Morphological differences between Saturn's ultraviolet aurorae and those of Earth and Jupiter

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It has often been stated that Saturn's magnetosphere and aurorae are intermediate between those of Earth, where the dominant processes are solar wind driven[1], and those of Jupiter, where processes are driven by a large source of internal plasma[2–4]. But this view is based on information about Saturn that is far inferior to what is now available. Here we report ultraviolet images of Saturn, which, when combined with simultaneous Cassini measurements of the solar wind[5] and Saturn kilometric radio emission[6], demonstrate that its auroral differ morphologically from those of both Earth and Jupiter. Saturn's auroral emissions vary slowly; some features appear in partial corotation whereas others are fixed to the solar wind direction; the auroral oval shifts quickly in latitude; and the aurora is often not centred on the magnetic pole nor closed on itself. In response to a large increase in solar wind dynamic pressure[5] Saturn's aurora brightened dramatically, the brightest auroral emissions moved to higher latitudes, and the dawn side polar regions were filled with intense emissions. The brightening is reminiscent of terrestrial auroral, but the other two variations are not. Rather than being intermediate between the Earth and Jupiter, Saturn's auroral emissions behave fundamentally differently from those at the other planets.

Geomagnetic activity and brightenings of the Earth's auroral emissions are controlled primarily by the interaction of the solar wind with the Earth's magnetic field. Geomagnetic substorms occur during intervals of southward interplanetary magnetic field (IMF), permitting reconnection between the IMF and geomagnetic fields. Substorms are manifested as bright auroral emissions, which typically shift the brightened auroral oval to lower latitudes and also fill in the midnight sector of the oval[1]. The Earth's auroral oval is adjacent to and equatorward of the boundary between open and closed magnetic field lines, and its statistical location is fixed with respect to the solar wind direction rather than rotating with the planet. By contrast[2], Jupiter's main auroral oval occupies field lines that extend only to the middle magnetosphere, where outward diffusing plasma lags behind the rotational speed of Jupiter, driving strong currents in and out of Jupiter's ionosphere[3,4]. Jupiter's total auroral power is relatively constant, rarely changing by as much as a factor of two, whereas the localized auroral storms that are observed consist of rapid flares poleward of the main oval and more gradual brightenings of the dawn sector of the main oval.

The brightness of Saturn's auroral emissions, the size of its magnetosphere, and its magnetic moment all exceed those at the Earth and are less than those at Jupiter (Table 1). Because Saturn's auroral oval appears at higher magnetic latitudes than Jupiter's, it has long been believed[7] to map close to the boundary of open and closed field lines, and on theoretical grounds[8] it has been considered more likely to be controlled by the solar wind than Jupiter's. At the same time, Saturn's magnetosphere is much larger than the Earth's (Table 1), and Saturn's rapid rotation and internal plasma sources suggest that jovian-like processes should also be active. The approach of the Cassini spacecraft to Saturn has provided a unique opportunity to examine the nature of Saturn's auroral. A series of five Hubble Space Telescope (HST) orbits on 8 January 2004 provided measurements of the longitude variations of the auroral emissions over 70% of a Saturn rotation, while single orbit observations on 12 other days were obtained to compare the auroral activity with varying solar wind conditions. Twelve image subframes are shown in Fig. 1, obtained with the HST Space Telescope Imaging Spectrograph (STIS).

From the complete set of observations, it has become clear that Saturn's auroral vary on timescales down to tens of minutes, similar to Jupiter's main oval but far slower than its polar emissions. The images from 8 January (Fig. 1) show the presence of a localized bright emission region along the main oval at 130–170° λ_{SLS} (Saturn longitude system), rotating in the direction of the planet, becoming fainter with time, and shifting to higher latitudes. This emission region may correspond to earlier reports of an active sector in both the ultraviolet and Saturn kilometric radiation (SKR) emissions based on Voyager measurements[7], and might correspond to the source of SKR emission[6]. The brightest ultraviolet emissions (concentrating on emissions that appear stable over time) move at 30–65% of Saturn's rotation speed, whereas the motion of the overall emission pattern appears to be best fitted by 75% of the corotation rate. This would imply that the emissions map along Saturn's magnetic field to a region where the plasma is moving at 30–75% of the corotation rate in Saturn's magnetic field. As the plasma generally rotates at a lower angular velocity with increasing distance, the rotational motions of auroral emissions can be compared with plasma flow speeds to estimate the equatorial distance from the planet connecting to these auroral emissions. From earlier Voyager measurements of the plasma flow[9], this could be consistent with a wide range of distances from the planet, from 6–7 Saturn radii (R_S) out to the magnetopause boundary. Plasma flow measurements from Cassini orbiting Saturn, in comparison with auroral images, will be helpful in determining the distance to which the main auroral oval maps. This observation of partially corotating emissions contrasts with earlier HST images of Saturn's auroral[10–12], which indicated auroral emissions consistently brightest in the dawn sector—that is, fixed in local time. This raises the possibility of different states of Saturn's magnetosphere, leading to different auroral emission distributions. Such states could be related to the orientation of Saturn with respect to, or variations in, the solar wind and IMF.

The general distribution of the auroral emissions is not what was expected from the known axisymmetric magnetic field and internal plasma environment of Saturn. The auroral oval was thought to be symmetric about the rotational and magnetic axis. It was also expected to map to near the open/closed field line boundary and be longitudinally continuous, with possible local time variations in intensity reflecting the solar wind's interaction with Saturn's magnetosphere. The present observations show the entire southern oval, owing to the 26° tilt of Saturn at this epoch. To determine the central location and size of the auroral oval, a least squares fit has been made of a circular auroral oval, with variable radius and centre, to the brightest emissions in the oval for each day. This reveals an offset averaging 3–4° toward midnight in 10 of the 17 observing periods, similar to what is seen in the Earth's auroral. This may be understood as simply reflecting the solar wind's effect of compressing the dayside magnetosphere and expanding the nightside magnetotail, shifting the dayside auroral oval to higher latitudes and the nightside oval to lower latitudes. By contrast, the partial corotation of the emission features is similar to Jupiter's main oval aurora, which

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Table 1 **Parameters of magnetospheres and auroral emissions**

Planet	Magnetic moment/ field strength	Magnetosphere cross-section diameter	Solar wind travel time, bow to planet	Average auroral brightness/ input power
Earth	1/0.3 G	3×10^5 km	3 min	1–100 kR/1–100 $\times 10^9$ W
Jupiter	20,000/4 G	200×10^5 km	200 min	10–1,000 kR/a few $\times 10^{13}$ W
Saturn	580/0.2 G	70×10^5 km	50 min	1–100 kR/1–10 $\times 10^{11}$ W

Field strengths are average values at the equator, and magnetic moments are scaled to 1 for the Earth. Travel times are listed for an assumed solar wind speed of 400 km s^{-1}. Average auroral emission brightnesses are measured, whereas the input power is determined by detailed modelling of energy deposition in the atmosphere as related to the product of brightness and emitting area. Initial observations of Saturn's magnetosphere and aurora were carried out by the Pioneer 11[13] and Voyager 1 and 2 spacecraft[14] over 1979–81. In the 1980s there were occasional measurements of strong auroral H Lyα emission brightenings by the IUE satellite[15,16], and in the past decade about 30 high resolution images of Saturn's ultraviolet auroral emissions were obtained with the HST, both the Wide Field and Planetary Camera 2[10] and STIS[11,12]. There has been one other attempt to relate Saturn's auroral intensity to the solar wind based on two images and a 9 AU extrapolation of the solar wind from the Earth to Saturn[17].

maps to the middle magnetosphere region of sub-corotating plasma. The broken appearance of the oval on several days and latitudinal motions of several degrees are both pronounced and surprising, and may initially be interpreted in terms of the response to variations in the solar wind pressure or perhaps to reconnection-related phenomena. These motions, much larger than seen on Jupiter, indicate a more dynamic environment than expected in Saturn's magnetosphere.

One intriguing feature in Saturn's auroral oval is an apparent spiral pattern with local time. The brightest emissions in the dawn sector, when followed through noon, dusk and midnight, frequently returned to the dawn sector much fainter and at lower latitudes, not connecting to the brighter start of the oval. This is reminiscent of Io's footprint emission and downstream trail in Jupiter's auroral, but an analogous phenomenon at Saturn would require a source of plasma near the open/closed field line boundary. Saturn's satellite Titan orbits at the required distance, but the spiral pattern appeared

fixed in local time while Titan moved through more than one complete orbit during the period of imaging. Furthermore, Saturn auroral images from January 2001 showed a spiral pattern having the same rotational sense but with the disconnected region near dusk rather than near dawn[12]. This phenomenon will require further study. The apparent presence of an active region in a specific longitude range on 8 January 2004, perhaps due to a magnetic anomaly in that longitude sector[6], implies some degree of rotational control and also deserves further study. If this were shown to be a long-lived feature of Saturn's auroral at a fixed magnetic longitude, that would support its identification as a magnetic anomaly.

More detailed information on the response of Saturn's auroral to the solar wind and IMF has been provided from two disturbances in the solar wind passing Saturn during the period of observations. On 18 January 2004 the auroral oval appeared brighter than average, with a reduced radius. These images were obtained about 40 hours after a solar wind shock had arrived at the bow of Saturn's magneto-
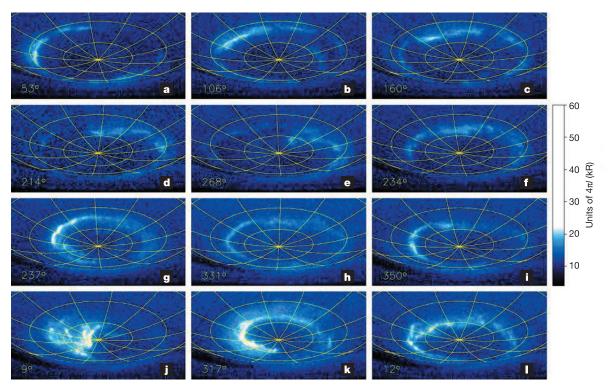

Figure 1 Ultraviolet images of Saturn's southern aurora from HST STIS. The first five frames are images from five HST orbits on 8 January 2004 (**a**–**e**), followed by images from 14 (**f**), 18 (**g**), 23 (**h**), 24 (**i**), 26 (**j**), 28 (**k**) and 30 January 2004 (**l**). Saturn north is up in each frame, with latitude and longitude lines plotted every 10° and 30°. Numbers in each panel are the central meridian longitude in degrees in the Saturn longitude system (SLS). The 26° tilt of Saturn's southern pole towards the Earth makes the entire auroral region visible. The planet and rings are seen in reflected ultraviolet sunlight, while the auroral emissions about the south pole are excited by precipitating energetic electrons. Each frame combines two clear images (total 540 s exposure) taken in one HST orbit, with a logarithmic stretch of the surface brightness in kilorayleighs (kR). The limiting sensitivity and the brightest emissions are approximately 1 and 100 kR, respectively. The images have a bandpass of 115–174 nm, with sensitivity to the auroral spectrum including the H$_2$ Lyman ($B^1\Sigma_u^+$–$X^1\Sigma_g^+$) band emissions and part of the Werner ($C^1\Pi_u$–$X^1\Sigma_g^+$) band series plus the H Lyman-α line. The pixel size of 0.024 arcsec provides reasonable sampling of the point spread function of 0.08 arcsec (or 490 km on Saturn), but the imaging resolution is further degraded by Saturn's rotation of roughly 1° per 100 s.
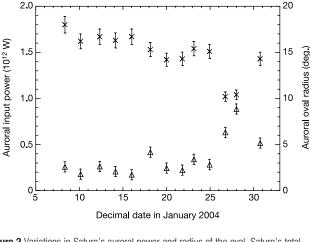
Figure 2 Variations in Saturn's auroral power and radius of the oval. Saturn's total southern auroral input power (triangles; left-hand *y* axis) for each day of observations in January 2004 is overplotted with the mean radius (crosses; right hand *y* axis) of the auroral oval. The oval radius has been determined from a least squares fit of the brightest emissions to a circle. The total input power is estimated by adding all the polar emissions after subtraction of a simulated Saturn background disc and ring image, multiplying by 1.1 to account for ultraviolet emissions outside the STIS clear bandpass, then converting from photons produced to charged particle input energy, assuming that $1\,mW\,m^{-2}$ of input energy corresponds to 10 kR in ultraviolet emission. This value is based on detailed modelling of the input energy deposition, interaction with the upper atmosphere, and radiative transfer of the departing emissions[11], which give a best fit mean energy for the incoming electrons of 12 keV. The measurements of the radius of the auroral oval are average values from each day for the measured locations of the brightest emissions over a range of longitudes, with error bars indicating relative uncertainties from day to day. An anti-correlation is seen between the auroral brightness or power and the radius of the auroral oval.

sphere[5]. A larger solar wind shock reached Saturn on 26 January[5] about 11 hours before the images on that day shown in Fig. 1. This disturbance led to the most dramatic auroral brightenings on 26–28 January, when the auroral power increased by a factor of three from the mean over 8–24 January, and the dawn side oval completely filled in with bright emissions on 26 January. The morphology implies active precipitation over the entire dawn side of the polar cap. Overall, as seen in Fig. 2, the auroral power appears to have been anti-correlated with the radius of the auroral oval in January 2004, opposite to the trend observed at Earth, where the oval's brightness is positively correlated with its size.

Although the event of 26 January on Saturn bears some resemblance to the onset of an auroral substorm at Earth, terrestrial substorms usually begin in the midnight sector and last for tens of minutes, whereas Saturn's brightening was in the dawn sector and only slightly decreased over 50 minutes of observations on that day. Moreover, terrestrial substorms thicken the nightside oval both poleward and equatorward from its pre-substorm position, whereas at Saturn the brightening is restricted to latitudes poleward of the pre-existing oval.

Within the limits of non-continuous observations, in the images

on 28 and 30 January 2004 the auroral oval appeared to fade and expand in radius on a timescale of several days. The long timescale contrasts sharply with substorm processes at the Earth, possibly reflecting the much larger scale size of Saturn's magnetosphere.

Comparison with measurements of the approaching solar wind from Cassini[5] indicates that the auroral brightness and power correlate best with the solar wind dynamic pressure, rather than with any specific orientation of the IMF. Although solar wind driving is reminiscent of substorms on the Earth, the brightening of the dawn sector, the continued contraction of the oval, and the primary correlation with solar wind dynamic pressure rather than IMF direction are all characteristics that appear to be unique to Saturn. The latitudinal motions of the main oval, large response to solar wind changes, and filling in of the dawn side polar region are all in contrast with Jupiter. In addition, the polar flares observed on Jupiter have not been observed at Saturn. We conclude that among the three magnetospheres in the Solar System sufficiently well studied to be compared, the properties of auroral emissions at Saturn are unique to that planet. ☐

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