

What astronomy has learned from observations of H_3^+

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This paper is dedicated to Dr. Gerhard Herzberg on the occasion of his 90th birthday

We review the uses to which H_3^+ astronomical observations have been put, in the five years since the first detection of this molecular ion in the aurorae of Jupiter. Spectroscopy of Jupiter shows that the ionospheric temperature is high (~ 1000 K) compared with the lower atmosphere and that auroral column densities are between 10^{12} and 10^{13} cm^{-2} . The molecule is also distributed widely across the planet in concentrations about 10% of peak auroral densities. Imaging in H_3^+ -sensitive wavelengths links the aurorae to open magnetic field lines, rather than those encompassing the Io plasma torus. Uranus shows H_3^+ emission intensities of a few percent of the peak jovian auroral lines, with somewhat weaker emission from Saturn. On Uranus, H_3^+ is distributed fairly evenly across the planet, with some indication that auroral enhancement is not more than a factor of two. Saturnine H_3^+ appears to be concentrated more towards the magnetic poles. The identification of H_3^+ in the spectrum of the type II supernova SN1987a constrains models of the explosion to avoid microscopic mixing during much of the first year of the event. So far no reliable detection of H_3^+ in the interstellar medium has been reported.

Nous passons en revue l'utilisation qu'on a faite des observations astronomiques de H_3^+ au cours des cinq années écoulées depuis la première détection de cet ion moléculaire dans les aurores de Jupiter. La spectroscopie de Jupiter montre que la température ionosphérique est élevée (environ 1000 K) en comparaison avec celle de la basse atmosphère, et que les densités des colonnes aurorales se situent entre 10^{12} et 10^{13} cm^{-2} . La molécule est aussi largement distribuée sur toute la planète, avec des concentrations de l'ordre de 10% des densités aurorales de pointe. L'imagerie en longueurs d'onde sensibles à H_3^+ relie les aurores à des lignes de champ magnétique ouvertes plutôt qu'à celles qui encerclent le tore plasmatique de Io. Les émissions H_3^+ observées sur Uranus ont des intensités de l'ordre de quelques pour-cent de celles des pics auroraux de Jupiter, alors que les émissions de Saturne sont encore plus faibles. Sur Uranus, la distribution de H_3^+ est assez uniforme, et tout indique que le renforcement auroral est au plus d'un facteur deux. Sur Saturne, H_3^+ semble davantage concentré vers les pôles magnétiques. L'identification de H_3^+ dans le spectre de la supernova de type II SN1987 a contraint les modèles de l'explosion à exclure le mélange microscopique durant la majeure partie de la première année de l'événement. Jusqu'à maintenant, aucune détection de H_3^+ dans le milieu interstellaire n'a été rapportée de façon certaine.

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1. Introduction

It came as rather a surprise when the spectrum of H_3^+ was detected for the first time outside of the laboratory in the auroral regions of the giant planet Jupiter [1]. Nor was the outer shell of a supernova the most obvious place to look for this energetic molecular ion [2, 3]. But, since its discovery by Thomson in 1912 [4], H_3^+ has always produced the unexpected. Its very existence, three protons held together by just two electrons, was a challenge to theories of bonding until the work of Hirschfelder finally showed that a triangular structure was stable and strongly bound [5]. And during the search for the infrared spectrum of H_3^+ , commenced by Herzberg in 1967 [6] and accomplished by Oka [7] in 1980, the neutral parent H_3 turned up [8]. This discovery gave rise to the field of molecular Rydberg spectroscopy.

Until 1988, when Drossart and his co-workers measured the $2 \mu\text{m}$ spectrum of the auroral regions of Jupiter [1], conventional wisdom had been that, astronomically, H_3^+ would be detected in stellar nurseries such as those associated with the Orion and Taurus molecular clouds, where it plays a central role in the gas chemistry [9]. Searches for H_3^+ absorption features in likely astronomical regions found no trace of the molecule, however [10, 11].

But the ionosphere of Jupiter had been proposed as a possible source of the ion a quarter of a century before its eventual detection [12]. And the Voyager II spacecraft detected the ion during its flyby in 1979 [13] in the jovian magnetosphere. The timing of the eventual astronomical detection of H_3^+ , and the uses

we are now able to make of its spectrum, are intimately tied up with advances in laboratory spectroscopy, computational quantum chemistry, and the development of high-spectral, high-spatial resolution infrared astronomy, particularly at the summit of Mauna Kea in Hawaii.

2. The jovian ionosphere and aurorae

Several workers, such as Gross and Rasool [12], Hunten [14], and Atreya et al. [15], discussed the existence of H_3^+ in the ionosphere of Jupiter, long before its eventual detection [1]. There, as elsewhere, it was produced by the ionization of molecular hydrogen, which in turn reacted with neutral hydrogen thus:



Normally extremely reactive, H_3^+ would survive in the jovian ionosphere because this region is above the homopause, where only hydrogen and helium are sufficiently light to have appreciable concentrations. The only effective destruction mechanism in such a region is dissociative recombination with electrons:



In Gehrels' authoritative 1976 collection of articles on Jupiter,

Atreya and Donahue's model of the jovian ionosphere [16] was dominated by H^+ ; but in a thin (<50 km) layer close to the homopause, where its concentrations reached about 10^3 cm^{-3} , H_3^+ took over. It was also in this region that their model had a sudden increase in temperature from 150 to over 1000 K as a result of energy dissipated from inertia gravity waves. The production of ions was put down to solar extreme ultraviolet radiation (EUV) and impacts due to the electrons freed by the resulting photoionization, giving rise to an air-electroglow. Prins and Owen [17] used the dissociative recombination of H_3^+ with electrons as a source of H atoms critical to their modelling of hydrocarbon chemistry.

Although much was known about the spectroscopy of neutrals in the jovian atmosphere, Larson's 1980 review of *Infrared spectroscopic observations of the outer planets* [18] made no mention of molecular ions; molecular ion infrared spectroscopy was in its infancy even in the laboratory. In the same year, Hamilton et al. [13], analysing the data from Voyager II's low-energy charged-particle detector, reported the discovery of H_2^+ and H_3^+ in the jovian magnetosphere. These ions were not known in the solar wind and thus had to have their origin in Jupiter. Prophetically they commented:

It may be that the source [of these particles] is not the normal ionosphere but some other region much farther from equilibrium ... the escaping particles could be produced ... by energetic particle precipitation (i.e., aurorae).

Regular observations of jovian auroral activity also began in earnest in 1980. Caldwell et al. [19], using the NASA Infrared Telescope Facility (IRTF) in Hawaii, which had been built to enable planetary scientists to follow up interesting discoveries made by the Voyager mission, proposed that brightening of the polar regions at $8 \mu\text{m}$ was due to aurorae arising from the ν_4 band of methane. At the same time, Clarke et al. [20] used the International Ultraviolet Explorer (IUE) to look at jovian aurorae due to H Lyman- α and the electronic transitions of H_2 , the first of a long series of such studies (see Livengood et al. [21]).

Caldwell et al. [19] initially estimated that the auroral output of the $CH_4 \nu_4$ band mapped onto magnetic field lines associated with the magnetotail of Jupiter and peaked, around the north pole, at a magnetic (System III) longitude of 168° . Follow-up studies established that the methane polar brightenings were relatively constant over a time scale of at least a year [22], and that there were polar brightenings visible in bands of both acetylene [23] and ethane [24].

In August of 1987, a workshop on *Time Variable Phenomena in the Jovian System* was held in Flagstaff, Arizona. By that time the emphasis on the aurorae had shifted to the Io plasma torus as a source for the precipitating particles. This torus is produced by the volcanic activity of Jupiter's closest Galilean moon, Io, and is connected to Jupiter by field lines that cross the magnetic equator at a distance equal to six jovian radii from the centre of the planet (the distance from Jupiter to Io). Such field lines are denoted $L = 6$ lines. Estimates of the input power needed to account for the UV emissions were in the order of 10^{14} W , about a thousand times that required for terrestrial aurorae. UV emission was considered to correlate spatially with the hydrocarbon emission in the northern hemisphere [25].

At the same workshop, Trafton et al. [26] presented moderate resolution spectra of the aurorae ($\lambda/\Delta\lambda \sim 1000$) that showed emission due to the $H_2 (\nu = 1 \rightarrow 0, S(1))$ transition at $2.122 \mu\text{m}$

and, without the authors knowing it, H_3^+ . Modelling of the ionosphere with ionization controlled by solar EUV radiation, McConnell and Majeed [27] produced H_3^+ concentrations up to 10^4 cm^{-3} around 1000 km above the cloud tops, and an associated column density between 6×10^{12} and $10 \times 10^{12} \text{ cm}^{-2}$. They also predicted that this ion could dominate over H^+ if the controversial dissociative recombination rate were as low as $10^{-11} \text{ cm}^3 \text{ s}^{-1}$ [28]. A "hot spot" in the CH_4 emission was noted in the northern hemisphere located at latitude 60° and longitude 180° [29], close to the Io torus footprint at this longitude.

3. Observations of Jupiter's aurorae using H_3^+

In September 1988, Drossart et al. [1] used a Fourier transform spectrometer (FTS) mounted on the Canada-France-Hawaii telescope to follow up the work of Trafton et al. [26] and look for infrared emission due to molecular hydrogen in the auroral regions of Jupiter at high spectral resolution. H_2 vibrational transitions are dipole forbidden, but quadrupole transitions are allowed. Intrinsically, these transitions, which occur around $2 \mu\text{m}$, are extremely weak; typical Einstein A_{if} values are 10^{-7} s^{-1} . But column densities of H_2 in the emitting region of the aurorae are of the order of 10^{21} – 10^{22} cm^{-2} , and the emissions occur in a spectral region that is not strongly obscured by the Earth's atmosphere, known as the K window.

The aim of Drossart et al.'s observations was to obtain a temperature for the hydrogen in the 1–0.01 μbar (1 bar = 100 kPa) region of the jovian atmosphere. The observations were successful; the derived temperature for auroral H_2 emissions was $730^{+490}_{-400} \text{ K}$ [30]. In addition to the H_2 quadrupole transitions, however, Drossart's group found a series of lines that were, if anything, even more intense than the ones they were actually looking for. Drossart's team was observing at high resolution ($\lambda/\Delta\lambda > 10,000$) the lines that Trafton et al. had previously reported [26] and would report again [31], the latter eventually assigning them to (probably) three unknown emitters. The story of the identification of Drossart's spectrum with the overtone ($2\nu_2(l = 2) \rightarrow 0$) transitions of H_3^+ has been told elsewhere [32, 33]. But it is worth reemphasizing that the whole episode required the development of high-resolution astronomical instrumentation, involved laboratory spectroscopists in Chicago [34] and the Herzberg Institute [35], made use of the latest developments in quantum chemical calculations [36, 37], and was truly an international achievement.

The 1988 data of Drossart et al. [1] remain the most detailed extensive spectral coverage of Jupiter in the K window, and contain three lines that are still unassigned. The most intense spectrum was obtained in the south of the planet, with the telescope beam centred on latitude -60° and longitude 60° . The paper concluded that H_3^+ emissions were coming from the 0.1–0.001 μbar atmospheric levels (i.e., somewhat higher than the H_2 emission), that the temperature was 1100 K (much higher than the lower atmosphere) and that column densities in the emitting $2\nu_2(l = 2)$ levels were $1.4 \times 10^9 \text{ cm}^{-2}$. There appeared to be a correlation between H_3^+ intensities and the Lyman and Werner bands of molecular hydrogen measured simultaneously with IUE.

That such relatively low column densities of H_3^+ could produce an overtone spectrum more intense than the abundant molecular hydrogen is itself a quirk of chemistry. Normally overtone infrared spectra, which are forbidden in the harmonic approximation, are at least an order of magnitude weaker than

the corresponding fundamental spectrum. But H_3^+ is an extremely "floppy" molecule, with a large vibrational anharmonicity that causes the A_{if} values of the overtone transition to be even larger than those of the fundamental, a fact first predicted computationally by Carney and Porter [38].

The observations of Drossart et al. [1] raised a number of important questions. Were the emissions of H_3^+ due to nascent molecules, freshly formed in excited vibrational states, a form of vibrational chemiluminescence? If not, was H_3^+ being resonantly excited into the $2\nu_2$ level by collisions with vibrationally excited H_2 , whose ($v = 1$) levels closely match the overtone of the molecular ion? What would be the spatial distribution of H_3^+ emission and would temporal variability be observed? And what role would H_3^+ be seen to play in the energy balance of the upper atmosphere of Jupiter?

In 1990 three groups [39–41] published measurements of the fundamental spectrum of H_3^+ in the jovian aurorae. Some of the most important transitions in this band occur between 3 and 4 μm , the astronomical L window. This region also corresponds to very strong methane absorption in Jupiter, due to the CH_4 ν_3 band. As a result, the planet reflects almost no incoming solar infrared (IR) radiation. Thus the 3–4 μm region is highly sensitive to the abundance and distribution of H_3^+ .

Using the United Kingdom Infrared Telescope (UKIRT), Oka and Geballe [39] reported that they had been unable to observe the overtone spectrum and that the temperature derived from their measurements of the fundamental was only 670 K, much lower than had previously been observed. The more spectroscopically extensive FTS data obtained by Maillard et al. resulted in a temperature of 1000 K [40]. Miller et al. [41] were able to make moderate ($\lambda/\Delta\lambda \sim 1000$) resolution measurements on NASA's IRTF of both the fundamental and overtone spectrum on the same night. The fundamental spectrum fitted well to the $T \sim 1100$ K simulation and the ratio of overtone to fundamental intensity gave a temperature of $1099(\pm 100)$ K.

These observations answered immediately some of the questions from Drossart et al. [1]. Miller et al.'s close approximation to thermal ratios for the vibrational intensities meant that it was unlikely that either nascent H_3^+ was responsible for the observed emissions or that the $2\nu_2$ levels were being resonantly populated by collisions with vibrationally excited H_2 [41]. This near-thermal interpretation has been confirmed recently by Drossart et al. [42] who managed to resolve individual H_3^+ lines and obtain the intrinsic line profile. From this they deduced a translational temperature of 1150 ± 60 K, very close to their derived rotational temperature of 1250 ± 70 K. Oka and Geballe's derived temperature for the fundamental showed that large variations could occur over time scales at least of several months; their failure to observe the overtone spectrum was in line with near-thermal population of H_3^+ vibrational levels [39].

In December 1990, attempts were made to determine the spatial distribution of the emissions spectroscopically. Joseph and Miller located the 2.7" beam of the IRTF on the limbs of Jupiter in an effort to maximize the emission of H_3^+ while reducing the background as much as possible owing to the longer column of absorbing CH_4 [43, 44]. In the auroral regions average temperatures measured on two successive nights remained fairly constant around 800 K in the southern hemisphere, but dropped from 1040 to 810 K in the north, showing time variations on the

order of a day were possible. (Smaller temperature variations detected in the original 1988 data [1] were also reported by Billebaud et al. [45].)

Total column densities of H_3^+ , assuming complete thermal equilibrium, reached as high as $6 \times 10^{12} \text{ cm}^{-2}$ [44], in line with model predictions [1], but were generally lower than that. But a note of caution in comparing model predictions of H_3^+ and column densities obtained from spectroscopy is required. Kim et al. [46] have demonstrated that the high A_{if} values coupled with the relatively low densities at which H_3^+ is being produced lead to radiative cooling that results in more molecules in the ground-vibrational state than simple thermal equilibrium implies.

Joseph et al. [44] detected no appreciable H_3^+ emission with the beam centred on latitudes less than 60° in either hemispheres. They reported maximum column densities with the beam centred on latitudes $\pm 75^\circ$. This suggested that the H_3^+ emissions were more closely linked to field lines connecting to the magnetotail than to the Io plasma torus, prompting the authors to question whether H_3^+ was mapping a different precipitation phenomenon than were the UV and hydrocarbon emissions, since the then accepted position was that both were located at lower latitudes [44].

This work also highlighted the role H_3^+ could play in maintaining the energy balance of the auroral regions. From measurements of the UV aurorae, energy inputs are assumed to be of the order of $30 \text{ ergs cm}^{-2} \text{ s}^{-1}$ ($1 \text{ erg} = 0.1 \mu\text{J}$) [25]. Joseph et al. calculated that H_3^+ could be radiating between 1.5 and 15% of this amount [44]. Since the model of Kim et al. [46] was able to produce column densities of H_3^+ comparable with those observed with an energy input of precipitating electrons of just $1 \text{ erg cm}^{-2} \text{ s}^{-1}$, it appears that H_3^+ emissions can play a net cooling role in the ionosphere.

More precise location of the H_3^+ emissions became possible with the addition of a new infrared camera, ProtoCAM, on the NASA IRTF towards the end of 1990. This prototype instrument employed an InSb charge couple device (CCD) array of 58×62 pixels with a spatial resolution that could go as low as $0.15''$. Spectral resolution was provided by a circular variable filter that gave a typical band pass of between 1 and 2% in the region from 1 to 5 μm . Baron and Owen [47] first tried this instrument by looking at the jovian auroral regions at a wavelength of 4 μm , centring on the strong $Q(3)$ manifold of the fundamental H_3^+ band. They noticed brightening around the polar region, but at this wavelength their images had considerable structure on the body of the planet due to incomplete absorption of solar IR which made it difficult to distinguish H_3^+ emissions. A typical 4 μm image of Jupiter is shown in Fig. 1.

Early in 1991, two groups [48, 49] measured images at wavelengths sensitive to H_3^+ that were closer to the centre of CH_4 ν_3 . This had the effect of reducing reflected solar IR almost to zero, while highlighting the strong auroral emissions. The data of Baron et al. [48] consisted both of single frames of the auroral regions and mosaics of nine separate images from which the whole planet could be reconstructed. Images taken at 3.4 and 3.55 μm showed strong polar emissions; at H_3^+ "nulls," polar emission was typically no more than 20% of the maximum observed. From this Baron et al. concluded that these wavelengths were indeed sensitive to H_3^+ and little else.

By constructing full mosaics of the planet, to which a jovian ellipse could be fitted, this group concluded that the bright H_3^+

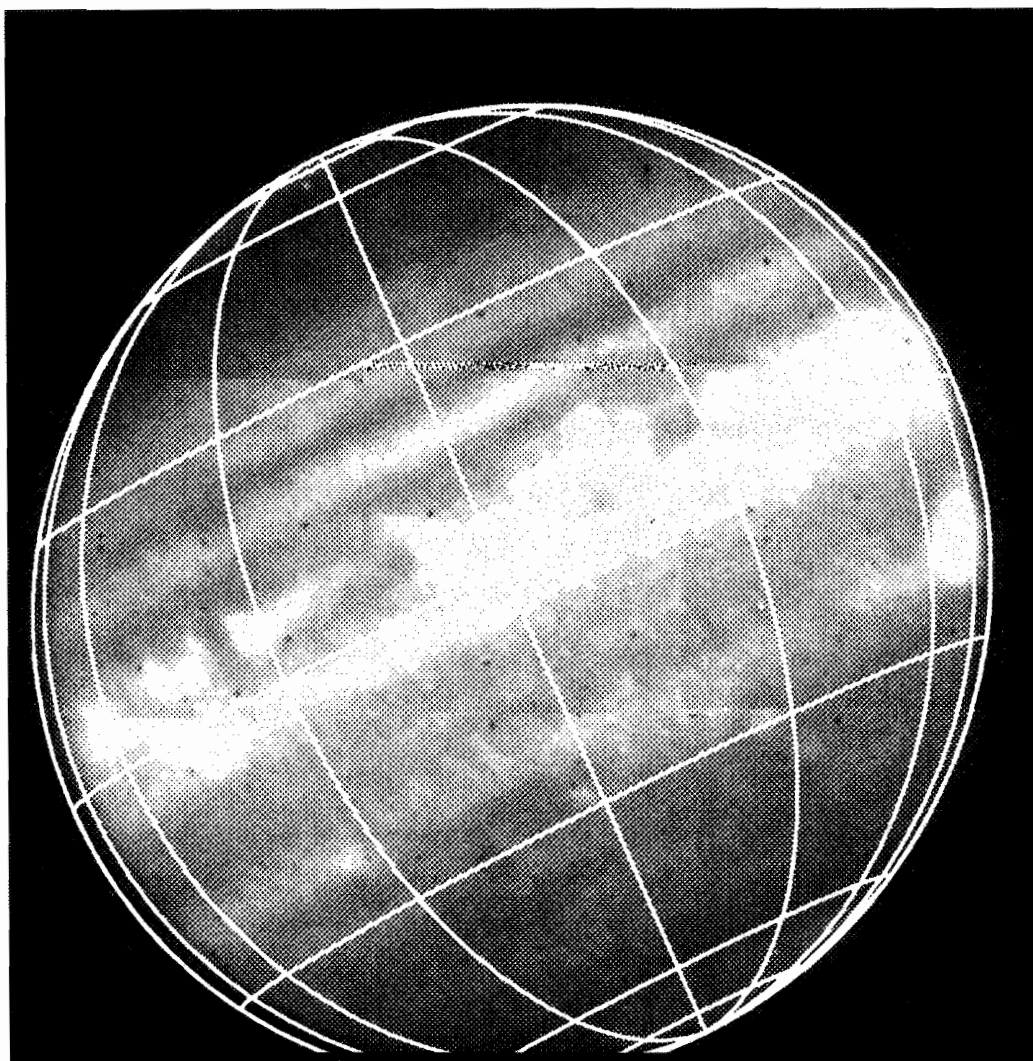


FIG. 1. Image of Jupiter obtained at $4\ \mu\text{m}$ using a 1% circular variable filter (cvf) on ProtoCAM, the facility infrared camera of the NASA IRTF. The image was constructed from a mosaic of nine separate images taken over a period of 15 min on April 23, 1993. The pixel scale is $0.25''$ and seeing was $\sim 0.5''$. Some enhancement of emission due to H_3^+ is visible around the poles. On the body of the planet partial absorption of incoming solar infrared radiation enables cloud features to be distinguished. The Great Red Spot can be seen on the dusk terminator (west limb).

emissions were generally coming from latitudes that mapped the open field lines connected to the magnetotail. A typical H_3^+ sensitive mosaic is shown in Fig. 2. Baron et al. [48] found that there was a relative minimum in the intensity of the northern aurorae at 180° , the region of the CH_4 emission hot spot, and suggested that this indicated precipitating particles were depositing most of their energy below the homopause there. Baron et al. also proposed that variations in auroral intensity could occur on time scales as short as 1 h, and certainly from day to day.

Kim et al. [49] put a different interpretation on the images they obtained. They did not use mosaics to fit their planetary ellipse, instead they relied on superimposing images taken at wavelengths where the limb of the planet showed up clearly on top of their H_3^+ sensitive images. This procedure led them to ascribe the H_3^+ emissions as coming from latitudes close to the footprint of the Io torus, i.e., lower than those of Baron et al. [48]. Kim et al. also argued that methane emission was playing a significant role in the total flux measured in the images [50], although this effect was later estimated to be no more than

10% around $3.5\ \mu\text{m}$ [51]. The location of the H_3^+ emission at lower latitudes led to the interpretation of the images as showing hot spots on either side of the central meridian [52, 53]. Drossart et al. [52] noted local time effects in the auroral zones.

The most impressive work in this area has been carried out by Satoh and Baron and their co-workers. Using images obtained in 1991 and 1992 at sub-arcsecond seeing conditions, itself an enormous achievement, obtained by optimizing conditions in the telescope dome to minimize blurring, this group has carried out months of careful analysis [54, 55]. Their work shows conclusively that the main auroral emissions locate onto the footprint of open, $L > 30$, field lines connecting to the magnetotail, confirming the analysis of Baron et al. [48]. The northern aurora in particular is concentrated in a narrow arc, with brighter, more diffuse emission centred on it around longitude 150° , a region that coincides with the maximum magnetic field in Connerney's O6 model [56].

In addition, in a remarkable follow-up paper these researchers have been able to locate the footprint of the flux tube connecting Io to Jupiter, which accounts for small auroral spots that fix the

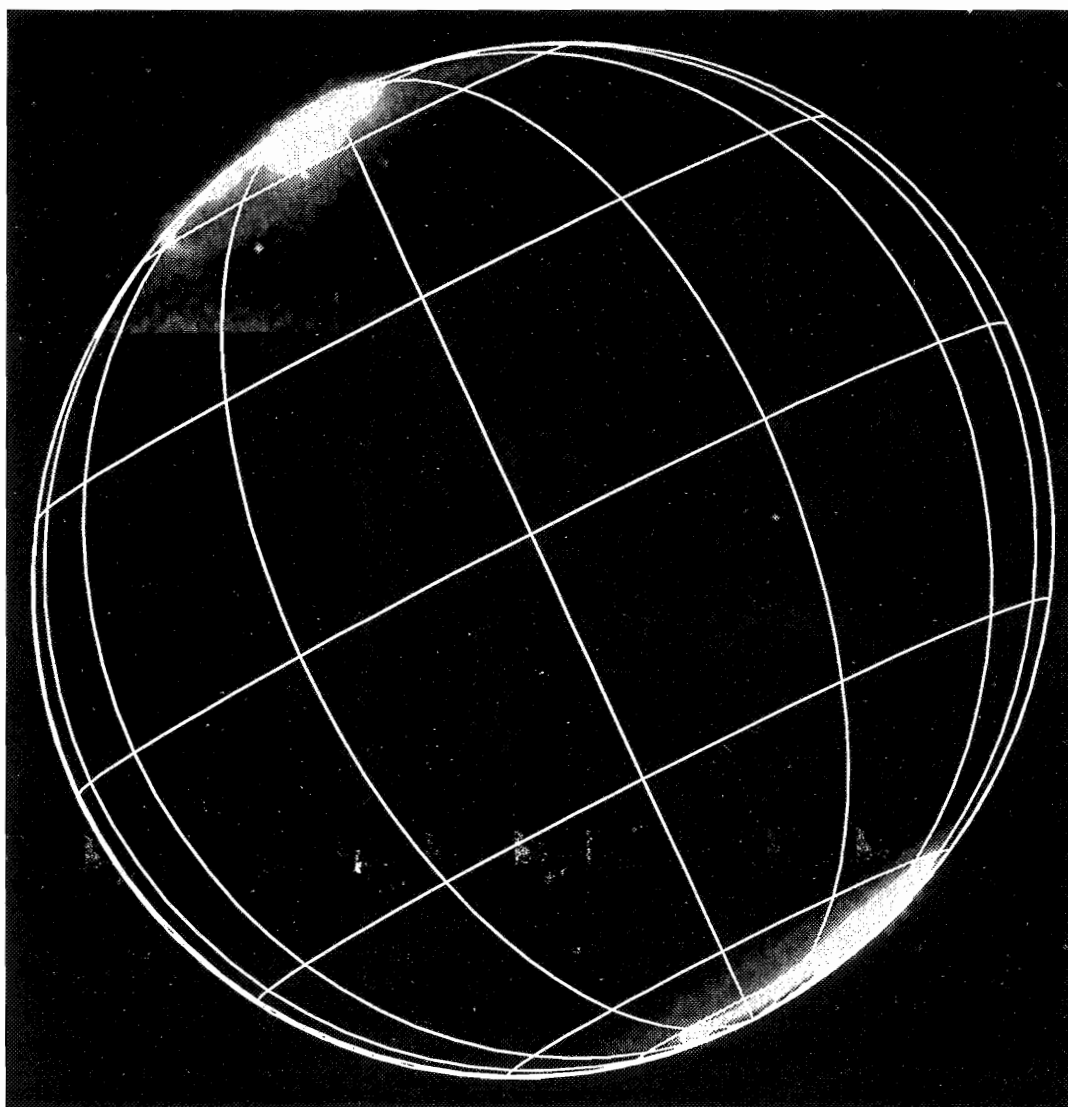


FIG. 2. As Fig. 1, but with the cvf centred at $3.53 \mu\text{m}$. As methane absorbs all the infalling solar IR on the body of the planet, only H_3^+ auroral emissions remain visible. The CML of this image is 188° . In the north, a limb brightened auroral arc is visible, centred on the magnetic pole (longitude 202° , latitude 80°). Enhanced emission shows up on the west of the arc.

position of the $L = 5.9$ shell [57]. Spectroscopic measurements using sub-arcsecond spatial resolution confirm the width of the main auroral arc to be less than one arcsecond [58]. In this respect, H_3^+ images of Jupiter have proved decisive in locating the auroral arcs and constraining models of the jovian magnetic field. Interestingly, the latest UV images are now being interpreted as showing narrow auroral arcs, correlating with $L = 30$, together with similar diffuse emissions [59]. The wheel would thus appear to have come full circle from the proposal of Caldwell et al. [19] that the aurorae were linked to the magnetotail, through the Io torus as the determining factor (see Prangé ref. 60) and back again to the magnetotail.

4. Jovian H_3^+ air-electroglow

In 1992, three groups [61–63] obtained spectra from the body of Jupiter which showed that H_3^+ emission could be detected away from the auroral regions. De Bergh et al. [61] found H_3^+ in the northern equatorial belt of Jupiter; spot intensities were about 10% of those in the auroral zones, with temperatures around

$800 \pm 100 \text{ K}$ and column densities (assuming thermal equilibrium) about 1×10^{12} to $2 \times 10^{12} \text{ cm}^{-2}$. This concentration was similar to that computed by Majeed and McConnell from solar EUV ionization [64], using more realistic rates for the dissociative recombination rate of H_3^+ [65, 66] than previously [27].

Miller et al. [62] made use of the long slit spectrometer CGS4, mounted on UKIRT, to obtain a pole to pole spectral image of Jupiter around $3.45 \mu\text{m}$. This showed H_3^+ emission at all latitudes with intensities of more than 10% of auroral, after correction for line of sight effects. Oka and Jagod [63] reported a similar detection in a wavelength range centred on $3.54 \mu\text{m}$. They also reported detection of the “hot band” transition $2v_2(l = 0) \rightarrow v_2(9, 9 \rightarrow 8, 9^{+1})$ in their auroral spectrum.

Analysis of the data obtained by Miller et al. [62], on April 2, 1992, at a central meridian longitude (CML) of 102° , indicated that the planet could be roughly divided into three zones: northern and southern regions close to the aurorae, where temperatures were around 800 K, and a central region of higher, approximately 1200 K, temperatures [67]. The CML of the image

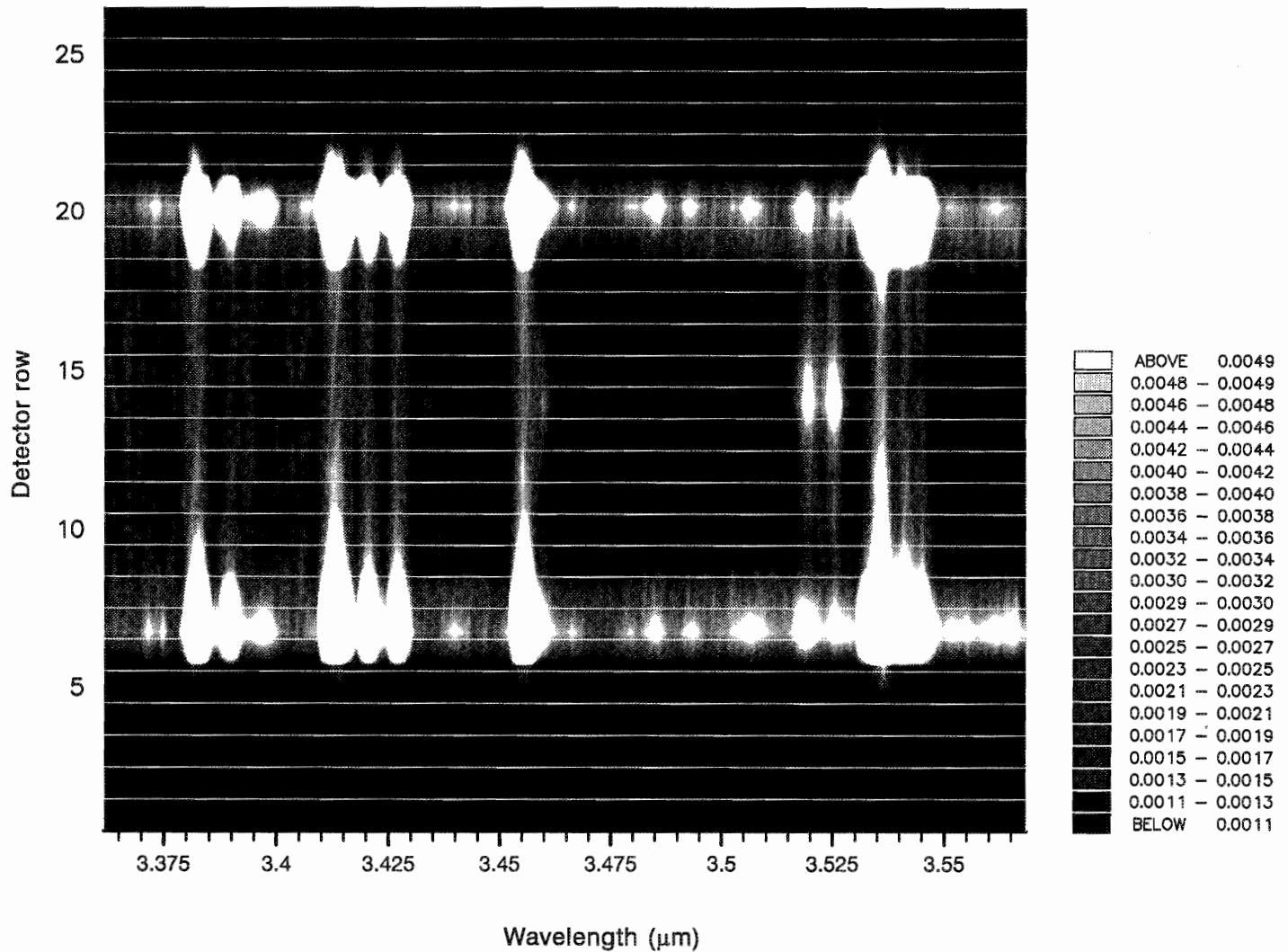


FIG. 3. Pole to pole spectral image of Jupiter taken using the CGS4 spectrometer on UKIRT on May 1, 1993. The resolving power was ~ 1200 , with a pixel scale of $3.1''$. Strong auroral emissions show up at the poles, but these have been saturated on the intensity scale so that the weaker H_3^+ lines on the body of the planet may clearly be seen. Outside of the polar regions, the observed intensity decreases towards the equator, suggesting that auroral H_3^+ is being transported to lower latitudes.

corresponded to a region where there is a "bulge" in the equatorial Lyman- α emission from Jupiter [68]. This bulge had been found recently to have been considerably extended in longitude [69]. Modelling of this effect intriguingly predicted heating of the upper atmosphere in this region [70].

During 1993, much more extensive data were collected from UKIRT concerning the emission from the nonauroral regions [71], along with spectra of the aurorae themselves. H_3^+ emission was found to give rise to an air-electroglow over the entire planet. These data were collected before it was known that comet Shoemaker Levy-9 was going to collide with Jupiter in July 1994, but it is likely to prove extremely useful as a baseline for "normal" auroral-ionospheric activity.

The full analysis of the new data is still underway; the spectra from the body of the planet are particularly hard to analyse because of the low signal to noise ratio. So far no evidence for higher temperatures in the 1993 nonauroral emission is being found.¹ Indeed, while auroral temperatures are in the 900–1100 K

range, the body temperatures are typically 700–800 K. Some interesting effects are noticeable already, however. Figure 3 shows a CGS4 pole to pole spectral image at $3.45 \mu\text{m}$, with the bright polar regions saturated to emphasise the low-level emissions. Figure 4 is a spectral image with the slit aligned along the jovian equator. Together, these figures include important constraints for any model attempting to explain the observed distribution of H_3^+ .

Figure 3 shows that as one moves away from the auroral regions towards the jovian equator, H_3^+ line intensities diminish. If the main source of ionization in the ionosphere is solar EUV [64], then the intensity ought to fall off, roughly, with the cosine of the latitude (corrected for the subsolar point). Emission intensities seen from Earth, on the other hand, ought to increase with the cosine of latitude (corrected for the sub-Earth point). Neglecting the slight difference in effective latitude seen from the Sun and the Earth, one might expect a constant intensity across the planet, except for the auroral zones. That a gradient is observed would suggest that somehow H_3^+ is being transported from the auroral regions, where it is produced in greater

¹H.A. Lam. Manuscript in preparation.

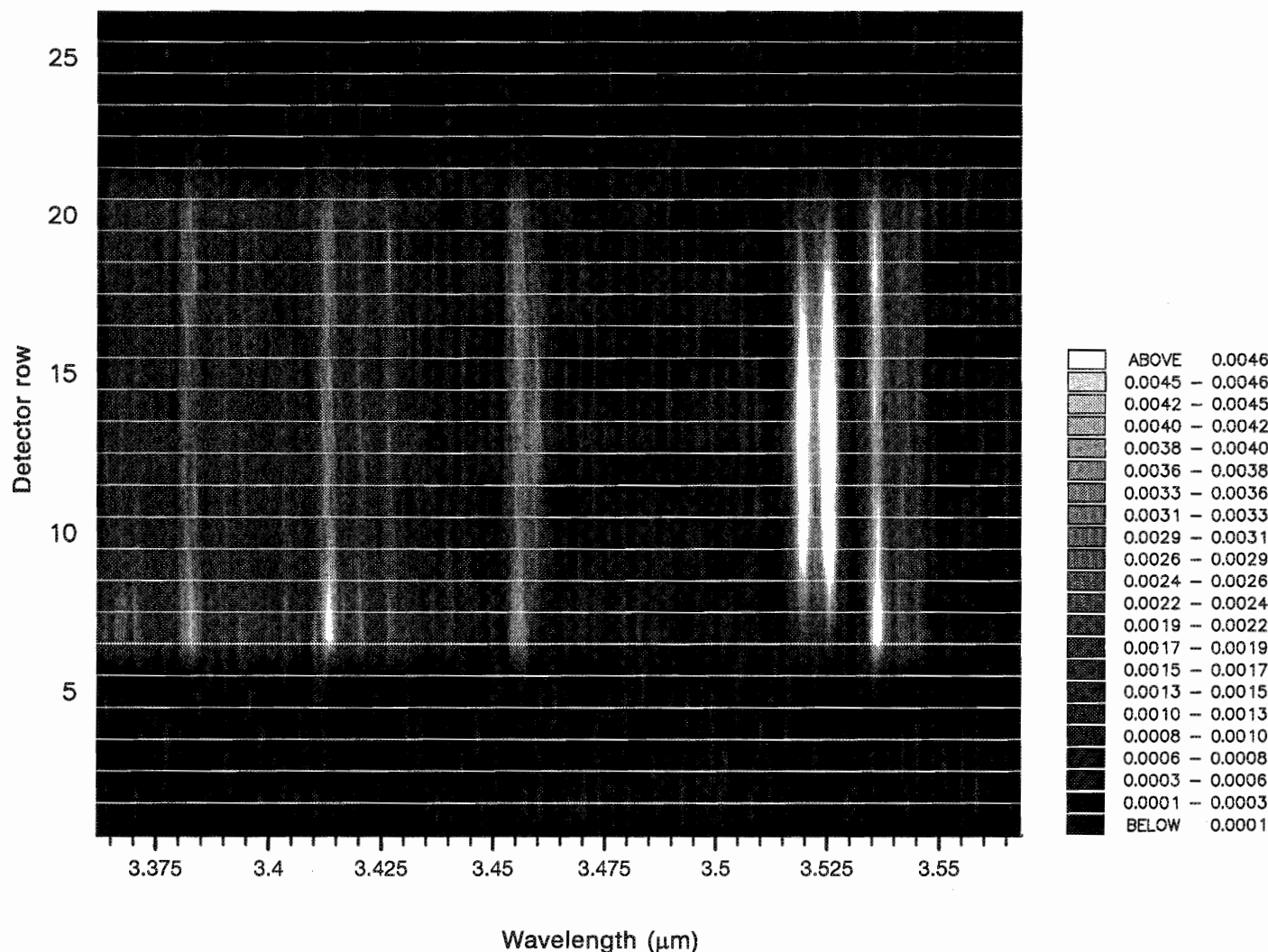


FIG. 4. Equatorial spectral image of Jupiter taken as Fig. 3. In this image, the intensity of the H_3^+ lines increases towards the western, setting, limb, suggesting a production rate of about $1 \times 10^4 \text{ cm}^{-3}$ molecules of H_3^+ during the 5 h of jovian daylight.

concentrations, to lower latitudes, or that low-intensity particle precipitation occurs outside the main auroral latitudes.

Allowing for line of sight effects, Fig. 4 shows that the western, setting, limb of Jupiter is somewhat brighter than the rising east. From the derived column density it is possible to estimate that the rate of production of H_3^+ is of the order of 10^{12} cm^{-2} in the 5 h from jovian sunrise to sunset. But there is clearly H_3^+ visible on the rising limb, raising the question as to whether this is left over from the day before, or is being continuously produced by some mechanism other than photoionization.

Another explanation for the distribution of H_3^+ across the body of Jupiter could be ionization by energetic particles "leaking" into the ionosphere at low latitudes from field lines connected to Io [72]. (This model could also explain nightside H Lyman- α emission detected by Voyager [73].) To complicate matters further, other equatorial images we have obtained do not show anything like as marked a limb to limb variation. Further modelling of the air-electroglow emission of H_3^+ is clearly required if we are to understand it fully.

5. Saturn, Uranus, and Neptune

After the detection of H_3^+ in Jupiter, it made sense to see if this ion could be seen in the other jovian planets. However, it was not going to be easy, since the magnetic fields (as represented by the dipole contribution) of Saturn and Uranus are only 5% of that of Jupiter, and Neptune's is just 3% [56]. That, coupled with the greater distances from Earth, meant that H_3^+ fluxes of a few percent of those measured from Jupiter were expected. Being the nearest of the three, Saturn was the first target for further measurements.

It was, however, from Uranus that H_3^+ emissions were next observed. On April 1, 1992, (N.B. after 12:00 UT) Trafton et al. detected the fundamental spectrum of H_3^+ from Uranus in a spectral region centred on $4 \mu\text{m}$ using CGS4 on UKIRT [74]. Peak intensities were about 1% of those normally measured in the jovian auroral regions. Fitting the spectrum using the parameters of Kao et al. [75] gave a temperature of $740 \pm 25 \text{ K}$ and a column density of $6.5 \times 10^{10} \text{ cm}^{-2} (\pm 10\%)$. It was not possible to resolve the distribution of the H_3^+ emission because the pixel size ($3.1''$) was very similar to the angle subtended by the planet ($3.57''$).

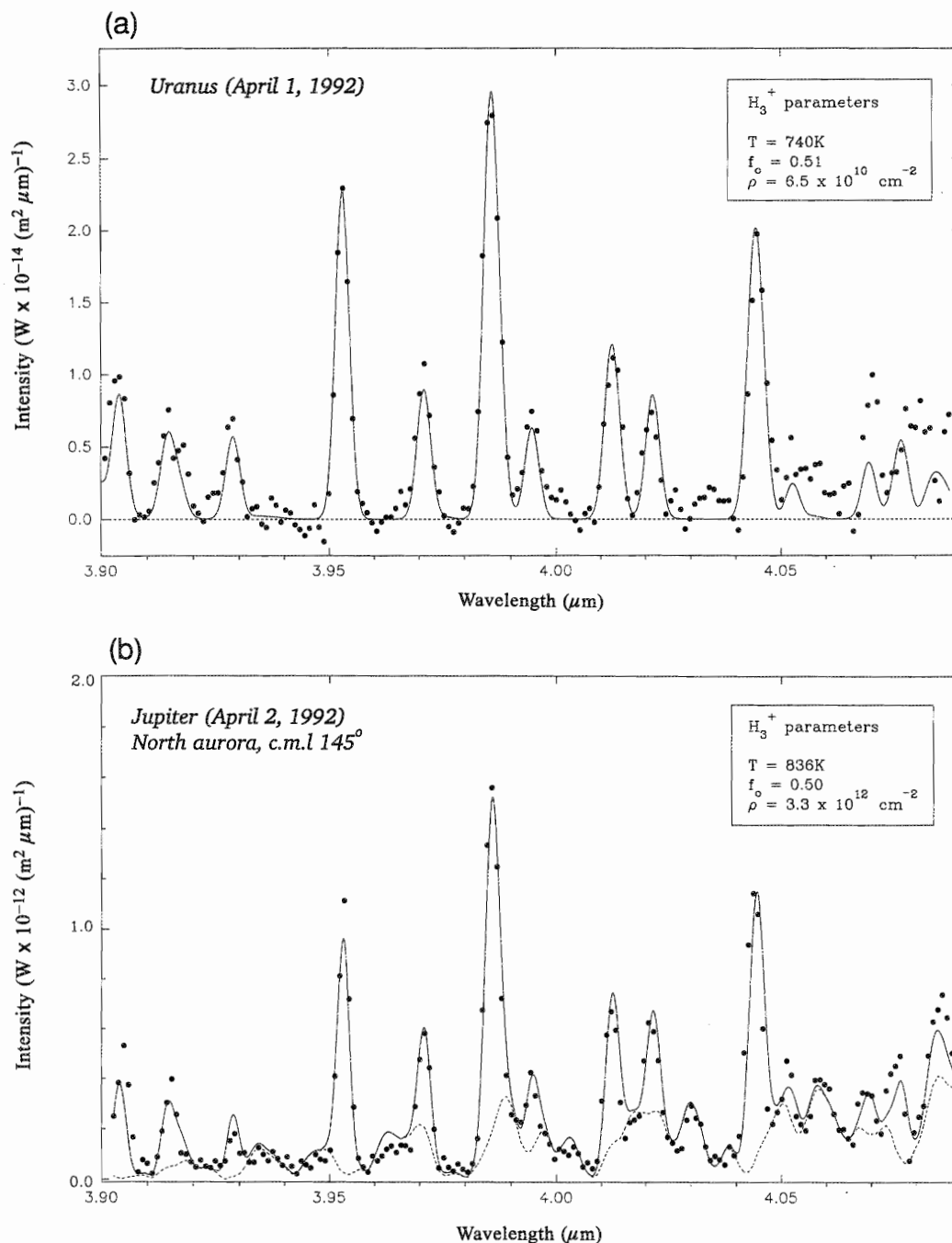


FIG. 5. Comparison of 4 μm CGS4 spectra of (a) Uranus and (b) Jupiter (north auroral zone). The data (●) are fitted by calculated H₃⁺ emission plus a background (broken line) to give the final spectrum (solid line). The jovian background increases rapidly towards longer wavelengths. By comparison the uranian background is almost zero.

Uranian auroral activity was first positively detected by Voyager II [76]. The dipole contribution to the uranian magnetic field is $0.23G - R_U^3$, compared with $M_J = 4.30G - R_J^3$ [56]. The planet's rotational axis is set in the plane of the ecliptic with the south rotational pole pointed roughly 60° away from the Sun (at the time of Trafton's observations). The magnetic field is aligned such that the north magnetic pole is at latitude -15°, with the south magnetic pole located at about +45° [56]. An additional complication is that the moon Miranda is inside the uranian magnetosphere, causing a footprint that encom-

passes both magnetic poles. At the time of the Voyager II flyby, Broadfoot [76] deduced that total energy deposition required to power the auroral activity and dayside electroglow was between 0.17 and 0.20×10^{12} W.

But extrapolation of the H₃⁺ emission indicated that this molecule alone was responsible for emitting 0.5×10^{12} W. Assuming a conversion rate of 10%, this result indicated that nearly ten times as much energy was being put into Uranus than had been the case at the time of the Voyager flyby [74]. The variation in solar wind activity is a possible cause of this

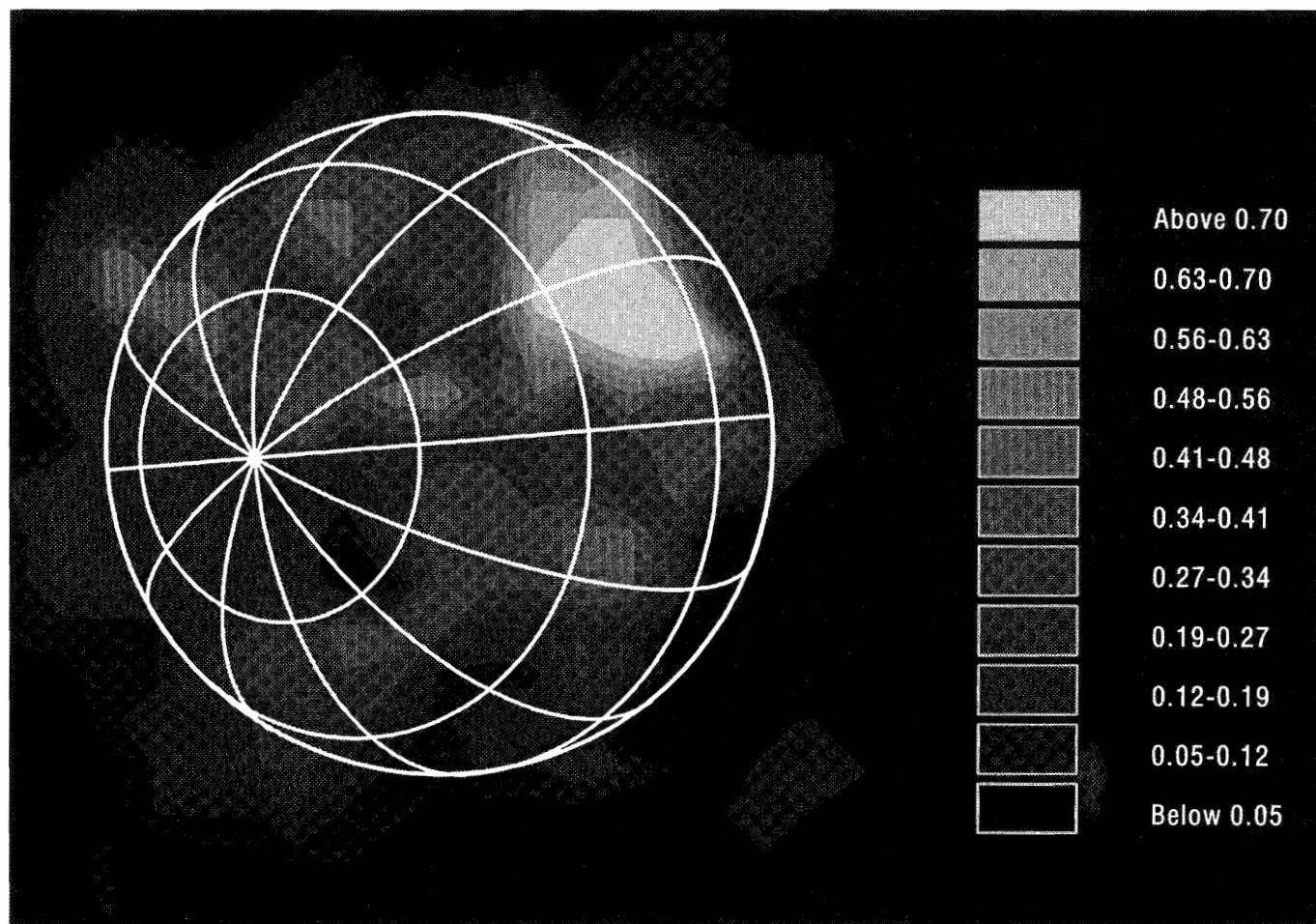


FIG. 6. Image of Uranus taken at $3.986 \mu\text{m}$ on April 23, 1993, as Fig. 1, except for a pixel scale of $0.25''$. The north polar auroral zone could be located in the brighter northwestern quadrant of the planet.

difference; the Voyager flyby took place at a time of relative local minimum in the solar wind activity, whereas the 1992 data were collected nearer to solar maximum.

The spectrum obtained by Trafton et al. [74] was also remarkable for its very low background. Typical jovian auroral spectra at $4 \mu\text{m}$ show a background that rises steadily with increasing wavelength as methane below the homopause becomes less efficient at absorbing the incoming solar IR. The uranian equivalent, however, has almost no sign of background radiation until wavelengths of $4.05 \mu\text{m}$ are reached (see Fig. 5). This is a consequence both of the weaker insolation of Uranus and the higher concentrations of methane below the homopause.

The first indications of how the H_3^+ emissions are distributed over the surface of Uranus have been obtained only recently. Lam et al.² obtained a total of six images in April 1992, four at wavelengths sensitive to H_3^+ (two each at 3.533 and $3.986 \mu\text{m}$) and two at $3.80 \mu\text{m}$, a relative null in the ion's spectrum. The images were obtained using the NASA IRTF ProtoCAM, with a pixel scale of $0.25''$ on a night when the seeing conditions were better than $0.5''$. The best images required a total of half an hour integration on the planet and an equal amount of time on the sky. Uranus has a rotation period of 17.24 ± 0.01 h, so the images

were inevitably smeared by the motion of the planet. Despite the good seeing, the addition of tracking and atmospheric effects make fixing the planetary ellipsoid difficult.

Nonetheless, the results were fascinating. The best image, obtained at $3.986 \mu\text{m}$ on April 23, 1993, shows considerable structure (Fig. 6). Although Voyager was able to locate the magnetic pole of Uranus, the uncertainty in the period of rotation, coupled with the featurelessness of the planet, means that we now have no idea where it is along the circle marking the -15° line of latitude. Figure 6 indicates that H_3^+ emission is occurring all over the planet. The integrated brightness is in good agreement with that measured by Trafton et al. [74]. But there is some enhancement in the northwest (top right) quadrant of the planet, which falls in an area that could be a candidate for the north magnetic polar auroral zone [56].

If this is the case, however, the auroral enhancement is no more than 75% above the ambient disk emission. That is much less than the jovian auroral enhancement, which is at least an order of magnitude greater than the air-electroglow emission from the body of the planet. Work is under way to obtain further images of Uranus and spectra taken at high spatial resolution to investigate these emissions further. In addition to the information they contain about auroral and air-electroglow processes in the uranian atmosphere, the images of Lam et al.² also hold out the tantalizing prospect of our being able to tie down the position of

²H.A. Lam, S. Miller, R.D. Joseph, and J. Tennyson. Manuscript in preparation.

the pole with far greater precision than has previously been possible.

The eventual detection of H_3^+ emission from Saturn did not occur until more than 3 months after its spectrum had been obtained from Uranus. In July 1991, Geballe and co-workers had unsuccessfully looked for the saturnine spectrum. A year later, however, their perseverance was rewarded [77]. Once more, the remarkable CGS4 spectrometer was responsible for the detection. The lines detected were about 1% as intense as those seen in Jupiter, weaker even than Uranus. Analysis of Geballe et al.'s spectra indicated a temperature of ~ 800 K and a column density of $\sim 1 \times 10^{11} \text{ cm}^{-2}$.

Geballe et al. [77] found that their spectra were brightest at the north and south poles, but concluded that they had too little data to say if this was due to limb brightening or auroral effects; the aurorae of Saturn are thought to be much weaker than their jovian counterparts possibly due to the interference of the rings with the normal particle precipitation processes. The question of the spatial distribution of H_3^+ emissions on Saturn could be solved by imaging; so far, however, no one has successfully obtained images that can be conclusively shown to represent emission from this ion rather than reflected solar IR.³

H_3^+ has yet to be detected on the remaining jovian planet, Neptune. Although it is the same size as Uranus, its magnetic dipole is about half the uranian value [56] and it is much farther from us. Trafton et al. [74] placed upper limits on the H_3^+ line emission from Neptune, which were several times greater than those measured successfully on Saturn, so time may remedy this shortfall. At the point when H_3^+ is successfully detected on Neptune, detailed comparison of the four gas giants will be possible.

6. Supernova 1987a

The explosion of SN1987a on March 23, 1987 (~ -150 000 years), in the Large Magellanic Cloud gave astronomers a chance to observe a type II supernova [78] in considerable detail. Reviewing the first year's infrared spectroscopy, Meikle et al. [2] made the point that this was the first supernova in which molecular emission had been seen; as well as the atomic species they listed, Meikle et al. also cited evidence for CO, CO^+ and CS. But they had no identification for two features in the 3–4 μm region which caught our eye, peaks at 3.41 and 3.53 μm , exactly the wavelengths that had proved so useful for mapping H_3^+ on Jupiter.

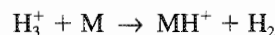
Attempts to fit the Day 192 spectrum, in which these features showed up most strongly, gave a temperature of 2050 K, a mass of $5 \times 10^{-8} M_\odot$, H_3^+ in the ν_2 vibrational level, and a velocity of 3200 km s^{-1} . Modelling of the chemistry by Lepp and Dalgarno produced the required quantities of H_3^+ and the work was published in *Nature* [3].

But the fit produced a peak at 3.2 μm , which was not seen in the spectrum. There are a number of possibilities to account for this. The data are heavily compromised at this wavelength by absorptions in the Earth's atmosphere and may not be totally reliable. Or it could be that the temperature derived from fitting just the 3.41 and 3.53 μm features is too high. Lowering the temperature to 1000 K and refitting so as to give no peak at 3.2 μm gave a mass of H_3^+ in ν_2 of $2.3 \times 10^{-8} M_\odot$ [3]; it also allowed for a contribution by sodium to the peak at 3.41 μm , a

rather lukewarm suggestion by Lucy et al. [79]. Recently Sarre et al. [80] suggested that the two observed peaks may have been produced by pumping from the wing of Brackett- α emission, a mechanism that does not produce an extensive H_3^+ spectrum. This explanation ties in well with Miller et al.'s observation that the intensity of the 3.41 and 3.51 μm features seen in a number of SN1987a spectra during the first year followed that of the Brackett- α peak [3].

This identification of H_3^+ for the first time outside of our solar system has provoked considerable controversy. At a meeting of the Faraday Society of the Royal Society of Chemistry, for example, Oka described the *Nature* paper [3] as "surprising" [63]. He was particularly concerned at the rather low temperature that had been assumed to get a fit that did not produce the unwanted 3.2 μm peak [81]. Oka's remarks triggered off an illuminating debate. Other concerns included the low intensity of the ν_2 Q-branch transitions around 4 μm [82]. Miller [83] and Dalgarno [84] summed up the arguments for their identification, stressing in particular the absence of any real competitors for the features and the derived velocity, which located H_3^+ in the expanding shell.

Perhaps the most interesting aspect of this issue is, taking the H_3^+ identification as proven, the way it constrains the model of the SN1987a explosion. At least initially (i.e., for the first few hundred days) there could not have been microscopic mixing between the outer envelope gas, containing only H and He, and derived species, and the metal-rich expanding core [85]. Had there been mixing, H_3^+ would have been rapidly destroyed by:



This observation also ties in with the formation of both CO [86] and SiO [87]. Both these molecules would have been destroyed by charge exchange with He^+ had microscopic mixing occurred.

7. Conclusions

H_3^+ is such a fundamental species and, with this partial review's particular slant, it has not been possible to look at the enormous amount of experimental [88] and theoretical⁴ work that has taken place and is continuing to characterize this molecular ion from its lowest levels to the point of dissociation. Our aim has been to indicate that H_3^+ has already been of considerable use to the astrophysical community, albeit mainly to planetary astronomers.

Although previous searches for this ion outside of the solar system concentrated on cool molecular clouds where it might be seen in absorption against a suitable source of infrared radiation [10, 11], all positive detections have so far been in emission. We have, therefore, tried to detect H_3^+ in clouds, supernova remnants, and star-forming regions where emission might be possible [89]. Attempts to date have been frustrating. Suggestive bumps obtained at moderate resolution evaporate like the Cheshire Cat when the spectrometer is switched to echelle mode; all that remains is a mocking grin amid the noise.

But the advances that enabled H_3^+ spectroscopy and imaging of the jovian planets to progress so rapidly are carrying on apace. We are optimistic that another closeby supernova will soon give us the chance to see if SN1987a was a one-off or typical. H_3^+ , if past form is anything to go by, will undoubtedly have some other surprises in store.

³R. Baron, private communication.

⁴J. Tennyson. Manuscript in preparation.

Finally, at the time of writing, Jupiter is expecting a shock in July 1994 when comet Shoemaker Levy-9 crashes into it. The million megaton explosions (one megaton of TNT is equivalent to $\sim 4 \times 10^{22}$ ergs) and billions of tonnes of ice that will be dumped into the planet's atmosphere are bound to disrupt the jovian magnetosphere-ionosphere system. H_3^+ is certain to be a sensitive probe of just how much Jupiter's upper atmosphere is perturbed by this event and how long it takes to recover.

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