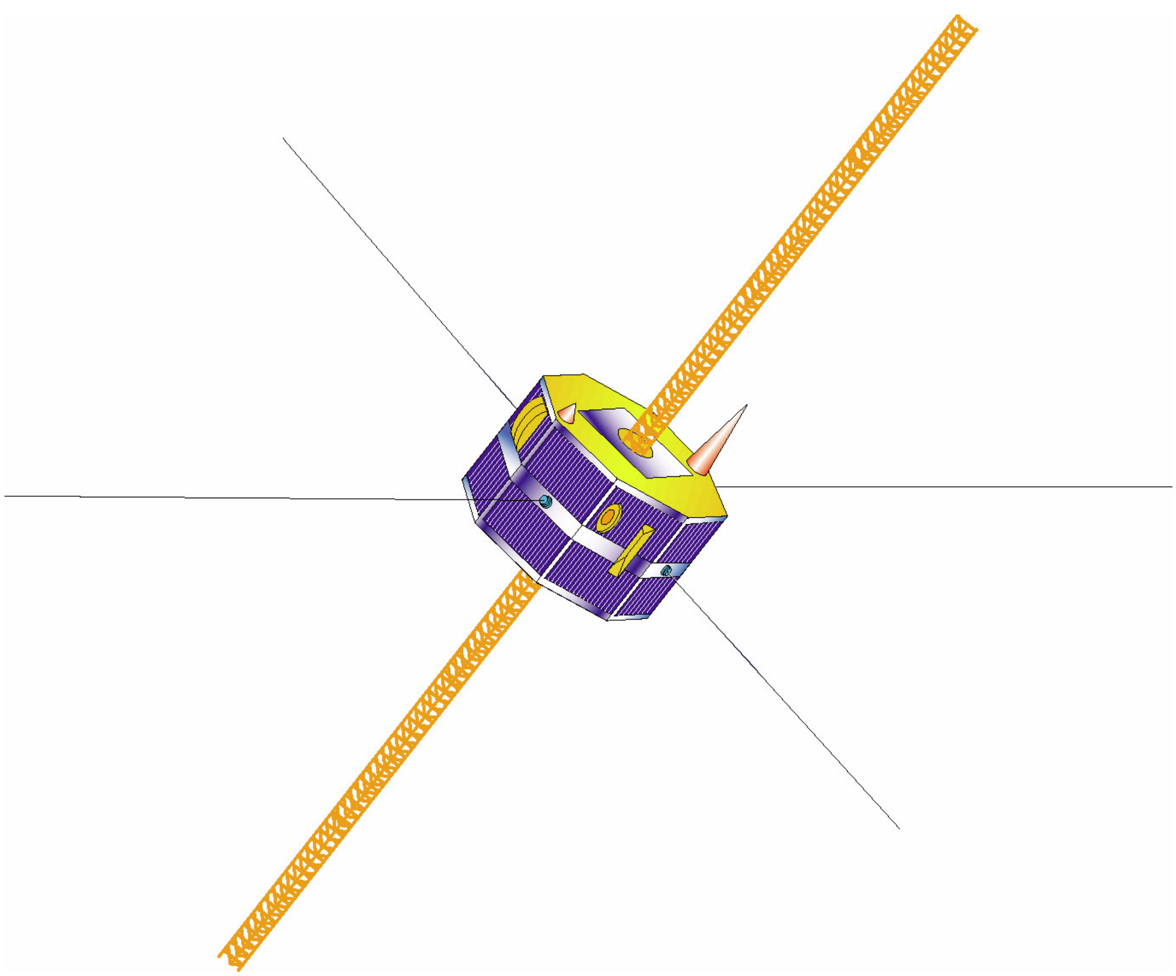
National Aeronautics and Space Administration

The Mission and Instruments of IMAGE

Part 2

An Analysis of a NASA Mission for High School Physics Students



The Mission and Instruments of IMAGE – Part 1 is available in electronic format through NASA Spacelink – one of the Agency's electronic resources specifically developed for use by the education community.

The system may be accessed at the following address:

http://spacelink.nasa.gov

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Information about the IMAGE mission is available at:

http://image.gsfc.nasa.gov

Resources for teachers and students are available at:

http://image.gsfc.nasa.gov/poetry/

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National Aeronautics and Space Administration
Goddard Space Flight Center

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Table of Contents

Level: High School Physics (Second Semester Review)
Pre-Calculus Mathematics

By: Bill Pine
Chaffey High School
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Science Process Skills for
The Mission and Instruments of IMAGE – Part 2

This chart is designed to assist teachers in integrating the activities with existing curriculum.

RPI	Problems 1-5	Magnetopause Range
RPI	Problems 6-10	Magnetopause Direction
NAI	Problems 1-17	Time of Flight Problems
NAI	Problems 18-23	Total Count Determination
UV	Problems 1-3	Doppler Shift

	RPI		NAI		UV
	1-5	6-10	1-17	18-23	1-3
Observing					
Classifying				x	
Communicating	x				
Experimental Design					
Gathering Data				x	
Organizing Data				x	
Controlling Variables					
Developing Hypothesis					
Extending Senses					
Researching					
Teamwork					
Mathematics	x	x	x	x	x
Interdisciplinary					
Introductory Activity	x			x	
Advanced Activity		x	x		x

Science and Mathematics Standards for
The Mission and Instruments of IMAGE – Part 2

NATIONAL SCIENCE STANDARDS	RPI		NAI		UV
	1-5	6-10	1-17	18-22	1-3
A. SCIENCE AS INQUIRY					
Science as Inquiry	x	x	x	x	x
B. PHYSICAL SCIENCE					
Motions and Forces	x	x	x	x	x
Conservation of Energy					
Interactions of Energy and Matter	x	x	x	x	x
C. LIFE SCIENCE					
D. EARTH AND SPACE SCIENCE					
Energy in the Earth System	x	x	x	x	x
Origin and Evolution of the Earth System					
E. SCIENCE AND TECHNOLOGY					
Understandings about Science and Technology	x	x	x	x	x
F. PERSONAL AND SOCIAL PERSPECTIVES					
G. HISTORY AND NATURE OF SCIENCE					
Science as Human Endeavor	x	x	x	x	x
Nature of Scientific Knowledge	x	x	x	x	x
Historical Perspectives					

NCTM MATH STANDARDS	RPI		NAI		UV
	1-5	6-10	1-17	18-22	1-3
Number and Operations Standard					
Large/small numbers	x	x	x		x
Compute fluently	x	x	x	x	x
Algebra Standard					
Analyze change: graphical data				x	
Geometry Standard					
Specify locations: polar coordinates		x			
Measurement Standard					
Units and scales	x	x	x	x	x
Data and Probability Standard					
Display and discuss bivariate data					
Problem Solving Standard					
Apply a variety of problem solving strategies					x
Reasoning and Proof Standard					
Various types of reasoning		x		x	
Connection Standard					
Contexts outside of mathematics	x	x	x	x	x

Appendix A

Teacher Notes

The Mission and Instruments of IMAGE – Part 2 is designed to be used in conjunction with **The Mission and Instruments of IMAGE – Part 1** and **Tracking a Solar Storm Parts 1 and 2** although it may be used by itself.

The second cover (Page ix although not numbered) and the pages that follow are designed to be distributed to the students and constitute their resource for doing this work. In addition to this document, the internet is a resource that may also be used. The links in the sidebars will lead to web sites that contain much valuable background information.

Since this material is so new, vocabulary words that appear in **boldface** the first time they are used are defined in the Glossary (Page 39).

The problems sets that appear throughout the document can serve as class work and homework problems. Some may be extracted to serve as assessment questions. The teacher may also create similar problems using the formats given.

The material contained here probably consists of topics that the typical student (and teacher!) is not familiar with. The fact that it is new material is both a positive and a negative. The positive is that the topics described here, and the mission of IMAGE itself, represent the latest in space physics. The material here is not in the typical high school physics text. The main reason for this is that IMAGE is attempting to answer questions that have not been answered yet and, in fact, to answer questions that have not even been posed yet.

The negative aspect of studying such new material is that typically students (and teachers) are less comfortable with new concepts than with the more familiar. That being said, you can kind of relax knowing that many of the questions asked by students can be answered with a little research on the web. It is also important to note that many of the questions that may come up have not been answered by anybody …yet. It is important for students to have some contact with a truly "cutting edge" area of science.

The IMAGE Education and Public Outreach Team hopes you find this material useful. Any comments, criticism, and suggestions are welcome.

Bill Pine
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Appendix B

Answers to Exercises:

Page 9, RPI Problems 1-5:

1. $9\ R_E$
2. $12.5\ R_E$
3. $7.1\ R_E$
4. $10.1\ R_E$
5. $6.94\ R_E$

Page 11, RPI Problems 6-10:

6. 150.3^o
7. 58.2^o
8. 332.4^o
9. 215.3^o
10. 225^o

Page 23, HENA Problems 1-5:

1. 2.67×10^{-26} kg
2. 3.4×10^{5} m/s
3. 9.8×10^{6} m/s
4. 7.4×10^{-7} s
5. 2.6×10^{-8} s

Page 23, MENA Problems 6-9:

6. 1.1×10^{5} m/s
7. 2.4×10^{6} m/s
8. 2.3×10^{-6} s
9. 1.0×10^{-7} s

Page 23, LENA Problems 10-13:

10. 1.1×10^{4} m/s
11. 2.4×10^{5} m/s
12. 2.3×10^{-5} s
13. 1.0×10^{-6} s

Page 23, NAI Problems 14-17

14. Oxygen, 16 amu
15. 1 amu, 81.6 eV
16. 16 amu, 15 keV
17. Hydrogen, 1.3×10^{-7} s

Page 26, NAI Problems 18-19

18. R 14.5, O 13, Y 12, G 10, LB 7, DB 4, V 2
19. R 62, O 55, Y 51, G 43, LB 28, DB 18, V 8

Pages 28-31, NAI Problems 20-23

20. Total = 668 counts
21. Total = 433 counts
22. Total = 631 counts
23. Total = 474 counts

Page 38, UV Imager Problems 1-3

1.
   A. 2.465×10^{15} Hz
   B. 2.472×10^{15} Hz
   C. 8.514×10^{5} m/s
   D. 6.052×10^{-16} J
   E. 3.783×10^{3} eV

2.
   A. 2.465×10^{15} Hz
   B. 2.457×10^{15} Hz
   C. -9.730×10^{5} m/s
   D. 7.905×10^{-16} J
   E. 4.941×10^{3} eV

3.
   A. 2.465×10^{15} Hz
   B. 2.478×10^{15} Hz
   C. 1.543×10^{6} m/s
   D. 1.988×10^{-15} J
   E. 1.242×10^{4}

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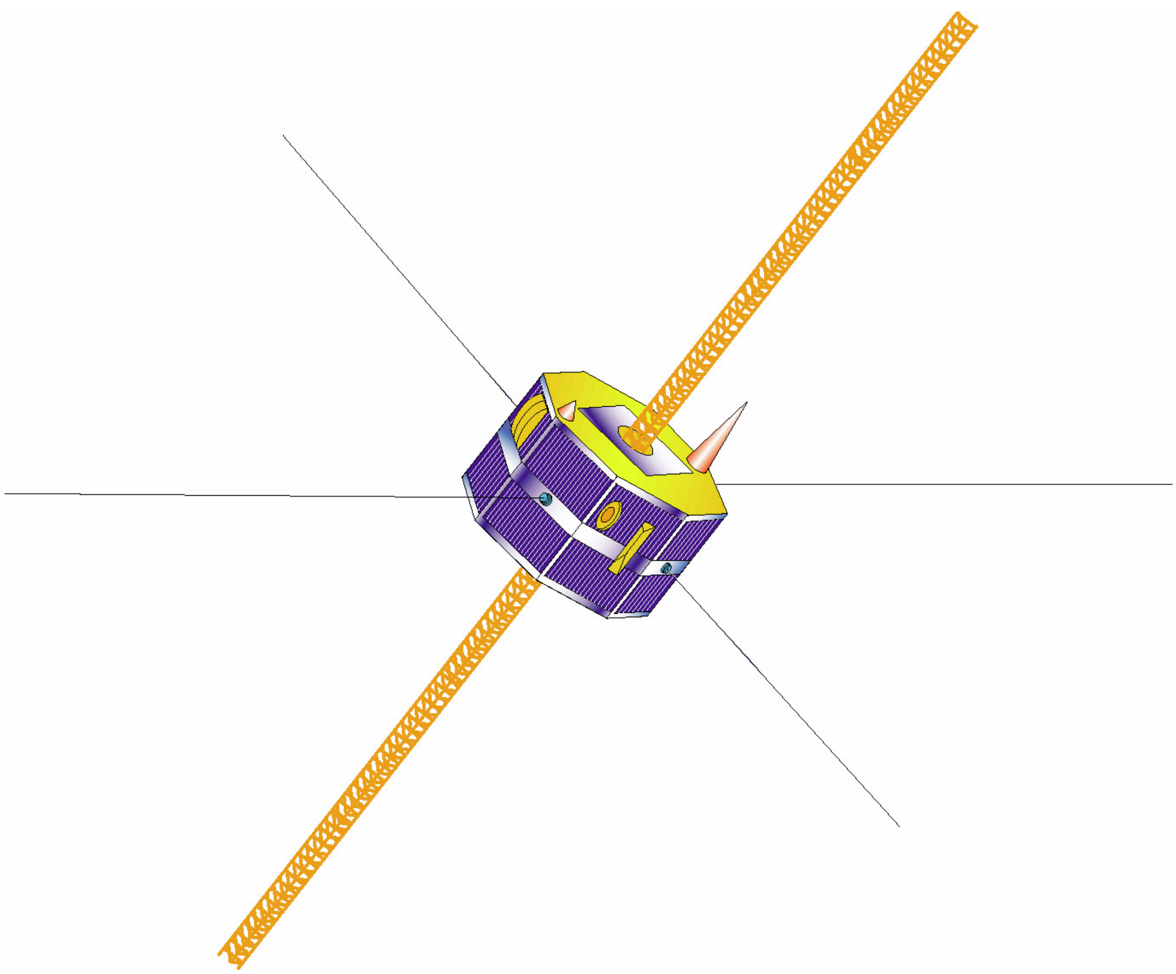

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Level: High School Physics (Second Semester Review)
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Chapter 4 Radio Plasma Imager (RPI)

The Beginnings: [In 1959], James A. Van Allen and his colleagues forever changed our popular view of near-Earth space as a bland and empty void. Using instruments onboard the first NASA satellite, Explorer 1, they discovered an unexpected and teeming population of charged particles confined within the Earth's magnetic field. Immediately following this discovery, global models of these trapped particles - the Van Allen radiation belts - were developed from their theoretically expected motions in the Earth's field as it was known at the time. This desire to build a global picture based upon the few available measurements in the Earth's space environment has proven prophetic. From these earliest days one of the major quests of space plasma physics has been to develop an accurate global perspective of the magnetosphere and its component parts.

- *Magnetosphere Imager Science Definition Team Interim Report*
NASA Reference Publication 1378

Magnetic Fields in the Solar System

Earth is protected from the **solar wind**, a continuous flow of energetic charged particles from the sun, by Earth's magnetic field. The magnetic field diverts the particles so that most of them flow past Earth without getting very close to the surface. Some of the particles follow magnetic field lines toward the north and south magnetic poles where they cause the **aurora** as they enter Earth's lower atmosphere. Understanding exactly how these particles behave as they flow outward from the sun toward Earth and what the effect is on Earth's magnetic field and the region around Earth are the goals of the instruments on the IMAGE satellite.

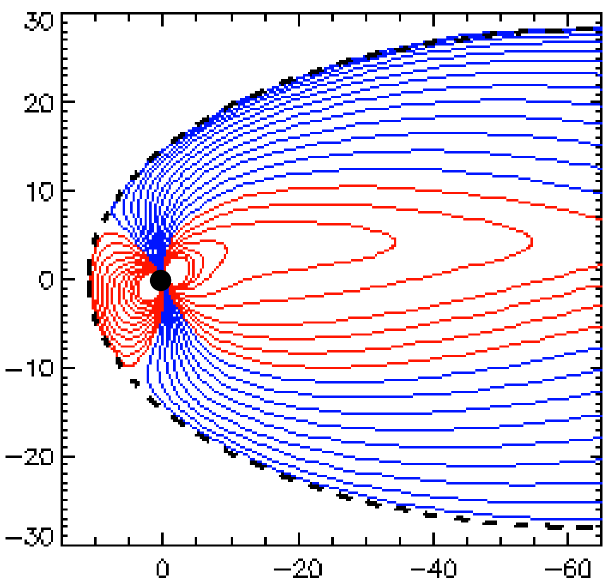


Figure 1. Earth's **Magnetosphere**

Distances are given in **Earth radii**.

Earth (●) is at (0,0).

The dashed line is the **magnetopause**.

The sun is to the left.

The solar wind distorts Earth's magnetic field: it compresses the **day side** (toward the sun) and stretches the **night side** (away from the sun).

Distances in the magnetosphere are often measured in Earth radii (**R_E**), with one Earth radius amounting to 6371 km or 3960 miles. In these units, the distance from the Earth's center to the "nose" of the magnetosphere is about 10.5 R_E and to the flanks abreast of the Earth about 15 R_E, while the radius of the distant tail is 25-30 R_E. By way of comparison, the moon's average distance is about 60 R_E.

These, though, are just averages: the pressure of the solar wind rises and falls, and as it does, the magnetopause shrinks or expands. For instance, when the boundary is hit by a fast flow from a coronal mass ejection, the "nose" is pushed in, occasionally (a few times a year, usually) even past the **synchronous orbit** at 6.6 R_E.

The Exploration of the Earth's Magnetosphere
by: David P. Stern - NASA/GSFC Code 695
Mauricio Peredo - Raytheon STX Corporation

URL: http://www-spof.gsfc.nasa.gov/Education/Intro.html

The region around Earth where Earth's magnetic field is the predominate field is called the magnetosphere. The region of interplanetary space where the solar magnetic field predominates is called the **Interplanetary Magnetic Field**, or **IMF**. As the solar wind flows outward from the sun, the IMF is carried along. The boundary between the IMF and the magnetosphere is called the magnetopause. The location of the magnetopause at any given time depends on the balance between the pressure exerted by the solar wind on the magnetosphere pushing in and the pressure of Earth’s magnetic field and of the particles within the magnetosphere pushing out. The pressure exerted by the solar wind depends on the speed of the particles and their density. When an energetic solar event, such as a **coronal mass ejection** (**CME**), occurs, the resulting solar wind will have a higher density and higher speed exerting an increased pressure and as a result compressing the day-side of the magnetosphere and decreasing the distance from Earth to the magnetopause.

Determining the location of the magnetopause is important to scientists (and people in general!) because knowing where the magnetopause is and how its location responds to changes in solar wind activity will help us understand the connection between what happens on the sun and the consequences for us here on Earth.

How can the Location of the Magnetopause be Determined?

In the past, the only way to determine the location of the magnetopause was to have a satellite carrying a **magnetometer** (a device for measuring magnetic fields) pass through the boundary. As it passed through the magnetopause, the satellite could determine the location of the magnetopause in that region of space and at that particular time only. This is called an ***in situ*** measurement, meaning that the instrument was at the location of the magnetopause when the measurement was taken. If there were a change in solar activity, it would be unlikely that there would be a satellite with the appropriate instruments anywhere near the magnetopause at the right time.

From *in situ* measurements in the past it has been determined that the magnetopause on the side toward the sun is located at a distance from Earth that varies from around 90,000 kilometers (14 Earth radii (R_E)) down to about 32,000 kilometers (5 R_E) with 64,000 kilometers (10 R_E) as a common value. The exact location at any time depends on the recent activity of the sun and the resultant strength of the solar wind. To determine the location of the magnetopause constantly over a period of time using *in situ* measurements would require an huge fleet of satellites equipped with magnetometers. Due to the enormous cost, this is not a workable solution. What is needed is a different approach.

> Time variations: The greatest obstacle in all our attempts to synthesize an accurate global picture of the magnetosphere is its time variability. Major regions of the magnetosphere can alter significantly their shape, composition, and interconnectivity over time scales far shorter than our capability to observe them by *in situ* measurements. The vast size of the magnetosphere will, in all probability, always preclude the establishment of a sufficiently dense network of *in situ* observations to accurately measure the global magnetosphere.
> \- *Magnetosphere Imager Science Definition Team Interim Report*
> *NASA Reference Publication 1378*

Remote Sensing

Remote sensing is a measurement technique that is an alternative to *in situ* measurements. In remote sensing, the instrument does not need to be at the location where the measurement is taken. A simple example of a remote sensing instrument is a camera. A camera uses light from the subject to form an image which can then be captured on film. The result is a photograph of an object taken without the camera getting anywhere near the subject. Remote sensing is required to obtain photographic images of distant galaxies and other astronomical bodies.

There is a problem with using remote sensing to measure magnetic fields at locations away from the instruments: at the low magnetic fields found at the magnetopause, it is nearly impossible! There is no easy way to detect or measure the magnetic field itself without being at the location of the measurement. When that is the case, scientists look for something else that can be measured remotely that will give the desired information. In the case of the magnetopause there is something else that occurs: at the magnetopause, the charge density of space changes. Just inside the magnetosphere, the charge density (made up mostly of free electrons and hydrogen ions - protons) is about 5 electrons per cubic centimeter or less. Outside the magnetosphere, in the interplanetary medium, the density is about the same. At the magnetopause the charge density is much higher - up to 100 electrons per cubic centimeter. Unfortunately, electron charge densities can't easily be remotely sensed either!

This leaves us with the problem of finding something that can be measured remotely to indicate where the magnetopause is located. The solution to our dilemma is to use radio frequency electromagnetic waves. These waves travel through space at the speed of light and, like light, their path is changed when they encounter a different medium. For radio waves, the change in charge density at the magnetopause is a change in medium just like when visible light waves encounter a change in medium such as traveling from from air into glass. When light travels from air to glass, several things happen: the light changes to a slower speed in the glass, the light path changes direction and some of the light is reflected. The last of these behaviors can be used to remotely sense the location of the magnetopause. When radio waves from a satellite within the magnetosphere encounter the increased electron density at the magnetopause, some of the radio wave is reflected. If you can measure the time it takes for the radio wave to travel to the magnetopause and back to the satellite and you know the speed of light, you can easily calculate the distance from the satellite to the magnetopause. This is the principle behind the **radio plasma imager** (**RPI**)..

The Radio Plasma Imager

> 3.3 - Radio Plasma Imager (RPI)
>
> The Radio Plasma Imager (RPI) is a transmitter/receiver system that responds to the science requirement for the continuous remote sensing of plasma densities, structures and dynamics in the magnetosphere and plasmasphere. The instrument measures the time delay, angle-of-arrival, and Doppler shift of magnetospheric echoes over the frequency band from 3 kHz to 3 MHz. This frequency range makes possible remote sensing of plasma densities from 0.1 to 10^5 cm^{-3}..
>
> IMAGE RPI Technical description: URL: http://image.gsfc.nasa.gov/rpi/

One role of the Radio Plasma Imager is to determine the location of the magnetopause. To accomplish this, radio waves are transmitted by IMAGE and the reflections of these waves from the magnetopause are received. To determine the location of the magnetopause, two questions need to be answered:

1. What is the distance from Earth to the magnetopause?

and 2. In which direction is that distance measured?

Determining the Distance to the Magnetopause

In principle, this determination is made by using the definition of velocity to determine the distance. A radio signal is sent out from IMAGE and the time for the signal to reflect from the magnetopause is measured. This time is called the "**echo time**". Since you know the speed of light (3.0×10^8 m/s), the distance from IMAGE is found by multiplying half the echo time times the speed. If you know the position of IMAGE relative to Earth, the distance from Earth to the magnetopause can be determined easily. For example, if IMAGE is at apogee (a distance of 8 R_E from Earth's center) and the echo time is .086 seconds, calculations show that the magnetopause is located 10 R_E from Earth's center (See Example Problem 1). This is a typical location for the magnetopause for normal levels of solar activity.

[NOTE: The following analysis is given in 2 dimensions only (the x-y plane). IMAGE must do the computation in three dimensions. This involves the use of the third antenna - the z-antenna. This antenna is shorter than the x- and y- antennas, so the voltages induced on it by a given signal echo will be smaller. The z-voltage is amplified by IMAGE before the computation is made to allow for the difference in antenna lengths. The method of determining the distance and direction to the magnetopause is similar to the 2-dimensional analysis. **It is also assumed in the following that the returning radio wave is linearly polarized. In fact, the reflected wave is elliptically polarized.**]

> RPI will have two crossed 500-m tip-to-tip thin wire dipole antennas in the **spin plane**, and a 20-m tip-to-tip dipole antenna along the **spin axis**. All three antennas will be used for reception to determine the angles of arrival of the echoes [Calvert et al., 1995].
>
> IMAGE RPI Technical description: URL: http://image.gsfc.nasa.gov/rpi/

Determining the direction to the Magnetopause:

Radio waves reflect according to the Law of Reflection just like light does. In order for radio waves to be reflected back to their point of origin (the IMAGE spacecraft), the waves have to strike the boundary between media - the magnetopause - perpendicular to that boundary. The waves must travel right down the normal to the surface in order to be reflected back to IMAGE. If the inner surface of the magnetosphere is smooth, then the reflection will come from exactly one point. If the inner surface of the magnetosphere is not smooth, then reflection could be returned to IMAGE from several locations on the magnetosphere. The following figures illustrate two possibilities.

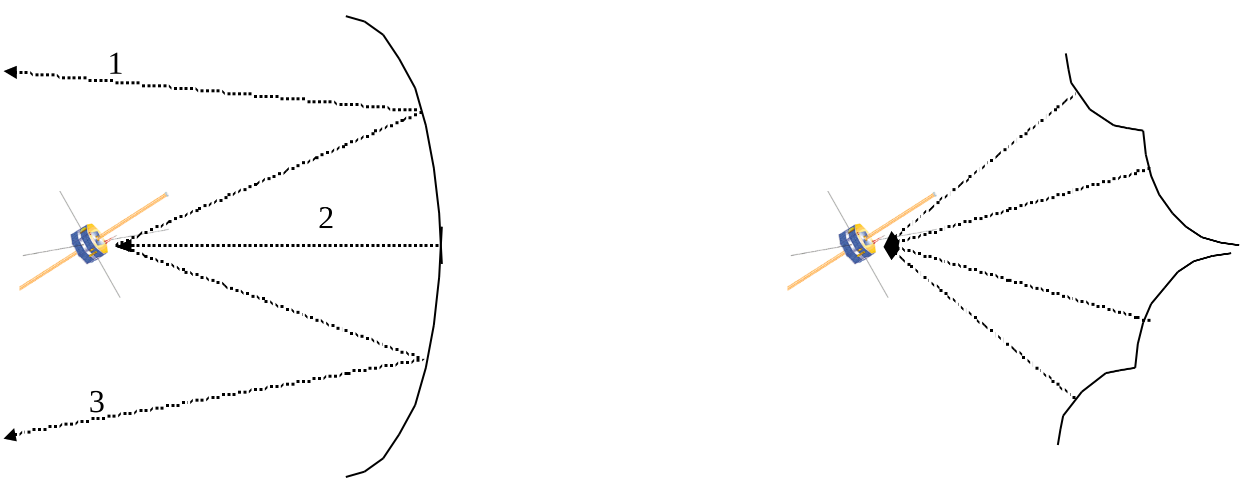


Figure 2. Ray diagrams of reflection from the magnetopause.

(a) Reflection from a smooth curved surface. Only Ray 2 will reflect back to IMAGE.

(b) Reflection from a more complex surface. IMAGE will receive reflections from all four rays shown.

The radio signals radiate outward from IMAGE in all directions. It is possible that the reflected wave could come from just about any direction (and from more than one direction). The antennas of IMAGE will receive the returned signal and from the strength of the signal in each antenna, the direction that the signal came from can be determined. Figure 3 shows a top view of the crossed long wire antennas and the **E-field component** of the reflected radio wave as it approaches the antennas.

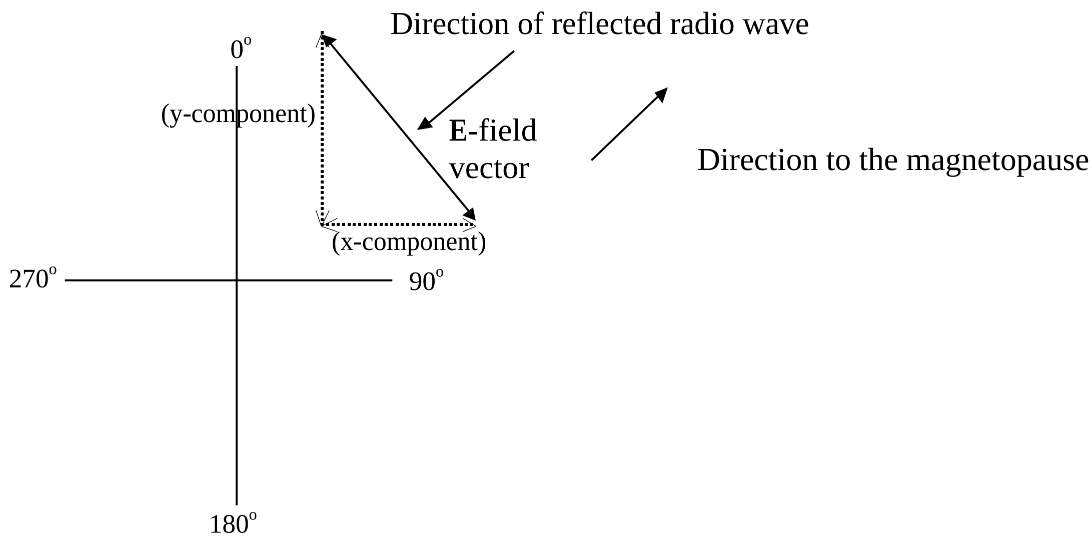


Figure 3. Reflected Radio Wave Returns to the IMAGE Antenna
As the reflected wave returns, one antenna wire will register the voltage due to one component (the y-component) while other wire will register the voltage induced by the x-component.

Radio waves, like all electromagnetic waves, are transverse waves. The E-field oscillates at right angles to the direction of travel of the wave. When the returned signal encounters the crossed antennas, only the component of the signal parallel to the antenna wire will induce a voltage in that wire. The voltage induced will be proportional to the length of the wire and the E-field component in that direction. From the measured voltages, the direction of the returned signal can be determined.

In Figure 3, the angle that the E-field makes with the antenna is 45°, so the x-component and the y-component will be equal. But if the x- and y-components are equal, the reflected radio wave could have come from any of four possible directions: 45°, 135°, 225° or 315°, since a wave reflected from any of these directions would have equal components. (See figure 4.)

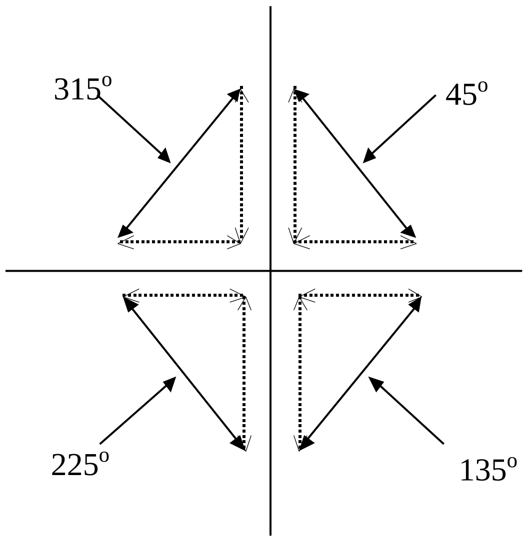


Figure 4. Radio wave echoes from several directions can have the same components

IMAGE must distinguish among these possibilities. The way this is done is by determining the **phase** between the components. Figure 5 illustrates the difference in the phase of the components between waves returning from 45^o and 135^o.

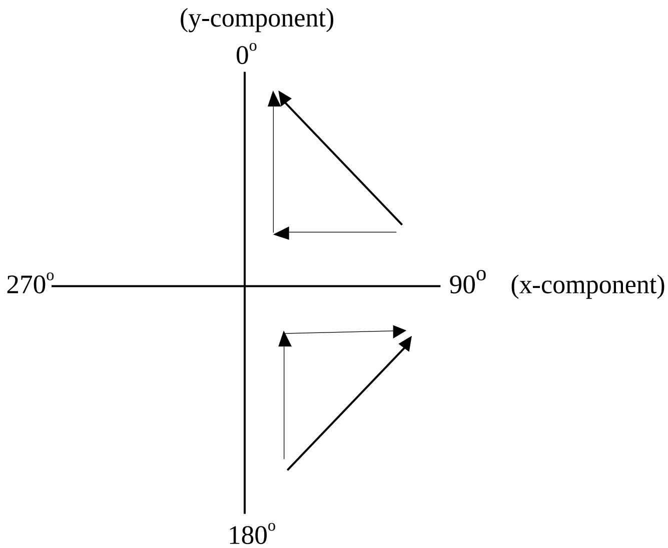


Figure 5. Phase relationship between E-field components.

To consider phase, select one direction for the E-field vector and compare the components:

For the top vector (arriving from 45^o), the x-component is negative and the y-component is positive. These components are said to be **out of phase**.

For the bottom vector (arriving from 135^o), the x-component is positive and the y-component is also positive. These components are said to be **in phase**.

Notice that if the returning radio wave is coming from a direction of 225^o, the phase relation of the components will be the same as if the echo were returning from 45^o. This ambiguity can be resolved in two ways. First, it is known that the magnetopause is located generally away from Earth as viewed from IMAGE. Second, if IMAGE is traveling toward the magnetopause then the reflected wave will be Doppler shifted to a higher frequency and so will its components. The components which show the expected Doppler shift can be used to determine the direction to the magnetopause.

Once the general direction to the magnetopause is known, analysis of the phase relationship between the components of the E-field vector can then determine which of the two remaining possible directions is correct.

For example, if the general direction to the magnetopause is between 0^o and 180^o, the x-component antenna registers a .29 microvolt induced voltage, the y-component antenna registers a .50 microvolt induced voltage and the voltages are in phase, then the signal is reflecting from a direction of 120.1^o. (See Example 3a.) If the voltages were out of phase, the direction would be 59.9^o. (See Example 3b.)

All of the computations are done automatically by IMAGE as it rotates in space and moves along its orbit. A complete set of measurements and computations is done every two minutes which is the rotation period of IMAGE. As the measurements are taken, IMAGE keeps track of its orientation in space and the location of Earth so that the results can be given in Earth-centered coordinates.

RPI Problems

Example problem 1:

If the echo time is .086 seconds and the IMAGE spacecraft is at apogee (8 R_E from the center of Earth), what is the location of the magnetopause in Earth radii measured from the center of Earth?

First find the distance from IMAGE to the magnetopause in meters.

t = echo time/2 = .086/2 = .043 s $\quad v = d/t \quad d = vt$

($v = c = 3.0 \times 10^8$ m/s)

$d = (3.0 \times 10^8 \text{ m/s})(.043 \text{ s})$

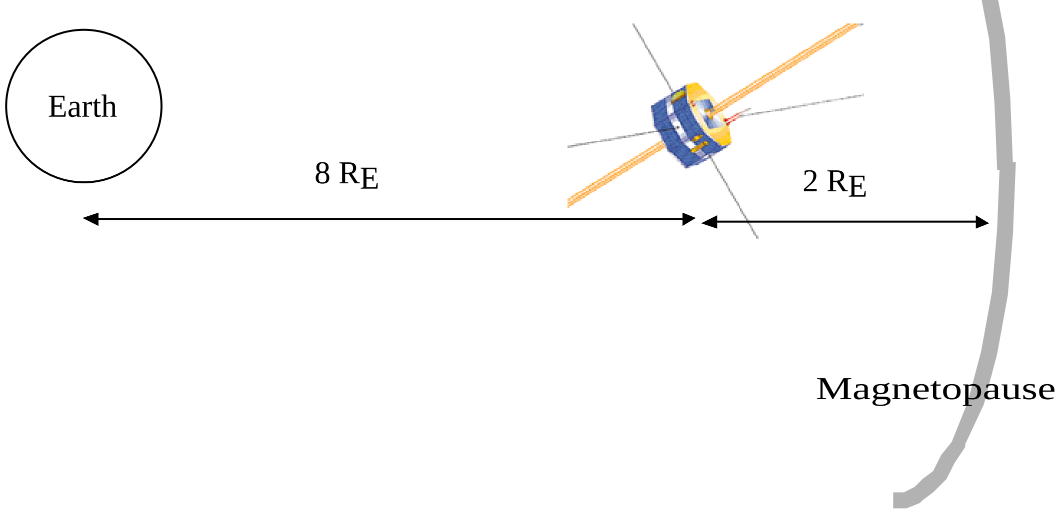
$d = 1.29 \times 10^7 \text{m}$

Next convert the distance to Earth radii (R_E).

1 Earth radius = 1 R_E = 6.4×10^3 kilometers

$d = 1.29 \times 10^7 \text{ m}(1 \text{ km}/1\times10^3 \text{ m})(1 R_E/6\times10^3 \text{ km}) = 2.0 R_E$

Finally, find the distance in R_E from the center of Earth.



Magnetopause distance = D = 8 R_E + 2 R_E = **10 R_E**

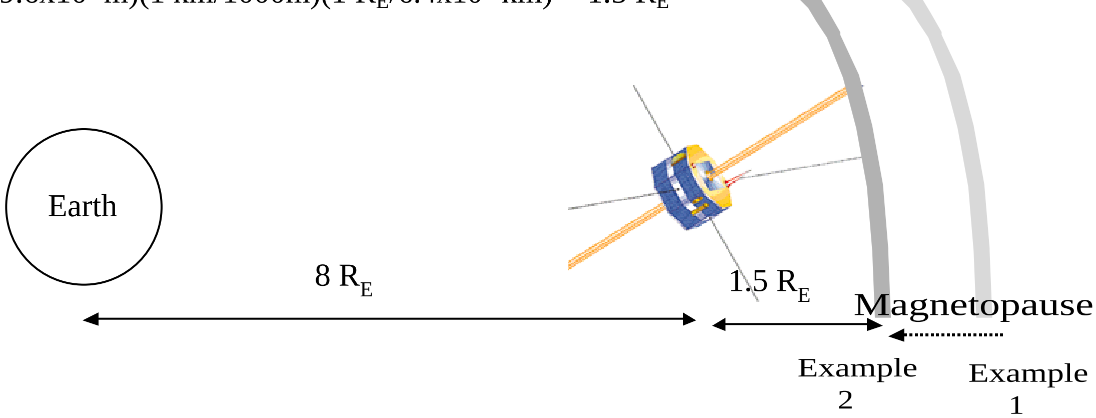
Example Problem 2:

One orbit later (14 hours later) IMAGE is again at apogee. The echo time is measured as .064 seconds. Find the magnetopause distance from the center of Earth at this time.

v = c = 3 x108 m/s
t = ..064/2 = .032 s

d = vt
d = (3x108 m/s)(.032 s) = $9.6\text{x}10^6$ m

d = ($9.6\text{x}10^6$ m)(1 km/1000m)(1 $R_E/6.4\text{x}10^3$ km) = 1.5 R_E



Magnetopause distance = D = 8 R_E + 1.5 R_E = **9.5 R_E**

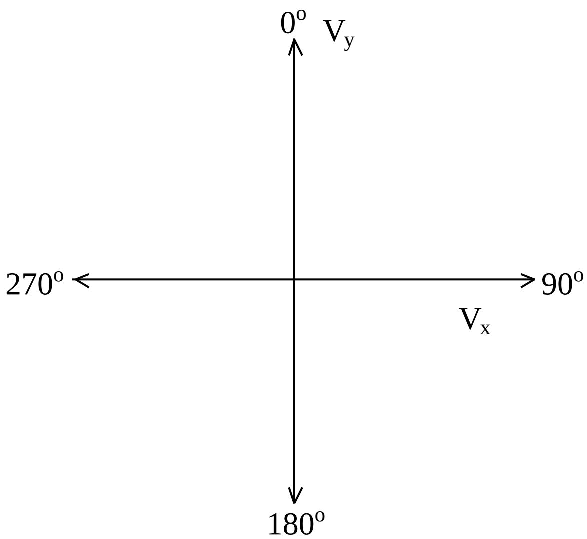
In comparing the results of Examples 1 and 2, it is apparent that during the 14-hour orbit the magnetopause was displaced toward Earth by .5 Earth radius. This indicates a significant increase in the solar wind during that time which is the result of a disturbance on the sun. If a Coronal Mass Ejection (CME) had been observed prior to this change in the magnetopause then there would be a presumed connection between the two events. This connection is one of the areas that IMAGE is investigating.

RPI Problems:

Given the echo time and the location of IMAGE, calculate the distance to the magnetopause in Earth radii. In these problems it is assumed that IMAGE lies on a straight line between Earth and the reflection point on the magnetopause. We will see later that this is not always the case, but for now we will make that assumption.

Problem	Echo Time	IMAGE Location	Magnetopause Location
	(seconds)	(Earth Radii R_E)	(Earth Radii R_E)
1	.13	6	
2	.34	4.5	
3	.09	5	
4	.26	4	
5	.04	6	

Example Problem 3a

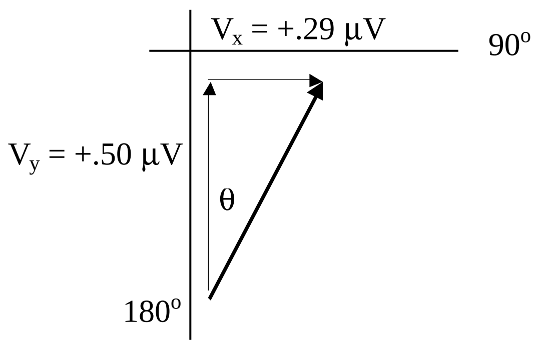


The following are given:

The general direction to the magnetopause is between 0^o and 180^o.
The x-component voltage is .29 μV.
The y-component voltage is .50 μV.
The components are in phase.

What is the direction to the reflection point on the magnetopause?

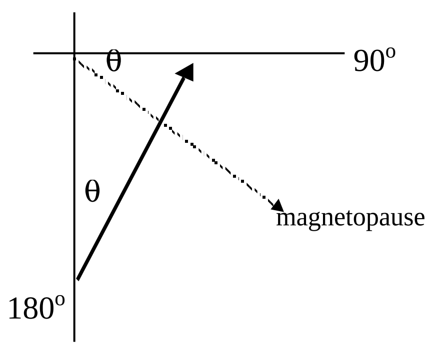
First add the components to find the direction of the E-field of the reflected signal:



$\tan\theta = V_x / V_y = .29 / .50 = .58$

$\theta = 30.1^o$

Remember that the direction of propagation of an electromagnetic wave is perpendicular to the E-field vector, so the direction to the origin of the reflected wave is:



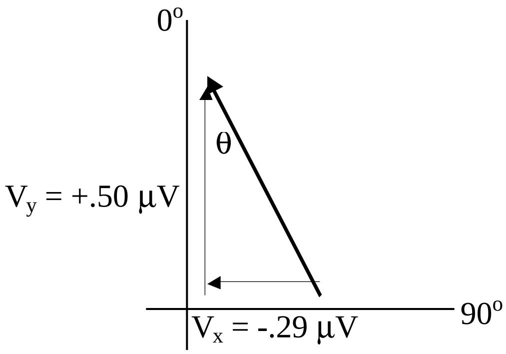
Direction to magnetopause = $90 + \theta = 90 + 30.1$

Direction to magnetopause = 120.1^o

Example 3b.

Find the direction to the magnetopause of the componenets from Example 3a are out of phase.

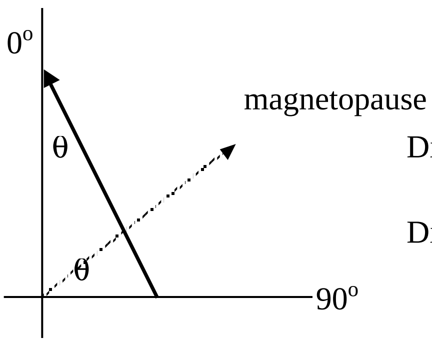
First find the direction of the E-field of the reflected signal:



$\tan \theta = V_X / V_Y = .29 / .50 = .58$

$\theta = 30.1^o$

Remember that the direction of propagation of an electromagnetic wave is perpendicular to the E-field vector, so the direction to the origin of the reflected wave is:



Direction to magnetopause = 90 – θ = 90 - 30.1

Direction to magnetopause = 59.9°

Given V_x , V_y and the phase, find the direction to the magnetopause.

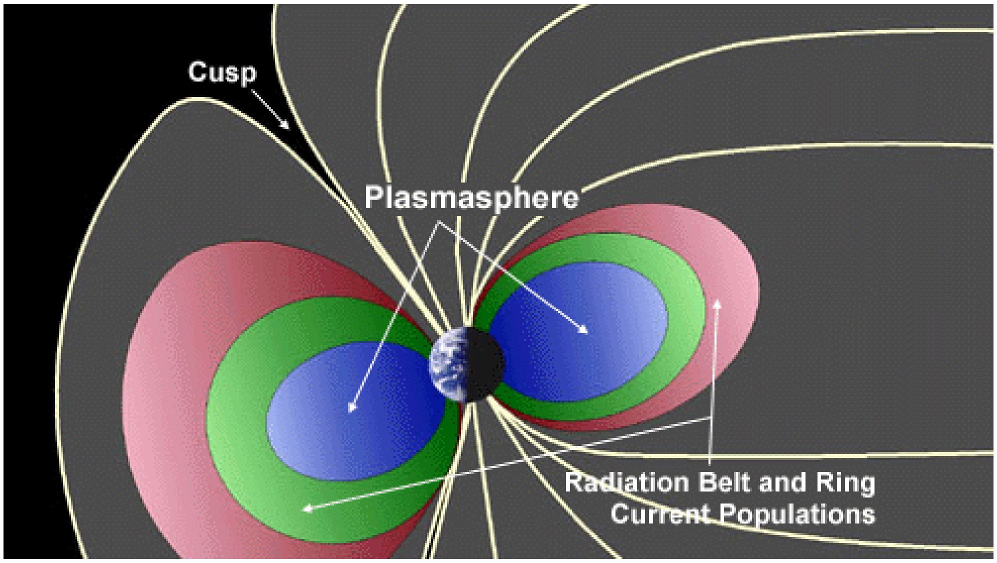
Problem Number:	**6**	**7**	**8**	**9**	**10**
General direction to magnetopause	0°-180°	0° - 180°	180° - 360°	180° -360°	90° - 270°
Phase	In	Out	In	Out	In
V_x (μV)	.72	-.36	-.88	.72	.66
V_y (μV)	.41	.58	-.46	-.51	.66

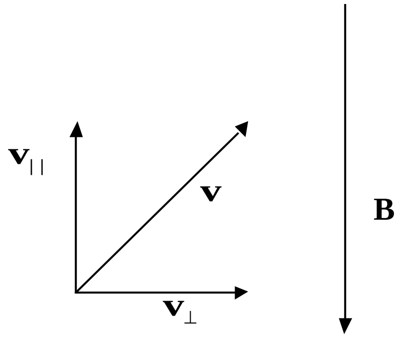
Chapter 5 Neutral Atom Imagers (NAI)

The IMAGE spacecraft will carry three energetic neutral atom (ENA) imagers whose combined energy coverage permits the detection of ENAs with energies ranging from 1 eV to 500 keV (per atomic mass unit). Each neutral atom instrument will generate images showing the intensity and spatial distribution of ENA emissions produced in the inner magnetosphere through charge exchange reactions between geocoronal neutral hydrogen and various magnetospheric ion populations. These images will be transmitted from the IMAGE spacecraft to Earth, where forward-modeling and image inversion techniques will be used to translate them into images of the ion source populations. The images thus produced will reveal the global morphology of inner magnetospheric plasma regions and document their dynamic response to changes in the solar wind. The particular focus of the IMAGE neutral atom imaging investigations is on the "hot" ion populations of the ring current and inner plasma sheet and on the outflow of "cooler," less energetic ions from the ionosphere.

Neutral Atom Imaging
URL: http://pluto.space.swri.edu/IMAGE/NAI_instrument.html

The inner part of the magnetosphere, near the Earth, contains charged particles the motion of which is influenced primarily by Earth's magnetic field. Famous structures in this region are the **Van Allen Radiation Belts** which were discovered by Explorer I, the first US satellite placed in orbit in 1958. Another feature of this part of the magnetosphere is the **ring current**. The ring current consists of charged particles trapped on magnetic field lines rotating with the Earth and its magnetic field. During **solar storms**, the populations of charged particles in the ring currents change both in number and energy. The mechanisms for movement of charged particles into and out of the ring current are not well understood. IMAGE will attempt to determine exactly how and when the charged particles get into the ring current and where they go from there.
The first thing to consider is how charged particles can get trapped by magnetic field lines. As a charged particle approaches a magnetic field line, its velocity can be resolved into two components: a component parallel to the field line and a component perpendicular to the field line.





v = velocity of charged particle

B = Earth's magnetic field

$\mathbf{v}_{\perp}$ = velocity component perpendicular to the field

$\mathbf{v}_{||}$ = velocity compnent parallel to the field

The parallel component ($\mathbf{v}_{||}$) of the velocity results in no force due to the magnetic field, so inertia carries the particles along the field line in the parallel direction. The perpendicular component ($\mathbf{v}_{\perp}$) results in a force ($\mathbf{F} = q\mathbf{v}\mathbf{B}$) directed at right angles to this motion which results in uniform circular motion about the magnetic field line. So the motion of the charged particle becomes a spiral motion with the particle traveling around the field line as it is carried along the field line by the parallel component of its velocity.

The Ring Current

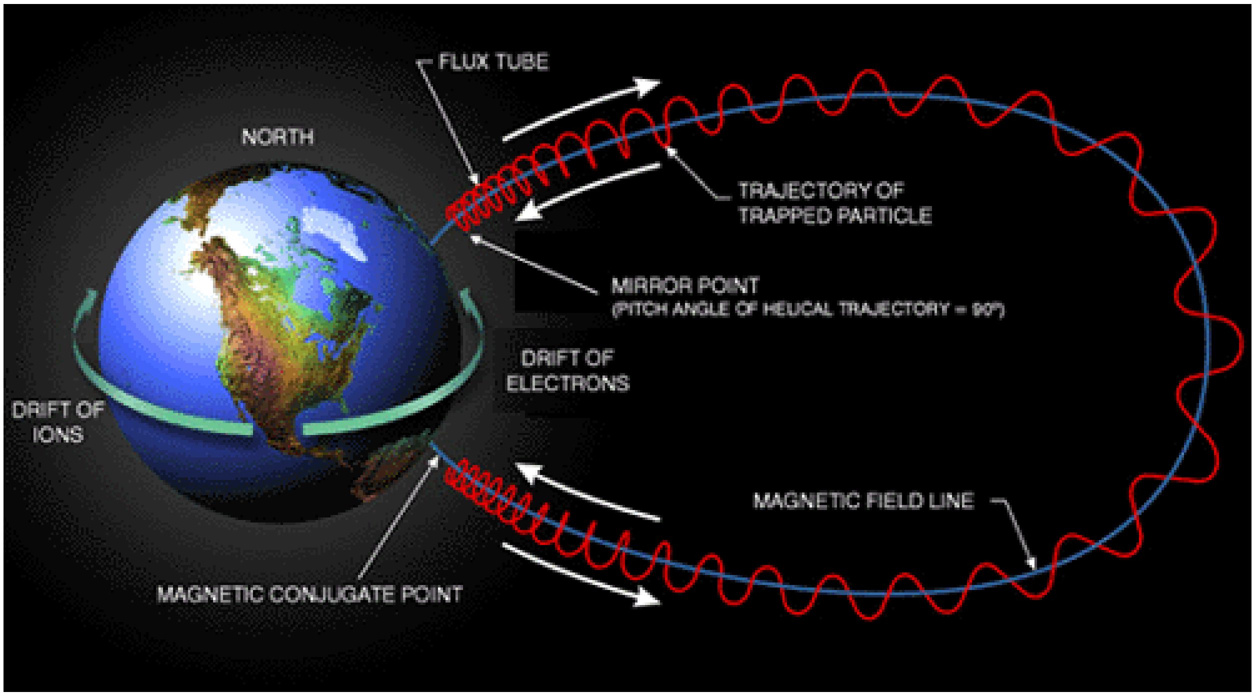
Ring Current

The ring current is one of the major current systems in the Earth's magnetosphere. It circles the Earth in the equatorial plane and is generated by the longitudinal drift of energetic (10 to 200 keV) charged particles trapped on field lines between L ~ 2 and 7. During geomagnetic storms, ring current particle fluxes are dramatically increased, with the peak enhancements occurring in the inner ring current (at L < 4). The quiet-time ring current consists predominantly of H+, while the storm-time ring current also contains a significant component of ionospheric O+, whose contribution to ring current energy density may even exceed that of H+ for brief periods near the maximum of particularly intense storms.

Neutral Atom Imaging - Glossary
URL: http://pluto.space.swri.edu/IMAGE/glossary/ring_current.html

NOTE: "L"s refers to the magnetic field line whose distance from the center of Earth is L Earth radii at the equator. The L = 7 field line intersects the equator at a distance of 7 Earth radii from the center of Earth.

When the charged particle nears one of the magnetic polar regions, the magnetic field lines converge causing the particle to bounce back along the field line and travel toward the opposite pole. At that pole it bounces again and the process continues. As these particles oscillate along the magnetic field lines between the magnetic poles they also drift around Earth. This drift movement of charge around Earth is called the **ring current**.

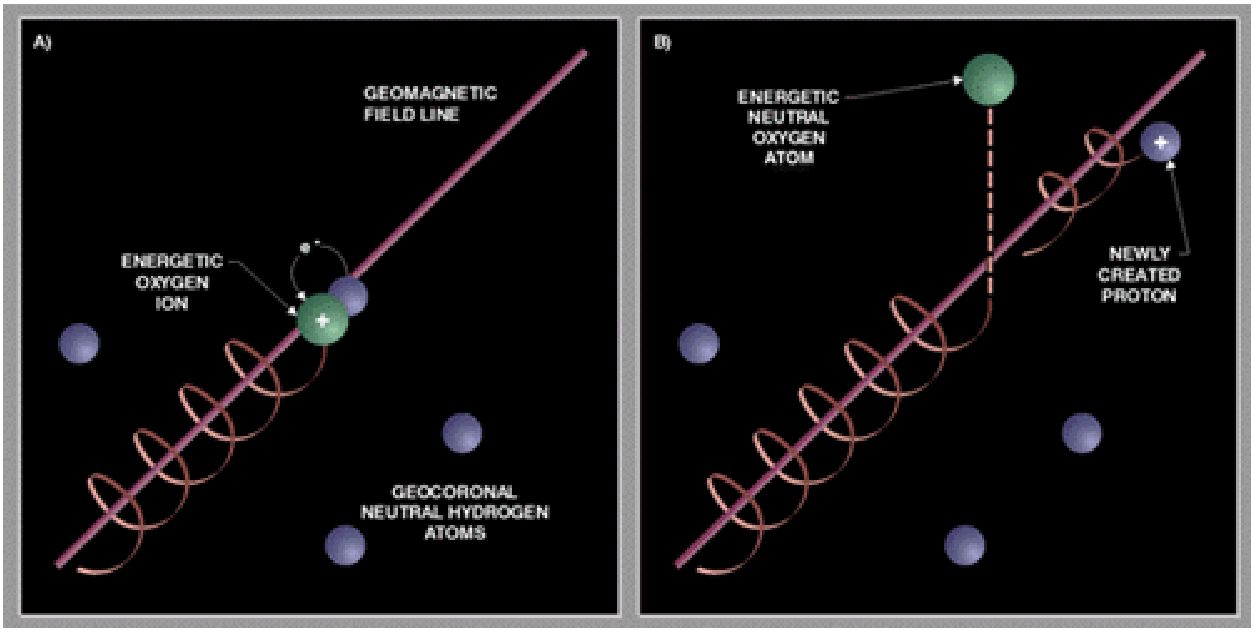


This cartoon illustrates the three basic motions of charged particles in a magnetic field: gyro, bounce between mirror points, and drift. (Based on Figure 5-10 in the "Handbook of Geophysics and the Space Environment," edited by A. S. Jursa and published by the United States Air Force, 1985.)
NOTE: “gyro” refers to the spiraling of the charged particle around the magnetic field line; “mirror points” are the locations on a field line where the charged particles bounce; “drift” refers to the ring current motion around Earth. Notice that positive ions and electrons drift in opposite directions around Earth.

IMAGE is using the neutral atom imagers to observe the ring current as it changes in response to variations in solar activity. The ring current consists of charged particles of various elements. The primary constituent of the ring current is **ionized** hydrogen (H^+) carried to Earth by the solar wind (although some H^+ comes from ionosphere).. There is a smaller amount of doubly ionized helium (He^{++}) also from the solar wind. Other components of the ring current originate in the ionosphere. These include ionized hydrogen (H^+), ionized oxygen (O^+ and O^{++}), ionized helium (He^+), and ionized nitrogen (N^+).

Until now, the only way to sense the ring current was to fly through it and detect and count the charged ions. This would give a good idea of the composition of the ring curreent only at that particular location and at that particular time. IMAGE is looking at the entire ring current all of the time. (Note: Actually the neutral atom imagers operate during the part of the orbit of IMAGE when IMAGE is farther than 4 Earth radii from Earth.) The major difficulty in observing the ring current from the location of the IMAGE spacecraft is that, as long as the particles are charged, they remain in the ring current and cannot be sensed by remote instruments. If, by some means, they become neutral, then the magnetic field will no longer hold them and inertia will carry them away. The next problem is that if the particles are not charged, when they arrive at IMAGE they are not directly detectable. These two problems would seem to make it impossible to remotely sense the ring current.

The first problem, that of the ring current particles being permanently trapped on magnetic field lines, is solved by the process of charge exchange.



The above illustrates the process of charge exchange. As the ion (in this case an oxygen ion) spirals down the magnetic field line it encounters the **geocorona**, a cloud of neutral hydrogen atoms held in place around Earth by gravity. A collision can result in the transfer of an electron from the hydrogen atom, resulting in the formation of a hydrogen ion, to the oxygen ion, resulting in the formation of an energetic neutral oxygen atom. The neutral atom, which no longer has a force on it exerted by the magnetic field, moves **inertially** away. The direction of movement of the energetic neutrals is random, but a sample of these will reach IMAGE and be counted.

Once the neutral particles arrive at IMAGE, they have to be made detectable. Each of the neutral atom imagers does this in a different way and each of the imagers will be described separately. As IMAGE rotates, the imagers gather and count the charged ring current particles (which arrive as neutrals) and form pictures of the ring current area for various energies of the particles.

The exact mechanism for movement of ions into the ring current is not well understood. One theory is that **plasma** (charged particles) is injected into the inner magnetosphere from storage in the **magnetotail**, the extension of the magnetosphere on the side of Earth away from the sun. Another theory is that solar storm activity causes ions to be convected, or carried, downward from the outer part of the magnetosphere to the **plasmasphere** where the ring current resides. Which of these theories (or possibly what other explanation) is correct is not known. By making constant observations of the ring current using the neutral atom imagers, IMAGE hopes to contribute to the resolution of this question.

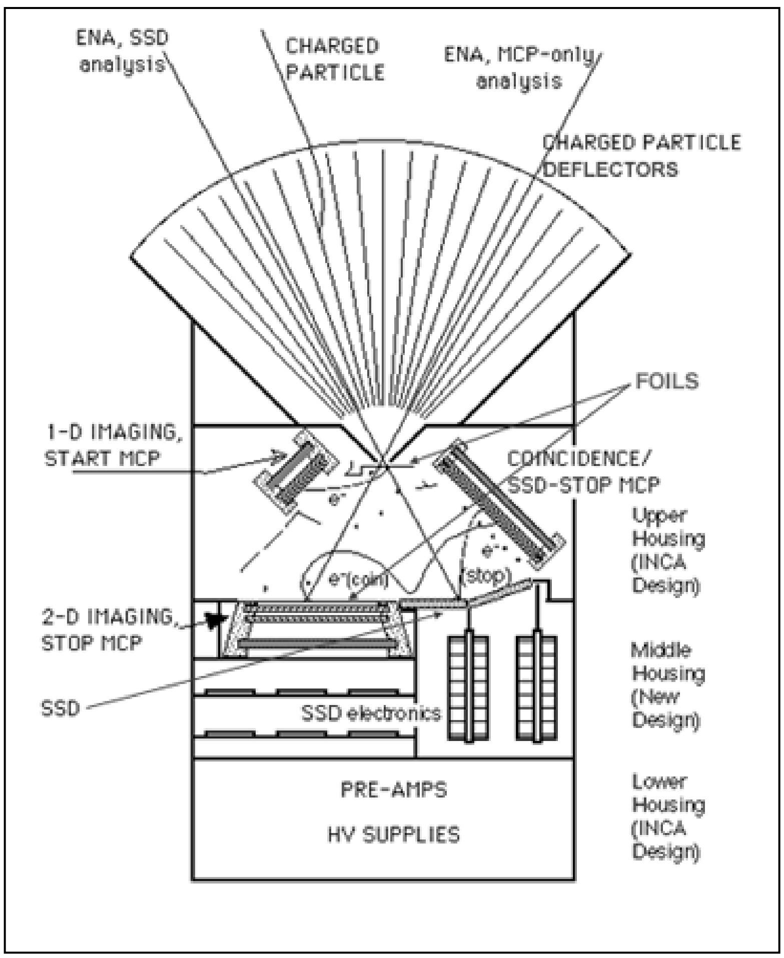
High Energy Neutral Atom Imager (HENA)

The HENA instrument determines the velocity, trajectory, energy, and mass of ENAs in the10-500 keV energy range and from these data generates images of ENA source regions in the inner magnetosphere. The two main HENA components are the sensor and the main electronics unit (MEU).

The HENA sensor (see figure) consists of alternately charged deflection plates mounted in a fan configuration in front of the entrance slit; three microchannel plate (MCP) detectors; a solid-state detector (SSD); two carbon-silicon-polyimide foils, one at the entrance slit, the other placed just in front of the back MCP; and a series of wires and electrodes to steer secondary electrons ejected from the foils (or the SSD) to the MCPs. Power for the MCPs and deflection plates and for secondary electron steering is provided by high-voltage power supplies that reside with the sensor.

The MEU contains HENA's data processing unit (DPU); the analog electronics that amplifies and processes signals from the sensor and performs housekeeping monitoring; analog-to-digital converters; and a low-voltage power supply.

HENA Imager – Instrument Description
http://pluto.space.swri.edu/IMAGE/HENA_description.html



The High Energy Neutral Atom (**HENA**) Imager is designed to observe neutral atoms with energies in the 10-500 **keV** range.

HENA's sensor unit is illustrated to the left. Particles enter from the top through a set of alternately charged deflection plates which serve the purpose of removing any charged particles. When the particles pass through the thin foils, they cause some secondary electrons to be emitted from the foil. The first foil provides a start time for the determination of the time of flight (TOF) of the neutral through the instrument. The second foil, and its secondary electrons, provides a stop time for the TOF measurement. By measuring the (TOF) and knowing the distance between the foils, the velocity of the neutral can be calculated.
The microchannel plate detectors (MCP) are used to determine the direction that the neutral came from and the solid state detector (SSD) is used to determine the energy of the neutral since the amplitude of the current pulse

generated in the SSD is proportional to the energy of the neutral. So the neutral atom is not detected directly, but instead by the secondary electrons and currents that are created by its arrival.

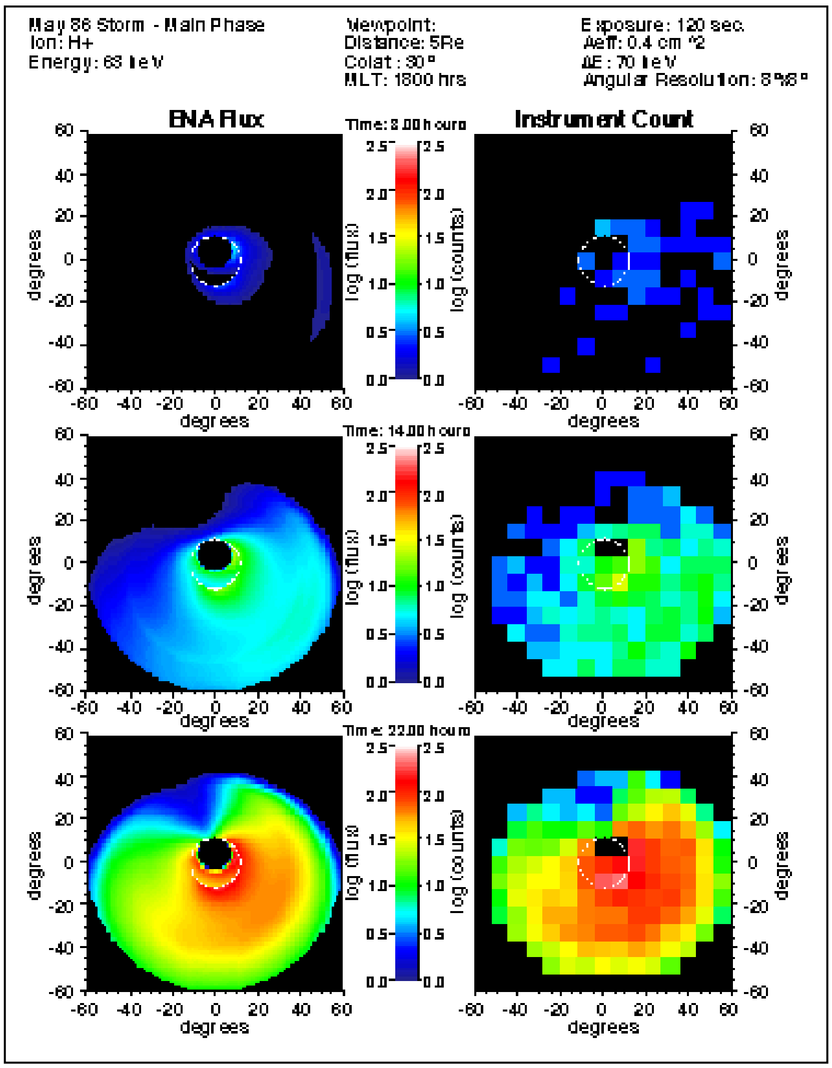
The data is processed in the main electronics unit (MEU). Here the time of flight is computed, the velocity determined and the energy determined. From the energy and the velocity, the mass can be determined using:

$$KE = \frac{1}{2} mv^2$$

$$m = \frac{2\,KE}{v^2}$$

where:

KE = (kinetic) energy
v = velocity
m = mass of the neutral atom



From the counts of the energetic neutrals, images can be formed illustrating the **neutral atom flux** (flow) from the ring current region. The panel at the left shows some simulated results. The left image in each pair (top to bottom) shows the model of the neutral atom flux at a particular time. The field of view is 60^{o} each way from the center which allows the imaging of the entire ring current region when IMAGE is near **apogee**. The right image of each pair is the simulated HENA data. Notice that the image is made up of small squares (**pixels**) that show the area sampled by the sensor at a time. The colors show the count of neutrals for each pixel. These images show the counts for 63 keV hydrogen (m = 1 amu). Notice the particle density is much higher at the later time (in the lower pair of images).

Medium Energy Neutral Atom Imager (MENA)

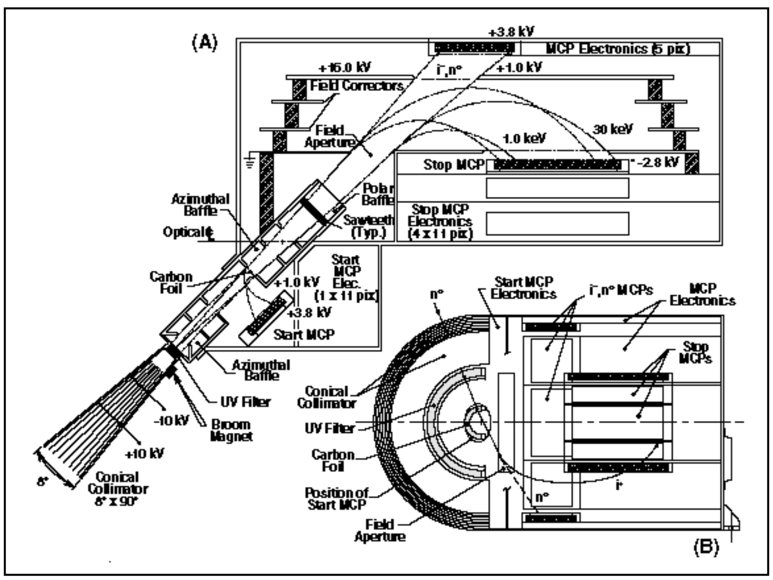
IMAGE's Medium Energy Neutral Atom (MENA) imager is a slit-type imager designed to detect energetic neutral hydrogen and oxygen atoms with energies ranging from 1 to 30 keV. The instrument determines the time of flight and incidence angle of the incoming ENAs; from these raw data it calculates their trajectory and velocity and generates images of the magnetospheric regions from which they are emitted.

How MENA Works

The time of flight for each ENA detected is determined by the front end electronics from the start and stop pulses triggered in the MCP. This value, together with the positions of the start and stop pulses on the MCP, is processed by the look-up tables to compute the incidence angle of an incoming ENA, the length of its path through the detector, and its velocity. The amplitude of the start and stop pulses--their "pulse height"--is also measured. This information can in principle be used by the look-up tables to estimate the mass of the incident ENAs and, together with the computed velocity, their energy. Because the pulse height distributions for hydrogen and oxygen are broad and overlap one another, however, species (mass) discrimination on the basis of the pulse height will be challenging. In addition to the raw sensor data, the DPU receives information on the spacecraft spin phase from the CIDP. Knowledge of both the spin phase and the incidence angle is needed to determine the position in the sky from which the detected ENAs are emitted and to produce the image of the ENA emission region.

MENA Imager – Instrument Description
http://pluto.space.swri.edu/IMAGE/MENA_description.html

The Medium Energy Neutral Atom (**MENA**) Imager observes neutral atoms in the energy range of 1 to 30 keV. It operates on similar principles to the HENA imager with some modifications. A foil of the type used in HENA would not work because the neutral atoms would lose too much of their energy in passing through. Instead, a gold grating is used to reflect ultraviolet light from entry into the instrument as it could give false counts. The neutrals then pass through an ultra-thin carbon foil to create the secondary electrons to indicate the time and location of the arrival in MENA. The neutrals then pass to the back of MENA where they strike a multichannel plate (MCP) detector that records their time and location of arrival.



From the information provided by the detectors, the direction the neutral came from can be determined. The distance between the entry point and the final location and the time of flight (TOF) can be used to find the velocity. The size of the start and stop TOF pulses can also be used to estimate the mass of the neutral. Since the primary neutrals are hydrogen and oxygen, it is only necessary to distinguish between these two. The mass and velocity can then be used to calculate the kinetic energy of the neutrals.

The image formed by MENA is similar to that of HENA: a display of neutral counts as a function of position for a particular mass (H or O) and a particular energy. A complete set of images can be generated every two minutes.

Low Energy Neutral Atom Imager (LENA)

LENA combines spaceflight-proven plasma analyzer techniques with well-established, high-efficiency cesiated neutral-to-negative-ion surface conversion technology to measure composition and energy spectra of neutral atoms at 10-300 eV. LENA mass resolution [m/[[Delta]]m] of about 4 is sufficient to separate the major species of interest: H, D, 3He, 4He, and O. LENA [Ghielmetti et al., 1994] consists of a collimator, conversion unit, extraction lens, dispersive energy analyzer, and TOF mass analyzer with position-sensitive particle detection. LENA's high geometric factor, 0.2 cm^2 sr, is achieved by simultaneously imaging in azimuthal angle, energy, and mass/charge (i. e., the spectrograph approach).

IMAGE Mission Proposal
URL: http://image.gsfc.nasa.gov/Sci_prop/IMAGESci2.html#RTFToC2_1

The Low Energy Neutral Atom (**LENA**) Imager observes neutral atoms in the energy range of 10 – 300 **eV**. LENA will look specifically for hydrogen and oxygen neutral atoms that have migrated up into the ring current from the ionosphere, the charged layer of the upper atmosphere. The nature of this migration of ions (how, when and how many) is not well understood and LENA should be able to answer questions about the relationship of this movement to magnetic storms.

LENA Instrument Objectives

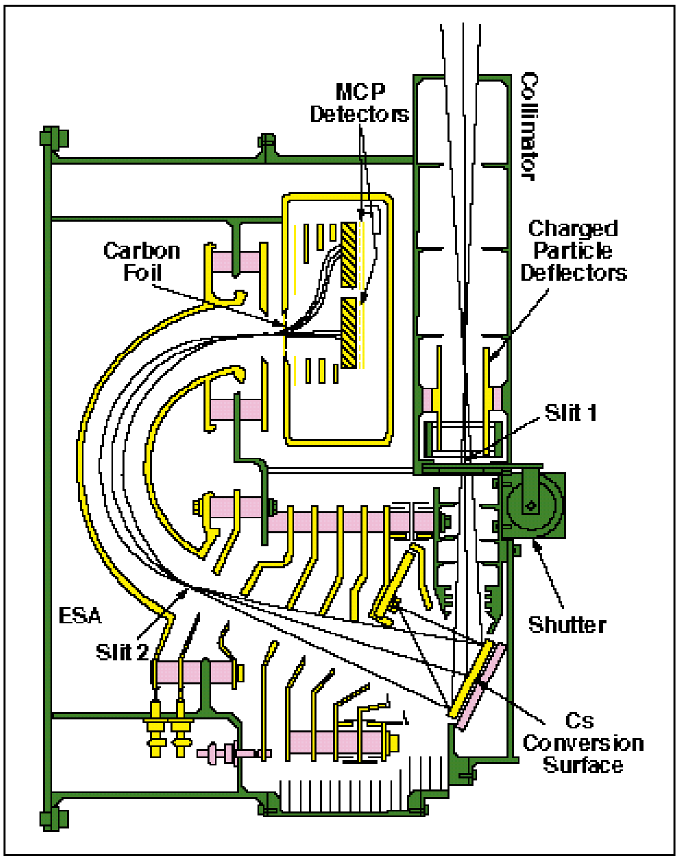
1. Measure neutrals without interference from electrons, ions, or UV
2. Distinguish neutral protons from oxygen
3. Determine ion outflow on five minute time scales over broad range of local times
4. Measure energies as low as 10 eV with high counting statistics

URL: http://lepjas.gsfc.nasa.gov/~seminar/lena_rest/lena_obj_01.html

The LENA instrument consists of a collimator, conversion unit, extraction lens, dispersive energy analyzer and time-of-flight mass analyzer with position-sensitive particle detection.

Neutral particles (1) enter the instrument through a collimator (2) which filters charged particles. LENA converts neutrals to negative ions through a near specular glancing reflection from a tungsten surface (3). Negative ions from the surface are then collected by the extraction lens (4) which focuses all negative ions with the same energy to a fixed location. In the extraction lens, the ions are accelerated by 20 kV (5) prior to entering the electrostatic analyzer (6). Finally, the ions pass into a time-of-flight/position sensing section where ion mass, energy, and angle are determined.

LENA Instrument Operation
URL: http://lepjas.gsfc.nasa.gov/~seminar/lena_rest/lena_inst_oper_01.html



Like HENA and MENA, after a particle enters the instrument it passes between two charged plates designed to remove any charged ions. The shutter is used to close off LENA during the perigee portion of each orbit to avoid contamination

The neutral atoms collide with a tungsten plate which removes one electron and reflects the ionized particle. The ion is then accelerated by 20 kilovolts and passed into a curved electric field which directs the ions to a carbon foil and microchannel plate (MCP) detector as in HENA and MENA. The time of flight and path of the ion in the electric field allow the mass and energy to be determined.

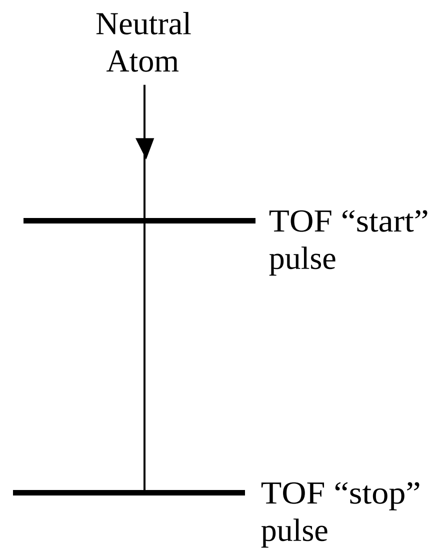
Two separate images are formed: one for hydrogen atoms and one for oxygen atoms. A set of images can be created every two minutes while IMAGE is outside the plasmasphere.

Neutral Atom Imagers – Problems and Exercises

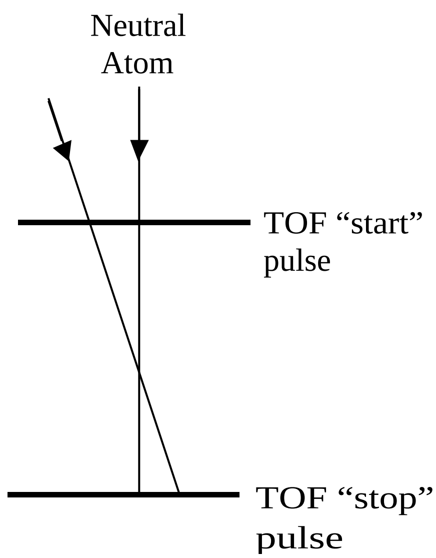
While the three neutral atom imagers (**NAI**) have differences in their internal structures and processes, they each accomplish the following:

1. Determination of the time of flight (TOF) of the neutral through the instrument.
2. Determination of the direction from which the neutral arrived.
3. Determination or calculation of the energy of the neutral.
4. Determination or calculation of the velocity of the neutral.
5. Determination or calculation of the mass of the neutral.

1. The time of flight is measured directly as the time between triggering the start signal and the stop signal. To the right is a diagram illustrating this process.



2. The direction is determined by combining the direction the aperture of the instrument was pointing at the time of arrival and projecting back along a line connecting the two points where the neutral passed through the start and stop sensors. Notice that this can give two different distances through the instrument depending on the direction the particle comes from. In the following problems we will make the simplifying assumption that all neutrals travel the same distance through the instrument. We will also assume that all three NAI have the same internal dimensions (even though this is not the case).



3. Energy determination is done by different methods in the NAI. We will take the energy value as a given and not worry about how it was determined.

4. Velocity will be calculated using the definition of velocity. ($v = d/t$)
5. Mass will be calculated using the definition of kinetic energy, solved for mass. ($KE = mv^2/2$)

NOTE: For all problems, use d = 25 centimeters as the internal dimension of the NAI.
Use two significant figures for all results.
Be careful of the units that quantities are expressed in.

Example Problem.

On Page 17, some simulated results were given using 63 keV (kilo electron volt) hydrogen atoms.

Find the following:

a. the mass of a hydrogen atom.
b. The velocity of a 63 keV hydrogen atom.
c. The time of flight (TOF) of the atom in the NAI.

a. hydrogen: m = 1 **amu**

$$m = 1 \text{ amu } (1.67 \times 10^{-27} \text{ kilograms} / 1 \text{ amu})$$

$$m = 1.7 \times 10^{-27} \text{ kg}$$

b. $KE = 63 \text{ keV } (1.6 \times 10^{-19} \text{ Joules} / 1 \text{ electron volt}) = 1.0 \times 10^{-14} \text{ J}$

$$KE = \frac{1}{2} mv^2$$

$$v = (2\,KE / m)^{\frac{1}{2}}$$

$$v = [2(1.0 \times 10^{-14}) / (1.7 \times 10^{-27})]^{\frac{1}{2}}$$

$$v = 3.5 \times 10^{6} \text{ m/s}$$

c. $d = 25 \text{ centimeters} = 25 \text{ cm } (1 \text{ m} / 100 \text{ cm}) = .25 \text{ m}$

$$v = d/t$$

$$t = d/v$$

$$t = (.25) / (3.5 \times 10^{6})$$

$$t = 7.2 \times 10^{-8} \text{ s}$$

HENA Problems

HENA has an energy range of 10-500 keV.

1. Find the mass in kilograms of an oxygen-16 atom.
2. Find the velocity of a 10 keV oxygen atom.
3. Find the velocity of a 500 keV hydrogen atom.
4. Find the TOF of a 10 keV oxygen atom.
5. Find the TOF of a 500 keV hydrogen atom.

MENA Problems

MENA has an energy range of 1-30 keV.

6. Find the velocity of a 1 keV oxygen atom.
7. Find the velocity of a 30 keV hydrogen atom.
8. Find the TOF of a 1 keV oxygen atom.
9. Find the TOF of a 30 keV hydrogen atom.

LENA Problems

LENA has an energy range of 10-300 eV.

10. Find the velocity of a 10 eV oxygen atom.
11. Find the velocity of a 300 eV hydrogen atom.
12. Find the TOF of a 10 eV oxygen atom.
13. Find the TOF of a 300 eV hydrogen atom.

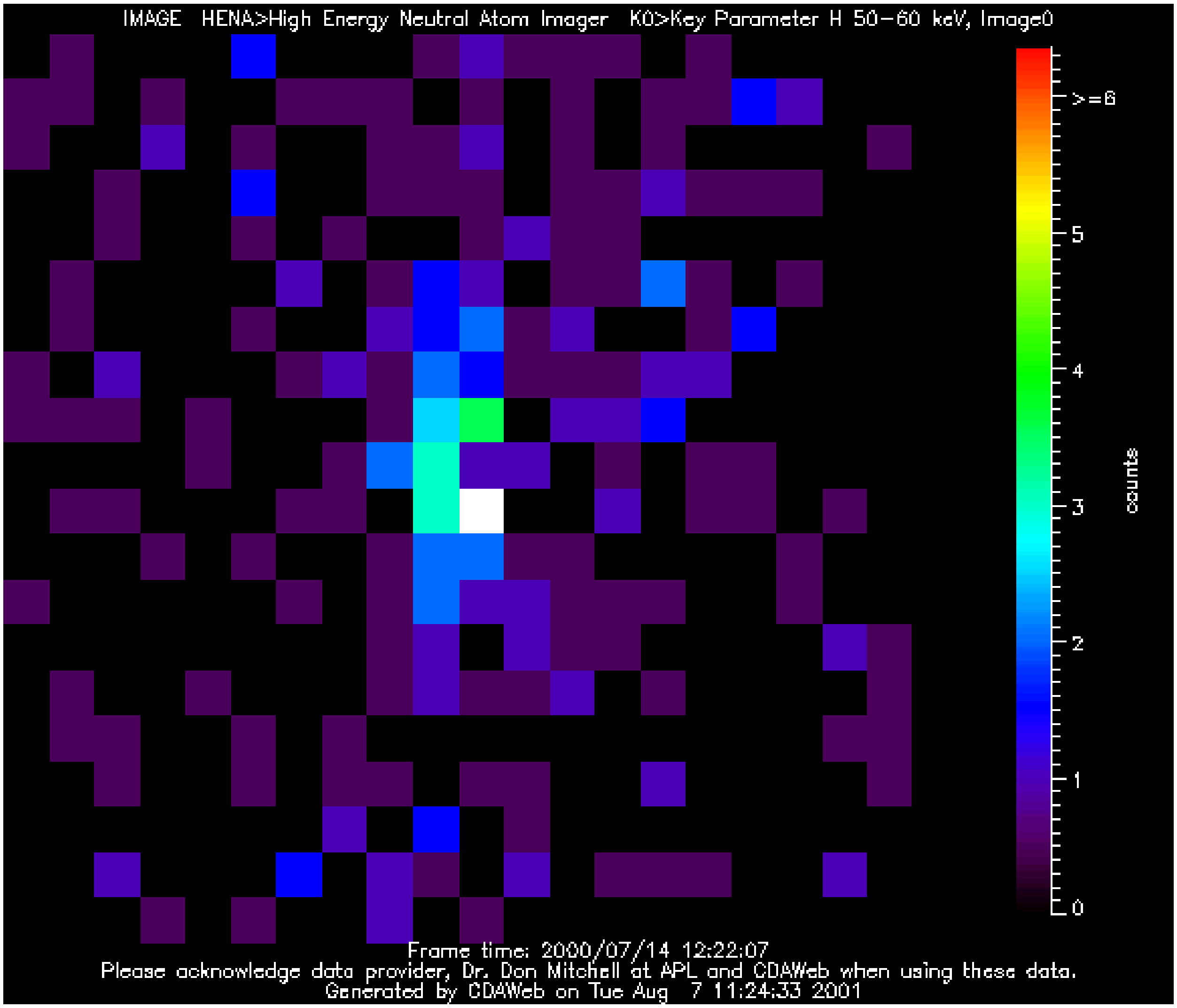
For the following table, calculate the missing quantity in each row.

(d = 25 cm)

	Neutral Atom	mass	Time Of Flight	Energy
		(amu)	(s)	(eV)
14.			1.3×10^{-8}	300 k
15.	Hydrogen		2.0×10^{-8}	
16.	Oxygen		5.9×10^{-8}	
17.		1		20 k

Example Problem: Determining the Total Ring Current Activity using NAI data.

Below is shown a sample of actual data from HENA.

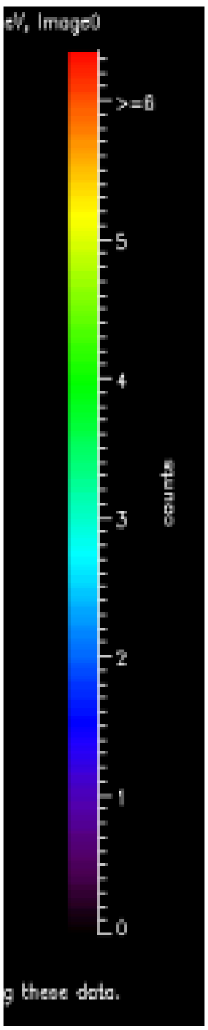


HENA data panel consists of a 20x20 array of pixels in which the counts are encoded using a color bar scale shown at the right. In addition to showing the counts, the data panel also shows the spatial distribution of the counts. In this activity we will devise a method to approximately determine the total number of counts represented by a data panel. The key to doing this is the color bar scale on the right. This scale is not held constant for all data panels, but instead the counts represented on the scale are changed to match the general activity level. To determine the total count, three steps will be followed:

1. A count value will be assigned to each of the colors in the spectrum.
2. The number of pixels of each color will be counted and multiplied by the count value.
3. Finally, the counts for the individual colors will be totaled to give the total count for the data panel. This is the Total Ring Current Activity.

Step 1: Assign count values to colors.

On the color bar scales, red orange, yellow and green are on the top half of the scale and blue and violet are on the bottom half. To provide more divisions on the bottom half of the scale, blue will be divided into "light blue" and "dark blue". The following examples show how values can be assigned. It should be emphasized that approximations and judgment are involved in this process, so answers may vary for the exercises that follow.



Red = 6

Orange = 5.7

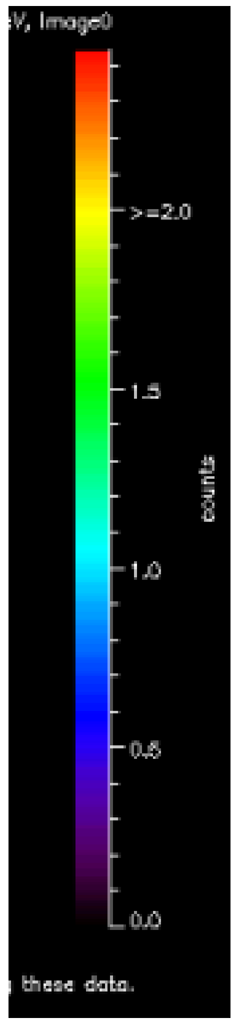
Yellow = 5.2

Green = 4

Light blue = 3

Dark blue = 2

Violet = .7



Red = 2.4

Orange = 2.2

Yellow = 2.0

Green = 1.6

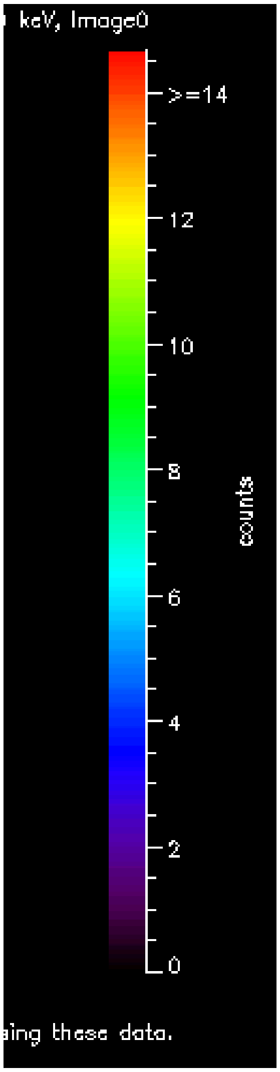
Light blue = 1.1

Dark blue = .6

Violet = .3

For the following scales, assign counts to colors:

Problem 18.



Red = ______

Orange = _____

Yellow = _____

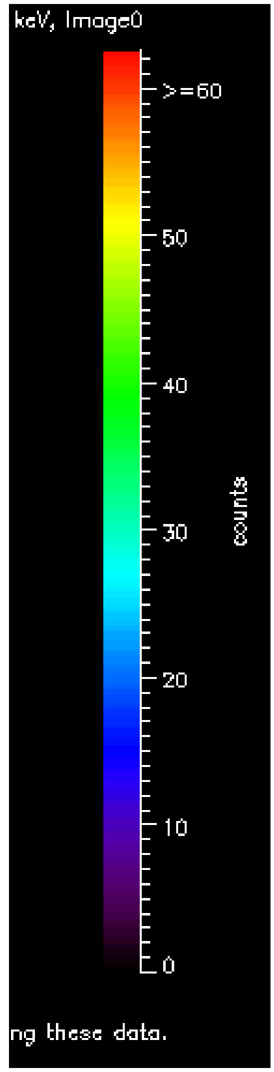
Green = ______

Lt blue = ______

Dark blue = ____

Violet = ______

Problem 19.



Red = ______

Orange = _____

Yellow = _____

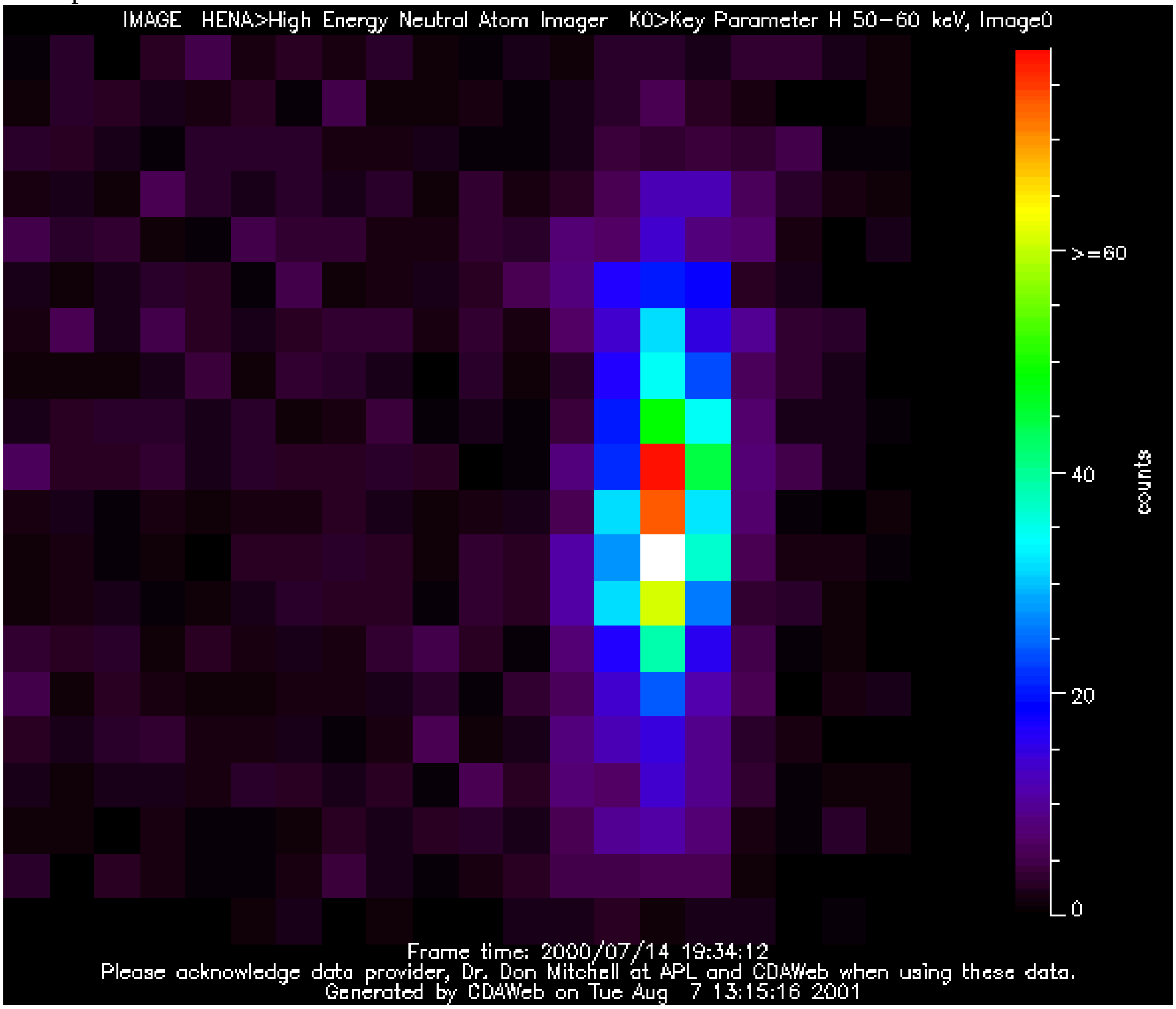
Green = ______

Lt blue = ______

Dark blue = ____

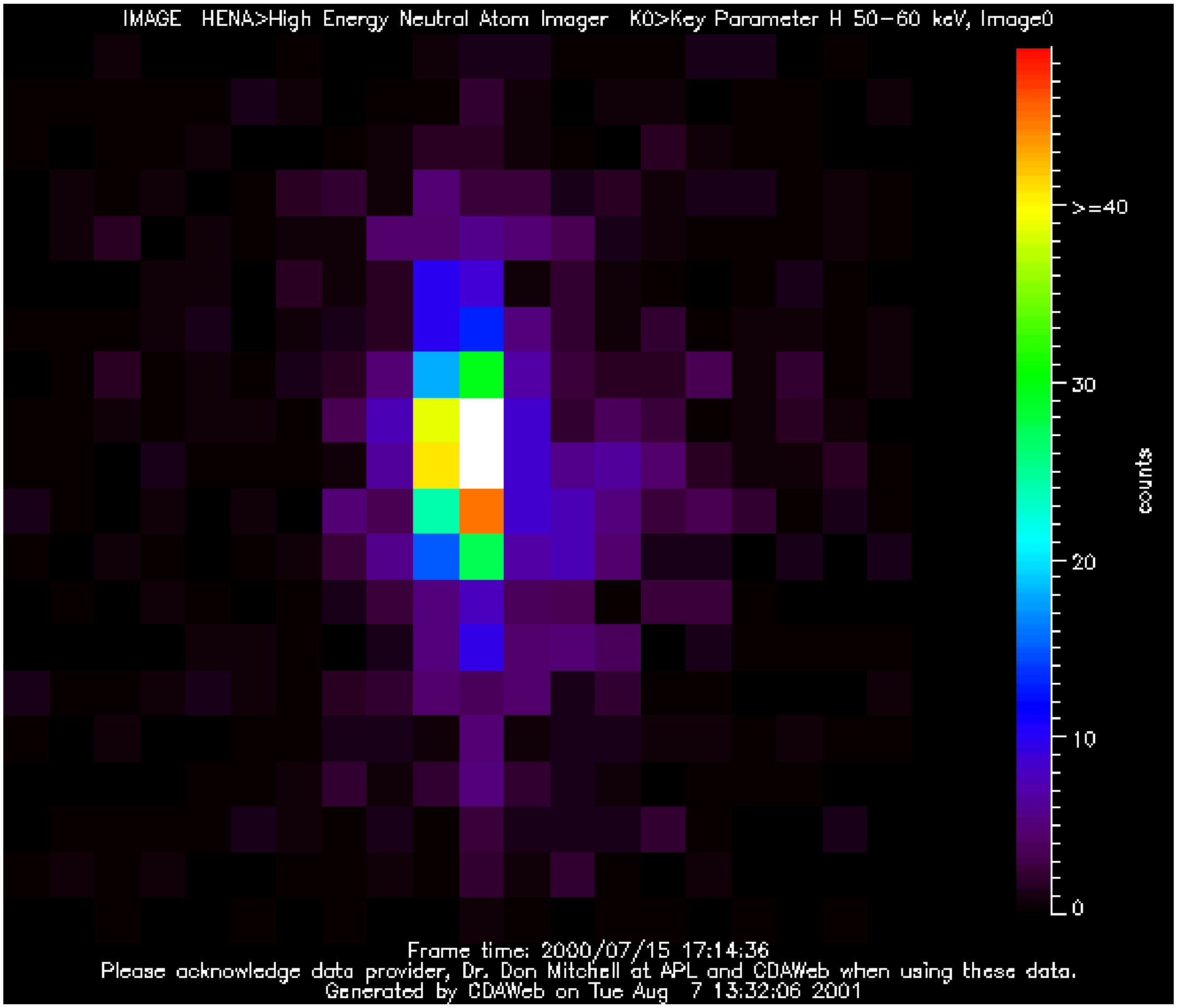
Violet = ______

Step 2: Count the pixels of each color and multiply by the pixel value. (Ignore white pixels.)
Step 3: Add up the counts of the colors to find the Total Ring Current Activity:
Example Problem:



Color	**Value**	**Pixels**	**Color Count**
Red	80	1	80
Orange	70	1	70
Yellow	65	1	65
Green	50	3	150
Lt. Blue	35	8	280
Dk. Blue	20	17	340
Violet	10	72	720
	TOTAL RING CURRENT ACTIVITY:		1705 counts

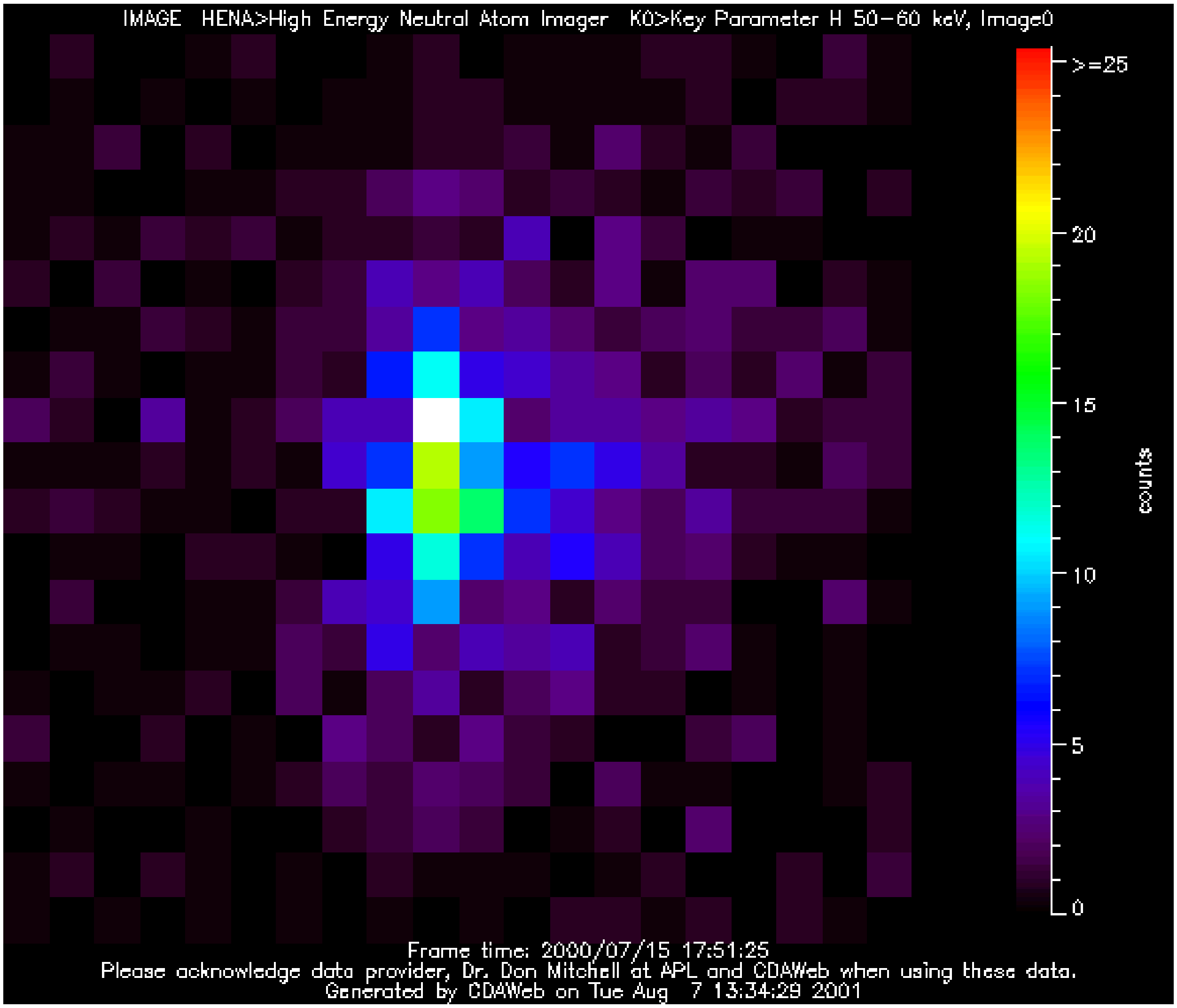
Problem 20. Find the Total Ring Current Activity.



Color	**Value**	**Pixels**	**Color Count**
Red	_____	_____	_____
Orange	_____	_____	_____
Yellow	_____	_____	_____
Green	_____	_____	_____
Lt. Blue	_____	_____	_____
Dk. Blue	_____	_____	_____
Violet	_____	_____	_____

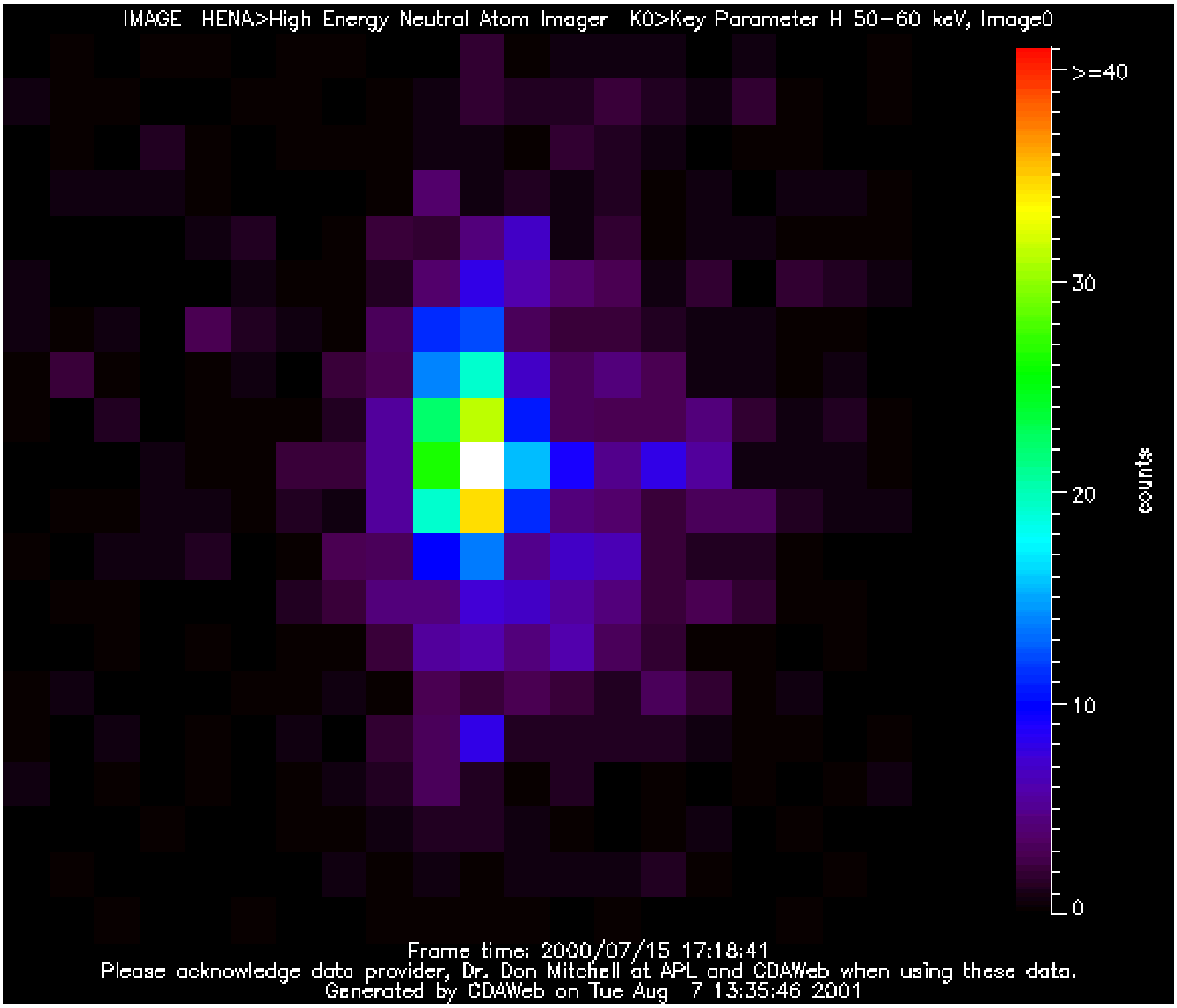
TOTAL RING CURRENT ACTIVITY: __________

Problem 21. Find the Total Ring Current Activity.



Color	**Value**	**Pixels**	**Color Count**
Red	_____	_____	_____
Orange	_____	_____	_____
Yellow	_____	_____	_____
Green	_____	_____	_____
Lt. Blue	_____	_____	_____
Dk. Blue	_____	_____	_____
Violet	_____	_____	_____
	TOTAL RING CURRENT ACTIVITY:		___________

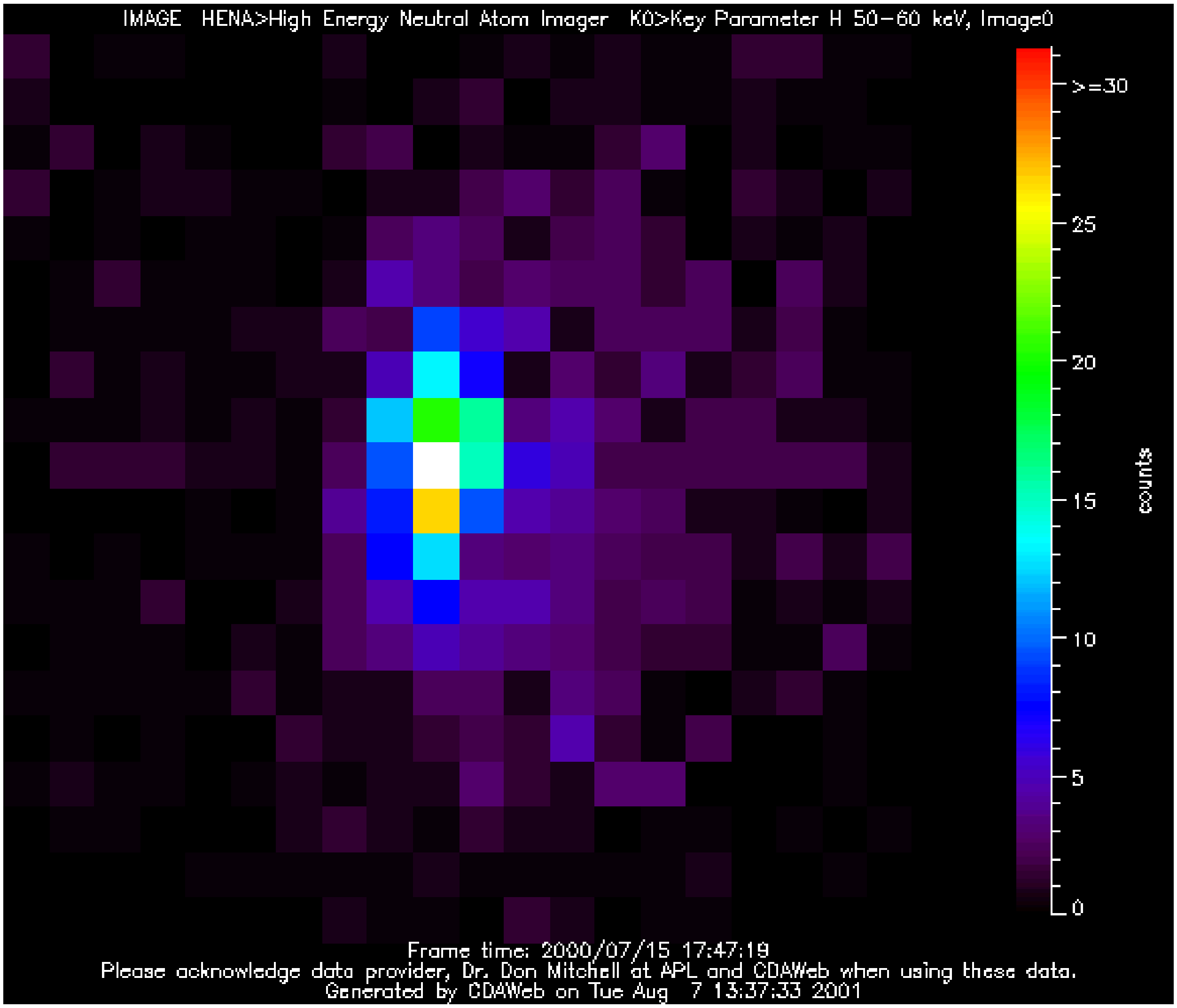
Problem 22. Find the Total Ring Current Activity.



Color	Value	Pixels	Color Count
Red	_____	_____	_____
Orange	_____	_____	_____
Yellow	_____	_____	_____
Green	_____	_____	_____
Lt. Blue	_____	_____	_____
Dk. Blue	_____	_____	_____
Violet	_____	_____	_____

TOTAL RING CURRENT ACTIVITY: __________

Problem 23. Find the Total Ring Current Activity.



Color	**Value**	**Pixels**	**Color Count**
Red	_____	_____	_____
Orange	_____	_____	_____
Yellow	_____	_____	_____
Green	_____	_____	_____
Lt. Blue	_____	_____	_____
Dk. Blue	_____	_____	_____
Violet	_____	_____	_____
	TOTAL RING CURRENT ACTIVITY:		__________

Chapter 6 Ultraviolet Imagers (EUV and FUV)

The **ultraviolet** portion of the electromagnetic spectrum is defined as a wavelength between 400 **nanometers** and 1 nanometer. IMAGE will carry two instruments designed to work in this part of the spectrum: the IMAGE Far Ultra Violet (FUV) Instrument and the IMAGE Extreme Ultra Violet (EUV) Instrument. These two instruments, working in adjacent parts of the electromagnetic spectrum, will be looking at very different parts of the Earth's magnetic environment.

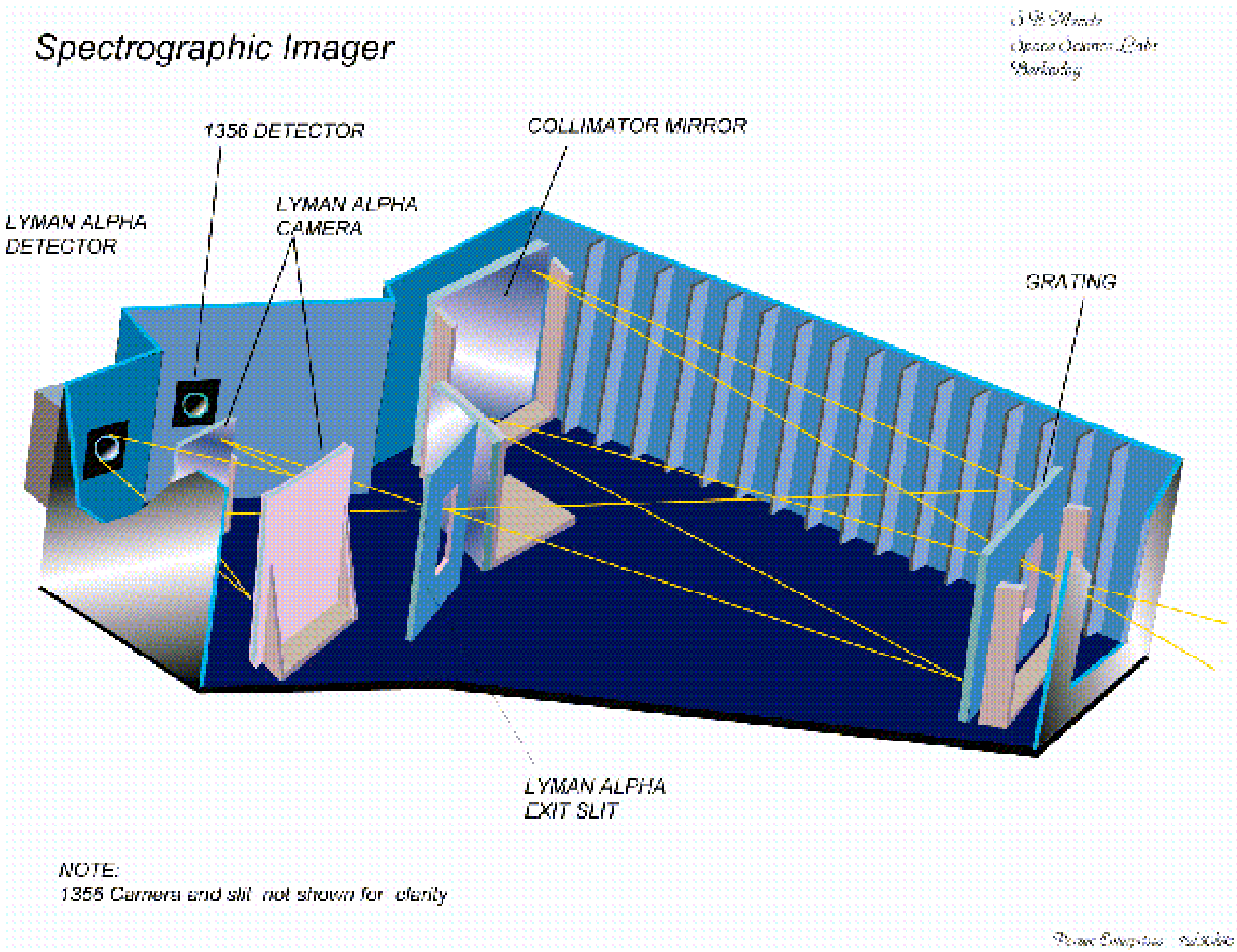
IMAGE Far Ultra Violet (FUV) Instrument

> **2.b.2.b. Far Ultraviolet Imagers (FU**V). Science requirements driving FUV imager designs are (1) to image the entire auroral oval from a spinning spacecraft at 7 RE apogee altitude, (2) to separate spectrally the hot proton precipitation from the statistical noise of the intense, cold geocorona, and (3) to separate spectrally the electron and proton auroras. FUV consists of two imagers that combine high spectral discrimination, high spatial resolution, and the greatest possible sensitivity to meet these requirements.
>
> In the FUV range up to ~160 nm, there are several bright auroral emission features that compete with the dayglow emissions. For the electron aurora, the brightest is 130.4 nm OI, which is multiply scattered in the atmosphere and thus cannot be used for auroral morphology studies. The next brightest is the 135.6 nm OI emission [Strickland and Anderson, 1983]. Separation of the 130.4 and 135.6 nm lines necessitates the use of a spectrometer because even reflective narrow-band filter technology cannot satisfy the ~3 nm wavelength resolution requirement. Above 135.6 nm, weak LBH lines can be detected using narrow-band filter technology. Separate imaging of the intense, cold geocorona (Lyman [[alpha]] emissions at 121.6 nm) and the less intense, Doppler-shifted Lyman [[alpha]] auroral emissions requires significantly higher spectral resolution (0.2 nm).
>
> IMAGE Mission Technical Proposal
> URL: http://image.gsfc.nasa.gov/Tech_prop/IMAGETech2.html#RTFToC2_b

The **FUV** Imager uses two different instruments to gather information about the magnetosphere near Earth. One of these instruments is a **spectrometer** that spreads the light out and examines particular wavelengths; the other is a camera used to make images of the auroral regions.

> Spectrographic Imager (SI). The relatively high wavelength resolution requirement is satisfied by the SI. The 0.2-nm wavelength resolution drives the size of the instrument and consequently the number of mirrors in the optics system. Also the narrowness of the slits in the spectrometer limit the dwell time during which a pixel is in the field of view.
>
> IMAGE Mission Technical Proposal
> URL: http://image.gsfc.nasa.gov/Tech_prop/IMAGETech2.html#RTFToC2_b

The Spectrographic Imager (**SI**) measures light at two wavelengths. The selection of the wavelengths is accomplished by reflecting the light from a **grating** then passing the light through two narrow slits of different sizes. Slit 1 allows a very narrow (0.2 nm) band of wavelengths to pass that contains the 121.6 **nm Lyman** α emission line of hydrogen. This line appears from two sources that are both of interest to IMAGE. The normal Lyman α emission comes from the geocorona, the upper level of Earth's atmosphere containing atomic (non-ionized) hydrogen. At a slightly different wavelength due to **Doppler shifting** caused by the high speed of the atoms is the same line from the proton aurora, the aurora caused by the presence of energetic protons in the upper atmosphere.



The Spectrographic Imager is designed to image the whole Earth proton aurora from satellite distances greater than 4 Earth radii to the center of the Earth. It uses a reverse Wadsworth design to select the Doppler shifted Lyman H-alpha line at 121.82 nm in the ultraviolet part of the optical spectrum and to reject the non-Doppler shifted Lyman H-alpha from the geocorona at 121.567 nm. The field of view is 15x15 degrees. The temporal resolution between two images is 120 s and the size of the final images is 128x128 pixel elements, corresponding to spatial resolutions of less than 100 km at apogee distances.

An interesting feature of the images formed by SI is that there is not typically enough light to form an image in one rotation of the IMAGE spacecraft, so the counts are stored and added for five rotations of IMAGE and the sum is used to create the image. In the case of FUV, two counts are stored – one for each wavelength.

Wideband imaging camera (WIC). The relatively high sensitivity requirement for auroral imaging is satisfied by the WIC. This imaging camera uses the basic design flown on the Viking and Freja satellites (Figure 2.b.5.) to measure the auroral LBH emissions in a relatively broad band from 134 nm to 160 nm [Anger et al., 1987]. The large field of view permits a long dwell (or integration) period and increases the apparent sensitivity.

IMAGE Mission Technical Proposal
URL: http://image.gsfc.nasa.gov/Tech_prop/IMAGETech2.html#RTFToC2_b

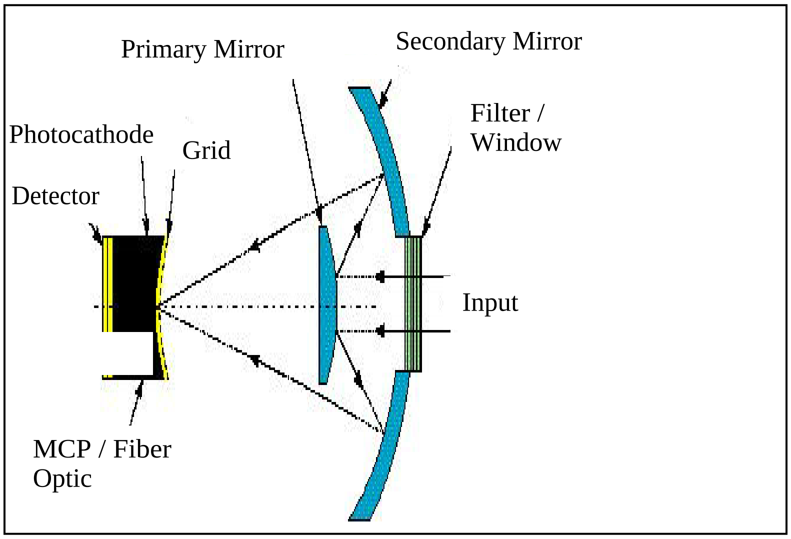
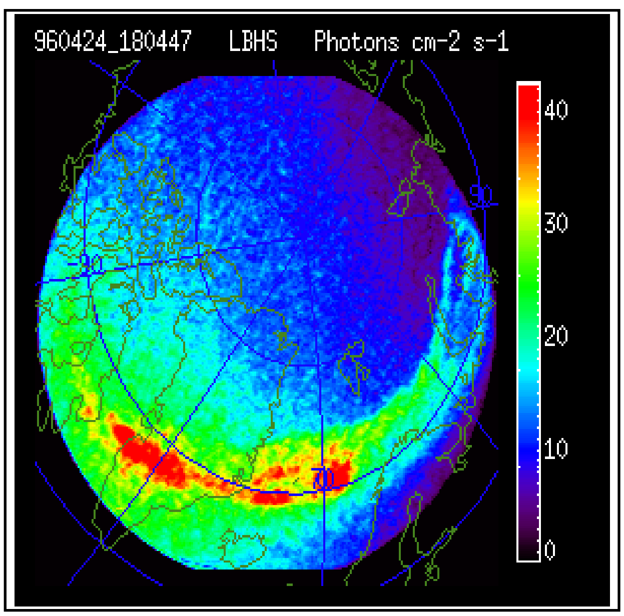


Fig. 2.b.5. A copy of the WICs flown successfully on Viking and Freja, the IMAGE WIC will provide high-sensitivity images of **auroral LBH emissions**.

The Wideband Imaging Camera (**WIC**) uses a range of wavelengths (134-160 nm) to form images of the aurora using the LBH emissions from excited nitrogen atoms in the atmosphere.



Images like this taken by the UVI instrument of the POLAR satellite are expected to be taken by the FUV instruments.

When a magnetic storm occurs, the aurora intensifies and the auroral oval, centered on the magnetic pole, widens and moves toward the equator. The result is that the aurora may be seen in regions farther south (in the case of the Aurora Borealis, or Northern Lights) than is normal. FUV will be able to add to the picture of when and how these changes occur during a magnetic storm.

IMAGE Extreme Ultra Violet (EUV) Imager

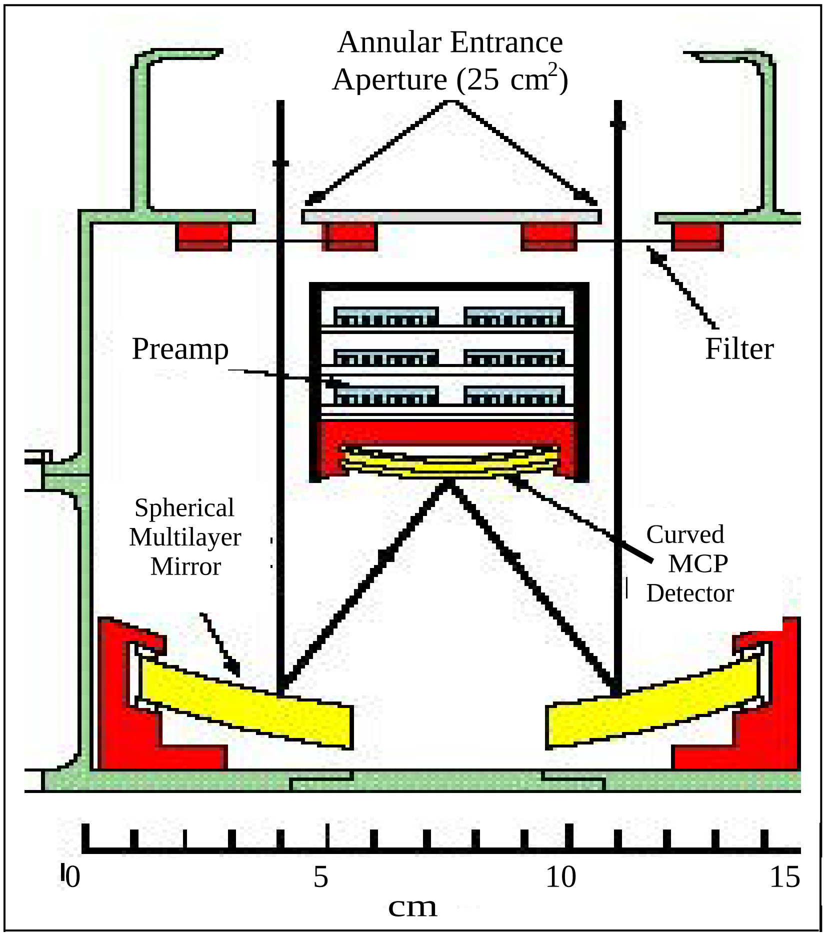
> The IMAGE spacecraft will carry an extreme ultraviolet (EUV) imager to detect solar EUV photons that are resonantly scattered by singly ionized helium in the plasmasphere, the torus of cold dense plasma surrounding the Earth in the inner magnetosphere. A sophisticated computer deconvolution technique will be used to translate the EUV photon counts registered by the instrument into images of the plasmasphere. Because of the IMAGE spacecraft's high apogee (8 Earth radii) and the EUV imager's wide field of view, images generated from data acquired at apogee will show the structure of the entire plasmasphere. The combined analysis of the EUV images and RPI data on plasmaspheric plasma density will allow researchers to study the global structure and dynamics of the plasmasphere and plasmapause as they change in response to changing levels of magnetospheric activity, while correlated analyses of EUV and NAI images will yield insights into the nature of the interaction between the cold plasma of the plasmasphere and the hot plasmas of the ring current and the near-Earth plasma sheet.
>
> IMAGE Spacecraft Science Payload
> http://pluto.space.swri.edu/IMAGE/EUV_intro.html

The magnetospheric structure that **EUV** will study is the plasmasphere, the cold dense plasma near Earth in the inner magnetosphere. The primary component of the plasmasphere is ionized hydrogen, or protons. Atoms and ions give off electromagnetic waves when the electrons change from one energy level to another. Protons, since they have no electrons, do not radiate electromagnetic energy. EUV will examine the ultraviolet radiation given off by singly ionized helium (He+) with a wavelength of 30.4 nm. From this, knowing the proportion of hydrogen to helium in the plasmasphere, an image of the plasmasphere can be formed

EUV consists of three identical instruments in a fan-like arrangement to increase the field of view. Each instrument has a 30^{o} field of view, but the total field of view of EUV is 84^{o} since the three are overlapped so that each can cover the central blind spot in the neighboring instrument. As the IMAGE spacecraft rotates, EUV will scan a region 84^{o} high by 360^{o} around.

The mirrors on EUV feature a multilayer coating designed to enhance the reflectivity of the mirror for 30.4 nm photons. The increased reflectivity is due to **constructive interference** of the photons as they pass through the layers.

In one rotation of IMAGE, the fainter regions of the plasmasphere, especially when viewed from apogee, will not provide enough light to contribute to the image. EUV will store the photon counts for each region in space for a total of up to 5 rotations and integrate the result into single image. Since IMAGE rotational period is 2 minutes, an image will be formed by EUV every 10 minutes. At positions closer to Earth, fewer rotations may be used to form the images.



Schematic diagram of the Extreme Ultraviolet Imager (EUV).

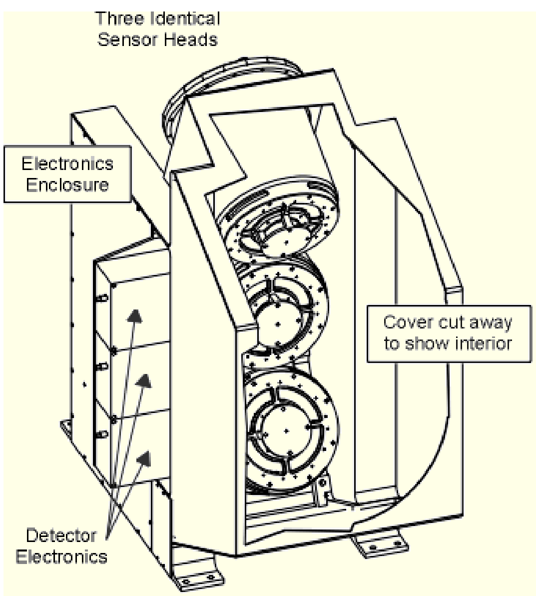
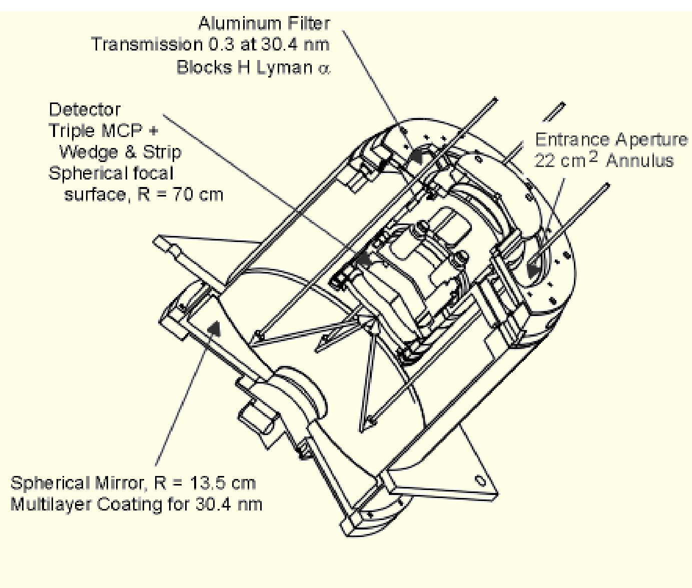


IMAGE Extreme Ultraviolet Imager



EUV Sensor Head (cutaway view)

Ultraviolet Imager Problems

The spectrographic imager (SI) uses Lyman α emissions of hydrogen to image both the geocorona and the proton aurora. The problem is that in order to "see" the proton aurora, SI must look through a huge cloud of hydrogen gas, the geocorona. How can the Lyman α light from the proton aurora be distinguished from the Lyman α light from the geocorona?

The answer involves the Doppler effect, the shift in frequency and wavelength of light caused by the motion of the source relative to the detector of the waves. The Lyman α wavelength detected from an atom that is at rest with respect to the detector is 121.57 nanometers. Instead of looking at this wavelength, however, SI looks at a "shifted" wavelength of 121.82 nanometers. Lyman α light that has been shifted must come from rapidly moving hydrogen atoms. Since the geocorona is composed of low energy, or cold, hydrogen, then the shifted Lyman α light must come from the aurora.

The following set of questions will lead the answer to the question: What is the energy of the hydrogen atoms that are providing the shifted Lyman α light/

A. What is the frequency (f) of unshifted Lyman α light?
B. What is the frequency (f') of the shifted Lyman α light?
C. What is the velocity (v) of the hydrogen atom emitting the light?
D. What is the kinetic energy (KE) of the hydrogen in Joules?
E. What is the kinetic energy (KE) of the hydrogen in electron-volts?

A. Given:

$\lambda = 121.6 \text{ nm} = 1.216 \times 10^{-7}$ m
$c = 2.998 \times 10^{8}$ m/s
$f = ?$

$c = \lambda f$

$$f = \frac{c}{\lambda}$$

$$f = \frac{2.998 \times 10^{8}}{1.216 \times 10^{-7}}$$

$$f = 2.465 \times 10^{15} \text{ Hz}$$

B. Given:

$\lambda' = 121.8 \text{ nm} = 1.218 \times 10^{-7}$ m
$c = 2.998 \times 10^{8}$ m/s
$f' = ?$

$c = \lambda' f'$

$$f'' \quad \frac{c}{\lambda'}$$

$$f' = \frac{2.998 \times 10^{8}}{1.218 \times 10^{-7}}$$

$$f' = 2.461 \times 10^{15} \text{ Hz}$$

C. $v = ?$ Doppler equation:

$$f' = \left(\frac{c + v_s}{c - v_d}\right) f$$

where: v_s = velocity of the source
v_d = velocity of the detector
(for simplicity, we will assume that $v_d = 0$)

Solve for v_s:

$$f' = \left(\frac{c + v_s}{c - v_d}\right) f \qquad c + v_s = \frac{c\,f'}{f}$$

$$v_s = \frac{c\,f'}{f} - c$$

$$v_s \quad \frac{2.998 \times 10^8\ (2.461 \times 10^{15})}{2.465 \times 10^{15}} - 2.998 \times 10^8$$

$$v_s = -4.865 \times 10^5 \text{ m/s}$$

(Note: The negative sign indicates that the hydrogen atom is moving away from the detector on IMAGE, which is consistent with a shift to a longer wavelength and a lower frequency.)

D. KE = ? J KE = $1/2\ m\ v^2$ $m = 1.67 \times 10^{-27}$ kg

$KE = (.5)\ (1.67 \times 10^{-27})\ (-4.865 \times 10^5)^2$

$KE = 1.980 \times 10^{-16}$ J

E. KE = ? eV $KE = 1.980 \times 10^{-16}\ \text{J}\ \dfrac{1\ \text{eV}}{1.6 \times 10^{-19}\ \text{J}}$

$KE = 1.237 \times 10^3$ eV (1.237 keV)

Answer the same five questions to find the kinetic energy of a hydrogen atom if the shifted wavelength of the Lyman α emission is:

1. 121.3 nm
2. 122.0 nm
3. 121.0 nm

BIBLIOGRAPHY – Part 2

amu	"atomic mass unit", a convenient unit of mass for atoms and ions; 1 amu = 1.67 x 10^{-27} kilograms
apogee	greatest distance from Earth to a satellite in orbit; the apogee of IMAGE is 8 Earth radii from the center of Earth (7 Earth radii from Earth's surface)
aurora	glowing lights in the polar region sky caused by solar wind particles entering Earth's atmosphere and causing atmospheric gases to glow; Aurora Borealis can be seen in the north polar region, Aurora Australis can be seen in the south polar region.
auroral LBH emissions	Lyman-Birge-Hopfield emissions of ultraviolet light from N_2 gas in the atmosphere resulting from energetic particles entering the atmosphere; the Wide-field Imaging Camera (WIC) on IMAGE forms images of the auroral LBH emissions in the 140-160 nanometer range
CME	"coronal mass ejection"; a large-scale ejection of charged material from the sun's corona extending out into the solar system; can cause magnetic disturbances on Earth (space weather)
constructive interference	two waves in the same place such that their displacements are in the same direction resulting in increased wave activity at that location
coronal mass ejection	CME (see above)
day side	the lighted half of Earth; the side towards the sun
Doppler shifting	the changing of the observed frequency of a wave due to the motion of the source or of the detector
Earth radii	a convenient unit of distance for use in the region around Earth; 1 R_E = 6400 kilometers
echo time	the time for the radio signal from RPI to reach the magnetopause or plasmapause and return to IMAGE

E-field component — the electric field component of an electromagnetic wave; it is perpendicular to the direction of travel of the wave and to the magnetic field component of the wave (B-field)

EUV — "Extreme Ultraviolet" electromagnetic waves; the EUV instrument on IMAGE will look at the 30.4 nm spectral line of singly ionized helium (He^+) in order to image the plasmasphere

eV — "electron volts"; a convenient unit of energy for ions and electrons; 1 ev = 1.6×10^{-19} Joules

FUV — "Far Ultraviolet" electromagnetic waves; the FUV instrument on IMAGE will look at various spectral lines in the 120-160 nanometer range to image the aurora and geocorona

geocorona — a large cloud of neutral hydrogen surrounding Earth

grating — device with closely spaced slits; used for spreading light into a spectrum using the principle of diffraction

HENA — "High Energy Neutral Analyzer"; instrument used to form images of the ring current particles with energies ranging from 10 keV to 500 keV

keV — "kilo electron volts"; see eV

IMF — "Interplanetary Magnetic Field"; the region within the solar system where the magnetic field of the sun determines the motion of charged particles

inertially — describes the motion that results when there is no force on an object; the object moves according to the Law of Inertia in a straight line at constant velocity

in situ — meaning at the location of; a measurement taken *in situ* is a measurement of the value of a quantity at that particular location in space; the other method of measurement is remote sensing

ionized — describes an atom that has lost one or more electrons, forming an ion

Interplanetary Magnetic Field — see IMF

LENA — "Low Energy Neutral Atom" Imager; instrument used to form images of the ring current particles with energies ranging from

10 eV to 300 eV

Lyman α spectral line emitted by atomic hydrogen as the electron moves from the n=2 level to the ground state (n=1); the Lyman α wavelength is 121.6 nm (ultraviolet)

magnetometer instrument for measuring the magnetic field at a particular location

magnetopause boundary between Earth's magnetic field (magnetosphere) and the IMF

magnetosphere region where Earth's magnetic field determines the motion of charged particles

magnetotail the part of the magnetosphere that extends from Earth in the direction away from the sun

MENA "Medium Energy Neutral Atom" imager; instrument used to form images of the ring current particles with energies ranging from 1 to 30 keV

NAI "Neutral Atom Imager"; includes HENA, MENA and LENA

nanometers unit of distance equal to 10^{-9} meter

neutral atom flux flux refers to the number of neutral atoms passing through a region per unit time

night side the dark half of Earth; the side away from the sun

nm "nanometers"; abbreviation for the unit of distance

phase refers to the relationship between the components of an electromagnetic wave as they reach an antenna; if the components are both positive, they are "in phase", if they have different signs, they are "out of phase"

pixels short for "picture elements"; refers to the small square boxes of various colors that make up an image

plasma a collection of charged particles; ions and electrons

plasmasphere region around Earth populated by cold (low energy) plasma consisting mainly of ionized hydrogen (protons) and electrons

R_E abbreviation for "Earth radii"; see Earth radii

radio plasma imager	instrument used to form images of the magnetosphere including the magnetopause and the plasmapause; abbreviated RPI
remote sensing	measuring a quantity from a distance; technique used by IMAGE to make *in situ* measurements unnecessary
ring current	charged particles of various energies that are trapped by magnetic forces on magnetic field lines where they spiral along the field line, are reflected from the polar regions and drift slowly around the equator
RPI	"Radio Plasma Imager"
SI	"Spectrographic Imager"; uses the Lyman α line of hydrogen to form images of the geocorona and the proton aurora
solar storms	magnetic disturbances originating from the sun
solar wind	stream of charged particles given off by the sun and carried away by the solar magnetic field
spectrometer	instrument for analyzing the wavelengths present from a source of electromagnetic waves
spin plane	the geometric plane of IMAGE containing the four long antennas
spin axis	the line through IMAGE about which it spins; the shorter "Z-antenna" is on the spin axis
ultraviolet	the part of the electromagnetic spectrum with wavelengths shorter that visible light and longer than X-rays; wavelengths range from around 400 nm down to about 10 nm
Van Allen radiation belts	high energy protons and electrons trapped on Earth's magnetic field lines; discovered in 1958 using the first US satellite placed in orbit, Explorer 1
WIC	"Wide-field Imaging Camera"; part of FUV used to form images of the aurora using wavelengths in the range from 140 to 160 nanometers