The Space Environment

It is a great privilege to be invited to share with you my interest in the space environment. To do so as part of the Kusch lecture series is indeed a great honor. It is also a pleasure to have Professor Kusch’s daughter and husband in the audience and I would like to personally welcome them to the campus that benefited so greatly from Professor Kusch’s presence. Professor Kusch arrived at UTD in 1972 one year before I did. At that time I was a post doc and he was a Nobel Laureate. He retired before I joined the faculty and thus I never interacted with him as a faculty member. But he was always curious about space physics, as he was about science in general, and he incorporated much of his understanding into his “Phenomenon of Nature” lectures. Above all Professor Kusch had a real skill for sharing his understanding of Physics with others. I hope that in a similar way, I will be able to convey to you some of the fascinating properties of our space environment and the need for us to understand them more thoroughly.

Outer space is fascinating to almost all of us. Many of us have viewed the stars, the planets, and the moon of the Earth and perhaps wondered at our apparent uniqueness as living beings with the capability to think about our place in the universe. Our nearest star is 93 million miles away. It is the Sun. It is a pretty run of the mill object along side billions of others like it in the universe. But it provides all the essential inputs that support life as we know it and the Earth has all the important features that make it a habitable planet. For example, it is the right distance from the Star, it has the right minerals and gases to sustain life, and as we shall see it has an atmosphere and a magnetic field that protect us from the harmful radiation from the host Star. It seems quite reasonable to ask “are we unique? What do we know about our planetary environment and its interaction with the Sun? What should we look for to find other solar systems with planets like ours?” These are rather fundamental intellectual questions that we’d like to answer but at the same time we are challenged to understand how our planetary environment interacts with the Sun for other practical reasons. Our society is changing the space environment and our society is becoming increasingly dependent on space-based communication and navigation systems that must function in that environment. Many of you may have
satellite pagers, watch satellite TV, and use GPS navigation systems. There are now over 2600 satellites orbiting the Earth providing different functions varying from sophisticated imaging to radio and TV broadcasting. More important perhaps are over 6000 pieces of space junk that must be avoided to prevent catastrophic failure of some of these space-based systems. All this means that along with the intellectual challenge of understanding our space environment comes a payoff that is of immediate benefit to our society. With that background I would like to begin with giving you a broad-based image of our space environment and how it interacts with the Sun and to end by looking outward beyond our planet and beyond our solar system.

I hope my task is made easier by the recent advent of sophisticated Earth and space-based imagery at many different wavelengths where our eyes are not sensitive. Also computer animation from sophisticated models allow us to visualize what has before now been invisible and thus appreciated by only those with an intimate knowledge of the underlying physics. Now I believe we all have an opportunity to at least appreciate the vast Earth-space environment, its variability, and its interaction with the Sun. This would not have been possible a few years ago. Let us start with the Earth’s atmosphere.

The Earth’s atmosphere now originates from the rocks, vegetation, and water on the surface. We are quite familiar with the vast amounts of oxygen, and nitrogen that make up most of the atmosphere near the surface of the Earth. Along with these major gases are much smaller amounts of gases such as water vapor, carbon dioxide, carbon monoxide, ozone, and particulate matter like soot. While the quantities of these gases are small we are all aware that they have a significant effect on the quality of our life. This is the first signal from our environment telling us that the small things can be important. I hope you will become aware that this rule applies to many different facets of the behavior of our space environment. All the atmospheric gases are gravitationally bound to the planet and as we rise higher in the atmosphere the lighter gases tend to sit on top of the heavier ones. Above the stratosphere, about 50 miles above the surface of the Earth where atmospheric pollution and most of the water vapor clouds cease, our atmosphere is essentially transparent at visible wavelengths.

Figure 1 shows a beautiful view of our planet from space. It was taken from the Galileo spacecraft as it passed by the Earth on its way to Jupiter. We see the blue oceans, the
brown land-masses and white clouds in the lower atmosphere. But otherwise the atmosphere appears as a transparent envelope around the Earth. This gives rise to the popular misconception that outer space is empty; but it is not. Luckily we are no longer constrained in terms of what we can visualize by the sensitivity of our eyes on the planet surface. We can take advantage of sophisticated imagery from space, which enables us to see at other wavelengths, and thus to gain a different perspective of our atmosphere. With space-based imagers we can see the envelope of our atmosphere with very sensitive cameras that observe a glow from the oxygen and nitrogen.

Figure 2 shows such a view from space where the previously transparent envelope of our atmosphere now appears as a thin glowing shell above the surface. Light from the surface of clouds can also be seen, as well as the diffuse glow from a ground urban area. This gives us a first glimpse of our hospitable atmosphere. As we rise higher in the atmosphere the gravitational attraction of the Earth decreases. At some altitude we reach a state where the dominant gas is the lightest one, namely hydrogen, and it is no longer bound to the planet. This is as big as our atmosphere gets but how big is it?

Figure 3 shows the extent of our atmosphere seen by observing ultraviolet radiation from the Sun scattered from the hydrogen gas envelope around the Earth. The spherical shell seen here extends about 15 Earth radii (60,000 miles) from the surface and can only be seen on the dayside of the Earth where it is sunlit. It is called the Earth’s geocorona and though the neutral density is too small to be detected beyond this limit it actually extends about 30 Earth radii (120,000 Miles) from the surface. On the night side, behind the Earth, it extends away from the Sun in a short tail much like that of a comet. This envelope represents the outer limit of our atmosphere that is gravitationally bound to
the planet and rotates at the approximately the same rate as the Earth. The first message we get from these pictures is that outer space is not empty. The gas out there is very thin. The gas density is small but its influence can be dramatic.

But even from these views we may think that the atmosphere is a quiet unchanging envelope that coexists with a similarly quiet and constant Sun. Nothing could be further from the truth. The atmosphere expands and contracts every day under the influence of heat from the Sun and large perturbations are produced by explosive variations on the Sun. We are well aware of the hurricane force winds at the surface of the Earth reaching 100 miles per hour or more. In the upper atmosphere the winds commonly blow at 100 to 200 mph with velocities 2 or three times greater during times of solar activity. To appreciate what happens we must visualize the Sun in terms of more than just a constant heat and light source that we generally take for granted and we must visualize the Earth’s atmosphere as more than a spherical shell that envelopes the surface. First we will look at the Sun in more detail.

Of course you should never look directly at the Sun but figure 4 shows a filtered image of the solar surface at visible wavelengths. It appears quite uniform except for small dark features called sunspots where the gas is cooler and the magnetic field is more intense. But heat and light represent only subsections of a much broader spectrum of electromagnetic radiation from the Sun. The Sun, is a giant nuclear furnace that has been burning for nearly 5 billion years and will continue to burn for 5 billion years more. Over 1 million Earth’s would fit inside the visible envelope of the Sun and at its core nuclear fusion occurs at temperatures of about 14 million degrees C. The energy released in the core is transported outward on a journey of 400,000 miles that takes nearly a million years to reach the visible surface. This slow transport process is called diffusion. Magnetic fields are also generated in the transport of charged particles in the Sun and at the surface the energy in the particles and the magnetic field continuously powers the visibly luminous surface of the Sun, which has a temperature of about 6000 degrees C. The Sun continuously produces 40-billion-billion
megawatts of power. It is radiated in all directions and the Earth receives a small fraction of this power but still enough to continuously run an electric kettle on every square meter of the Earth’s surface. The Sun emits radiation over a wide range of energies in the so-called electromagnetic spectrum.

![The Electromagnetic Spectrum Diagram](image)

Figure 5 is a diagram indicating the full range of wavelengths. As the wavelength decreases the energy increases, so energy increases in to the right in this picture. The radiation ranges from radio and microwaves at the lowest energies (longest wavelengths) to deadly gamma rays at the highest energies (shortest wavelengths). Heat and light lie in between these extremes and represent more than 80% of the total radiative power output from the Sun. Because the heat and light output are quite constant the Sun is often viewed as a constant star. From an astronomy point of view this may be about right. But in considering the interaction between the Sun and the Earth this can be a serious misconception. The processes that produce higher energy radiation near the surface of the Sun and inject energetic particles into space are highly variable. It is these energetic particles and the higher energy radiation, the other 20% or less of the power output of the Sun, that have the largest effects on our space environment. The recent development of sophisticated space-based cameras that look at x-ray and extreme ultraviolet radiation now allow us to “see” the outer layers of the Sun’s atmosphere, where this radiation originates, and to witness the upheavals and the ejection of material from the surface in spectacular events known as solar storms. In fact the latest cameras have quite narrow wavelength ranges and allow us to pick an energy, equivalent to picking a temperature and to ask what does the gas density look like at that temperature. At 6000 degrees the sun is visible to the naked eye and looks quite uniform.
But figure 6 shows a set of pictures at temperatures equivalent to 800000 degrees, 1000000 degrees, 1500000 degrees, and 2000000 degrees. These hotter gases are at higher altitudes than the visible surface and already we start to see a star that is not so uniform, with gas densities that are highly variable.

Figure 7 shows a picture of our Sun as it would look if our eyes were sensitive to x-rays with much higher energy than visible light. In this picture we are looking at charged particles that are several million degrees. The usually visible surface of the Sun looks dark and we are able to see plumes of gas rising from the surface with much higher energies than the gas at the surface. This gas is confined in giant loops and twists of magnetic field that show the Sun as a much more structured body than you would assume by looking at the projected visible surface. These bright regions are associated with intense magnetic fields and the sunspots on the Sun that were seen in figure 4. The structure seen here is not just spatial. Many of the features rotate with the Sun and show a characteristic periodicity of about 27 days.

In addition to the spatial and temporal variations seen in the previous figures there is a much longer time variation. Figure 8 shows the Sun using the same x-ray "eyes" looking over a period of about 5 years. On the left the Sun is bright and active. On the right it is dark and relatively inactive. These two periods are called solar maximum and solar minimum respectively.
The active bright regions seen in x-ray emission largely correspond to the dark regions on the visible surface called sunspots. Thus this so-called solar cycle has been studied for many years by viewing the spots on the Sun, that were seen earlier, where the surface is cooler than the surrounding area. The entire solar cycle from maximum to maximum occurs in about 11 years. The last solar maximum occurred in 2001. The number of sunspots increases and decreases dramatically between solar maximum and solar minimum, a period of approximately 5 years, and the sunspot number is directly related to the frequency and intensity of eruptions on the solar surface. This important property of the Sun is thought to be caused by a small effect called differential rotation. The rotation rate of the Sun is different at different depths and at different latitudes. This produces an oscillation in the energy diffusion rates. The frequency of oscillation is not exactly constant so that the period of the solar cycle may change a little and the degree of activity may change from cycle to cycle.

Figure 9 shows a detailed picture of the structure in the energy distribution near the solar surface. In this figure the brightness is proportional to the energy of the gas. The surface from which high-energy particles are ejected can be easily seen. This is just above the visible surface. Much of the gas is lifted from the surface and is contained in giant loops of magnetic field as seen here. To appreciate the scale-size of these structures the white dot shows the size of the Earth. Thus we are viewing giant regions that rise from the surface of the Sun to many times the size of the Earth. Much of the gas cools as it streams away from the surface and streams down the magnetic field back to the surface. But not all the energy is contained. In some regions the magnetic field is weak and points directly away from the surface. From these regions energetic particles are continuously ejected into interplanetary space. This stream of energetic particles flowing away from the Sun is called the solar wind. It flows supersonically at speeds of several hundred kilometers per second (200 miles per second) radially away from the Sun and drags the magnetic field of the Sun into a flat disc throughout the solar system. In addition to the almost continuously flowing
solar wind the solar surface also undergoes dramatic eruptions of the particles and magnetic field in a phenomenon called a solar storm.

One class of these eruptions is called a solar flare in which large amounts of magnetic energy are released as gamma rays, x-rays and energetic particles. Flares are produced when the magnetic energy near the solar surface is used to accelerate particles to very high energies. This very high-energy radiation contains particles that are traveling very close to the speed of light. They can reach the Earth’s space environment in a matter of minutes and can be extremely hazardous to astronauts and to sophisticated space-borne electronics inside and outside a space vehicle. For this reason the Sun is monitored continuously during shuttle and space station EVA’s to insure the safety of the astronauts and protection from solar flare events is a significant factor in considering the safety of humans spending extended time in space.

While solar flares represent the highest energy ejection events they are frequently associated with large ejections of solar mass and magnetic field called coronal mass ejections (CME’s). Figure 10 shows a CME as seen in x-ray emission as a bright loop of magnetic field lifted from the surface of the Sun. The CME is initially quite similar to the loops of energetic particles that we saw in figure 9. In this case however, the magnetic field that contains the particles is destroyed at the base producing a solar flare. Then the particles and magnetic field are ejected into interplanetary space. CME’s can be seen in visible light at the edges of the Sun, if the Sun itself is blocked from the image.

Figure 11 shows such a white light picture with the Sun occulted by a disk and indicated by the white circle. These pictures, taken from a satellite orbiting the Earth, show solar material and magnetic field being continuously ejected from the Sun. This is the solar wind. Interspersed in the solar wind are giant eruptive events where the energetic particles from the Sun inflate the magnetic fields and are eventually violently ejected into interplanetary space. The CME seen here is not directed at the Earth, but all we know about activity on the Sun and the 27
day rotational period of the Sun should make it easy to understand that the Earth is equally lashed by events similar to the one seen here. A CME lifted from the Sun in the direction of the Earth will take about 3 days to arrive. Thus a typical solar storm begins first with solar flares and highly energetic particles that arrive at Earth in a few minutes. Then days later a CME may arrive with its enhanced magnetic field and charged particle densities producing further disruptive effects. What do we know about the effects of these disruptions?

Those of you who closely watch the science news will have seen the tell-tale reports. About 5 years ago for example, a Telstar television relay satellite failed during a period of intense solar activity. Since we cannot perform a postmortem on the satellite electronics it is not possible to state unequivocally that the satellite failed from damage due to solar influences, but there is a mounting preponderance of evidence that this could have been the case. The evidence is so strong that significant effort is now being made to predict the occurrence of solar storms and their effects. We want to know why they happen? Can we forecast when they will happen. How long they will last? How damaging will they be? These questions are intimately related and at present we cannot fully answer them. But I hope I can give you a tantalizing glimpse into how eruptions on the Sun are related to the hazards of weather in outer space. To do this we must again visualize what we cannot see with our eyes. We must visualize the particles and the magnetic field streaming away from the Sun and we must visualize the Earth and its magnetic field.

We know that the magnetic field, energetic particles, and radiation that stream away from the Sun engulf the Earth. We are fortunate that the Earth has a magnetic field. It represents our first line of defense from this onslaught from the Sun. While we commonly think of the mineral and vegetation resources of the planet as the features that make it habitable, the magnetic field is also an important contributor since it shields our atmosphere from the solar wind. This is a significant difference between Earth and other planets like Mars and Venus that have atmospheres but no large-scale magnetic field to prevent the solar wind from directly impacting the atmosphere.
The Earth’s magnetic field begins as a simple bar magnet. But as the solar wind streams past the Earth, the magnetic field is stretched radially away from the sun producing a long tail as shown in figure 12. This magnetic envelope of the Earth is very large. It is called the magnetosphere. It is 30 Earth radii (120,000 miles) wide and can extend half a million miles behind the planet away from the Sun. Our next line of defense is the atmosphere. It absorbs much of the harmful radiation, particularly the ultra-violet radiation from the Sun. Thus, together the atmosphere and the magnetic field provide a protective shield for humanity. One, absorbing the radiation that is so harmful to human tissue, and the other deflecting the charged particles that would otherwise bombard our atmosphere and dramatically change the composition and electrical properties. But there is a price to pay. Charged particles are produced as the upper atmosphere absorbs the harmful radiation. These charged particles are trapped in the magnetic field in much the same way that most of us have used iron filings to trace out the magnetic field of a bar magnet. One family of these trapped particles is called the Van-Allen radiation belt in honor of the scientist who first discovered them. This radiation belt contains the highest energy particles trapped in the Earth’s magnetic field. It is indicated as the white shaded torus in figure 12 and is very close to the location of satellites in geosynchronous orbit that are commonly used for a wide variety of television and telephone services. But this picture is deceiving for it illustrates a static and steady configuration of the radiation belts and the magnetic field. If this were the case we would be unconcerned.

In fact the magnetosphere is highly dynamic. It is illustrated in figure 13 using a sophisticated model of the Earth’s magnetic field and particle environment. The magnetic tail of the Earth flaps in the solar wind in much the same way as a flag waves in the wind. These dramatic changes in the Earth’s magnetic field change the energy and the location of the charged particles in the radiation belts. Imagine the magnetic field as a giant pliable
bottle containing the energetic particles in our environment. As the solar wind stretches, compresses and releases this bottle the particles within are energized and moved around quite violently. The consequences are many and varied. The energy of the particles in the radiation belts is so high that they embed themselves in electronic circuitry. The results can vary from unreliability in switches to catastrophic failure of satellite systems. These problems become more and more apparent as our reliance of satellite communications and navigation systems increases. Entire satellites can be become dysfunctional. Pager systems can be rendered inoperative. Telephone and television service can be interrupted. The costs can be large. Telecommunications satellites cost about one hundred million dollars to build and place on orbit. The loss of a satellite includes not only the cost of the satellite but also the costs of re-routing service and lost revenues due to service changes. Over the last three years insurance claims for satellite losses or all kinds were over 500 million dollars per year. Not all these losses are due to the effects of space weather but space weather is now considered as a real hazard to these systems.

Satellites are not the only victims of storms in space. As the magnetic field of the Earth is jostled by the solar wind some of the energetic particles trapped by the field are injected into the Earth’s atmosphere. Referring back to the pliable bottle analogy, think of the mouth of the bottle being in the atmosphere. As the bottle is stretched and squeezed some of the energetic particles are pushed out of the mouth and into the atmosphere. These particles can carry huge electric currents and the
particles that carry these currents act on the atmosphere in much the same way as the electrons in a fluorescent tube. The beautiful emissions that result such as seen in figure 14 are called the aurora. They are seen most often in the polar regions because here the Earth’s magnetic field connects directly to the radiation belts. Almost all who watch the aurora, marvel at the rapid changes in colors and location which send us a message that all is not steady. To a researcher in the field they are a constant reminder of the challenges that await a full understanding of this Sun Earth system. Sometimes the aurora can be seen at low latitudes. Figure 15 shows a beautiful red glow in the sky at Macdonald Observatory in Texas. At these lower latitudes the aurora are more uniform both in space and in color. But they may be quite bright and impressively fill the sky.

These auroral emissions are the signature of large electric currents in the atmosphere that can be a problem for two reasons.

First they generate heat and change the atmospheric density. Just like the heat of the day rearranges air masses at the surface, heat generated by energetic particles in the aurora also moves around the air masses in the upper atmosphere. The changing air densities change the drag on large space vehicles like the space station and the space shuttle. Some will remember the premature re-entry of our first space station called skylab in 1979. Solar storms were directly responsible for this loss. The Department of Defense is responsible for monitoring orbiting space vehicles and debris and regularly has to relocate 100’s of orbiting objects after a solar storm.

A second problem arises because the atmosphere and electrical conductors at the ground act just like a transformer. The large currents in the atmosphere can induce large currents in oil pipe lines and in the power grid. Unfortunately the power grid is designed to handle AC currents while the induced currents are DC. The results can be disastrous. Figure 16 shows a multi-million dollar power distribution transformer that was not isolated from the grid during a large solar storm. You can easily see the irreparable damage that has been
done. These losses produce so-called brown-outs and black-outs in the electricity grid and the costs to restore service and replace equipment can be very large.

Our dynamic Sun produces a wide range of phenomena affecting a variety of operational systems. At the highest altitudes, geosynchronous satellites providing communications can fail. Solar flare particles represent hazards to humans in space. Space vehicles are affected by energetic particles that also act to heat the atmosphere and change the drag on large space vehicles like the Hubble space telescope, space station and space shuttle. Currents in the atmosphere affect radio wave propagation and on the ground can disrupt power systems and telephone lines. These systems on the ground and the in space represent billions of dollars of assets that are vulnerable to the weather in space. But I am happy to report that we are now moving toward a time when continuous observations of the Sun and continuous assimilation of key environmental parameters will allow us to determine when, where, and how solar-induced variations will affect these key space and ground based systems. In this arena the Sun is both our friend and our enemy and to use the parlance of a recent NASA initiative we are now learning to live with our Star, the Sun.

It is important to consider a bigger picture? Imagine you are an observer in space. As you orbit the Earth the auroral lights at the poles are a constant reminder of the planets interaction with the solar wind. Figure 17 shows the auroral emissions in our atmosphere as seen from space. They depict an almost circular area that represents the mouth of the magnetic bottle confining the energetic particles in our environment. Sometimes a ring of emission is
completely filled as dramatic variations in the size and shape are seen. These dramatic variations indicate that our planet has a magnetic field that protects us from the hazards of the solar wind. But we find that our planet is not the only one in the solar system with these attributes. Figure 18 shows images from the Hubble space telescope. The upper panel shows aurora at Jupiter. The lower panel shows aurora at Saturn. Thus within our own solar system there are many planets with magnetospheres and atmospheres that can be identified by the atmospheric glows that they produce. Viewed from even greater distances our solar system is itself a magnetosphere that moves through the interstellar medium. Figure 19 shows a schematic visualization of our solar system. At some point the solar wind, which is moving supersonically will approach the surface where the solar wind interacts with the interstellar medium. This is called the termination shock. It lies somewhere near 80 astronomical units (the distance from the Sun to the Earth) from the Sun and a Pioneer or Voyager spacecraft may soon pass through it. The boundary between our solar system and the interstellar medium is called the heliopause. It is the outer boundary of the comet shaped object located near 110 AU.

Are there other such solar systems with attributes like our own? This is a quest for the future and progress is being made. Jupiter-like planets are so large that the orbit around their star perturbs the velocity. These velocity perturbations can be observed and
recently evidence for a Jupiter sized planet orbiting a Sun-like star at comparable distances to Jupiter and our Sun has been discovered. We are unable to see the auroral signatures that would indicate that the planet has a magnetic field that interacts with the solar wind but it is highly likely that our ability to identify other habitable planets will depend on our capability to detect such atmospheric emissions. A planetary atmosphere from another solar system was recently discovered as the planet passed between the star and the Earth and absorption of the stellar light indicated the presence of sodium. Thus indeed progress is being made on the investigations of other solar systems while we continue to learn to live in our own solar system. The need to understand how the Sun-Earth system works is an exciting challenge to me and I hope you have some feel for that excitement. It is my hope that we will not only learn to live with a Star in our own solar system but that we will learn to live with each other at a rate that will maximize our opportunities to investigate the possibility that other Earth-like planets exist.