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Recent Magnetic Field Results from the Galileo and Ulysses Spacecraft [and Discussion]

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Recent magnetic field results from the Galileo and Ulysses spacecraft

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Both Galileo and Ulysses spacecraft have made important exploratory measurements before either start the main phase of their missions. Galileo has flown by several objects in the inner Solar System before its reaching Jupiter. The most notable results from the spacecraft magnetometer are the detection of magnetic field deflections in the vicinity of the two asteroids, Gaspra and Ida, that the spacecraft has flown by. The signatures are not the result of a direct sensing of an internal asteroid field. The asteroid disrupts the solar wind flow by emitting low-frequency waves and these form the signature that the spacecraft detects. The size of the disrupted region set up by Gaspra has led the Galileo magnetometer team to propose that the asteroid may have a substantial dipole moment, a result that raises substantial questions about how and where the object cooled. Ulysses not only sent continuous data back from its flight out to 5 AU in the ecliptic plane but also flew past Jupiter as a prelude to its climb out of the ecliptic in polar solar orbit. Despite being the fifth spacecraft to visit Jupiter, Ulysses in 1992 has produced some surprising new information. For example, the null field regions first identified by Ulysses and then discovered not only in the earlier data sets but also in the Voyager data at Saturn, indicate that the current sheet appears to sporadically shed material at its outer edge. The contrast between the field and plasma environment detected on the inbound (morning sector) and outbound (dusk) pass of Ulysses raises challenging questions about how much acceleration occurs as material rotates around the dayside of Jupiter.

1. New results from the Galileo spacecraft magnetometer

The Galileo spacecraft launch took place in October 1989. Its ultimate mission is an orbital survey of the Jovian system. In the past four years it has flown by Venus, twice flown by the Earth and flown by two asteroids, Gaspra and Ida. On each of these occasions magnetometer data were returned to Earth. The first Earth fly-by provided a unique pass straight up the centre of the geomagnetic tail during a series of geomagnetic substorms (Kivelson *et al.* 1993*a*). The Venus fly-by provided multiple shock encounters and an indication of the occurrence of an intermediate shock (Kivelson *et al.* 1991). The asteroid fly-bys have, however, provided the most dramatic results of the mission so far.

As described by Kivelson *et al.* (1993*a*), as the Galileo spacecraft flew by the asteroid Gaspra the magnetometer detected a rotation in the magnetic field. The signature started one minute before closest approach and the field rotated

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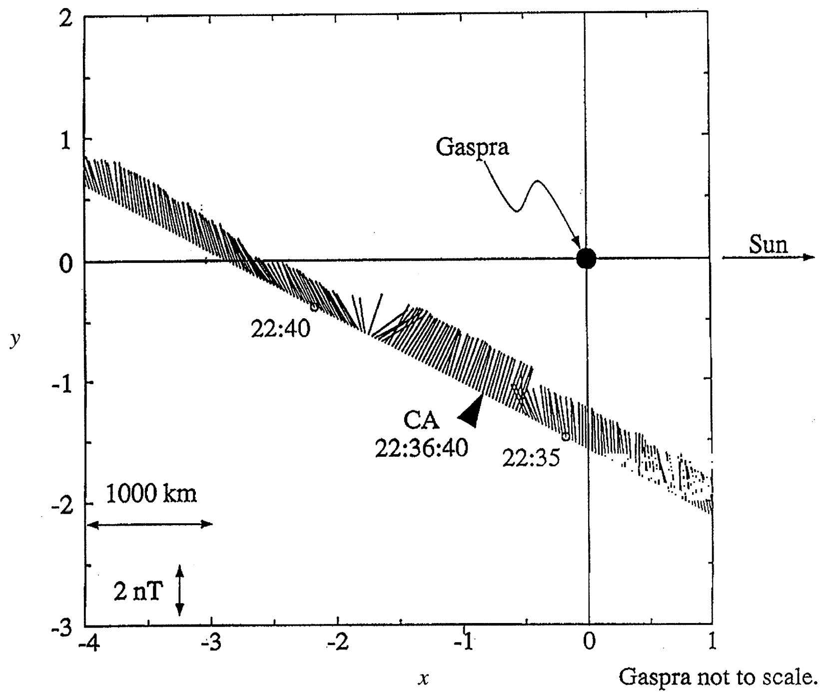

Figure 1. Galileo fly-by of the asteroid Gaspra. A two-dimensional projection of the magnetic field vectors is displayed. Vectors are plotted successively along the spacecraft orbit in a plane containing the asteroid–Sun line (X-axis) and the upstream field. The signature started one minute before closest approach and the field rotated back two minutes afterwards. As can be seen the field rotates sharply towards Gaspra in the disturbance. The X-component reverses in this process.

back two minutes afterwards. Figure 1 shows field vectors in a plane containing the asteroid–Sun line (X-axis) and the upstream field. As can be seen the field rotates sharply towards Gaspra in the disturbance. The X-component reverses in this process.

The magnetic deflection recorded near closest approach to Gaspra is not in itself exceptional; rotations in the magnetic field in the solar wind are often seen. Also there is no question that the signature is a direct detection of the internal field of the asteroid. What is detected could only be a disturbance in the plasma that is generated by Gaspra. Any object that disrupts the flow of the highly conducting solar wind will launch waves into the surrounding medium rather like the bow wave of a ship moving through water. The scale size of the signal emitted is likely to be comparable to the scale size of the source object. The signature detected in the data extends over a range of about 2000 km, a scale that is considerably larger than Gaspra itself but very short compared with the local gyroradius of solar wind protons (*ca.* 13 000 km).

The scale size is critical to the proposed interpretation of the Gaspra signature. A large enough object (e.g. a planet or a planetary magnetosphere) launches a shock rather than a wave as the solar wind speed exceeds the speed of any magnetohydrodynamic wave modes. The Gaspra signatures do not look like shocks; there appears to be negligible change in field strength for example. However not only Gaspra itself but also the more extended size of the apparent obstacle it seems to create in the solar wind are small enough that the magnetohydrodynamic limit is not applicable. Gaspra should launch waves in the whistler mode in a regime where the wave speed is substantially higher than the solar wind speed. The whistler mode radiation pattern set up in a flow by an obstacle has not received much study. This is an object of current work within the team. Stenzel & Urrutia (1989) have performed laboratory experiments in the appropriate regime which certainly indicate a radiation pattern similar to what is proposed by Kivelson *et al.* (1993*a*).

If the source of the interaction between Gaspra and the solar wind were due simply to the finite electrical conductivity of the body the scale size of the waves set up would be likely to be of order the size of Gaspra itself which has a radius of 7 km. The size of the signature detected seems to preclude this possibility. One circumstance in which the obstacle to the solar wind would be much larger than the solid body would be if the object were outgassing and ionization of the outgassed material was resulting in the pick up of asteroidal material by the solar wind. However, in this case, the cometary case, the scale length for the process would be very much larger than the scale on which the spacecraft detects the signature, as the gyroradius for the ions picked up by the solar wind flow would be of order 10^5 km. With pick-up rejected, the final possibility is that the obstacle presented to the solar wind is a magnetic cavity formed due to an internal field, i.e. a magnetosphere. Kivelson *et al.* (1993*a*) produce an estimate for the size of magnetic moment required to offset the upstream boundary of the disturbance, 30–100 km, that is implied by the signature detected at Galileo. On this basis they predict a magnetic moment for Gaspra of between 6×10^{12} A m^2 and 2×10^{14} A m^2. As they point out the magnetic moment per unit mass is not inconsistent with reported values for stony-iron meteorites; the problem however is how Gaspra obtained an apparently relatively uniform magnetization. It or its parent body would appear to have cooled through its Curie point in a steady and rather large field.

On 28 August 1993, Galileo flew by a second asteroid, Ida. Once again a signature that could be attributed to the presence of the asteroid was detected in the vicinity of closest approach. Ida is larger than Gaspra (radius $\approx$ 25 km). Furthermore the orientation of the magnetic field upstream of Ida in the solar wind was very different. The present analysis of the signature leaves the question open whether Ida is magnetized (Kivelson *et al.* 1993*b*).

2. The Jovian magnetosphere

The primary purpose of the Galileo mission is to make the first orbital survey of the Jovian system. Rather than speculate on what Galileo may or may not detect it seems more interesting to look at some of the new results afforded by the recent Ulysses spacecraft Jupiter fly-by undertaken as an injection manoeuvre into solar polar orbit. The fly-by took place in February 1992. Four spacecraft (Pioneers 10 and 11 and Voyagers 1 and 2) had previously flown past Jupiter and Ulysses was not designed for planetary investigation. Nevertheless it was capable of making very useful *in situ* measurements in the magnetosphere of Jupiter of fields, plasma and radio waves and charged particles (see Smith *et al.* (1992) and succeeding papers in *Science*).

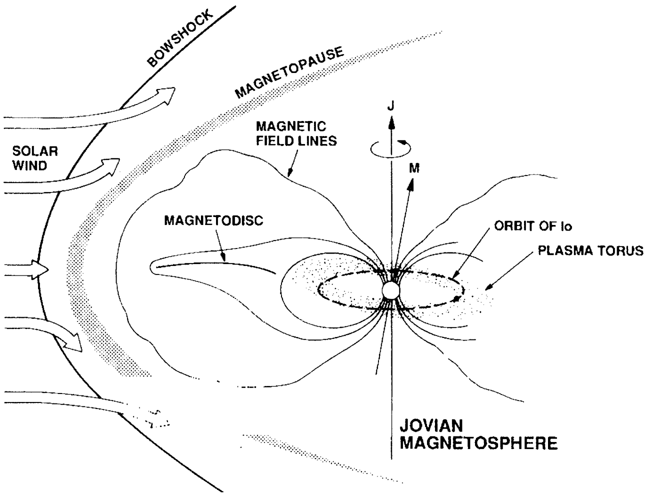

Figure 2. Schematic of the Jovian magnetosphere (Smith *et al.* 1992). J and M represent the rotation axis and magnetic dipole axis of the planet, respectively.

The Ulysses inbound pass was in the morning sector of the magnetosphere and was very similar to the orientation of the earlier spacecraft approaches. In contrast, the outbound pass was in the hitherto unexplored dusk sector of the magnetosphere and was moreover at relatively high latitude. In fact both inbound and outbound passes yielded new results. Concentrating on the measurements made by the magnetometer (Balogh *et al.* 1992), we shall review some of the new results obtained.

A schematic of the Jovian magnetosphere is shown in figure 2 (Smith *et al.* 1992). The magnetosphere of Jupiter is extremely interesting. Not only does the planet have the largest internal field of all the planets and so the largest magnetosphere by volume, but also, in contrast with the Earth, rotation is of central importance in the system's dynamics. Not only does the strong coupling of much of the magnetosphere to the 10 hourly rotation of the planet provide a large source of internal energy but also the ionization of Io's volcanic material provides a strong internal source of mass. The mass injected at Io has to be continually transported outwards from the deep magnetosphere ultimately out into the interplanetary medium. In this process it seems that the magnetosphere continually accelerates and heats the charged particles.

3. Inbound pass

The first encounter with the magnetosphere was at a distance of $110R_\mathrm{J}$ (Jovian radii) from the planet, the most distant detection ever (Balogh *et al.* 1992). The spacecraft approached the planet at low latitudes. Balogh *et al.* describe three field regimes first outlined in the Pioneer spacecraft data. In the outermost region the field is primarily southwards as the sketch in figure 2 shows. Deductions of the plasma flow direction from the energetic particle detectors indicate that material is not corotating with the planet in this region (Staines *et al.* 1993).

A surprise discovery in the outer region was the occurrence of field nulls (Haynes

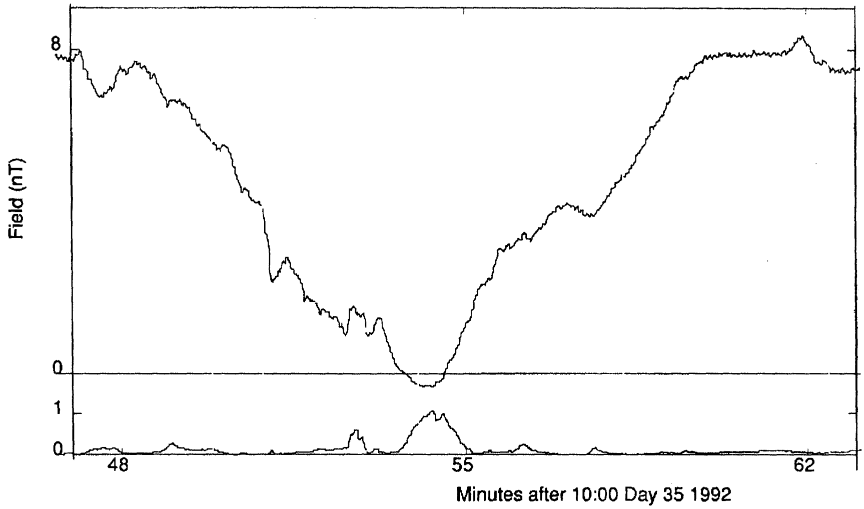

Figure 3. The southward field component detected by the Ulysses spacecraft from 10:46.5 to 10:63.3, Day 35 (February 4) 1992. The lower panel shows the difference between the total field strength and the magnitude of the component illustrated in the top panel.

et al. 1993). An example is shown in figure 3. The plot shows the southward component of the field. Throughout the event the dominant field is southward; a measure of the dominance is given by the lower panel which displays the difference between the field strength and the magnitude of the component displayed.

As can be seen in the figure, the field strength passes through zero shortly before minute 55 after which the field is weakly northward for an interval of less than a minute. The event lasts for about 15 minutes. Somewhat similar events have been detected in the solar wind (Turner *et al.* 1977) but until the Ulysses fly-by the phenomenon had not been identified in a planetary environment. Subsequent re-examination of the earlier Pioneer and Voyager data sets has revealed that similar null field regions were recorded on previous spacecraft encounters with Jupiter (Leamon *et al.* 1994); furthermore similar events have been detected in Saturn's magnetosphere by both Voyager spacecraft (Barbosa 1990; Kivelson, personal communication). The weak reversal of the field evident near the centre of the event shown in figure 3 is present on many examples of nulls and it is possible that nulls had previously been identified as magnetodisc encounters. The field precisely reverses across the magnetodisc current sheet so that a simple passage through the magnetodisc would cause the field to reverse with the reversed field eventually achieving the same magnitude as before the encounter. A signature like that shown could be produced by a current sheet approaching close to the spacecraft but only if the current sheet started to recede from the spacecraft just at the time when the current peaked.

Comparison of the field data with measurements of the plasma density deduced from the Ulysses radio science experiment has revealed that plasma density in general rises in the nulls and furthermore that the temperature is of order 1 keV (Southwood *et al.* 1993). Both temperature and density are comparable to the material in the magnetodisc found in the equatorial plane closer to the planet and this suggests the origin. The magnetodisc itself consists of ionized material being spun around the planet by the magnetic field. Its outer edge presumably

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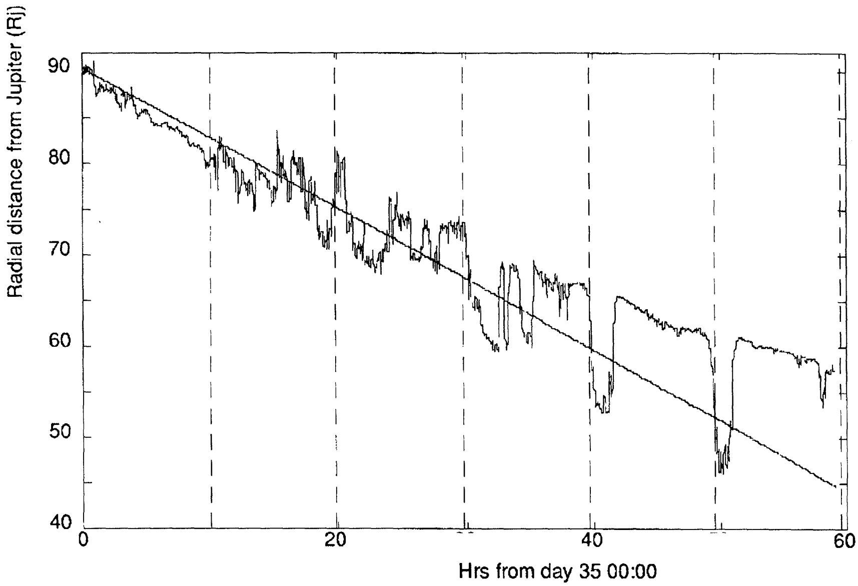

Figure 4. Plot of the radial distance of Ulysses from Jupiter, Day 35 00:00 to Day 37 12:00. Superimposed on the plot is the radial component of field. (Units: nT.)

marks where the stress required to maintain the rotation exceeds the elastic limit of the field. The nulls are likely to be material breaking off the outer edge of the magnetodisc current sheet. The idea deserves further analysis for the implications for our understanding of transport within the system as well as the light it may throw on the manner in which field lines blow open, a subject of interest elsewhere in the heliosphere (for example, in the solar wind originating on closed solar field lines).

Somewhere in the vicinity of a radial distance of $70R_J$ from the planet the dominant field switches from southwards to predominantly radial. In the middle magnetosphere the radial field is the dominant field component and is directly associated with the magnetodisc. The stress in the field is balanced by the combination of centripetal acceleration imposed on the rotating magnetodisc material by the planetary rotation and plasma pressure anisotropies and gradients in the magnetodisc material. In figure 4 we show the radial component through the outer and middle magnetosphere in a display that incorporates the radial position of the spacecraft.

Superimposed on the plot are 9 h 55 min markers indicating the planetary rotation period. The plot reveals increasing planetary control as the spacecraft approaches the planet. Indeed in the outer regions the radial field shows no indication of a rotational periodicity. The radial field component points towards the planet ($B_r < 0$) for the entire rotation illustrated. Recalling that the Jupiter planetary dipole points oppositely to Earth's indicates the puzzling nature of this result. The orbit spacecraft is such that the spacecraft is above the magnetic equator for the bulk of the planetary rotation; as one can see later, in the last four rotations the radial component is increasingly dominated by a positive radial component. There is no explanation at present of the anomalous radial field in the outer region. The radial component is not the dominant component in the outer region; the main component is the southward component. There is no equatorial current sheet here. As noted above, Staines *et al.* (1993) have shown that the material is not corotating here. The anomalous direction of the field no doubt is symptomatic of the weak planetary control of the outer region.

The plot shows the increasing imposition of planetary control of the field at the spacecraft as it moves towards the planet. The last two rotations shown indicate a clear periodicity at the rotation period and the radial field now is predominantly away from Jupiter consistent with the location of Ulysses above the equatorial plane. Were the Jovian current sheet rigidly held in the magnetic equatorial plane, the lowest value of B_r would occur as the magnetic dipole tilts away from the spacecraft. In fact, the vertical lines on the plot represent the point where the dipole tilts away from the spacecraft. As can be seen, the lines occur where the spacecraft is crossing the current sheet.

The second, third and fourth rotations displayed, where the spacecraft is between $80R_J$ and $60R_J$ radial distance, mark an intermediate region in which the current sheet appears capable of large distortion. An extreme instance is the current sheet crossing near hour 35 where the planetary dipole is at its maximum tilt towards the spacecraft.

4. Origin of nulls

The outer segments of the Ulysses inbound pass reveal a magnetosphere that is highly time variable. The outermost region is not corotating but it does contain magnetic null regions discovered by Ulysses but subsequently identified in previous fly-by data. The nulls need further investigation. They probably originate closer to the planet and contain plasma which has broken off from the outer edge of the magnetodisc. One simple scenario for material breaking off on the dayside is that it occurs as a result of a drop in the external pressure of the system, i.e. the solar wind pressure decreasing. Although the non-corotating outer region lies between the solar wind and the outer edge of the sheet the regions contains little plasma and simply acts as a cushion between the solar wind on the magnetopause and the outer edge of the sheet. The sheet material will move out in response to a decrease in the external pressure. The outer edge of the sheet must itself mark the limit beyond which the magnetic field is not capable of sustaining material in rotation about the planet. It follows immediately that any outward motion in response to a drop in external pressure cannot but result in the loss of material and the breaking of field lines. The plasma blob released in a break-off event will contain only a weak field. Beyond the edge of the current sheet the material is in a mainly southwards field. Whatever its precise geometry, the roughly field-free material will elongate along the field direction at roughly the thermal speed of the plasma. In signatures such as that shown in figure 3 where the field is southward almost throughout the field, elongated configuration has been achieved. As one expects the material to leave the magnetodisc moving in a direction roughly tangential to the disk rotation, the scenario given here implies that the material in a null on the morning side of Jupiter should have a large Sunward component of flow. It will be a challenge to see if such evidence can be deduced from the Ulysses particle measurements (which of course were made by instruments not optimized for the Jovian environment).

The Ulysses nulls were recorded far from the planet. Within about $80R_J$ radial

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distance, field drop-outs are caused by magnetodisc encounters, albeit a highly distorted magnetodisc. One evidence of distortion is that the disk itself can be encountered at any part of the planetary rotation cycle (see, for example, the field reversals during the third cycle shown in figure 4). In fact, the field on each side of these magnetodisc encounters departs far from the radial and azimuthal orientation characteristic of the middle magnetosphere proper and more work can usefully be done on this region too.

5. The outbound pass

The outbound pass of Ulysses took place on the dusk meridian, a region never before visited by spacecraft at relatively high latitude (the magnetic latitude is of order 30–50°). Results published so far (Balogh *et al.* 1992; Dougherty *et al.* 1993) indicated that near the planet the 'swept back' magnetic field was consistent with flux tubes rotating in the planetary rotation direction. At a radial distance of about $20R_J$ from the planet the spacecraft enter a regime where the field no longer appears to be corotating. Large field aligned fluxes of charged particles were detected on the outbound pass (Keppler *et al.* 1992; Lanzerotti *et al.* 1992; Simpson *et al.* 1992). The magnetometer team indicated the apparent difference in the nature of the current sheet (that the latitude would have been expected to be much further away from the spacecraft than on the inbound pass) (Balogh *et al.* 1992).

In figure 5 we show a feature of the outbound field that makes a sharp contrast with the inbound pass. The field is primarily in the radial direction in the range shown. Detrended field components in the azimuthal (ϕ) and colatitude (θ) direction are shown. There is clear ten hour periodicity evident in both components with an amplitude of a few nT. There is a quarter cycle phase difference between the components. The implication is that the roughly radially directed field detected by the spacecraft is rotating about the mean field direction. The coning angle can be estimated as of order 5°–6° i.e. less than the 11° predicted if the field were that of just the planetary dipole. The periodicity is imposed along the field by field stress. The spacecraft moves from near $20R_J$ to beyond $50R_J$ in the range shown here.

In contrast with the inbound pass, the magnetosphere here is relatively magnetically rigid. The dynamics of the field and plasma regimes in the dusk sector may form a crucial element in our understanding of the global circulation of the Jovian magnetosphere. The extreme anisotropy of the particle fluxes along the field direction referred to above is consistent with the field lines on the dusk side traversed by Ulysses extending far into the magnetotail. The relatively high fluxes seen far from the magnetic equator outbound contrast strongly with the inbound pass and one needs to ask how much longitude-dependent acceleration there is in the Jovian system.

The Ulysses data with both their contrasts and similarity with the earlier data have reawakened interest in the Jovian magnetosphere that only lends anticipation for the Galileo programme of observations scheduled to begin in December 1995 when Galileo arrives in Jovian orbit. Regions like the magnetotail and many satellite environments remain for entirely new exploration. However, in addition it is probably only with the orbital data set that Galileo will provide that we

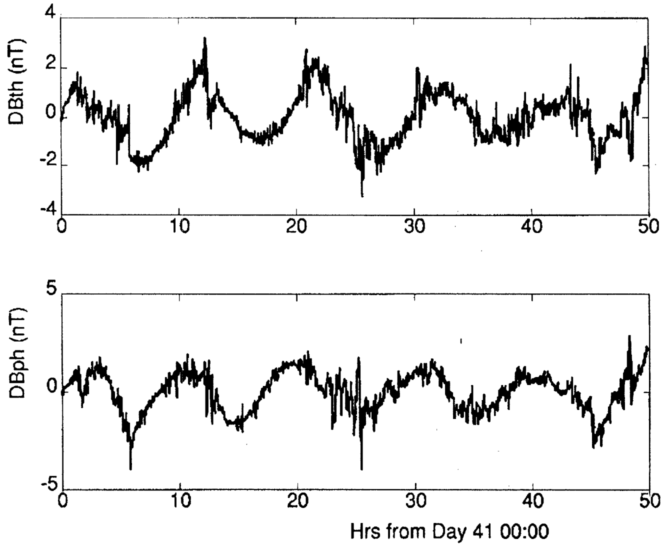

Figure 5. Transverse field components from the outbound pass. The 10 h periodicity is evident.

shall sort out the dynamical processes that govern the phenomena seen on the five fly-bys so far.

The author is very grateful to the Galileo and Ulysses magnetometer principal investigators, M. G. Kivelson and A. Balogh, respectively, for their assistance in providing the data used in this paper.

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Discussion

S. Miller (*University College London, London, U.K.*). The purpose of this contribution is to bring the meeting up to date with the latest information concerning the impending collision between Comet Shoemaker-Levy 9 (SL9) and Jupiter. The information I am presenting has appeared on the bulletin board of the International Jupiter Watch. SL9 was first discovered on 24 March 1993, by Carolyn Shoemaker (U.S. Geological Survey, Flagstaff, Arizona) and David Levy. Calculations of its orbit by Brian Marsden (Minor Planet Center, Cambridge, Massachusetts) showed that it passed within 120000 km of the centre of Jupiter in approximately July 1992. This is well within the Jovian Roche limit, and the tidal forces broke the original parent comet into 21 large fragments. The next perijove (July 1994) will see the fragments actually colliding with Jupiter.

Infrared images taken by David Jewitt and Jane Luu of the University of Hawaii have been interpreted as showing fragments of the order of 1 km in diameter. Later images taken using the Hubble Space Telescope by Harold A. Weaver and T. E. Smith (Space Science Institute) give diameters for the largest 11 fragments between 2 and 4.5 km. Impacting at 60 km s^{-1}, and assuming a density close to 1 g cc^{-1}, a 1 km diameter object will cause an explosion of approximately 10^{28} ergs; larger bodies will cause proportionally larger explosions. There remains uncertainty as to the exact size of the fragments – and, by implication, of the parent comet. If the HST diameters are accepted, the total energy input into Jupiter could be as high as 10^{31} ergs, similar to that assumed to have been associated with the impact which caused the K/T mass extinction on Earth some 65 million years ago.

The latest calculations by Donald K. Yeomans and Paul W. Chodas (JPL, Pasadena) indicate that the SL9 fragments will commence to impact on July 16, the largest fragment hitting on July 20 and the last impact occurring on July 22. Latitudes range between South 42 and South 45. The Earth–Jupiter–fragment angles are computed to be between 91 and 100, the impacts occurring just before the Dawn Terminator. This means that affected areas will be in view from Earth within 1 to 17 min of the impact event.

Satellites which will be involved in the programme of observations include HST, IUE, Galileo and Voyager 2. On the ground, most of the world's leading observatories have set aside time to study the collisions. University College's involvement is with the programme of infrared observations due to be carried out at Mauna Kea, Hawaii, and using UKIRT and the NASA Infrared Telecscope Facility (IRTF). Previous IR observations have shown that there are wavelengths which are extremely sensitive to auroral and dayglow activity in the Jovian ionosphere, picking up emission from the molecular ion H_3^+ against a planetary disc made dark by the absorption of infalling solar radiation by methane below the homopause (Baron *et al.* 1991; Miller *et al.* 1993). Wavelengths around 3.5 μm are especially sensitive to ionospheric activity and are expected to be extremely useful for monitoriing the impacts.

M. K. WALLIS (*University of Wales, Cardiff, U.K.*). If field nulls at Jupiter and Saturn are associated with plasma ejected from the planetary co-rotating sheet, where would the plasma associated with the high heliolatitude field nulls come from?

D. J. SOUTHWOOD. I agree that Dr Wallis's point is very interesting. I think it remains to be seen what the source of the high latitude nulls seen by Ulysses is, and whether they will also be found to have been generated from extinct current sheets.

S. MILLER. Professor Southwood may like to know that the latest infrared and ultraviolet images of Jupiter show that the aurorae are associated with the open field lines, $L > 20$, rather than those associated with the Io torus as previously thought. There are also features which appeared fixed to the magnetic field lines. In the northern hemisphere, the aurora appears to have the form of a narrow arc, with broader, more diffuse emmission regions. There is a particularly noticeable broad emission region around longitude 150° (System III). There also appears to be a local minimum in the UV and H_3^+ emission around 180°, a region that has been associated with 'hot spots' in the emission due to hydrocarbons.

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