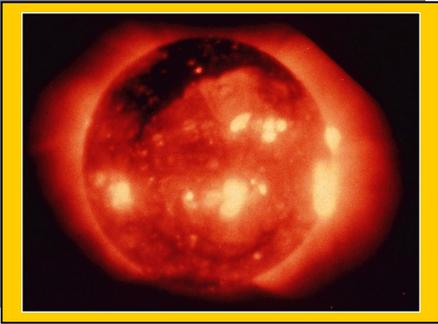


Cosmic Chemistry: Planetary Diversity

Plasma Wars

STUDENT TEXT

NASA



SOLAR WIND

Our sun generates a strong **solar wind**, which is quite different from our surface winds created by differences in our atmospheric pressures. The solar wind carries about one million tons of hot plasma, at a temperature of about  $10^5$  K, away from the sun every second. Solar wind plasma contains a mixture of 95.9 % protons ( $H^+$ ) and 4% alpha particles ( $He^{2+}$ ). The remaining 0.1% is made up of ions of other elements, including carbon, nitrogen, oxygen, neon, magnesium, silicon, and iron and enough electrons to electrically balance all the positive ions.

The plasma behaves like an electrically conducting fluid, carrying with it a magnetic field arising from systems of electrical currents within the sun's corona. The strength of this magnetic field decreases with increasing distance from the sun.

Because plasma particles have sufficient kinetic energy to escape the sun, the solar wind becomes an extension of the sun's corona, continuously present in interplanetary space. Evidence of the solar wind has been observed well beyond the orbit of Saturn, at a distance of about 75 AU by Voyager I.

Solar wind streams move at different speeds. When streams collide, they produce regions of strong, turbulent magnetic fields. (see Figures 1a,1b, & 2). The regions prevent low-speed cosmic rays from distant astronomical sources from entering the solar system.

Figures 1a & 1b

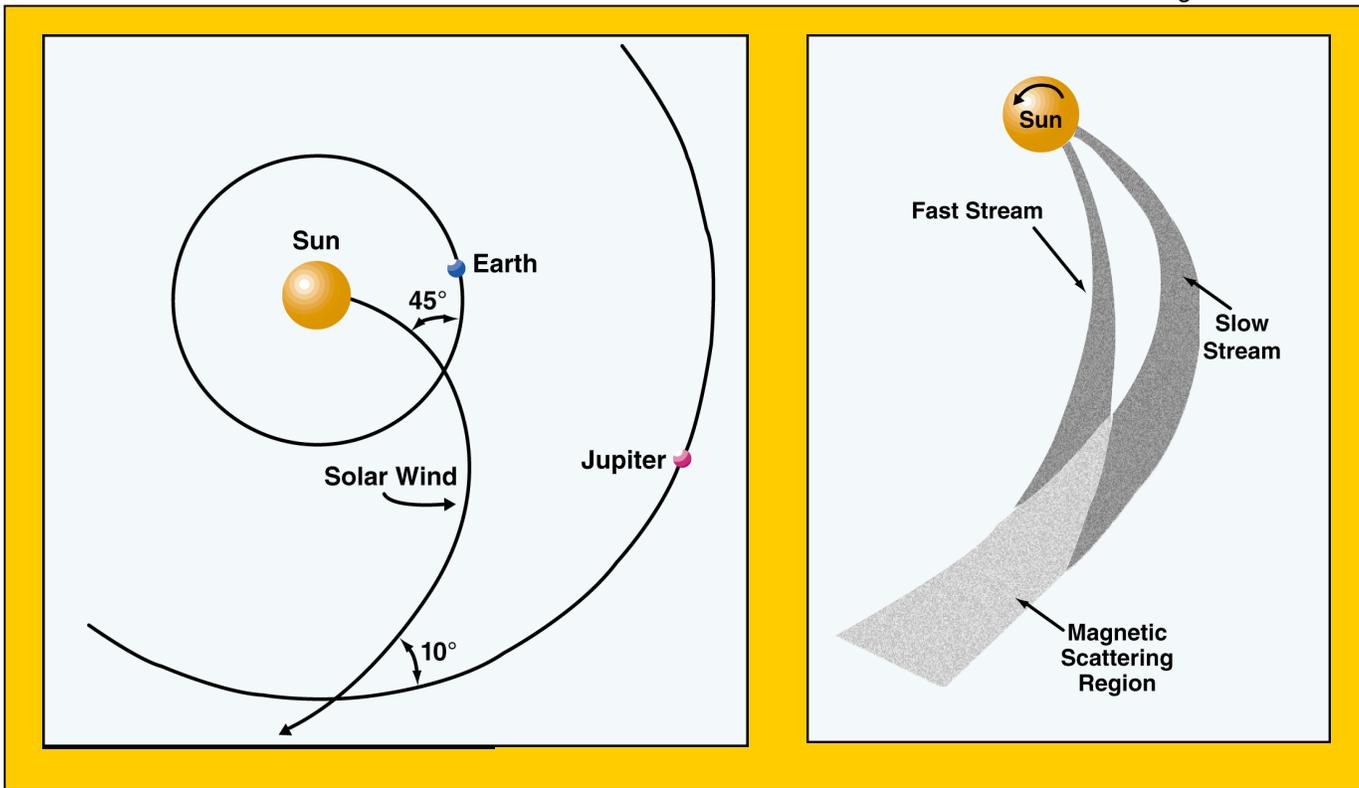
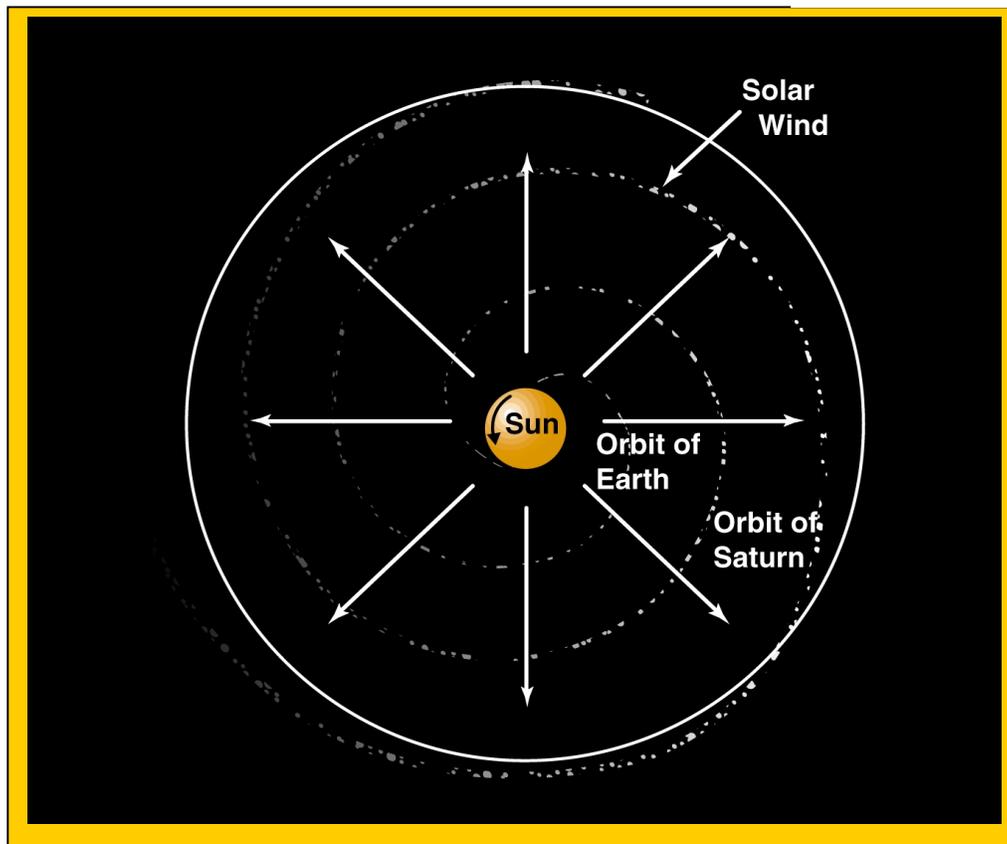


Figure 2



**Figure 2.** The solar wind moves radially away from the sun. **Note.** The data in Figures 1a, 1b, & 2 are from The New Solar System, (Figure 1, Chapter 3), by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press, and Exploration of the Solar System, (Figure 12-11, p. 423), by W. J. Kaufmann III, 1978, New York: Macmillan Publishing Co, Inc.



After escaping from the sun's gravitational field, the solar wind flows radially outward. A rotating garden sprinkler is a good analogy. Each drop moves straight out from the source, but the pattern rotates. The streams' travel speeds vary from 300 to 1000 km/sec and are independent of their distance from the sun. The density of the solar wind varies between 1 and 10 particles/cm<sup>3</sup> at the orbit of Earth and diminishes with the inverse square of the distance from the sun's center. Solar activity can cause sporadic order-of-magnitude fluctuations, however.

The solar wind has a negligible effect on the movements of planets, but it can have other profound effects in their immediate vicinity. For example, Mars and Venus may have lost former oceans and Mars may have lost much of its atmosphere to space as a direct result of the solar wind.

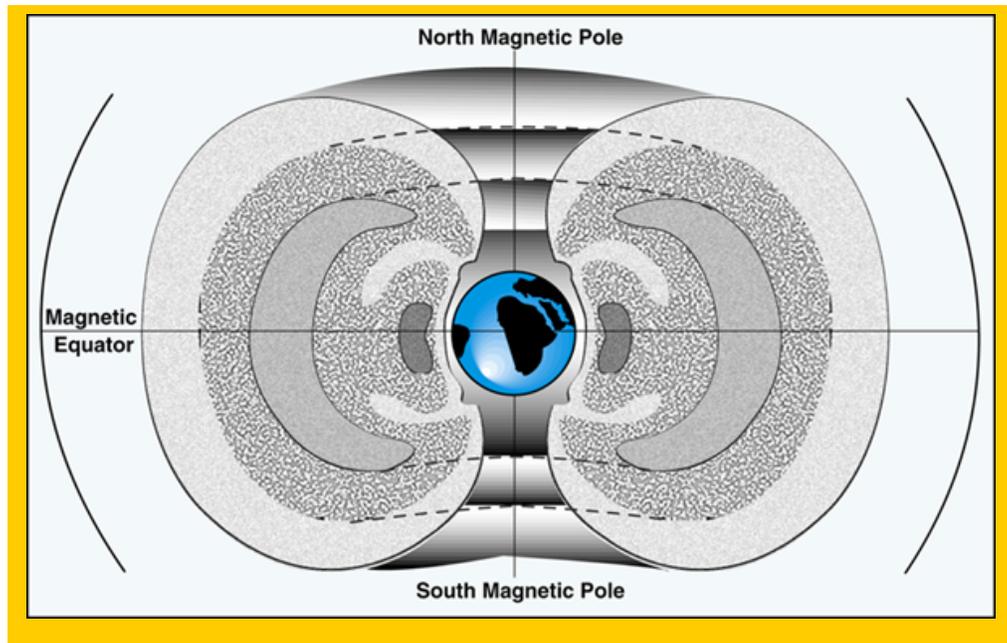
So what has protected the Earth's atmosphere, its water supply, and its inhabitants from the searing affect of the solar wind? The ionized gases of the solar wind are prevented from striking the Earth's atmosphere by its magnetic field.

## MAGNETOSPHERES

The Earth's **magnetosphere** was discovered in 1958, when a Geiger counter in Explorer 1 detected a region of intense radioactivity as it orbited elliptically around the Earth. Later in the same year, radiation detectors aboard Explorer 3

observed large populations of very energetic charged particles trapped in two large belts that completely encircle the Earth. The inner belt starts at an altitude of about 2,000 kilometers above the Earth and extends to an altitude of 5,000 kilometers (see Figure 2). The outer belt starts at an altitude of 15,000 kilometers and is about 6,000 kilometers thick. Both belts are electrically neutral with equal numbers of protons (or other ions) and electrons. The protons in the inner belt have been accelerated to high energies whereas in the outer belt it is the electrons which have high energies. This optically transparent space around the Earth, where the behavior of these electrically charged particles is determined by the planet's magnetic field, is the Earth's **magnetosphere**.

Figure 3



**Figure 3.** Cross-sectional diagram of the two large belts of charged particles, the Van Allen Radiation belts, are part of the Earth's magnetosphere. They are named for Dr. James Van Allen, who conducted the Explorers 1 and 3 experiments. **Note.** The data in Figure 3 are from *Exploration of the Solar System* (Figure 6-42, p. 219), by W. J. Kaufmann III, 1978, New York: Macmillan Publishing Co, Inc.

The Earth's magnetosphere and the solar wind do not interact smoothly. When the solar wind plasma flows past the Earth, it has difficulty penetrating into the planet's magnetic field. This leads to the creation of a huge bow-shaped **shock wave**, similar to that of the wake of a speed boat moving through water, which deflects the solar wind around the magnetopause. The bow shock, which marks the limit of the Earth's magnetic influence, occurs where the velocity of solar wind particles decreases from supersonic to subsonic speeds. Figure 3 is a diagram of the Earth's magnetosphere.

Figure 3a

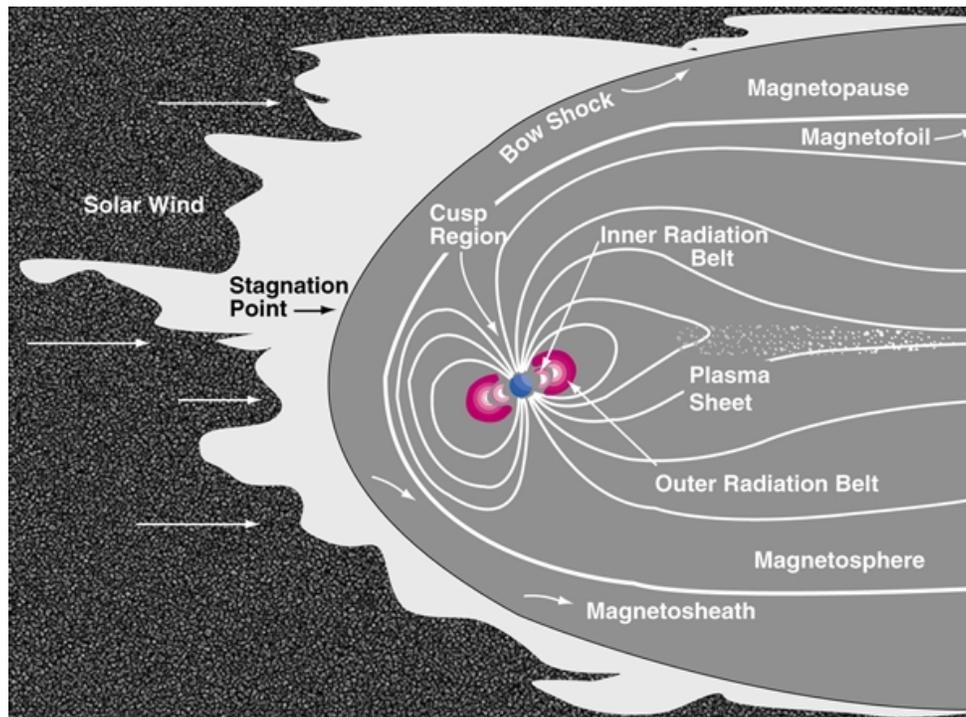


Figure 3a. A cross-sectional diagram of the Earth's magnetosphere showing how the magnetic field is distorted by the "blowing" of the solar wind. Note The data in Figure 3a are from The New Solar System (Figure 9, p. 35), by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press and Exploration of the Solar System (Figure 2, p. 222), by W. J. Kaufmann III, 1978, New York: Macmillan Publishing Co, Inc.

The solar wind compresses the Earth's magnetic field on the sunward side, and, as the magnetic field accompanying the solar-wind plasma partially merges with that of a planet, the planetary field is stretched into a **magnetotail**, an elongated "wake" on the side opposite the sun. The length of the Earth's magnetotail was determined by spacecraft instrumentation to be at least several million km long.

Between the shock wave and the Earth's magnetic field is a **magnetosheath**, a turbulent region where the solar wind flows around the magnetosphere. The **magnetopause** marks the outer boundary between the Earth's atmosphere and interplanetary space. This boundary is constantly changing, depending upon how the solar wind and the magnetosphere interact at a given time.

The solar wind plasma comes closest to the center of the Earth at the **stagnation point**, where the pressure of the planet's magnetic field balances the solar wind's pressure. The position of the stagnation point, which is variable with the respect to the center of the planet, depends on both the solar-wind pressure and the magnetic moment of the planet, which remains constant. Earth's stagnation point is about 64,000 km (10 times the Earth's radius) out from the sunward side of the planet.

Electrically charged particles speed up and slow down because of fluctuations in the solar wind and its magnetic field, so the affected particles can diffuse in both directions across the magnetopause. Those that move inward, toward the stronger field, become trapped in the Earth's inner magnetosphere. Others work their way back out into the magnetosheath and are lost to space.

The small number of the charged solar wind particles that enter the magnetosphere become trapped in the Earth's magnetic field, bouncing from the north pole to the south pole and back again. If these particles strike gaseous atoms and molecules

in the Earth's atmosphere, they excite them. When the atoms and molecules "de-excite," they emit bright colored light at high altitudes. We call this phenomenon the auroras, or the Northern and Southern Lights.

The solar wind is not the only source of energetic, charged particles found in a planet's magnetosphere. Low-energy ions and electrons can be produced in a planet's ionosphere (the upper region of a planet's atmosphere where there is sufficient energy to ionize atoms) and in the ionospheres and atmospheres of a planet's satellites. In addition, when galactic cosmic rays and solar wind particles bombard the gases in the Earth's atmosphere, neutrons are produced. A small fraction of these neutrons decay into energetic protons and electrons, injecting charged particles directly into the magnetosphere. These trapped particles can spend anywhere from hours to years in the Earth's magnetosphere.

## OTHER PLANETARY MAGNETOSPHERES

Spacecraft have now also measured the magnetic properties of seven other planetary bodies—the moon, Mercury, Venus, Mars, Jupiter, Saturn and Uranus (see Table 1).

Table 1

Planet	Typical stagnation point <sup>^</sup> distance (in planetary radii*)	Magnet Field at equator (gauss)	Plasma Sources#
Mercury	1.1	0.003	W
Venus	1.1	<0.00003	W,A
Earth	10	0.305	W,A
Mars	1.1?	0.0003	A
Jupiter	60-100	4.28	W,A,S
Saturn	17-25	0.22	W,A,S
Uranus	17-25	0.23	W,A
Neptune	25-40	0.14	S

Note. <sup>^</sup>This is also an estimate of typical magnetopause distance (see Data Table 1 in the Student Data Sheet, "[Are We Related?](#)" in this module for equatorial planetary diameter in km (planetary radii is one half of the planets diameter). Gauss is the intensity of magnetic induction equal to that produced by a magnetic pole of unit strength at a distance of one centimeter. The symbols under Plasma Sources are: W is solar wind; A is planetary atmosphere; and S is for satellites (or rings). The data in Table 1 are from [The New Solar System](#) by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press.

## MERCURY

The only close up observations of Mercury's magnetosphere were made in 1974 and 1975 when Mariner 10 made three flybys. The planet has a magnetic field whose strength is about 1% that of the Earth's, but strong enough to interact substantially with the solar wind. Mercury's magnetic field is oriented in the same direction as the Earth's (see Figure 4). A bow shock was observed, which was a surprise because Mercury lacks an appreciable atmosphere and ionosphere, and its magnetic field is apparently too weak to maintain a belt of trapped particles. Mercury has a very thin tenuous atmosphere surrounding the planet. It is so thin that the atoms rarely collide with one another. Mercury's magnetic field is apparently strong enough to trap some atoms from the solar wind.

Figure 4

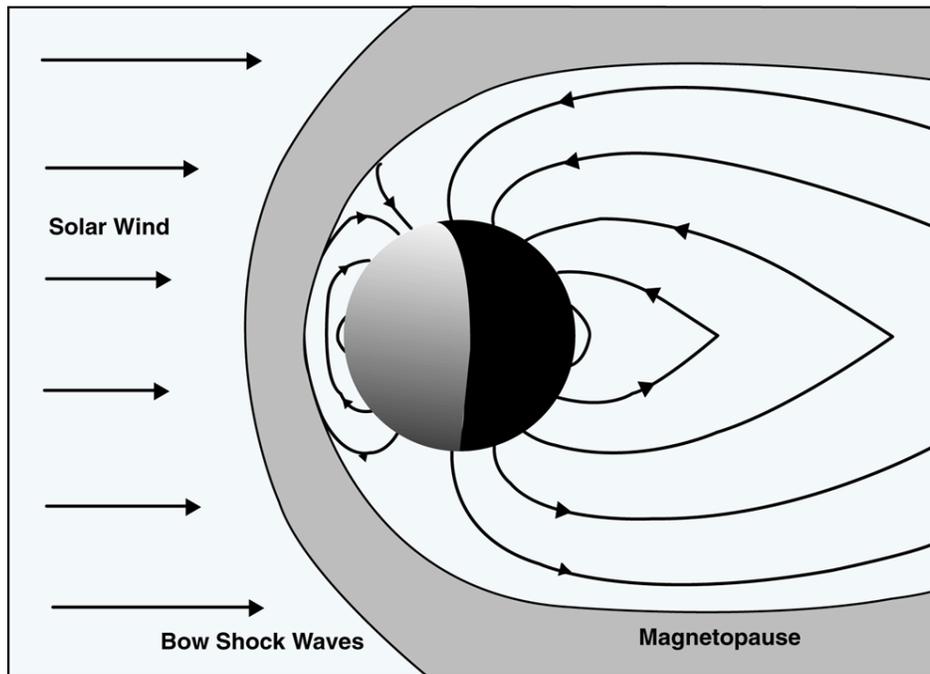


Figure 4. Cross-sectional diagram of the Mercury's magnetosphere, showing how the magnetic field is distorted by the "blowing" of the solar wind. Note. The data in Figure 4 are from *Exploration of the Solar System* (Figure 11-20, p. 408), by W. J. Kaufmann III, 1978, New York: Macmillan Publishing Co, Inc.

## VENUS

Since 1962, American and Soviet spacecraft—Mariners 2, 5, 10; the Venera series; Vegas 1 and 2; and Pioneer 12—have gathered data on Venus' very weak magnetosphere; however, the magnetometers aboard Mariners 5 and 10 detected no radiation belts surrounding the planet.

There is a well-developed bow shock in Venus' outer atmosphere, but, like Mercury, there is no evidence of charged particles being trapped. Note that the position of the bow shock front shown in Figure 5 indicates that the solar wind approaches Venus much more closely than it does Earth. When solar wind encounters a nonmagnetic planet with an atmosphere, the planet's ionosphere creates forces that slow and divert the flow. The barrier that separates planetary plasma from the solar wind is called an **ionopause**, which is analogous to a magnetopause. It appears that even though Venus' magnetic field is no more than 0.09% that of the Earth's, the planet's dense atmosphere and the large-scale currents induced in its conducting ionosphere prevent the solar wind from reaching its surface.

Figure 5

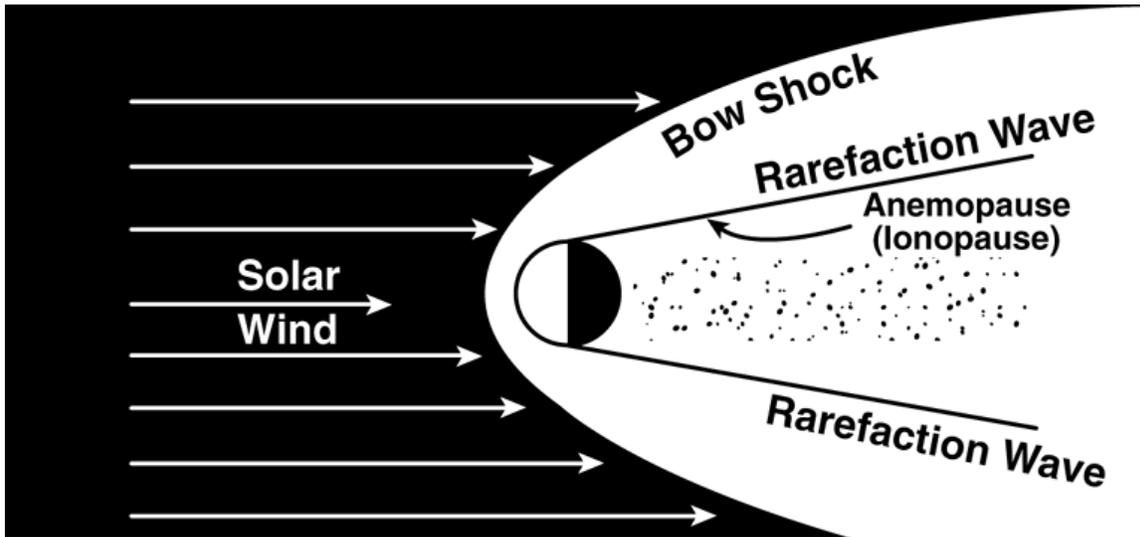


Figure 5. Cross-sectional diagram of the Venus' outer atmosphere, showing an anemopause. Note. The data in Figure 5 are from *The New Solar System* (Figure 13, p. 37), by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press and *Exploration of the Solar System* (Figure 10-18, p. 383), by W. J. Kaufmann III, 1978, New York: Macmillan Publishing Co, Inc.

## MARS

Measurements of the solar wind by particle detectors on board Mariner spacecrafts indicated that the magnetic field of Mars is about 0.2% that of Earth's. With such a weak magnetic field, no radiation belts would be able to form. The solar wind apparently interacts with the planets' conducting ionosphere, creating a weak bow shock and other phenomena in a manner similar to that observed for Venus. Data from the Soviet spacecraft, Phobos 2, indicate that the solar wind may remove as much as 30,000 tons of atmospheric gases from Mars each year.

Mars Global Surveyor (MGS) detected a planet-wide magnetic field in 1997 as the spacecraft began to orbit and study the planet. The magnetometer on MGS discovered the bow shock during the inbound leg of its second orbit around the planet at a distance of 2.33 Mars radii. The global magnetic field of Mars is too weak and the atmosphere too thin to protect the planet's surface from cosmic rays and solar flares. Mars like Venus' magnetic field do not originate from internal dynamos. It is believed that the Mars dynamo may have stopped working some time ago. The core has either frozen out or never formed. Mars Global Surveyor was the first spacecraft that observed the magnetic field below the ionosphere in a region shielded from solar wind interaction.

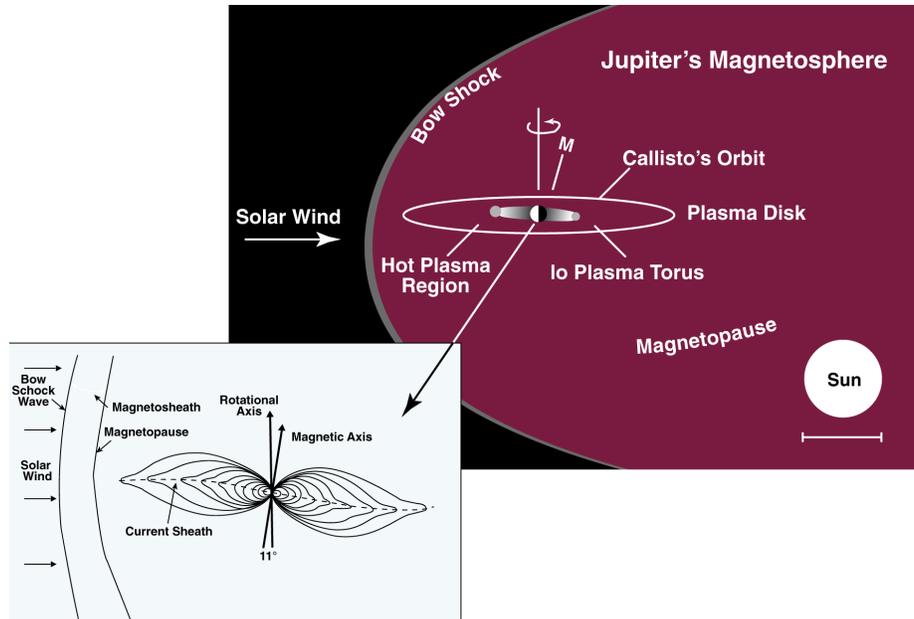
## JUPITER

Pioneer 10 and 11, Voyager I and II, Ulysses, and Galileo measured the configuration and structure Jupiter's bow shock. The Pioneer instruments detected electrons with energies greater than 21 million electron volts in an enormous disk-shaped region of the radiation belts of the planet's magnetosphere.

Jupiter's magnetosphere is about 100 times larger than that of the Earth's. It also rotates very rapidly (once every 10 hours), so the great mass of low-energy plasma trapped by the magnetic field rotates with the planet. Very large centrifugal forces push the plasma outward to form a thin disk of charged particles confined near the plane of the planet's the equator (see Figure 6). Note that Jupiter's rotational axis and its magnetic axis are closely aligned.

Voyager observations have confirmed that Jupiter's magnetotail extends at least 650 million km—to the orbit of Saturn and beyond. There are at least two reasons for this—the fact that Jupiter's magnetic field is 20,000 times greater than Earth's and, at 5.2 AU's, which is Jupiter's distance from the sun, the solar wind pressure is only 4% of that of Earth's.

Figure 6



**Figure 6.** Diagrams of Jupiter's magnetic field, which is 100 times the size of the Earth's magnetosphere. The size of Jupiter is not drawn to scale in this diagram. Note. The data in Figure 6 are from The New Solar System (Figure 16, p. 37), by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press, and Exploration of the Solar System (Figure 12-13, p. 424), by W. J. Kaufmann III, 1978, New York: Macmillan Publishing Co, Inc.

The plasma in Jupiter's magnetosphere is derived mainly from ionized sulfur dioxide, hydrogen sulfide, and other gases vented by volcanic eruptions on Jupiter's satellite, Io. These gases form the Io torus, the doughnut-shaped region in the plasma disk.

Five of Jupiter's moons have orbits inside the planet's magnetosphere. Io, the innermost moon, is thought to limit the number of charged particles in Jupiter's magnetosphere by scattering those that have diffused into the inner magnetosphere. In spite of this periodic clearing, the density of Jupiter's charged particles is several orders of magnitude greater than that of the Earth's. In addition, the energies of Jupiter's charged particles are about an order of magnitude greater than Earth's.

Plasma energies are so great, in fact, that trapped radiation caused transistor circuit failure on both Pioneer 10 and 11. The cumulative effects felt by both spacecraft was about 400,000 rads. Compare that to the fact that the effect of 400 rads on a human body is severe enough to cause radiation sickness or death.

## SATURN

In 1979, Pioneer 11 discovered Saturn's bow shock 1.44 million km from the center of Saturn on its sunward side and encountered the planet's intense magnetosphere, populated with charged particles, as it passed beneath its A ring (Saturn's faint outer ring). Saturn's magnetosphere is between 500 and 1000 times stronger than the Earth's but 36 times less than Jupiter's. So, its size, its population of charged particles, and its disk-like properties caused by satellites are somewhere between those of Earth and Jupiter. Saturn's outer magnetosphere is greatly distended on the dawn side but much less so on the sunward side.

Data from Voyager 1 (1980) indicates that Titan, Saturn's largest satellite, loses nitrogen gas from its upper atmosphere. The nitrogen ionizes, producing substantial quantities of plasma for Saturn's inner magnetosphere. Other sources may be Saturn's inner satellites, the planet's rings and its hydrogen-dominated upper atmosphere. The large inner satellites appear to absorb diffusing energetic electrons and protons. The intensity of all trapped particles decreases dramatically at the outer edge of ring A, indicating that they may be absorbed by ring material.

## URANUS

In the early 1980's, The International Ultraviolet Explorer satellite observed aurora-like emissions from hydrogen in Uranus' upper atmosphere, leading us to anticipate that Uranus has a magnetosphere. In 1986, Voyager 2, found that Uranus has a magnetic field that is about 0.1 that of Saturn, but its orientation is tilted 60 degrees away from its rotational axis and is offset by 0.3 Uranus' radii from the planet's center (see Figure 7).

Voyager 2 also confirmed that Uranus has a magnetosphere that is larger than the sun, but not so large as Jupiter's (see Figure 8.) It is comprised of plasma and a large population of energetic particles. Some of these particles are absorbed by Uranus' satellites and by particulate matter in the planets' rings, thus controlling the development of the inner magnetosphere.

Figure 7

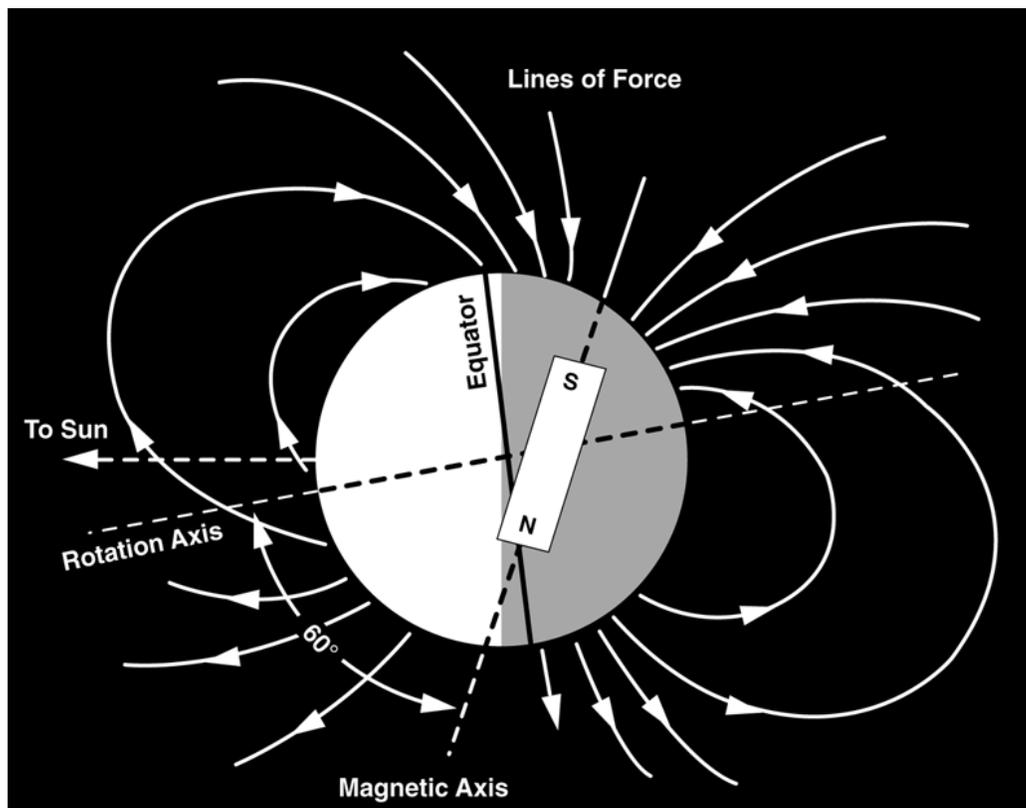


Figure 7. Diagram of Uranus' magnetic field, showing how the magnetic field is not only tilted away from the rotational axis but also offset from the planet's center. Note. The data in Figure 7 are from The New Solar System (Figure 17, p. 38), by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press.

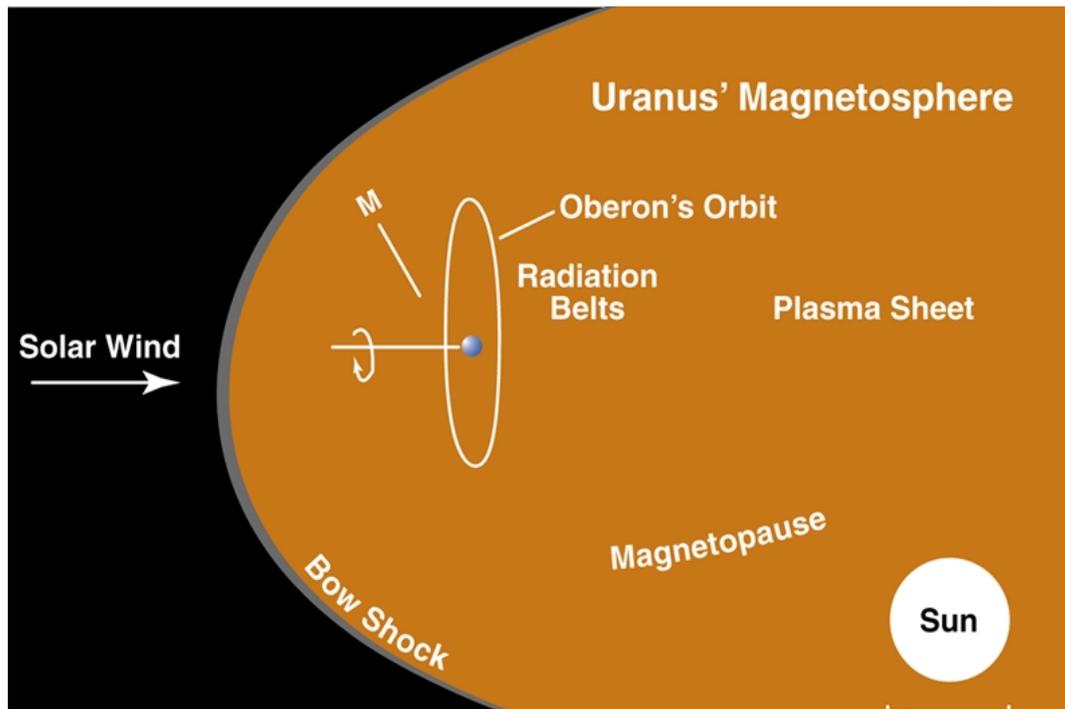
Uranus' upper ionosphere seems to be the primary source of energized particles, since the planet's extended magnetotail is rich in plasma, but helium and the heavier nuclei that characterize the solar wind were conspicuously absent from the trapped-particle population.

## NEPTUNE

Pioneer 10 established that the solar wind extends beyond Neptune. Voyager 2 found that Neptune's magnetic field is tilted 47 degrees from the planet's rotational axis and, like that of Uranus, is offset about 13,500 kilometers from the center of the planet. This causes marked changes in the magnetic field as the planet rotates in the solar wind. Its field strength varies from 0.1 gauss in the northern hemisphere to more than 1.0 gauss in the southern hemisphere.

Voyager 2 crossed the bow shock and entered the planet's magnetosphere, where it remained for almost four hours. It detected auroras similar to those on Earth. Unlike Earth's, which occur only near the planet's magnetic poles, those on Neptune occurred over wide regions of the planet's surface. Neptune's auroral power is close to 50 million watts, compared to Earth's 100 billion watts.

Figure 8



Note. The data in Figure 8 are from The New Solar System (Figure 18, p. 39), by J. K. Beatty and A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press.