolved the mapping problem, in large part. Such images are, in effect (IFT) in images of jovian H_3^+ aurora (Connerney *et al.* 1993) resolved the mapping
problem, in large part. Such images are, in effect, self-calibrating. Each observation
of the IFT footprint is a fiducial marker, ide problem, in large part. Such images are, in effect, self-calibrating. Each observation
of the IFT footprint is a fiducial marker, identifying a specific latitude and longi-
tude on Jupiter's surface with a known equatoria of the IFT footprint is a fiducial marker, identifying a specific latitude and longitude on Jupiter's surface with a known equatorial radial distance, Io's orbital radial distance of $5.9R_i$. One could simply measure the tude on Jupiter's surface with a known equatorial radial distance, Io's orbital radial distance of $5.9R_j$. One could simply measure the angular separation between auroral emissions and the IFT footprint and infer the cor distance of $5.9R_j$. One could simply measure the angular separation between auro-
ral emissions and the IFT footprint and infer the correct magnetic latitude for the
auroral emissions and (with the help of the magnetodis ral emissions and the IFT footprint and infer the correct magnetic latitude for the auroral emissions and (with the help of the magnetodisc model) the corresponding source region in the magnetosphere. Over the last few ye auroral emissions and (with the help of the magnetodisc model) the corresponding
source region in the magnetosphere. Over the last few years, many IFT footprints
were observed in the IR and UV (Clarke *et al.* 1996, 1998; leading to a new and improved jovian internal magnetic field model (Connerney *et al*. 1998). The mapping error for the IFT footprint has been reduced to *ca*. 1 or 2¯ leading to a new and improved jovian internal magnetic field model (Connerney *et al.* 1998). The mapping error for the IFT footprint has been reduced to *ca.* 1 or 2° in latitude, equal to the estimated error in loc al. 1998). The mapping error for the IFT footprint has been reduced to ca . 1 or 2° in latitude, equal to the estimated error in location of the IFT footprint in current IR (NASA IRTF) and UV (HST) imagery. At higher in latitude, equal to the estimated error in location of the IFT footprint in current
IR (NASA IRTF) and UV (HST) imagery. At higher magnetic latitudes, mapping
to the more distant magnetosphere, accuracy may be limited by IR (NASA IRTF) and UV (HST) imagery. At higher magnetic latitudes, mapping to the more distant magnetosphere, accuracy may be limited by time variations and local time variations that are not yet accounted for in the magne the more distant magnetosphere, accuracy may be limited by time variations and
cal time variations that are not yet accounted for in the magnetospheric models.
Figure 3a, b shows H_3^+ emissions in the jovian polar regi

local time variations that are not yet accounted for in the magnetospheric models.
Figure $3a, b$ shows H_3^+ emissions in the jovian polar regions. The mapping between
the ionosphere and the distant magnetosphere can be Figure 3a, b shows H_3^+ emissions in the jovian polar regions. The mapping between
the ionosphere and the distant magnetosphere can be visualized by reference to the
dotted lines, which trace out the ionospheric footpr the ionosphere and the distant magnetosphere can be visualized by reference to the
dotted lines, which trace out the ionospheric footprints for several equatorial radial
distances. The spatial distribution of H_3^+ emis dotted lines, which trace out the ionospheric footprints for several equatorial radial distances. The spatial distribution of H_3^+ emissions can be inferred from many such images obtained through 360° of jovian rota distances. The spatial distribution of H_3^+ emissions can be inferred from many such images obtained through 360° of jovian rotation. Satoh and co-workers (Satoh *et al.* 1996; Satoh & Connerney 1999*a*) used a deta images obtained through 360° of jovian rotation. Satoh and co-workers (Satoh *et al.* 1996; Satoh & Connerney 1999*a*) used a detailed emission model and a powerful inverse technique to deduce several important chara al. 1996; Satoh & Connerney 1999a) used a detailed emission model and a powerful
inverse technique to deduce several important characteristics of the emission. The
model uses the bands illustrated in figure 3 to organize inverse technique to deduce several important characteristics of the emission. The model uses the bands illustrated in figure 3 to organize polar emissions, allowing for system III and local-time variability within each z model uses the bands illustrated in figure 3 to organize polar emissions, allowing for
system III and local-time variability within each zone. The 'main oval', representing
the most intense emissions, is found within the system III and local-time variability within each zone. The 'main oval', representing
the most intense emissions, is found within the $12-30R_j$ band, indicating an origin in
what has traditionally been called the middle m the most intense emissions, is found within the $12-30R_j$ band, indicating an origin in
what has traditionally been called the middle magnetosphere. Weaker emissions are
found to be distributed within the $30R_j$ oval (map what has traditionally been called the middle magnetosphere. Weaker emissions are found to be distributed within the $30R_j$ oval (mapping to the distant magnetosphere, beyond $30R_i$ radial distance) and equatorward of the and to be distributed within the $30R_j$ oval (mapping to the distant magnetosphere,
yond $30R_j$ radial distance) and equatorward of the main oval.
Main-oval emissions maximize near system III longitudes of 260° in the

 130° in the south, corresponding to minima in the magnetic field magnitude. Between Main-oval emissions maximize near system III longitudes of 260° in the north and Main-oval emissions maximize near system III longitudes of 260 $^{\circ}$ in the north and 130 $^{\circ}$ in the south, corresponding to minima in the magnetic field magnitude. Between the $8R_j$ and $12R_j$ ovals, emission peaks at 130° in the south, corresponding to minima in the magnetic field magnitude. Between
the $8R_j$ and $12R_j$ ovals, emission peaks at 215° in the north and 25° in the south.
This is where the surface magnetic f the $8R_j$ and $12R_j$ ovals, emission peaks at 215° in the north and 25° in the south.
This is where the surface magnetic field begins to decrease for electrons drifting
azimuthally towards higher system III longitud This is where the surface magnetic field begins to decrease for electrons drifting azimuthally towards higher system III longitudes in Jupiter's magnetic field. This kind of longitudinal variation of the emission pattern (azimuthally towards higher system III longitudes in Jupiter's magnetic field. This

kind of longitudinal variation of the emission pattern (called the 'windshield-wiper'

effect) can be expected (Dessler & Hill 1979; Dess kind of longitudinal variation of the emission pattern (called the 'windshield-wiper'
effect) can be expected (Dessler & Hill 1979; Dessler & Chamberlain 1979; Prangé
& Elkhamsi 1991) if the precipitating particles respon effect) can be expected (Dessler & Hill 1979; Dessler & Chamberlain 1979; Prangé
& Elkhamsi 1991) if the precipitating particles responsible for the energy deposi-
tion are drawn from a trapped population. The location of & Elkhamsi 1991) if the precipitating particles responsible for the energy deposition are drawn from a trapped population. The location of the peak H_3^+ emissions suggests that trapped electrons suffering slow pitch-an tion are drawn from a trapped population. The location of the peak H_3^+ emissions
suggests that trapped electrons suffering slow pitch-angle diffusion (compared with
an azimuthal drift period) are responsible for the 8 suggests that trapped electrons suffering slow pitch-angle diffusion (compared with
an azimuthal drift period) are responsible for the 8–12 R_j emissions. In the 12–30 R_j
band, an isotropic distribution of rapidly pitchan azimuthal drift period) are responsible for the $8-12R_j$ emissions. In the $12-30R_j$
band, an isotropic distribution of rapidly pitch-angle scattered electrons is implicated
(Satoh *et al.* 1996; Satoh & Connerney 1999 band, an isotropic distribution of rapidly pitch-angle scattered electrons is (Satoh *et al.* 1996; Satoh & Connerney 1999*a*). The probability of precsuch particles is inversely proportional to the surface field magnitud *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 3. Image of the north (a) and south (b) polar regions of Jupiter at a wavelength of 3.4 μ m
showing H⁺ emissions. Dotted lines indicate the ionospheric footprint of field lines crossing the Figure 3. Image of the north (*a*) and south (*b*) polar regions of Jupiter at a wavelength of 3.4 μ m
showing H₃⁺ emissions. Dotted lines indicate the ionospheric footprint of field lines crossing the
Equator at ra showing H_3^+ emissions. Dotted lines indicate the ionospheric footprint of field lines crossing the Equator at radial distances of 6, 8, 12 and $30R_j$.

Polar cap H_3^+ emissions (greater than $30R_i$) are significantly more intense in the
ening sector (Satoh *et al.* 1996; Satoh & Connerney 1999*a*) as are the UV emis-Polar cap H_3^+ emissions (greater than $30R_j$) are significantly more intense in the evening sector (Satoh *et al.* 1996; Satoh & Connerney 1999*a*), as are the UV emissions (Clarke *et al.* 1996–1998). These emissions Polar cap H_3^+ emissions (greater than $30R_j$) are significantly more intense in the evening sector (Satoh *et al.* 1996; Satoh & Connerney 1999*a*), as are the UV emissions (Clarke *et al.* 1996, 1998). These emission evening sector (Satoh *et al.* 1996; Satoh & Connerney 1999*a*), as are the UV emissions (Clarke *et al.* 1996, 1998). These emissions occur on field lines that extend to large radial distances, where the asymmetry impose large radial distances, where the asymmetry imposed by the solar-wind interaction

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 Δ log(solar-wind ram pressure)
Figure 4. Change (relative to the previous observation) in the total integrated intensity of the
aurora as a function of the change in solar-wind ram pressure. Open symbols are used for t Figure 4. Change (relative to the previous observation) in the total integrated intensity of the aurora as a function of the change in solar-wind ram pressure. Open symbols are used for the northern aurora filled symbols f aurora as a function of the change in solar-wind ram pressure. Open symbols are used for the northern aurora, filled symbols for the southern aurora.

are observed to co-vary with variations in the solar-wind ram pressure arriving at Jupiter (Baron *et al*. 1996; Connerney *et al*. 1996), with increased auroral emissions observed during periods of increasing solar-wind pressure (figure 4). This observa-Jupiter (Baron *et al.* 1996; Connerney *et al.* 1996), with increased auroral emissions observed during periods of increasing solar-wind pressure (figure 4). This observation is consistent with 'magnetic pumping', a proc observed during periods of increasing solar-wind pressure (figure 4). This observa-
tion is consistent with 'magnetic pumping', a process by which charged particles
are collectively energized by fluctuations of the magneti are collectively energized by fluctuations of the magnetic field (Alfvén 1963; Goertz 1978). Since the efficacy of this process depends on the relative magnitude of the are collectively energized by fluctuations of the magnetic field (Alfvén 1963; Goertz 1978). Since the efficacy of this process depends on the relative magnitude of the field fluctuations $(\delta B/B)$, it should be most effect 1978). Since the efficacy of this process depends on the relative magnitude of the field fluctuations $(\delta B/B)$, it should be most effective in the distant magnetosphere (beyond 20 or 30 R_j), where a few nT of δB associ field fluctuations $(\delta B/B)$, it should be most effective in the distant magnetosphere
(beyond 20 or 30 R_j), where a few nT of δB associated with variations in solar-wind
ram pressure are a significant fraction of the a ram pressure are a significant fraction of the ambient field strength (Connerney *et al.* 1981). This process also requires relatively rapid pitch-angle scattering, otherwise the energy gained during an increase in the ma 1981). This process also requires relatively rapid pitch-angle scattering, otherwise the

4. Io interaction

A remarkable relationship between Jupiter and Io became apparent in the 1960s when Bigg (1964) discovered that the observation of high-frequency (22 MHz) radio signals
Bigg (1964) discovered that the observation of high-frequency (22 MHz) radio signals
from Jupiter was strongly correlated with Jo's orbit A remarkable relationship between Jupiter and Io became apparent in the 1960s when
Bigg (1964) discovered that the observation of high-frequency (22 MHz) radio signals
from Jupiter was strongly correlated with Io's orbital Bigg (1964) discovered that the observation of high-frequency (22 MHz) radio signals
from Jupiter was strongly correlated with Io's orbital phase. Reception is greatly
increased when Io's orbital phase (measured from geoce increased when Io's orbital phase (measured from geocentric superior conjunction *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 5. Propagation of Alfvèn waves generated by Io's passage through Jupiter's magne-
tosphere. Alfvèn waves propagate relatively slowly northward and southward through the
high-density plasma torus and may be partly re tosphere. Alfven waves propagate relatively slowly northward and southward through the high-density plasma torus and may be partly reflected at density gradients in the torus or in Jupiter's ionosphere.

in the direction of Io's orbital motion) is near 90° or 240°. This peculiarity was
attributed to an electromagnetic interaction between Jupiter and Io that ultimately in the direction of Io's orbital motion) is near 90° or 240° . This peculiarity was attributed to an electromagnetic interaction between Jupiter and Io that ultimately gives rise to radio emission from the foot o attributed to an electromagnetic interaction between Jupiter and Io that ultimately gives rise to radio emission from the foot of the IFT (Goldreich & Lynden-Bell 1969; attributed to an electromagnetic interaction between Jupiter and Io that ultimately
gives rise to radio emission from the foot of the IFT (Goldreich & Lynden-Bell 1969;
Piddington & Drake 1968). Jupiter's magnetic field s gives rise to radio emission from the foot of the IFT (Goldreich & Lynden-Bell 1969;
Piddington & Drake 1968). Jupiter's magnetic field sweeps past Io at *ca*. 57 km s⁻¹,
generating a motional electric field ($V \times B$) th Piddington & Drake 1968). Jupiter's magnetic field sweeps past Io at $ca.57 \text{ km s}^{-1}$,
generating a motional electric field $(\mathbf{V} \times \mathbf{B})$ that drives electrical currents along field
lines to and from Jupiter's ionospher generating a motional electric field $(V \times B)$ that drives electrical currents along field
lines to and from Jupiter's ionosphere. Radio emission is generated at the foot of
the IFT, beamed into space along the surface of a lines to and from Jupiter's ionosphere. Radio emission is generated at the foot of the IFT, beamed into space along the surface of a hollow cone (the axis of the cone aligns with B and the cone half-angle is $ca. 75^{\circ}$ the IFT, beamed into space along the surface of a hollow cone (the axis of the aligns with B and the cone half-angle is $ca.75^{\circ}$). The emission is visible when arrow conical beam sweeps past an observer near the jovig gns with B and the cone half-angle is $ca.75^{\circ}$). The emission is visible when the rrow conical beam sweeps past an observer near the jovigraphic equator.
In Goldreich & Lynden-Bell's (1969) model, the lack of symmetry

narrow conical beam sweeps past an observer near the jovigraphic equator.
In Goldreich & Lynden-Bell's (1969) model, the lack of symmetry in the observation of radio waves from Earth is explained by the twist imposed upon In Goldreich & Lynden-Bell's (1969) model, the lack of symmetry in the observa-
tion of radio waves from Earth is explained by the twist imposed upon the IFT by a
few times 10^6 A of current flowing in the flux tube, cl tion of radio waves from Earth is explained by the twist imposed upon the IFT by a
few times 10^6 A of current flowing in the flux tube, closing in Jupiter's ionosphere.
The essential feature of this DC circuit model is The essential feature of this DC circuit model is the current closure in the ionosphere.
The ionospheric footprint of the IFT 'leads' that of an undisturbed flux tube (one The essential feature of this DC circuit model is the current closure in the ionosphere.
The ionospheric footprint of the IFT 'leads' that of an undisturbed flux tube (one
carrying no current) by $ca. 10^{\circ}$ for every 10 The ionospheric footprint of the IFT 'leads' that of an undisturbed flux tube (one carrying no current) by $ca. 10^{\circ}$ for every 10^6 A of current carried by the flux tube and closing in the ionosphere. Changes in the c carrying no current) by $ca.10^{\circ}$ for every 10^6 A of current carried by the flux tube and closing in the ionosphere. Changes in the circuit must be communicated by Alfvèn waves travelling at the Alfvèn velocity. The D closing in the ionosphere. Changes in the circuit must be communicated by Alfvèn
waves travelling at the Alfvèn velocity. The DC circuit model is applicable only if an
Alfvèn wave can propagate from Io to Jupiter and back waves travellin
Alfvèn wave ca
slips past Io.
More recent fvèn wave can propagate from Io to Jupiter and back again before the flux tube
ps past Io.
More recent theoretical models favoured an 'open-loop' Io interaction, in which the
po-way Alfvèn wave travel time is too great to

More recent theoretical models favoured an 'open-loop' Io interaction, in which the two-way Alfvèn wave travel time is too great to allow for current closure (Neubauer More recent theoretical models favoured an 'open-loop' Io interaction, in which the
two-way Alfvèn wave travel time is too great to allow for current closure (Neubauer
1980; Bagenal 1983). In this case, Alfvèn waves radiat two-way Alfvèn wave travel time is too great to allow for current closure (Neubauer 1980; Bagenal 1983). In this case, Alfvèn waves radiate away into space (figure 5) and may experience multiple reflections at density gra 1980; Bagenal 1983). In this case, Alfvèn waves radiate away into space (figure 5) and
may experience multiple reflections at density gradients in the torus or in Jupiter's
ionosphere. The angle of propagation of the Alfv may experience multiple reflections at density gradients in the torus or in Jupiter's
ionosphere. The angle of propagation of the Alfvèn wave (with respect to B) depends
on the density of the medium through which it pro ionosphere. The angle of propagation of the Alfvèn wave (with respect to B) depends
on the density of the medium through which it propagates. Without current closure,
the maximum 'lead' of the foot of the flux tube is a on the density of the medium through which it propagates. Without current closure, the maximum 'lead' of the foot of the flux tube is at most a few degrees, depending on how much high-density torus the wave propagates thro *Phil. Trans. R. Soc. Lond.* A (2000)

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The observation of H₃^t</sub> emission at the instantaneous foot of the IFT (Connerney *et*¹⁹⁹³) provided a new and powerful diagnostic for the Io interaction and Jupiter's understood (Bagenal & Leblanc 1988).
The observation of H_3^+ emission at the instantaneous foot of the IFT (Connerney *et al.* 1993) provided a new and powerful diagnostic for the Io interaction and Jupiter's magnetosp al. 1993) provided a new and powerful diagnostic for the Io interaction and Jupiter's magnetosphere. The first direct measurements of the position of the IFT footprint % agnostic for the Io interaction and Jupiter's

ments of the position of the IFT footprint

, in accord with Goldreich & Lynden-Bell's
 al 1993) In the following years literally magnetosphere. The first direct measurements of the position of the IFT footprint
confirmed a 'lead' of between 15 and 20^o, in accord with Goldreich & Lynden-Bell's
(1969) DC circuit model (Connerney *et al.* 1993). In (1969) DC circuit model (Connerney *et al.* 1993). In the following years, literally hundreds of IFT footprint observations have been accumulated, mostly in H_3^+ IR imagery but also in the UV (Clarke *et al.* 1996, 199 $\frac{1}{3}$ IR (1969) DC circuit model (Connerney *et al.* 1993). In the following years, literally hundreds of IFT footprint observations have been accumulated, mostly in H_3^+ IR imagery but also in the UV (Clarke *et al.* 1996, 199 hundreds of IFT footprint observations have been accumulated, mostly in H_3^+ IR imagery but also in the UV (Clarke *et al.* 1996, 1998; Prangé *et al.* 1996, 1998). These have been put to use in improving models of Jup imagery but also in the UV (Clarke *et al.* 1996, have been put to use in improving models of *al.* 1998) and in studying the Io interaction.
Recent observations of the IFT footprint (J Recent observations of the IFT footprint (J. E. P. Connerney *et al.*, unpublished
Recent observations of the IFT footprint (J. E. P. Connerney *et al.*, unpublished
ta) have revealed multiple emission features not unlike

d. 1998) and in studying the Io interaction.
Recent observations of the IFT footprint (J. E. P. Connerney *et al.*, unpublished data) have revealed multiple emission features not unlike those expected of multiply reflected Alfvèn waves propagating downstream of Io ($figure 6$). In this example, one data) have revealed multiple emission features not unlike those expected of multiply
reflected Alfvèn waves propagating downstream of Io (figure 6). In this example, one
can see as many as five equally spaced peaks in the reflected Alfvèn waves propagating downstream of Io (figure 6). In this example, one
can see as many as five equally spaced peaks in the H_3^+ emission extending along
the Io footprint in the downstream direction. At 1 can see as many as five equally spaced peaks in the H_3^+ emission extending along
the Io footprint in the downstream direction. At 110° system III longitude, Io is
near the centre of the plasma torus at this time, the Io footprint in the downstream direction. At 110° system III longitude, Io is
near the centre of the plasma torus at this time, so one would expect a pattern of
equally spaced Alfvèn waves in both hemispheres (see midd near the centre of the plasma torus at this time, so one would expect a pattern of equally spaced Alfvèn waves in both hemispheres (see middle section of figure 5). An image of the southern hemisphere at this time shows t equally spaced Alfvèn waves in both hemispheres (see middle section of figure 5). An
image of the southern hemisphere at this time shows two distinct emission features
separated by *ca*. 4[°] longitude. We have now observe image of the southern hemisphere at this time shows two distinct emission features
separated by $ca.4^{\circ}$ longitude. We have now observed several such examples, all in
the last two years (1998 and 1999). These intensity v separated by $ca.4^{\circ}$ longitude. We have now observed several such examples, all in
the last two years (1998 and 1999). These intensity variations are small and difficult
to resolve spatially. It may well be that they ha the last two years (1998 and 1999). These intensity variations are small and difficult
to resolve spatially. It may well be that they have been observed in the last two
years as a result of improvements to our observing pr to resolve spatially. It may well be that they have been observed in the last two
years as a result of improvements to our observing programme. These include the
introduction of narrow-band fixed-wavelength H_3^+ filter years as a result of improvements to our observing programme. These include the introduction of narrow-band fixed-wavelength H_3^+ filters on NSFCAM in 1997 and image quality improvements at the IRTF during the same tim introduction of narrow-band fixed-wavelength H_3^+ filters on NSFCAM in 1997 and
image quality improvements at the IRTF during the same time. However, one cannot
dismiss the possibility that the nature of the Io interac image quality improvements at the IRTF during the same time. However, one cannot dismiss the possibility that the nature of the Io interaction has changed in response to long-term changes in the density of the plasma torus dismiss the possibility that the nature of the Io interaction has changed in response to long-term changes in the density of the plasma torus. An increased plasma density in 1998 and 1999 would favour observation of multip to long-term changes in the density of the plasma torus. An increased plasma density

Evidently, over some Io longitudes, and possibly at some times, the Io interaction is 'closed loop', like that described by Goldreich $\&$ Lynden-Bell (1969). At such Evidently, over some Io longitudes, and possibly at some times, the Io interaction
is 'closed loop', like that described by Goldreich & Lynden-Bell (1969). At such
times, a closed current loop exists and a substantial 'le is 'closed loop', like that described by Goldreich & Lynden-Bell (1969). At such
times, a closed current loop exists and a substantial 'lead' of the IFT footprint may
be observed. Over other Io longitudes, and possibly at be observed. Over other Io longitudes, and possibly at other times, the interaction is 'open loop'. The Alfvèn wave cannot propagate from Io to Jupiter's ionosphere be observed. Over other Io longitudes, and possibly at other times, the interaction
is 'open loop'. The Alfvèn wave cannot propagate from Io to Jupiter's ionosphere
and back again in time to close the loop. What is lacking is 'open loop'. The Alfvèn wave cannot propagate from Io to Ju
and back again in time to close the loop. What is lacking at prese
encompasses both behaviours and the transition between them.
Remote observation of the IFT f d back again in time to close the loop. What is lacking at present is a theory that
compasses both behaviours and the transition between them.
Remote observation of the IFT footprint can, thus, be used as a diagnostic of
p

encompasses both behaviours and the transition between them.
Remote observation of the IFT footprint can, thus, be used as a diagnostic of
Jupiter's magnetosphere. In principle, the separation between multiple reflections Remote observation of the IFT footprint can, thus, be used as a diagnostic of Jupiter's magnetosphere. In principle, the separation between multiple reflections of the IFT can be monitored as a measure of plasma density in Jupiter's magnetosphere. In principle, the separation between multiple reflections of
the IFT can be monitored as a measure of plasma density in the torus. Likewise, in
the closed-loop mode, the intensity and position of t the IFT can be monitored as a measure of plasma density in the torus. Likewise, in the closed-loop mode, the intensity and position of the IFT footprint communicates information on the electrical current closing in the ion pation in the ionosphere. The electron beam itself can be used to probe Jupiter's information on the electrical current closing in the ionosphere and on power dissi-
pation in the ionosphere. The electron beam itself can be used to probe Jupiter's
ionosphere. Approximately 500 000 MW of power are depos pation in the ionosphere. The electron
ionosphere. Approximately 500 000 MV
IFT (Goldreich & Lynden-Bell 1969). **IFT** (Goldreich & Lynden-Bell 1969).
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A remote diagnostic of the jovian magnetosphere 2481
29 July 1998 11.45 UT NASA IRTF NSFCAM 126° CML $\Phi_{I_0} = 196^\circ$ $\lambda_{\rm Io} = 110^\circ$ **Callisto** $\Delta \approx 5^\circ$.

Figure 6. Image of the north polar region of Jupiter at a wavelength of 3.4 µm showing multiple
H⁺ emission features extending downstream (in the plasma flow direction) of the IET footprint H_3^+ emission features extending downstream (in the plasma fl
 H_3^+ emission features extending downstream (in the plasma fl
 $\overline{5}$. Summary igure 6. Image of the north polar region of Jupiter at a wavelength of 3.4 μ m showing multiple $_3^+$ emission features extending downstream (in the plasma flow direction) of the IFT footprint.

 $5.$ Summary
The H_3^+ ion has emerged as a very useful probe of Jupiter and its environment, and,
most particularly the interaction between Jupiter's magnetic field and the satellite The H_3^+ ion has emerged as a very useful probe of Jupiter and its environment, and,
most particularly, the interaction between Jupiter's magnetic field and the satellite
Io. This tool has been used to improve models o The H_3^+ ion has emerged as a very useful probe of Jupiter and its environment, and,
most particularly, the interaction between Jupiter's magnetic field and the satellite
Io. This tool has been used to improve models o most particularly, the interaction between Jupiter's magnetic field and the satellite
Io. This tool has been used to improve models of Jupiter's magnetic field; contribute
to our understanding of the Io interaction; better Io. This tool has been used to improve models of Jupiter's magnetic field; contribute
to our understanding of the Io interaction; better understand jovian aurora, the
relationship between the aurora and magnetospheric dyna to our understanding of the Io interaction; better understand jovian aurora, the relationship between the aurora and magnetospheric dynamics; and the response of Jupiter's magnetosphere to variations in the solar wind. Thi relationship between the aurora and magnetospheric dynamics; and the response of Jupiter's magnetosphere to variations in the solar wind. This is a very promising start for an ion that had not yet been observed, prior to 1 Jupiter's magnetosphere to variations in the solar wind. This is a very promising start for an ion that had not yet been observed, prior to 1988, beyond the Earth.

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the staff of the Institute for As of IRTF telescope operators D. Griep, W. Golish and C. Kaminski. We also thank R. Joseph and for NASA. J.E.P.C. and T.S. are visiting astronomers at the IRTF.

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