Solar Weather: Solar Storms to Auroral Substorms
Presentation Notes

Slide	Notes
1	The images show how a solar storm can propagate through the solar system to Earth and its protective magnetic shell.
2	The Sun is a star, only appearing different (larger) than other stars because of its relative closeness to the Earth. The fact that the Sun is a star was theorized by several ancient astronomers, but the proof did not come until the late 19th/early 20th century, when the light from the Sun and stars was split into its component colors (spectra), recorded, compared and found to have the same spectrum. The Sun is so hot from nuclear fusion that the heat removes electrons from most of the Sun's gas, leaving an electrified ball of gas known as a plasma. The Sun is considerably larger than the Earth (109 times Earth's radius). Its equator rotates once every 27 days—but its poles rotate only once every 31 days. Its power output is huge and the surface temperature is extremely hot (water boils at 373 K). The Sun is incredibly massive - hundreds of thousands of times more massive than Earth. It is made up of mostly hydrogen, some helium, and a very small amount of heavier elements. It is a middle-aged star at 5 billion years old.
3	Although the Sun doesn't look particularly large in the sky, it is huge compared with Earth, but also very far away. The diameter of the Sun is 109 times that of Earth's diameter. Over 1,000,000 Earths would fit inside the Sun. Don't forget that there is a difference between linear dimensions and volume. The diameter of the Sun is 109 times that of Earth, but its volume is 109x109x109 times bigger. We can conceptualize this difference by considering how many marbles we would need to line up side by side to stretch from one wall of the classroom to the other side. It would probably be a few hundred. How many marbles it would take to cover the floor? (a few tens of thousands). How many marbles would you need to fill the entire room with them? (hundreds x hundreds x hundred = millions). Note that the difference between rectangular and spherical volumes does not matter here since in a ratio between spherical volumes, the factor of $(4/3)*\pi$ cancels out. So all that matters is the ratio between radii. The image on the right is an artist's conception of the Earth and Sun as seen from the Moon. Once students understand how much bigger the Sun is than the Earth, this view should impress upon them that the Sun must indeed be very far away in order for it to look so small. In the image, the Earth actually appears bigger than the Sun. Students should realize this illusion is because Earth is much, much closer than the Sun. Even though the Sun is relatively close to us compared to other stars, it is still very far away on a human scale (150 million kilometers away from Earth). Light

travels at a finite and set speed. Light does not instantaneously move from one point to the next. It takes time for light to move from place to place. Light is still pretty fast though. It moves at a speed of 300,000 km/s (186,000 miles per second). It takes 8 minutes for light to travel to Earth from the Sun. This means that when we look at the Sun from here on Earth, we see it as it was eight minutes ago. For probes that travel deep out into the Solar System, it takes light even longer to travel between them and Earth. The average distance between the Sun and Earth is called an "Astronomical Unit" or AU. 1 AU is defined to be the average distance between Earth and the Sun (93 million miles; 150 million km).

4 Here is an image of the Sun in white light, otherwise known as visible light, since our eyes can see all the colors that make up white light (the rainbow of colors from red to violet). The wavelength of this range of light is 400-700 nanometers, which basically means very, very small! 1 nm would have eight zeros after the decimal place and then the number 1 appears at the 9th decimal place. The layer of the Sun we see with white light is called the "*photosphere*" or the "surface of the Sun." The photosphere is hardly a surface, since its density is still about 0.1% of the density of air at sea level on Earth. But for the Sun, this is pretty dense, and thus we call it the "surface of the Sun."

5 Here is an image of the Sun in extreme ultraviolet light, known as EUV light, for short. Our eyes cannot detect EUV light. Most of this light is absorbed by our upper atmosphere so it does not reach the ground. This is fortunate since EUV light could cause some damaging skin cancer. This image was taken by the camera on a satellite that is part of the STEREO mission. Scientists colored it violet to represent extreme ultraviolet, the "color" we cannot see. The wavelength of this range of light is much shorter than the visible wavelength at 17.1 nanometers. The layer of the Sun we see with EUV light is called the *corona*. The corona is the outermost atmosphere of the Sun so this is a layer above the photosphere. Notice that now the Sun seems dark with bright areas whereas in the photosphere image, the Sun seemed bright with dark areas. Darker represents cooler areas; brighter represents hotter. So, unlike most objects, such as a human body which gets cooler as you move away from its surface, the Sun first gets hotter as you move away from its surface and then it cools down. I'll explain why in a couple of slides.

6 The corona extends outward into space. We can see the outer corona by blocking out the bright light of the photosphere. In this first image, the corona can be seen from Earth during a total solar eclipse, when the moon moves between the Earth and the Sun. Now it is clear how the corona was named. Corona means "crown," and the corona looks like a crown around the Sun.

Spacecraft can make themselves a kind of permanent eclipse because they are away from the atmosphere, which scatters the sunlight. This scattering is why you cannot block out the light from the photosphere with your thumb and see the corona. But when spacecraft block the light from the photosphere, there is only empty space and the corona to look at—no sunlight bouncing around in the atmosphere. This is what you see in the bottom image. There are actually three images combined in this one image: the very middle image shows the photosphere blocked out and only the near corona is visible. In the second circle in this bottom image is a middle-zoom of the corona. The outermost part of the image is a complete zoom-out of the corona taken from the SOHO spacecraft. Notice that the corona appears as bright rays coming away from the center of the image. The lower left very bright "ray" was caused by sunlight scattering off the mechanical arm of the spacecraft camera as it held up the disc blocking the Sun. The benefit of such a way to look at the corona is that scientists can study the dynamic corona as it changes over minutes, hours, days, months, and years.

7 The solar wind can be thought of as part of the outermost corona. It is a stream of mostly charged particles coming from the Sun and traveling out past all the planets in the Solar System. Remember that this wind is not like wind on Earth — it is electrically charged and will therefore interact with magnetic fields, unlike the neutral wind on Earth.

8 Sunspots are dark splotches on the surface of the Sun (its photosphere). They are on average 2,000 K cooler than the rest of the photosphere and five times dimmer. However, Sunspots are actually quite bright. In fact, if one could block out all of the light from the normal photosphere of the Sun and just allow the light from sunspots to come through, our daytime sky would appear almost as bright is it does normally. The reason we see sunspots as dark splotches, is that the dynamic range of eyes and scientific images cannot account for the large difference in brightness, and so we see the sunspots as dark.

Galileo was one of the first people to watch sunspots rotate and to determine the rotation of the Sun from the rotation of the sunspots. It turns out that the Sun spins faster at the equator than at the poles (once every 27 days versus every 31 days). This is possible because the Sun is not a solid object.

If we look at the Sun's photosphere and compare it with the Sun's corona on the exact same day, we will notice that the dark sunspot on the photosphere is a bright region in the corona. This tells us that the sunspot is cooler on the photosphere compared to the rest of the photosphere but hot in the corona compared to the rest of the corona. Why is this? What is happening at these regions?

9 The mystery is solved by knowing that an electrified gas (plasma) like that of the Sun will create magnetic fields. Putting all the information together creates a picture revealing that sunspots are the "footprints" of the coronal magnetic loops. The coronal loops are made of plasma trapped in a very strong magnetic field. The two images on the right show real data images from the TRACE satellite. The gas in these loops is glowing from being bombarded by charged particles trapped on the magnetic loops. These charged particles are energized

by different processes involving the magnetic field and they heat the corona, especially in these magnetic field regions.

These same magnetic field loops penetrates down into a region just below the photosphere called the *convection zone* and inhibit the convection of gas in that region. This is depicted in the diagram on the left. The inhibition of convection causes the gas below the photosphere to cool faster than the surrounding region.

The average strength of the magnetic fields in sunspots is around 1,000 Gauss (Gauss is a unit of magnetic field strength). The average field strength on the surface of Earth is about 0.5 Gauss, the average magnetic field strength on the surface of the Sun is about 1 Gauss, and the average magnetic field in the solar wind is 0.00005 Gauss (50 microGauss). The magnetic fields in sunspots are extremely strong.

10 The Sun goes through a cycle of periods when it has many sunspots and active regions in its corona and then it has periods where it is relatively free of sunspots and is very quiet. The period of the entire cycle of the increasing and decreasing sunspots is 11 years, and has now been observed for several centuries. The top three images show the Sun during different phases of its cycle: a quiet phase, a moderately active phase, and an active phase. Note how many more bright sunspots are observed in the corona during the active phase. The plot below these images shows the number of sunspots at different years from 1985 to 2007. The 11 year cycle can be observed in this plot.

The Sun has an overall magnetic field, much as Earth does with two poles. During "quiet" times, it resembles the dipole (two pole) field of a bar magnet. It is thought that the field is generated by currents of electric charges in the convection zone of the Sun.

Because the Sun is gaseous, it does not rotate like a solid body. It rotates *differentially*; that is, the equator rotates faster than the poles, as we've mentioned previously. In plasma, charged particles cannot cross from one magnetic field line of force to another neighboring field line. So, in this way the magnetic field becomes "frozen" into the plasma. If the particles move with some bulk motion due to a different force they will drag the magnetic field with them. This can distort the magnetic field if different parts of the gas move at different rates or in different directions. This is what happens to the Sun. The regular dipole magnetic field gets twisted and wrapped up as a result of the differential rotation of the Sun.

As the field becomes more and more twisted, little loops of the magnetic field push up through the surface forming sunspots and coronal loops. Eventually, the field becomes so complex that it essentially breaks, and reforms into a simpler shape. This process is what is thought to be behind the observed solar cycle. Moreover, the polarity of the Sun's magnetic field flips every 11 years, so the complete solar cycle is actually 22 years for the Sun to return to its original state.

11 When these loops of magnetic fields "pop," they release energy. Sometimes these magnetic fields "pop" in "small" regions and release mostly light and heat, while causing charged particles to move along the magnetic loop and run into other particles, lighting them up. This process is called a solar flare.

Sometimes these magnetic fields "pop" in large regions on the sun and eject huge amounts of mass from the Sun's corona, called a *coronal mass ejection*, or CME for short. The magnetic fields are also dragged out with the mass in this process. Although this mass amounts to many mountains on Earth, it is a small percentage of the Sun's mass.

12 Do these solar storms ever affect anything on Earth? Indeed they do, and this is why space weather is an important phenomenon to study. Solar flares affect some aspects of our lives fairly quickly, since flares mostly give off x-rays that travel at the speed of light to Earth. This takes eight minutes. However, the matter (charged particles) from CME's takes longer to reach Earth, about one to three days. This is faster than the normal four days it takes the solar wind to reach Earth, but much slower than the x-rays from a solar flare. The right top image shows a flare directed at Earth. The bottom image shows a CME headed towards Earth.

13 Solar Flares and CMEs can affect life on Earth in different ways. Both solar flare x-rays and the CME particles can directly and indirectly cause damage to satellites, including changing their orbits. Solar flares can disrupt radio communications. The very high-energy CME particles are dangerous radiation to Astronauts working outside the space station. CMEs can intensify auroras, which can increase electric currents in the ground, feeding into the "grounds" of power grids and tripping the fuses of large power grids. This can —and has— plunged cities into darkness. These same enhanced electric currents create interesting magnetic field variations detectable on Earth by magnetometers (instruments that measure magnetic fields).

14 *Auroras*, also known as the *Northern and Southern Lights* or Aurora Borealis and Aurora Australis, are lights in the upper atmosphere at around 100-300 kilometers above Earth's surface. The top images are photographs of auroras taken by aurora photographer, Jan Curtis. The bottom images are images of the aurora taken from space, showing both the northern and southern auroras.

There are two misconceptions about auroras. One is that they are caused by reflection of water or ice off particles in the atmosphere and the other is that solar wind particles directly cause most auroras. Neither of these ideas is true. The most recent understanding of aurora formation is that most aurora are caused by electrified (charged) particles coming from Earth's magnetosphere hitting Earth's upper atmosphere and making it glow.

15 The magnetic field around Earth starts off roughly like that of a bar magnet, with a North and a South pole. This magnetic field is known as a dipole magnetic field and is similar to the Sun's magnetic field during its quiet periods. A diagram of this magnetic field is shown on the top left image.

The solar wind is made up of charged particle and it distorts this symmetric magnetic field and pushes it on the side closest to the Sun (the dayside) and elongates it, making a "tail," on the side farthest from the Sun (the nightside). This elongated side is known as the *magnetotail*. This can be seen on the bottom center image.

16 This magnetic field surrounding Earth is known as Earth's *magnetosphere*. Since magnetic fields cause charged particles to move around them, Earth's magnetic field acts as a shield that protects us. The solar wind particles are deflected around Earth's magnetosphere.

17 Most of the particles that cause auroras come from inside this magnetic cavity. The charged particles inside the magnetosphere have, at some point, come from the solar wind and from the charged particles in our upper atmosphere's ionosphere. The ionosphere is mostly created from Sun's light hitting the upper atmosphere, where it gets absorbed and separates the electrons from the atoms, leaving positively charged ions and electrons moving around with the atmosphere. These particles can then escape to the magnetosphere.

How do the solar wind particles enter Earth's magnetosphere if they are all deflected? This is an active area of science research, but scientists believe that it is related to the interaction between the magnetic field of the solar wind and the magnetic fields of the Earth. This interaction causes a "magnetic reconnection" region, which opens a small door for particles to move from the solar wind to inside Earth's magnetosphere.

18 The electrons from the magnetosphere spiral down into the upper atmosphere and cause the atmosphere to glow, like the electrons carrying an electric current make a fluorescent bulb or plasma ball glow. These electrons scatter off molecules and atoms and lose their energy in collisions, exciting and ionizing the neutral gas (oxygen and nitrogen). The ionizations create more free electrons which have enough energy to again collide and excite the atmospheric gas. Also, more atoms and molecules are again ionized, causing even more electrons. This is a cascade of electrons.

The excited gas then calms down, or de-excites, emitting a photon, and creating auroral light. The deep red aurora shown on the bottom right, and the green aurora shown in both images are from atomic oxygen. The pink at the bottom of green arcs is from nitrogen emitting blue and red light.

(Optional) The reason atomic oxygen emits both red and green light at different altitudes has to do with how long it takes oxygen to de-excite from different electronic states. The red color comes from an electronic state that stays excited for 110 seconds. The green color comes from an electronic state that stays excited for 0.7 seconds. The excited oxygen atoms at the lower altitudes, around 100 km, will hit the atmospheric gas, losing energy before they can emit a photon. This is why atomic oxygen does not have red at the lower altitudes where the green is located.

19 Auroral ovals always exist. Their shape and location will change, however. On the left are images in ultraviolet light of Earth from space. The top left image shows the upper atmosphere "glowing" where the Sun is hitting it on the left. The circle in the middle is the aurora. Scientists put a map on top of the image to give context to the aurora's location. You can see that very little aurora would be seen by those in Alaska, but a lot of aurora would be visible over Greenland and Northern Europe. The bottom left image shows the auroral oval in the Southern Hemisphere, again in ultraviolet light— but without the "dayglow" visible, due to the angle at which the image was taken. The "cusp" aurora is a relatively small spot of aurora that is caused by direct solar wind particles likely coming through a region of "magnetic reconnection" that was mentioned earlier. The right image shows the two auroras as seen from a satellite far enough from Earth to see both poles.

20 One way the aurora can change due to alterations in Earth's magnetosphere is known as an *auroral substorm*. Auroral substorms are a global phenomenon in which the auroral oval follows a somewhat defined pattern which changes in time over about two hours. Here is a movie showing a couple of substorms, again in ultraviolet light. The glow at the bottom right of the circle is the sunlight. The circle of light in the middle of the image is the auroral oval. Note how the auroral oval expands in the growth phase of the substorm, which takes about 30 minutes. Then suddenly it changes to a thick and expanded oval in a matter of seconds. This sudden change is called *substorm onset*. The thickening and rapid changes that occur in the next 10 to 30 minutes are known as the *break-up* or *expansion phase*. Then the oval takes a while longer (about an hour) to recover back to its original shape. This time is known as the *recovery phase*.

What goes on during substorm onset has been a mystery for 30 years, mainly because there hasn't been a good alignment of satellites out in the magnetosphere to pinpoint where this onset is being triggered.

21 Sometimes CMEs will trigger a substorm. One model suggests that the CME will pass by Earth, exchanging energy with the magnetosphere. This can further elongate the magnetotail, stretching it to a "breaking point." This breaking point accelerates particles in the magnetosphere, which then travel along the magnetic field lines to Earth's upper atmosphere. Along the way, the particles are again sped up in a region called the *acceleration region* and then they hit the upper

atmosphere with lots of energy, creating brilliant auroras and sometimes substorms. This “breaking point” is another magnetic reconnection region and may be the trigger region for substorm onset.

22 The THEMIS mission uses five satellites placed in very specific orbits to try and pinpoint where exactly the substorm onset occurs in Earth’s magnetosphere. THEMIS is an acronym for “Time History of Events and Macroscale Interactions during Substorms.” It is also a name of the Greek goddess of justice, and the idea is that THEMIS will fairly determine which of two models is correct for the substorm onset. Does the onset occur, as shown in the previous movie, with the magnetic reconnection, then to a region called “current disruption,” and then cause the auroral substorm onset? Or does the onset occur in the “current disruption” region, sending the current changes to the aurora, causing the aurora substorm onset, and then a low-density pressure wave that travels from the current disruption region to the magnetic reconnection region? These are the two models for substorm onset, and every four days THEMIS will place the five satellites along the line in space connecting these regions in order to determine the exact timing of these events and find out where substorm onset occurs.