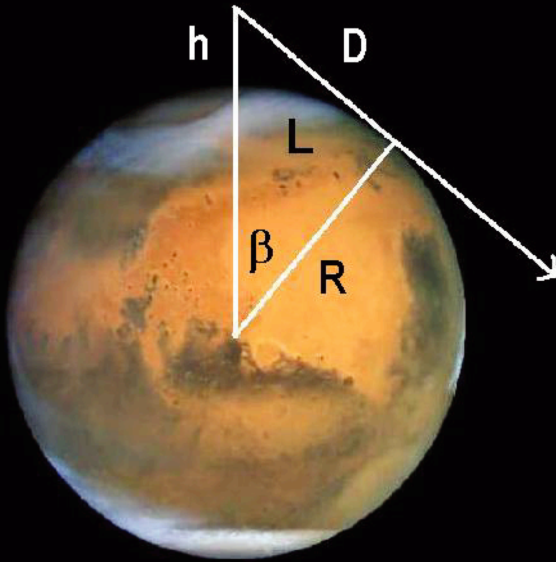
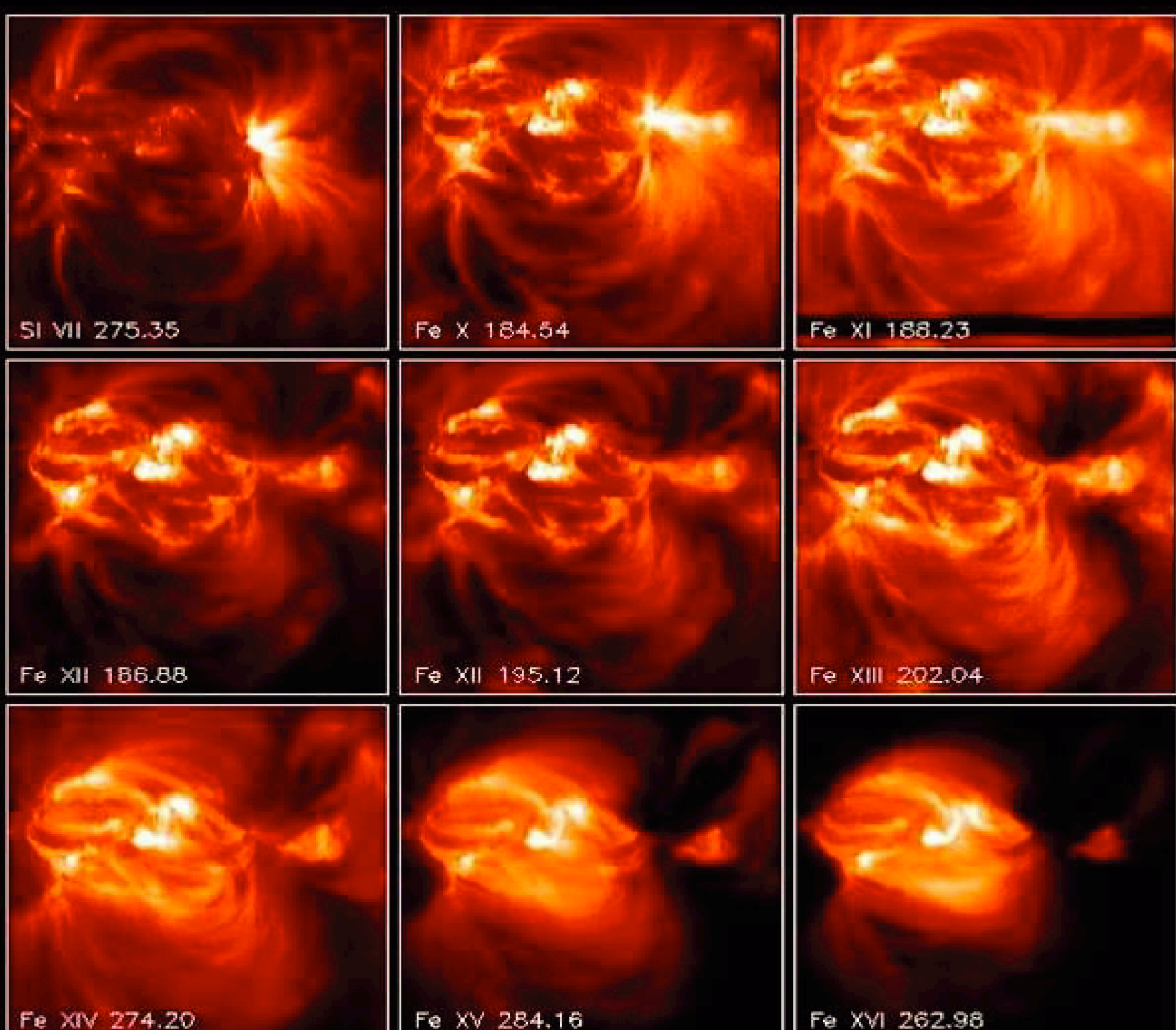
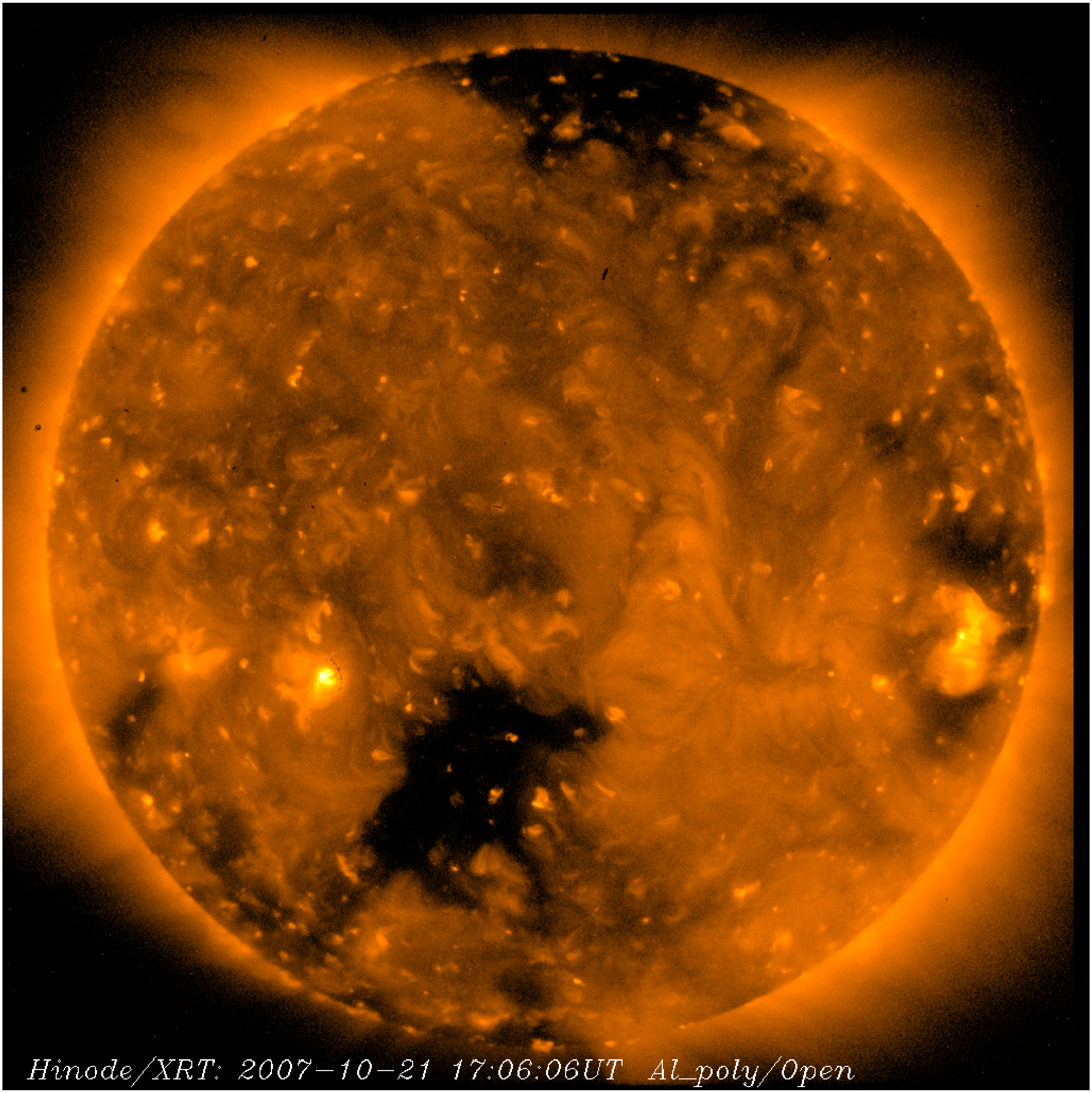
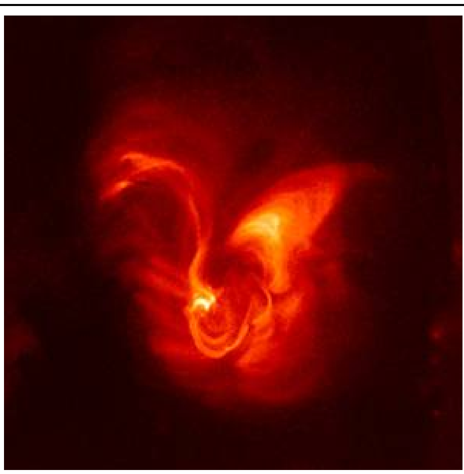
National Aeronautics and Space Administration

Hinode Math









The Hinode satellite was launched on September 22, 2006 and began taking images of the sun through x-ray light. The goal was to study the intense releases of magnetic energy which cause solar flares and the heating of the sun's corona.

These two images show the full-sun on October 21, 2007, revealing the orange glows of million-degree solar plasmas, along with coronal 'holes'. The small points of light are active regions, such as the one to the left, in which magnetic energy is released to heat the local solar gases.

By using the Hinode Extreme Ultraviolet Imaging Spectrometer (EIS), solar scientists hope to understand the physical conditions that lead to these violent releases of energy.

This collection of activities is based on a weekly series of space science problems distributed to thousands of teachers during 2006-2008 school year. They were intended as extra-credit problems for students looking for additional challenges in the math and physical science curriculum in grades 9 through 12.

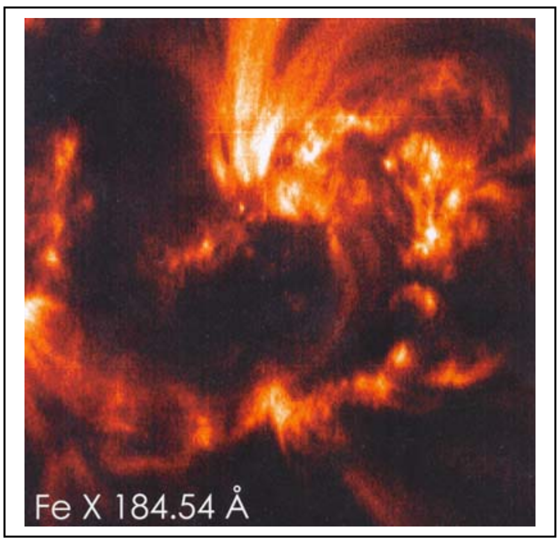
The problems were designed to be authentic glimpses of modern science and engineering issues that come up in designing satellites to work in space, and to provide insight into the basic phenomena of the Sun-Earth system.

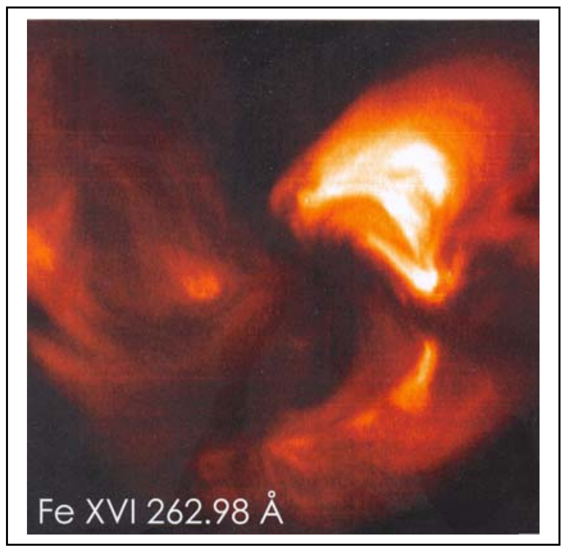
The problems are designed to be 'one-pagers' consisting of a Student Page, and Teacher's Answer Key. This compact form was deemed very popular by participating teachers.

This booklet was created by the Naval Research Laboratory, Hinode EIS-Education and Public Outreach Project.

Dr. Sten Odenwald ***(NASA - Hinode)***

Dr. George Doschek (NRL, *Hinode*/EIS Co-I)





These images, provided by the EIS Imaging Spectrometer, show the locations of solar plasma near an active region, with temperatures near 950,000 K (left) and 1,600,000 K (right).

Images such as these can be assembled into detailed movies that help solar physicists study the heating and movement of plasmas within intense solar magnetic fields.

For more weekly classroom activities about the Sun-Earth system visit the NASA website,
http://spacemath.gsfc.nasa.gov
Add your email address to our mailing list by contacting Dr. Sten Odenwald at
sten.f.odenwald@nasa.gov

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Alignment with Mathematics Standards

The following table connects the activities in this booklet to topics commonly covered in geometry, algebra and calculus textbooks. The cells are shaded according to these three math content areas. The specific national math and science education standards (NSF 'Project 2061') targeted by this product are:

Grade 4-7 - pre-Algebra

Find answers to problems by substituting numerical values in simple algebraic formulas.
Use tables, charts and graphs in making arguments and claims in oral and written presentations.
Perform unit conversions in multi-step problems.

Here is the order in terms of the mathematics topics covered:

Image Scales, Metric Measurement, Unit Conversions

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Area Calculation (square, rectangle)

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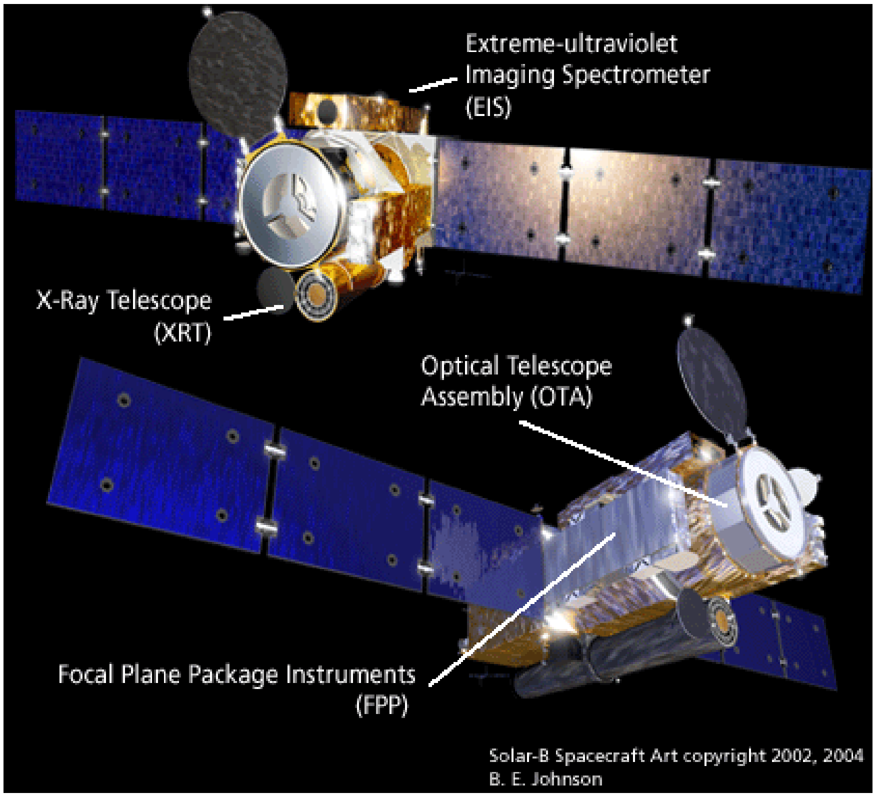
Hinode Satellite Power



The Hinode satellite weighs approximately 700 kg (dry) and carries 170 kg of gas for its steering thrusters, which help to maintain the satellite in a polar, sun-synchronous orbit for up to two years. The satellite has two solar panels (blue) that produce all of the spacecraft's power. The panels are about 4 meters long and 1 meter wide, and are covered on both sided by solar cells.

Problem 1 - What is the total area of the solar panels covered by solar cells in square centimeters?

Problem 2 - If a solar cell produces 0.03 watts of power for each square centimeter of area, what is the total power produced by the solar panels when facing the sun? Can the satellite supply enough power to operate the experiments which require 1,150 watts?

Problem 3 - Suppose engineers decided to cover the surface of the cylindrical satellite with solar cells instead. If the satellite is 4 meters long and a diameter of 1 meter, how much power could it produce? Can the satellite supply enough power to keep the experiments running, which require 1,150 watts?

Answer Key:

The Hinode satellite weighs approximately 700 kg (dry) with some 170 kg of thruster gas for maintaining a polar, sun-synchronous orbit for more than two years. The satellite has two solar panels (blue) that produce all of the spacecraft's power. The panels are about 4 meters long and 1 meter wide ,and are covered on both sided by solar cells.

Problem 1 - What is the total area of the solar panels covered by solar cells in square centimeters?

Answer: The surface area of a single panel is 4 meters x 1 meter = 4 square meter per side. There are two sides, so the total area of one panel is 8 square meters. There are two solar panels ,so the total surface area covered by solar cells is 16 square meters. Converting this to square centimeters:

$$8 \text{ square meters} \times (10{,}000 \text{ cm}^2/\text{m}^2) = 80{,}000 \text{ cm}^2$$

Problem 2 - If a solar cell produces 0.03 watts of power for each square centimeter of area, what is the total power produced by the solar panels when facing the sun? Can the satellite supply enough power to operate the experiments which require 1,150 watts?

Answer: Only half of the solar cells can be fully illuminated at a time, so the total exposed area is 40,000 cm^2. The power produced is then:

$$\text{Power} = 40{,}000 \text{ cm}^2 \times 0.03 \text{ watts/cm}^2 = 1{,}200 \text{ watts.}$$

Yes, the satellite solar panels can keep the experiments running, with 50 watts to spare!

Problem 3 - Suppose engineers decided to cover the surface of the cylindrical satellite with solar cells instead. If the satellite is 4 meters long and a diameter of 1 meter, how much power could it produce? Can the satellite supply enough power to keep the experiments running, which require 1,150 watts?

Answer - Surface area of a cylinder = $2 \pi R^2 h$

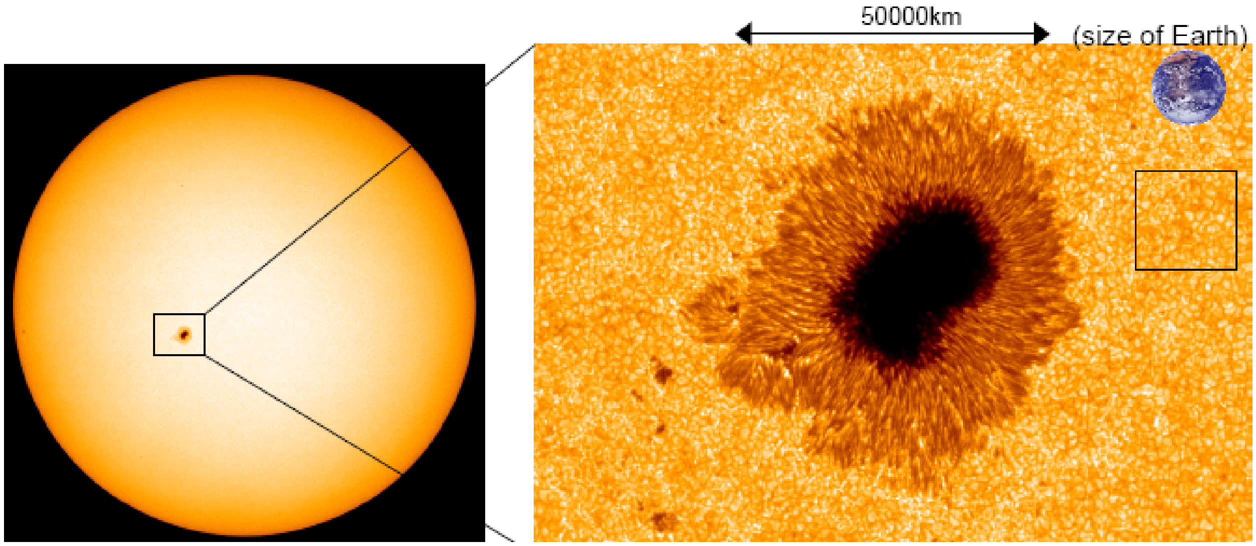
so for the satellite

$$S = 2 \times (3.14)\ (0.5 \text{ meters})^2\ (4 \text{ meters}) = 6.28 \text{ square meters}$$

Only half of the solar cells can be illuminated, so the usable area is 3.14 square meters or 31,400 square centimeters. The power produced is 31,400 x 0.03 = 942 watts.

No..the satellite cannot keep the experiments running. They require an extra 1,100-942 = 158 watts.

Hinode - Close-up of a Sunspot



After a successful launch on September 22, 2006 the Hinode solar observatory caught a glimpse of a large sunspot on November 4, 2006. An instrument called the Solar Optical Telescope (SOT) captured this image, showing sunspot details on the solar surface.

Problem 1 - From the clues in this image, what is the scale of the image on the right in units of kilometers per millimeter?

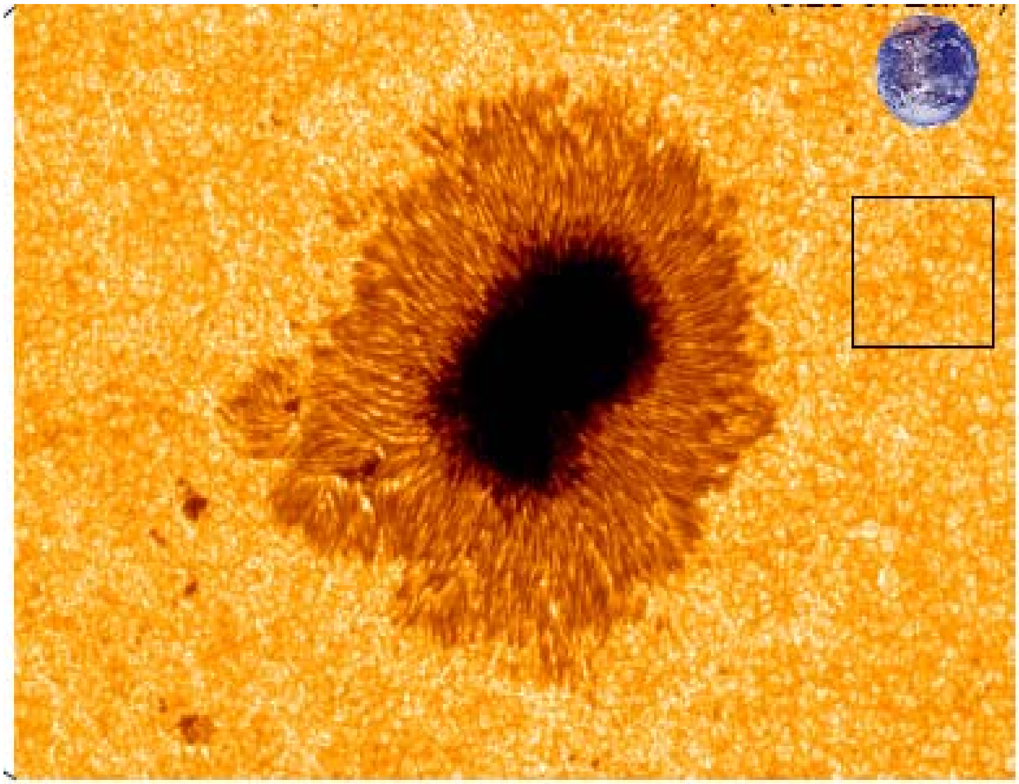
Problem 2 - What is the size of the smallest detail you can see in the image?

Problem 3 - Compared to familiar things on the surface of Earth, how big would the smallest feature in the solar image be?

Problem 4 - The gold-colored textured surface is the photosphere of the sun. The texturing is produced by heated gas that is convecting from the hot interior to the cooler outer layers of the sun. The convecting gases form cells, called granulations, at the surface, with upwelling gas flowing from the center of each cell, outwards to the cell boundary, where it cools and flows back down to deeper layers. What is the average size of a granulation cell within the square?

Problem 5 - Measure several granulation cells at different distances from the sunspot, and plot the average size you get versus distance from the spot center. Do granulation cells have about the same size near the sunspot, or do they tend to become larger or smaller as you approach the sunspot?

Answer Key:



Answer 1 - From the 40 millimeter length of the 50,000 km arrow marker, the scale of the image is 50,000 km/40 mm = 1250 kilometers per millimeter

Answer 2 - The smallest detail is about 0.5 millimeters or 0.5 x 1250 = 625 kilometers across.

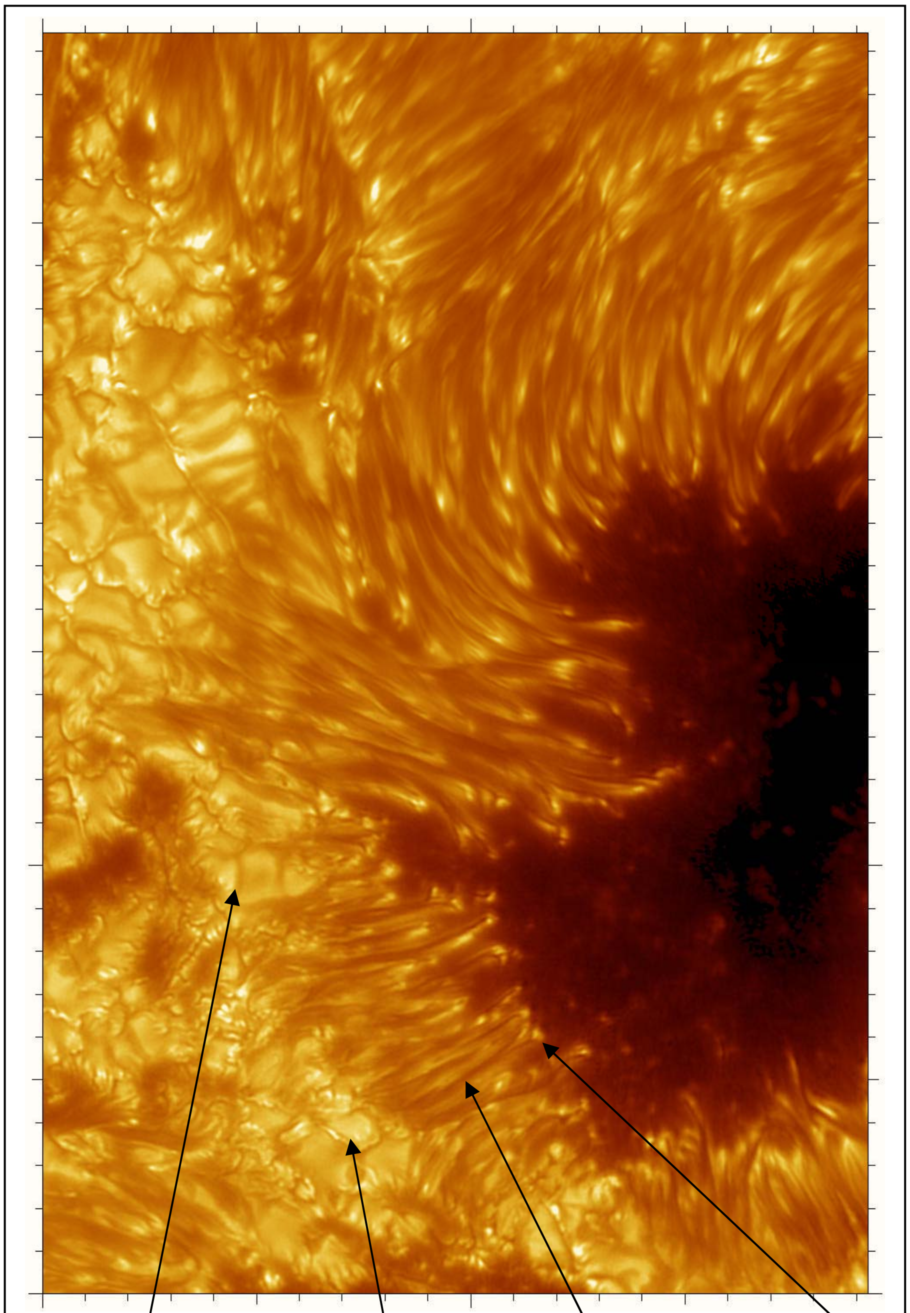
Answer 3 - Similar features on Earth would be continents like Greenland (1,800 km) or England (700 km).

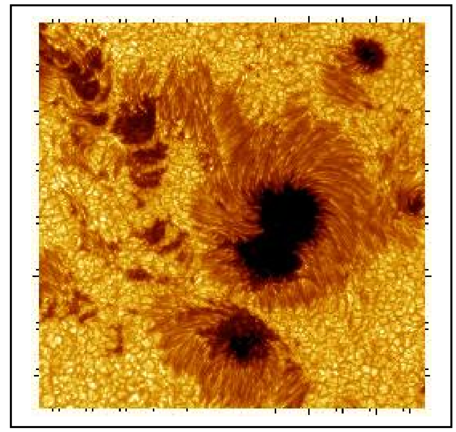
Answer 4 - Measure about 5 cells to get: 1.5 mm, 1.0 mm, 0.8mm, 1.2mm and 1.4 mm. The average is about 1.2 mm, so the average size is (1.2) x 1250km = 1,500 km.

Answer 5 - Students should measure about 5 granulation cells in three groups; Group 1 should be far from the center of the spot. Group 3 should be as close to the outer, tan-colored, 'penumbra' of the spot as possible, and Group 2 should be about half-way in between Group 1 and 3. The average granulation sizes do not change significantly.

Solar Surface Details

The sun is our nearest star. From Earth we can see its surface in great detail. The images below were taken with the 1-meter Swedish Vacuum Telescope on the island of La Palma, by astronomers at the Royal Swedish Academy of Sciences (http://www.astro.su.se/groups/solar/solar.html). The image to the right is a view of sunspots on July 15, 2002. The enlarged view to the left shows never-before seen details near the ‘penumbral’ edge of the largest spot. Use a millimeter ruler and the fact that the dimensions of the left image are 19,300 km x 29,500 km to determine the scale of the photograph, and then answer the questions.





Question 1 - What is the scale of the image in km/mm?

Question 2 – What is the smallest feature you can see in the image?

Question 3 – What is the average size of a Solar Granulation region?

Question 4 – How long and wide are the Dark Filaments?

Question 5 – How large are the Bright Spots?

Question 6 – Draw a circle centered on this picture that is the size of Earth (radius = 6,378 km). How big are the features you measured compared to familiar Earth features?

Question 1 - What is the scale of the image in km/mm? **Answer:** the image is about 108mm x 164mm so the scale is 19300/108 = 179 km/mm.

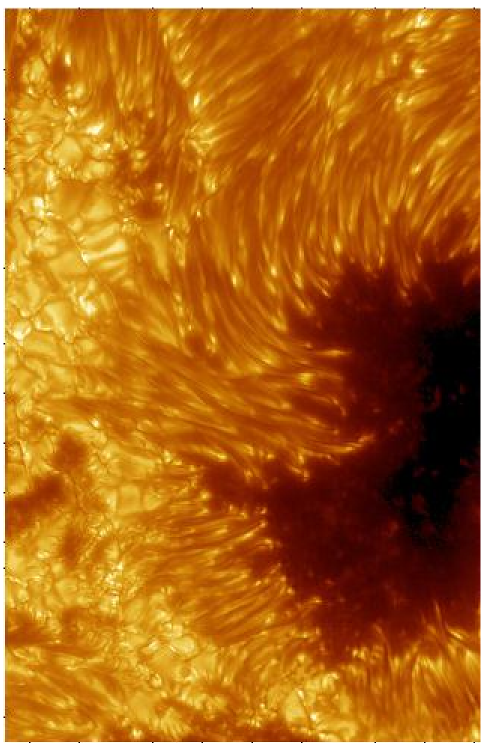
Question 2 – What is the smallest feature you can see in the image? **Answer:** Students should be able to find features, such as the Granulation Boundaries, that are only 0.5 mm across, or 0.5 x 179 = 90 km across.

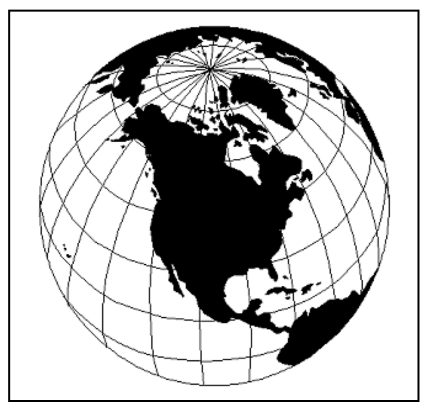
Question 3 – What is the average size of a Solar Granulation region? **Answer:** Students should measure several of the granulation regions. They are easier to see if you hold the image at arms length. Typical sizes are about 5 mm so that 5 x 179 is about 900 km across.

Question 4 – How long and wide are the Dark Filaments? **Answer:** Students should average together several measurements. Typical dimensions will be about 20mm x 2mm or 3,600 km long and about 360 km wide.

Question 5 – How large are the Bright Spots? **Answer:** Students should average several measurements and obtain values near 1 mm, for a size of about 180 km across.

Question 6 – Draw a circle centered on this picture that is the size of Earth (radius = 6,378 km). How big are the features you measured compared to familiar Earth features? **Answer:** See below.



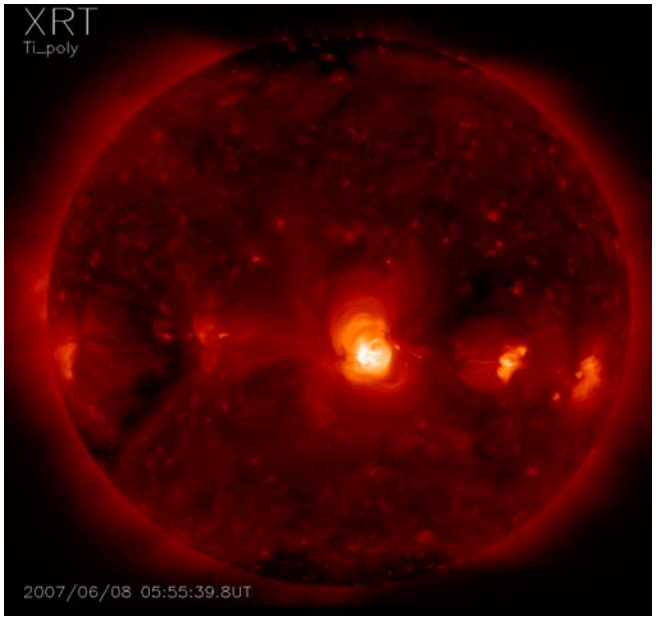


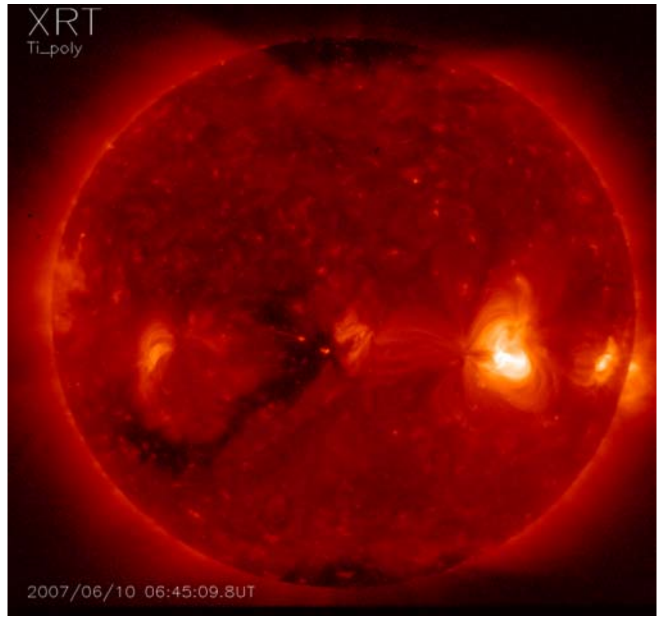
Granulation Region – Size of a large US state.

Bright Spot – Size of a small US state or Hawaii

Filament – As long as the USA, and as narrow as Baja California or Florida.

How fast does the sun spin?





The sun, like many other celestial bodies, spins around on an axis that passes through its center. The rotation of the sun, together with the turbulent motion of the sun's outer surface, work together to create magnetic forces. These forces give rise to sunspots, prominences, solar flares and ejections of matter from the solar surface.

Astronomers can study the rotation of stars in the sky by using an instrument called a spectroscope. What they have discovered is that the speed of a star's rotation depends on its age and its mass. Young stars rotate faster than old stars, and massive stars tend to rotate faster than low-mass stars. Large stars like supergiants, rotate hardly at all because they are so enormous they reach almost to the orbit of Jupiter. On the other hand, very compact neutron stars rotate 30 times each second and are only 40 kilometers across.

Rotation is a complicated phenomenon in astrophysics. In most cases, the rotation speed of a star as it ages has to do with a principal called the Conservation of Angular Momentum. If a star doubles in its physical size, its rotation speed drops by a factor of two so that none of its angular momentum is lost. This usually happens as a star evolves to become a giant or supergiant star towards the end of its life. On the other hand, very young stars nearly the size of the sun at birth, slow down because of magnetic braking, much like a car slows down by friction applied by its metal breaks.

The X-ray telescope on the Hinode satellite creates movies of the rotating sun, and makes it easy to see this motion. A sequence of these images is shown on the left taken on June 8, 2007 (Left); June 10 2007 (Right) at around 06:00 UT.

The radius of the sun is 696,000 kilometers.

Problem 1 - Using the information provided in the images, calculate the speed of the sun's rotation in kilometers/sec and in miles/hour.

Problem 2 – About how many days does it take to rotate once at the equator?

Inquiry Question: What geometric factor produces the largest uncertainty in your estimate, and can you come up with a method to minimize it to get a more accurate rotation period?

Answer Key:

1) **Problem 1** - Using the information provided in the images, calculate the speed of the sun's rotation in kilometers/sec and in miles/hour.

First, from the diameter of the sun's disk, calculate the image scale of each picture in kilometers per millimeter.

Diameter= 76 mm. so radius = 38 mm. Scale = (696,000 km)/38 mm = 18,400 km/mm

Then, find the center of the sun disk, and using this as a reference, place the millimeter ruler parallel to the sun's equator, measure the distance to the very bright 'active region' to the right of the center in each picture. Convert the millimeter measure into kilometers using the image scale.

Picture 1: June 8 distance = 4 mm d = 4 mm (18,400 km/mm) = 74,000 km
Picture 2; June 10 distance = 22 mm d = 22 mm (18,400 km/mm) = 404,000 km

Calculate the average distance traveled between June 8 and June 10.

Distance = (404,000 - 74,000) = 330,000 km

Divide this distance by the number of elapsed days (2 days)…………….. 165,000 km/day

Convert this to kilometers per hour………………………………………….. 6,875 km/hour

Convert this to kilometers per second……………………………………….. 1.9 km/sec

Convert this to miles per hour ………………………………………………. 4,400 miles/hour

Problem 2 – About how many days does it take to rotate once at the equator?

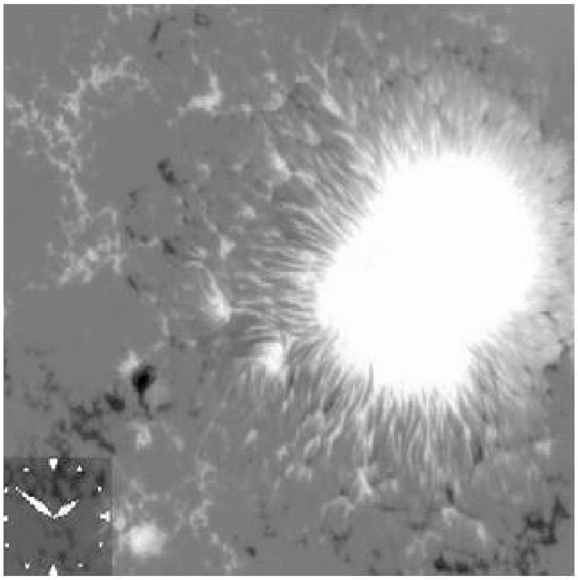
The circumference of the sun is 2 π (696,000 km) = 4,400,000 kilometers.

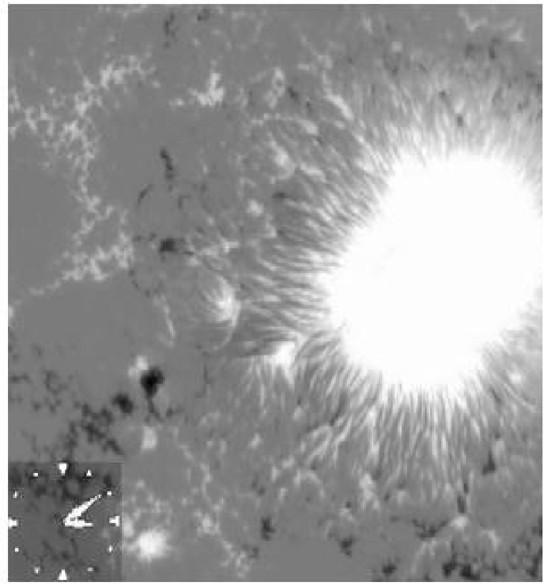
The equatorial speed is 66,000 km/day so the number of days equals
4,400,000/165,000 = **26.6 days.**

Inquiry Question:
Because the sun is a sphere, measuring the distance of the spot from the center of the sun on June 10 gives a distorted linear measure due to foreshortening.

The sun has rotated about 20 degrees during the 2 days, so that means a full rotation would take about (365/20) x 2 days = 36.5 days which is close to the equatorial speed of the sun of 35 days.

Moving Magnetic Filaments Near Sunspots





These two images were taken by the Hinode (Solar-B) solar observatory on October 30, 2006. The size of each image is 34,300 km on a side. The clock face shows the time when each image was taken, and represents the face of an ordinary 12-hour clock.

1) What is the scale of each image in kilometers per millimeter?

2) What is the elapsed time between each image in; A) hours and minutes? B) decimal hours? C) seconds?

Carefully study each image and look for at least 5 features that have changed their location between the two images. (Hint, use the nearest edge of the image as a reference).

3) What direction are they moving relative to the sunspot?

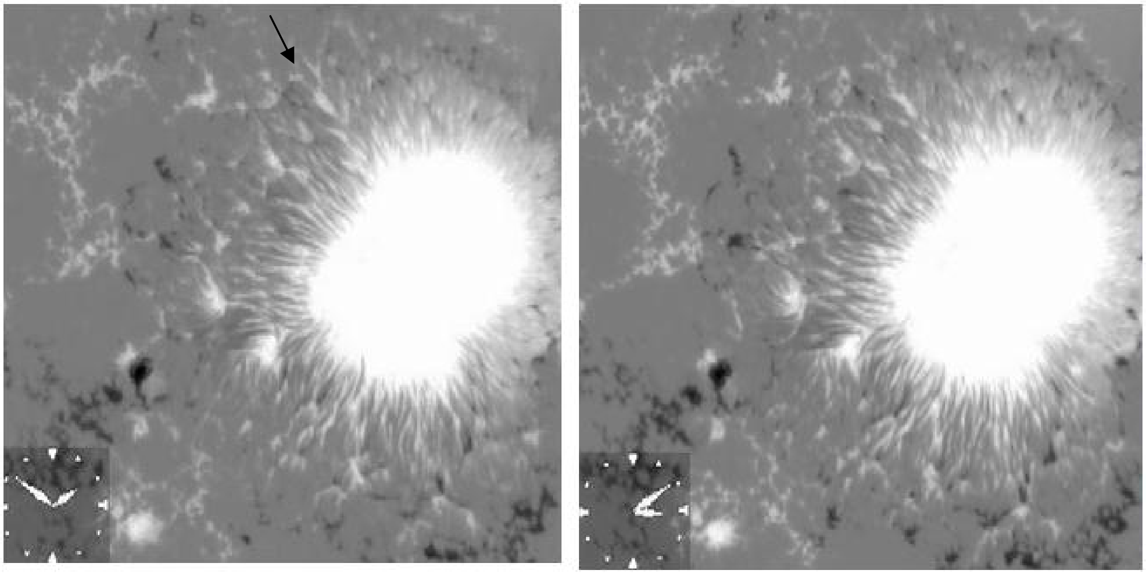
4) How far, in millimeters have they traveled on the image?

5) From your answers to questions 1, 2 and 4, calculate their speed in kilometers per second, and kilometers per hour.

6) A fast passenger jet plane travels at 600 miles per hour. The Space Shuttle travels 28,000 miles per hour. If 1.0 kilometer = 0.64 miles, how fast do these two craft travel in kilometers per second?

7) Can the Space Shuttle out-race any of the features you identified in the sunspot image?

Answer Key:



These two images were taken by the Hinode (Solar-B) solar observatory on October 30, 2006. The size of each image is 34,300 km on a side. The clock face shows the time when each image was taken.

1) What is the scale of each image in kilometers per millimeter? **Answer:** The pictures are 75 mm on a side, so the scale is 34,300 km /75mm = **457 km/mm**

2) What is the elapsed time between each image in;

A) hours and minutes? About 1 hour and 20 minutes.
B) decimal hours? About 1.3 hours
C) seconds? About 1.3 hours x 3600 seconds/hour = 4700 seconds

Carefully study each image and look for at least 5 features that have changed their location between the two images. (Hint, use the nearest edge of the image as a reference). Students may also use transparent paper or film, overlay the paper on each image, and mark the locations carefully.
The above picture shows one feature as an example.

3) What direction are they moving relative to the sunspot?
Answer: Most of the features seem to be moving away from the sunspot.

4) How far, in millimeters have they traveled on the image? **Answer:** The feature in the above image has moved about 2 millimeters.

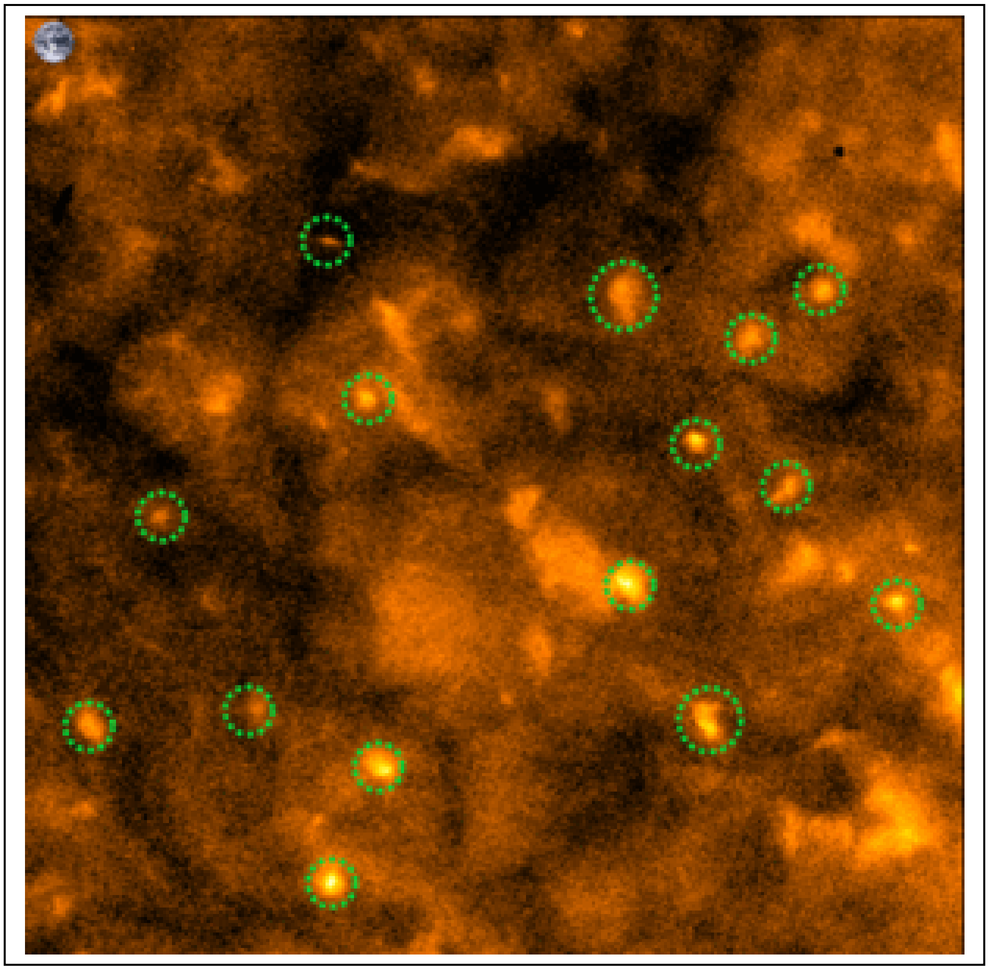
5) From your answers to questions 1, 2 and 4, calculate their speed in kilometers per second, and kilometers per hour. **Answer:** 2 mm x 457 km/mm = 914 kilometers in 4700 seconds = 0.2 kilometers/sec or 703 kilometers/hour.

6) A fast passenger jet plane travels at 600 miles per hour. The Space Shuttle travels 28,000 miles per hour. If 1.0 kilometer = 0.64 miles, how fast do these two craft travel in kilometers per second? Jet speed = 600 miles/hr x (1 / 3600 sec/hr) x (1 km/0.64 miles) = **0.26 km/sec**. Shuttle = 28,000 x (1/3600) x (1/0.64) = **12.2 km/sec.**

7) Can the Space Shuttle out-race any of the features you identified in the sunspot image? **Answer:** Yes, in fact a passenger plane can probably keep up with the feature in the example above!

8) Are the features moving at increasing speed away from the sunspot, or traveling at a constant speed?

Hinode Sees Mysterious Solar Micro-flares



The Sun's surface is not only covered with large magnetically active regions such as sunspots, it is also dotted with intense spots of X-ray light called 'X-ray bright points'. Although sunspots can be over 100,000 kilometers across and easily seen with a telescope, these Bright Points are so small that even the largest solar telescope only sees a few of them in detail enough to reveal their true shapes. As for most magnetic phenomena on the sun, they release their energy in a process called Magnetic Reconnection, which converts a tangled magnetic field into a smoother one, and liberates large quantities of stored magnetic energy. For that reason, these Bright Points can be thought of as micro-flares. The resolution of Hinode's X-ray telescope (XRT) has now made it possible to see loop structures of which the bright points are apparently composed. In the image above, individual bright points are circled in green. A few of them can be resolved into tiny magnetic loops. These data were taken on March 16, 2007.

The image is 300 x 300 pixels in size. Each pixel views an area on the sun that is 1 arcsecond x 1 arcsecond on a side.

Problem 1: If the diameter of the sun measures 1800 arcseconds and has a radius of 696,000 km, what is the scale of the above image in kilometers per millimeter?

Problem 2: What are the dimensions of the smallest circled Bright Point in the image?

Problem 3: How many Bright Points cover the solar surface if the above picture is typical?

Answer Key:

The image is 300 x 300 pixels in size. Each pixel views an area on the sun that is 1 arcsecond x 1 arcsecond on a side.

Problem 1: If the diameter of the sun measures 1800 arcseconds and has a radius of 696,000 km, what is the scale of the above image in kilometers per millimeter?

Answer: The image is 300 pixels across, which measures 115 millimeters with a ruler. Each pixel is 1 arcsecond in size, so if the radius of the sun is 1800/2 = 900 arcseconds, the radius of the sun is 3 times as large as the width of the image. This means that the image is 1/3 of the sun's radius across or 696,000/3 = 232,000 kilometers. This represents 300 pixels in the image, so each pixel is about 232,000/300 = 773 kilometers.

Problem 2: What are the dimensions of the smallest circled Bright Point in the image?

Answer: With a ruler, the circled Bright Point at the top of the picture seems to be the smallest. It measures about 2 millimeters across and 1 millimeter wide. This corresponds to about 1,500 km x 770 km.

Problem 3: How many Bright Points cover the solar surface if the above picture is typical?

Answer:

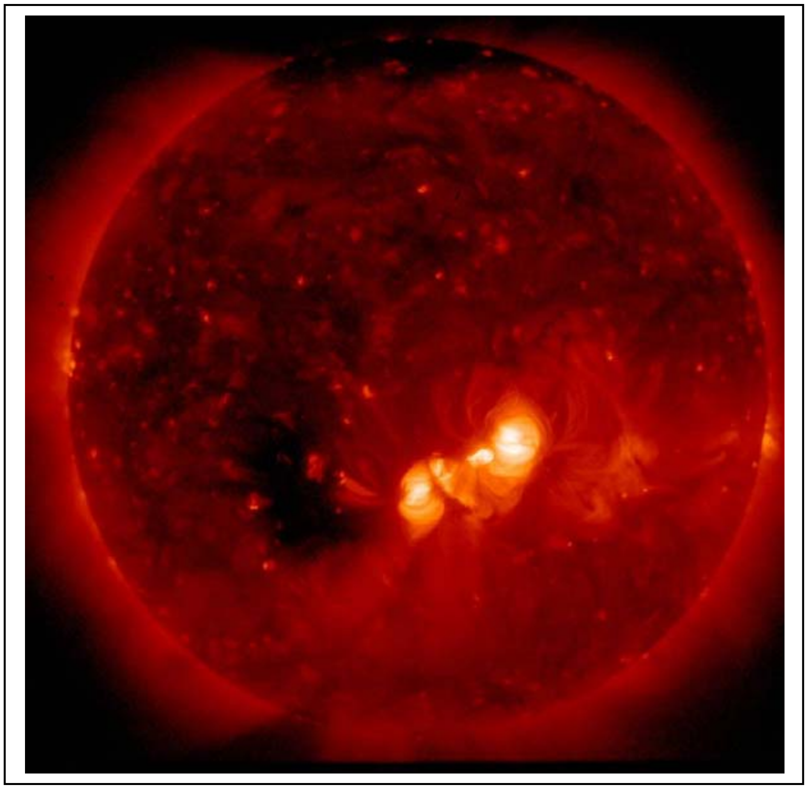
The sun is a sphere with a radius of 696,000 kilometers. The area of a sphere is given by $4 \pi R^2$, so the surface area of the sun is $4 \times 3.141 \times (696{,}000 \text{ km})^2 = 6.1 \times 10^{12}$ kilometers^2.

The size of the Hinode image is 300 pixels x 773 km/pixel = 232,000 km on a side. The area covered is about (232,000 km x 232,000 km) = 5.4×10^{10} km^2. Note, this is an approximation because of the distortion of a flat image attempting to represent a curved spherical surface. The actual solar surface area covered is actually a bit larger.

The solar surface is about 6.1×10^{12} km^2 / 5.4×10^{10} km^2 = 113 times larger than the Hinode image.

There are 16 Bright Points in the Hinode image, so there would be 15 x 113 = 1,695 Bright Points covering the full solar surface if the Hinode image is typical.

The Hinode satellite views the sun

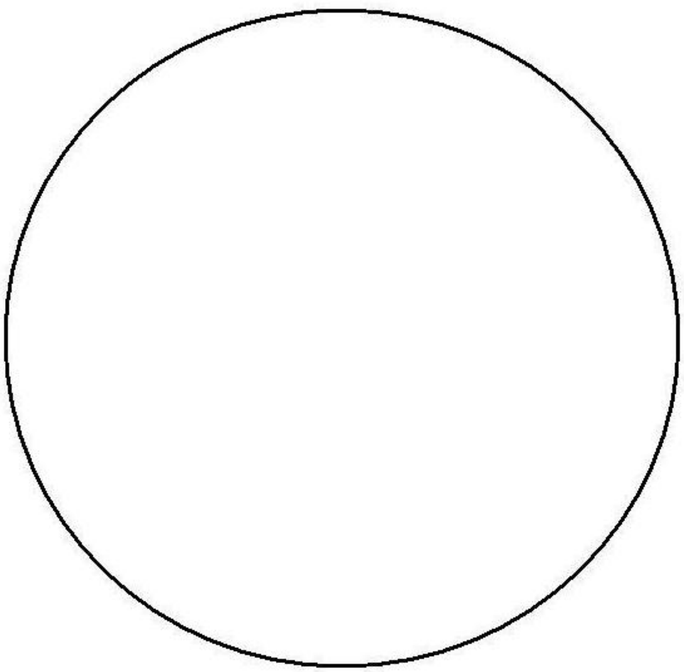


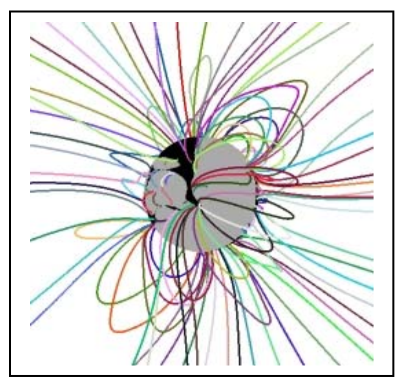
This image was taken by the X-Ray Telescope (XRT) on the Hinode solar observatory in December, 2006. It shows the complex magnetic structure over a large sunspot called Active Region AR930. You can also see large numbers of bright 'freckles' - each representing a small micro-flare.

The large black 'holes' are places in the corona of the sun where high-temperature gas is free to escape from the sun, and so there is little gas to illuminate these regions of the solar corona. This is because in these 'coronal holes' magnetic field lines open out to interplanetary space. Closed field lines near the surface act like magnetic bottles and keep the heated plasma close to the sun, creating the bright areas (red and yellow colors).

Using a black pen or pencil, try your hand at predicting what the magnetic field lines look like using the clues from Hinode picture!

Below is an example of a field line model calculated from an image by the SOHO satellite.

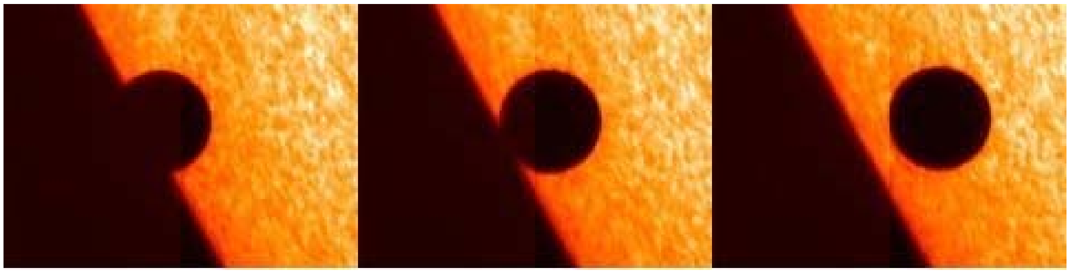


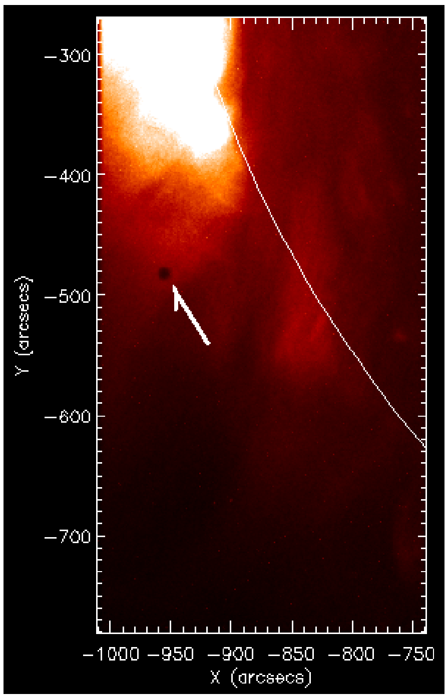


Answer Key:

Students may come up with several different versions. The main thing to look for is that in the regions where the Hinode picture shows orange or yellow, students should draw loops of magnetism…like a bar magnet field….that are close-in to the solar surface. In the black regions (north pole) of sun and the large spot to the left of the sunspot (yellow), they should draw magnetic lines that start in the dark region but end outside the picture because they are continuing on into interplanetary space. Below is a possible drawing! Students may notice that the gases are brightest in the lower-right quadrant so there are more closed magnetic field 'loops' there. There are also more dark areas in the top half of the image so there are probably a mixture of open and closed field lines, and not as many closed ones as in the lower-right quadrant. They should definitely realize that the two large dark areas at the top 'north' pole and to the left of the bright yellow sunspot region contain open field lines. The bright yellow active region should have a number of large loops and a higher density of them than elsewhere.

The Transit of Mercury





Every few times a century, the planet Mercury and Earth are lined up in such a way that Mercury passes across the disk of the sun as seen from Earth. The last time this happened was on November 8, 2006, and the next time this will happen will be on May 9, 2016. Since they were first observed in the 1600's, astronomers have studied them intently to learn more about Mercury, and to determine how far the sun is located from Earth. In recent times, astronomers no longer view these transits with much interest since the information that provide can be found by other more direct means. Still, when transits occur, astronomers turn their telescopes, now located in space, to watch the spectacle.

Top) Transit of Mercury obtained with Solar Optical Telescope (SOT) on the Hinode satellite on November 8, 2006. Left) Image obtained with the EUV Imaging Spectrometer (EIS). Solid curve indicates solar limb. The arrow shows the location of Mercury seen against the solar corona.

Problem 1: If the diameter of Mercury as viewed from Earth during the transit was 10 arcseconds, and the diameter of the sun at that time was 1900 arcseconds, what would be the diameter of the circle in the Hinode EIS image in centimeters that would represent the solar disk at this scale?

Problem 2: At the time of the transit, Mercury was about 55 million kilometers from the sun and about 92 million kilometers from Earth. How large, in arcseconds, would Mercury have appeared if it were at the distance of the Sun at this time?

Problem 3: How old will you be when the next Transit of Mercury happens?

Inquiry Problem: Why are transits of Mercury so rare?

Answer Key:

Problem 1: If the diameter of Mercury as viewed from Earth during the transit was 10 arcseconds, and the diameter of the sun at that time was 1900 arcseconds, what would be the diameter of the circle in the Hinode EIS image in centimeters that would represent the solar disk at this scale?

Answer: The tic marks on the lower image are 10 arcseconds apart. With a millimeter ruler, the separation is about 2 millimeters. The scale of the image is then 5 arcseconds/millimeter. If the solar diameter is 1900 arcseconds, its size on this page would be 1900 arcseconds / (5 arcseconds/mm) = 380 millimeters or 38 centimeters.

Problem 2: At the time of the transit, Mercury was about 55 million kilometers from the sun and about 92 million kilometers from Earth. How large, in arcseconds, would Mercury have appeared if it were at the distance of the Sun at this time?

Answer: The distance to the sun would be 55 + 92 = 147 million kilometers. At a distance of 92 million kilometers from Earth, mercury is 10 arcseconds in size, so at 147 million kilometers it would be 10 arcseconds x (92 million km /147 million km) = 6.2 arcseconds.

Problem 3: How old will you be when the next Transit of Mercury happens?

Answer: If you are 13 years old in 2007, you will be 13 + (2016 - 2007) = 13 + 9 = 22 years old, and will be graduating from college!!

Inquiry Problem: Why are transits of Mercury so rare?

Students may use GOOGLE to look up 'transit of Mercury' to find pages that discuss how transits occur.

They should deduce that the circumstances to not re-occur each year because Earth and mercury are on orbits that are tilted with respect to each other.

Hinode Studies Loopy Sunspots!

The solar surface is not only a hot, convecting ocean of gas, but is laced with magnetism. The sun's magnetic field can be concentrated into sunspots, and when solar gases interact with these magnetic fields, their light lets scientists study the complex 'loopy' patterns that the magnetic fields make as they expand into space. The above image was taken by NASA's TRACE satellite and shows one of these magnetic loops rising above the surface near two sunspots. The horseshoe shape of the magnetic field has foot points which coincide with the dark sunspot regions.

The heated gases become trapped by the magnetic forces in sunspot loops, which act like magnetic bottles. The above image only tells scientists where the gases are, and the shape of the magnetic field, which isn't enough information for scientists to fully understand the physical conditions within these magnetic loops. Satellites such as Hinode carry instruments like the EUV Imaging Spectrometer, which lets scientists measure the temperatures of the gases and their densities as well.

Problem 1: The Hinode satellite studied a coronal loop on January 20, 2007 associated with Active Region AR 10938, which was shaped like a semi-circle with a radius of 20,000 kilometers, forming a cylindrical tube with a base radius of 1000 kilometers. What was the total volume of this magnetic loop in cubic centimeters assuming that it is shaped like a cylinder?

Problem 2: The Hinode EUV Imaging Spectrometer was able to determine that the density of the gas within this magnetic loop was about 2 billion hydrogen atoms per cubic centimeter. If a hydrogen atom has a mass of 1.6×10^{-24} grams, what was the total mass of the gas trapped within this cylindrical loop in metric tons?

Answer Key:

Problem 1: The Hinode satellite studied a coronal loop on January 20, 2007 associated with Active Region AR 10938, which was shaped like a semi-circle with a radius of 20,000 kilometers, forming a cylindrical tube with a base radius of 1000 kilometers. What was the total volume of this magnetic loop in cubic centimeters assuming that it is shaped like a cylinder?

Answer: The length (h) of the cylinder is 1/2 the circumference of the circle with a radius of 20,000 km or h = 1/2 (2π R) = 3.14 x 20,000 km = 62,800 km

The volume of a cylinder is $V = \pi R^2 h$ so that the volume of the loop is

$V = \pi (1000 \text{ km})^2 \times 62,800$ km

$= 2.0 \times 10^{11}$ cubic kilometers.

1 cubic kilometer = 10^{15} cubic centimeters so

$= 2.0 \times 10^{26}$ cubic centimeters

Problem 2: The Hinode EUV Imaging Spectrometer was able to determine that the density of the gas within this magnetic loop was about 2 billion hydrogen atoms per cubic centimeter. If a hydrogen atom has a mass of 1.6×10^{-24} grams, what was the total mass of the gas trapped within this cylindrical loop in metric tons?

Answer: The total mass is the product of the density times the volume, so

Density = 2×10^{9} particles/cc x (1.6×10^{-24} grams/particle) = 3.2×10^{-15} grams/cm^3

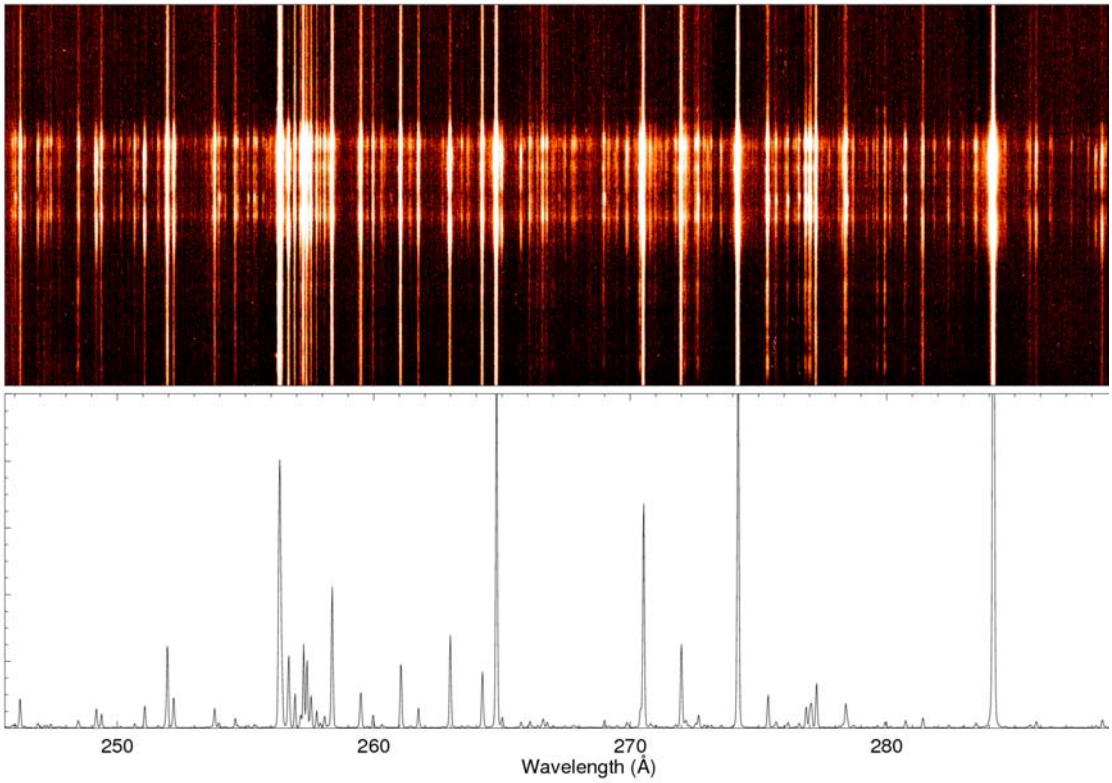
The approximate volume of the magnetic loop in cubic centimeters is

$V = (2.0 \times 10^{11} \text{ km}^3) \times (1.0 \times 10^{15} \text{ cm}^3/\text{km}^3)$

$= 2.0 \times 10^{26} \text{ cm}^3$

Mass = Density x Volume = (3.2×10^{-15} grams/cm^3) x (2.0×10^{26} cm^3) = $6.4 \times 10^{26-15}$ = 6.4×10^{11} grams or 6.4×10^{8} kilograms or **640,000 metric tons.**

Find the mystery lines...if you can!



This is an image (top) from the Hinode satellite's Extreme Ultraviolet Spectrometer (EIS). The figure (below) is a series of atomic spectral lines from known ions. Each line in the bottom graph has an intensity that is indicated by its length along the vertical axis of the figure. The table to the right gives the wavelengths of some spectral lines that fall within the wavelength range of the figure.

Table 1: List of ionic lines

He II	256.32 A
Fe XVI	262.98
S X	264.23
Fe XIV	264.79
Si VII	275.35
Fe XV	284.16

Note: Wavelengths in Angstrom (A) units.
1 A = 10^{-8} cm.

Problem 1) What is the scale of the horizontal axis in Angstroms/millimeter?

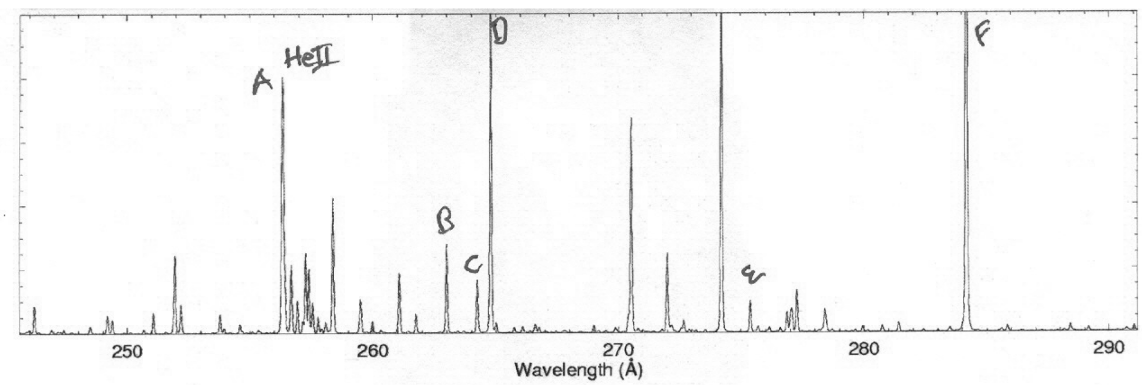
Problem 2) Using your answer to Problem 1, A) Match up the tabulated lines with the lines shown in the above figure. *(Hint: Use the '250' mark and calculate the number of millimeters to the He II line at 256.32 A (21.8 mm) and convert to Angstrom units using your answer to Problem 1. Then add this to '250' to get the wavelength of the He II line.)*

Problem 3) Compare the identified lines in the figure, with the solar spectrum from the EIS instrument in the top illustration. Which lines can you match up?

Problem 4) What percentage of lines in the Hinode solar data are not identified?

Inquiry problem: Can you find any resources online that help you identify some of the missing lines?

Answer Key:



Problem 1) What is the scale of the horizontal axis in Angstroms/millimeter?

Answer: (290 - 250) A/138 millimeters = 0.29 Angstroms / millimeter.

Problem 2) Using your answer to Problem 1, A) Match up the tabulated lines with the lines shown in the above figure.

A	He II	(256.32 - 250) / 0.29 = 21.8 mm
B	Fe XII	(262.98 - 250)/0.29 = 44.8 mm
C	S X	(264.23-250)/0.29 = 49.0 mm
D	Fe XIV	(264.79 - 250) / 0.29 = 51.0 mm
E	Si VII	(275.35 - 250) / 0.29 = 87.4 mm
F	Fe XV	(284.16 - 250) / 0.29 = 117.8 mm

Problem 3) Compare the identified lines in the figure, with the solar spectrum from the EIS instrument in the top illustration. Which lines can you match up?

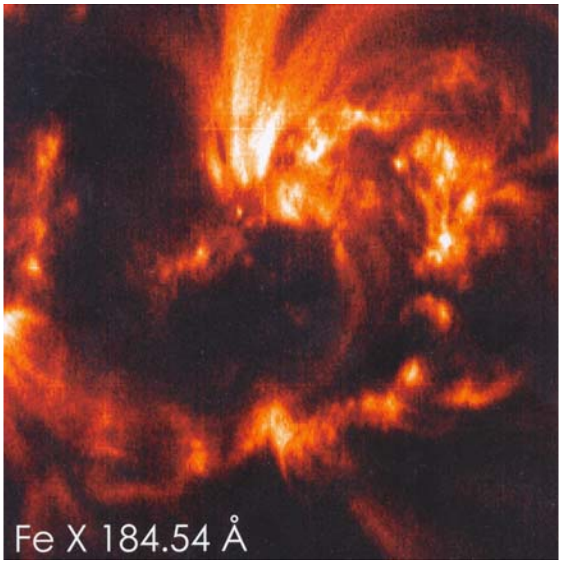
Answer: All of the known lines in the table can be matched up as shown in the above diagram.

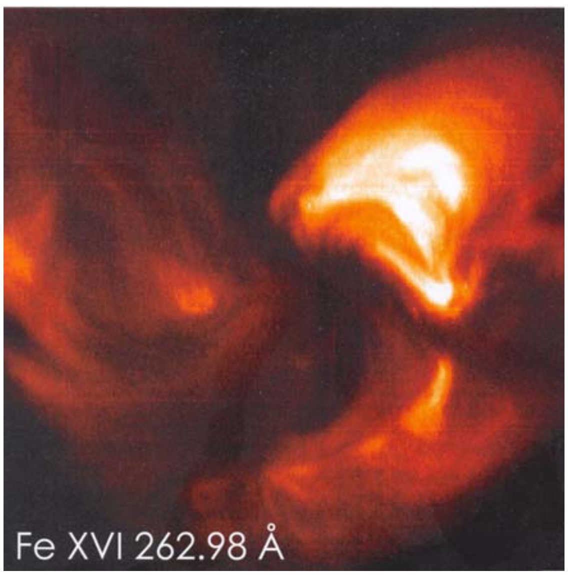
Problem 4) What percentage of lines in the Hinode solar data are not identified?

Answer: There are about 127 lines in the top Hinode spectrum, but only 6 lines are known from the table, so (121/127) x 100 = 95% of the lines in the Hinode spectrum are unknown.

Inquiry problem: Can you find any resources online that help you identify some of the missing lines?

Hot Gas and Cold Gas





The Hinode Extreme Ultraviolet Imaging Spectrometer (EIS) sorts the light from the sun into a spectrum. It works in a part of the spectrum far beyond the visible light we see, and which can only be studied from space. The atmosphere of Earth absorbs this light, so satellite telescopes have to be placed in orbit to study this light.

Very hot gas near the sun produces this light, and by carefully measuring it, scientists can deduce the exact temperature, density and speed of motion of the gas that produces it. When atoms are heated, they produce specific wavelengths of light, called spectral lines.

The two pictures were taken of the same active region (AR-10940) over a sunspot on February 2, 2007, and are exactly overlapping images. The size of each square image is about 200,000 km on a side.

The top picture is produced by iron atoms in a cool plasma in which 9 of their 26 electrons have been ionized. The light is from a single line at a wavelength of 184.54 Angstroms. The bottom picture is from iron atoms in a hot plasma in the same active region, which have lost 15 of their 26 electrons, and is from the light from a single line at 262.98 Angstroms.

The Fe X emission is produced in plasma with a temperature of 950,000 K. The Fe XVI emission is produced in plasma with a temperature of 2,600,000 K.

Problem 1 - From the information, what is the scale of the images in kilometers per millimeter?

Problem 2: At what gas temperatures do you find the smallest clumps, and how big are they?

Problem 3: Higher-temperature features tend to be found at higher elevations above the solar surface than the colder features. Use the information in the two images to create a hypothetical scaled drawing of this active region, showing the locations of the various features.

Answer Key:

Problem 1 - From the information, what is the scale of the images in kilometers per millimeter?

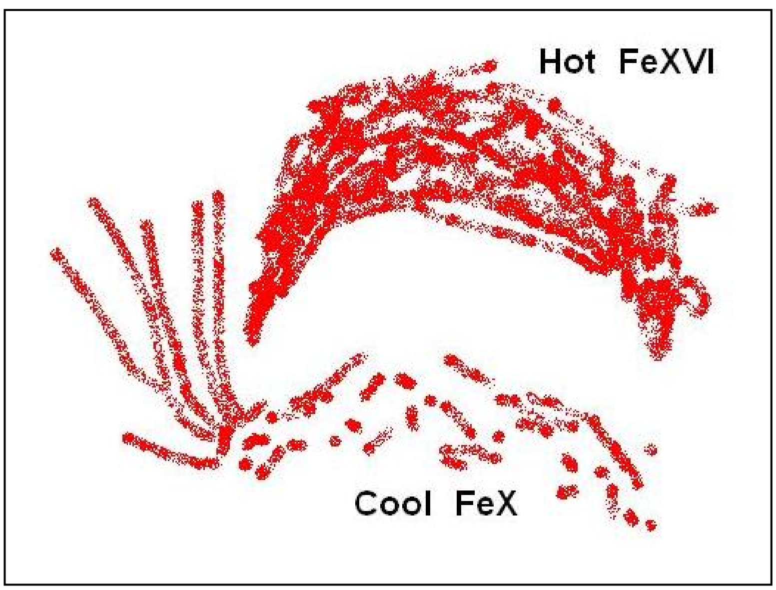
Answer: The images are 74 millimeters on a side, which corresponds to 200,000 km, so the scale is 200,000 kilometers/74 mm= 2,700 km/mm

Problem 2: At what gas temperatures do you find the smallest clumps, and how big are they?

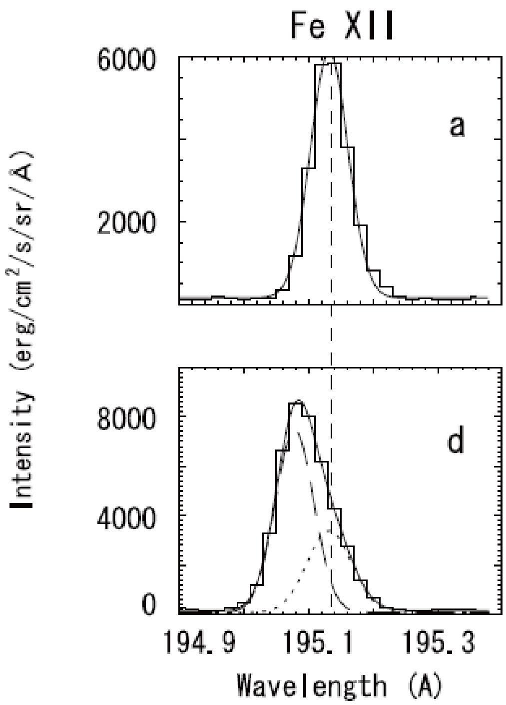
Answer: The cold gas revealed by the Fe X light has the smallest clumps, which can be about 2 millimeters across or 5,400 kilometers in physical size.

Problem 3: Higher-temperature features tend to be found at higher elevations above the solar surface than the colder features. Use the information in the two images to create a hypothetical scaled drawing of this active region, showing the locations of the various features.

Answer: Student's sketches and interpretations may vary, but they should show smaller details from the cooler gas at lower altitudes and the broader, hotter gases at higher altitudes. One possibility is a sketch of the arch-shaped feature in the upper right of the image, which could be rendered like the sketch below.



Using the Doppler Shift to Study Gas



The Hinode Extreme Ultraviolet Imaging Spectrometer (EIS) sorts the light from the sun into a spectrum. When atoms are heated, they produce specific wavelengths of light, called spectral lines.

When a fire truck races towards you, the siren sounds at a higher pitch than when it races away. This is called the Doppler Shift, and it can be precisely used to measure the speed of a gas cloud that is emitting energy at a precise wavelength.

By measuring the Doppler Shift of the FeXII line, solar physicists can determine how fast the plasma was moving on the sun, even though they cannot see any features in the images that show this movement in a series of time-lapse photographs. Here's how they do it!

The figure to the left shows the intensity of the light produced by an iron atom that has lost 11 of its electrons. The top panel shows the light produces by a cloud that was at rest near the solar surface. The bottom panel shows a similar plasma cloud that was in motion during an X-class solar flare, which occurred on December 13, 2006. The plots were published by Dr. Shinsuke Imada and his co-investigators in the *Publications of the Astronomical Society of Japan* (v. 59, pp. 759).

Problem 1 - To the nearest one-hundredth of an Angstrom, what is the wavelength of the FeXII emission line for: A) the gas at rest: λ(rest)? B) the gas in motion: λ(moving)?

Problem 2 - The Doppler Formula relates the amount of wavelength shift to the speed of the gas according to

$$V = 300{,}000 \text{ km/sec} \times \frac{\lambda\,(\text{rest}) - \lambda(\text{moving})}{\lambda\,(\text{rest})}$$

From the information in the two panels, what was the speed of the plasma during the solar flare event?

Problem 3 - From the location of the peak of the moving gas, is the gas moving towards the observer (shifted to shorter wavelengths), or away from the observer (shifted to longer wavelengths)?

Problem 4 - From your answer to Problem 3, during a flare, is the heated plasma flowing upwards from the solar surface, or downwards to the solar surface? Explain your answer by using a diagram.

Answer Key:

Problem 1 - To the nearest one-hundredth of an Angstrom, what is the wavelength of the FeXII emission line for: A) the gas at rest: λ(rest)? B) the gas in motion: λ(moving)?

Answer: Using a millimeter ruler, the wavelength scale between 194.9 Angstroms and 195.1 Angstroms is 17 millimeters, so the scale of the spectrum is 0.2 Angstroms/17 mm = 0.01 Angstroms per millimeter, so A) the peak of the curve in Panel A is at 195.1 + 0.01 x 3 mm = 195.13 angstroms. B) The peak in Panel D is at 195.1 - 0.01x1mm = 195.09 Angstroms.

Problem 2 - The Doppler Formula relates the amount of shift to the speed of the gas according to

$$V = 300{,}000 \text{ km/sec} \times \frac{\lambda\text{ (rest)} - \lambda\text{(moving)}}{\lambda\text{ (rest)}}$$

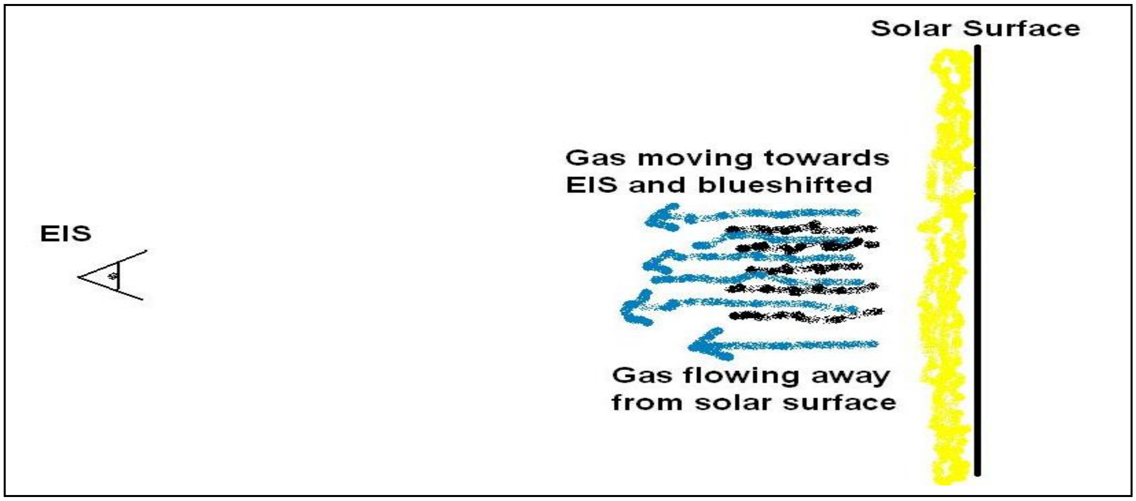
From the information in the two panels, what was the speed of the plasma during the solar flare event?

Answer: λ (rest) = 195.13 Angstroms, λ(moving) = 195.09 Angstroms. So

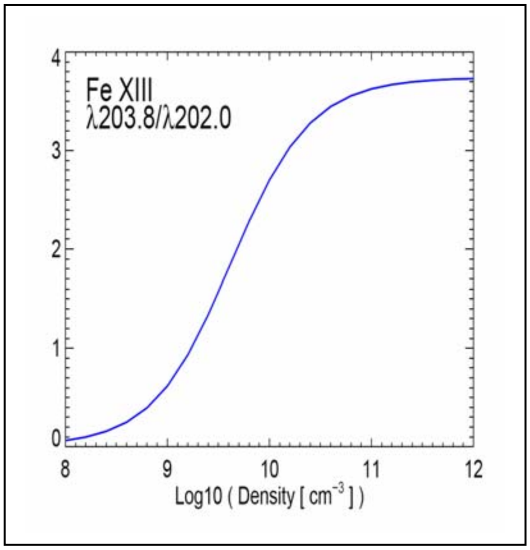
$$V = 300{,}000 \times (195.13 - 195.09)/195.13$$
$$= 61 \text{ kilometers/sec}$$

Problem 3 - From the location of the peak of the moving gas, is the gas moving towards the observer (shifted to shorter wavelengths), or away from the observer (shifted to longer wavelengths)? Answer: The peak in panel B is shifted towards smaller, shorter, wavelengths so the gas is 'blue-shifted' and moving away from the observer.

Problem 4 - From your answer to Problem 3, during a flare, is the heated plasma flowing upwards from the solar surface, or downwards to the solar surface? Explain your answer by using a diagram. Answer: The FeXII measurement showed plasma flowing towards the observer. Because the gas was located between the solar surface and the observer, it must have been flowing upwards from the surface.



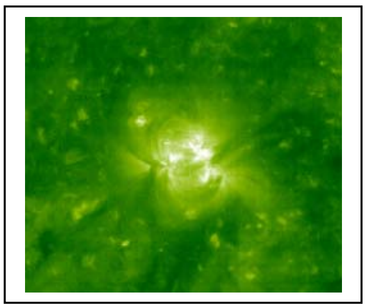
Spectroscopy and Gas Density

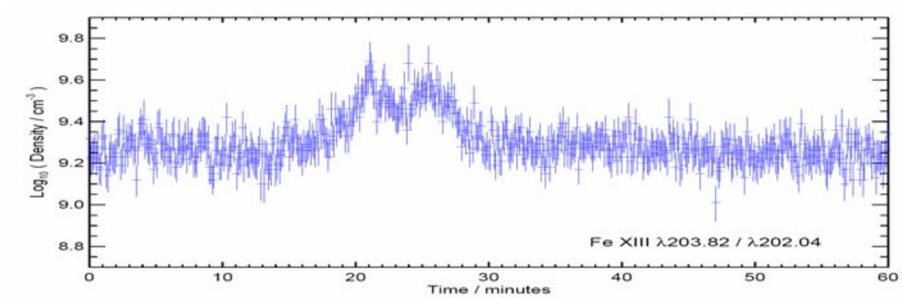


The Hinode EIS instrument can detect the individual 'fingerprint' lines from dozens of elements. Each line has its own unique wavelength. The intensity of an atomic line can be used to learn about the properties of the gas near the solar surface.

Two particular atomic lines produced by the element iron appear at wavelengths of 203.8 and 202.0 Angstroms. The ratio of the intensities of these two lines can be converted into a measurement of the density if the gas producing them, as shown in the figure to the left.

For example, if the intensity of the Fe XII line at 203.8 Angstroms were measured to be 300 units, and the line at 202.0 Angstroms were measured to be 150 units, the ratio yields 300/150 = 2.0. From the figure, a value of '2.0' on the vertical axis, corresponds to a density of Log_{10} D = 9.6. In normal units, this is $10^{9.6} = 4.0 \times 10^9$ atoms per cubic centimeter.





Problem 1 - The figures above were developed by Dr. Peter Young at the Rutherford Appleton Laboratory in England as part of an international science meeting that occurred in Dublin Ireland in August, 2007. The image shows an active region on the sun, and the graph to its right is the density measured near the center of the active region over the course of 60 minutes. The line ratio of the two Fe XIII lines was determined from two images of the active region made at each of the two wavelengths. A) What is the average density of the region during the last 20 minutes of the study? B) What is the average line ratio that corresponds to the average density?

Problem 2 - What is the maximum density that was recorded during this time period?

Problem 3 - The temperature of the gas producing these lines is about 1.6 million K. If the gas pressure in dynes/cm^2 is given by the formula P = D k T where D is the average particle density, and k is Boltzman's Constant (1.38×10^{-16}), what is the estimated average gas pressure in this region?

Problem 4 - Magnetic pressure is given by $P = B^2/8\pi$. Where B is the strength of the field in units of Gauss (note 0.5 Gauss is the strength of of Earth's magnetic field at ground level). If the gas pressure and magnetic pressure in this region are in balance, how strong would the magnetic field have to be to confine the million-degree gas?

Answer Key:

Problem 1 - The figures above were developed by Dr. Peter Young at the Rutherford Appleton Laboratory in England as part of an international science meeting that occurred in Dublin Ireland in August, 2007. The image shows an active region on the sun, and the graph to its right is the density measured near the center of the active region over the course of 60 minutes. The line ratio of the two Fe XIII lines was determined from two images of the active region made at each of the two wavelengths. A) What is the average density of the region during the last 20 minutes of the study? B) What is the average line ratio that corresponds to the average density?

Answer: A) About $\log_{10} D = 9.25$ or $D = 1.8 \times 10^9$ particles/cm^3

Problem 2 - What is the maximum density that was recorded during this time period?

Answer: The center of the data crosses between 21 - 26 minutes are about
$\log_{10} D = 9.70$ or $D = 5.0 \times 10^9$ particles/cm^3

Problem 3 - The temperature of the gas producing these lines is about 1.6 million K. If the gas pressure in dynes/cm^2 is given by the formula $P = D\,k\,T$ where D is the average particle density, and k is Boltzman's Constant (1.38×10^{-16}), what is the estimated average gas pressure in this region?

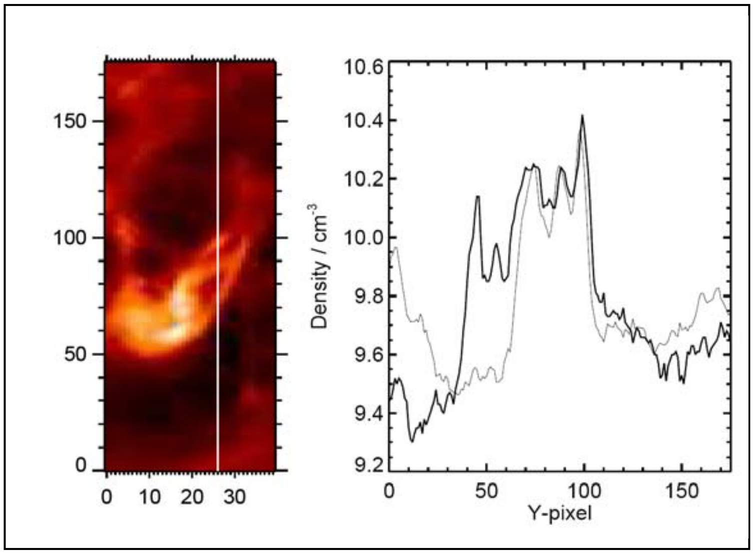
Answer: $P = (1.8 \times 10^9$ particles/cm$^3) \times (1.38 \times 10^{-16}) (1.6 \times 10^6) = 0.397$ dynes/cm^2

Problem 4 - Magnetic pressure is given by $P = B^2/8\pi$. Where B is the strength of the field in units of Gauss (note 0.5 Gauss is the strength of of Earth's magnetic field at ground level). If the gas pressure and magnetic pressure in this region are in balance, how strong would the magnetic field have to be to confine the million-degree gas?

Answer: $0.397 = B^2/8\pi$ so $B^2 = 0.397 \times 8\pi$ and $B = 3.1$ Gauss.

Density Structure of an Active Region

The Hinode EIS instrument has been used to study many active regions in order to determine how the density of the plasma varies through each region. One of these studies was reported by solar physicist Dr. Peter Young from the Rutherford Appleton Laboratory in England in August 2007. Below-left is an image of a coronal loop with the X and Y axes indicating the pixel number in each direction. The white line is a slice through the data at an X-pixel value of 26, and reveals the density variation in the vertical Y direction shown in the graph on the right. The density is rendered on the vertical axis in terms of the base-10 logarithm of the density value so that '10' means 10^{10} particles/cm^3



The gas densities are found by observing the same region of the sun at two different wavelengths emitted by the iron atom at a temperature near 1.5 million degrees K. *The ratio of the light intensity emitted at these two wavelengths is directly related to the density of the gas producing the light.* This shows how spectroscopy can provide vastly more information about the sun and solar activity, than what you would get from a single image alone.

Problem 1 - About what is the average density of the gas in the dark regions covered by the pixels in the range from Y=10 to Y=30? Convert answers to normal decimal units of density in scientific notation.

Problem 2 - About what is the average density of the gas in the dark regions covered by the pixels in the range from Y=140 to Y=170? Convert answers to normal decimal units of density in scientific notation.

Problem 3 - If higher gas densities tend to be found closer to the solar surface, in which part of the image may we be looking at a deeper layer of the solar atmosphere?

Problem 4 - About what is the density of the three ribbon-like features at Y= 70, Y=90 and Y=100? Convert answers to normal decimal units of density in scientific notation.

Problem 5 - What is so peculiar about the density feature near Y= 40? Can you explain what might be happening?

Answer Key:

Problem 1 - About what is the average density of the gas in the dark regions covered by the pixels in the range from Y=10 to Y=30? Convert answers to normal decimal units of density in scientific notation.

Answer: About Log D = 9.4 or $D = 10^{9.4} = 2.5 \times 10^{9}$ particles/cm^{3}

Problem 2 - About what is the average density of the gas in the dark regions covered by the pixels in the range from Y=140 to Y=170? Convert answers to normal decimal units of density in scientific notation.

Answer: About Log D = 9.6 or $D = 10^{9.6} = 4.0 \times 10^{9}$ particles/cm^{3}

Problem 3 - If higher gas densities tend to be found closer to the solar surface, in which part of the image may we be looking at a deeper layer of the solar atmosphere?

Answer: The upper end of the image has a higher density than the lower end so the upper end may be looking closer to the solar surface.

Problem 4 - About what is the density of the three ribbon-like features at Y= 70, Y=90 and Y=100? Convert answers to normal decimal units of density in scientific notation.

Answer: The log densities are LogD = 10.25, 10.25 and 10.4 respectively, for densities of $D = 1.8 \times 10^{10}$ particles/cm^{3} $D = 1.8 \times 10^{10}$ particles/cm^{3} and $D = 2.5 \times 10^{10}$ particles/cm^{3}

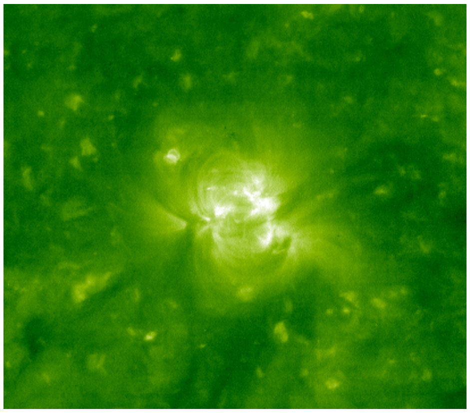
Problem 5 - What is so peculiar about the density feature near Y= 40?

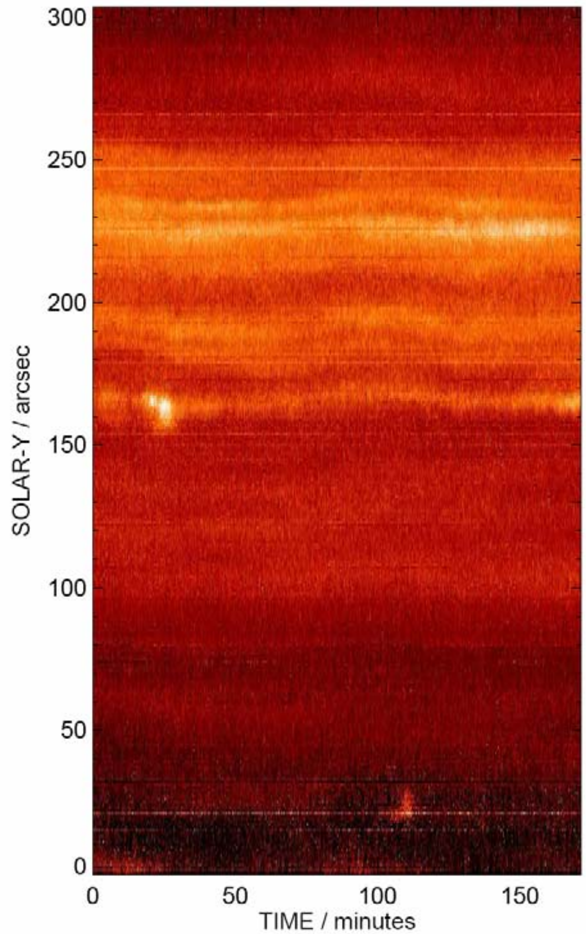
Answer: It corresponds to a density of about $\text{Log } D = 10^{10.15}$ or $D = 1.4 \times 10^{10}$ particles/cm^{3} but the picture shows a black area.

One possibility is that it is dense gas that is too faint to be emitting much light at the two wavelengths of the iron atom to be easily seen in this picture. The **ratio** of these two small intensity values could still be just large enough to indicate a large density.

For example, suppose the image only shows emission brighter than 100 units, but the two iron lines in the 'dark' region have intensities of 20 units and 5 units. The ratio would be 4.0, and indicate a large density, just as it would for a brighter region where the intensities are 400 units and 100 units and so are easily seen in the image.

Plasma Speeds in Active Regions





The Hinode EIS instrument can study a single slice of an active region and detect subtle changes in position over time. The image above shows an active region near a sunspot, and reveals its 'bar magnet' magnetic field loops.

The strip plot to the right shows the motion of the plasma sliced vertically along the center line of the active region, over a span of about 200 minutes. The vertical axis gives the location of the plasma in units of arcseconds, where one arcsecond equals a physical distance of 725 kilometers on the solar surface.

Individual features in the upper image appear as bands on the strip plot. The slope of the band is a measure of the speed of motion of the gas.

Problem 1 - Select the bright feature near Y=160. What is the change in the Y-position during the period from A) 0-50 minutes? B) 50 - 100 minutes? C) 100-150 minutes?

Problem 2 - From your answer to Problem 1, what is the average speed of this feature during each 50-minute period from A to C in kilometers per second?

Problem 3 - How soon after the start of the data did a flare occur in this feature? How long did it last?

Answer Key:

Problem 1 - Select the bright feature near Y=160. What is the change in the Y-position during the period from A) 0-50 minutes? B) 50 - 100 minutes? C) 100-150 minutes?

Answer: Students need to use a millimeter ruler and determine the Y-axis scale of the plot. The total height represents 300 arcseconds or a physical length of 300 x 725 km = 217,500 kilometers. The vertical length of the figure is 116 millimeters, so the scale is 1,875 km/mm

A) The change in the Y-axis location between the beginning and end of this segment is about 1 millimeter or 1,875 kilometers.

B) The change in the Y-axis location between the beginning and end of this segment is about 3 millimeters or 5,625 kilometers.

C) The change in the Y-axis location between the beginning and end of this segment is about 2 millimeter or 3,750 kilometers.

Problem 2 - From your answer to Problem 1, what is the average speed of this feature during each 50-minute period from A to C?

Answer: Each segment is 50 minutes long or 3000 seconds. Dividing the distances in Problem 1 by 3000 seconds you get A) 0.625 kilometers/sec; B) 1.87 kilometers/sec and C) 1.25 kilometers/sec.

Problem 3 - How soon after the start of the data did a flare occur in this feature? How long did it last?

Answer: The flare event is located in the strip plot between Y = 160 and 170 arcseconds. 50 minutes equals 18 millimeters so the scale is 2.8 minutes/mm. The flare occurred about 7 mm or 19.6 minutes after the start of the data, and lasted 3 mm or 8.4 minutes.

A note from the Author:

Hi again!

This booklet will introduce you to the Hinode satellite, and a few of its many discoveries. Many of the problems involve the basic skill of measuring the size of an image, and converting the measurement into an actual physical unit (kilometers, seconds, etc). Most students can successfully perform this activity by grade-5 when they have become familiar with decimal-math and division.

Calculating the scale of an image is a critical operation in just about any scientific investigation. You know all those pretty pictures that NASA loves to show you of planets, stars and galaxies? Well before an astronomer can make any sense of them, he has to be able to figure out how many millimeters on the image/photograph corresponds to a meter, kilometer or even a light-year in actual physical units. Otherwise, you have no clue how big the object is that you are investigating! Also, it is a fun exercise to see what the smallest detail in an image is in physical units.

The Hinode satellite creates many images of the sun at various sizes to study phenomena as big as the sun, or as small as a micro-flare. The X-ray and optical imager are good for establishing a size to things, and the movies give us a sense for how quickly or slowly things occur. But the satellite can do much more than this!

The Extreme Ultraviolet Imaging Spectrometer dissects the ultraviolet light from the sun, and is able to use the 'fingerprints' of various atoms producing light, to work out the density, temperature and speed of the various phenomena being studied. You cannot get this information by just looking at a picture of the sun. Solar scientists need this kind of information in order to mathematically model how a phenomenon changes in time, how the gases flow, and how magnetic energy heats the various gases found near sunspots and other active regions on the sun.

Ironically, spectroscopy is the unsung hero of solar and astrophysics. Students that view dazzling pictures of nebula, galaxies, planets and solar storms instinctively enjoy these images because they represent an image, like a photograph of a house, mountain or lake. It is very easy to explain what the image represents because we have many familiar examples of the same kind of data in our family photo albums!

Spectroscopy is different. It is a technology that sorts the electromagnetic spectrum by wavelength. Each atom produces its own 'fingerprint' lines of light that resemble a bar code. Scientists can read this bar code, and even take a picture of the sun by the light from one particular 'bar'. The relative intensities of the different spectral bars or 'lines', can be used to calculate the density and temperature of the gas that is producing it. Some of the problems in this book will give students a taste of how this kind of information is used to more clearly understand how solar flares and other phenomena on the sun are 'put together'.

Enjoy!!

Sincerely,
Dr. Sten Odenwald
NASA Astronomer

Useful Internet Resources

The Hinode Mission education page

http://solarb.msfc.nasa.gov/for_educators/index.html

NASA Space Math Problem of the Week and Archives

http://spacemath.gsfc.nasa.gov

The human and technological impacts of solar storms and space weather:

http://www.solarstorms.org

NOAA space weather forecasting center

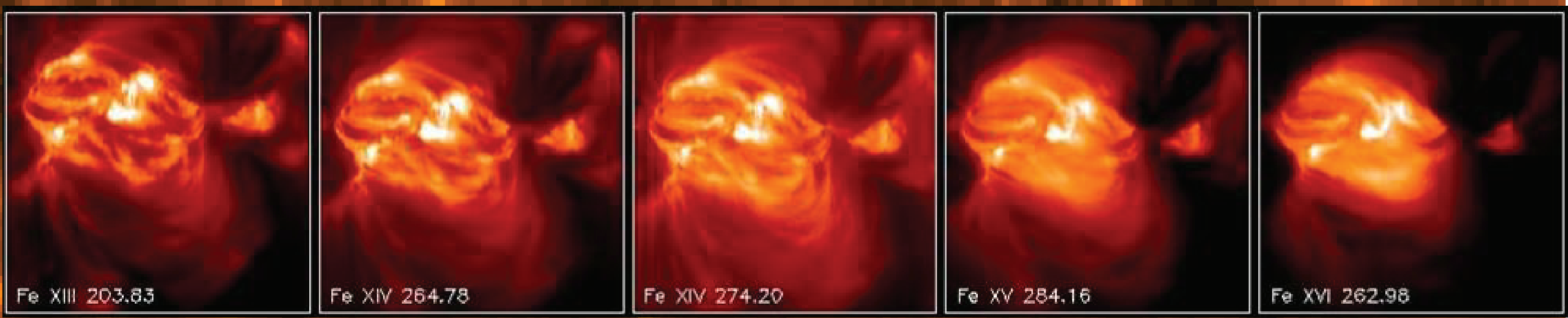
http://www.noaa.sec.gov/SWN

NASA Student Observation Network –Tracking a Solar Storm

http://son.nasa.gov/tass/index.htm

Elementary Space Mathematics Primer

http://image.gsfc.nasa.gov/poetry/MathDocs/spacemath.html



National Aeronautics and Space Administration

Space Math @ NASA
Goddard Spaceflight Center
Greenbelt, Maryland 20771
http://spacemath.gsfc.nasa.gov

www.nasa.gov