Lecture Fourteen

Solar Storms and Planetary Consequences

Scope: Our Sun shows both gradual changes on billion-year timescales and stormy outbursts on human timescales. The main visible surface features—sunspots—progress through an orderly 11-year cycle tied to the Sun's internal magnetic field. However, in higher-energy radiation, the Sun is constantly seething with activity and punctuated by explosive flashes. Magnetic forces drive both gentle winds and fierce storms of charged particles across interplanetary space. These particles interact with Earth's magnetic field and atmosphere to form radiation belts wrapping our planet's midsection and create spectacular auroral displays at the poles. Well outside the planetary orbits, the solar wind encounters the pressure of interstellar space and marks the outer extent of our star's stormy emissions.

Outline

I. The main changes in our Sun will happen over billion-year timescales.

- **A.** Our Sun is about 4.6 billion years into a roughly 12-billion-year lifetime.
- **B.** Most of the Sun's development is sedate, slowly getting a little bigger and a little hotter.
- **C.** In the latter part of the Sun's life, Earth will be heated enough to lose its oceans and become inhospitable to life.

II. The Sun shows considerable activity on human timescales as well.

- **A.** The easiest changes in the Sun to track are sunspots.
    1. Sunspots are regions of intense magnetic fields, and they appear dark because they are cooler than the surrounding plasma.
    2. The number of sunspots varies from a few to a few hundred on a period of 11 years.
    3. The locations of sunspots migrate over the solar cycle from higher latitudes to the equator.
    4. Sunspots also show that the Sun rotates considerably faster at its equator than at the poles.

    5. The magnetic polarity of the Sun flips at each sunspot minimum; hence, the complete solar cycle is 22 years long.
- **B.** The magnetic field of the Sun is thought to be produced by an interior dynamo.
    1. The generation of a magnetic field through a dynamo requires rotation, conduction, and convection.
    2. Internal motions of the Sun resemble the Hadley cell convection seen on Venus.
    3. Helioseismology observations indicate that differential rotation of the Sun extends through the convective zone, with uniform rotation beneath.
    4. The turbulent boundary region between the convective zone and the radiative zone may be the site of the solar dynamo.
- **C.** The Sun's high energy characteristics include active regions, solar flares, and coronal mass ejections.
    1. The active regions are associated with sunspots.
    2. A solar flare is a powerful release of magnetic energy that appears bright in radio and X-ray wavelengths.
    3. A coronal mass ejection is an eruption that spews billions of tons of hot plasma into interplanetary space.
- **D.** The Sun's corona produces a wind of charged particles that sweeps across the solar system.
    1. Hot plasma (charged particles) thermally streams out from the Sun along the equator and at the poles, forming the solar wind.
    2. The speed of the solar wind is roughly constant, but its density drops as the square of the distance from the Sun.
    3. The particles of the solar wind carry the Sun's magnetic field into a spiral across interplanetary space.

III. The storms on the Sun produce high-energy activity around Earth.

- **A.** Earth's region of magnetic influence is called the magnetosphere.
    1. Earth's magnetic dynamo is generated in its molten iron outer core.
    2. The magnetic field surrounding Earth resembles the dipole field of a bar magnet.
    3. Currently, Earth's magnetic north pole is located near its geographical South Pole, but the configuration changes every few hundred thousand years.
    4. The solar wind flowing across Earth's magnetic field forms the magnetosphere.

5. The pressure of the solar wind creates a bow shock (called the magnetopause) on the sunward side and a long tail (magnetotail) on the night side.

B. Earth's magnetic field shields it from most radiation, but some highly energetic interactions still exist.

1. Charged particles flow along Earth's magnetic field lines and strike the polar atmosphere with sometimes spectacular auroral displays.
2. Changes in the solar emissions can trigger magnetic substorms in the magnetotail.
3. The Van Allen belts are regions where high-energy charged particles have relatively stable orbits within Earth's magnetic field.
4. This energetic radiation makes the space around Earth hazardous for both astronauts and satellites.
5. It is intriguing to imagine how Earth may be left unprotected when its magnetic field reverses.

C. The interaction with the solar wind is weaker for the more distant planets.

1. Jupiter and Saturn do show auroral displays at the poles.
2. The density of the solar wind is 1/25 at Jupiter and 1/100 at Saturn what it is at Earth.

IV. The outer boundary of the Sun's emissions is called the heliopause.

A. The heliopause is where the pressure of the solar wind equals the pressure of the interstellar medium.

B. The heliopause is estimated to be about 100 to 150 AU from the Sun in the direction of the Sun's motion through the galaxy.

C. The termination shock is the point, inside the heliopause, where the solar wind slows down to subsonic speeds.

D. The bow shock is the point, outside the heliopause, within which the interstellar medium dominates.

E. The twin Voyager satellites have already passed through the termination shock and will pass through, and hopefully measure, the heliopause in the next couple of decades.

Suggested Readings:

Beatty, Petersen, and Chaikin, *The New Solar System*, chap. 4.

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*, chap. 14.

De Pater and Lissauer, *Planetary Sciences*, chap. 7.

Golub and Pasachoff, *Nearest Star*.

McFadden, Weissman, and Johnson, *Encyclopedia of the Solar System*, chaps. 5, 11, 28.

Questions to Consider:

1. The convective granules on the Sun are about a thousand kilometers across, while sunspots are typically tens of times larger. What do you think drives these size scales?
2. If a satellite observes a large coronal mass ejection headed for Earth, what precautions should be taken by astronauts, power plant operators, and others?
3. Venus and Mars have no magnetic fields. How do you think the solar wind interacts with those planets?