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SMALL H_3^+ EMISSION PATCHES IN THE VICINITY OF JUPITER'S AURORAL REGIONS

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ABSTRACT

We examined a total of 166 images of 3.5 μm H_3^+ emission in the auroral regions of Jupiter observed with the Protocam on IRTF in 1991 and 1992, and found that 30 images contain a clearly isolated small emission patch in the vicinity of the northern auroral regions. Two different time sequences of the images show the small patches at the dusk limb in the range of System III longitudes from 270° through 0° to 90°. The small patches in one sequence of the images, which were taken at Io phase between 240° and 260°, may be related to the Io flux tube, similarly suggested by Connerney *et al.* (1993). However, the small patches in the other sequence are separated from Io as much as 80° in longitude. The positions of the small patches in both sequences are deviated equatorward from the Io footprint oval by 5° - 8° latitude in the longitudinal range of 270°- 360°. A significant modification is required in current Jovian magnetic field models near the Jupiter's surface if the small patches are produced at the foot of the Io flux tube.

Key Words : Jupiter:aurora, infrared:imaging

I. INTRODUCTION

Following the discovery of the Jovian ultraviolet aurorae by the Voyager spacecraft in 1979 (Broadfoot *et al.* , 1979), the Jovian infrared aurorae were discovered by observations of polar regions in 8 μm (Caldwell *et al.* , 1980; (Kim *et al.* 1985; Drossart *et al.* 1986; Kostiuk *et al.* , 1987). However, studies of the 2 - 4 μm Jovian infrared aurorae did not progress significantly until Trafton *et al.* (1989) observed unidentified strong emission lines around 2.1 μm, which were subsequently identified as the $2\nu_2$ band of H_3^+ by Drossart *et al.* (1989) using high spectral resolution data. Miller *et al.* (1990) observed auroral emission lines of H_3^+ fundamental ν_2 band at 3 - 4 μm. Utilizing the strong intensity of the H_3^+ emission lines of the fundamental band in the auroral regions, both Kim *et al.* (1991) and Baron *et al.* (1991) successfully obtained Jovian auroral images of the H_3^+ emission using the Protocam infrared camera on the IRTF (Infrared Telescope Facility). These images revealed the detailed structure and temporal variation of the infrared aurorae. Recent analysis of 3.53 μm H_3^+ images has revealed a continuous auroral oval around each pole (Y.H. Kim *et al.* , 1994).

The 3.53 μm Protocam images also show a small isolated H_3^+ emission patch (hereafter called small patch) in the vicinity of the main auroral feature. Kim *et al.* (1993) presented the locations of the small patches in the north polar region, and reported that the small patches apparently moved into and then moved out of the main auroral feature. The apparent speeds of the small patches were a few km/s, frequently greater than the sound speed in the Jupiter's thermosphere. Recently Connerney *et al.* (1993) suggested that a small pointlike feature of H_3^+ emission occurs at the footprint of the Io's flux tube (IFT), based on an apparent correlation between Io's phase angles and the positions of the small feature appearing in their H_3^+ Protocam images. An electric current, which is driven by an electric field due to Io's motion relative to the corotating Jovian magnetic field, is conducted through a circuit along the IFT that closes through the Jovian ionosphere at the foot of the IFT (Goldreich and Lynden-Bell, 1969).

Nearly 2× 10^{12} W of power is dissipated in the system (Ness *et al.* , 1979). Connerney *et al.* (1993) suggested that part of the dissipated energy is in the form of H_3^+ emission at the foot of the IFT. In this study, we analyze a set of 3.53 μm H_3^+ images obtained both in 1991 and 1992 to investigate the spatial characteristics of the small patches in the light of the new suggestion.

II. OBSERVATIONS AND DATA REDUCTION

Observations were made at the NASA IRTF on March 7 and 8, 1991, and March 3 through 6 , 1992, using the Protocam IR camera with an InSb array (62 by 58 pixels). Protocam images were obtained with the CVF (Circular Variable Filter) at 3.53 μm, where strong H_3^+ lines occur and the Jovian disk is very dark due to strong CH_4 absorption. The spectral band width at 3.53 μm was about 0.05 μm. The pixel size in the images was 0.35 arcsec. The seeing was about 0.7 arcsec on March 7 and 8, 1991, and it varied from night to night between 0.8 and 1.4 arcsec between March 3 and 6, 1992, as measured by the full width at half maximum (FWHM) of intensity profiles of calibration stars, HD772819 and BS4227, respectively.

The exposure time was about 50 sec for both the 1991 and 1992 observations, ensuring negligible rotational effects of Jupiter on the images. The raw images were flat-fielded and bad pixels were replaced by the average of 8 neighboring pixels. For each Jupiter image, a deep-sky image had been obtained for the subtraction of sky emission in the Jupiter image. The sky emission varies rapidly, especially near dawn and dusk. During the subtraction, we considered the sky-emission variation which might occur between the exposures for Jupiter and sky images. For the north and south polar regions, 12 and 15 images were obtained in 1991, and 69 and 67 images in 1992, respectively. In the 1992 observations, both northern and southern sets of the images cover one full rotation of Jupiter, although not in a continuous time sequence. Some ranges of CML (central meridian longitude) were observed more than once. The limb fitting method and determination of longitude and latitude have been discussed extensively by Y.H. Kim *et al.* (1994).

III. SMALL ISOLATED H_3^+ EMISSION PATCHES

When the 3.53 μm images of the north polar region of Jupiter were taken on March 4, 1992, a small but bright isolated patch was noticed in real time near the sunset terminator outside the main aurora. The small patches appeared clearly in two consecutive images with CML = 9° and 12°, but they became very faint and unidentifiable when the observation resumed 3 hours later. The brightness of the small patches is about 40% of the maximum brightness of the main aurora. Observations on March 6, 1992 yielded another sequence of images containing the small patches on the sunset terminator of the polar region. In this sequence, 22 subsequent images show the small patches on the sunset terminator, in apparent motion relative to the main aurora: first toward the pole and outward later. Fig. 1 shows three images in the sequence observed on March 4, and six sequential images of March 6. The small patches seen on March 6 were even brighter than that of March 4. The last three frames in Fig. 1 seem to suggest that there is an additional feature outside the marked small patch. The small patches and additional features seem to move outward from the main aurora.

We have searched for similar small isolated patches systematically in our entire set of auroral images taken both in 1991 and 1992. We scan each image along both X and Y-directions of the image frame to distinguish statistically significant feature that is clearly detached from the main aurora in the image. In Fig. 2 we show limb intensity profiles along the X-direction for three H_3^+ images of the north polar region taken at the central meridian near 0°. The limb intensity was chosen as a maximum intensity value in each column of pixels in the image frames. In Fig. 2, Io phase angle is also presented to relate the small patches to Io flux tube, as Connerney *et al.* (1993) suggested. The Jupiter's north pole is indicated with a vertical line that divides the dawn and dusk limbs: its right side is dusk limb. The short vertical lines represent 1 σ statistical error bars. The profiles have a broad maximum representing the main aurora near the Jupiter's north pole. A clearly isolated feature from the main aurora is marked with an arrow in the profiles of March 4 and 6. The intensity profile of March 5 shows a change of slope (also marked with an arrow) at the dusk side of the main aurora, which we do not regard as an isolated patch in our analysis. It

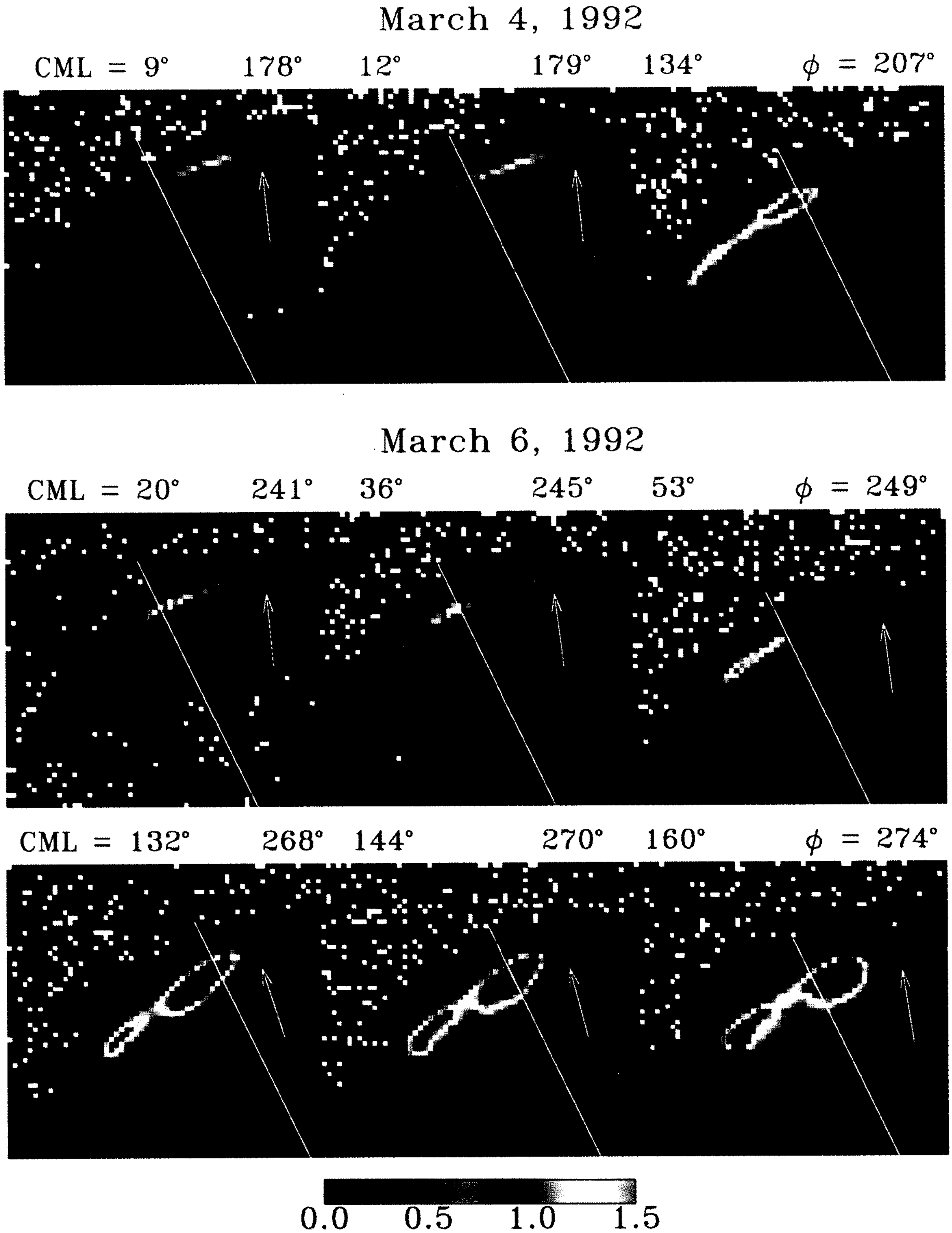

Fig. 1. Protocam images of the north polar region of Jupiter, taken on March, 4 and 6, 1992, through a filter centered at 3.5 μm, where H_3^+ emission is strong. A small isolated patch, marked with an arrow, is seen on the western limb outside the main auroral feature during the period of the observations except for the third image of March 4. In the images north is up and east is left. The central meridian longitude (CML) and Io phase angle(ϕ) are present in each image. Jupiter's rotation axis is also indicated by a white line. There are additional faint H_3^+ patches in the the last three frames. Notice that the color scale is chosen to reveal the small patches, so that the bright areas in the images at CML = 132°, 144°, and 160° are saturated.

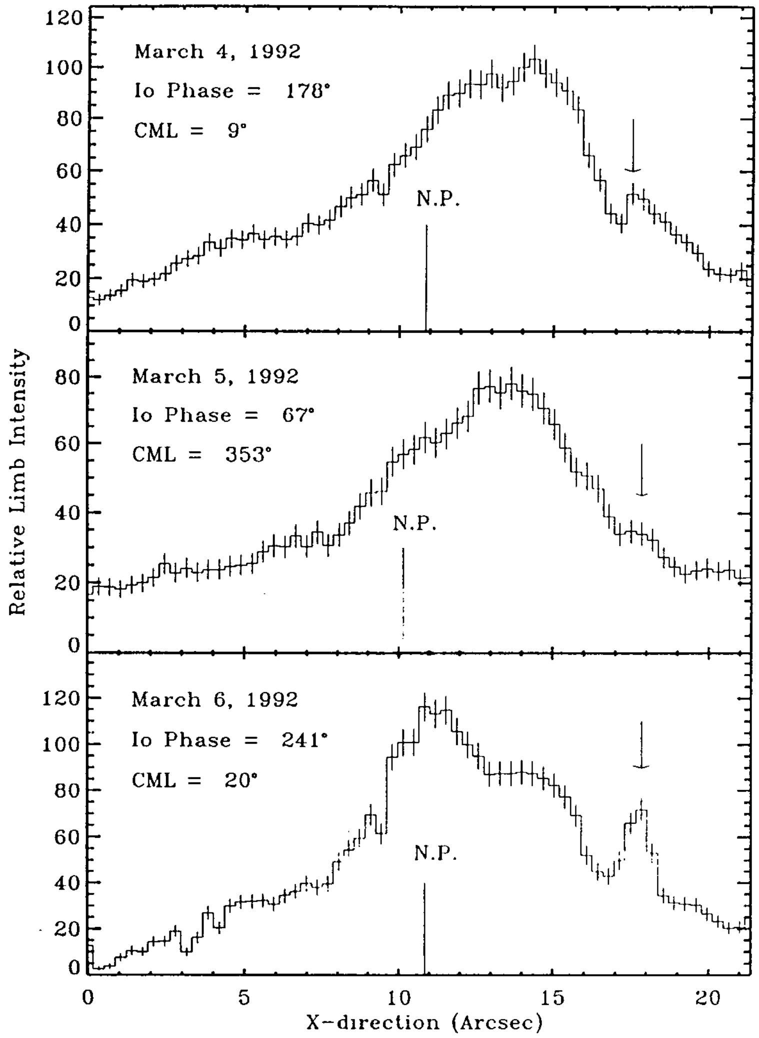

Fig. 2. Relative limb intensity profiles for three H_3^+ images. The limb intensity is chosen as a maximum intensity in each column of pixels in the image frames and plotted against the X-direction of the frame. Each pixel covers 0.35″ x 0.35″. The location of the Jupiter's north pole (NP) is indicated. The first and third panel show a clearly isolated feature marked with an arrow, defined as the small patches in the text, whereas the second panel contains a marginal feature at the same location.

is interesting, however, to note that the change of the slope coincides with the small patch location in other two profiles, hinting that a feature may exist outside the main aurora regardless of the Io phase in this range of the CML.

By examining this limb intensity profile, we find 24 northern images containing an isolated small patch. We here define an isolated small H_3^+ emission patch as a region that is is clearly outside the main aurora area and is brighter by at least 2 σ statistical error than the surrounding level of the limb intensity profile. This is a very stringent criterion that rejects as many as 9 other images with a seemingly isolated small patch in our image set. The 24 images consist of two time sequences, one for March 4 and the other for March 6, 1992. Some of these are shown in Fig. 1.

Our criterion for the small patches has certainly caused a selection effect in favor of detecting the small patches near the limb. The small patches may exist well inside the limb, where it may be merged into the main auroral feature since the apparent angular separation between the patch and the main aurora decreases as it nears the central meridian. In addition, limb brightening effect will enhance the brightness of the patch when it is on the limb. No small patches, even a marginally isolated feature, appear at the dawn limb, which may be explained by the fact that our image set lacks an Io's phase range between 70° and 150°, if the small patches are related to the Io flux tube. Here the Io phase angle is defined as an angle from a point at a superior conjunction to Io in the direction of its orbital motion.

The small patch on March 6 in Fig. 2 was brightest where Io phase was 241°, indicating that the foot of the IFT is near the dusk limb since the foot of the IFT leads Io by 30°, according to the O_6 model (Connerney *et al.* , 1981). However, the small patch on March 4 occurred at approximately the same latitude of the dusk limb when Io phase was 178°, that is about the inferior conjunction. Io was then connected by magnetic field lines to the foot at the System III longitude of 32° (hereafter System III longitude). Since the CML was 9°, the foot of the IFT was in the morning side of Jupiter, rather than the afternoon side or near the dusk limb. The longitudinal difference between the small patch and the foot of IFT is more than 80°, exceeding the estimated uncertainty (30° at 70° latitude) of the observed small patch by a large margin. Furthermore, a sequence of 6 images observed subsequently contains a marginally isolated feature on the dusk limb. If the small patches observed on March 4 occurred at the foot of the IFT, the current magnetospheric model should have to be modified significantly near the Jupiter's north polar region. In the O_6 model, the foot of the IFT is leading Io toward Io's orbital motion (thus smaller longitude for the foot) in the Io's longitude range of 170° to 350°, whereas it is led by Io (thus larger longitude for the foot) in the rest of the longitudes. Thus the foot of the IFT is moving very fast in the direction of increasing its longitude on the Jupiter's surface when Io crosses the 350° boundary as Jupiter rotates. If the 350° boundary exists at a longitude of about 20°, the foot of the IFT would appear at the afternoon side at the time of observations of the first two images on March 4, and would move to the morning side so that the small patches should not be observable in our images taken subsequently.

The locations of 24 small patches are plotted on a polar projected map as in Fig. 3. Since all the small patches are identified near the limb, the longitudinal uncertainty is quite large, which are 30° and 60° at the latitudes of 70° and 80°, respectively. The latitudinal uncertainty is estimated to be ± 2° . Also shown are the Io footprint and the L = 30 footprint of the magnetospheric O_6 model and the boundary of aurora estimated by the Voyager UVS (Broadfoot *et al.* , 1981). Between 270° and 360° longitude, the small patches consistently occur at lower latitudes by 5° - 8° than the Io footprint, and they appear to follow approximately the Voyager UVS boundary. The small patches are not seen between 110° and 240°, where the surface magnetic field is greater than other regions, as Connerney *et al.* (1993) pointed out. In Fig. 4, we compare the longitudes of the small patches with those of the foot of the IFT. The IFT foot is located well within the longitude range of the small patches except two images taken on March 4, as pointed out above.

IV. DISCUSSIONS

The small patches identified here are likely to be the result from interaction between magnetospheric particles and the thermosphere of Jupiter, as is believed for the main auroral feature. Relating the small patches to the IFT (Connerney *et al.* 1993) has a good theoretical base (Goldreich and Lynden-Bell, 1969). Majority of the small isolated patches described in the previous section shows an apparent correlation between their longitudes and Io's longitudes, although a sequence of the small patches significantly departs from the correlation. In addition to the longitudinal correlation, Connerney *et al.* (1993) inferred the absence of the Io associated H_3^+ feature in north polar regions between longitudes of 90° - 240° due to strong surface magnetic fields which may prohibit particle precipitation. The small patches in our observations also did not occur in that longitude range.

If the small patches indeed occur at the foot of the IFT, significant modification of the magnetospheric O_6 model is required near the Jupiter's surface in the north polar regions. The foot of the IFT is as much as 80° away from the small patches in longitude for one observational sequence (March 4, 1992), even after considering the worst case in the logitude uncertainty (30° at a latitude of 70°). This large discrepancy could be explained if the boundary at which leading field lines convert to receding ones with respect to Io occurs at 20° longitude rather than 350° as in the O_6 model. In addition, the positions of the small patches are significantly equatorward by 5° - 8° in latitude from the Io footprint between longitudes of 270° and 360° as shown in Fig. 3. The uncertainty in latitude for these small patches are ±2°. The mismatch of the foot of the IFT in latitude is found in the both sequences of the small

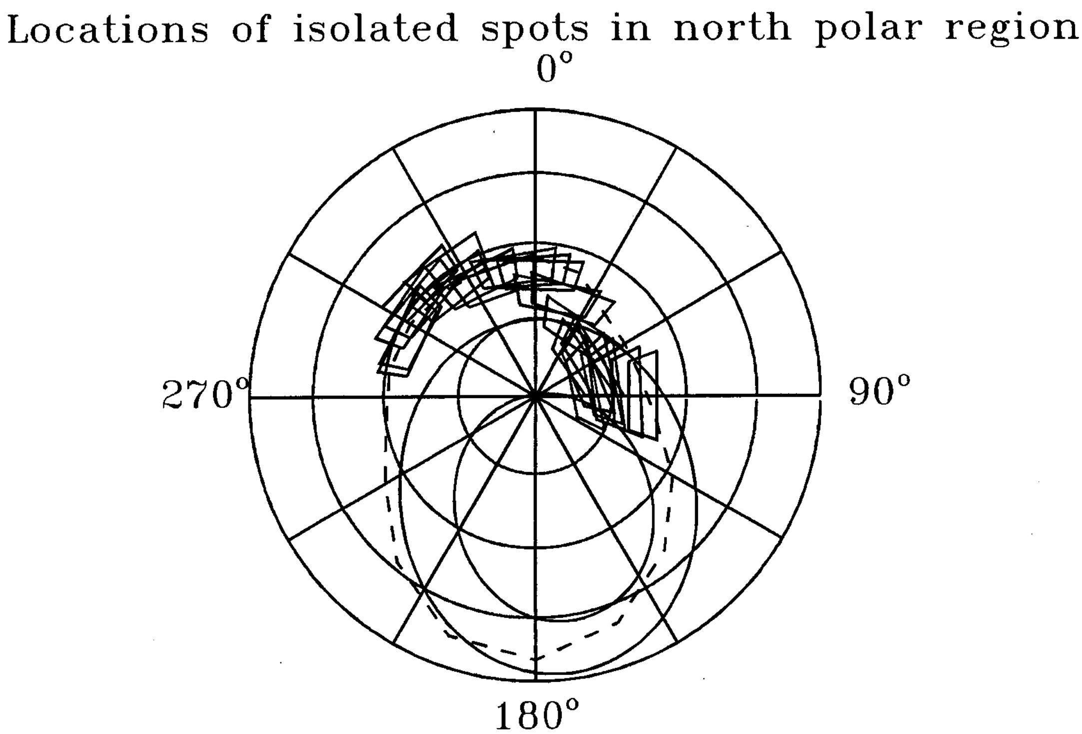

Fig. 3. Polar projected plot for the locations of the small isolated patches. The locations for the patches are indicated with boxes, of which longitude and latitude extents represent estimated uncertainties. Also plotted are the footprints of Io (L = 5.9), the last closed field line (L=30) in the magnetospheric O_6 model, and an auroral boundary resulted from Voyager UVS observations (dashed line).

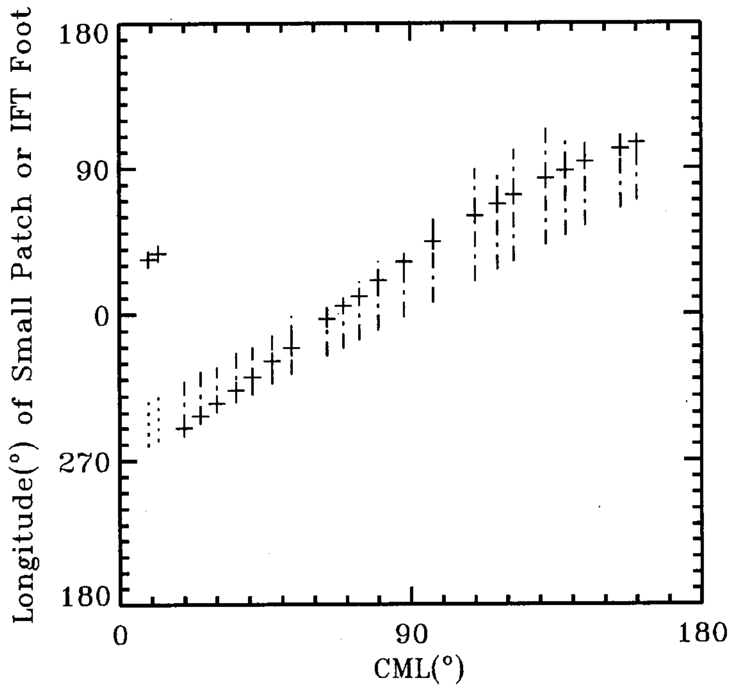

Fig. 4. A comparison of longitudes of the small patches and the IFT foot in the north polar region. Each vertical bar represents a longitudinal uncertainty of the small patches, and + sign marks the Io foot longitude. Dotted, and dash-dotted bars are for the small patches observed on March 4, and 6, 1992, respectively.

patches observed on March 4 and 6, thus strongly suggesting that poloidal components of the magnetic field lines are deviated from those of the O_6 model near the Jupiter's surface. Connerney *et al.* (1993) indeed proposed that locations of the Io-associated feature can be used to improve the current magnetic model near the surface.

Although not identified as clearly as the small patches, an additional feature appears along the dusk limb (particularly as shown in the last three frames in Fig. 1). It is difficult to explain the additional features in terms of the connection to the IFT. The additional features usually occur at the dusk limb when CML = 130°- 160° and appear to move outward together with the small patches. This apparent movement may be related to H_3^+ ions moving out from the main aurora, as Ben Jaffel *et al.* (1992) proposed a H_3^+ jet from aurora.

In conclusion, a part of our observations seems consistent with a theory that the small patches are connected to the IFT. If the small patches indeed occur at the foot of IFT, our observations indicate that Jovian magnetic field lines near the surface may be deviated (or perturbed while Io is sweeping) significantly from what the current model predicts. In one case, the deviation is as much as 80° in longitude. Latitudinal deviations of 5° - 8° were persistently seen in a longitudinal range of 270°- 360°. Further observations of IR H_3^+ and UV aurora, simultaneously if possible, are needed for a detailed investigation of the origin of the small patches as well as the main aurora itself.

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