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Detection of the southern counterpart of the Jovian northern polar cusp: Shared properties

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[1] A transient auroral feature in the northern (N) polar region of Jupiter, referred to as an 'auroral flare' [Waite *et al.*, 2001], or as the N polar cusp [Pallier and Prangé, 2001], strangely seemed to lack any southern (S) counterpart. Here, using a new HST/STIS dataset, we find a similar bright spot in the south. We suggest that both features are located near the open/closed field line boundary. They remain close to a fixed-magnetic-time profile, near noon, as Jupiter rotates. Their brightness varies concurrently in both hemispheres. We thus propose that the conjugate spots are really the Jovian polar cusps, and that their brightening results from transient reconnection processes with the interplanetary magnetic field. A STIS spectrum reveals primary particles penetrating deeply into the atmosphere. It implies that either the particles are very energetic (~ 200 keV 'equivalent-electron' energy), or the hydrocarbon layers are significantly uplifted by the power input. **INDEX TERMS:** 2407 Ionosphere: Auroral ionosphere (2704); 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 5737 Planetology: Fluid Planets: Magnetospheres (2756); 6220 Planetology: Solar System Objects: Jupiter. **Citation:** Pallier, L., and R. Prangé (2004), Detection of the southern counterpart of the Jovian northern polar cusp: Shared properties, *Geophys. Res. Lett.*, *31*, L06701, doi:10.1029/2003GL018041.

1. Introduction

[2] Far ultraviolet (FUV) Jovian auroral emissions have been observed at high spatial resolution with the Earth-orbiting Hubble Space Telescope (HST) since 1994. Jovian auroral processes are found to be much more complex than at Earth, with charged particle losses in the inner-to-middle magnetosphere (≤ 20 jovian radii, R_J) dominated by processes of internal origin, and more 'Earth-like' auroral losses in the outer magnetosphere presumably controlled by the solar wind. In between, precipitation from a partially corotating current-sheet (extending on average from 20 to $\sim 50 R_J$) gives rise to two magnetically conjugate 'main auroral ovals' bearing the combined signature of internally and externally driven processes [Clarke *et al.*, 1996, 1998; Prangé *et al.*, 1998; Cowley and Bunce, 2001, 2003]. At higher N latitudes, Pallier and Prangé [2001] (hereinafter referred to as PP) also identified two similarly shaped faint ovals. They state that the innermost one, surrounding a small emission-free region ($\sim 10^\circ$ in radius) and somewhat variable in shape, is at the boundary between closed magnetic field lines and open ones (polar cap boundary).

The outermost faint oval is thought to be connected to the outer magnetosphere near the magnetopause [Prangé *et al.*, 2002]. Between the inner ovals, PP have noted a transient spot, quite bright at times, up to ~ 1 MR for 10–15 mn exposures ($1 R = 10^6$ photons $\text{cm}^{-2} \text{s}^{-1}$ radiated in 4π sterad). The emission is not fixed in longitude or in local time, but it remains at constant magnetic-local-time (local time of the magnetic field line apex, MLT) curve, near noon, when Jupiter rotates. By analogy to features in the Earth's ionosphere, the spot was tentatively considered as the surface footprint of the N Jovian polar cusp. Here, cusp, used in its broader sense (region of more or less direct entry of solar wind/magnetosheath plasma) includes adjacent regions, which connect to a broad area from the dayside magnetopause to the plasma mantle.

[3] A spectacular brightening of the N 'cusp' spot was investigated by Waite *et al.* [2001] using the photon time-tag mode of the Space Telescope Imaging Spectrograph (STIS). They found the brightness highly variable, reaching a ~ 40 MR peak and vanishing within a few tens of seconds. For this reason they referred to the emission as an 'auroral flare'.

[4] But, amazingly, Prangé *et al.* [1998] and PP unsuccessfully searched for inner ovals or cusps in the S hemisphere. The only structure ever reported inside the S main oval was observed during the Shoemaker-Levy 9 campaign in July 1994, and it was shown to coincide with the magnetic footprint of the Q comet fragment, which was traveling at the edge of the S dayside polar cap at $\sim 7 R_J$ from the planet Prangé *et al.* [1997]. In this study, we investigate a new sequence of HST images. We find that emissions can be found at the edge of the polar cap in both hemispheres, and that these emissions display consistent variations. This suggests that our previous conclusions may have been biased by a denser coverage and better observational conditions of the N hemisphere. Following PP, we study the azimuthal motion of the spots in both hemispheres. Finally, we use a STIS spectrum taken between two images to estimate the emission brightness and the precipitating particle energy.

2. Observations and Data Processing

[5] The dataset consists of 31 FUV images acquired on August 14, 15 and 16, 1999. We used STIS in the clear 25 MAMA configuration, and with the broadband FUV filters F25SRF2 and F25QTZ (centered at 1374 Å, 1469 Å, 1589 Å). We have also downloaded 7 extra images, taken on August 8 and 13, 1999, from the HST archive to extend the sequence. Exposure times vary from 60 to 600 sec. During an exposure, a feature would rotate by less than 0.6° to 6° if it were corotating with Jupiter. In fact, we will show

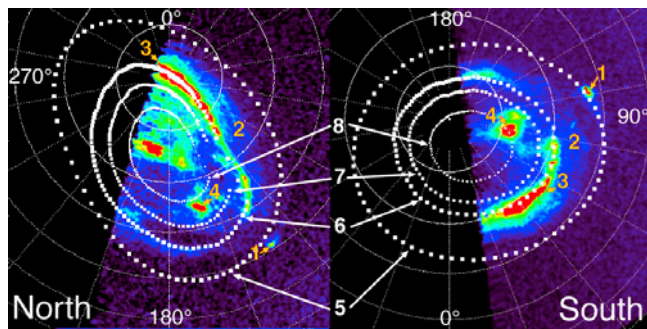


Figure 1. Two consecutive S&N color-coded polar projected maps of Jupiter on August 15, 1999 with STIS + clear filter ($\sim 1180\text{--}1530\text{ \AA}$ FWHM). Dark blue: the faint solar reflected flux, light blue-green: moderate emissions including (2) the ‘low-latitude belt’, and red: brightest auroral features, (1) Io footprint, (3) main oval, (4) conjugate polar cusps. The dotted curve on top of (3) is the Pallier-Prangé (PP) reference main oval (see text). (7, 8) are the PP derived inner reference ovals, and (5) is the VIP4 Io footprint.

that our spots are largely subcorotating, so that smearing is not a problem. The pixel size is 0.0246 arc sec (i.e., 78 km projected on the Jovian disk). The field of view, $\sim 25 \times 25$ arc sec square, does not allow us to map the whole Jovian disk at a time. We thus consecutively observe each hemisphere with a few-minute delay. Each image is then polar projected adopting the assumption that the H_2 source lies at 400 km altitude, whereas the Lyman α source is more extended with a peak in the 1000 km range as shown by long slit near-limb data. A grid of coordinates (planetocentric latitude, System III longitude λ_{III}) and a series of reference auroral ovals are also overplotted (Figure 1). The largest ones (5) are the *Connerney et al.*'s [1998] VIP4 Io orbit footprints. The next ones (6) are the mean main oval loci. They were initially derived by PP from a series of Faint Object Camera (FOC) images and are referred to as the PP-FOC reference main ovals. However, for the North we replace it here by a PP-STIS reference oval derived from archive STIS images. We expect it to be more accurate, especially in the reversed curvature, ‘bean-shaped’, region, because it is based on a larger set of images (~ 150) of better sensitivity. The other two ovals are the PP inner reference ovals, scaled down from the reference main oval and best fitted to the FOC inner ovals. They stand for the footprints of the outer magnetosphere (7) and of the polar cap (8). Any ‘cusp’ emission (4) is expected to appear as a localized spot on the dayside between these two inner ovals.

[6] The conversion between image count rate and surface brightness is deduced using two STIS spectra taken on

Table 1. Conversion Factors From STIS Image Count Rate to Surface Brightness^a

Bright Cusp Present	F25MAMA	F25SRF2	F25QTZ
yes	854	1467	2446
no	706	1975	4132

^aUnits are kR (count pixel⁻¹ sec⁻¹)⁻¹. Two high latitude spectra and three filters are used. The cusp spot is said bright when it exceeds 200 kR on average.

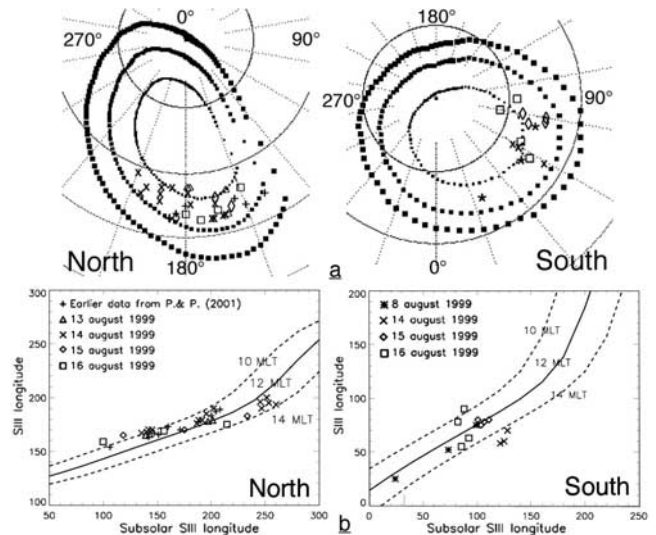


Figure 2. (a) Polar maps of the N&S spots from the August 8–16, 1999 images. Symbols are as in panels 2b. Dotted curves are as in Figure 1. (b) SIII longitude of the bright spots versus subsolar longitude, i.e., CML seen from the sun. Overplotted are fixed-MLT profiles computed from the VIP4 model (see text). The data from *Pallier and Prangé* [2001] are added to improve the statistics.

August 15, one from a bright polar cusp and the other one from a nearby region, typical of high latitude/non cusp emission. Each spectrum is extrapolated below $\sim 1150\text{ \AA}$ with a synthetic H_2 spectrum (D. Shemansky, personal communication, 1998) scaled to the observed spectrum in the range where they overlap. The conversion factors, which depend on the shape of the spectrum, are displayed in Table 1.

3. Results

[7] We have investigated each polar map for dayside localized spots exceeding the nearby level by more than 6 counts (50–100 kR) between the two inner reference ovals. Their distribution is displayed on Figure 2.

3.1. Detection of an S Equivalent to the N Cusp: Brightness Variations

[8] On August 13, we targeted only the N aurorae, and a spot is present just equatorward of the polar cap in all four images, but it is not bright (peak values of ~ 300 kR), and decreases with time (Figure 3). On August 14, there is again a similar spot in all but one image, and its brightness varies abruptly from faint (~ 150 kR) to moderate (~ 850 kR) and back. On August 15 and 16, a bright spot is present over a global auroral brightening during the full ~ 3.5 hour survey periods, near the edge of the N polar cap (up to 1.5 MR on August 15).

[9] On August 15 and 16, we started with the S aurorae. Surprisingly, in most images we also find a localized spot near, or just equatorward of, the smallest reference oval. On August 15, a faint spot barely exceeds the more diffuse high latitude emission. It suddenly intensifies at the end of the sequence to an intensity comparable with that of the first N spot some 20 minutes later. On August 16, the spot is faint,

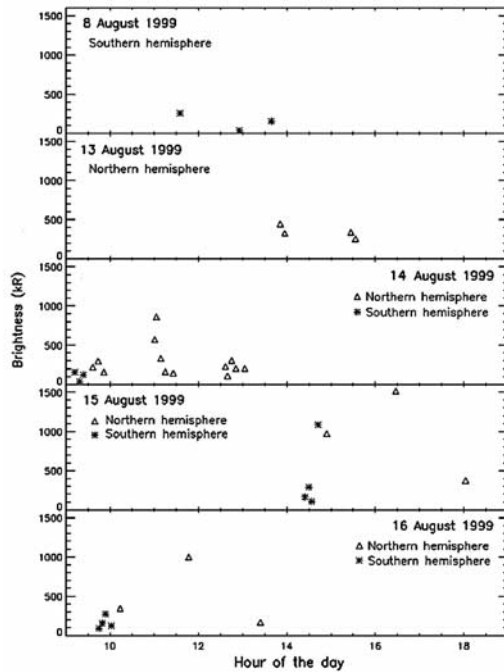


Figure 3. Temporal evolution of the average peak brightness during each observing sequence. Crosses refer to the S spots and triangles to the N ones.

but it slowly brightens up to the level of the first N spot. In both cases, the four S spot brightnesses and the first two N ones increase continuously before a maximum is reached. On August 8, we also find a faint localized spot at a similar location in the South, but no images were taken in the North.

[10] So, not only have we observed an FUV spot near the edge of the S polar cap boundary, but, as shown in Figure 3, its brightness is quite consistent with the evolution of the N spot's one when both are observed sequentially.

3.2. MLT Dependence in Both Hemispheres

[11] One might wonder whether, as for the main oval, the spot emissions could be in partial corotation with Jupiter. We have thus plotted their S_{III} longitude versus CML. In the longitude visibility windows of both hemispheres, the spots are indeed rotating more slowly than the planet. A linear least square fit (LLSF) to the data shows that the N spot moves at 26% of the planet's angular velocity and the S one at 56%. This is not consistent with subcorotation, as the whole field line should move at the same velocity.

[12] On the other hand, PP identified the N spot with the polar cusp footprint on the basis of two properties: it lies near the polar cap boundary and it remains fixed in MLT as Jupiter rotates. We have thus replotted S_{III} versus the subsolar point (local noon) longitude (Figure 2b), and overplotted the surface longitudes of some selected MLTs. The Jovian field is highly multipolar, so that magnetic field lines are extremely distorted in azimuth near the planet. The MLT profiles are thus highly non-linear, and they largely differ from North to South. In the observing windows, the MLT curves are nearly linear with a slope of 0.36 ± 0.02 in the North and 0.60 ± 0.01 in the South. In the South, the data are reasonably well aligned, except for August 14

where all the points are shifted by ~ 2 hours. Something must have affected them, and they are atypical. The LLSF slope and σ then vary from $[0.65, 17.3^\circ]$ if these data are neglected to $[0.54, 15.6^\circ]$ if they are weighted by 0.25. Both estimates are quite consistent with the MLT slope. In the North the LLSF slope is 0.25 and $\sigma = 4.2^\circ$ (indicating very little scatter). The data are thus well aligned along a curve of smaller slope than the MLT curve. However, alignment at fixed longitude is excluded because of a much poorer fit ($\sigma = 16.5^\circ$). We suggest that the MLT curves, based on the VIP4 magnetic field model, are inaccurate at high N latitudes, and could in fact have a smaller slope matching the data. This is supported by the observed 'bean-shaped' distortion of the N auroral ovals which PP assigned to a local magnetic anomaly not accounted for by the VIP4 model.

[13] The VIP4 model is, at present, the most accurate one near the planet where the major field distortions occur, but it ignores the effects known to affect the shape of distant field lines, especially in azimuth. However this does not invalidate our conclusions, because we find that the active field line is always at the same local time (where its shape is given). Consequently, the difference in footprint longitude we introduce by neglecting the field line bending is independent of the subsolar longitude, and it is the same in the North and in the South. For field lines crossing the equator near noon, it is of the order of one hour ($< 20^\circ$, K. K. Khurana, personal communication, 2003).

[14] We can thus confidently infer that the source of the high latitude spots is fixed in local time and confined between ~ 11 MLT and ~ 13 MLT once field line bending is included.

3.3. Spectroscopic Diagnosis of Precipitating Particles

[15] ~ 10 Å resolution H and H_2 spectra were also taken across the auroral zone with the STIS grating G140L + long slit 52×0.2 . On August 15, 1999 at 16:07:30, we recorded one such spectrum between two images exhibiting a very active 'cusp' spot. Precise analysis of the pointing following *Gérard et al.* [2002] shows that the slit crosses the bright N spot. Several spectra were extracted, from the bright spot and from the more diffuse emissions nearby. Below ~ 1450 Å, the hydrocarbon absorption cross sections increase by several decades. Figure 4 reveals that the

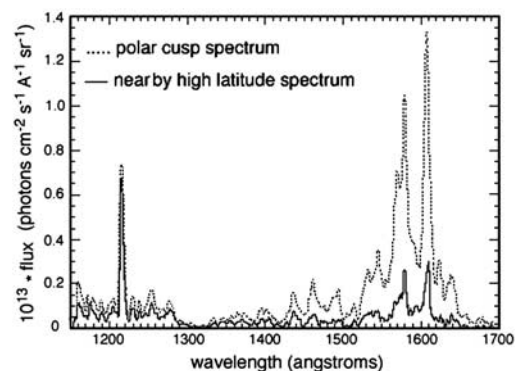


Figure 4. STIS spectra taken at high latitude on August 15, 1999 at 16:07:30. Dotted line: from the bright spot. Solid line: from the polar emission a few pixels away.

attenuation is very strong in the spot, whereas it returns to more usual values everywhere outside. This indicates that the particles precipitating in the spot when it is active are very different from those precipitating elsewhere at high latitude. These particles penetrate very deeply into the hydrocarbon layer. Thus, either the particles are very energetic, or the atmosphere is severely disturbed by the power input and the hydrocarbon layers are significantly raised in altitude. Under the first assumption, we calculate the classical “color ratio”, attenuated to non-attenuated, for two spectral range intensities defined by Livengood [1991], $C = \frac{I(1557 - 1619 \text{ \AA})}{I(1230 - 1300 \text{ \AA})} \times \frac{1300 - 1230}{1619 - 1557}$. Within the bright spot, $C = 6.7 \pm 0.2$, the largest value we have ever encountered in the Jovian aurorae. Under the assumptions of a Maxwellian energy distribution and of precipitation along field lines, Rego et al. [1999] modeled the variation of C as a function of the characteristic energy α . The high color ratio found in the spot indicates an ‘electron-equivalent’ energy $\alpha = 200 \text{ keV} \pm 10 \text{ keV}$.

[16] By comparison, $2.1 < C < 2.3$, implying that $50 \text{ keV} < \alpha < 60 \text{ keV}$, everywhere else in the high latitude diffuse emission, even within a few pixels from the spot boundary.

4. Summary and Discussion

[17] We report here the first repeated observations of a bright FUV spot well inside the S main auroral oval of Jupiter. We suggest that, as in the North, it is located between the footprint of an outer magnetosphere boundary layer and the polar cap boundary. When Jupiter rotates, both remain fixed at the same magnetic local time, between 11 MLT–13 MLT, despite a very different surface MLT profile in the North and in the South. Finally, the peak brightness of the S spot varies very consistently with the N spot one when observed close in time. For these reasons, we suggest that this newly identified spot is the S counterpart of the N polar cusp previously discussed in Pallier and Prangé [2001]. The issue they raised concerning the theoretical possibility of a single Jovian polar cusp is therefore irrelevant since both cusps appear to be present. The sharp brightness variations observed in the spots are consistent with the assumption of transient injection of charged particles related to flux tube reconnection with the solar wind at the dayside or tail magnetopause, or flux transfer events, as widely observed on Earth [e.g., Sibeck et al., 1999]. Spectroscopic studies indicate that, during these events, the particle beams are more energetic in the polar cusp than around, possibly up to $\sim 200 \text{ keV}$ ‘equivalent-electron’ energy. This energy must be compared with that of the energetic ion beams thought to trigger the polar X-ray source observed by Chandra [Gladstone et al., 2002] and seemingly colocated with our cusp emission. Numerous studies of the Earth’s cusp have now proven that solar wind

particles injected into newly opened flux tubes can be efficiently accelerated up to several tens of keV [e.g., Lockwood et al., 1996]. An even more efficient acceleration process must thus be at work in the Jovian polar cusps and this issue will be the goal of future studies.

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