ESS 200C
Lecture 16
The Solar Wind Interaction with Unmagnetized Bodies
- To be an obstacle to the solar wind a body must be conducting.
- Imagine a planet with an atmosphere.
  - In sunlight some of the neutral atoms and molecules can be ionized.
  - If the solar wind is magnetized currents can be generated in the ionosphere that will keep the magnetic field from penetrating the planet.
• Venus
  – The main constituent of the Venus’ atmosphere is carbon dioxide.
  – Venus’ lower atmosphere is warmer than Earth’s because of the greenhouse effect, the upper atmosphere is much colder because of the absence of heating by the magnetosphere.
  – Scale height of Venus’ atmosphere is small being only a few kilometers on the night (cold) side.
    - Atmospheric density falls off with height according to the equation of hydrostatic equilibrium that balances the upward pressure gradient with the downward force of gravity.
      \[ nmg = -d(nkT)/dh \]
      where \( n \) is the number density of molecules, \( m \) is their mass, \( g \) is the force of gravity, \( k \) is Boltzman’s constant, \( T \) is the temperature of the gas and \( h \) is the height.
    - For an isothermal atmosphere the density decreases as
      \[ n = n_0 \exp(-h/H_n) \]
      where \( H_n = kT/mg \).
    - This isothermal description fails at the highest altitudes. For instance atomic oxygen has a cold component with a scale height of km and a hot component with a scale height of 100’s of km.
– The upper atmosphere is partially ionized by solar ultraviolet radiation.

- The rate of ionization decreases rapidly with decreasing altitude at low altitudes where ionizing radiation is absorbed.
- The rate of ionization decreases with increasing altitude at high altitudes where the number of neutral particles decreases.
- There is a maximum ion production rate at some altitude \( h_m \).
- The rate of ionization, \( Q \), varies with altitude for a simple one-component isothermal ionosphere as
  \[
  Q = Q_m \exp[1 - y - \exp(-y)]
  \]
  where \( Q_m \) is the peak production rate and \( y = (h - h_m)/H_n \) with \( H_n \) is the neutral scale height and \( h_m \) the height of peak production.

- The rate of recombination of electrons and ions is proportional to the product of the electron and ion number densities (provided there is no vertical transport).
  \[
  N_e = N_{m0} \left\{1 - z - \sec \chi \exp(-z)\right\}/2
  \]
  where \( \chi \) is the solar zenith angle and the density have been referenced to the maximum density at the subsolar point, \( N_{m0} \), \( z \) to its altitude, \( h_{m0} \), and the scale height, \( H_n \).
- The Chapman layer ionosphere of Venus.
  - Top – UV radiation drops as it is absorbed in the photoionization process.
  - Middle – The rate of electron production versus altitude.
  - Bottom - The electron density profile.
- The high altitude electron temperature is about 5000K.
- The peak of the density is at about ~140 km and the density is ~10^6 cm^-3. At 400 km the density is ~20000 cm^-3 under solar maximum conditions.
- In general the solar wind plasma doesn’t penetrate below about 400 km.
- At Venus’ the solar wind is supermagnetosonic.
- A bow shock forms upstream of Venus.
  - At solar maximum the shock front is about 2000 km above the subsolar point.
  - At solar minimum the typical ionosphere doesn’t completely hold off the solar wind.
- Downstream of the shock the velocity of the solar wind drops drastically.
- The IMF is compressed near the stagnation point and the field drapes around the obstacle.
- In the compressed region the thermal velocity of the plasma empties the field lines and a magnetic barrier results.
– The magnetic barrier has the effect of confining the ionosphere to regions close to Venus.
– The boundary is called the ionopause.
  - Ionospheric plasma is not detected above the barrier because the ions produced there are immediately removed by the interplanetary magnetic field.
  - The ionopause nominally forms where solar wind dynamic pressure ($\rho v^2$) equals the ionospheric thermal pressure ($n k T$).
– Examples of observed altitude profiles for ionospheric electron densities (points) and magnetic fields (solid line). The ionopause is where the magnetosheath field decreases and the plasma density increases.

\[ N_e \text{ (cm}^{-3}\text{)} \]

\[ \text{ALTITUDE (km)} \]

\[ \text{IBI (nT)} \]
When the solar wind pressure increases the ionopause moves closer to Venus.

When the boundary layer is close to Venus it thickens and a large-scale magnetic field appears inside of the ionosphere.

These penetrating magnetic fields have roughly the same orientation as the IMF and can be thought of as IMF field that is not completely shielded by the ionospheric currents.
- The currents at the ionopause are very good at excluding the magnetic field from the ionosphere but some gets through.

- The spikes in the magnetic field are “magnetic flux ropes”.
  - Flux ropes are untwisted at high altitudes.
  - They become twisted as they sink toward the planet. A flux rope is thought to arise as the structure sinks through a vertical shear in the horizontal flow.

- When the solar wind pressure increases the ionopause moves toward Venus.
  - At low altitudes some field diffuses into the ionosphere.
  - The inward diffusion on the dayside is matched by outward diffusion at night.
– The “flux ropes” tend to become “force free” structures. \[ \vec{F} = -\nabla P + \vec{J} \times \vec{B} = 0 \]

- The currents in the flux rope tend be along the magnetic field so that \( \vec{J} \times \vec{B} = 0 \)
- This means that pressure gradient forces are not important.
– The downward magnetic flux on the dayside is balanced by upward magnetic flux at night.

- Since magnetic field lines in the ionosphere have their ends in the solar wind those on the night side are far from Venus and the field is mainly radial.

- These regions appear as “holes” to a plasma detector.

– When the dayside “magnetosphere” becomes completely magnetized the plasma to the nightside is cut off and the “ionosphere vanishes”.

- A similar phenomenon occurs at solar minimum when the dayside solar wind pressure is higher than the typical solar wind pressure.
• Comets
  – Gas sublimed from comets is ionized in the solar wind. Conservation of momentum causes the solar wind to slow down.
  – This also happens at Venus but the effect is less dramatic.
    - Venus’ large size keeps the atmospheric gas from expanding rapidly.
    - Venus does have a neutral oxygen exosphere formed by dissociative recombination of $O_2^+$ in which ions recombine with an electron to form two suprathermal oxygen atoms.
    - These oxygen atoms can get to high altitudes where if reionized they will be carried away by the solar wind.
  – Solar wind field lines are slowed down near Venus but their ends in the solar wind keep on moving rapidly producing a long comet like induced tail. (These ions have been detected at Earth!)
When comets are near the Sun they have huge atmospheres compared to their small bodies.

- Gases from the comet are ionized and added to the solar wind. This process is called “mass loading”.
- Mass loading can be thought of as adding source terms to the MHD equations.
- The production function for a comet is a combination of two effects: an inverse-square dependence due to the spherical expansion of the outflowing gas in vacuum and an exponential decay due to the loss of gas to ionization processes like photoionization.

\[ Q = \frac{Q_0}{r^2} \exp \left( -\frac{r}{u\tau} \right) \]

where \( u \) is the neutral gas outflow velocity, \( r \) is the distance from the nucleus and \( \tau \) is the ionization time.

- At Venus (and Mars) the mass-loaded solar wind plasma is confined to the low-altitude magnetosheath because of gravitational effects.
- At comets the gas flows away at about 1 km s\(^{-1}\) creating a planet sized cavity.
The cavity is formed by the pressure of the outflowing plasma instead of by the ionospheric thermal pressure and magnetic pressure. The boundary is called the “contact surface”.

- However, the plasma is mass loaded and slowed down well away from the contact surface because there is so much neutral atmosphere outside the boundary.

- Because of this mass loading much of the plasma interacting with the comet is of cometary origin. The boundary where the composition of the solar wind plasma changes is called the “cometopause”.

- The figure on the left shows a cartoon of the regions of a cometary system while the figure on the right shows a simulation of the magnetic field around the comet.
– Cometary tail disconnection events.
  - When a comet crosses the heliospheric current sheet the tail can disconnect and be lost.
In this simulation the loss of the tail is caused by reconnection associated with the reversal of the interplanetary magnetic field during a heliospheric current sheet crossing.
• The moon
  - A body like our moon composed of insulating material and embedded in a flowing plasma absorbs the plasma particles that hit it.
    • The lunar soil contains a record of the solar wind.
    • There is no bow shock at the moon because there is no obstacle to the flow.
    • The magnetic field diffuses into the outer layers of the moon quickly.
    • If the flow is slow compared to the thermal speed a short wake forms behind the obstacle.
    • If there is no magnetic field (or the flow is parallel to the magnetic field) and the flow speed is large compared to the thermal velocity a wake will persist to large distances.
    • For perpendicular flow the wake will be shorter.