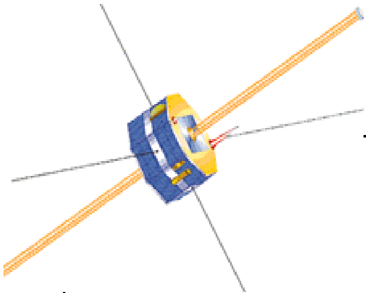


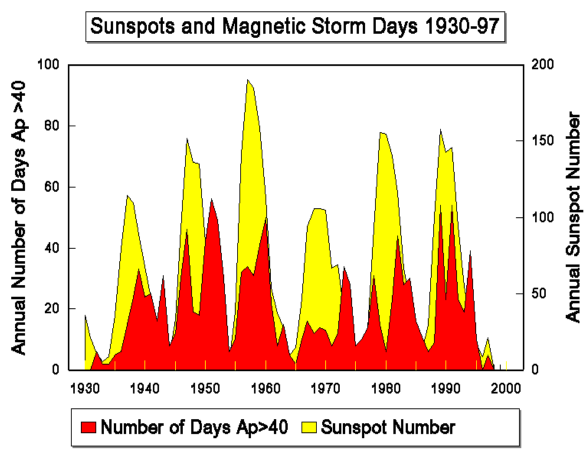
IMAGE Explores:
Geomagnetic Storms

The magnetic field of the Earth extends hundreds of thousands of kilometers into space, and is often buffeted by changes in the solar wind: a dilute stream of gas ejected by the Sun in all directions. These changes cause disturbances in the magnetic field that can be detected even at ground level on the Earth, with compasses or sensitive instruments called magnetometers. The *Imager for Magnetosphere-to-Auroral Global Exploration* (IMAGE) will study the space environment near the Earth during geomagnetic storms, and investigate how the particles and fields respond to solar storm conditions.

In the early 1800's Alexander von Humbolt studied these geomagnetic disturbances carefully for several years, and discovered that the ground level field would occasionally erupt in 'magnetic storms' in which compass directions could change by several degrees within an hour. Geomagnetic storms were soon found to occur at about the same time as aurora borealis displays in the northern hemisphere arctic regions. Scientists measure the strength of a geomagnetic storm by a quantity called the 'Ap index' which ranges from 0 to 400 depending on the intensity of the magnetic changes recorded at magnetic observatories.

Typically, the ground level field stays between 10-20, but occasionally storms of magnitude 70-90 occur which cause aurora and transformer problems. At a magnitude exceeding 250, blackouts are almost a certainty.

The number of geomagnetic storms, and their severity, follow the solar sunspot cycle as it increases and decreases over a roughly 11-year time period. During the most severe geomagnetic storms, electrical power networks experience transformer problems and even blackouts. A major geomagnetic storm on March 13, 1989 left six million people in Quebec without lights for up to 12 hours.



The IMAGE satellite is designed to 'photograph' the near Earth environment within the magnetosphere, and to study how trapped particles and their currents respond to changes in the solar wind and solar activity. Some of these changes lead to aurora, while others can lead to problems with satellites. Every five minutes, the satellite will return new images to scientists on the Earth to help them improve their theoretical understanding of the near-Earth environment . Forecasters will also use the data to spot 'storms in space', and provide improved predictions for space weather conditions.

IMAGE

For more classroom activities about space science, and information about the IMAGE satellite, visit http://image.gsfc.nasa.gov/poetry

In this activity, students will use two data tables that record the number and severity of geomagnetic storms during a solar cycle. They will plot this data and answer several questions having to do with how often geomagnetic storms occur during the year, and the frequency of their severity.

Table 1

Number of days with Ap > 40

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total	Sunspot Number
1976	1	0	2	2	1	0	0	0	1	1	0	1	9	13
1977	0	0	0	2	1	0	1	2	2	1	1	2	12	27
1978	2	1	2	5	2	4	2	2	3	0	2	1	28	92
1979	1	1	3	6	0	1	0	3	1	1	0	0	17	155
1980	0	1	0	0	1	1	1	0	0	2	0	1	7	154
1981	0	1	3	4	5	1	1	1	1	5	1	0	23	140
1982	0	10	2	3	3	2	3	3	4	3	3	4	40	115
1983	1	4	5	3	6	2	1	1	2	2	4	0	31	66
1984	0	4	2	3	1	1	3	1	4	2	1	0	22	45
1985	2	2	1	4	0	1	1	1	2	1	2	2	19	17
1986	1	1	0	0	2	0	0	0	2	1	2	0	9	13
1987	0	0	0	0	0	0	1	2	3	1	0	0	7	29
1988	2	1	2	3	1	0	0	0	1	1	0	1	12	100
1989	3	1	8	2	3	2	0	4	3	1	2	2	31	157
1990	0	1	5	3	1	1	1	2	0	2	1	0	17	142
1991	0	0	1	2	3	4	5	8	4	4	5	0	36	145
1992	0	6	0	0	2	3	0	2	4	1	1	1	20	94
1993	1	1	6	1	2	1	0	1	2	1	2	3	21	54
1994	0	5	4	5	6	0	0	0	1	6	1	0	28	29
1995	2	1	2	1	4	0	1	0	2	2	0	0	15	17
1996	0	0	0	0	0	0	0	0	0	1	0	0	1	8
1997	0	1	0	0	1	0	0	0	1	1	2	0	6	21
1998	0	1	1	1	2	1	1	2	1	1	2	0	13	64
1999	1	2	0	1	0	0	1	1	3	2	1	0	12	95

Table 2

List of Storms with Ap>40

Date	Ap
96/10/22	59
97/02/27	51
97/05/14	55
97/09/30	46
97/10/10	45
97/11/06	49
97/11/22	75
98/02/17	43
98/03/10	63
98/04/23	40
98/05/03	120
98/05/04	43
98/06/25	43
98/07/23	40
98/08/06	73
98/08/26	144
98/09/24	126
98/10/19	62
98/11/07	74
98/11/13	63
99/01/13	51
99/02/18	83
99/02/28	43
99/04/16	56
99/07/30	62
99/08/16	40
99/09/12	53
99/09/22	70
99/09/26	45
99/10/11	47
99/10/21	93
99/11/13	43

Ap data archive at NOAA ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/APSTAR/apstar.lst
Sunspot archive at NOAA ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/

Table 1 gives the number of days in which geomagnetic storms were more severe than Ap=40. Example: In 1982 during February (F) there were 10 such days. Also shown is the total number of stormy days per year, and the averaged sunspot number for that year in the last two columns.

Table 2 shows the actual storms recorded for the years 1996-1999 and when they occurred. Example: The only severe storm in 1996 was recorded on October 22 with an Ap index of 59. Table 1 for the year '1996' reflects this fact under the column 'O' which shows only 1 event.

1) Graph the number of stormy days (y-axis) vs the year (x-axis). Also plot on the same graph the sunspot number during each year.

Question 1: Do the annual number of severe geomagnetic storms follow the sunspot cycle?
Question 2: Relative to the average sunspot cycle, about when does the geomagnetic storm cycle peak?
Question 3: During which months are there, on average, more geomagnetic storms?

2) Graph the severity (Ap) of the storms between 1996 and 1999.

Question 4: About how often will you see storms more severe than Ap=60? 80? 119?
Question 5: During which part of a sunspot cycle do the most severe storms seem to occur? During maximum? During Minimum? 1-2 years before maximum?
Question 6: If you were planning a once-in-a-lifetime trip to view the aurora borealis, when would be the best time to take such a trip in order to maximize your chances of actually seeing one?

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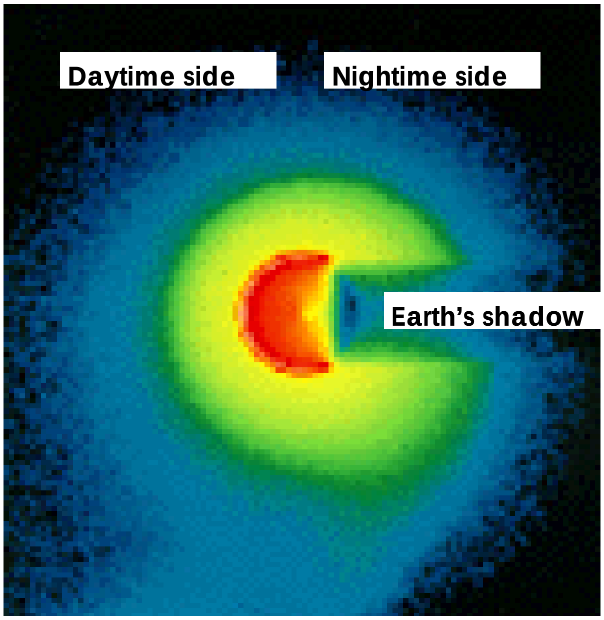
Educational Brief

Exploring the Plasmasphere with IMAGE



Simulated EUV image of the plasmasphere.

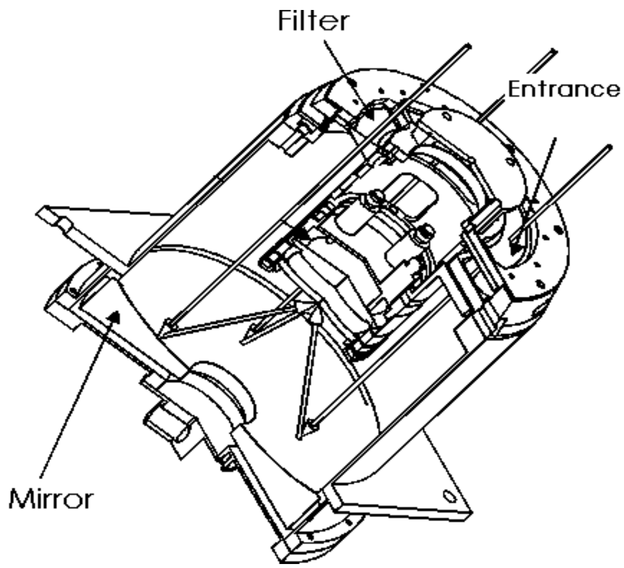
The Earth is surrounded by an invisible, and complex, region called the *magnetosphere*, in which charged particles, called *plasmas*, are affected by the terrestrial magnetic field. A particularly large collection of plasma resides within the so-called *plasmasphere.* This zone includes the van Allen radiation belts, and is an extension of the Earth's ionosphere.

The plasmasphere consists mostly of hydrogen and helium atoms. This cold, low energy plasma is illuminated by the sun, and the light from the helium atoms can be detected. This allows space scientists to study the plasmasphere by directly imaging it with the proper instruments.

The Imager for Magnetosphere-to-Auroral Global Exploration (IMAGE) will study how aurora are produced using an instrument called the Extreme Ultraviolet Imager. (***http://image.gsfc.nasa.gov/poetry***)

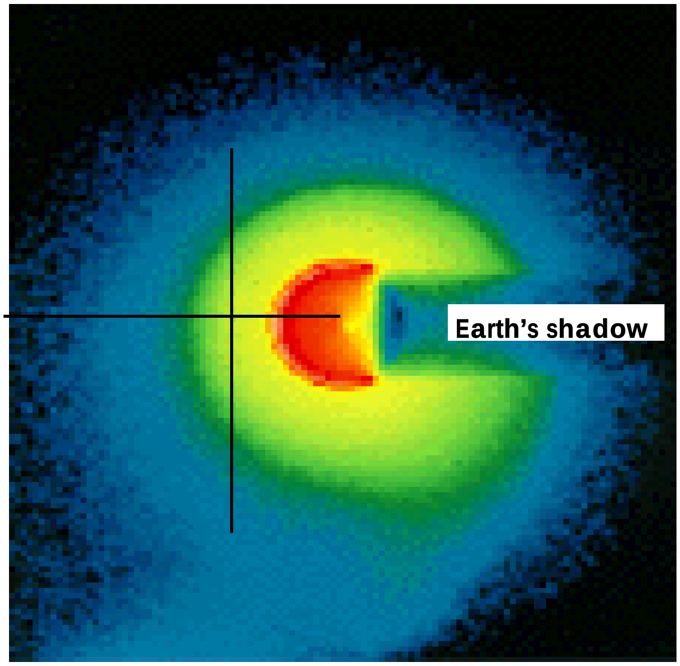
Extreme Ultraviolet Imager (EUV)

EUV operates like an electronic camera to detect the light from the plasmasphere produced by helium atoms. The plasmasphere is an important gateway for the transfer of particles and energy into the inner magnetosphere and the upper atmosphere. It is also an important storage area for low-energy, charged particles from the Earth's ionosphere. Space scientists want to investigate how the plasmasphere changes during magnetic storms. From previous satellite investigations, we know that it fills-up and discharges low-energy plasma, but space scientists don't as yet understand where the plasma goes. There has been some speculation that the plasmasphere produces 'plasma clouds' which then leave the plasmasphere on the daytime side of the Earth, but this has never been observed.



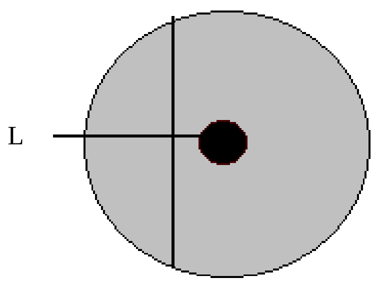
Schematic of the EUV camera.

Where Does Outer Space Start?

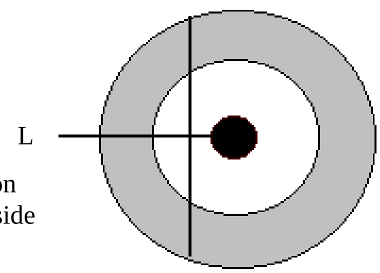


This picture, taken by the EUV camera, shows the size of the Earth's outer atmosphere. This region of the atmosphere is called the 'Exosphere'.

The colors you see, tell scientists how much gas there is at different distances from the Earth. There is about 100 times less gas in the blue areas than in the red areas of the picture.



This is a spherical cloud centered on the earth, that fills the complete volume.



This is a cloud centered on the earth that is empty inside and forms a shell of gas around the earth.

The brightness of a spot on the image of the exosphere depends on the length of the path through the cloud.

1...Draw a series of 10 equal-spaced chords along each line, L, across the two figures above. The one on the left shows a cloud of gas that completely fills the spherical volume. The one on the right shows a similar cloud that is hollow. An example of one of these lines is shown in each figure. Use the radius of the earth in each image to establish the correct scale for the plot.

2...If the intensity depends on the length of each chord that traverses the gas-filled part of the cloud, on a graph, plot the intensity of each chord (Y-axis) against the minimum distance of the chord from the center of the sphere (X-axis). For the above two lines, the one on the left will correspond to the brightest intensity because it intersects more of the light-emitting gas.

3...Use the image from the EUV camera to plot the actual intensity of the exosphere at a range of distances from the center of the earth in the figure at the top of the page. The marked line corresponds approximately to the ones in the two figures.

4...Is the exosphere brightness more consistent with a completely filled gas cloud or with a cloud that has a hollow center? How thick could the shel of gas be, and still be consistent in brightness with the EUV data?

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Educational Brief

Exploring the Aurora with IMAGE

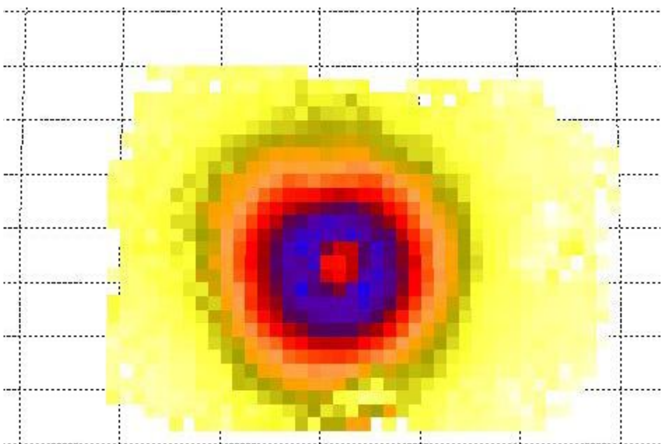


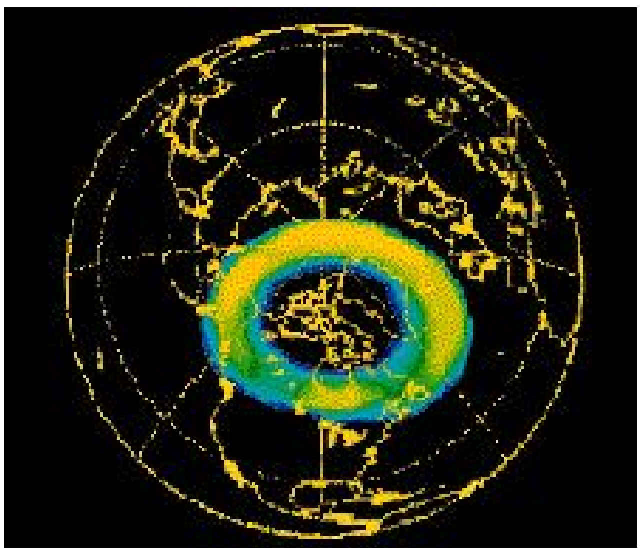
Image of the Geocorona obtained by the SOHO satellite.

The Earth is surrounded by an invisible, and complex, region called the magnetosphere, in which charged particles, called plasmas, are affected by the terrestrial magnetic field. Resembling a comet, the magnetosphere is drawn out into a long tail, called the magnetotail, on the nightime side of the Earth. The Earth's field changes in complex ways when the sun, or the solar wind are active, causing magnetic storms detectable from the ground. During the most severe magnetic storms, the magnetotail accelerates plasma into the interior of the magnetosphere. There, these currents collide with oxygen and nitrogen atoms to produce the aurora borealis and aurora australis, also called the Northern and Southern Lights.

The Imager for magnetosphere-to-Auroral Global Exploration (IMAGE) will study how aurora are produced using an instrument called the Far Ultraviolet Imager. (http://image.gsfc.nasa.gov/poetry)

Far Ultraviolet Imager (FUV)

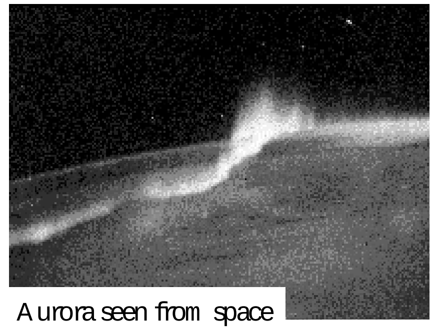
The FUV instrument, onboard the IMAGE satellite, consists of three separate sensors; the Spectroscopic Imager (SI), the Wide-band Imager (WIC) and GEO. These instruments work like a home video camera where focussing lenses concentrate the light, and an imaging sensor array detects the light and builds-up the picture electronically. These instruments also have filters to limit the detected, ultraviolet light to specific wavelengths. This helps space scientists investigate specific issues having to do with the way that aurora are produced and how they change in time. The instruments will be used to study the extended atmosphere of the Earth (called the exosphere), auroras produced by the bombardment of oxygen and nitrogen atoms by



The auroral oval as viewed by the POLAR satellite

The Magnetotail Battery and Aurora

Scientists have proposed that changes in the magnetic field in the magnetotail region, cause releases of energy that eventually supply the battery to 'light-up' the aurora on Earth. Let's explore this idea in more detail to see what they are talking about!



Aurora seen from space

1 How big a battery?

Energy is stored in a magnetic field, and the amount depends on how strong the field is, and how big a volume it occupies. Let's suppose the volume of the magnetotail region is a cylinder with a height of 300,000 kilometers, and a radius of 60,000 kilometers. Use the formula for a cylinder to estimate the magnetotail volume, in cubic meters.

$$V = \pi r^2 h = 3.14 \times (6\times10^9 \text{ meters})^2 \times (3\times10^{10} \text{ meters}) = 3.4 \times 10^{30} \text{ cubic meters}$$

The formula for the energy of a magnetic field is:

$$E = \frac{10^7}{8\pi} B^2 \times V$$

where B is expressed in Teslas, V in cubic meters, and the energy will then be in units of Joules.

For a magnetic field with a strength of 1×10^{-9} teslas, and the volume of space you just calculated, the total energy of the magnetotail field is:

$$E = 3.9\times10^5 \times (1 \times 10^{-9} \text{ teslas})^2 \times 3.4 \times 10^{30} \text{ m}^3$$
$$E = 5\times10^{17} \text{ joules}$$

As a comparison, your house uses about 10^8 joules of electricity per day.

2 How much energy do you need to light-up the auroras in the Northern and Southern Hemispheres?

Auroras are powered by currents of electrons that carry about 1,000,000 Amperes. Your home uses about 200 Amperes at 110 Volts. The atmosphere that this auroral current has to flow through has a resistance of about 0.1 Ohms.

Electrical power is calculated using a formula that relates resistance (R) and current (A) to the power (P) that they can produce in a circuit:

$$P = I^2 \times R \quad \text{Joules/second}$$

where R is measured in Ohms, and I is in Amperes.

The total auroral power is then:

$$P = (10^6 \text{ Amperes})^2 \times (0.1 \text{ Ohms})$$
$$= 10^{11} \text{ Joules/second}$$

3 How many seconds can the magnetotail 'battery' continue to supply energy to the aurora to keep them going?

Suppose that only 1% of the available energy from the magnetotail actually went into producing the aurora. About how long would the aurora last before it has used up the available energy? The answer to the first question tells us how much power is available. The answer to the second question tells us at what rate (energy per second) the aurora are wasting energy as light and heat are generated. To find out how long this can continue, divide the answer from question one, by the answer from question two:

$$\text{Time} = \frac{0.01 \times 5\times10^{17} \text{ Joules}}{10^{11} \text{ Joules/second}} = 5\times10^4 \text{ seconds, or about 14 hours}$$

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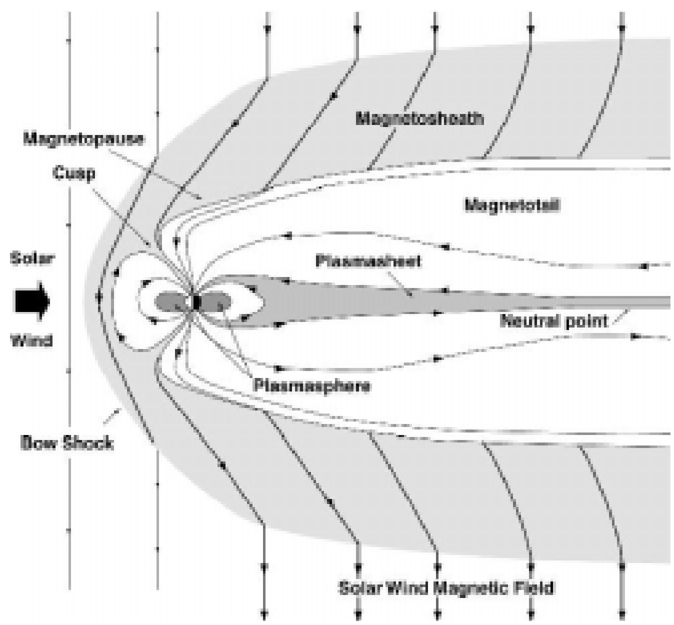
Educational Brief

Exploring the Magnetopause with IMAGE

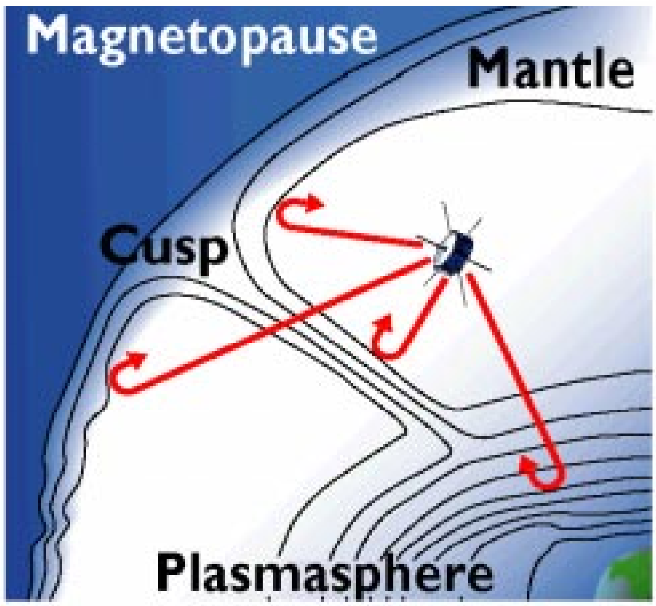


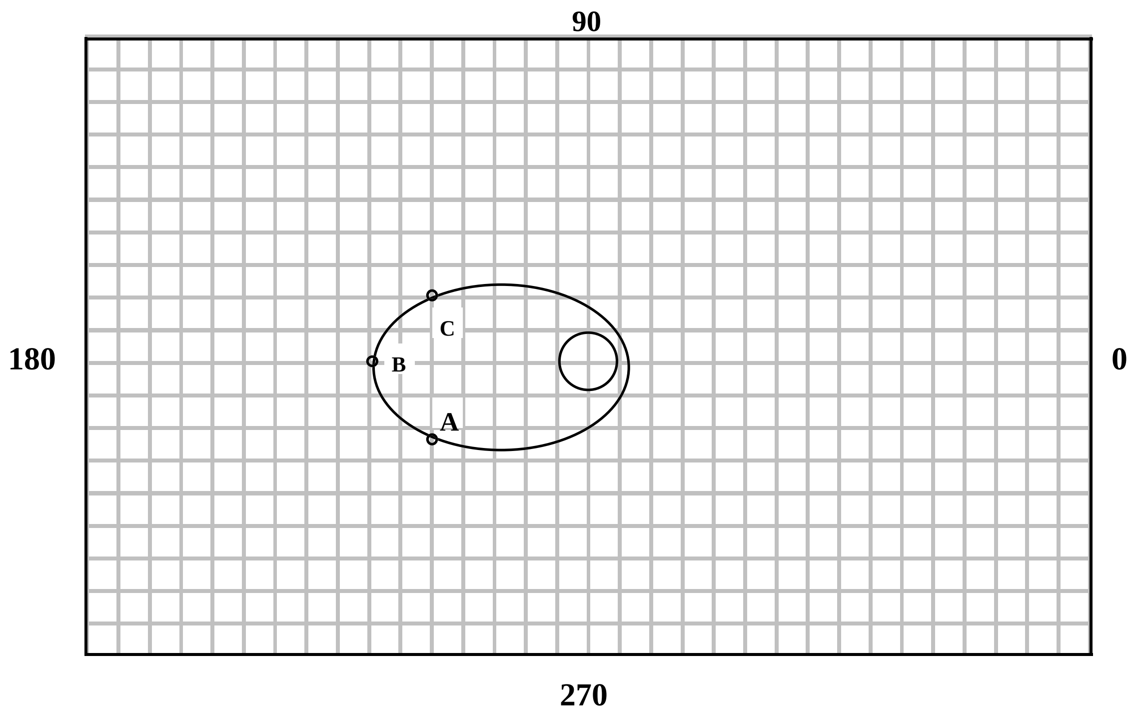
The Earth is surrounded by an invisible, and complex, region called the *magnetosphere,* in which charged particles, called *plasmas,* are affected by the terrestrial magnetic field. This field changes in complex ways when the Sun is active and 'stormy'. Space scientists have identified a number of important parts to the magnetosphere as you can see in the diagram to the left. The van Allen radiation belts occupy a region called the *plasmasphere.* The magnetosphere is stretched out into a comet-like region, called the *magnetotail.* Like a boat making headway in the water, a bow wave or *bow shock* forms in the incoming solar wind. Behind this *bow shock* is a complex region of turbulent gas called the *magnetopause.*

The Imager for Magnetosphere-to-Auroral Global Exploration (IMAGE) will study this region using an instrument called the Radio Plasma Imager.

Radio Plasma Imager (RPI)

The RPI instrument onboard the IMAGE satellite works like a policeman's radar speed detector, but on a much bigger scale. Every 5 minutes, RPI emits a series of radio pulses between 3 kiloHertz and 3 MegaHertz using its 10-watt transmitter. The 500-meter tip-to-tip antennas detect the returning echos from the pulses after they have been reflected by distant clouds of plasma. By studying the intensity and timing between the outgoing and incoming signals, scientists can 'take a snapshot' of the charged particle clouds, and their movements around the earth. This is the first time such an instrument has been flown into space. Space scientists expect that by imaging and tracking the motions of these clouds of plasma, they will be able to understand much better how the earth's environment in space is affected by solar storms. These storms can cause electrical blackouts and satellite malfunctions.





RPI Data Table

RPI scientists recorded six echos from the magnetopause at three locations along the IMAGE satellite's orbit. The location of the satellite is identified by 'A', 'B' and 'C' in the figure, and makes two soundings at each location as shown in the table. Each square in the grid equals the radius of the earth (6378 kilometers). The numbers 0, 90, 180 and 270 define specific satellite viewing directions in degrees, in a coordinate system centered on the satellite's location. All times are given in seconds.

Location	Transmit Time	Receive Time	Direction (Degrees)
A1	19.187	19.461	255
A2	20.397	20.587	210
B1	7256.848	7256.986	190
B2	7393.217	7393.397	130
C1	14513.802	14514.014	120
C2	14681.379	14681.697	80

1) Compute the difference between the transmit and return times to determine the round-trip signal delay. (Example: 19.461 - 19.187 = 0.274 seconds)

2) Divide the round-trip times by 2 to get the one-way time for the signal to echo from the cloud and return to the satellite. (Example 0.274 seconds/2 = 0.137 seconds)

3) Multiply the answer in #2 by the speed of light in kilometers/sec to get the distance traveled from the point of reflection (Example: 0.137 sec x 300,000 km/sec = 41,100 km) Divide by the radius of the earth to convert to grid units in the above graph. (Example: 41,100 km/6378km = 6.4 earth radii)

4) Place a protractor on Point A in the diagram above, and place a dot on the map along the direction given in the table entry, and mark it at a distance from the satellite equal to the number of earth radii computed in Step 3.

5) Repeat Steps 1-4 for each of the 6 echo measurements in the table, and when finished, connect the dots with a smooth line to show where the RPI instrument found the magnetopause.

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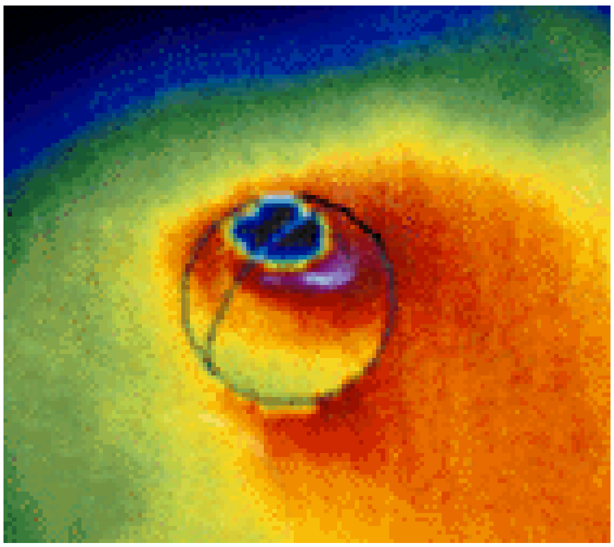
Educational Brief

Exploring the Ring Current with IMAGE



Simulated view of neutral atom cloud near the Earth

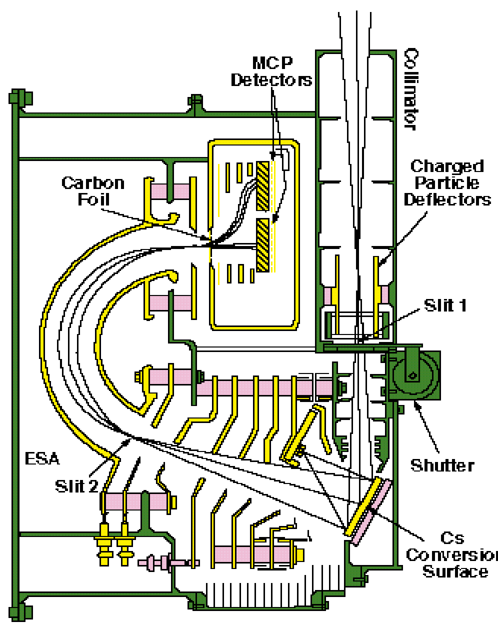
Electrically-charged particles from the Sun can become trapped in the Earth's magnetic field. Some of them circulate around the Earth's equatorial regions at distances between 1,000 and 40,000 kilometers. Positively charged particles circulate from west to east, while negatively charged particles flow from east to west. Space scientists call these the *ring current*, and they can cause rapid changes in the magnetic field of the Earth. These changes are especially severe during solar storm conditions when the ring current becomes very strong.

The Imager for Magnetosphere-to-Auroral Global Exploration (IMAGE) will study how the ring current is produced using instruments called Energetic Neutral Atom imagers: LENA, MENA and HENA (***http://image.gsfc.nasa.gov/poetry***)

Energetic Neutral Atom Imagers (ENA)

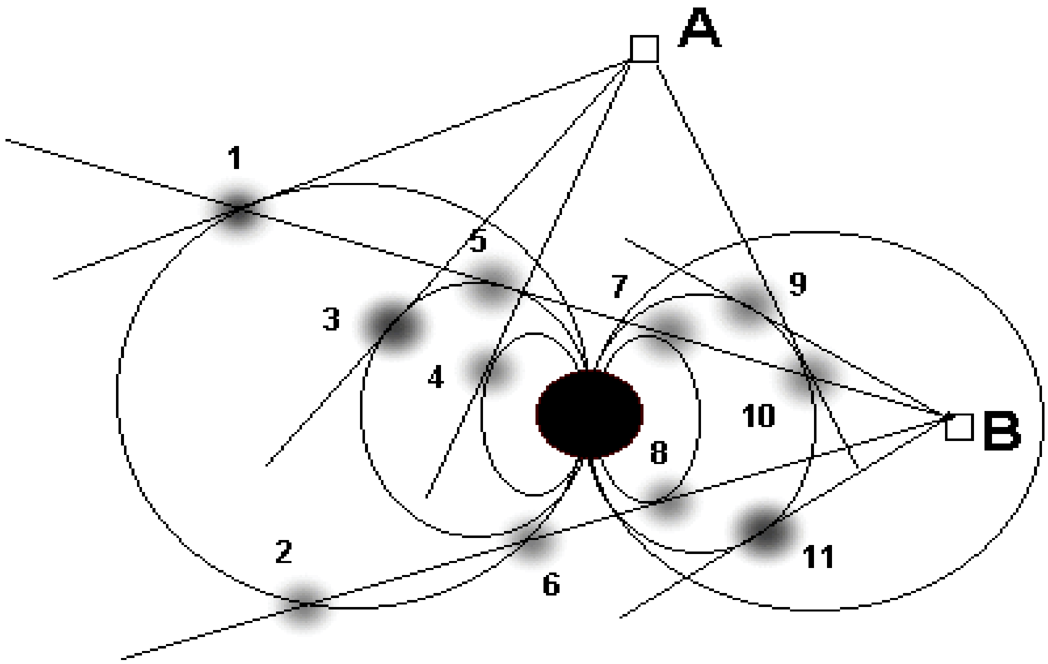
The ring current involves charged particles, but scientists cannot study them directly. Instead, the ENA imager onboard the IMAGE satellite detects the neutral atoms in the Earth's outer atmosphere which the ring current particles collide with. Like a gigantic billiard game, the charged particles collide with the neutral particles. Some of these neutral particles escape to where the IMAGE satellite is located in its orbit, and enter one of the three ENA imagers. Each imager detects one of three types of particles: low-energy (LENA), medium-energy (MENA) and high-energy (HENA). Together, these particles help scientists explore the ring current.

From this data, space scientists will study how plasma enters the magnetosphere and gets accelerated to high energies, and how the ring current populations change during large solar storm events.



Schematic of the LENA instrument.

Exploring clouds of plasma near the Earth



The IMAGE satellite sees the ring current as a blob of light near the equatorial plane of the Earth, but scientists have to use other clues to decide where parts of this blob are located in space. In this simplified example, let's assume that the instruments can only detect neutral atoms if they come from collisions with charged atoms near the point where the local magnetic field is tangent to the line-of-sight of the instrument. By knowing what the geometry of the Earth's field is like, scientists can work backwards to find where the particles were.

In the above figure, the IMAGE satellite observes a set of clouds located at the indicated positions from two vantage points in its orbit: A and B. From what you have learned about how the neutral atom imagers operate, identify which of the 11 clouds can be seen at satellite locations A and B.

Answer:
Location A: Cloud 1, 3, 4 and 10.
Location B: Cloud 7, 8, 9 and 11.

Are there some clouds seen at one satellite location but not at another?
Answer: Yes. Cloud 10 can be seen at Location A but not at Location B even though it is close to location B.

Which clouds cannot be seen at either location? Answer: Cloud 2 and 6.

Where would additional vantage points have to be to see these clouds?