

4C65/SS109/4680 Handout - Solar Wind Interaction with Other Bodies (Examinable)

Other Planetary Magnetospheres

The basic solar wind – magnetosphere interactions described earlier in the course occur at every magnetized planet. Hence Mercury, Jupiter, Saturn, Neptune and Uranus each have a bow shock and a magnetospheric cavity. The main difference is in the size of each magnetosphere (illustrated in Figure 23), which is a function of the strength of the planetary dipole moment and the solar wind parameters at the planets orbit. However, each planet has one or more unique and significant distinguishing features, which make them interesting to magnetospheric physicists in their own right. For example, Mercury has no ionosphere and an insulating regolith, yet still seems to show evidence of substorm type activity, even though there can be only limited flow of field-aligned currents to the planet. As we have seen, field aligned currents play a key role in substorm dynamics at the Earth. Jupiter's magnetosphere is the largest in the solar system, and strong centrifugal forces associated with the rapid rotation of the planet cause significant distortions in the inner magnetosphere. In addition, the moon Io is a significant internal source of magnetospheric plasma, which forms a *plasma torus* about the planet adding an extra feature to the magnetospheric dynamics. Neptune and Uranus have dipole axes which have significant tilts away from the rotation axes. Also at Uranus the rotation axis lies close to the ecliptic plane. Consequently these two gas giants have times when the dipole axis points directly into the solar wind, which may have direct access to the planet down the funnel of the magnetic cusps.

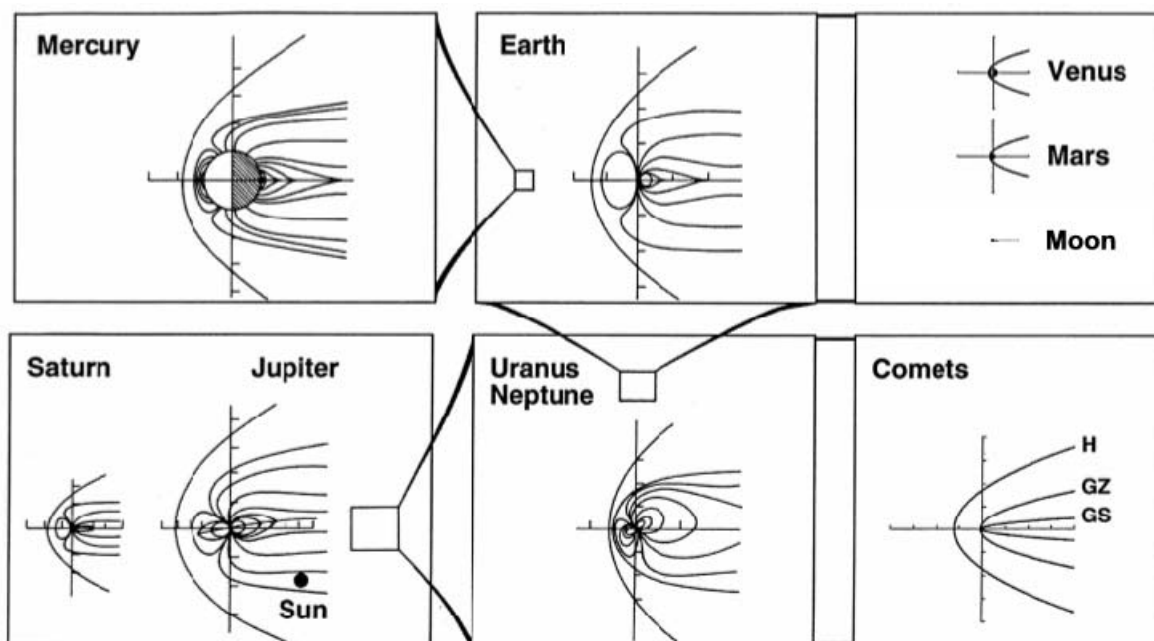


Figure 23. Comparison of the sizes of the magnetospheres of the magnetized planets (left 4 panels), the solar wind disturbances caused by some non-magnetized bodies (Venus, Mars and the Moon in the upper right panel) and comets (bottom right panel, H = Halley, GZ = Giacobini-Zinner, GS = Grieg-Skellerup).

Solar Wind - Ionosphere Interaction

Venus has no significant magnetic field, but has a very thick atmosphere. The intensity of sunlight at Venus orbit leads to high levels of photo-ionization, resulting in a dense ionospheric plasma. This plasma constitutes a conducting obstacle to the solar wind flow

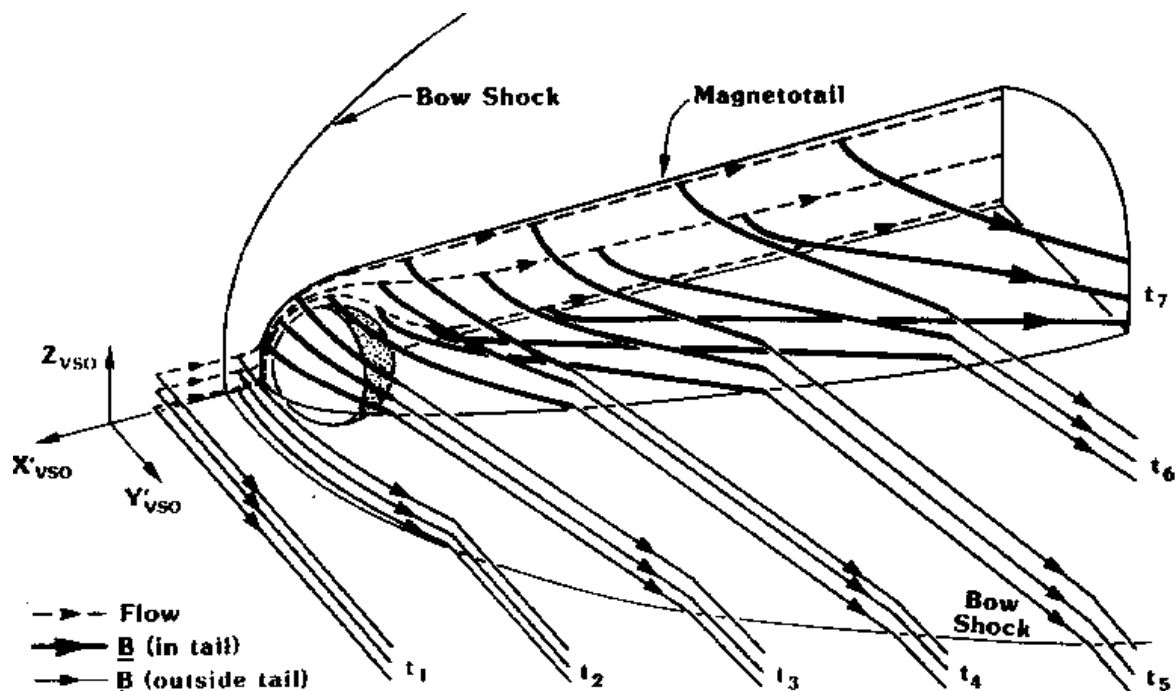


Figure 24. Formation of an induced magnetic tail at Venus, which has no intrinsic magnetic field but a dense ionosphere. IMF field lines passing close to the planet are mass-loaded, and thereby slowed, by newly-ionized particles from the planetary atmosphere. Parts of the field lines further from the planet continue at the solar wind flow speed, such that the magnetic field forms a tail-like structure. [Saunders and Russell, 1986]

(Figure 8.5 from K&R, reproduced overleaf). The solar wind and IMF are frozen out of the cavity occupied by the ionospheric plasma. Thus there is a bow shock upstream of Venus that acts to slow and deflect the solar wind and a magnetosheath between the topside of the ionosphere and bow shock, where the flow is subsonic. The obstacle to the flow presented by Venus's ionosphere is of course much smaller than the obstacle presented by Earth's magnetosphere (even though the two planets are similar sized bodies). The boundary between solar wind and ionospheric plasma, the *ionopause*, is located at the point where the solar wind dynamic pressure is balanced by the thermal pressure of the Venus ionospheric plasma (Figure 8.7 from K&R, reproduced overleaf). Note however that a small fraction of neutral particles from the atmosphere may reach altitudes above the ionopause, before they are photo-ionized. These newly created ions are 'picked-up' in the flowing magnetosheath plasma, and rapidly travel downstream from Venus. This process thus removes ions of planetary origin from above the ionopause, and is termed 'scavenging' (Figure 8.11 from K&R, reproduced overleaf). However, the pick-up process causes a *mass-loading* of the IMF field lines in the vicinity of the planet. Hence the solar wind is further slowed in this region since the solar wind momentum must be shared with the new ions. Since the more distant portions of the field line are unaffected by this process, these sections continue at the undisturbed solar wind speed. This has the effect of draping the IMF field lines over the ionospheric obstacle, thus creating an induced magnetotail structure in the region downstream from the planet (Figure 24).

Insulator Bodies (e.g. The Moon)

The Moon is a non-conducting body, and with the exception of some isolated areas of weak remnant magnetism, it has no significant magnetic field. Thus there are no processes which act to deflect solar wind plasma from the Moon. The solar wind impinges directly on the

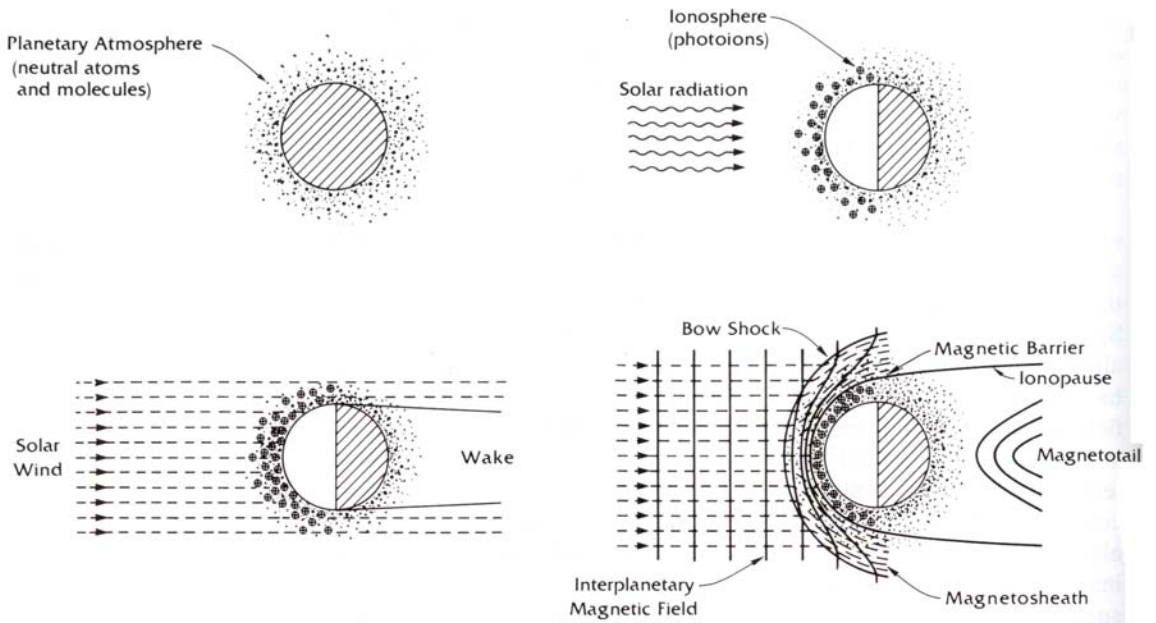


FIG. 8.5. Illustration of the steps that lead to the formation of an ionospheric planetary obstacle in a flowing plasma like the solar wind. Ionization by solar radiation, for example, is followed by diversion of the external plasma flow only if that flow is magnetized.

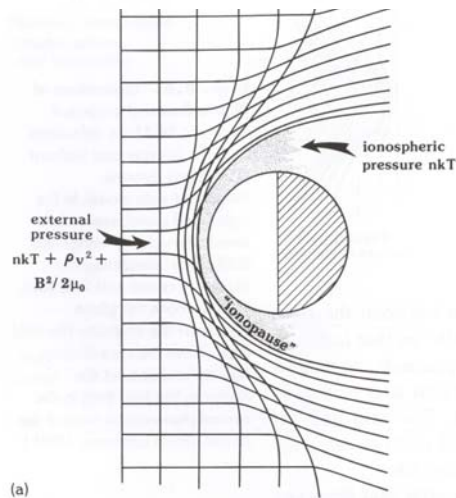


FIG. 8.7. Illustration of pressure balance between the solar wind and the thermal pressure of the ionosphere, which determines the height of the ionopause. The observed variability of the solar-wind pressure is indicated by the histogram on the right. ((a) From Luhmann, 1986; (b) and (c) from Luhmann et al. 1987.)

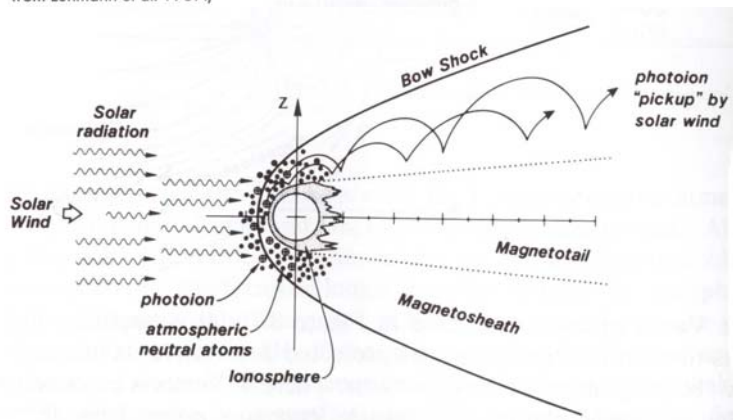


FIG. 8.11. Illustration of planetary pickup-ion trajectories at Venus. The cycloid sizes are approximately scaled for O^+ (oxygen is the main constituent of the Venus upper atmosphere, as shown in Figure 8.10).

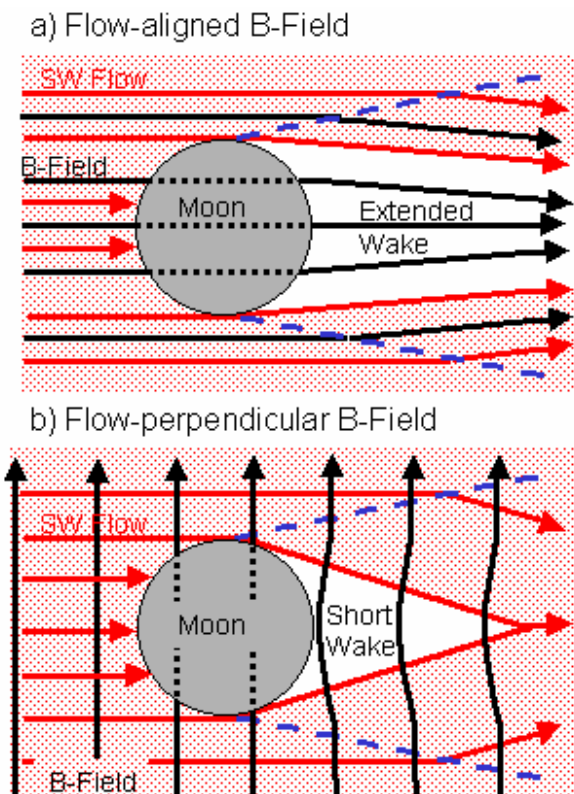


Figure 25. Solar wind interaction with the Moon, an insulating body with no intrinsic magnetic field and no significant ionosphere. The solar wind impinges directly on the sunlight surface, while the IMF passes through the Moon almost unaffected. The extent of the wake region downstream of the Moon depends on the relative orientation of the IMF to the flow: a) For a flow -aligned field, the solar wind plasma cannot easily convect perpendicular to the field so the wake is extended; b) for an IMF perpendicular to the flow, the solar wind plasma quickly fills in the wake as it may move readily along the field direction.

when the field is near-perpendicular to the flow, the wake will fill in relatively quickly (Figure 25b).

Note that the Moon does have small regions of remnant surface magnetization, perhaps formed during meteor impacts in the past. These have recently been shown to form mini-magnetospheres, which cause a small deflection in the solar wind near the surface. Note also that the moon spends part of its orbit inside the terrestrial magnetosphere, such that its interaction at these times is with the various magnetospheric fields and plasma populations discussed above, rather than the solar wind.

Comets

A comet nucleus is a relatively small body (~ a few 10's of kilometers in size) made up predominantly of volatile materials such as water ice. The comet spends most of the time far from the sun, where this material remains mostly inert. However near orbit perigee, when the comet passes rapidly close to the Sun, some of the volatiles are sufficiently heated to be

lunar surface at supersonic speeds. There is no bow shock or magnetospheric or ionospheric cavity. The particles are absorbed at the surface such that lunar soil must contain a record of the ancient solar wind, although spluttering of lunar material following impact may also result in a scavenging process by the solar wind.

Conversely, the lunar surface and interior conductivity are thought to be very small, so the magnetic diffusion time for magnetic fields through the Moon is very small. Thus the IMF passes through the Moon virtually unaffected. This magnetic flux emerges from the nightside of the moon into a plasma-free lunar wake in the downstream region. Close to the moon this wake has the same cross section as the moon, but this fills in as solar wind plasma which missed the Moon flows along the field lines into the void. The length of the wake thus depends on the ratio of the solar wind flow speed to thermal speed, since the latter is the characteristic filling speed (a hotter plasma will migrate along the field more quickly to fill up the depleted wake). It also depends strongly on the magnetic field configuration. During periods when the field is closely aligned with the flow, the plasma needs to migrate across the field to fill in the wake, and we have seen this is not easy for a high-conductivity plasma. Thus an extended wake persists (Figure 25a). Conversely,

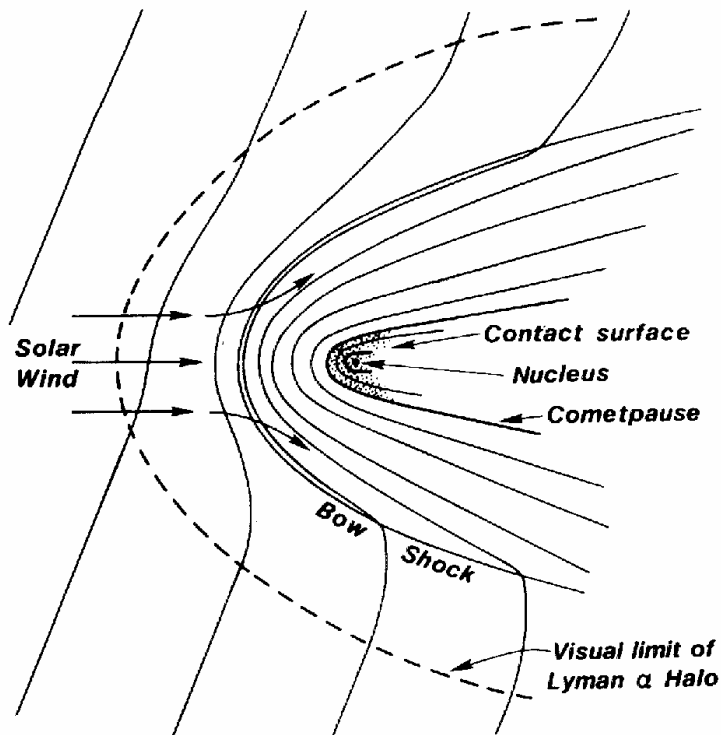


Figure 26. Solar wind interaction with a comet. Mass-loading of IMF field lines by newly-ionized outgassing cometary material acts to slow the solar wind flow in the vicinity of the comet. Since the IMF is frozen to the solar wind flow, this slowing induces a cometary magnetic tail downstream of the coma. [Luhmann, 1991]

released as neutral atoms, which form a vast ($\sim 10^6$ km) gas cloud, or coma, around the nucleus. The solar wind does not interact significantly with the neutral atoms, or with the nucleus. However, atoms in the gas cloud are photo-ionized to form cometary (water group) ions. These heavy ions are picked up in the solar wind. More ions are picked up where the gas cloud is denser (i.e. nearer the nucleus) and, as at Venus, the momentum associated with the solar wind must be shared with the additional mass of cometary plasma. Thus a solar wind flux tube which passes through the cometary plasma will be retarded in the vicinity of the comet by this mass-loading process. The IMF field lines are draped around the nucleus and thus create an induced magnetotail downstream from the comet (Figure 26). Note that two other plasma boundaries are often defined for the solar wind comet interaction. The contact surface

defines the region from which the solar wind is effectively excluded by a balance of the solar wind dynamic pressure with that of the outflowing cometary plasma. The cometopause defines the region beyond the contact surface in which the plasma is predominantly of cometary origin.

(Taken from 'Space Plasma Physics – A Primer', C.J. Owen, MSSL Book, Imperial College Press, 2004 and Kivelson and Russell, Chapter 8)