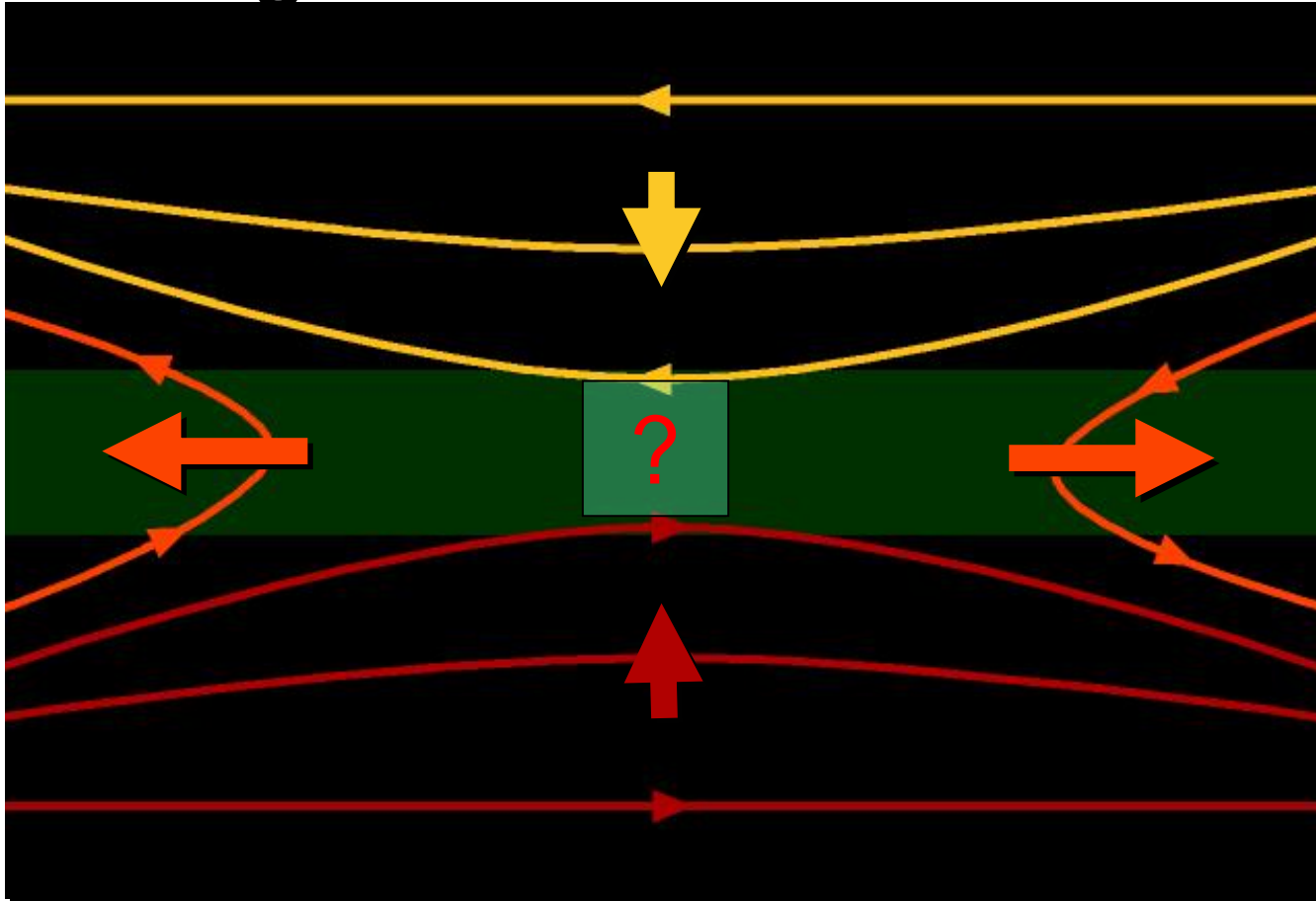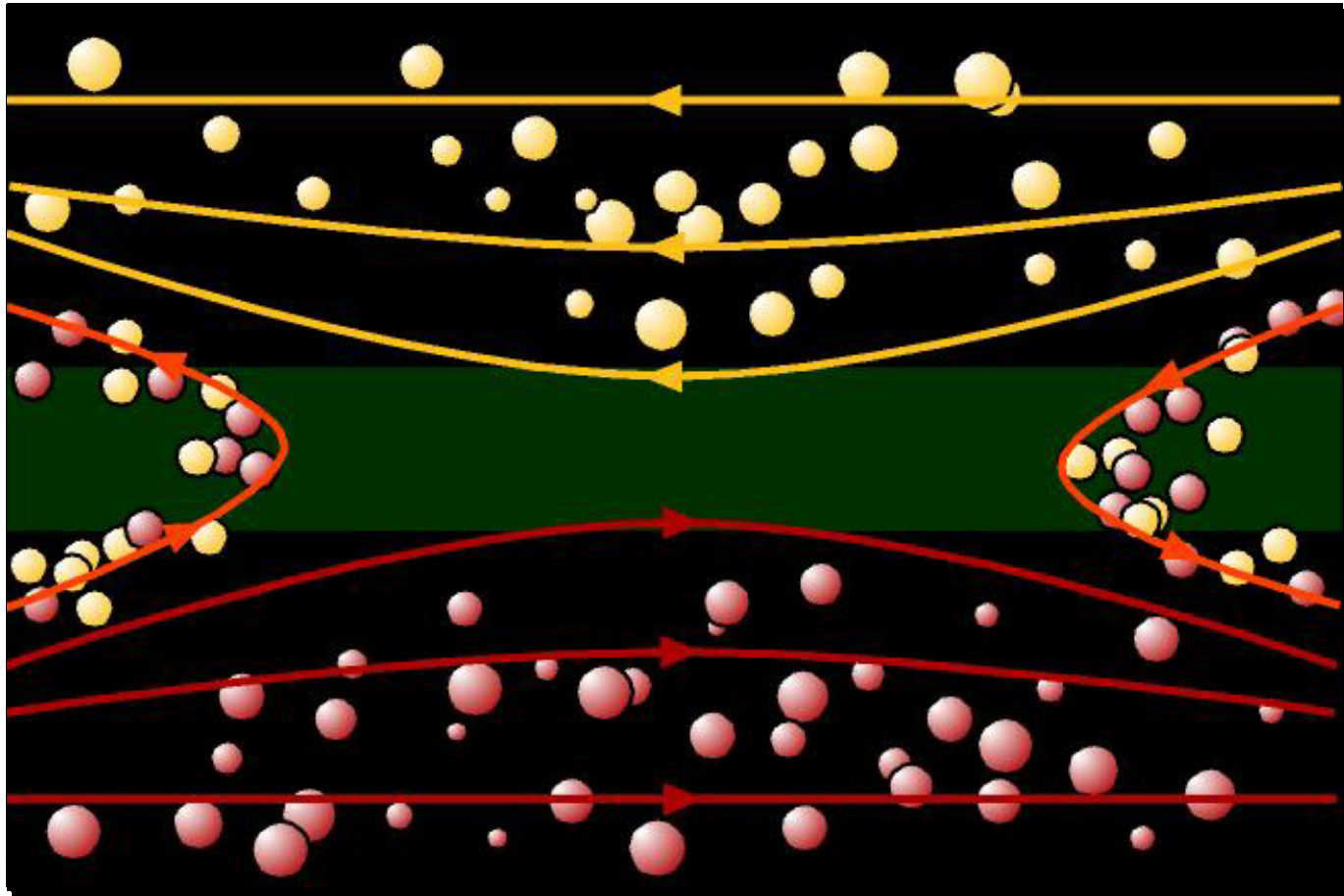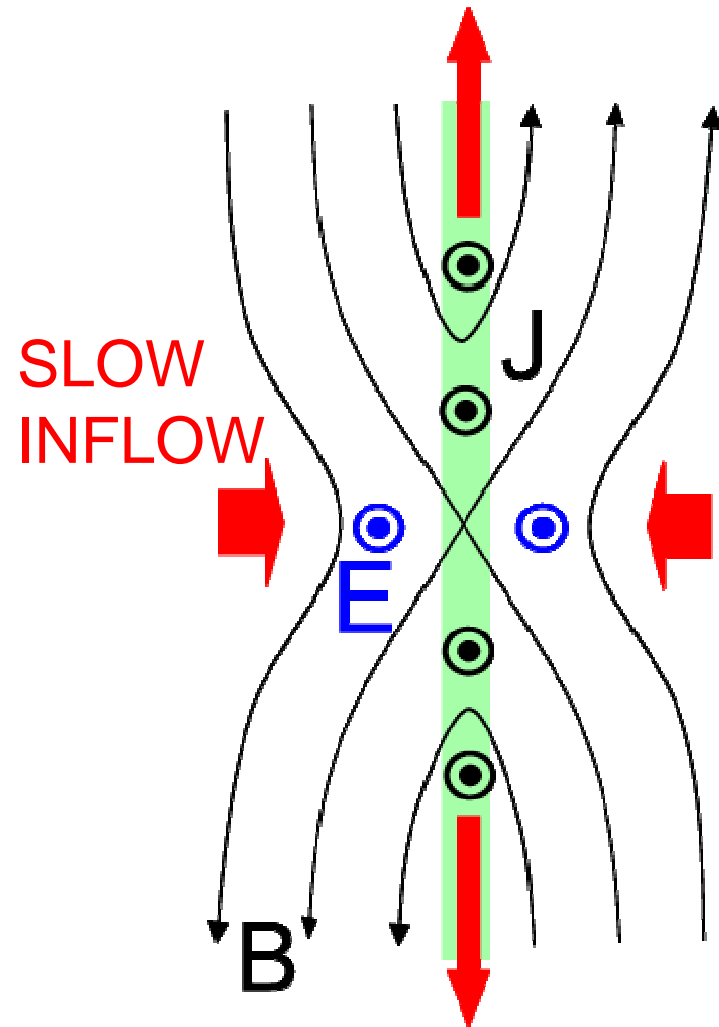# Magnetic Reconnection

On small scale-lengths (i.e. at sharp gradients), a diffusion region (physics unknown) can form where the magnetic field can diffuse through the plasma (i.e. a breakdown of the frozen-in principle).

Magnetic Reconnection – Mixing of Plasma Populations
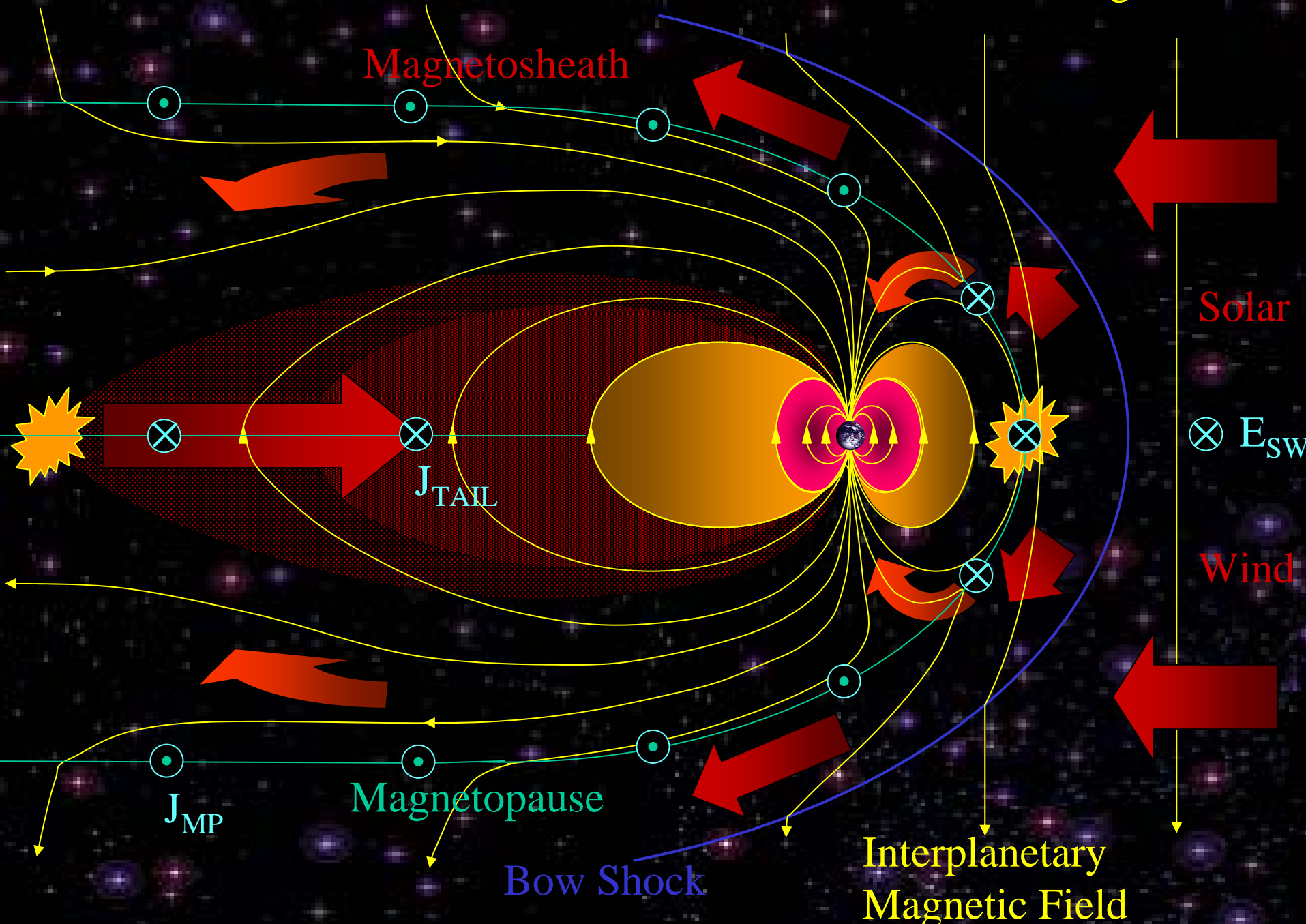
Magnetic Reconnection – Key Points

FAST OUTFLOW JET

SLOW
INFLOW

J

E

B

Application of strict frozen-in flow implied that magnetic field and plasma from different sources could not mix;

- However, the frozen-in flow approximation is not always valid where gradients are sharp;
- Reconnection allows:
  1. Magnetic field regions that were previously independent to interact;
  2. The plasma populating the magnetic fields to intermix;
  3. Plasma is accelerated into jets as magnetic energy is released.

Formation of the Magnetotail

Magnetosheath

Solar

E_{SW}

Wind

J_{TAIL}

J_{MP}

Magnetopause

Bow Shock

Interplanetary
Magnetic Field

Southward IMF (opposite to B_{EARTH} at Equator)

Reconnection at or near dayside subsolar magnetopause

Open magnetic field lines

Solar wind plasma can enter magnetosphere along open field.

Reconnection plasma jets ($\mathbf{J.E} > 0$)

Foot dragged slowly through the ionosphere

Open field lines unwind over poles, stretched out along tail magnetopause and added to tail ($\mathbf{J.E} < 0$)

Solar wind mass, momentum and energy transferred to magnetopshere (and ionosphere), stored as magnetic energy in magnetotail.

Reconnection between open lobe field lines at cross-tail current sheet

Closed magnetic field lines

IMF magnetic field lines

Convects back to dayside

Reconnection plasma jets ($\mathbf{J.E} > 0$)

Convects back to solar wind

Steady State Magnetospheric Convection in an Open Magnetosphere - Plasma Circulation

When the IMF has a southward component, conditions are favourable for magnetic reconnection to occur at or near the subsolar magnetopause. If reconnection occurs, the newly 'open' field lines have one end in the solar wind and the other in the ionosphere, and are highly kinked as they pass through the magnetopause – they thus experience a large magnetic tension force which acts to try to straighten them out.

The exterior end of the field line is frozen into the solar wind, which continues to flow rapidly tailwards, while the ionosphere end moves more slowly through the ionosphere. In order to move the ionospheric foot, momentum is transferred from the solar wind plasma to the ionospheric plasma, both to move the foot, and to move surrounding ionospheric plasma out of the way. As the kink at the magnetopause straightens out, the open magnetospheric field line moves through the cusp region and over the magnetic pole. Solar wind plasma may enter the magnetosphere along the newly opened field line, and is accelerated as it does so (magnetic energy is liberated to the plasma, **j.E** > 0 on the dayside part of the magnetopause)

The difference in speed between the solar wind end and the ionospheric end now causes a new kink at the magnetopause, angled in the other direction. Now the tension force opposes (but cannot prevent) the stretching of the field line as the solar wind carries the exterior end away. The open field line ends up stretched out along the magnetic tail. The solar wind flow is now doing work on the magnetic field (**j.E** < 0 on the tail magnetopause, such that solar wind energy is tapped and stored as magnetic field energy in the two tail lobes).

The open field lines laid down in the tail lobes cause a considerable inwards pressure, creating the conditions for reconnection at the internal tail current sheet (the boundary between the North and South tail lobes). Reconnection occurs there, taking two open field lines, and creating a closed field line and an unattached field line. Again these are sharply kinked, and due to the tension force they rapidly move away from the reconnection site on both sides as they become less curved. Here the magnetic energy stored in the lobes is again released to the plasma (**j.E** > 0 in the tail current sheet) which jets away from the reconnection site on both sides.
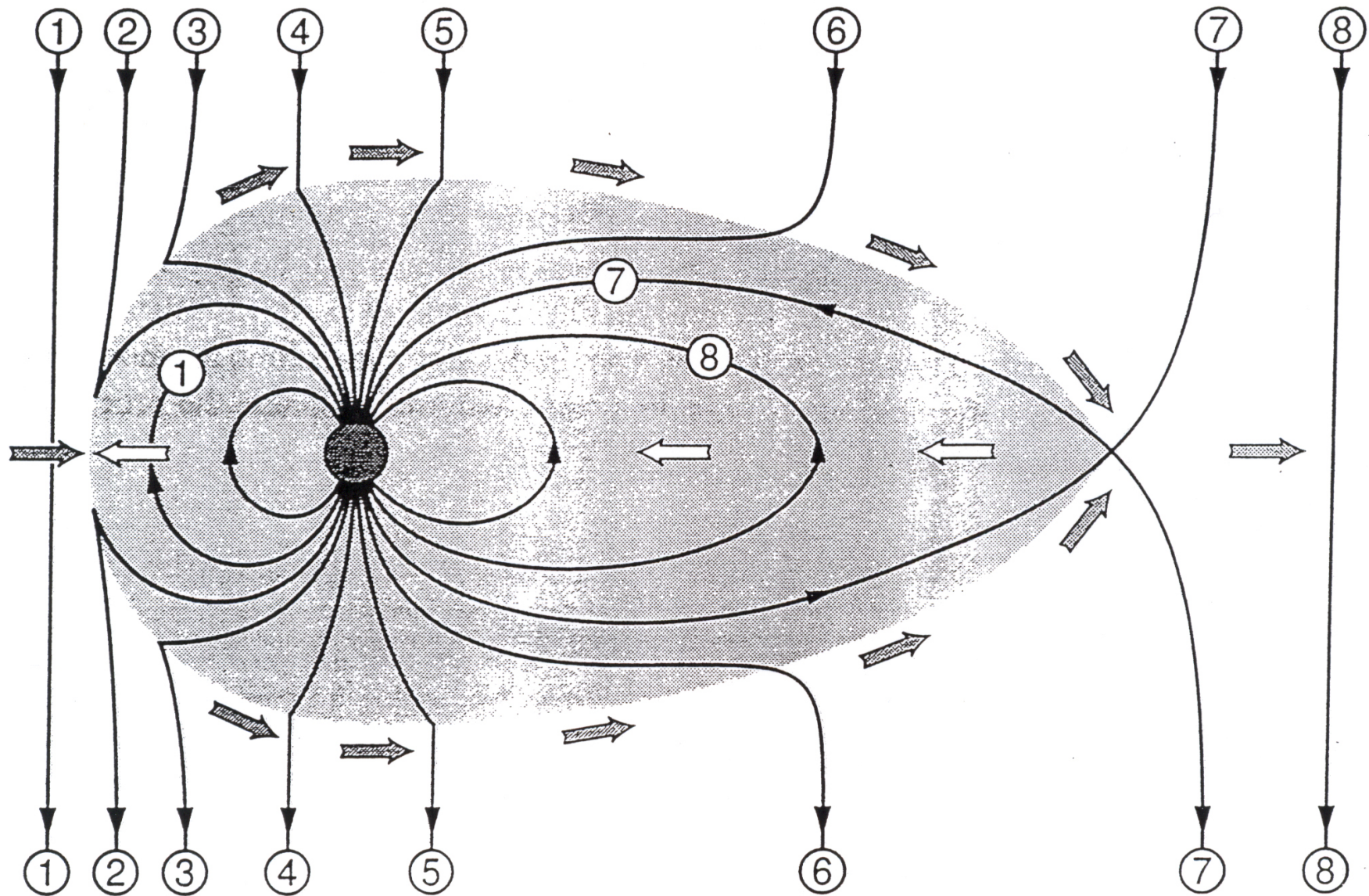
The newly detached field line rejoins the solar wind flow, gradually straightening up and losing the mark of its encounter with the magnetosphere. The closed field line contracts and moves sunwards, back towards the planet. Within the near-Earth magnetosphere there is a plasma circulation which has the net effect of letting closed field lines from the flanks move around to the dayside to replace closed field lines that are opened by dayside reconnection, while newly closed field lines from the tail move up to replace the field lines on the flanks. In a steady state, the rate of dayside and tail reconnection is in balance and a net circulation of plasma and magnetic flux is maintained within the magnetosphere.
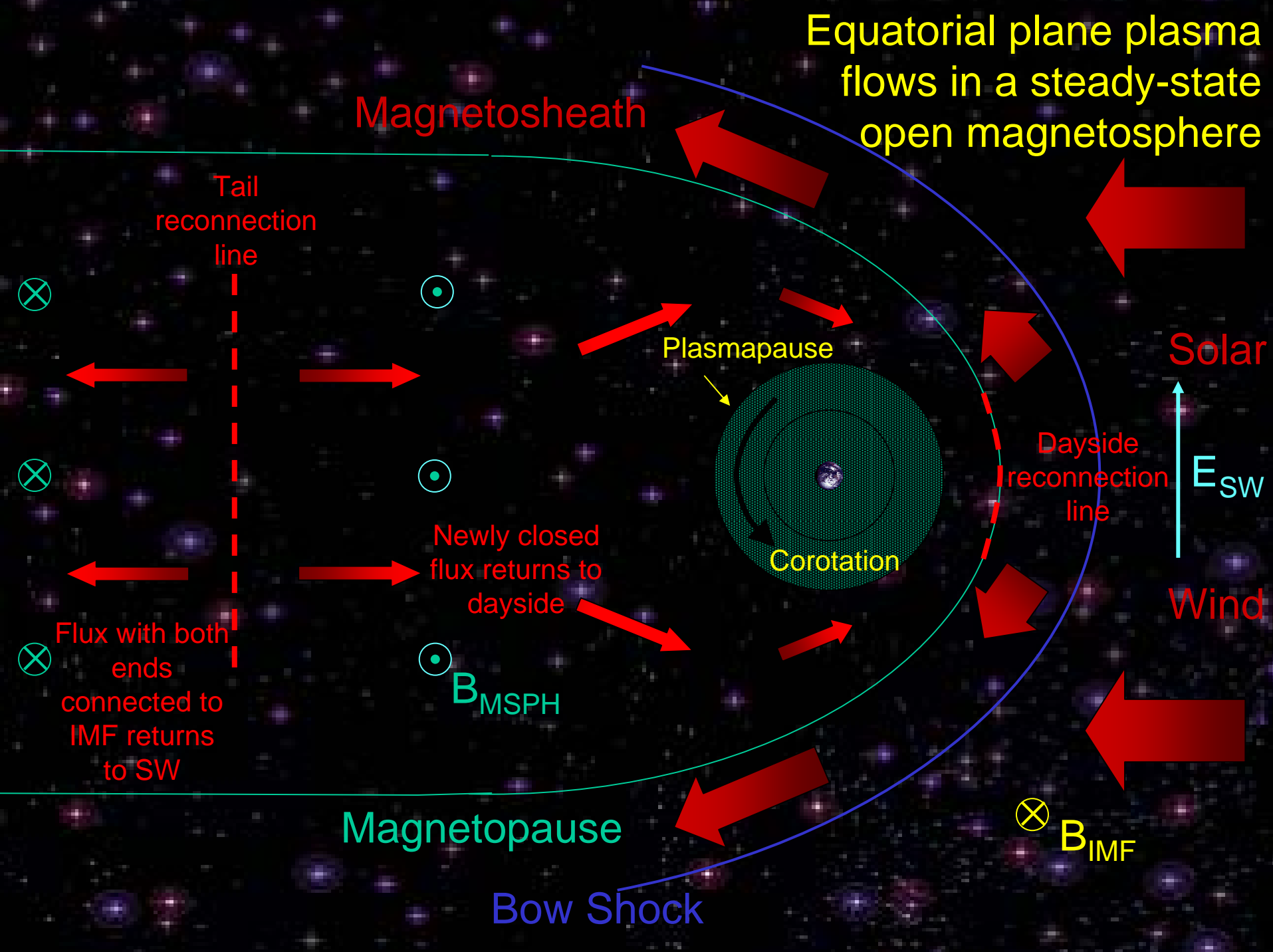
Following Reconnection:

On the magnetopause and in the tail current sheets:
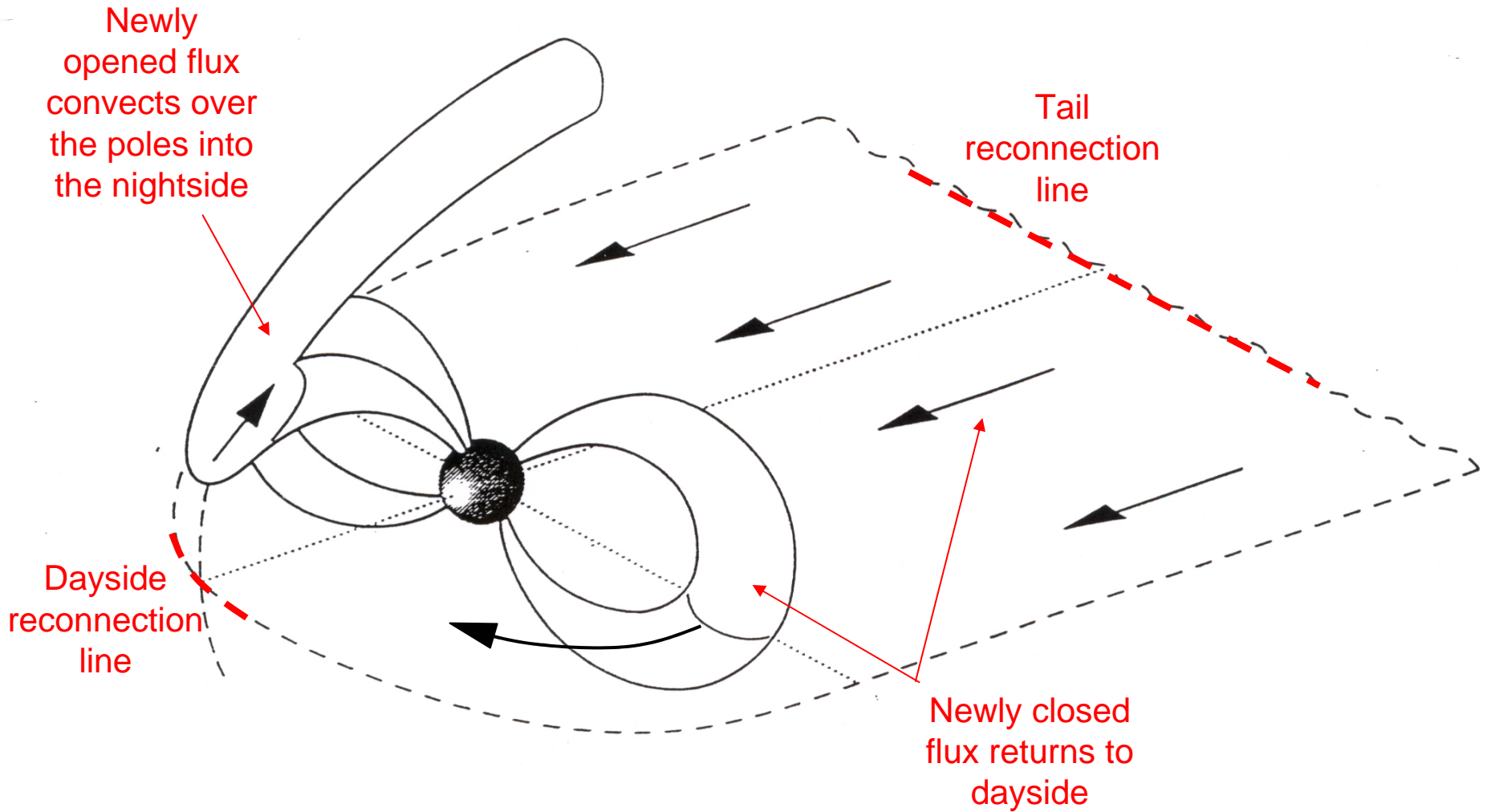
- If **j.E** > 0 (current parallel to E-field), B-field is doing work on the plasma, magnetic energy $\Rightarrow$ plasma energy, field 'unkinks', plasma heated and accelerated;

- If **j.E** < 0 (current anti-parallel to E-field), plasma is doing work on the B-field, plasma energy $\Rightarrow$ magnetic energy, plasma slowed, field 'stretches'.

Reconnected Field Line history

Equatorial plane plasma flows in a steady-state open magnetosphere

Magnetosheath

Tail reconnection line

Plasmapause

Solar

Dayside reconnection line

E_{SW}

Corotation

Newly closed flux returns to dayside

B_{MSPH}

Wind

Flux with both ends connected to IMF returns to SW

Magnetopause

B_{IMF}

Bow Shock

Reconnected Flux tubes in 3-D

Newly opened flux convects over the poles into the nightside

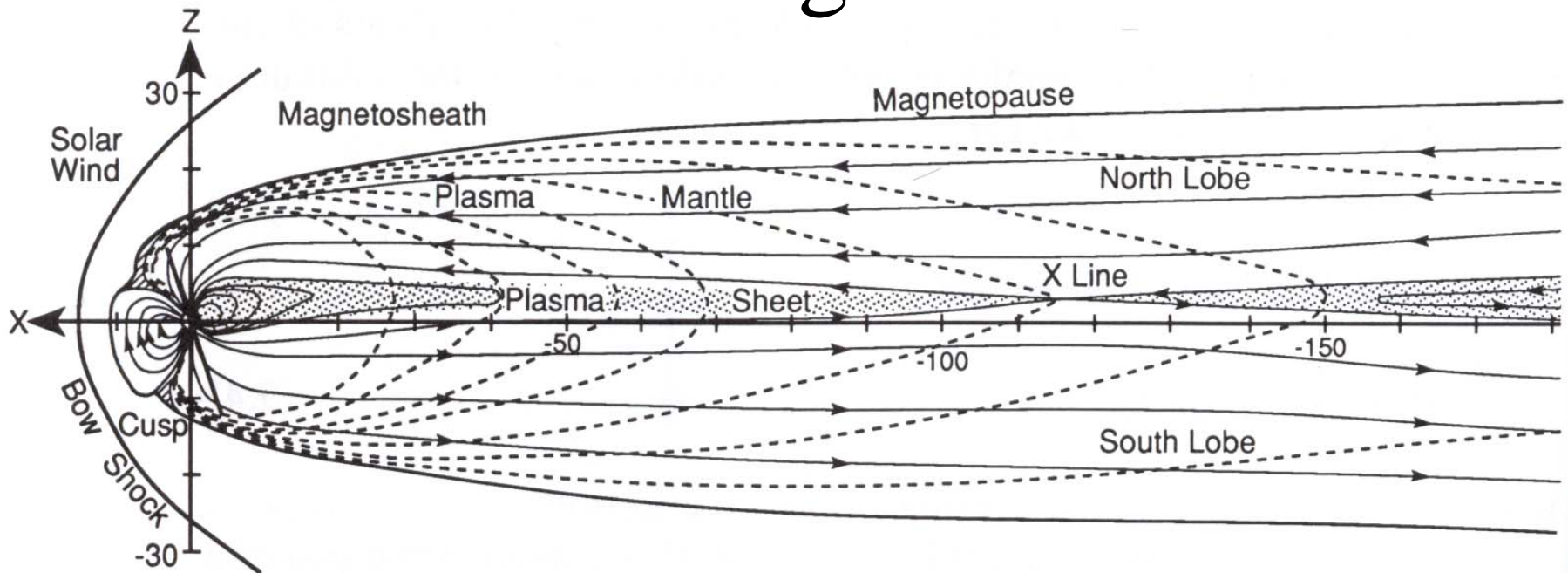Tail reconnection line

Dayside reconnection line

Newly closed flux returns to dayside

The Magnetotail

- The real magnetotail is many 1000's of Earth radii (R_E) long;
- The steady state X-line appears to be about 100 R_E downtail;
- The asymptotic diameter is ~50 R_E;
- Solid lines in figure are field lines, dashed lines are plasma streamlines after entry through the dayside magnetopause
- See handout for details.

Section *9.3* The Magnetotail.

In an open magnetosphere, the nightside magnetotail region can be extremely large (see figure in the handout). We can estimate some typical sizes by comparing the properties of the magnetic field in the tail with that in the ionospheric polar cap – this is the region occupied by the 'feet' of the open, or reconnected field lines, and is generally bordered by the auroral oval, the ring of auroral luminosity around the poles, at a typical latitude of ~65°.

A) Tail Width

Magnetic flux is conserved, so the flux threading one of the polar caps is roughly the same as that threading one of the tail lobes.

$$\int_{PC} \mathbf{B.dS} = \int_{LOBE} \mathbf{B.dS}$$

$$B_{PC} . \pi \, r_{PC}^2 = B_{LOBE} . \frac{\pi \, r_{LOBE}^2}{2}$$

B_{PC} = 50000 nT (polar surface field)
B_{LOBE} = 20 nT $\qquad \Rightarrow \qquad$ r$_{LOBE}$ ~ 20 R$_E$.

B) Tail Length

The feet of the open magnetic flux tubes move across the polar cap from dayside to nightside during the time T between their creation by reconnection at the dayside magnetopause and their re-closing by reconnection in the cross-tail current sheet. In the same time, the solar wind end of the field line travels a distance V$_{SW}$ T, which is then an estimate of tail length.

Ionospheric convection speeds V_{PC} = 300 m s^{-1}
Solar Wind Speed V_{SW} = 450 km s^{-1} $\Rightarrow \qquad$ L$_{TAIL}$ ~ 600 R$_E$.

C) The Cross-Tail Current Sheet and Plasma Sheet

The two tail lobes, with their oppositely directed fields, must be separated by a current sheet. This region is about 1 – 2 R$_E$ thick. Given the magnitude of the field reversal across it (+/- 20 nT, see above), the current density is of order 30 mA m^{-1}. This current is carried within a hot (1-10 keV), moderately dense (~1 cm^{-3}) plasma sheet, which may be formed by the liberation of lobe magnetic energy during magnetotail reconnection.

(See other handout for details on the Aurora).

The Plasmasphere

The plasmasphere is a region of very cold (1 eV), dense (1000 cm^{-3}) plasma which lies in roughly the same region as the energetic particles of the radiation belts. Plasmasphere field lines are closed, and the plasma is actually the most energetic component of the (much more dense) ionospheric plasma, which has managed to overcome the gravitational potential in order to reach to very high altitudes (the plasma must travel along the field lines as it ascends). It takes time for an empty field line to fill up with plasma, so we only see high densities on plasmaspheric flux tubes which have spent a long time as closed flux tubes corotating with the planet.

In an open magnetosphere, a low energy particle ExB drifts in the combined potential due to the corotation electric field and the solar wind driven convection electric field. The outermost closed path defines the boundary of the plasmasphere. Particles on paths beyond it do not circulate repeatedly and so cannot build up in plasma density, instead they typically encounter the magnetopause.

Variations in the convection electric field cause variations in the position of the boundary of the plasmasphere. If the boundary moves inwards, field lines full of plasma are shed from the outer part of the plasmasphere. If the boundary moves outwards, previously empty flux tubes can be filled up (UV on the atmosphere keeps generating plasma) given time.

The Aurorae

The Aurorae are a visible manifestation of the magnetosphere. Their constantly changing form and brightness reflects the dynamic nature of magnetospheric processes.

The aurorae are usually present in a belt called the auroral oval, encircling each of the Earth's magnetic poles. Typical latitudes are around 60° to 70°.

The auroral light is emitted by neutral atoms and molecules which have been excited by collision with precipitating electrons and which de-excite by releasing the energy as photons. Green light is emission at 558 nm, usually occurring at altitudes of 100 to 200 km. Red light is at 630 nm and comes from greater altitudes. In both cases, the emitter is atomic oxygen. Emission does not occur at lower altitudes for two reasons; fewer precipitating particles reach lower, and the gas density is higher at lower altitudes so the de-excitation is usually by a collision before light emission can occur.

The precipitating particles are a source of ionisation, and significantly enhance the ionospheric conductivity in the auroral oval region.