# EDUCATION IN SPACE SCIENCE

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## ABSTRACT

The educational process for teaching space science has been examined as a topic at the 17th European Space Agency Symposium on European Rocket and Balloon, and Related Research. The approach used for an introductory course during the past 18 years at Penn State University is considered as an example. The opportunities for using space science topics to motivate the thinking and efforts of advanced undergraduate and beginning graduate students are examined. The topics covered in the introductory course are briefly described in an outline indicating the breath of the material covered. Several additional topics and assignments are included to help prepare the students for their careers. These topics include discussions on workplace ethics, project management, tools for research, presentation skills, and opportunities to participate in student projects.

## 1. INTRODUCTION

The wide ranges of scientific and engineering topics encompassed in the study of Space Science provide exciting challenges and opportunities for students to study and understand the physics in the world around them. A vision of the opportunities to participate in discovery at the frontiers of science and engineering often attracts the best and the brightest students. Many of the important discoveries, and the most fascinating career opportunities of the past 40 years, are encompassed in space science areas. Space science draws upon essentially all of the disciplines of science and engineering, and provides a chance for students to see values in interdisciplinary activities.

During the past 18 years, it has been a privilege and pleasure to lead advanced undergraduate and graduate students through an introduction to our planet, and the influences of space weather upon it. The journey starts with a review of the foundations of electromagnetic theory, the idea of using Planck's Law to describe blackbody radiation, and the fundamentals of gas kinetic theory embodied in the Maxwell-Boltzmann velocity distribution function. Much of our understanding of space physics is founded in the physics and mathematics of electromagnetic theory, and thus an E&M course is considered to be a prerequisite for an advanced step into space science. The initial course, EE/AERSP492 Introduction to Space Physics, is taken by advanced undergraduates in Electrical Engineering and Aerospace Departments, and by graduate students from many departments around the university to gain an introductory understanding of the topics. A semester project is used to develop the students' independent learning experience, research ability, organization skills, and presentation skills. Related course offerings are introduced, and student opportunities to work on space related projects are described.

## 2. CONCEPTS OF SPACE PHYSICS

The equations of Maxwell, Lorentz and Coulomb provide a foundation for an introduction to plasma physics. The ideas and principles of plasma physics are necessary to describe the particles and fields in the region near Earth, in the interplanetary medium, and in deep space. Electromagnetic theory describes the sources of electric and magnetic fields, as well as the electromagnetic fields. The concept of coupling the electric and magnetic field components by the acceleration of charge provides students a special insight into electromagnetic waves and the E&M spectrum, which extends from the ELF portion of the radio spectrum through the wavelengths of the optical spectrum, and extends to the high energies of gamma rays and neutrinos. Currents are described as the motions of charged particles that are experiencing forces due to the presence of electric and magnetic fields, rather than as the conduction of electrons due to the voltage difference between the ends of a wire. The force applied to a charge by the presence of a magnetic field cause charged particles to circle the lines of magnetic flux at the gyroradius. The gyrofrequency is a fundamental descriptor for plasmas that can be separately considered from other motions, so that we are able to use the guiding center approach to model the bulk motion of the gyrating plasma. These particle motions in a magnetic field lead naturally to the description of the three adiabatic invariants. A study of the basic particle motions leads to descriptions of the solar wind and to models of the Earth's magnetosphere. The flow of the solar wind particles, and their interaction with the Earth's magnetic field, result in the several current systems flowing within the Earth's magnetosphere.

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Atmospheric physics processes describe the properties of the thin layer of gasses that compose the Earth's neutral atmosphere. Solar irradiation of the atmosphere results in the formation of the ionospheric conducting layer that completely encircles the Earth at altitudes between 100 and 300 km. The spherical waveguide cavity formed between the conducting layers of the Earth's surface and the ionosphere is useful for long distance communications over a range of HF wavelengths. Winds of the neutral atmosphere combine with magnetic fields and electric fields to force the motions of the ionospheric plasma, thereby generating ionospheric currents, particularly interesting are the equatorial and the auroral electrojets.

## 3. A PHILOSOPHY FOR TEACHING

When one enters the teaching profession, particularly as I did after a twenty-year career in a research laboratory (Air Force Cambridge Research Laboratory), there is a personal search for a philosophy for the activity undertaken. I am fortunate to have selected two themes that appear to have been effective in the classroom during this time. The first is from a statement attributed to Galileo, and second is the idea that curiosity is an important ingredient of the learning process.

Galileo is credited with the statement, "You cannot teach a man anything, you can only help him to find it within himself." In this case, the primary goal of formal education becomes motivating the student to learn from their own search for knowledge and satisfaction from discovery. We need to motivate students' efforts in applying themselves to understand physics and use the language of mathematics to appreciate the physical processes describing the world in which we live. The excitement of discovery and a desire for learning will carry over into other courses of study, develop additional areas of interest, and point the directions to many career paths.

The second theme used in each class is the idea that students should become "curious observers" of the world around them. The idea is that the best learning experiences happen when you are a curious observer. A curious observer thinks while using all of the information communicated by the five senses of human nature to observe their world. Then the curious observer as a scientist or engineer extends those senses with observations using instruments that broaden the observation wavelength range, sensitivity, recording, magnification or other properties by applying technology. Once a person becomes self-motivated from becoming a curious observer, the whole lifelong process for learning is established, and this is most valuable for an individual's career and for enjoyment of life's pathways.

Studies of topics in space science excite and motivate the curious observer's qualities. A fundamental idea that confronts a student of space science is that we live in a sea of electric fields, magnetic fields and electromagnetic radiation fields. Even though space weather seems more remote than terrestrial weather, it is more important in establishing the environment in which we live. Shields provided by the magnetosphere and the atmosphere protect life from the hazards of space weather and make life possible on planet Earth. Those shields include the deflection and trapping of the energetic charged particles, absorption of hazardous ultraviolet and x-ray radiation, slowing down and evaporation of micrometeorites, and the atmospheric water vapor cycle to moderate and distribute the thermal energy around our planet.

One important aspect of space science education is to consider the factors that are necessary in preparing instruments for use under vacuum conditions, in regions of energetic particle radiation, and where high reliability performance and low power consumption are required. The introductory course in space science also includes topics from areas such as astronomy, solar physics, magnetic field models, radio wave propagation, and shielding from energetic particles.

In addition to the technical materials discussed, it is very important to provide the students some useful tools, since many of the students entering the senior level class will be headed for a job in the months ahead. Three specific sets of tools are presented: (1) project planning and management, (2) teamwork and ethics, and (3) presentation skills. Each of these three topics is also put into practice as an exercise during the semester. Many students, even at the senior level, have still not grasped the idea that their future employer will not be interested in their ability to solve problem #2 in Chapter 4. To help with this transition, the problems assigned during the semester require students to seek information from other books and reference materials to complete the solution. Some students do not appreciate this approach, but many have made contact years later to say that was a valuable step for them to take.

Finally, the learning experience is much more vivid when it includes opportunities for hands-on work related to space experiments. A major effort has been made to provide opportunities for students to design, build, and test instruments that measure various properties of our space weather environment as volunteer activities or as projects for senior honors and special topic courses. Several projects have been developed that provide opportunities for students to build instruments and payloads, and to participate in the launch activities for balloon, rocket, satellite and space shuttle payloads.

## 4. SPACE WEATHER BACKGROUND

Early in our national space exploration program, Wernher von Braun made the statement that "There is beauty in space, and it is orderly. There is no weather, and there is regularity. It is predictable . . . Everything in space obeys the law of physics. If you know these laws and obey them, space will treat you kindly." While this statement emphasizes the beauty existing in the physics concepts, it is incorrect because there is weather in space, and today it influences much of what we do, and our understanding will be even more important tomorrow.

We live within a sea of electric and magnetic fields, electromagnetic waves and energetic particles. While these omnipresent features are mostly undetectable by our human senses, they do influence much of our planet's environment. Five senses tell us about the world – but imagine the world if we could sense the fields and view the world in the entire electromagnetic spectrum. Many of the efforts of engineers and scientists are focused on expanding the range and sensitivity of our ability for sensing throughout the electromagnetic spectrum.

## 5. INTRODUCTION TO SPACE PHYSICS

A course taught each year at Penn State University is used as an example for the material covered for an introductory course, EE/AERSP492 Introduction to Space Physics, a brief outline includes topics:

- Review of E&M, Radiation, Gas Kinetics
- Space Plasma Physics
- Beginnings of the Universe
- Space Astronomy
- Solar Physics
- Interplanetary Medium
- Magnetosphere
- Neutral Atmosphere
- Ionosphere
- The Project Engineer/Scientist
  - Instruments in Space
  - Project Management and Ethics
  - Tools, Projects & Presentations

### 5.1 Introduction and Review

The prerequisites for the course include E&M theory and a physics and mathematics background that includes topics in dynamics and radiation. The first week is devoted to helping the students recall the beauty in the mathematical statements of Maxwell's equations, blackbody radiation using the Planck Law in expressions for both frequency and wavelength, and their understanding of gas kinetic theory basics in describing velocity using a Maxwell-Boltzmann distribution and defining the meaning of the term 'temperature'.

### 5.2 Space Plasma Physics

Most of the students have studied circuits and electronic devices in previous courses, and so their concept of current must be expanded to include the motions of both positive and negative charges in space. Ohm's Law is changed to the idea of representing a current density as a tensor conductivity product with the electric field,

$$\bar{J} = \bar{\sigma}_{ij} \cdot \bar{E} \qquad (1)$$

While beginning to view the properties of plasma, the student must grasp the idea of the Debye length as the shielding distance for the extent of the Coulomb force exerted by a charge. The students use Lorentz force (Eq. 2) to exercise the right-hand rule in describing single particle motion in the presence of a magnetic field.

$$\bar{F} = q\bar{v} \times \bar{B} \qquad (2)$$

The Lorentz force equation is the starting point to derive the relationships for gyroradius and gyrofrequency. Fig. 1 shows several cases of single particle motion in the presence of additional forces including electric field, gravity, and magnetic field gradient. Analysis of single particle motion also provides the explanation for the magnetic mirror, as in Fig 2. The simple analysis that can be carried out to describe single particle motion is quite useful for describing many properties and current systems in the magnetosphere and ionosphere. When the gyration of a charged particle is separated from the other motions, then the analysis is described by the 'guiding center' approach. Fig. 3 illustrates the key components of single particle motion that describe the Earth's plasmasphere and the bounce and drift motions of particles in the trapped particle belts. The charged particle motions are divided into three categories. First, the gyration of charged particles around magnetic field lines is associated with the conservation of angular momentum, and referred to as the 1st Adiabatic Invariant. Second, the motion of charged particles along the magnetic field lines, between magnetic mirror points, is associated with conservation of linear or parallel momentum, and referred to as the 2nd Adiabatic Invariant. Third, the drift of charged particles across the magnetic field is forced by the curvature of the field lines and by the vertical gradient of the field strength (curvature and gradient drift). Particle drift is associated with conservation of magnetic flux lines contained within the flux tube that the particle gyrates around, and referred to as the 3rd Adiabatic Invariant. In addition, the concepts of frozen-in magnetic flux, magnetohydrodynamic equation, magnetic pressure, Alfven velocity, and conductivity are introduced to the students.

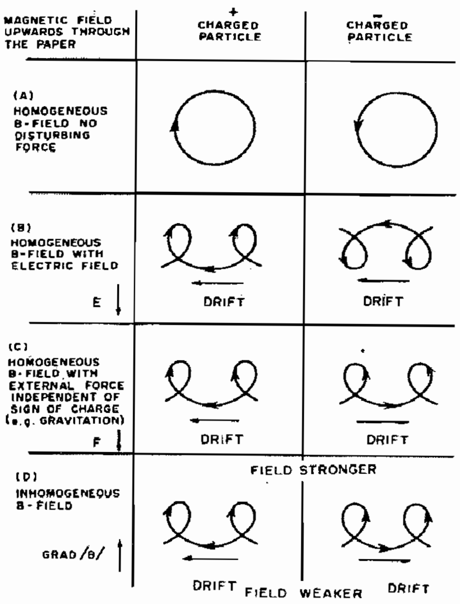


Fig. 1. Charged particle motion in a magnetic field with other forces present can produce currents. [1]

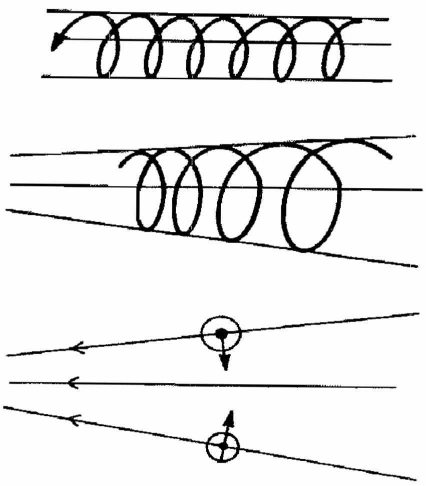


Fig. 2. Charged particle motion in a field gradient result in a force directed toward lower flux, and the process leads to a device called a magnetic mirror. [1]

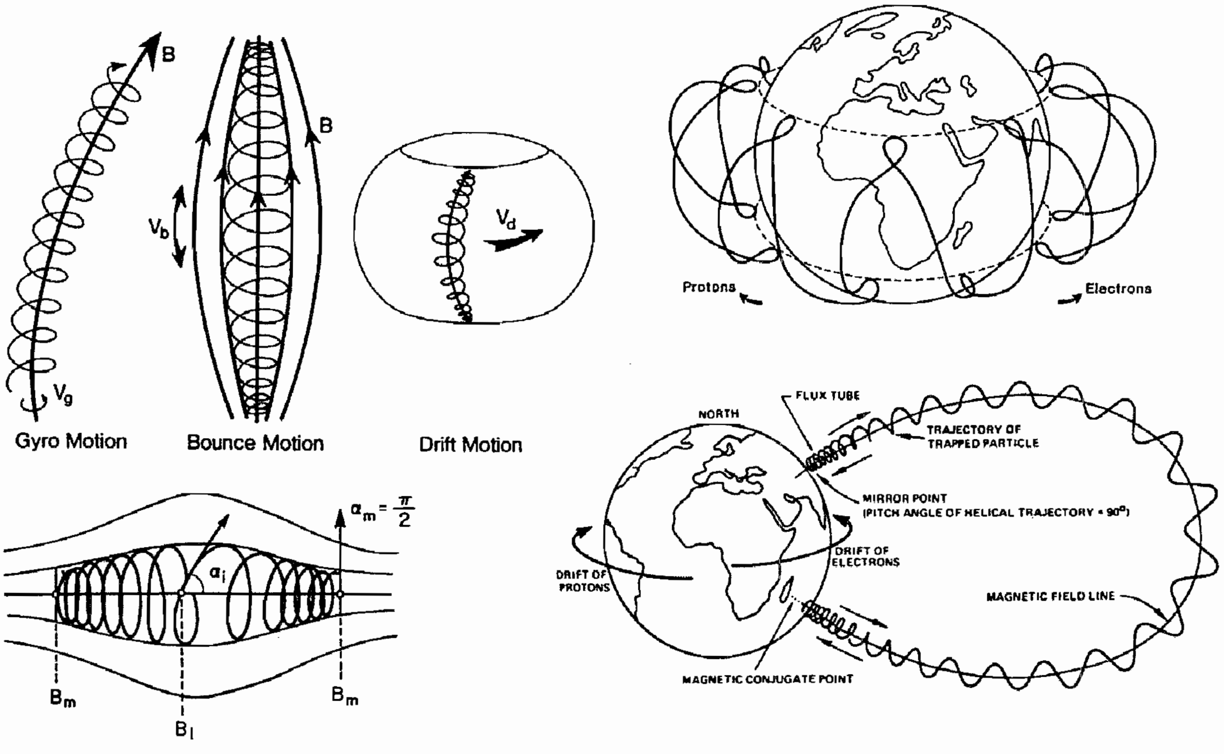


Fig. 3. Illustrations of charged particle motions in the Earth's magnetic field experience forces that demonstrate the three adiabatic invariants and the guiding center concept: (a) gyration, bounce between mirror points, and drift describe the meaning of adiabatic invariants, (b) a magnetic mirror, (c) guiding center motion, and (d) combined motions. [1, 3]

## 5.3 Beginnings of the Universe

The distant views of astronomers into the past, and theories developed from their measurements have allowed us to understand the early stages of the formation of the galaxies in our universe. While the earliest times are hidden from our view, the cosmological descriptions provide intriguing insights. We do know that soon after an energetic event, the matter fields began forming elementary particles in the radiation fields. And with further cooling, the four primary forces that we recognize today (see Table 1) began the coalescence of matter into the galaxies. The fact that we live in the Milky Way Galaxy and its location in the universe is not an accident. In fact, the location of our galaxy in the universe and the Sun in the galaxy is optimal for supporting life. At this distance from the center of the galaxy, the lifetime of our star is sufficiently long for evolutionary processes of plants and animals, and yet the region was formed sufficiently close to the initial supernova to provide the needed high Z-number materials. The student learns about measuring age and distance in the universe with Hubbles constant and the Doppler red-shift.

Table 1. The four forces existing after the initial instant.

| Force | Quanta | Relative Strength |
|---|---|---|
| Strong Force | gluon | 1 |
| Electromagnetic | photon | $10^{-3}$ |
| Weak Force | $W^{\pm}$ and $Z^{0}$ | $10^{-6}$ |
| Gravity | graviton | $10^{-39}$ |

Particles

Hadrons – baryons, hyperon, mesons

Leptons – electrons, muon, tauon

Field Particles – gluon, photon, $W^{\pm}$ and $Z^{0}$, graviton

## 5.4 Space Astronomy

The transition to astronomy follows naturally from consideration of the beginning of the universe. The ideas involved in classifying stars into the H-R Diagram and the meaning of stellar magnitude are among the topics discussed. One or more evenings each year, astronomy sessions provide a chance for each student to use telescopes to view the planets with their rings and moons, and observe several other galaxies. The students learn to orient themselves using sky charts and identify constellations and other celestial bodies. Each student learns enough about celestial navigation to find the Right Ascension and Declination of locations in celestial sphere using the chart in Fig. 4 combined with star maps.

## 5.5. Solar Physics

The processes of hydrogen fusion provide the energy of the sun and the source for essentially all other energy forms that we use. It is the sun that has given the anthropogenic fuel sources through the photosynthesis and decay, the evaporation of water that powers hydroelectric generation, and the surface heating that drives the wind to turn power turbines. Even though we only see the outer layer of the sun, the photosphere, we know about some features of its interior, see Fig. 5. The process of hydrogen fusion is the source of energy in the Sun's core. Energy is transferred out from the core through the radiative zone by gamma radiation to the convective zone. This region boils and swirls the fluid plasma to transfer energy to the photosphere, where the black body radiation, described by Planck's Law, provides most of the energy radiated into the solar system. The energy of the solar spectrum is well described by Planck Law radiation corresponding to about 5500 K. The spectrum also extends into the far-ultraviolet and x-ray region due to emissions from flares and energetic processes in the solar atmosphere. It also extends on the low energy end into the radiowave region because of the radiation from acceleration of charge in the large scale surges of plasma in the photosphere.

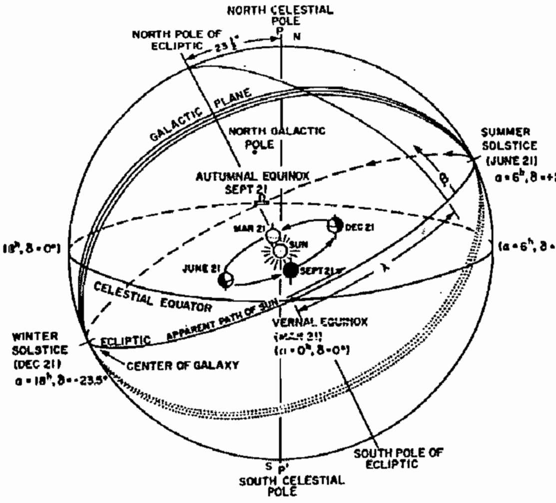
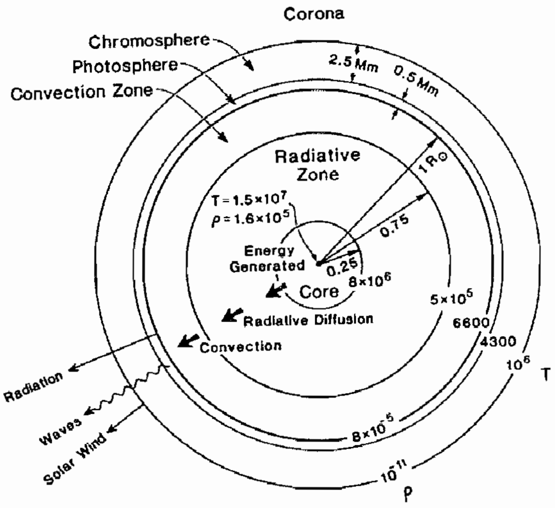


Fig. 4. The celestial sphere is used for stellar navigation and for describing the solar illumination angles on the atmosphere and ionosphere. [1]

From observations of photosphere, we learn about the dynamical processes within the sun. The butterfly pattern that results from plotting the latitude of the sun spots during the 11-year solar cycle, the reversal of the magnetic poles at the end of each cycle, the variations of intensity of the magnetic fields, and the differential rotation rate between the equator and poles, tells us much about the dynamical process in the fluid that composes the Sun. The temperature of the solar atmosphere increases through the chromosphere, and even more rapid in the corona to more than one million degrees before it transitions into the solar wind. The energetic particles ejected into space by coronal mass ejections (CMEs) and by acceleration of particles in flares are the primary contributors to the space weather environment. The energetic particles, and interplanetary magnetic fields are measured by instruments at the Lagrangian stable point (L-1). The x-ray and UV radiation are measured by several satellites, and the Sun is imaged in several wavelengths by the SOHO satellite.

Fig. 5. The regions of the Sun's interior and atmosphere are shown, and the characteristics of the temperature, density, and energy transfer processes are indicated. [3]



## 5.6. Interplanetary Medium

In the upper corona, the temperature of the plasma increases to more than one million degrees and the Sun's upper atmosphere transitions into the interplanetary medium. The solar wind is accelerated above its sonic velocity beyond the critical radius, by the pressure from the energy density deposited in the plasma near the Sun. The solar wind carries the frozen-in magnetic field of the Sun into space and creates the Archimedes spiral arms shown in Fig. 6a. Typical solar wind plasma density at the distance of Earth is about 3/cm$^3$ hydrogen nuclei with a velocity of 400 km/s, but can exceed 20/cm$^3$ at velocity of 800 km/s during active periods. The plasma sheet that forms in interplanetary space has a wavy character, which at times carries the sheet above or below the Earth's location, see Fig. 6b. The typical wavy pattern causes four sectors in the ecliptic plane during each solar rotation where the direction of the magnetic field alternates between pointing away and toward the Sun, as the Earth is located above or below the sheet. The wavy pattern is referred to as the ballerina skirt model.

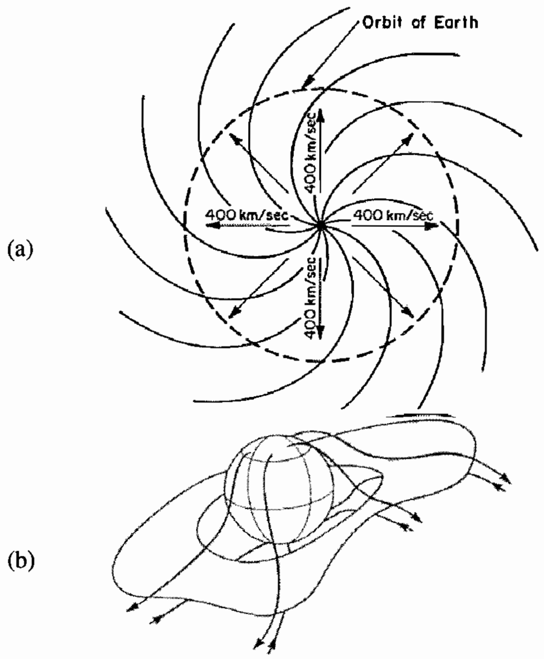


Fig. 6. The solar wind particles carry the frozen-in magnetic flux of the sun throughout the solar system; (a) magnetic field lines are stretched in space while anchored in the rotating sun; (b) the magnetic field wavy character results in a field component directed out or inward with typically four sector crossings per solar rotation. [1, 3]

## 5.7 Magnetosphere

The swirl of the Earth's molten interior produces the intrinsic magnetic field generated by the current from the motion of charge. The field can be approximated by a bar magnet oriented with its north pole embedded in the Southern Hemisphere that is tilted and off-centered about 400 km toward the western Pacific. The Earth's field lines are distorted by the interaction of the solar wind as the charged particles grab the field lines and transfer their momentum to apply magnetic pressure that compresses the field on the upstream side and drags the field downstream around Earth, see Fig 7. The magnetopause current is generated by the Lorentz force as the solar wind plasma encounters the Earth's field, which is compressed from a typical standoff of 12-15 $R_E$ to a distance of 6-7 $R_E$ during flare events. Several current systems are formed on the surface and inside of the magnetosphere by the interaction between the solar wind particles and fields and the Earth's magnetic field. The plasmasphere formed inside of the magnetosphere is composed of the gyrating, bouncing and drifting energetic particles that have been injected through the magnetospheric boundary (see Fig. 3, 7, 8). Acceleration of the charged particles in the plasmasphere results in the 'songs' of kilometric radiation that we recognize as whistlers, spherics, etc. The plasmasphere consists primarily of inner belt energetic protons and an outer belt energetic electrons, see Fig. 8. The loss rate of electrons from the outer belt is much faster than the protons from the inner belt, and it exists because it is continually refilled by particles from the solar wind during flares and CME activity. The off-center location of the Earth's magnetic dipole brings the intense particle radiation to altitudes as low as 800 km in the South Atlantic Anomaly.

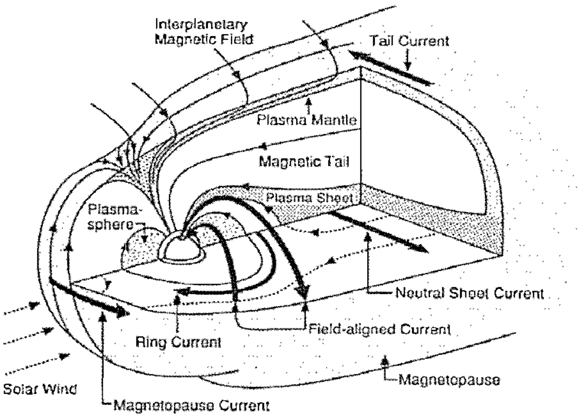


Fig 7. Magnetosphere boundary is shaped by the solar wind particles interacting with Earth's magnetic field. [3]

### 5.8 Neutral Atmosphere

The distribution of the thin shell of gas around the Earth can be described using the hydrostatic equation and the ideal gas law, with mixing below 95 km and diffusive separation above, see Fig. 9. The description of the atmosphere is based upon the temperature which separates the regions by several 'pauses' at inflections in the profile, see Fig. 10. The temperature structure of the atmosphere results from solar radiation heating at the surface, absorption of the 200 to 300 nm ultraviolet radiation by ozone to produce the stratosphere, and from EUV and x-ray radiation absorbed in the thermosphere that results in molecular dissociation and ionization. The temperature gradient determines atmospheric stability and chemical processes that define the composition of the atmosphere. The dissociation of molecular oxygen produces oxygen atoms, which form ozone by 3-body reactions in the region below 80 km, and become the major constituent at altitudes between 180 and 800 km. Topics in this section include the greenhouse gas effect on Earth's climate and discussion on the 'ozone hole'.

### 5.9 Ionosphere

Ultraviolet and x-ray radiation below 160 nm accounts for less than $10^{-5}$ of the solar flux, but its absorption in the upper atmosphere is responsible for formation of the ionosphere. The ion/electron density profiles in the D-, E-, and F-regions, which are depicted in Figure 11, are controlled by the balance between production by ionizing radiation, and loss processes due to recombination and redistribution. Other sources contributing to ion production are cosmic radiation and energetic particles from the solar wind that penetrate the magnetospheric shield. These sources contribute to the trapped particles of the plasmasphere, and the low density tail plasma which are accelerated into the polar region as Birkeland currents, that produce the aurora. Ionospheric plasma flows in two significant current systems at E-region heights, the equatorial and auroral electrojets.

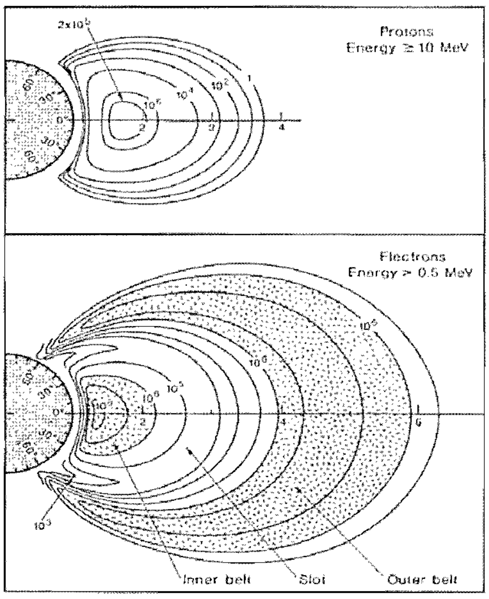


Fig. 8. The inner and outer trapped particle belts are primarily composed protons and electrons. [3]

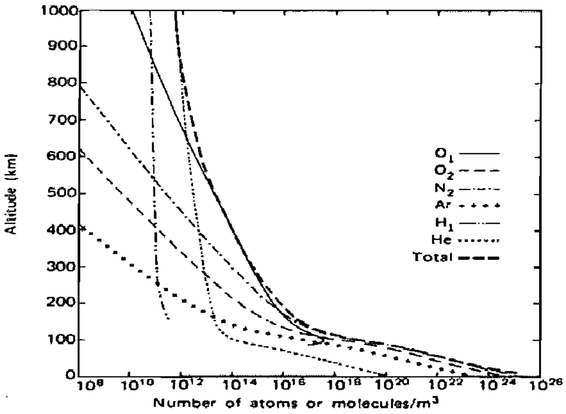


Fig. 9. The profiles of the atmospheric species are well mixed below 95 km and undergo diffusive separation above, with wide changes over a solar cycle. [4]

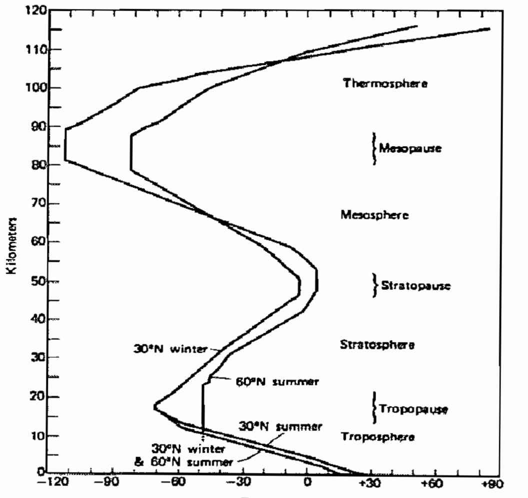


Fig. 10. The regions of the atmosphere are defined by the thermal structure depicted. [4]

The ionospheric effects on radiowave propagation have been the focus of much effort during past decades. While the distant propagation of HF waves in the waveguide between the ionosphere and the earth is less important today, the ionospheric plasma scintillation affects on satellite communications at VHF and higher frequencies are quite important.

### 5.10 The Project Engineer/Scientist

Many of the students will soon be working on scientific/engineering projects in an industrial or government complex, and so an introduction to the duties and responsibilities of a Project Engineer/Project Scientist are discussed. These include the importance of developing a code of ethics as part of a successful and satisfying career experience. In addition, the students are given an introduction to tools that can be important for their future success. In particular, the Work Breakdown Structure (WBS), the Gantt Chart, and the Program Evaluation Review Technique (PERT) are presented. [6] As part of the students semester project, a simple WBS and Gantt Chart are required assignments.

## 6. SPACE PHYSICS PROJECTS

One of the best opportunities for a student to begin developing work skills is available by joining a team effort to build an instrument or a subsystem for a rocket, satellite or balloon payload. Table 2 lists several of the space science projects in which PSU undergraduate students have had the opportunity to participate during the last several years. Graduate students often work on space related topics for their MS and PhD degree requirements.

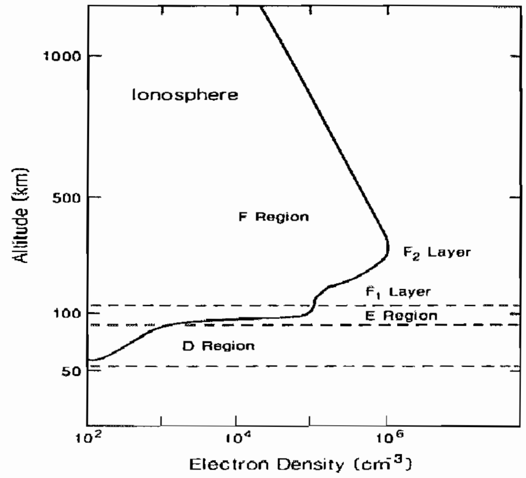


Fig. 11. Simplified diagram of the ionosphere. [3]

Table 2. Penn State University student opportunities.

| |
|---|
| GAS (Get-Away-Special) Shuttle launch packages |
| SPIRIT Rocket Payloads - ESPRIT – 3rd in series |
| LION-SAT – Small Satellite Program |
| CATS High Altitude Balloon Payload for Aerosol Study |
| REU (Research Experiences for Undergraduates) |
| Senior Honors Thesis projects |

## 7. SUMMARY

A special theme that should attract the notice of students during this course is that our spaceship, Earth, is at a special location in space and shielded by a magnetic field and an atmosphere that make life on this planet possible. Space science topics provide a special motivation for students effort in learning physics and mathematics, and student projects provide special opportunities to learn technical and teamwork skills. Space activities contribute to the developments in many areas of technology which lead to new commercial and industrial processes, thus pointing the directions for careers. Access to near real time data on the Web provides an opportunity to monitor space weather and examine the wonderfully complex environment in which we live, cf. [6]. Curiosity about the world in which we live provides many incentives for the life long learning experience.

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