A Remarkable Auroral Event on Jupiter Observed in the Ultraviolet with the Hubble Space Telescope


Two sets of ultraviolet images of the Jovian north aurora were obtained with the Faint Object Camera on board the Hubble Space Telescope. The first series shows an intense discrete arc in near corotation with the planet. The maximum apparent molecular hydrogen emission rate corresponds to an electron precipitation of ~1 watt per square meter, which is about 30,000 times larger than the solar heating by extreme ultraviolet radiation. Such a particle heating rate of the auroral upper atmosphere of Jupiter should cause a large transient temperature increase and generate strong thermospheric winds. Twenty hours after initial observation, the discrete arc had decreased in brightness by more than one order of magnitude. The time scale and magnitude of the change in the ultraviolet aurora leads us to suggest that the discrete Jovian auroral precipitation is related to large-scale variations in the current system, as is the case for Earth's discrete aurorae.

The first observations of the ultraviolet (UV) aurora on Jupiter were obtained by the UV spectrometer (UVS) on board the Voyager 1 and 2 spacecraft in 1979 (1-3). Data accumulated since 1980 with the UV spectograph on the International Ultraviolet Explorer (IUE) satellite (4) have been used to indirectly characterize the main features of the morphological and brightness distribution of the aurora. From these early observations, some information was derived on its temporal behavior. Livengood et al. (4) analyzed 10 years of IUE data and found that the average observed auroral brightness profile was generally stable within a factor of about 2 to 3. The lack of spatial resolution of these nonimaging instruments did not allow the determination of whether morphological changes (in auroral shape or latitude) were associated with the brightness variations (4, 5). Some morphological differences were observed in 1992 on two Hubble Space Telescope (HST) Faint Object Camera (FOC) images (6) with nearly identical central meridian longitudes separated by about 3 days. However, in this case, both the maximum local brightness and the integrated radiated power showed little variation. The question of temporal variability is of major importance in understanding the origin and the acceleration mechanisms of the auroral particles exciting the Jovian UV aurora.

Basic differences exist between the magnetospheres of Jupiter and the Earth. The Earth's magnetosphere dynamics, controlled by the solar wind dynamo, organize auroral processes in a local time frame of reference with peak activity in the midnight sector. These processes take place on magnetic field lines from the central to distant plasma sheet in the nightside magnetotail. By contrast, the much more extensive Jovian magnetosphere is in quasi-corotation with the planet up to distances of about 20 Jovian radii. This feature explains why the UV spectograph data on board Voyager (3) did not detect any significant day-night variation.

In July 1993, two series of three HST FOC images, each of the UV aurora, were taken nearly 20 hours apart to investigate the question of temporal variability. The filter isolated a 20-nm-wide region centered on 153 nm (7), which is dominated by the emission of the molecular hydrogen Lyman bands (H₂, Lyman) and the continuum. The relevant parameters of the observations are specified in Table 1.

Unexpectedly, the first series of exposures recorded a very bright auroral event that gave rise to a FOC count level above four times higher than any previous observations made with the same instrumental configuration. Nearly parallel spectrographic measurements made with the IUE (8) reveal that the emitted UV auroral radiation reached the second highest level recorded in 12 years of IUE Jovian auroral observations. In the first exposure of the series II (Fig. 1A), a bright but

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Table 1. Main characteristics of the HST FOC auroral observations. Abbreviations: UT, universal time; \( \lambda \), wavelength; CML, central meridian longitude; NUV, near ultraviolet.

<table>
<thead>
<tr>
<th>Date</th>
<th>UT</th>
<th>( \lambda ) (nm)</th>
<th>CML (degrees)</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 July</td>
<td>00:47</td>
<td>153</td>
<td>153</td>
<td>NUV</td>
</tr>
<tr>
<td>02:21</td>
<td>153</td>
<td>153</td>
<td>153</td>
<td>II</td>
</tr>
<tr>
<td>04:08</td>
<td>153</td>
<td>153</td>
<td>153</td>
<td>I3</td>
</tr>
<tr>
<td>07:45</td>
<td>153</td>
<td>153</td>
<td>153</td>
<td>W2</td>
</tr>
<tr>
<td>18 July</td>
<td>00:41</td>
<td>153</td>
<td>153</td>
<td>W3</td>
</tr>
<tr>
<td>01:01</td>
<td>153</td>
<td>153</td>
<td>153</td>
<td></td>
</tr>
</tbody>
</table>
A Remarkable Auroral Event on Jupiter
Observed in the Ultraviolet with the
Hubble Space Telescope

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G. R. Gladstone, V. Dois, F. Paresce, A. Storrs,
L. Ben Jaffel, and K. A. Franke
outside the discrete ctnission. It reaches an
comparison flux of 1/13 to the local
sphere (15-17), we fred that the 6 MR of
deposition (assuming that the auroral par-
us throughout the event.
variations, but the morphology is reminis-
ations. The bright arc previously seen at
uval described by the foot-
 the center of the model oval by a
few degrees. The leading edge of the
mission lies near λ = 180°, al-
ally, a weaker extension is observed up to
65°. A secondary weaker alignment is seen
ong the 16° meridian, extending from
62°N up to the limit of visibility. Dimmer
struction aurora is visible inside and
outside the discrete emission. It reaches an
equatorward limit of ~45°N at λ = 180°
at the 1σ threshold applied to the individ-
images. The correponing projection
20 hours later (Fig. 2D) shows, in agree-
ment with Fig. 2B, considerable bright-
variations, but the morphology is reminis-
cient of Fig. 2C. A weak emission band is
still present parallel to and outside of the 30
R_J oval at λ > 180°. These features lead to
the conclusion that the bright auroral arc
already observed previously in the sector
λ > 180° overlaid a diffuse auroral region
that remained nearly invariant in bright-
 throughout the event.
Table 2 lists the estimated total radiated
power over the half hemisphere facing the
Earth derived from both I2 and W1. Using
an energy conversion of ~7 for electron
deposition (assuming that the auroral par-
ticles are energetic electrons) in a H_2 at-
mosphere (15-17), we find that the 6 MR of
total H_2 emission correspond to a local flux
of ~1 W m^{-2} and a total radiated power
of 10^{12} W. The input of such a high energy
flux must considerably perturb the energy
balance and the temperature profile of the
Jovian upper atmosphere. As energetic elec-
trons interact with the hydrogen gas by
elastic and inelastic collisions, a large frac-
tion of the energy input is converted into
local gas heating. The consequences of an
electron power input of ~1 W m^{-2} can be
crudely estimated with simple one-dimen-
sional (1D) energy degradation and energy
balance models (16, 18).
Because no direct information on the
energy distribution of the auroral particles is
available, we base our estimates on the HST
spectroscopy observations of Trafton et al.
(19) with a correponing spectral power
index of -4 and a low-energy cutoff at 22
eV. Two situations may be analyzed: (i) A
1D numerical model provides an upper lim-
it of the temperature, and (ii) a more re-
listic concept that includes the time re-
ponse and horizontal transport of the 3D
atmospheric system is considered. The
high-altitude (exospheric) temperature for
the case of 1 W m^{-2} calculated at steady
state with a 1D model by Waite et al. (16)
is 230,000 K, which is much higher than
the observed H_2 temperature of 1000 to
1500 K (20). The molecular diffusion times
just above the methane homopause where
the maximum heating occurs are much
longer than a Jovian day. Therefore, we can
examine a zonally averaged heating rate,
which leads to a reduction in the vertically
integrated heat flux (15 ergs cm^{-2} s^{-1}) and
a corresponding exospheric temperature of
3000 K. The vertical temperature profile for
this zonally averaged case is shown in Fig. 3
along with an observationally constrained
profile for a more typical aurora (19) (10 to
100 less than the extremely bright aurora
of Figs. 1 and 2). The time-variable tempera-
ture profile is bounded by these two ex-
treme cases. The initial temperatures may
have risen locally to over 100,000 K. One
can speculate that transport subsequently
redistributed the heat by means of advect-
processes. Finally, a high exospheric temperature of over 3000 K quite likely persisted
for several hours at all auroral longitudes with infrared hot spot structures remaining
over the initial zone of heating and significant winds generated as a result of the large energy
input.
An additional consideration is the un-
certainty in our knowledge of the spectrum
of the incoming precipitating particles. The
exospheric temperature result is quite sen-
sitive to the low-energy portion of this
spectrum because the precipitating particles
deposit their energy at high altitudes (pressure
levels of about 1 nbar) that are further
removed from the hydrocarbon cooling lay-
er. For example, for 215-eV electrons, en-
ergy fluxes on the order of 100 ergs cm^{-2}
s^{-1} produce exospheric temperatures of
over 10^6 K. At these temperatures, the at-

Table 2. Local and integrated emission and energy flux.

<table>
<thead>
<tr>
<th></th>
<th>I2</th>
<th>W1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum local count (counts per pixel)</td>
<td>13.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Maximum apparent emission rate Lyman bands and continuum (MR)</td>
<td>&gt;3.6</td>
<td>0.46</td>
</tr>
<tr>
<td>Local energy flux (W m^{-2})</td>
<td>&gt;0.75</td>
<td>0.1</td>
</tr>
<tr>
<td>Total counts 18,100</td>
<td>5,400</td>
<td></td>
</tr>
<tr>
<td>Observed radiated power (H_2 bands) (10^{12} W)</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Estimated precipitated power (electrons) (10^{12} W)</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

mosphere is no longer in hydrostatic equilibrium and literally blows off, creating a hydrogen corona. A very high temperature may help explain the highly Doppler-broadened Lyman α profiles that have been observed by IUE and more recently by HST (21). They may also explain why the aurora seems to often occur near the homopause level rather than in the thermosphere (where cooling by hydrocarbons is negligible), particularly at its brightest intensity (22). Indeed, the only stable situation in the case of energy input over 50 ergs cm⁻² s⁻¹ is when the altitude of the heating and cooling rates nearly coincide.

In the case of the previous exceptional Jovian auroral event observed with IUE, it was demonstrated that the auroral enhancement coincided with the arrival at Jupiter of a solar density disturbance, identified as a coronal mass ejection (5). Therefore, we searched for similar associations with the July 1993 event. The Ulysses spacecraft was at high heliographic latitude in July 1993, and the plasma data confirm that it was out of the streamer belt at the time of our observations (23). Therefore, the Ulysses data are not useful in determining the solar wind conditions at Jupiter during the event.

The characteristic time of the observed brightness variation was less than 20 hours. This factor, together with the auroral location at high latitudes (30° R₉), indicates that the origin of auroral particles is not directly connected to the Io plasma torus (6 R₉). Rather, they appear to originate from the more distant (middle) magnetosphere and may be linked to field-aligned currents, observed during the Ulysses encounter with the Jovian magnetosphere, associated with a high-latitude auroral arc observed at the Lyman α wavelength with the HST (24). It is interesting to compare the auroral processes at Jupiter with the better documented and understood terrestrial counterpart. The above arguments (high latitude, short time scale) suggest field-aligned current-driven auroral precipitations analogous to the terrestrial discrete aurora.

The strongly enhanced auroral emission reported here was observed on dayside field lines and was essentially fixed in magnetic longitude, not in local time. Longitudinally fixed auroral forms are consistent with the dominance of the coronal convective flow within the Jovian magnetosphere. In the inner magnetosphere (<22 R₉), the plasma motion is dominated by the corotation electric field generated by the rapid rotation of the Jovian atmosphere-magnetosphere. Outside of this distance (20 R₉), the plasma acceleration time becomes longer than the plasma outflow time. This suggests a decoupling of the ionosphere from the magnetosphere, that is, a departure from rigid corotation (25). This presents the possibility that reconnection processes near the magnetopause may produce localized solar wind convection cells in the outer magnetosphere, which may result in shears in the plasma flow near the plasma corotation boundary, in turn producing the field-aligned currents that are responsible for the high-latitude aurora. Evidence therefore suggests that auroral precipitations, similarly driven on Jupiter and the Earth by field-aligned currents, nevertheless originate from different mechanisms.

REFERENCES AND NOTES


The vertical emission rate can be represented by a Chapman profile, used the nominal value of 100 km for the atmospheric scale height and an auroral height of 500 km above the cloud tops, and accounted for the diurnal caused by the spatial resolution of the FOC (but not for smearing from the rotation of Jupiter).

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