Chapter 14

Earth's Magnetosphere

Aims and Expected Learning Outcomes

The **Aim** is to explore the macroscopic structure of Earth's magnetosphere, relating the characteristically different regions to orbit theory, MHD theory, magnetic reconnection, and the magnetopause. This positions us for study of space weather, Earth's auroral regions and ionosphere, and the magnetospheres of the outer planets.

Expected Learning Outcomes. You should be able to:

- Identify the characteristic regions and boundary layers of the magnetosphere and describe the important plasma characteristics.
- Explain the basic physics of the cusps, magnetopause boundary layers, multiple magnetotail regions, ring current/radiation belt, and plasmasphere, including their linkages to the solar wind and Earth's auroral oval, ionosphere, and atmosphere.
- Explain the motions of charged particles in the magnetosphere as a function of the imposed solar wind electric field.

14.1 The Global Magnetosphere

Figure 14.1 offers another global view of the different plasma regions found in the magnetosphere, complementing Figures 13.9 and 13.10. We now describe these regions in some detail. Note that these regions are not all distinct; instead there may be smooth transitions from one region to another without clear boundaries.

1. **Cusps**. The polar cusps or clefts are two regions, one north and one south of the magnetic equator, in which the transition between terrestrial

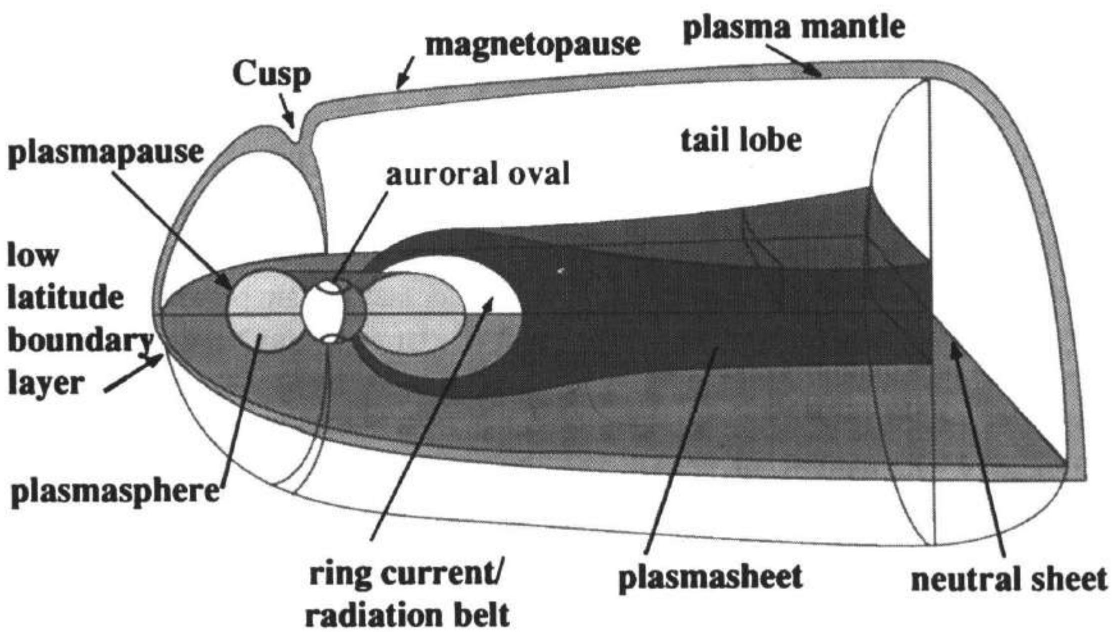

Figure 14.1: Schematic illustration of Earth's magnetotail, emphasizing the different plasma regions [Cravens, 1997]. Note the cusps, plasma mantle, tail lobes, plasmasheet, neutral sheet, ring current, radiation belts, plasmasphere, and auroral ovals.

magnetic field lines going sunward and poleward/tailward occurs. For an isolated dipole this transition would occur exactly along the magnetic pole, but the confining of the field to the magnetospheric cavity by the magnetopause current system causes the transition to occur at smaller magnetic latitudes. This is because the MP current system increases B in this region, thereby moving field lines there. The change in direction of the magnetopause current near the cusp (Figure 13.10) and the opposite signs of the non-radial components of the terrestrial field there means that the magnetic field strength is locally weak in the cusp and directed directly towards the Earth. As such the magnetic barrier to flow of plasma across the magnetopause is least there, causing a "caving in" of the magnetopause there, so that the cusp field lines act as funnels for magnetosheath plasma to enter the magnetosphere. Some of this magnetosheath/solar wind plasma penetrates all the way to the ionosphere, resulting in auroral displays and enhanced fluxes of energetic particles (Lectures 15-17).

Magnetic field lines leaving the cusp are magnetically connected to the solar wind (Figures 14.2 and 14.3), thereby permitting the solar wind's convection electric field to map across Earth's polar cap and causing convection of plasma there. The cusp maps to the auroral oval near noon, with the auroral oval generally separating the regions with closed and open terrestrial magnetic field lines.

2. **Magnetopause boundary layer & plasma mantle**. These names describe a transition region between the magnetosheath and magnetosphere proper in which plasma characteristic of both regions mixes and interpenetrates (Figures 14.2 and 14.3). This occurs for several reasons. First, the magnetopause is not a rigid boundary and fast, nonthermal charged particles can cross the magnetopause because their Lorentz force (cf. the $\mathbf{J} \times \mathbf{B}$ force) is insufficient to reflect them. Note that sufficiently fast particles have gyroradii much larger than the magnetopause thickness. Second, and most importantly, magnetic reconnection at the magnetopause leads to plasma being accelerated along the field and undergoing $\mathbf{E} \times \mathbf{B}$ drifts into/out of the magnetosphere (depending on whether $\mathbf{E}$ is directed dawn-to-dusk or vice-versa). These particle naturally develop cutoff distributions (Lecture 13) and drive plasma waves. These particles can also enter the cusp. Third, plasma flowing out of the ionosphere via the cusp undergoes $\mathbf{E} \times \mathbf{B}$ drift and fills a large volume with cutoff distributions.

3. **Magnetotail**. The magnetotail is the magnetospheric region behind the Earth in which, qualitatively, the solar wind flow tends to pull the dipole field lines into an equatorial current sheet with field lines that are almost anti-parallel or parallel to the Earth-Sun line above and below the current sheet (Figure 14.2). The situation is analogous to Figure 10.1 for the

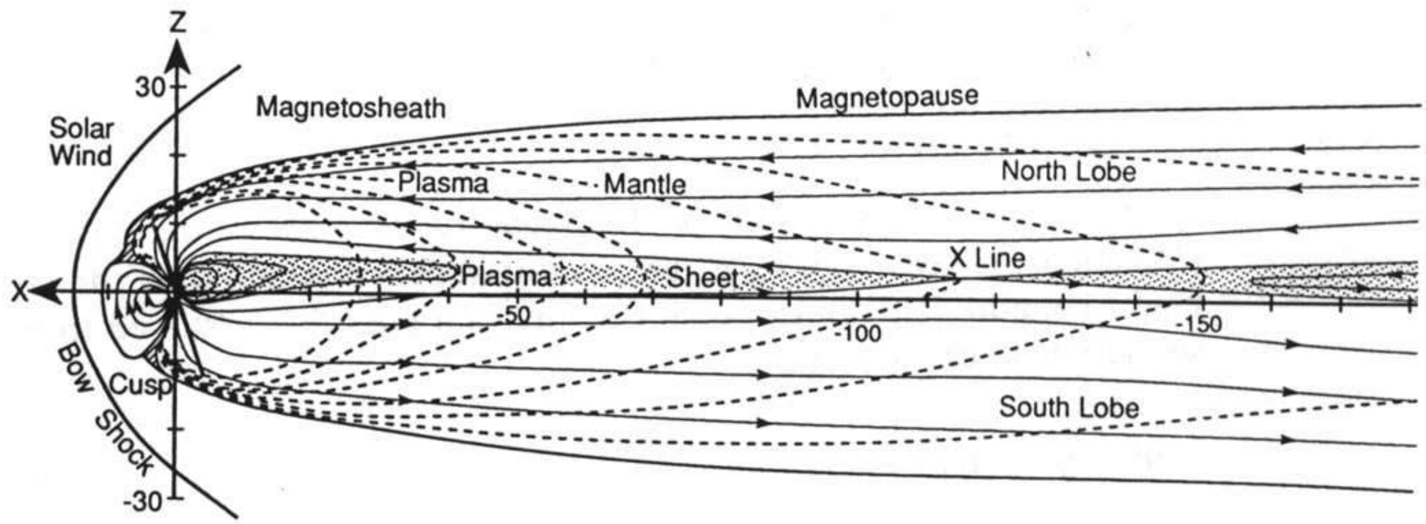

Figure 14.2: Noon-midnight cross section of the magnetosphere and geomagnetic tail [Hughes, 1995]. Magnetic field lines are shown using solid lines while the dashed lines shows particles moving along the field subject to the $\mathbf{E} \times \mathbf{B}$ drift for a solar wind convection field $\mathbf{E}$ directed from dusk-to-dawn.

heliospheric current sheets and coronal streamers. The magnetotail acts as a reservoir for plasma and magnetic field energy that is released in so-called "magnetic substorms" (Lecture 15). The magnetotail is at least 200 R_E long and may be thousands of R_E long. Jupiter's magnetotail, for instance, was observed by the Voyager spacecraft to sometimes stretch all the way to Saturn, that is for a distance ~ 5 AU.

The current sheet at the center of the magnetotail, sometimes called the "neutral sheet" (since $B_X = 0$ along the plane $Z = 0$, in GSE $X - Y - Z$ coordinates), is at the center of the plasmasheet. The current in the current sheet is called the "cross-tail current" (Figure 13.9 and 13.10) and it flows from dawn to dusk. Note that it is a large, macroscale current, which must be connected with the other macroscopic current systems of the magnetosphere. The major linkings are sketched in Figure 13.9.

4. **Tail lobes.** These lobes comprise the major part of the magnetotail, being found between the plasma sheet and the magnetopause. These are regions where the magnetic field pressure is large and the plasma pressure is small ($n_e \ll 0.1$ cm^{-3}), in pressure balance with the rest of the magnetosphere. The magnetic field is primarily directed parallel to

the neutral sheet with only a relatively small northward component, being greatly stretched tailwards from a pure dipole field. These magnetic field lines often appear to be magnetically open (i.e., connected from the Earth to the solar wind), presumably due to magnetic reconnection.

It is partly a matter of definition whether the tail lobes are distinct from the plasma mantle/magnetopause boundary layer, since any transition between the two is smooth. Figure 14.3 illustrates the conceptual difficulty posed by the mantle plasma as it (typically) convects toward the plasmasheet from the cusp and magnetopause and partly fills the tail lobe regions. Note that the plasma pressure in the lobes and mantle is very small compared with the magnetic field pressure.

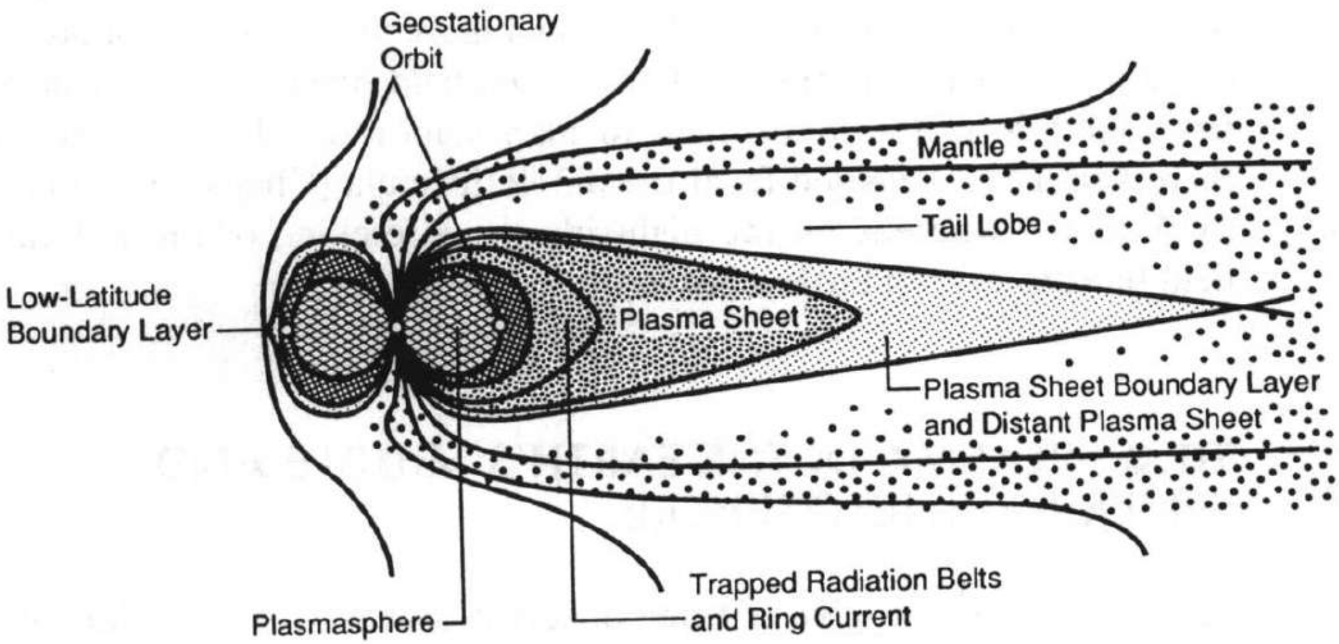

Figure 14.3: Schematic of plasma regions in Earth's magnetosphere [Wolf, 1995]. Note the smooth transition from plasma mantle to tail lobe, the plasma sheet boundary layer, plasma sheet, radiation belts and ring current, and the plasmasphere. Note that geosynchronous orbit often lies close to the boundary of the plasmasphere and the plasmasheet.

5. **Plasmasheet boundary layer** The plasmasheet boundary layer contains particles with "cutoff" distributions which stream both Earthward and tailward subject to $\mathbf{E} \times \mathbf{B}$ drifts. The ultimate source of these streaming

particles is thought to be magnetic reconnection at the distant tail reconnection site and/or the ionosphere and magnetopause reconnection. The plasmasheet boundary layer is magnetically connected to Earth's auroral field lines.

6. **Plasmasheet**. The plasmasheet, otherwise called the "central plasma sheet" or the "plasma sheet", is the region with hot, relatively dense plasma that is found at the centre of the magnetotail and that surrounds the neutral sheet. The plasmasheet is typically $4 - 8$ R_E thick and it carries the cross-tail current. (Note that the cross-tail current is another name for the current layer at the center of the neutral sheet). Characteristic plasma parameters are $n_e \sim 0.1 - 1$ cm^{-3}, $T_e \sim 1$ keV and $T_i \sim 5$ keV. In this region the magnetic field pressure is dominated by the plasma pressure. The magnetic field is relatively weak, especially in the field-reversal region at the center of the current sheet. The plasma in the plasmasheet typically has low flow velocities so that particle distribution functions are often symmetric with respect to the Sunwards and anti-Sunwards directions. Convection is primarily due to $\mathbf{E} \times \mathbf{B}$ motion. The plasmasheet is primarily connected to closed magnetic field lines.

   The plasmasheet is the scene of much geomagnetic activity, particularly to do with substorms. Most theories for substorms involve magnetic reconnection proceeding at a distant site approximately 100 R_E downtail from Earth and also at a near-Earth reconnection site near 9 R_E in the tail, from which energetic particles are injected into geosynchronous orbit. In quiet times the plasmasheet primarily contains plasma of solar wind origin but in active times plasma of ionospheric origin may dominate.

7. **Ring current & radiation belts** The ring current and radiation belts are formed by energetic particles moving in the inner portions of Earth's magnetosphere, inward of the plasmasheet proper but further out and extending to higher latitudes than the plasmasphere. The ring current plasma is very hot, with proton energies of tens of keV. The "trapped" or "Van Allen" radiation belts are the high energy extension of the ring current particles, with particle energies in the MeV. These particles are all on closed magnetic field lines (otherwise they could not be trapped in these orbits).

   The ring current is carried by energetic electrons and ions that are undergoing gradient and curvature drifts around the Earth (as well as their bounce and gyro motions). Figure 14.4 shows the directions of these drifts and the resultant westwards direction of the current, which opposes the Earth's field in the region interior to the current but adds to the Earth's field in the exterior region. Equation (1.30) shows why these drifts are energy dependent, so that the cold plasma population does not contribute significantly, and why the electron and ion currents add up. The ring

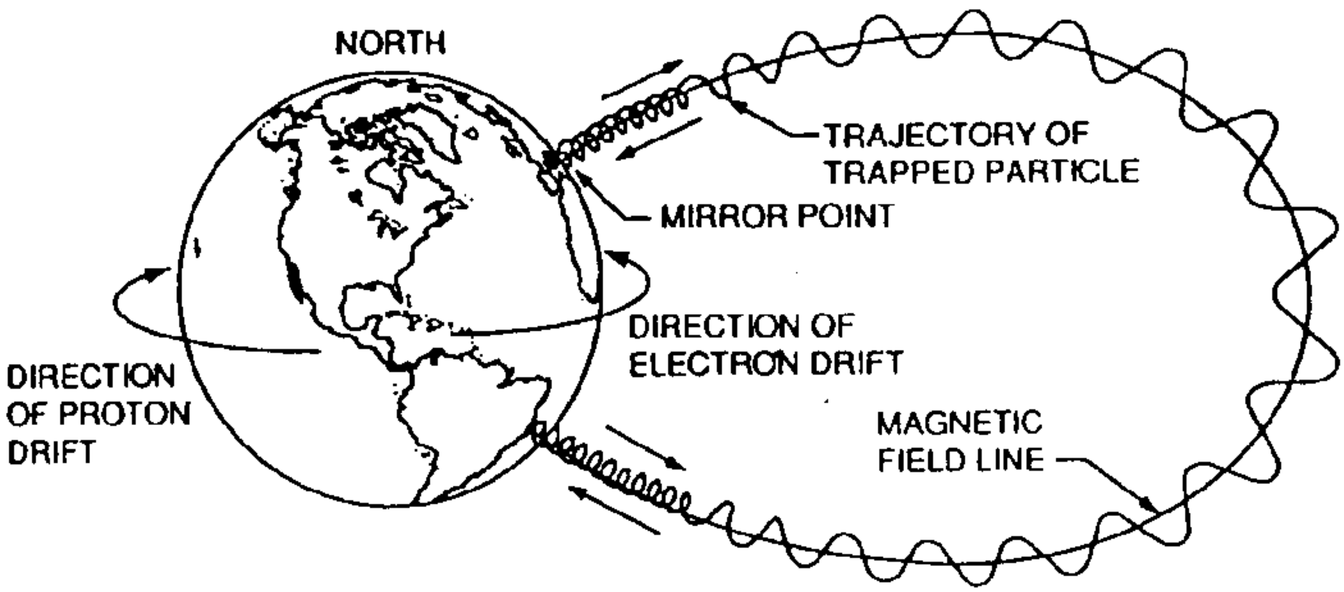

Figure 14.4: Illustration of why the ring current flows westward [Brand, 1999]. The figure also indicates why the ring current can depress the north-south magnetic field at Earth's surface but increase the effective field in the outer magnetosphere.

current is diamagnetic, so that times of enhanced ring current (during geomagnetic activity like substorms) correspond to decreases in the field observed at the Earth's surface (but increases near the magnetopause, for example, thereby affecting the bow shock's position). One geomagnetic activity index, D_{st}, measures the decrease in the surface magnetic field due to increases in the ring current and to the magnetopause current system moving sunwards.

The radiation belts have higher energies than the main ring current particles (e.g., MeV rather than keV) and are much more stable, having loss times (due to loss-cone effects, wave-particle scattering and collisions with ionospheric and plasmaspheric particles) that are much longer than the ring current particles (years rather than a few days). The radiation belts do not usually vary with geomagnetic activity. However, new radiation belts can be created due to the injection of unusually large amounts of energetic plasma into near-Earth orbit. Examples of this are the enhanced radiation belt formed after the atmospheric nuclear explosion *Starfish* and new belts formed by an unusually energetic solar shock a few years ago.

8. **Plasmasphere** The plasmasphere is a doughnut-shaped region within a few R_E of Earth and at mid- to equatorial latitudes that contains dense, cold plasma of primarily ionospheric origin and merges smoothly with the ionosphere. ($n_e > 100$ cm^{-3} and $T_e \sim T_i \sim 1$ eV.) The magnetic field here is accurately described as a dipole field.

   The plasmaspheric plasma corotates with Earth. This means that a large corotation electric field exists in the plasma, since the plasma is still collisionless and the magnetic field is "frozen-in" to the plasma. The corotation electric field is given by equation (2.29), with $\mathbf{U}$ equal to the corotation velocity $\mathbf{r}\times\omega$. This situation is analogous to that in Jupiter's magnetosphere and close to pulsars. Of course, corotation must break down eventually, for instance when U approaches the Alfven speed V_A or another speed that leads to significant instabilities, or the speed of light, or the electric field causes electron "run away" or other breakdown phenomena. The properties of the plasma are expected to change where corotation breaks down.

   Exercise: Show that the corotation speed is approximately V_A near $r \approx 3R_E$, which is near the nominal edge of the plasmasphere.

   The outer boundary of the plasmasphere, the **plasmapause** is relatively sharp. Both the sharpness and location of the plasmapause vary with geomagnetic activity, being sharper and located closer to Earth during times of larger geomagnetic activity.

14.2 The Importance of Orbit Theory and Plasma Drifts

As discussed in Lecture 1, the components of a charged particle's motion can be separated into the gyromotion, a motion parallel to the magnetic field, and drift motions perpendicular to the magnetic field due to electric fields or spatial gradients in the magnetic field. All three of these components are important and it should be emphasized that the magnetosphere is primarily collisionless, so that the paths of individual particles are directly relevant to the motion and characteristics of the plasma as a whole. The gyromotion and conservation of the first adiabatic invariant μ are important in understanding magnetic mirroring and particle precipitation. The parallel motion leads to particles bouncing between Earth's magnetic poles when on closed field lines or, if on open field lines, to the particle either precipitating into the ionosphere or leaving the magnetosphere. Drift motions are important for convection of the plasma as a whole ($\mathbf{E} \times \mathbf{B}$ drifts) and for plasma currents (∇B and curvature drifts).

The $\mathbf{E} \times \mathbf{B}$ convection of plasma is vital in understanding the large-scale motions of plasmas in the magnetosphere, the creation of unstable particle distributions and associated wave growth and particle scattering, and the motions of individual particles. Reconsider Figures 13.9, 13.10 and 14.1 – 14.3 from the point-of-view of $\mathbf{E} \times \mathbf{B}$ drifts.

Suppose first that the solar wind electric field is directed from dawn to dusk (i.e., eastwards) or out of the paper. This corresponds to a southwards component B_z of the interplanetary magnetic field. (Exercise: Why?) Then in the plasmasheet the $\mathbf{E} \times \mathbf{B}$ drift is Earthwards from the tail and sunwards from Earth, so that tail plasma is brought Earthwards, drifts around the Earth due to curvature and gradient drift, and then drifts to the magnetopause where it is lost. Similarly, plasma leaving the cusp tailward or plasma moving in the tail is convected down toward the plasma sheet, leading to cutoff distributions and a denser and thinner plasma sheet.

Notice now the effect of the solar wind electric field reversing in sign. (How could this happen? Consider the definition of $E_{sw} = -\mathbf{v}_{sw} \times \mathbf{B}_{sw}$ and the usual dominance of the radial or $-\mathbf{x}$ component of the solar wind velocity.) Now all the $\mathbf{E} \times \mathbf{B}$ drift velocities are reversed and so are the corresponding convection patterns. It can now be seen that solar wind activity can be expected to have major consequences on the plasma and "space weather" in Earth's magnetosphere. This subject is discussed in more detail in the next lecture.

The ∇B and curvature drifts are vital in understanding the ring current and associated variations in magnetic field near Earth's surface and in the magnetosphere. As described in the previous section, the ∇B and curvature drifts of particles moving in Earth's dipole magnetic field may be represented by Eq. (1.30) (since the plasma current is small compared with the curl of $\mathbf{B}$). Accordingly, charged particles with opposite charges drift in opposite directions, thereby carrying a current, the so-called "ring current". The magnetic field of the ring current opposes the Earth's magnetic field at locations interior to the ring current, but adds to the Earth's field at larger distances. (Ultimately, this is because plasmas are diamagnetic.) Put another way, the ring current diminishes the Earth's surface magnetic field but increases the field at the magnetopause. Variations of the ring current, due to injections of energetic particles during magnetic substorms or other space weather events, are therefore important for geological or other exploration studies that use magnetic sensors. The ring current can also move the magnetopause and bow shock closer or further from Earth.

14.3 References and Bibliography

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