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Jupiter tail phenomena upstream from Saturn

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Voyager 2 plasma wave and plasma probe measurements from February 1981 suggest that phenomena associated with a well defined tail of Jupiter have been detected at a distance of about 6,200 R_J. This indicates that Saturn's magnetosphere will be affected by the jovian tail and that by comparing Voyager 1 and 2 observations information on the physics of Saturn's magnetosphere can be obtained.

BEFORE Voyager arrived at Jupiter, the possibility of encounters with Jupiter's extended tail during the subsequent Jupiter-to-Saturn phase was noted[1]. It was shown that in the spring and summer of 1981, Voyager 2 and Saturn would both cross the expected region of tail or wake about 7,000–8,000 R_J downstream from Jupiter and that this tail might cause a change in characteristics of Saturn's magnetosphere[2]. In August 1980, Voyager investigators found evidence that Jupiter's tail extends out to at least 700 R_J (ref. 3). Here, we report Voyager 2 plasma wave measurements from February 1981 which are evidence for a well-defined distant tail of Jupiter at least 3 AU downstream, indicating that Saturn's magnetosphere will be affected by the jovian tail[1,2,4].

Tail encounter at $R = 6{,}200\ R_J$

Jovian continuum radiation was detected by the Voyager 1 plasma wave instrument as soon as the spacecraft entered the dayside magnetosphere[5], but the most intense signals were observed when Voyagers 1 and 2 were both traversing the nightside tail lobes[6–8]. Indeed, we regard the detection of this continuum radiation from the Voyager 16-channel spectrum analysers as the single plasma wave measurement characteristic most clearly associated with a spacecraft location within Jupiter's magnetosphere. Therefore, when Voyager 1 and 2 detected roughly similar plasma wave emissions after leaving the nominal close-in magnetosphere, simultaneous measurements from the on-board plasma probes were used[3] to identify whether the spacecraft had re-entered Jupiter's magnetosphere. One Voyager 1 event (with $R \simeq 163\ R_J$, $\phi \simeq 245°$) and six Voyager 2 events (with $184\ R_J \leq R \leq 706\ R_J$, and $\phi \simeq 224$–$225°$) were recognized as true encounters with the extended tail (here, ϕ is the azimuth angle in a right-handed Jupiter-centred system, with $\phi = 0$ oriented towards the Sun). The other 19 events, detected when the Voyagers were still in the solar wind, were interpreted in terms of leakage from an extended tail into a low-density solar wind trough, which would act as a wave guide, allowing signals from the distant tail to reach the spacecraft.

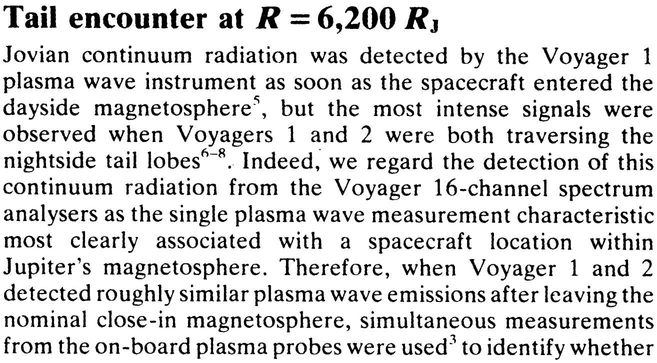

Fig. 1 Time profiles of average electric field strengths detected in five spectrum-analyser channels of the Voyager 2 plasma wave instrument. The scale on the right-hand side refers to the plasma density that gives an equivalent electron plasma frequency ($f_p^- = 9{,}000\sqrt{N_e}$).

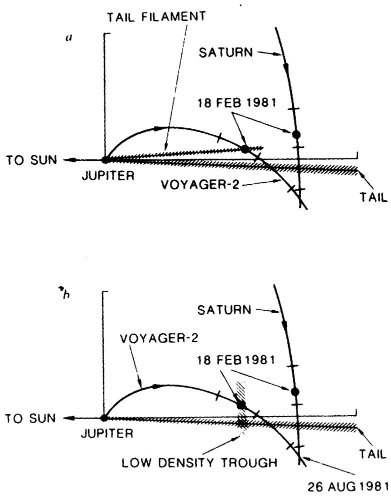

Fig. 2 Paths of Voyager 2 and Saturn with respect to the hypothetical extended tail of Jupiter (a Jupiter-centred Sun-oriented coordinate system is utilized). *a*, *b*, Different models that could account for the 18 February 1981 detection of continuum radiation from Jupiter's magnetosphere.

As Voyager 2 continued towards Saturn, the ϕ-value reached a maximum in summer 1980, and after that, the spacecraft moved progressively closer to $\phi \simeq 175$–$180°$, where the extended tail of Jupiter might again be encountered[1]. One of the first very clear events indicative of an actual distant tail traversal occurred in mid-February 1981, and Fig. 1 shows the corresponding wave measurements for the interval 11–22 February 1981; the time profiles of the average electric field strengths detected in 5 of the 16 spectrum analyser channels are displayed. For each channel, the height of the black area is proportional to the logarithm of the electric field strength averaged over a 12.8-min interval, and the distance between the baselines for adjacent channels represents three orders of magnitude in amplitude. The scale on the right-hand side refers to the density that gives an equivalent electron plasma frequency ($f_p^- = 9{,}000\sqrt{N_e}$, where N_e is electrons cm^{-3} and f_p^- is in Hz).

Figure 1 shows that tracking was almost continuous during this 12-day interval and that there were several small but abrupt level changes from one relatively steady amplitude to another. The upper eight channels (1–56 kHz) are mildly affected by a failure in the flight data system[3,8], leading to small repetitive or quasi-periodic sequences of changes in background (see, for example, the 1-kHz data for days 43–45). Figure 1 also shows natural (or irregular) changes in levels for the channels from 562 Hz to 5.62 kHz, and the line f_p^- traces the lower envelope of these variations. We interpret this as detection of continuum radiation from Jupiter's extended tail, and we need to determine whether Voyager 2 was within the tail or connected to it by a solar wind density trough.

These two possibilities are shown in Fig. 2, which uses a Jupiter-centred Sun-oriented coordinate system to show the paths of Voyager 2 and Saturn with respect to the hypothetical

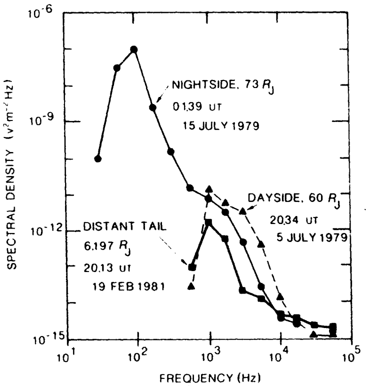

Fig. 3 Spectral densities of continuum radiation detected on Voyager 2 in 1979 (near Jupiter) and 1981 at 6,200 R_J. Low-frequency cutoff varies as the local plasma density changes, but the striking similarities in the spectra at high frequencies suggest Voyager 2 was back in Jupiter's tail early in 1981.

extended tail of Jupiter. Bars on the Voyager and Saturn curves represent the positions on 1 December 1980, 1 April 1981 and 1 August 1981 (more trajectory information is given in ref. 1), and the locations for 18 February 1981 are marked with dots. In mid-February, Voyager 2 was still well above the nominal $\phi \simeq 177.5°$ position for an aberrated anti-solar tail configuration, but had the tail fragmented as indicated in Fig. 2*a*, it is quite likely that Voyager 2 would have been within a tail filament at this time and could have been 'connected' to the tail by a low-density trough as indicated in Fig. 2*b*.

Voyager 2 plasma probe measurements suggest both phenomena were operative. For the early interval, days 43–48, the spacecraft was apparently immersed in streaming plasma which could have been low-density solar wind, or even a wake region[9] around a tail filament; the same applies for the end of the interval (days 52, 53). However, for the period centred around 19 February (day 50) when the f_p-profile of Fig. 1 was drawn between $f = 300$ and 500 Hz, the Voyager 2 plasma probe detected no streaming ions, and we propose that at this time the spacecraft was back in Jupiter's tail. Besides the filament hypothesis it is possible that a solar wind disturbance displaced the main tail[3].

During the 3-day period which includes this apparent crossing of the distant tail, Fig. 1 indicates that f_p(min) was ~400 Hz, leading to $N_e(\text{min}) \simeq 2 \times 10^{-3}$ electrons cm^{-3}. This N-value yields a current higher than the plasma probe threshold for ion measurements in the streaming solar wind, but if the flux is lowered because the flow speed is also much reduced, then no plasma will be measured. Thus, the absence of detectable plasma during this period, when N_e was at a minimum is consistent with an actual entrance into the tail cavity.

A final test of the tail-crossing hypothesis involves searching the plasma wave noise spectrum for the characteristics associated with continuum radiation. Figure 3 contrasts characteristic close-in continuum radiation spectra for 5 and 15 July 1979, with a distant tail spectrum from 19 February 1981; for $f \geq 1$ kHz all three spectra have very similar shapes, but at low frequencies there are marked differences. The complete 1979 Jupiter measurements indicate that the continuum radiation has an essentially constant spectral shape throughout the magnetosphere[6–8], and that the observed changes are primarily associated with variations in local plasma density, leading to shifts in the low-frequency cutoff. Thus, we associate the 5 July 1979 cutoff at $f \approx 1$ kHz with a local electron density of about 0.01 cm^{-3}, and the $f \approx 50$ Hz cutoff on 15 July 1979 with an extremely low local density value near 3×10^{-5} electrons cm^{-3}. Because for $f \geq 1.0$ kHz, the continuum noise spectrum detected at 6,200 R_J has essentially the same shape as the spectrum measured on 15 July 1979, when Voyager 2 was at 73 R_J on its way to the initial exit from the magnetosphere, this strongly supports the concept that Voyager 2 was again in the magnetosphere. Indeed, Fig. 3 shows that the high-frequency tail spectra from 15 July 1979 and 19 February 1981 differ no more from each other than the two close-in noise spectra. These comparisons suggest that Voyager 2 was within Jupiter's tail on 19 February 1981, and that the tail confines the noise extremely well, or that the continuum radiation is generated within the distant tail.

The demonstration[3] that many of the earlier tail-associated events involved leakage of continuum radiation into low-density solar wind troughs argues against an explanation based on noise confinement over a distance of 6,200 $R_J \approx 3$ AU; thus mechanisms that produce continuum radiation far from Jupiter seem more promising. One such process involves production of electromagnetic waves by mode conversion from electrostatic upper hybrid resonance emissions. Observations related to the terrestrial plasmapause, the Io torus boundary, and the perturbations of Saturn's plasma disk at the positions of Tethys, Dione and Rhea[10], suggest that strong mode coupling and intense electromagnetic radiation generally originate in regions with steep plasma density and temperature gradients.

That the magnetopause boundary also has steep gradients in plasma density and temperature suggests that continuum radiation could be generated all along the boundary. The initial Voyager 2 report[6] clearly showed that intense upper hybrid resonance emissions and weaker continuum radiation were detected immediately after the spacecraft crossed the dayside magnetopause at 71.5 R_J on 5 July 1979. Thus, we speculate that trapped continuum radiation at Jupiter is generated in the region of the magnetopause, so that its appearance at 6,200 R_J does not require strict confinement of the waves. This explanation can also readily account for the similarity in the noise spectra, as Barbosa[11] has proposed a wave-scattering mechanism with the spectrum of the continuum radiation controlled by fluctuations of the magnetopause surface.

Discussion

The filament picture in Fig. 2*a* is consistent with many aspects of the 1981 Voyager 2 measurements but it is useful to consider other sources of information. We can learn much about the possible configurations of extended magnetic tails in the solar wind by studying the structures of comet tails, as far downstream from any interplanetary object the only significant characteristic of the source region involves the close-in size of the obstacle. For visible comets in the inner Solar System, there is no firm knowledge of the true obstacle size, but the theoretical model of Biermann *et al.*[12] gives a contact surface or obstacle radius, R_B, of ~10^5 km. As the subsolar Jupiter magnetopause is nominally located at $R_B \approx 56\ R_J$, this means that the 18 February 1981 measurements were taken at $R \approx 110\ R_B$. For the comet case, 110 R_B translates to a downstream distance of about 1.1×10^7 km, and many photographs of the visible ion tails of fresh comets show clear evidence of filaments extending to this distance or beyond (for instance, comet Kohoutek, Fig. 1 in ref. 13). This fact suggests that filaments may develop naturally in extended magnetic tails and that Voyager 2 will continue to encounter them.

If the extended tail of Jupiter has this type of structure, then Saturn itself is likely to have many brief encounters with the jovian tail cavity leading to significant differences between the Voyager 1 and 2 Saturn encounters. It will be of great interest to search Voyager 2 data for such effects, including variations in magnetosphere size, bow shock location, radio emission strength and trapped radiation belt population.

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