acceleration to explain the sudden appearance of relativistic electrons in the terrestrial 'Van Allen' radiation belts[21]. A similar process could exist at Jupiter, although analogies between the terrestrial and jovian magnetosphere are not always appropriate.

Thus, the inner radiation belts of Jupiter and Earth both contain extremely high-energy electrons that require substantial acceleration by processes other than adiabatic radial diffusion. These two magnetospheres are arguably the most explored examples of planetary magnetospheres in the Solar System and in many ways represent the archetype for magnetospheric physics. The fact that both magnetospheres contain electrons that require acceleration processes beyond radial diffusion suggests that this may be a fundamental property of all magnetospheres. This implies that our theoretical understanding of the global properties of magnetospheres may need revision and that the importance of local acceleration mechanisms may currently be underestimated. □

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The dusk flank of Jupiter's magnetosphere

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Limited single-spacecraft observations of Jupiter's magnetopause have been used to infer that the boundary moves inward or outward in response to variations in the dynamic pressure of the solar wind[1–8]. At Earth, multiple-spacecraft observations have been implemented to understand the physics of how this motion occurs, because they can provide a snapshot of a transient event in progress. Here we present a set of nearly simultaneous two-point measurements of the jovian magnetopause at a time when the jovian magnetopause was in a state of transition from a relatively larger to a relatively smaller size in response to an increase in solar-wind pressure. The response of Jupiter's magnetopause is very similar to that of the Earth, confirming that the understanding built on studies of the Earth's magnetosphere is valid. The data also reveal evidence for a well-developed boundary layer just inside the magnetopause.

The measurements shown here are primarily from the radio and plasma wave science instruments on Cassini[9] and Galileo[10]; they make use of Cassini's fly-by of Jupiter centred on 30 December 2000 coupled with the extended Galileo orbital mission. Figure 1 shows the trajectories of Cassini and Galileo near Jupiter during the time interval surrounding the Cassini closest approach. Cassini first encountered the jovian bow shock at about 0419 spacecraft event time (SCET; HHMM UT at the spacecraft) on 28 December (day 363) 2000. As shown in Fig. 2, the shock is identified in the plasma wave data as a broadband burst of noise extending to about 1.5 kHz. The shock was preceded by about 3 h of Langmuir wave activity[11] at the electron plasma frequency f_{pe} near 2 kHz, giving an upstream solar-wind electron density n_e of 0.05 cm^{-3} using $n_e = (f_{pe}/8{,}980)^2$, where f_{pe} is measured in Hz. For several hours preceding the Langmuir wave activity, lower frequency, broadband, ion acoustic wave activity[12] in bursts was observed. We note that the Langmuir waves and ion acoustic waves are mutually exclusive. This would be consistent with Cassini's traversal of the ion foreshock into the electron foreshock. Cassini encountered the bow shock numerous times between 28 December 2000 and the end of the plotted interval. The bow shock was detected as late as early March 2001 to a distance of approximately 800 jovian radii (R_J).

On 9 January 2001 between 1250 and 2115 SCET, and again on 10 January between 0655 and 2035 SCET the Cassini radio and plasma wave instrument observed trapped continuum radiation[13,14], which is a clear indication that the spacecraft was within the jovian magnetosphere. Data from the Cassini plasma and magnetometer instruments confirmed the timing of the magnetopause crossings. A portion of the 10 January wave observations through the magnetopause crossing is shown in the upper panel of Fig. 3. The intense waves between about 300 Hz and 3 kHz are the trapped continuum radiation with the low-frequency cutoff being the electron plasma frequency, corresponding to an electron density of about 1×10^{-3} cm^{-3}. The cutoff frequency (electron density) increased to about 2 kHz (0.05 cm^{-3}) before the continuum radiation disappeared at the magnetopause. The Cassini magnetometer and plasma data confirmed the time of the magnetopause crossing.

At nearly the same time, Galileo was outbound on its 29th orbit (see Fig. 1) and observed a very similar pattern of continuum radiation as that observed by Cassini, as shown in the bottom panel of Fig. 3. Here, the minimum cutoff frequency of the continuum radiation was somewhat higher, 500 Hz, corresponding to a plasma density of 3×10^{-3} cm^{-3}, and the cutoff increased to a frequency of about 3 kHz before disappearing at 2052 SCET at the magnetopause. The time of the magnetopause crossing was confirmed by the Galileo magnetometer. Galileo was well sunward of Cassini; the difference in the *x* position of the two spacecraft was more than 100 jovian radii (R_J).

The nearly simultaneous magnetopause crossings initially suggest that the magnetopause shape might be approximated by a simple curve connecting the two spacecraft. However, steady-state magnetohydrodynamic models of the interaction of the solar wind with the jovian magnetosphere[15] are inconsistent with this interpretation. Superposed on the trajectories in Fig. 1 are four magnetopause models[16] representing contours on which an observer would have a 10, 25, 75 or 90% chance of being within the magnetosphere, where the 10% contour is farthest from Jupiter. The lower probability curves require smaller solar wind dynamic pressures. Galileo's crossing lies almost directly on the 25% model but the Cassini crossing is significantly more distant than even the 10% (outermost) model[16]. The model magnetopause shapes clearly do not allow a curve representative of a steady-state boundary to intersect both spacecraft. We conclude that the magnetopause was in a state of transition from a significantly inflated size at Cassini, to a large but nominal size at Galileo, and that there must have been a kink or wave in the boundary somewhere between the two as suggested in the qualitative model in Fig. 1. We have assumed that a solar-wind pressure increase is directly transmitted through the magnetosheath at a nominal speed of ~400 km s^{-1} and have modelled the reconfiguration of the magnetopause by smoothly connecting the 25% Joy *et al.* contour to one parallel to the Joy *et al.* 10% model[16], but at a distance consistent with the Cassini crossing. On the basis of magnetohydrodynamic modelling, the radius of curvature of this transition is not extreme. The pressure front would take some five hours to propagate from the position of Galileo to that of Cassini. The Cassini plasma science investigation[26] observed rapidly rising magnetosheath densities over the several hours following this outbound magnetopause crossing, by as much as a factor of ten by 0600 SCET on the following day. Hence, there is clear evidence of a region of increasing pressure moving from Galileo to Cassini's position on timescales similar to what might be expected for a region of increased pressure in the solar wind. Furthermore, after a few short periods of northward magnetosheath fields, Galileo observed continuous southward-directed magnetic fields for approximately a day. Simulations show[17] that southward-directed fields would cause the magnetopause to move outward, so the inward motion observed by both spacecraft could not have resulted from changes of the interplanetary magnetic field orientation. That each spacecraft observed only one outbound crossing on this day rules out a Kelvin–Helmholtz instability, which would have appeared as rather small-amplitude periodic motions of the boundary. Therefore, provided there were no internal variations, we conclude that

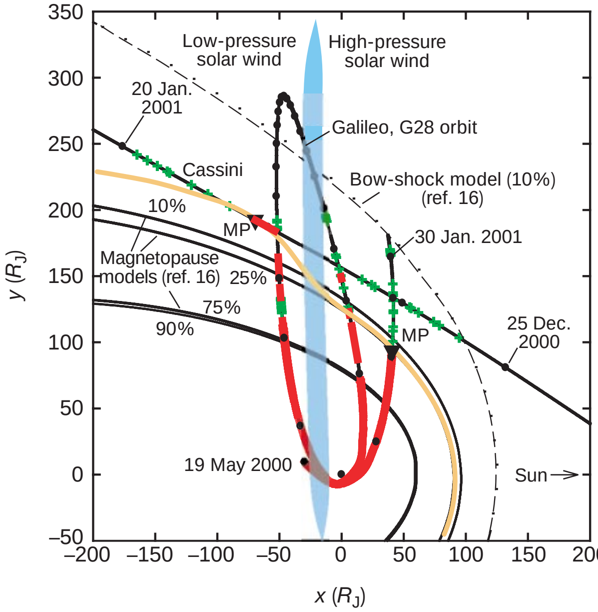

Figure 1 The trajectories of Cassini and Galileo during the time interval surrounding the Cassini closest approach. The coordinate system is centred on Jupiter with the positive *x* axis directed from Jupiter to the Sun. The *z* axis is normal to Jupiter's orbital plane with positive north. The *y* axis completes an orthogonal system. During this time Cassini skimmed the dusk flank of the magnetosphere and for the first three months of 2001 spent a considerable length of time in the dusk jovian magnetosheath, defined as the region between the bow shock and magnetopause. The portion of the Galileo trajectory shown is from its 28th orbit and a portion of the 29th. The apoapses of these orbits were also near dusk, providing some of the first observations of the dusk magnetosphere. On both trajectories, crosses indicate positions where the spacecraft crossed the jovian bow shock. Intervals with thick red lines indicate times when the spacecraft were in the magnetosphere. The triangles (MP) indicate the positions of the two spacecraft when they nearly simultaneously crossed the magnetopause. For comparison, four magnetopause models and one bow-shock model are shown[16]. The bow-shock model illustrated is a surface beyond which there is only a 10% probability of being inside of the shock; that is, it represents the inner boundary of the most distant shocks observed. We notice that Cassini first encountered the bow shock just beyond this model surface. Also included is a qualitative model magnetopause in orange, suggesting that at the time when the two spacecraft crossed the magnetopause roughly simultaneously, the magnetosphere was in transition between states corresponding to two different levels of solar-wind pressure.

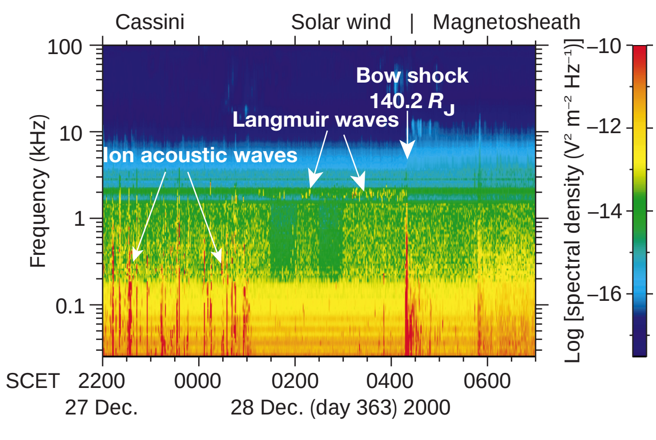

Figure 2 Plasma wave spectrogram. The initial Cassini bow shock crossing (appearing as the earliest cross on the Cassini trajectory in Fig. 1), upstream ion acoustic waves and Langmuir waves preceding the shock crossing are shown. Here the intensity of waves is shown as a function of frequency (ordinate) and time (abscissa), using the colour bar to indicate electric field spectral density. We note that the Langmuir waves are at a frequency of about 2 kHz, corresponding to an electron density of 0.05 cm^{-3}. Assuming a nominal solar-wind speed of 450 km s^{-1}, the derived solar wind dynamic pressure is 0.018 nPa. The Joy *et al.*[16] 10% bow shock model, which assumes a dynamic pressure of 0.02 nPa, crosses the Cassini trajectory very close to this observed shock.

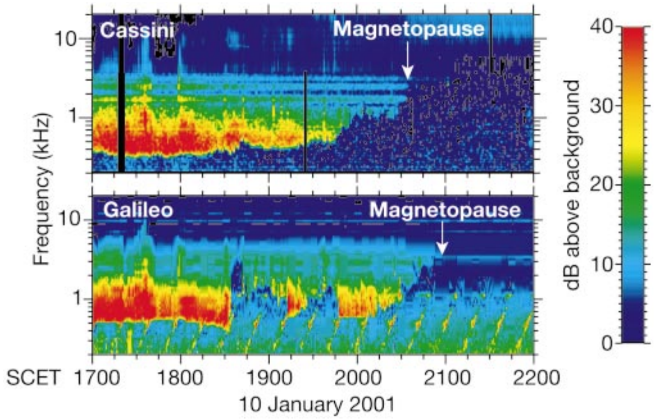

Figure 3 Simultaneous Cassini and Galileo observations of the jovian magnetopause. In the upper panel, Cassini radio and plasma wave observations show trapped continuum radiation at the beginning of the plotted interval with a low-frequency cutoff of about 300 Hz. The magnetopause crossing time indicated on the spectrogram was determined on the basis of the disappearance of the continuum radiation, changes in the magnetic-field direction and spectrum, and the low-energy plasma, and energetic-particle distributions (D. Mitchell, personal communication). In the bottom panel, similar observations from the Galileo plasma wave instrument are shown. Here the lowest cutoff frequency is somewhat higher than at Cassini.

the magnetosphere was compressed by increasing solar-wind dynamic pressure.

Variations in the size of the terrestrial magnetosphere have been reported for decades, for example, by Fairfield[18], with Sibeck *et al.*[19] giving a compendium of some 1,821 observations. At Jupiter, fewer, but similar observations have been reported on the basis of Pioneer[1] and Voyager[2–5] data and modelled with conic sections[6–8]. It is well recognized that the magnetopause distance should be controlled, in part, by the solar-wind dynamic pressure[18] and the consequences of these motions have been discussed at length[20–22]. Lepping *et al.*[23] suggested that the extended jovian magnetotail would assume a sausage-like shape owing to recurring pressure variations in the solar wind, suggesting that transients reported herein become a part of the magnetotail structure as they propagate downstream. Kivelson and Southwood[24] argued that in response to changes in pressure at the magnetopause, field-aligned currents would be driven into the auroral ionosphere and suggest that some auroral signatures at high latitudes could result. Although we have found no optical auroral observations concurrent with the observations presented here, Hubble observations[25] taken on 13 January 2001 revealed an auroral oval that was smaller and brighter (upon preliminary analysis) than observed during December 2000 (D. Grodent, personal communication) which might be expected for a compressed magnetosphere.

The gradual increase in electron density inferred from the continuum radiation cutoff from both sets of observations in Fig. 3 is suggestive of a boundary layer just inside the magnetopause where the plasma density changes from that in the magnetosphere to that in the magnetosheath. Galileo showed additional evidence for such a boundary layer during its orbit 28 outbound trajectory. Figure 4 shows a 4-h spectrogram illustrating a rather abrupt decrease in density (decrease in the lower frequency cutoff of the continuum radiation) at about 1645 SCET on 30 May 2000, preceded by a much more gradual decline. The actual magnetopause crossing, determined by a rotation of the field and a decrease in ultra-low-frequency wave activity observed by the magnetometer, occurred at about 1545 SCET. There was a slight decrease in plasma density at this time, but the spacecraft spent nearly an hour in an intermediate density regime, which is also suggestive of a boundary layer. □

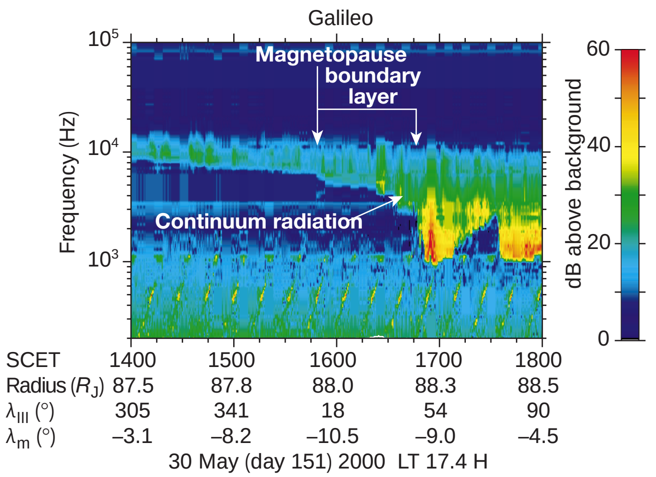

Figure 4 Spectrogram showing evidence for a boundary layer just inside the magnetopause. These observations were made on 30 May 2000 by Galileo and show an extended intermediate-density region between the magnetopause as determined by the magnetic field and the low-density magnetospheric lobe. We suggest that this region is analogous to Earth's low-latitude boundary layer. λ_{III}, system III longitude; λ_m, magnetic latitude; LT, local time; H, hours.

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A nebula of gases from Io surrounding Jupiter

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Several planetary missions have reported[1–4] the presence of substantial numbers of energetic ions and electrons surrounding Jupiter; relativistic electrons are observable up to several astronomical units (AU) from the planet. A population of energetic (>30 keV) neutral particles also has been reported[5], but the instrumentation was not able to determine the mass or charge state of the particles, which were subsequently labelled[6] energetic neutral atoms. Although images showing the presence of the trace element sodium were obtained[7], the source and identity of the neutral atoms—and their overall significance relative to the loss of charged particles from Jupiter's magnetosphere—were unknown. Here we report the discovery by the Cassini spacecraft of a fast ($>10^3$ km s^{-1}) and hot magnetospheric neutral wind extending more than 0.5 AU from Jupiter, and the presence of energetic neutral atoms (both hot and cold) that have been accelerated by the electric field in the solar wind. We suggest that these atoms originate in volcanic gases from Io, undergo significant evolution through various electromagnetic interactions, escape Jupiter's magnetosphere and then populate the environment around the planet. Thus a 'nebula' is created that extends outwards over hundreds of jovian radii.

The detectors on the Cassini mission are specifically designed to detect and 'image' such energetic neutral atoms emanating from planetary magnetospheres. The magnetosphere imaging instrument (MIMI)[8] uses an ion and neutral camera (INCA) sensor that rejects charged particles and can detect energetic neutral atoms over the velocity range $\sim10^3$ to $\sim10^4$ km s^{-1} using a time-of-flight technique, with crude separation into light (that is, H, He) and heavy (that is, O, S) components. A second MIMI sensor, the charge–energy–mass spectrometer (CHEMS) is capable of determining independently the charge state, mass, and energy of ions over the range of ~3 to ~220 keV per charge.

The presence of Jupiter in terms of energetic neutral atom fluxes became evident soon after the beginning of the Cassini Observatory phase on 1 October 2000, at a distance of ~0.5 AU from Jupiter. The intensity from the peak location in the 32×32 pixel image continued to grow, roughly as r^{-2}, as the spacecraft approached the planet. By the closest approach on 30 December, the image had spread to several pixels. A sample of these images is shown in Fig. 1. There is some evidence of structure in the image, although a significant amount of spreading is due to the point spread function in the instrument (arising from scattering of atoms as they encounter the first foil in the detector)[9]. The intensity is highest at the equatorial plane and extends north and south, as well as in radial distance, roughly as expected from pre-encounter simulations[10]. The velocity distribution in each image pixel is constructed by pulse-height analysis. Although not shown here, it reveals two populations in the measured velocity range corresponding to low and high mass, presumed to be H and O, respectively. Our preliminary view is that Cassini's spectra are consistent with an ion population originating inside about 10 R_J, where one jovian radius $R_J = 72,400$ km.

Detailed measurements of ion composition are obtained by the CHEMS sensor. Figure 2 shows an energy spectrogram of He^+ species for about a month before the first encounter of the jovian bow shock, on day 363. There is significant, low-level activity, above instrument background, throughout this period, interspersed with several intervals of more intense fluxes that are especially evident whenever the spacecraft $-x$ axis was pointed in the general direction of the Sun. Such orientation enables one of three CHEMS sensors

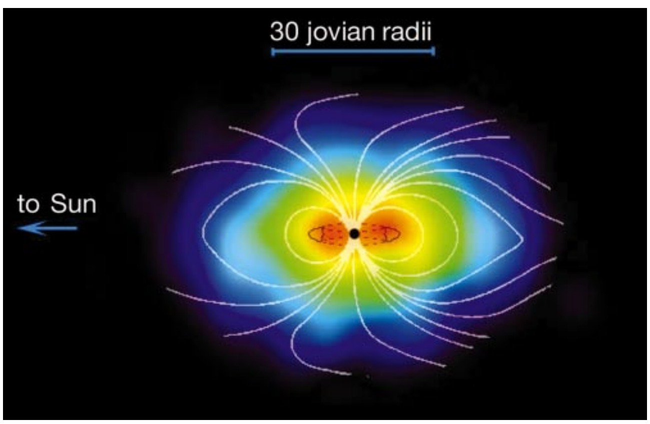

Figure 1 Energetic neutral atom image of Jupiter's magnetosphere as viewed from the dusk meridian soon after Cassini's closest approach on 30 December 2000. The image was generated by neutrals in the range $(3–4)\times10^3$ km s^{-1} or ~50–80 keV per nucleon, assuming the species to be hydrogen. The location of Io's plasma torus has been sketched in (dark lines, centre) and Jupiter's magnetic field (white lines) superimposed on the image for reference.