Temperature changes and energy inputs in giant planet atmospheres: what we are learning from H$_3^+$

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Since its discovery at Jupiter in 1988, emission from H$_3^+$ has been used as a valuable diagnostic tool in our understanding of the upper atmospheres of the giant planets. One of the lasting questions we have about the giant planets is why the measured upper atmosphere temperatures are always consistently hotter than the temperatures expected from solar heating alone. Here, we describe how H$_3^+$ forms across each of the planetary disks of Jupiter, Saturn and Uranus, presenting the first observations of equatorial H$_3^+$ at Saturn and the first profile of H$_3^+$ emission at Uranus not significantly distorted by the effects of the Earth’s atmosphere. We also review past observations of variations in temperature measured at Uranus and Jupiter over a wide variety of time scales. To this, we add new observations of temperature changes at Saturn, using observations by Cassini. We conclude that the causes of the significant level of thermal variability observed over all three planets is not only an important question in itself, but that explaining these variations could be the key to answering the more general question of why giant planet upper atmospheres are so hot.

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1. $\text{H}_3^+$ in the giant planets

Since $\text{H}_3^+$ was first discovered in the upper atmosphere of Jupiter in 1988 [1], our understanding of $\text{H}_3^+$ emission from the giant planets has advanced significantly. Observations of $\text{H}_3^+$ emission are now used not only as a direct measure of the auroral morphology of these planets, but also as a probe investigating both the magnetospheric conditions that drive the aurora and the ionospheric and thermospheric effects that they cause. Measurements of the $\text{H}_3^+$ temperature, which directly relates to the thermal conditions within the surrounding atmosphere, have allowed us to produce insights into the way energy is dissipated within the upper atmospheres of these planets [2].

(a) Aurorae in the giant planets

For both Jupiter and Saturn, a combination of interaction with the solar wind and internal processes drives currents from the magnetosphere down into the planet forming aurorae near the poles. At Jupiter, solar wind interaction results in a wide polar region of sporadic, highly variable and structured emission, suggesting that the polar regions are controlled either directly by field lines that are open to the solar wind [3] or indirectly through viscous interactions along the flanks of the magnetosphere [4]. At Saturn, interactions with the solar wind result in the formation of a main auroral oval, produced by upward-directed field-aligned currents flowing at and equatorward of the open–closed field line boundary [5]. As a result, the main oval is strongly controlled by changes in the solar wind, with compression in the solar wind brightening the dawn aurora, forming it into a spiral morphology and, at extreme compressions, filling the entire dawn side of the polar region with bright emission [6,7].

More equatorward aurorae are formed through currents that close within the magnetosphere. Neutral material lost from the volcanic moons Io and Enceladus is ionized to form a plasma torus. At Jupiter, this plasma torus is accelerated into co-rotation by the magnetic field and is centrifugally driven outwards, until the increasing momentum and decreasing magnetic field strength leads to a sudden breakdown in co-rotation at approximately 20 RJ. In turn, this breakdown sets up a strong current system that closes through the ionosphere along the magnetic field lines, driving the powerful and continual ‘main oval’ aurora at Jupiter [8]. At Saturn, however, sub-rotation is initiated by plasma production and transport near the inner edge of the Enceladus plasma torus, near 3–4 RS [9], resulting in a relatively weak mid-latitude auroral oval [7,10].

In addition to these aurorae, each moon also has currents that flow through the perturbed plasma in the moon’s vicinity, producing discrete spots of auroral emission on the planet [11,12]. Jupiter also has a mid-to-low latitude emission that varies between approximately 1 per cent and 40 per cent of the peak auroral emission; the source for this emission remains unexplained [13].

Thus, although the brightest aurorae at Jupiter and Saturn have very different magnetospheric origins, both planets experience a similar range of interactions, and it is only in the relative strength of these different current systems that the two planets differ.
The situation at Uranus is considerably more complicated. The rotational pole is offset 97° from the normal to the ecliptic plane and the magnetic field is inclined to the rotational axis at 58.6°, with unusually large quadrupole and octopole moments [14]. The effects these characteristics have upon the formation of both internal current systems and the interaction with the solar wind remain poorly understood and probably depend strongly upon season. However, an auroral signature was detected by Voyager, showing emission in the ultraviolet concentrated around the magnetic poles [15], and recent Hubble Space Telescope observations have shown bright spots of auroral emission [16].

Short-term studies have shown that it is H$_3^+$ produced by solar extreme ultraviolet (EUV) ionization that typically dominates across the disc of Uranus, with variability associated with auroral emission being measured at approximately 20 per cent. This correlates well with images of the emission, which appear to show the aurora spread across an extended disc [2], though the significant effect of seeing at Uranus (where typical high-quality seeing has a half-width of 0.5 RU) has limited the spatial details available for this planet.

(b) Extreme ultraviolet ionization at the giant planets

Figure 1 shows the normalized H$_3^+$ intensity profiles for each planet, summing across a spectrograph slit aligned with the rotational axis. The Jovian profile was produced from a number of IRTF-SpeX [17] spectra, taken on 8 February 2001, as the Jovian central meridian longitude varied between 150 and 170. The Saturn profile, published by Stallard et al. [9], was produced by summing IRTF-CSHELL [18] spectra over the period of 7–10 February 2010. The Uranus profile, previously unpublished, was produced by co-adding adaptive optic-corrected VLT-CRIRES [19] spectra from 28–30 October 2007, resulting in an unprecedented view of Uranus with significantly improved spatial resolution.

At Jupiter and Saturn, the brightest emission is clearly produced by the auroral processes discussed earlier. Aurorae associated with both solar wind and internal processes are concentrated near the poles, enhanced along the line of sight. For Jupiter, it has previously been shown that there is also significant H$_3^+$ emission across the disc of the planet. While this includes a significant component of unexplained emission at mid-to-low latitudes [20], at the equator it is produced entirely through EUV ionization, and is measured at approximately 1–2% of the auroral peak emission [13].

Here, we present the first measurement of equatorial H$_3^+$ emission from Saturn. Previous profiles of Saturn’s H$_3^+$ emission have not shown significant emission at latitudes below the auroral region [21]. Figure 1 shows Saturn’s H$_3^+$ emission profile, aligned along the central meridian. While the main profile has been selectively filtered to improve the spatial resolution (see Stallard et al. [9]), the equatorial profile uses all the spectra from this period, increasing the number of spectra used by a factor of 25. This shows that there is a significant non-auroral component within the H$_3^+$ emission at Saturn, where the emission at the equator is approximately 2.5(±0.4)% of the peak auroral emission. This suggests that the relative contribution of EUV ionization and particle precipitation to the global H$_3^+$ emission is similar for both Jupiter and Saturn. It is also possible that there is an equivalent to the Jovian mid-to-low latitude emissions at Saturn, but the resolution of the data is too limited to determine this with any certainty.
Figure 1. Profiles of $\text{H}_3^+$ emission aligned with the rotational axes of (a) Jupiter, (b) Saturn and (c) Uranus, taken on 8 February 2001, 7–10 February 2010 and 28–30 October 2007, respectively. On the left, the $\text{H}_3^+$ emission is shown (bold), along with the profile scaled up by a factor of 10 (dotted line). Calculated errors are shown in grey. The mean intensity on the body of the planet is also shown (solid horizontal line; s.e. is shown by the dashed surrounding lines). The calculated position of the aurora of each planet is marked; these aurorae are produced through interaction with the solar wind (most poleward, solid vertical line) and internally driven current systems (more equatorward, dot–dash vertical line; the origin is unclear for Uranus). Where the emission is diffuse, an extended region of emission is shown (in grey). For Saturn, the location of the rings is also shown (vertical dashed); the rings of Jupiter and Uranus cannot be seen within the spectral wavelengths used. On the right, matching colours are used to show each planet’s orientation within the slit used to make the measurements (vertical black lines). A grid of latitude and longitude is shown in steps of 10° and 30° degrees, respectively.

A new profile of the pole-to-pole $\text{H}_3^+$ emission profile at Uranus is also shown in figure 1. Because this profile was produced from data using adaptive optics, it has the highest spatial detail ever measured for such a profile on Uranus. What it clearly shows is that, averaged over three nights of data, the typical auroral profile is relatively flat, with no obvious variability caused by auroral brightening. The region in which auroral features were observed by Voyager is only approximately $10(\pm4)\%$ brighter than the rest of the planet (though the current rotational phase...
of Uranus is now unknown), suggesting that EUV ionization generally dominates as a source of $H_3^+$ at Uranus. Similarly, there is no strong evidence either of line of sight brightening at the limb or of the equatorial bulge observed by Trafton et al. [22].

2. Heat excess in the thermospheres of the giant planets

One of the leading questions that remains unanswered about the atmospheres of the giant planets is: why are the thermospheres of these planets so hot? Measurements of the upper atmosphere temperatures for each of these planets are consistently 300–700 K hotter than the temperatures predicted through solar heating alone [23]. This suggests that the measured temperatures are the result of a significant additional heating source.

One obvious suggestion for such heating would be that it is generated in the auroral regions by particle precipitation, Joule heating and ion drag. These processes produce heating of between a few (for Saturn, see Smith et al. [24]) and a few hundred (for Jupiter, see Melin et al. [25]) terawatts. These heating rates are one or two orders of magnitude greater than that produced by the absorption of solar EUV radiation by the upper atmosphere, and would easily fill the ‘energy gap’ if distributed globally. However, models of ionospheric and thermospheric interactions at these planets (e.g. Smith & Aylward [26] for Jupiter; Müller-Wodarg et al. [27] for Saturn) show that such heating is confined to high latitudes by the extreme Coriolis forces. Alternative localized sources for the heating in the equatorial regions have been proposed, such as propagation of heat from lower in the atmosphere through upward-flowing gravity waves or lower latitude particle precipitation, but there remains no definite evidence that these cause the required heating (see Matcheva & Strobel [28]).

For Uranus, Melin et al. [29] have combined data taken by numerous observatories and instruments and, having re-analysed the spectra, have used them to produce a measure of the variability in both temperature and column density between 1992 and 2009. These observations show that the column density generally remains relatively constant, independent of solar cycle or season, but that, in some cases, dramatic auroral intensifications drive up the $H_3^+$ density by a factor of 3–4, perhaps indicating the effects of compressions by the solar wind, or some other aurora-inducing event. Within the temperature measurements, however, there has clearly been a cooling trend for the past 15 years. Although temperatures measured over this period appear to be somewhat variable, with a typical short-term variability of 100 K during each observing run, the overall trend shows a steady decrease in more than 150 K with time. This downward trend has occurred over the period between the last solstice (in 1986) and equinox (in 2007) on Uranus.

This suggests that there is a strong seasonal variation in the upper atmosphere temperature at Uranus, with the entire northern hemisphere (under Uranus longitude system coordinates) continually lit during the solstice period, and each hemisphere seeing a full day and night cycle at equinox. However, because direct heating from the Sun cannot explain the degree of change in the temperatures, this seasonal effect must be indirectly driving the temperature changes. Melin et al. [29] have suggested that this heating is the result of changes in the
magnetospheric interaction between the solar wind and the planet. We suggest an alternative source for this long-term change in temperature. Seasonal solar heating changes are limited at high altitude, but deeper in the atmosphere the changing solar illumination will drive stronger changes in temperature. It is possible that energy is being transported vertically into the thermosphere–ionosphere from lower layers, perhaps through gravitational wave propagation (as has been proposed for Jupiter; see Yelle & Miller [23]). If this is the case, it has highly significant implications in our understanding of Jupiter and Saturn.

At Jupiter, our best understanding of sources of auroral heating comes from the modelling of an auroral event by Melin et al. [25]. This event, originally observed by Stallard et al. [30], occurred between 8 and 11 September 1998, resulting in an average temperature increase in 100 K over that period. This heating event occurred at the same time as a marked increase in the ion subrotation on the main auroral oval. Melin et al. [25] modelled this heating event by scaling a one-dimensional vertical profile of the ionosphere until it agreed with those conditions measured on 8 and 11 September. This showed that heating caused directly by particle precipitation was counteracted by increased cooling caused by the resultant auroral emission, but that the flow of the current through the atmosphere also resulted in significant Joule heating and ion drag heating, and it was these processes that drove the observed increases in temperature.

The auroral event observed was clearly accompanied by an increase in the electric field imposed on the ionosphere by coupling to the middle magnetosphere, probably caused by a change in conditions, either as a result of changes in the magnetodisc, perhaps through volcanism on Io, or as a result of changes in the solar wind strength. At Jupiter, the majority of the enhanced current driving this heating lies beneath the homopause, carried by ions and electrons within the hydrocarbon-rich lower thermosphere, suggesting that the $\text{H}_3^+$ temperatures are at least partially driven by variability deeper in the atmosphere.

Another significant finding from Melin et al. [25] was that, during the period of this auroral event, the upper atmosphere had a significant excess of heating. In order to explain the moderate temperature increases seen, it suggests that there must have been an additional loss process not accounted for in the one-dimensional model. The most likely explanation for this would be through meridional winds transporting heat equatorward, despite what current atmospheric models suggest.

At Saturn, the comparative weakness of $\text{H}_3^+$ emission has meant that reliable temperature measurements have proved difficult to produce. Individual temperatures have been measured for the entire auroral region, such as $380 \pm 70 \text{ K}$ on 17 September 1999 and $420 \pm 70 \text{ K}$ on 2 February 2004, measured using the UKIRT-CGS4 instrument, suggesting Saturn’s thermosphere is best fit with a general temperature of approximately $400 \text{ K}$ [31]. More recently, the temperature of a specific segment of the auroral oval was calculated from Cassini-VIMS observations [32], using very high spatial resolution images, resulting in a temperature of $440 \pm 50 \text{ K}$ [33].

3. Cassini measurements of the aurora of Saturn

Here we present new measurements of the temperature within the auroral region of Saturn using the Cassini-VIMS instrument. While Cassini has the distinct
advantage of observing Saturn from a close distance, where the instrument is able to collect significantly more photons and the signal is not affected by the Earth’s atmosphere, the spectral resolution of the VIMS instrument (approx. 400) is significantly poorer than telescopic spectrometers, a particular challenge as reflected sunlight and thermal emission from the interior of Saturn are as bright, if not brighter, than the \( \text{H}_3^+ \) emission across the majority of the VIMS’s wavelength coverage. Here, we have effectively reduced these limitations by using emissions only from above the limb of the planet, away from the background contributions of Saturn’s disc. However, this limits the observations we can use to those made where the bright aurora lies above the limb.

For each image, the specific location of each pixel was calculated using the NASA SPICE code. This provided a calculated height for each pixel above the 1 bar limb, in the plane perpendicular to the line of sight. From this, it was possible to average the intensity in a specified region above the limb for every wavelength bin within each image, in this case 300–1100 km above the limb. An additional background value was calculated by averaging pixels above 3000 km and was subtracted from this value.

This spectrum was then fitted with a theoretical \( \text{H}_3^+ \) emission spectrum, produced by combining theoretical emission lines from Neale et al. [34], with a partition function from Miller et al. [35], which were then convolved to the measured spectral characteristics for each wavelength bin within VIMS. This was repeated across a wide temperature range and these values were used to produce a minimum residual fit to the auroral spectrum.

We have analysed the emission from specific images (in figure 2a–f), taken on 9 June 2007. These images were taken during a period of bright and highly variable emission from the southern aurorae, including regions of dawn brightening and polar infilling, as described in Stallard et al. [7,10]. These images are spaced in time into three pairs, with the images in each pair separated by approximately 45 min and each pair of images by approximately 4 h, as described in table 1, providing an opportunity to attempt short-term thermal variability in Saturn’s main oval.

VIMS spectral bins are often relatively noisy owing to instrumental defects, and before individual bins can be used to produce a spectrum, they need to be individually checked for linear aberrations. This has been carried out on all the bins with strong auroral signatures, as well as those bins with obviously incorrect brightness values.

Having fitted these spectra, shown in figure 3, we can see that the fitted temperatures during this period vary between approximately 560 and approximately 620 K, as indicated in table 1. We have assigned an estimated uncertainty of ±30 K, based upon the error within the fit. These temperatures are significantly higher than temperatures measured in the past, suggesting that the significant variability in the \( \text{H}_3^+ \) aura during this period is likely to have resulted in significant heating, in a similar way to the energy deposition measured during auroral events at Jupiter.

There is clearly a drop in the measured temperature between the second and third pair of images. Combining the measured temperatures for each pair of images, weighted according to the integration time of the observation (either by 44 or 22 min), allows us to reduce the error further. This results in an average temperature of 611 K, 611 K and 567 K (±20) and a re-normalized brightness of
Figure 2. A sequence of images, taken by the Cassini-VIMS instrument on 9 June 2009, during a period of significant auroral variation. Each image is produced by combining a number of wavelength bins with H$_3^+$ emission lines within them, and subtracting non-auroral bins to remove reflected sunlight. Latitude and longitude (local time measured in hours) are shown as a grid, in steps of 10° and 3 h, respectively. The region of emission combined in figure 3, 300–1100 km above the limb of the planet, is delineated (grey lines above the limb). (Online version in colour.)

Figure 3. Spectra of H$_3^+$ above the limb for each image shown in figure 2, with normalized intensity plotted against wavelength in microns. The H$_3^+$ spectra (bold) were produced by combining the total intensity measured between 300 and 1100 km above the limb of the planet, and subtracting a background intensity from more than 3000 km. Each spectrum has been fitted with a modelled H$_3^+$ to produce a best-fit temperature (dashed line). (Online version in colour.)

0.934, 1.00 and 0.498 for each pair (a and b), (c and d) and (e and f), respectively. These indicate that the temperature and auroral brightness of Saturn’s northern hemisphere were essentially constant for the period between 04.35 and 08.50 (a slight increase in emission strength occurred), but that the temperature fell by 44 K in the 4 h and 14 min between the second and third pairs of images.

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Table 1. The observation time and integration time for each of the images used in figures 2 and 3, and together with the fitted temperature and normalized intensity for each image within the region 300–1100 km above the limb.

<table>
<thead>
<tr>
<th>time of observation (UT)</th>
<th>total integration time (time (ms) per pixel)</th>
<th>temperature (K)</th>
<th>normalized emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 04.16</td>
<td>44 min (640)</td>
<td>605 (±30)</td>
<td>0.833</td>
</tr>
<tr>
<td>(b) 05.04</td>
<td>22 min (320)</td>
<td>624 (±30)</td>
<td>0.998</td>
</tr>
<tr>
<td>(c) 08.28</td>
<td>44 min (640)</td>
<td>618 (±30)</td>
<td>1.000</td>
</tr>
<tr>
<td>(d) 09.22</td>
<td>22 min (320)</td>
<td>596 (±30)</td>
<td>0.852</td>
</tr>
<tr>
<td>(e) 12.40</td>
<td>44 min (640)</td>
<td>563 (±30)</td>
<td>0.485</td>
</tr>
<tr>
<td>(f) 13.38</td>
<td>22 min (320)</td>
<td>576 (±30)</td>
<td>0.451</td>
</tr>
</tbody>
</table>

The temperature variability is also matched by changes in auroral brightness. The halving in auroral brightness within the last pair of spectra is consistent with the decrease in emission strength that would be expected for a temperature drop from 611 to 567 K, assuming that the $H_3^+$ column density remained constant. This leads to the conclusion that VIMS observed a significant cooling in the upper atmosphere of Saturn during this period.

Recently, Miller and co-workers (unpublished calculations) have been calculating the changes in total energy content of Saturn’s auroral/polar upper atmosphere that temperature changes might represent. By using atmospheric profiles generated by Galand et al. [36] they concluded that, depending on whether the $H_3^+$ ‘temperature’ was sensitive to a temperature change in the whole column of air above the homopause or just that above the main $H_3^+$ emission altitude, a change in temperature of 1 K s$^{-1}$ represented heating or cooling of either $2.7 \times 10^{15}$ or $1.1 \times 10^{15}$ W, respectively. The drop of 44 K in 254 min represents a temperature change of 2.887 mK s$^{-1}$. In turn, this would correspond to a cooling rate of $7.8 \times 10^{12}$ W for the whole column above the homopause, or $3.2 \times 10^{12}$ W for the column above the main $H_3^+$ emission layer. This is a highly significant rate, and corresponds to the kind of heating rates produced in Saturn’s polar upper atmosphere by Joule heating and ion drag [24].

Cooling of the polar regions can be affected either by the lateral transfer of heat by winds to lower latitudes or by vertical transfer, mainly by conduction, to lower altitudes, below the homopause. It is hard to imagine downward conduction being sufficiently rapid to account for such a large temperature drop in so short a period: scaling the figures calculated in Melin et al. [25] for Saturn’s atmospheric density and temperature profile shows that cooling by downward conduction, when integrated across Saturn’s auroral region, is unlikely to exceed 0.3 TW. This is an order of magnitude too weak to account for the change. Steady-state modelling, as has already been noted, shows that horizontal transfer is difficult since coriolis forces turn equatorial winds westwards, so that they become zonal rather than meridional. But these VIMS observations indicate that Saturn is far from being in ‘steady state’, and it remains a challenge to the modelling community to see what effect conditions that vary on fairly rapid time scales will produce.

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As we have seen, the $\text{H}_3^+$ temperatures measured at Jupiter, Saturn and Uranus have all been found to undergo significant variability. These changes in temperature have been observed on a number of different time scales.

Uranus provides us with a unique view into a world where the auroral contributions appear to be somewhat limited and temperature variations occur on both short and long time scales. This potentially provides us with a view of how changes in heating within the underlying homosphere are driving conditions within the upper atmosphere, a form of ionospheric heating that has, in the past, been relatively ignored.

Recent observations of the apparently variable rotation rate of Saturn have re-ignited the debate about ionospheric–magnetospheric interactions. One of the leading theories to explain the changes in the magnetospheric rotation rate is that these changes are created somehow in the lower atmosphere and propagate into the magnetosphere through the ionosphere [37]. These changes in rotational period have also been associated with seasonal variation, though there is an apparent lag between the change in season and the rotation rate [38]. In this context, the results from Uranus suggest that energy exchange between the lower atmosphere and the ionosphere may be far more important than we have previously thought.

Short-term variations in the temperatures of all three planets appear to result from changes within the thermosphere itself, either within the lower hydrocarbon-rich auroral regions on Jupiter or even directly at the peak $\text{H}_3^+$ emission, as we have now measured at Saturn. These dramatic changes in temperature are one potential source for the elevated equatorial temperatures measured in all the giant planets. Most atmospheric models are run under the assumption that the atmospheres are in a steady state, and the effects of changes in temperature are included within a balanced system. What the observations we have presented here show is that all these planets are each far from achieving thermal equilibrium. Continual changes in temperature mean that energy is continually flowing through the auroral regions. This dynamism could easily lead to the formation of waves within the upper atmosphere, in turn driving heating away from the auroral regions and down to the equator.

Thus, in our future studies attempting to answer why the auroral temperatures within giant planets vary so greatly, we may, at the same time, make significant strides into explaining why the upper atmospheres are so hot.

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