Jupiter: Magnetosphere

Jupiter's magnetosphere is the cavity surrounding the planet which contains and is controlled by Jupiter's magnetic field (figure 1). It reaches to a distance of ~60 Jupiter radii on the dayside of the planet (one Jupiter radius, R_J, is taken to be 71 373 km), and extends into a long comet-like tail on the nightside which has a diameter of ~300–400 R_J and a length of at least 3000 R_J. Jupiter's field is confined to this cavity by SOLAR WIND PLASMA WAVES which flow away from the Sun throughout the solar system, and bound the magnetosphere on the outside. Because the solar wind is supermagnetosonic in the planet's rest frame, a bow shock stands in the flow upstream from the cavity, at a distance of ~75 R_J on the dayside, across which the solar wind is slowed, compressed, and heated. The location of the boundary of the magnetosphere, the magnetopause, is determined by the condition of pressure balance between the shocked solar wind plasma (termed the magnetosheath) on one side, and the magnetospheric plasma and field on the other. On the inside of the cavity, the magnetospheric magnetic field lines extend down into the ionosphere and upper atmosphere (thermosphere) of the planet (see JUPITER: ATMOSPHERE), such that the magnetosphere, ionosphere, and thermosphere are strongly coupled together. The plasma inside the magnetosphere contains contributions from both Jupiter's ionosphere and the solar wind, consisting mainly of ionized hydrogen and helium, but by far the most important plasma source is the Galilean moon IO, which orbits deep inside the magnetosphere at a radial distance of 5.9 R_J, and liberates about 1 ton s^{-1} of sulfur dioxide gas (comparable to the production rate of an active comet). Consequently, the magnetospheric plasma is dominated by the presence of ions of sulfur and oxygen. The most important source of momentum and energy for the magnetosphere is the planet's rotation at a period of 9 h 55 min, such that the most important dynamics result from the presence of the Io plasma source deep within the rapidly rotating magnetosphere. However, as in the case of the EARTH'S MAGNETOSPHERE, solar wind coupling at the magnetopause may contribute significantly to the dynamics of the outer regions, and certainly to the formation and properties of the nightside magnetic tail.

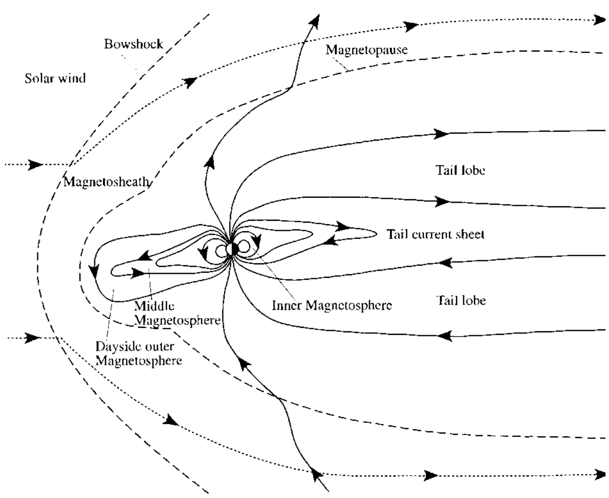


Figure 1. Sketch of Jupiter's magnetosphere in the noon–midnight meridian plane, with the Sun to the left and the solar wind blowing from left to right. The arrowed solid lines are the magnetic field lines, while the dashed lines are the magnetopause and bow shock, as indicated. The dotted lines are plasma streamlines.

Discovery and exploration

The discovery that Jupiter generates an intense magnetic field via dynamo currents flowing in its interior, was made in the 1950s from the observation that the planet is a source of radio emissions in the decametric (~10 MHz) and decimetric (~1 GHz) wave bands (see MAGNETOSPHERES: JUPITER, RADIO EMISSIONS). The decimetric emission is SYNCHROTRON RADIATION generated by gyrating energetic (~10 MeV) radiation belt electrons trapped by Jupiter's magnetic field near the equatorial plane within a few R_J of the planet. The spatial structure of this emission and its variations with planetary rotation indicated that the magnetic field is dipolar in form, like the Earth's, with the magnetic dipole axis tilted by ~10° relative to the planetary rotation axis. The POLARIZATION of the radiation, however, showed that the polarity of the field is opposite to Earth's, with field lines running from the northern hemisphere of the planet, via the equatorial regions, to the southern hemisphere. Whilst this decimetric emission is very steady in time, apart from a modulation at the planetary rotation period, the decametric radiation is instead characteristically bursty, and varies in intensity over several orders of magnitude on time scales of the order of minutes, with an averaged power around a hundred times that of the decimetric emission. Although the first to be discovered, by Burke and Franklin in 1955, the details of the decametric mechanism remain to be understood in detail. However, it is thought to involve emissions at the cyclotron frequency from ~keV electrons accelerated in the magnetosphere, which move along the magnetic field lines towards Jupiter's ionosphere. The upper cut-off frequency of 40 MHz then corresponds to the cyclotron frequency of the highest field strength accessible to these particles over the Jovian poles, equivalent to 1.4–10^{-3} T. This remarkably large field is about twenty times the strength of the Earth's polar field, despite the fact that Jupiter's radius is more than ten times that of the Earth. In 1964, Bigg also discovered that part of the decametric emission is directly influenced by the position of Io, thus providing the first evidence of a complicated electrodynamic interaction between Io and the jovian magnetosphere–ionosphere system. In 1974, Brown using ground-based optical observations also discovered the existence of a large cloud of neutral sodium atoms surrounding Io, which was followed in subsequent years by optical observations of gas and plasma tori in the vicinity of Io's orbit, composed of the atoms and ions of sulfur and oxygen.

In situ exploration of Jupiter's environment began in November–December 1973 with the fly-by of the NASA PIONEER 10 spacecraft, followed by Pioneer 11 in 1974, VOYAGER 1 and 2 in 1979, the European Space Agency's ULYSSES in 1992 (en route to the Sun's polar regions; see SOLAR WIND: ULYSSES), culminating in the insertion into orbit of the NASA GALILEO MISSION spacecraft in 1995. At the time of writing only the results of the initial analyses of Galileo data are available, mainly concerning the interactions of the Galilean moons with the magnetospheric environment (see MAGNETOSPHERES: JUPITER, SATELLITE INTERACTIONS). Most of the information described here, therefore, has been derived from the five earlier fly-by missions, augmented by radio and optical observations from Earth. The Pioneer spacecraft were instrumented principally to measure the jovian magnetic field and energetic particle environment at energies above ~1 MeV. The Voyager spacecraft made the first detailed *in situ* measurements of thermal plasmas at lower energies, at 10–100s eV and 10–100s keV, and of plasma waves. Similar measurements were also made by Ulysses. The trajectories of these spacecraft are shown projected onto Jupiter's orbital plane in figure 2, together with the locations of nominal magnetopause and bow shock positions. The *X* axis points towards the Sun, and the *Y* axis from dawn to dusk across the magnetosphere. It can be seen that all these spacecraft explored the pre-noon dayside magnetosphere on their inbound passes, and that Pioneers 10 and Voyagers 1 and 2 passed through the pre-dawn nightside sector outbound. All these trajectory segments were confined to the near-equatorial region. In contrast, Pioneer 11 passed out of the magnetosphere near noon at northern latitudes of ~33°, while Ulysses exited near to dusk at southerly latitudes of ~37°. Since the APOAPSIS of the Galileo spacecraft has also been confined mainly to the local time sector between midnight and dawn during the main phase of its mission, it can been seen that, while the dawn side of the magnetosphere has received considerable observational study, the dusk side remains almost unexplored.

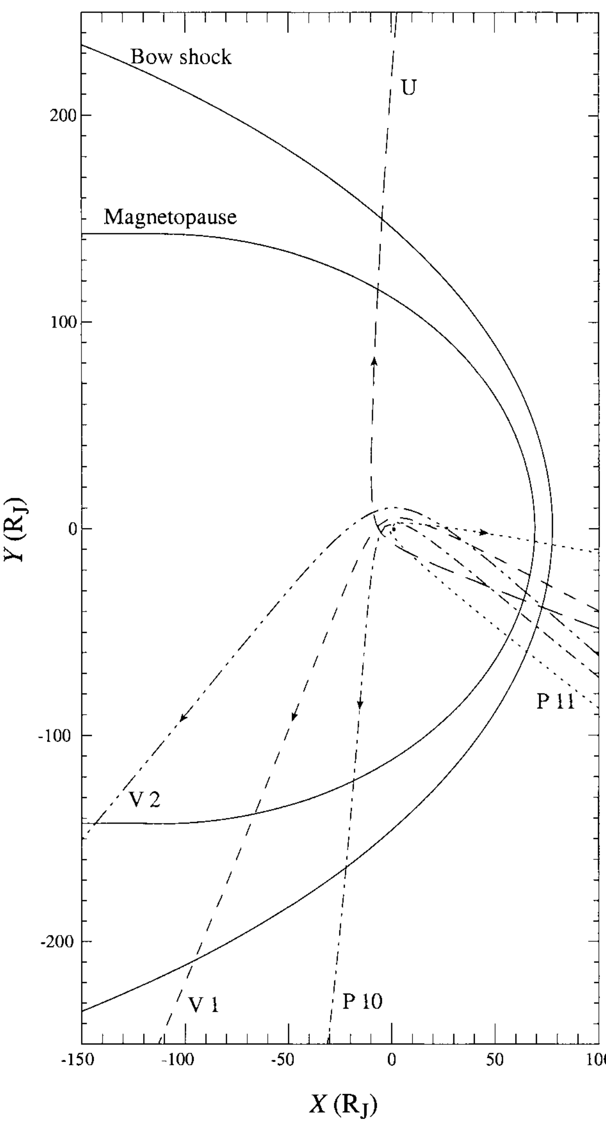


Figure 2. Trajectories of the five fly-by spacecraft relative to Jupiter, projected onto Jupiter's orbital plane. *X* points towards the Sun and *Y* from dawn to dusk. P 10 and P 11 refer to Pioneers 10 and 11, V 1 and V 2 to Voyagers 1 and 2, and U to Ulysses. Arrows are plotted in the direction of spacecraft motion on the outbound portions of the trajectories. Also plotted are the average positions of the bow shock and magnetopause (adapted from D E Huddleston *et al* 1998 *J. Geophys. Res.* **103** 20075–82).

Jupiter's magnetic field

Internal planetary field

Although the main features of the magnetic field produced by Jupiter's internal currents were inferred from radio observations prior to the first measurements by spacecraft, *in situ* data are required for detailed characterization. A recent model based on fits to the fly-by data, constrained also by Earth-based observations of jovian auroral emissions associated with the magnetic footprint of Io, indicates a best-fit centered dipole axis which is inclined at 9.5° to Jupiter's spin axis towards system III longitude 201°. The corresponding dipole moment is 4.26–10^{-4} T R_J^{-3}, such that the surface field is 0.4–10^{-3} T at the magnetic equator and approximately double that at the poles (neglecting the dynamical flattening of Jupiter's figure which increases the dipole polar surface field to ~1.0–10^{-3} T). However, large quadrupole and octupole moments are also present which produce significant asymmetries in the near-planet field, in particular increasing the peak surface field in the northern polar regions to ~1.5–10−3, in agreement with the value obtained from the 40 MHz upper cut-off in the decametric emission.

Size of the magnetosphere

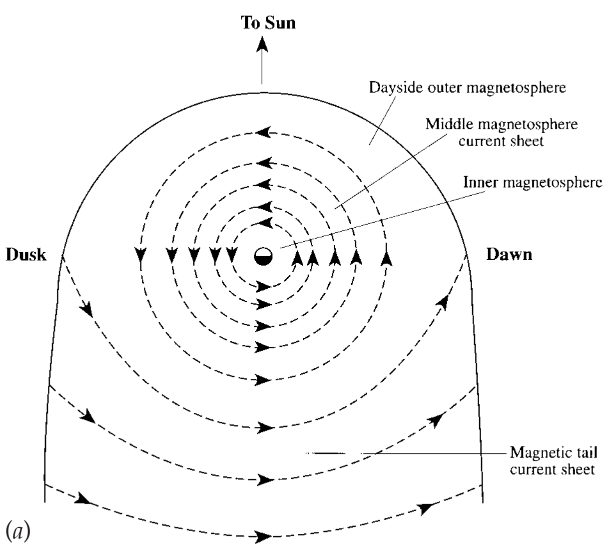
Using the above value of the dipole moment, a simple estimate can be made of the expected size of the magnetospheric cavity in the solar wind, based on pressure balance across the magnetopause. If magnetospheric plasma pressure is neglected such that the internal pressure is wholly magnetic, and taking a nominal solar wind dynamic pressure of ~0.1 nPa at Jupiter's orbit, a simple calculation shows that in the subsolar region (i.e. in the equatorial region near noon) the boundary should lie at a distance of ~35 R_J. In contrast, the fly-by observations of the dayside magnetopause, suitably adjusted to take account of the outward flaring of the boundary away from noon (see figure 2), indicate a typical distance of ~60 R_J. Furthermore, the response to variations in solar wind dynamic pressure indicates a much 'squashier' system than expected, with subsolar boundary positions varying between ~40 and ~80 R_J, indicating a position which varies inversely as the ¼ or (1/5) power of the dynamic pressure, compared with the (1/6) power expected for a dipole magnetic field. The reason for the great inflation of the magnetosphere, and for its 'squashy' nature, lies in the fact that (unlike Earth), the magnetospheric plasma makes a substantial contribution to the internal pressure, at least comparable to that made by the field.

Inner magnetosphere

The structure of the magnetic field within the cavity as revealed by spacecraft observations is indicated schematically in figure 1, which shows a sketch of the field lines in the noon–midnight meridian plane. Four basic regions are identified, whose boundaries are defined by the magnetic field lines. The inner magnetosphere is defined by the torus-shaped region of field lines which cross the equatorial plane within ~5 R_J of Jupiter's center. The field in this region is essentially an undisturbed planetary field, which contains the radiation zone of synchrotron-emitting energetic electrons. This region is distinguished from the middle magnetosphere, which bounds it on the outside, by the lack of significant electrical currents flowing in the plasma, such that the outer boundary of the region essentially coincides with the inner boundary of the Io plasma torus where strong equatorial currents begin. However, the inner region is affected by the fringing field of the latter currents, which produce a nearly uniform northward field in the inner region of strength ~200 nT. This field is directed opposite to the southward planetary field in the equatorial plane, but is much weaker than the latter, since even at ~5 R_J the equatorial dipole field is still 3400 nT.

Middle magnetosphere

As indicated above, the middle magnetosphere is characterized by the presence of strong azimuthal (eastward) electric currents flowing in the plasma near the equatorial plane whose magnetic effect distends the field lines outwards from the planet, as shown in figure 1. In the equatorial plane this region extends from the inner edge of the Io plasma torus at ~5 R_J to an outer limit on the dayside which depends upon the degree of extension of the magnetosphere, and lies typically ~15 R_J inside the magnetopause. For a typical ~60 R_J magnetopause position at noon, therefore, the outer edge of the middle



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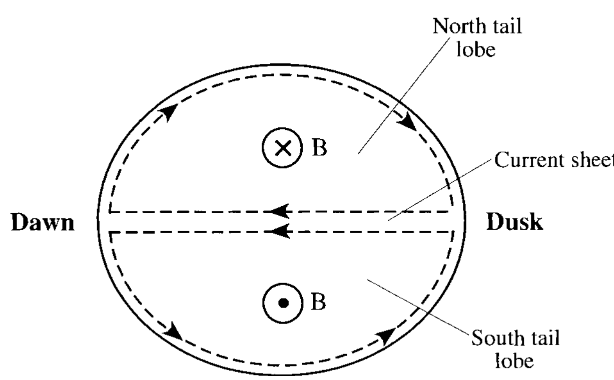

Figure 3. (*a*) Sketch of the current system in Jupiter's magnetic equatorial plane, showing the eastward current of the middle magnetosphere region, which closes round the planet, and the dusk-to-dawn currents of the tail current sheet, which separates the tail lobes, and closes around the magnetopause. (*b*) Sketch of the field and current in a cross section through the tail, looking down the tail from the planet. The north tail lobe field points away from the planet (circled cross), while that of the southern lobe points towards the planet (circled dot).

magnetosphere current sheet lies at ~45 R_J. On the nightside, the current sheet merges continuously into the current system of the magnetospheric tail. Figure 3(*a*) shows a sketch of the equatorial currents of the middle magnetosphere which, to a first approximation, close azimuthally around the planet, and the adjacent equatorial tail currents which flow from dusk to dawn across the system. The tail currents close north and south over the tail lobe magnetopause to form two D-shaped solenoidal current systems back-to-back, as shown in the cross section in figure 3(*b*). The full thickness of the current sheet is ~5 R_J, and the current within it, and hence the perturbation field produced, falls with distance from the planet approximately as $r^{-1.5}$. The value of the exponent depends somewhat on distance and local time, but is in any case considerably smaller than the r^{-3} dependence of the planetary dipole field. Consequently, while in the vicinity of Io's orbit the perturbation fields of the current sheet are relatively small compared with the planetary field (as indicated above), such that the field lines remain basically dipolar in form, they become dominant at distances beyond ~15 R_J. In the latter region the low latitude field is thus characterized by strong radial fields which point outwards from the planet north of the current sheet, and inwards to the planet south of the sheet, as shown in figure 1. At the center of the current sheet the field is weak and points south. The total current flowing in the annular middle magnetosphere current sheet (excluding the tail system) is ~200 MA.

Within ~30 R_J of the planet the current sheet is centered close to the planetary dipole equatorial plane, tilted at 9.5Â° to Jupiter's spin axis as indicated above. With increasing distance, however, the current sheet increasingly departs from this plane due to two effects. The first is that, as the dipole axis rotates around with the planet, the information about the rotation is communicated to the outer regions at a finite speed. Consequently, at a given distance from the planet the effective position of the dipole is increasingly retarded in azimuth relative to its true position. Within ~30 RJ the delays are insignificant, but beyond this distance the effective information propagation speed is ~40 RJ h–1 (~750 km s–1), leading to observable delays. The second effect is the 'hinging' of the current sheet in the magnetic tail, where the plane of the sheet departs from the dipole equator and becomes aligned with the tail axis (defined by the flow of the solar wind), as shown in figure 1. This effect becomes apparent at down-tail distances beyond ~35 R_J.

Outer magnetosphere

The outer magnetosphere is a dayside region observed during the inbound passes of the fly-by spacecraft of uncertain local time extent, in which there is no evidence of an equatorial current sheet. Instead, the field in this region, although rather variable, points on average to the south in the equatorial region, in the direction of the planetary equatorial field, and overlies the middle magnetosphere closer to the planet. The region is thus bounded by the magnetopause on one side, and by the middle magnetosphere on the other. A TRANSITION REGION of disordered field may occur between the outer and middle magnetosphere regions (particularly well marked on the inbound Ulysses pass), where the equatorial field undergoes sharp changes indicative of the presence of plasma current layers, but which are not ordered by magnetic latitude or planetary rotation period. The thickness of the outer magnetosphere in the equatorial region is ~15 R_J, and the average equatorial field strength varies between ~5 and ~15 nT, depending on the degree of extension of the magnetosphere. In all cases, however, the field is significantly stronger than that of the planetary dipole, due to the fringing effect of the current sheet field.

Magnetic tail

The magnetic tail on the nightside of the planet consists of two tail lobes of oppositely directed flux where the field is relatively uniform and strong, pointing away from the planet in the northern lobe and towards the planet in the southern lobe, which are separated by the thin (few R_J) equatorial current sheet mentioned above, where the plasma carries the required electric current from dusk to dawn across the tail. Overall, the tail has an approximately cylindrical shape with a diameter of ~300–400 R_J, such that the two lobes are D-shaped in cross section, as shown in figure 3(*b*). The field strength in the lobes falls with increasing distance as the tail expands in radius, reaching ~2 nT at a down-tail distance of ~150 R_J as measured by Voyager 2 (see figure 2). By analogy with Earth, it seems probable that the tail is formed by MAGNETIC RECONNECTION at the dayside magnetopause between the interplanetary and magnetospheric field, which results in the formation of open magnetic flux tubes which map from the planet's polar cap, through the magnetopause, and into interplanetary space (figure 1). The flow of the solar wind then carries them onto the nightside of the planet, where they are stretched out to form the tail lobes. As they are stretched out down-tail, the open tubes slowly sink in towards the center plane of the tail, where they reconnect again within the current sheet, returning closed magnetic flux tubes, attached to Jupiter at both ends, back towards the planet. However, where the reconnection and return flow take places in the jovian tail is at present unknown. On the basis of this model we may estimate that the lobe field lines flow towards the current sheet at a speed of a few tens of km s^{-1}, such that they remain 'open' for several Earth days. Consequently, the length of the tail (equal to the speed of the solar wind times the length of time for which lobe field lines remain open) will be several thousand R_J (i.e. a few AU). The amount of magnetic flux in each lobe is ~4–10^{11} Wb, corresponding to a region of

~10° latitude surrounding each magnetic pole at ionospheric heights.

Bending of the field meridian planes
For a pure dipole, field lines lie in planes of constant longitude relative to the dipole axis. However, the planetary field lines at Jupiter are noticeably bent out of such meridian planes, associated with the existence of azimuthal fields directed either eastward (in the sense of planetary rotation) or westward around the magnetic axis. The bending of meridian planes is of interest because it provides information about the transfer of magnetic forces between one plasma region and another connected by the magnetic field. Two major effects are illustrated in figure 4(*a*), which shows a view looking down onto the jovian magnetosphere from above the northern pole, and shows field lines in two regimes of latitude mapping out from Jupiter's ionosphere to the equatorial plane. The field lines in the high-latitude region mapping into the outer magnetosphere are bent away from noon and towards the tail as a consequence of the solar wind interaction, such that in the northern hemisphere (as shown) the perturbation fields are eastwards on the dusk side of the magnetosphere and westward on the dawn side (and vice versa in the southern hemisphere). The current system responsible is that of the magnetopause and tail (as sketched in figure 3(*b*)).

At lower latitudes, however, the field lines mapping to the middle magnetosphere current sheet show a consistent sense of bending independent of local time (insofar as it has been measured), with azimuthal fields which are westward above the current sheet (as shown), and eastward beneath it. This pattern of field bending is associated with a torque on the magnetospheric plasma which acts to spin it up towards the angular velocity of planetary rotation, i.e. it is associated with the transfer of angular momentum from the thermosphere/ionosphere to the magnetosphere, as will be discussed further below. The current system responsible is sketched in figure 4(*b*), and involves a radially outward current in the equatorial plane which closes along magnetic field lines through equatorward currents flowing in the ionosphere. Typically, outside the current sheet the observed azimuthal field is a small fraction of the radial field, such that the radial currents are a correspondingly small fraction of the azimuthal current. Figure 4(*a*) shows that the two effects discussed here produce similar effects which are difficult to separate in the dawn magnetosphere where most observations have been made. However, the Ulysses observations at dusk demonstrate that the two effects are separately present, one dominant in the middle magnetosphere, the other in the outer magnetosphere.

Jupiter's plasma populations and their dynamics

Sources of plasma mass and momentum
The nature of the plasma dynamics in a planetary magnetosphere depends on the nature of the plasma sources and sinks, and the nature of the transport processes which convey the plasma from the former to the latter. The plasma sources include the solar wind at the outer boundary and the planet's ionosphere at the inner boundary, together with the surfaces and atmospheres of any moons that happen to orbit within the cavity. The sources of momentum include the antisunward flow of the solar wind on the outside, and the planet's rotation

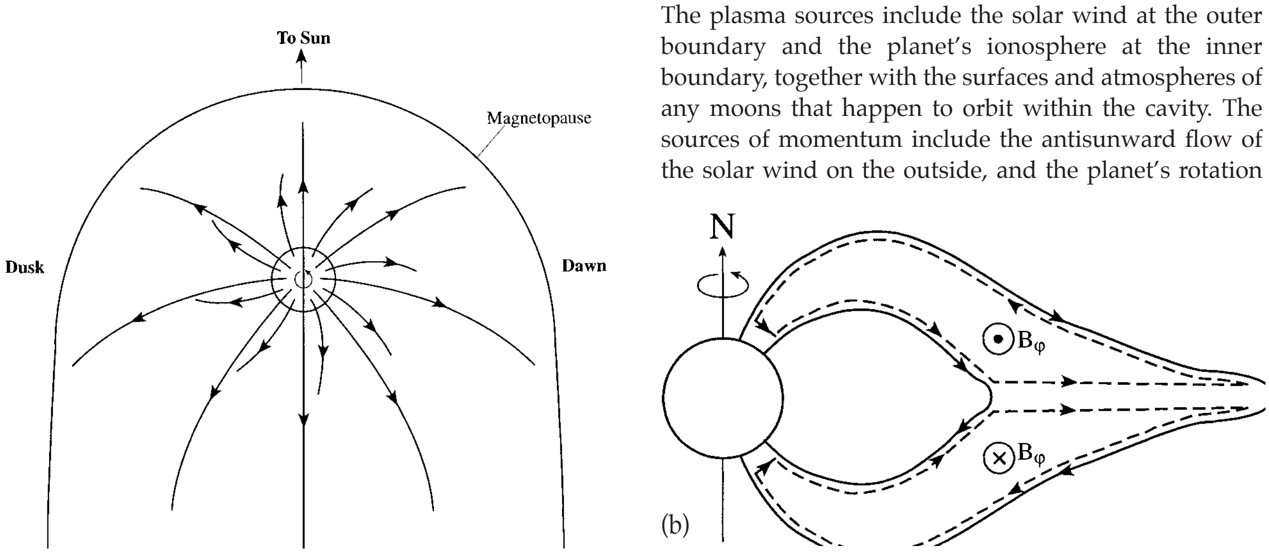

Figure 4. (*a*) Sketch of field lines emanating from the northern hemisphere of Jupiter projected onto the equatorial plane, showing the bending of the field lines out of meridian planes. High-latitude field lines mapping to the outer parts of the magnetosphere are bent away from noon by the interaction with the solar wind. The current system responsible is the magnetopause–tail system. Lower-latitude field lines mapping to the middle magnetosphere current sheet are bent consistently in the clockwise sense, associated with the transfer of anticlockwise planetary angular momentum from the thermosphere/ionosphere to the magnetosphere. (*b*) Sketch of the current system associated with planetary angular momentum transfer. The arrowed solid lines are magnetic field lines, and the dashed lines show the direction of current flow. The circled symbols marked B_φ indicate the direction of the azimuthal perturbation magnetic field produced by these currents, out of the diagram north of the current sheet, and into the diagram south of the sheet.

on the inside. Solar wind interaction at the boundary carries magnetospheric flux tubes from the dayside to the nightside in the outer regions of the magnetosphere, as discussed above in relation to the formation of the magnetic tail, from which closed flux tubes eventually return flowing sunward through the central regions of the magnetosphere. In the absence of such flows, the magnetospheric plasma and field will rotate with the planet, the angular momentum being transferred by ion–neutral collisions at the feet of the field lines in the lower ionosphere.

Brice and Ioannidis in 1970 were the first to consider the relative importance of these two flow systems at Jupiter. Flows of plasmas and embedded magnetic fields are associated with an electric field which is transverse to both the velocity vector $\boldsymbol{V}$ and to the magnetic field $\boldsymbol{B}$, given by $\boldsymbol{E} = -\boldsymbol{V}–\boldsymbol{B}$. The overall strength of a flow system can then be measured by the voltage associated with its electric field, since by Faraday's law 1 V is equivalent to the transfer of 1 Wb s^{-1} of magnetic flux embedded in the flow. The electric field associated with the solar wind driven flow is directed from dusk to dawn across Jupiter's magnetosphere, and by analogy with the Earth, the associated voltage can be estimated to be ~1 MV (i.e. the transfer through this flow system of ~1 MWb s^{-1} from the dayside to the tail in the outer regions, and the return of the same amount, in the steady state, in the central regions). The electric field associated with rotation is directed radially outwards in the equatorial plane, and for rigid corotation with the planet (i.e. rotation with the same angular frequency as the planet) the associated voltage is ~400 MV. Rotation with the planet is thus by far the most important flow at Jupiter, although as indicated above, this statement does not preclude the dominance of solar wind driven effects in the outer regions and magnetotail.

Estimates indicate that both the solar wind and the ionosphere represent sources of a few –10^{28} ion s^{-1} for Jupiter's magnetosphere, consisting principally of hydrogen (i.e. protons, together, of course, with sufficient electrons to keep the gas electrically neutral overall). The corresponding mass sources are a few tens of kg s^{-1}. The ionospheric source also uniquely provides molecular hydrogen ions, H^{+}_{2} and H^{+}_{3}, as minor constituents, while the solar wind provides He^{2+} and traces of heavier ions such as carbon. The identification of all these species within the jovian plasma has confirmed the presence of both sources. The major discovery of the Voyager fly-bys, however, was that the jovian system is not dominated by a hydrogen plasma as had previously been anticipated, but by a sulfur and oxygen plasma which originates from the sulfur dioxide atmosphere of the volcanic moon Io, which orbits at a distance of 5.9 R_J. The source rate is estimated to be ~3–10^{28} ion s^{-1}, similar to the solar wind and ionospheric sources, but because the ions are heavy, with a mean mass of ~21 amu, the corresponding mass source of ~1000 kg s^{-1} is overwhelmingly dominant. The sodium source at Io, though easily visible in optical emission, is less than this by a factor of around a hundred, and is thus negligible in overall terms. Recent estimates indicate that the moon EUROPA, which orbits at a radial distance of 9.4 R_J, is also a significant source of oxygen plasma originating from the surface water ice, with rates of ~2–10^{27} ion s^{-1} and corresponding mass rates of ~50 kg s^{-1}. The plasma dynamics of Jupiter's magnetosphere is therefore dominated by the consequences of the presence of strong heavy-ion sources lying deep within a rapidly rotating magnetosphere.

The Io plasma torus

The Io plasma which exists within Jupiter's magnetosphere originates principally from electron-impact ionization of the clouds of sulfur and oxygen atoms which orbit in the vicinity of Io, originating in the latter's atmosphere (see IO: PLASMA TORUS). The density of these atoms peaks at a few tens of cm^{-3} near the orbit of Io, with oxygen being the more numerous species as expected from the sulfur dioxide source, and falls off by an order of magnitude within ~1 R_J on either side. These neutral particles orbit with Io at Keplerian speeds of ~17 km s^{-1}, being influenced only by the gravitational force of Jupiter. When these atoms are ionized, however, the resulting ions and electrons suddenly sense the electromagnetic environment as well, that is to say the southward ~2000 nT magnetic field of the planet, and the ~0.1 V m^{-1}

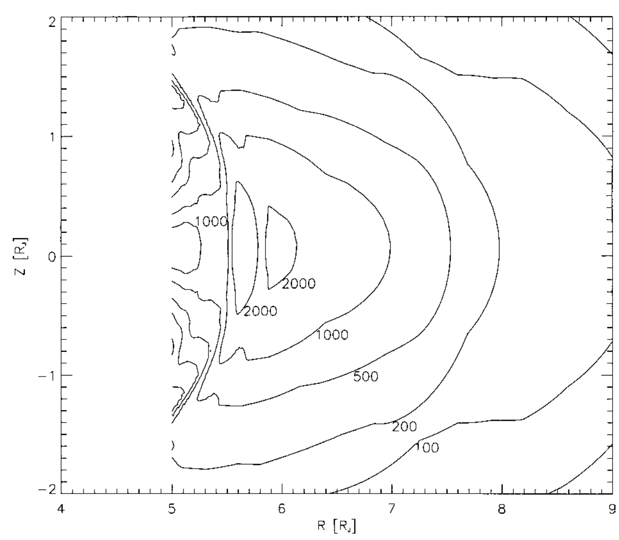

Figure 5. Contours of electron density in the Io plasma torus in the meridian plane, determined from Voyager 1 PLS data. The vertical scale is distance from the centrifugal equatorial plane, while the horizontal axis is distance from Jupiter's spin axis, both in R_J. The numbers on the contours give the electron density, equal to the ion charge density, in units of electrons cm^{-3}. (Taken from F Bagenal *et al* 1997 *Geophys. Res. Lett.* **24** 2119–22.) (Copyright 1997 by the American Geophysical Union.)

outward-directed electric field associated with the ~70 km s^{-1} flow of the near-corotating plasma. The effect of these fields is such as to cause the charged particles immediately to drift with the plasma at the corotation speed (they are 'picked up' by the plasma flow), and also to acquire a gyratory speed about the field lines equal to the difference between the corotation and Keplerian speeds, equal to ~55 km s^{-1}. This corresponds to a 'thermal' energy of ~250 eV for oxygen ions and ~500 eV for sulfur, but only 0.01 eV for electrons. Subsequently, the ions are cooled by Coulomb collisions with the electrons, and the consequently heated electrons are cooled by collisional excitation of the low-lying energy levels of the ions, thus leading to the observed optical emission from the torus.

The most detailed information about the low-energy plasma distribution which results from these processes was obtained during the inbound passage of Voyager 1. Figure 5 shows contours of electron density (equal to the ion charge density) which have been derived from these data. The principal population is the warm plasma torus which, in the equatorial plane, extends outwards from a jovicentric distance of ~5.6 R_J. The ions in this region consist of two populations, a suprathermal population of recently ionized few 100 eV particles (increasing in energy with increasing distance, up to ~2 keV at ~10 R_J), comprising ~10–20% of the population, and a cooled population with a temperature of ~60 eV (also increasing with distance up to ~300 eV at 10 R_J). The electron temperature in this region is ~10 eV. In the inner part of the warm torus, within ~7.5 R_J, there are approximately equal numbers of sulfur and oxygen ions, with the oxygen being principally O^+, while the sulfur is roughly equally divided between S^+ and S^{2+}. Outside this distance, the plasma is richer in oxygen, possibly due to the Europa source, with roughly equal numbers of O^+ and O^{2+}, and the density of S^{3+} becomes comparable with those of S^+ and S^{2+}. Inside ~5.6 R_J the plasma cools precipitately to form the cold plasma torus near the equatorial plane at distances of ~5.0–5.4 R_J. The ion and electron temperatures in this region are just a few eV, and the composition is a somewhat sulfur-rich combination of S^+ and O^+.

The distribution of the torus plasma along the field lines is determined by a balance between the plasma pressure force, the magnetic mirror force, the centrifugal force, the gravitational force due to Jupiter, and a field-parallel electric force which is required to ensure that the ion and electron charge densities are equal at all points. Apart from the latter, the most important physical effect is that the centrifugal force tends to compress the plasma at the centrifugal equator (the point of maximum distance along a field line from the planetary spin axis), while this compression is resisted by the plasma pressure. In the warm torus, equilibrium is reached for a scale height along the field lines away from the equator (the distance over which the density falls by a factor of ~2.7) of ~1 R_J. In the cold torus, however, the scale height is reduced by the lower temperatures to ~0.3 R_J.

The spatial structure of the torus plasma across the field lines reflects both the distribution of the atomic gas sources in the vicinity of the orbits of Io and Europa, together with the nature of the cross-field transport mechanism. Because the outwardly directed centrifugal force on the plasma is dominant (being much greater, certainly, than the inward force of Jupiter's gravity), flux tubes containing high-density plasma from the Io source will tend to 'fall' outwards to larger distances, restrained by the frictional drag of ion–neutral collisions at the feet of the field lines in the ionosphere. These flux tubes will be replaced by tubes containing lesser densities moving inwards, it being ultimately supposed, of course, that some mechanism (presently unknown) exists for emptying the flux tubes of their plasma content at large distances. This picture explains the basic cross-field structure shown in figure 5, which is indicative of rapid transport of warm dense plasma away from Jupiter at distances beyond the neutral gas sources. However, the inward transport from those sources towards Jupiter is much weaker, such that the plasma has time to cool by radiation, collapses onto the centrifugal equator due to the reduced pressure, and then recombines, thus explaining the existence and properties of the cold torus population.

Although the basic physical picture of outward radial transport of the torus plasma by centrifugally driven flux tube interchange thus seems clear, the details of the process are not yet determined, including basic time and spatial scales, and is simply parameterized in many theoretical models by an empirically determined spatial diffusion coefficient. Observationally, the warm torus plasma is found to pervade the equatorial current sheet out to the outer boundary of the middle magnetosphere at several tens of R_J. Due principally to the expansion of the flux tubes, the equatorial ion/electron charge density falls from at peak of ~3000 cm^{-3} (during the Voyager 1 flyby) near the inner edge of the torus at ~5.7 R_J, to ~70 cm^{-3} at ~10 R_J (as in figure 5), and down to ~0.1 cm^{-3} at several tens of R_J. The fraction of suprathermal particles in the population appears to increase with distance, however, such that the average energy also increases, rather than falling as expected for an expanding plasma. Typical values are a few 100 eV. Sporadic enhancements of low-temperature plasma are also observed in the dayside outer magnetosphere, correlated with decreases in the strength of the magnetic field. We may conjecture that these represent plasma fragments which have become detached from the middle magnetosphere current sheet.

Hot plasma population

The outwardly diffusing Io torus plasma is not, however, the only population which is present in Jupiter's magnetosphere. Observations by the Voyager and Ulysses spacecraft have shown that a low-density but high-energy population is also present, consisting of roughly equal numbers of protons and heavy ions (mainly sulfur and oxygen). The number density and average energy of this population both increase on moving towards the planet, before falling near the inner edge of the warm torus. In terms of the above discussion, we may picture this low-density population to be transported radially inwards as the high-density torus plasma is transported radially outwards. Indeed, evidence has been found in Galileo data for sporadic localized inward injections of hot ions within the current sheet at distances between ~10 and ~30 R_J. These injections have aspects in common with SUBSTORMS at Earth, but at Jupiter they are not confined to the nightside but occur at all local times. Inward transport of this plasma results in compression and heating as observed, the energy required being derived ultimately from the outward 'falling' torus plasma. The presence of the hot plasma thus acts partially to suppress this transport.

The hot plasma density is much less than that of the warm torus plasma throughout the system, being ~10^{-2} to 10^{-3} cm^{-3} in the outer regions, increasing to perhaps ~1 cm^{-3} in the inner part of the Io torus. These particles thus make little contribution to the overall mass or charge density compared with the low-energy plasma, except perhaps in the dayside outer magnetosphere. However, their average energy is sufficiently large that they make the dominant contribution to the plasma pressure at all points except for the innermost part of the warm torus where the extreme warm plasma density (figure 5) and the falling hot ion temperature combine to produce comparable warm and hot plasma pressures. In the outer part of the magnetosphere the hot ion temperature is a few tens of keV, with the distribution having a non-Maxwellian high-energy tail extending above 1 MeV. The average energy then increases with decreasing distance, reaching a peak of ~2 MeV at ~7 R_J according to Voyager 1 measurements, before falling to ~100 keV inside Io's orbit at 5.9 R_J. Electrons are also present with comparable energies but significantly lower densities, such that they make a smaller contribution to the pressure. It is these energetic particles in the inner part of the warm torus which form the source of the radiation belts within the inner magnetosphere. From the vicinity of Io's orbit these particles are more slowly diffused inwards due to the presence of fluctuating electric fields driven by winds in the thermosphere, gaining further energy as they do so. This input is balanced in the steady state by particle flux and energy losses in the inner magnetosphere which are due to wave-induced particle precipitation into the atmosphere, absorption by ring material and moons, and (for electrons) synchrotron radiation.

A key feature of the hot ion population is that within the outer part of the middle magnetosphere its pressure is comparable with that of the magnetic field. As a consequence it 'inflates' the planetary field to form the current sheet structure observed in this region (figure 1), a process which also inflates the magnetosphere beyond the size expected for pressure balance between the solar wind and the planetary magnetic field alone, as discussed above. The distended field lines then provide the inward force (the $\boldsymbol{j}$–$\boldsymbol{B}$ Lorentz force of the azimuthal current) which in the steady state balances the outward pressure gradient of the hot plasma. The Io torus plasma also plays a role in current sheet formation, though a lesser one, since the field must also provide the inward force necessary to balance the centrifugal and pressure gradient forces of this population. With regard to the dominant hot plasma population, Voyager observations indicate that the equatorial pressure remains greater than that of the field throughout the outer part of the middle magnetosphere, while falling below that of the field inside ~10 R_J, due to the rapidly increasing strength of the dipole field. Consequently, as noted above, the perturbation fields produced by the plasma at and inside these distances becomes smaller than the planetary field, such that the field geometry then assumes a quasi-dipolar form.

Plasma flow and field bending

Observations of the plasma flow within the middle magnetosphere, extending outwards from the orbit of Io, generally confirm a primary plasma flow in the sense of planetary rotation as discussed above. However, departures from rigid corotation are observed which are due to two main effects. The first occurs in the main source region of the torus plasma in the vicinity of Io's orbit, where neutral atoms are ionized and 'picked-up' by the plasma. Because ANGULAR MOMENTUM is continuously provided to the newly ionized particles, the plasma in this region rotates more slowly than for rigid corotation, by an amount which is just such that the ion–neutral collisions in the lower ionosphere provide the required torque. Ground-based spectroscopic observations of the plasma, together with *in situ* data from Voyager 1, indicate that the plasma flow is slowed by ~4 km s^{-1} in a ~2 R_J-wide region centered near to Io's orbit by this effect (the rigid corotation speed is 74 km s^{-1}). Outside this region, near-rigid corotation is resumed.

As the torus plasma diffuses radially outwards, however, angular momentum must again be continuously added to maintain plasma rotation at near-rigid speeds. If no angular momentum is added, conservation of plasma angular momentum requires the azimuthal speed of the plasma to fall inversely as the distance from the spin axis, while for rigid corotation the speed must increase in direct proportion to this distance. In order to maintain near-rigid corotation of an equatorial outwardly diffusing plasma, the angular momentum flux into the equatorial region must be constant, independent of distance. For radial mass fluxes corresponding to the Io source, it turns out that in the inner part of the torus, the required angular momentum flux can be supplied by ion–neutral collisions in the lower ionosphere for only minimal departures of the flow from rigid corotation. In this region, therefore, the plasma very nearly rigidly corotates with the planet outside the source region. However, with increasing distance from the planet a given area of the equatorial plane becomes connected via the magnetic field to a decreasing area of the ionosphere, which is located nearer to the rotation axis. Consequently, the ionospheric torque ultimately becomes small even for large departures from corotation. Thus beyond a certain radial distance, depending on the Io mass flux and the ion–neutral friction in the ionosphere, the azimuthal velocity is expected to break away from near-rigid corotation, to peak, and then to fall inversely with distance in the regime where the input of angular momentum becomes small. Voyager observations indicate that the flow is near to that expected for rigid corotation to equatorial distances of ~20 R_J, where the azimuthal flow speed is ~200 km s^{-1}, and falls below rigid corotation at larger equatorial distances. Voyager data for a relatively compressed magnetosphere indicate flows in the outer regions which do not fall with distance as then expected, but rather remain at values which are a factor of ~2 lower than rigid corotation speeds. When the magnetosphere is more extended during intervals of low solar wind dynamic pressure, however, the flow speeds in the outer regions are rather lower than this relative to rigid corotation, as indicated by data from both Pioneer 10 and Ulysses.

We should mention that, while in the above discussion we have described the input of angular momentum from the planet as being due to ion–neutral collisions in the lower ionosphere, this angular momentum is actually transmitted to the equatorial plasma via the bending of the field lines out of meridian planes which was shown in the inner part of figure 4(*a*), and whose current system is shown in figure 4(*b*). The ***j–B*** force associated with the radially outward current in the equatorial plane (into the diagram) acts to increase the speed of a sub-corotating equatorial plasma, while the ***j–B*** force of the closure currents in the ionosphere acts in the opposite direction as a drag force on the rotation of the thermosphere. The corotation of the thermosphere is maintained to the extent allowed by viscous coupling to the corotating denser atmosphere beneath.

Flows in the outer magnetospheric regions are exceedingly uncertain at the present time. Outbound Voyager 2 measurements established the existence of a layer of plasma adjacent to the dawn tail magnetopause at ~150 R_J which was flowing antisunward, opposite to

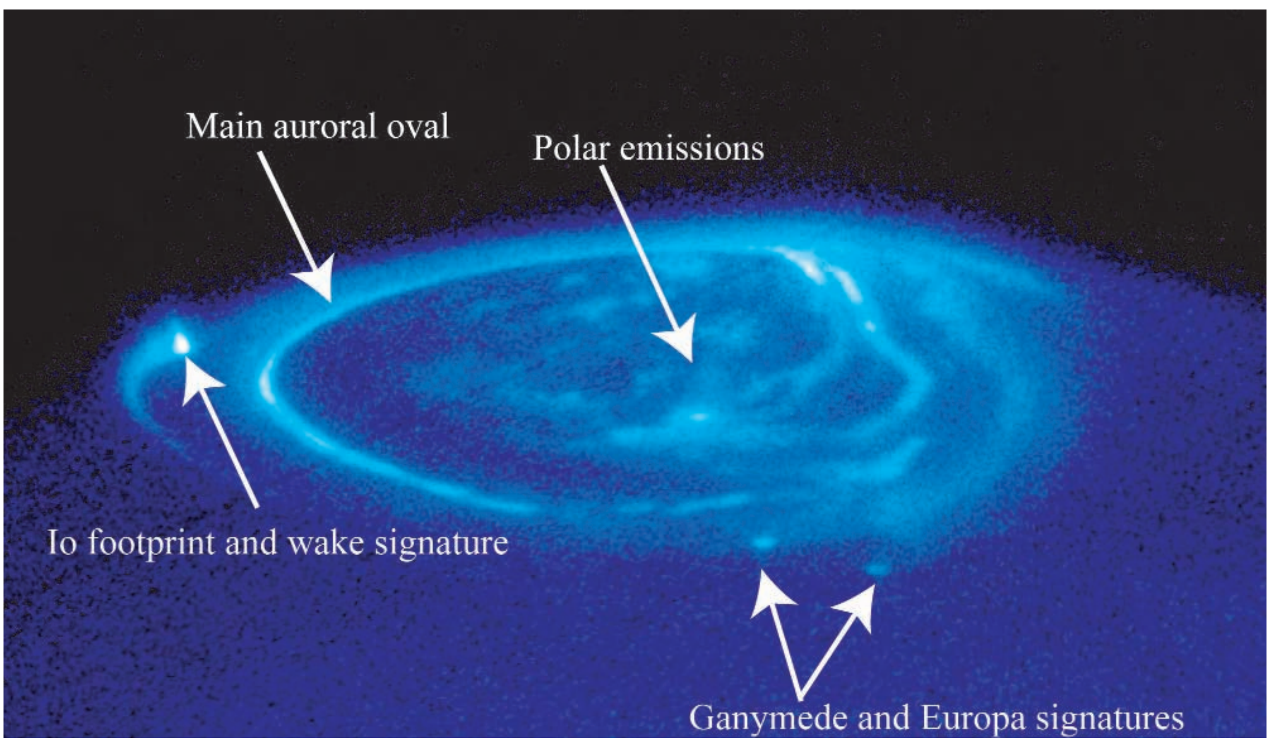

Figure 6. Ultraviolet image of the northern polar regions of Jupiter captured by the HST showing the main features of the auroral emissions as discussed in the text. Courtesy of John Clarke (University of Michigan) and NASA.

the direction of planetary rotation. The flow speed was ~500 km s^{-1} in a layer a few tens of R_J wide. The nature of the overall dynamics, however, concerning, e.g., the ultimate loss process for Io plasma, and the interaction between planetary and solar wind driven flows in the tail, are yet to be determined.

Jovian auroral emissions

Auroral emissions from the polar regions of Jupiter were first detected in the UV by two independent spacecraft missions: the International Ultra–Violet Explorer (1979) and the Voyager spacecraft (1979 and 1980). These particular emissions result from direct excitation of atmospheric species by collisions with precipitating energetic magnetospheric electrons (see JUPITER: ATMOSPHERE). Auroral features were subsequently observed at various other wavelengths including the infrared (thermal emissions) and near–infrared (particularly from ionospheric H^{3+} ions). The IR aurora is excited by particle heating, or from Joule heating by large–scale current systems closing in the ionosphere. The auroral regions have also been associated with strong x–ray signatures, and furthermore are powerful sources of radio emissions.

Since these early measurements, data of much higher spatial and temporal resolution have become available both at visible wavelengths from the SSI instrument on the Galileo spacecraft, in the UV from the HUBBLE SPACE TELESCOPE (HST), in the infrared from Earth–based telescopes, as well as x–ray emissions from the CHANDRA x–ray observatory. These observations show that there are perhaps four main types of auroral emission. First is the Io footprint (IFT) emission, a ~1 MR emission which maps magnetically to the vicinity of the moon. There is also an auroral 'tail' stretching downstream of the IFT in the near–corotating flow. The Io related emissions are thus quite distinct from the other jovian auroral emissions, and are clearly visible in figure 6. It is understood that the corotational electric field which is developed by the relative motion between Io and the near–corotating magnetic field lines flowing past the satellite induces a potential difference of approximately 500 kV between the outer and inner faces of the moon. This potential is thoght to cause currents to flow from Io toward the ionosphere, both northward and southward, along the outer portion of the magnetic flux tube linking the satellite to the ionosphere. Return currents then flow along the inner portions of the flux tube towards Io. This circuit closed through the jovian ionosphere and also in the ionosphere of the moon, and is associated with the Io–controlled decametric radio emissions (see JUPITER: RADIO EMISSIONS). This 'unipolar inductor' model explains the spot of aurora associated with the upward directed portion of the current system (implying downward flowing electrons), i.e. the IFT, but does not explain the existence of the 'tail' of auroral brightness downstream of Io by as much as ~180°. However, recent work by Hill and Vasyliunas (2002) associates this downstream wake signature with the plasma currents which are required to accelerate the newly injected plasma from Io up to approximate corotation with Jupiter. Recent images indicate that footprint and wake auroras are also associated with Europa and Ganymede, and it seems likely that these features are due to the same downtail mass–loss process.

The second auroral component is the main auroral oval (MAO), which has been the subject of a plethora of reports recently. The MAO is the most significant emission in terms of energy output, and takes the form of circumpolar bands around both the northern and southern magnetic poles, consistently observed in all the wavebands mentioned above. Although this emission is of variable width (on average ~500–1000 km) and intensity (up to a few MR), it appears to be essentially continuous in local time, at dipole co–latitudes of ~16°, closer to the pole than the Io flux tube. It has been known for some time that this auroral region maps magnetically to the middle magnetosphere. Recently it has been suggested to be associated with the current system which maintains corotation of the equatorial plasma in the middle magnetosphere. Specifically the MAO is thought to be associated with the upward–directed field–aligned current at the inner edge of the magnetosphere–ionosphere coupling current circuit shown in figure 4(*a*). The former of the models cited above proposes an empirical model of the aurora, using estimates of the angular velocity of the plasma in the equatorial plane and a suitable magnetic field model. An interesting consequence of this model is that one would then expect the auroral brightness to anti–correlate with the dynamic pressure of the upstream solar wind. As the magnetosphere contracts, the angular velocity increases due to conservation of angular momentum, the currents go down and the aurora dims; conversely as the magnetosphere expands, the angular velocity decreases, the currents go up and the aurora brightens. It is thought that the hectometric radio emissions would also follow this modulation, although recent observations show that at least part of this radio emission exhibits impulsive increases which correlate positively with shocks in the solar wind.

The third component of the aurora is the high latitude diffuse emissions, which occur regularly and have a brightness of a few x 100 kR. These polar cap auroras are generally extended across the dusk side of the polar cap poleward of the MAO. At this time, a production mechanism for these emissions has not been suggested. More recent papers have also discussed a fourth feature which is seemingly a regular occurrence in the auroral regions. This feature appears consistently near magnetic local noon, and is reminiscent of the Earth's polar cusp. This is referred to as a 'cusp–like' feature, which was reported by to be rapidly evolving, very bright (up to ~40 MR) and localised near noon. This feature lies poleward of the MAO and therefore it is conjectured that it may be controlled by pressure and/or magnetic field changes in the upstream solar wind. However, the intensity of this feature requires some form of acceleration mechanism, and could not be obtained simply by solar–wind particles flowing along open field lines (in the conventional 'cusp–like' sense).

The recent fly–by of Jupiter by the Cassini spacecraft en–route to Saturn (December, 2001), along with an intense HST campaign to complement Earth–based telescope observations, may help to unravel the response of the auroral regions to the upstream solar wind conditions monitored by Cassini.

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