PARTICIPATING ORGANIZATIONS

Headquarter, Air Force Systems Command
Andrews Air Force Base
Washington 25, D. C.

Air Force Cambridge Research Laboratory
L. G. Hanscom Field
Bedford, Massachusetts

Rome Air Development Center
Griffiss Air Force Base
New York

Rand Corporation
1700 Main Street
Santa Monica, California

Aeronautical Systems Division
Wright-Patterson Air Force Base, Ohio

SPACE ENVIRONMENT

M.B. Gilbert

Air Force Cambridge Research Laboratories,

Introduction

I have been asked to do two things in this presentation: first, to give a "broad-brush" description of the natural space environment, and secondly, to define possible problem areas for materials exposed to that environment.

The first task will be attempted, although it is difficult to give even a broad-brush treatment of such a subject in 30 minutes.

The second task, however, will not be attempted. You are already well aware of problems posed for materials by micrometeorites, trapped radiation, and sputtering. These and others are implicit in the information to be presented. In keeping with our research mission, AFCRL's Geophysics Research Directorate will continue to provide data concerning the aerospace environment which can, in turn, be applied by other agencies as the basis for establishing design criteria.

Solar Phenomena

Knowledge of the solar radiation (both electromagnetic and corpuscular) is probably the single most important factor in establishing the natural space environment, since so many physical phenomena are caused, or directly affected, by solar emissions. It is worthwhile, therefore, to start a discussion of the aerospace environment with a physical description of solar activity and emissions.

Disturbances are always present on the sun, even when it is described as "quiet." While these disturbances have little effect on the total electromagnetic radiation emitted, some of them cause large increases in the flux at very short or very long wavelengths. In contrast to the electromagnetic radiation, corpuscular emission from the sun appears to be predominantly transient.

Sunspots occur in the photosphere. They invariably have strong magnetic fields. The total number of spots fluctuates in a fairly regular 11-year cycle which seems to derive from a more fundamental magnetic periodicity of about 23 years. Faculae, which are regions of enhanced white-light brightness in the photosphere, are not well understood, but they are among the first intimations of the development of an active region, and often persist for weeks after the sunspots have disappeared. Plages, which are bright clouds low in the chromosphere, also frequently precede the appearance of sunspots and persist afterward.

The top of the chromosphere is in continual eruption. Cloud-like prominences often appear over both active and undisturbed regions. Prominences are luminescent gas clouds which take various forms, such as large quiescent masses, active loops, and the fast jets called surges. In the latter, incandescent matter is seen to stream outwards with speeds of 100 to 200 km/sec and occasionally up to 1000 km/sec. Surges and loops are always indicators of great activity.

In an active region, the typical "quiescent" phenomena are occasionally punctuated by extraordinarily sudden and violent eruptive bursts. These outbursts consist of a complex sequence of events, of which the solar flare is the first, and usually the most conspicuous.

Although it is not yet possible to predict with certainty, the onset of a particular solar flare, indications exist of conditions favorable to their occurrence. Flares occur most frequently at times of maximum sunspot activity, and tend to occur in association with sunspot groups which have a complex pattern of positive and negative magnetic poles. Also, flares usually occur in centers which display loop and surge prominences and coronal hot spots (emissions in the 5694 A line of Calcium XV). The firing of many small flares has good correlation with the probability that a large flare will occur.

There is some possibility that prediction of the precise time and location of a large solar flare may be possible one or two minutes in advance, on the basis of the sequence of radio noise, visible, Lyman-alpha, and x-ray emission from a disturbed area.

We do not yet have sufficient knowledge of solar processes to establish unique relationships between the observed characteristics of a specific solar event and subsequent disturbances in the vicinity of the earth. For example, some flares produce strong ionospheric reactions, knocking out radio communications over a whole hemisphere, while others which are apparently identical, merely produce an exciting solar spectacle. The explosive activities must be the result of some previous train of events in the active centers where they occur. A major goal of research in solar physics is to determine the nature of these precursory events, and discover characteristic features and processes that will identify various types of solar events with the kinds of disturbances they produce.

Solar Corpuscular Emission, Van Allen Zones, and Cosmic Rays

A considerable number of protons and electrons evaporate from the outer solar corona, a plausible estimate being 10^{33} protons and electrons per second. This estimate may be modified in view of recent observations, which indicate an elliptical, locally inhomogeneous corona that extends to 20 solar radii. The intermittent emission of high speed charged particles from active regions of the sun greatly increases the particle density.

Most of the particles emitted during a solar flare reach the earth's orbit about 24 hours after the onset of a sudden ionospheric disturbance, an abrupt increase of ionization probably caused by the short-wavelength component of the electromagnetic radiation emitted by the flare. There is evidence, however, that some particles reach the earth 65 minutes after the sudden ionospheric disturbance. The particles are channeled toward the auroral zones, and produce a widespread geomagnetic disturbance.

Corpuscular radiation can be trapped by the earth's magnetic field. The idealized contours of the Van Allen belts with inner and outer zones are familar to all of you. The composition and energies of the trapped radiation are quite different in the two zones. The situation is not as simple, however, as the idealized picture indicates. More recent measurements show that the outer zone has not nearly so well defined a structure. The intensities and the distributions vary in time by large factors. For example, Explorers VI and VII revealed a complex sequence of depletion and enhancement of the particle population and shifts in the spatial distributions which occurred in association with magnetic storms. On one occasion (30 March 1960) the outer zone disappeared, or at least was reduced below the level of detection, for almost 24 hours.

Below the outer zone above North America, an increase of a factor of 10 in the counting rate has occurred on magnetically disturbed days. This is believed to be caused by the escape of particles from the outer zone due to the magnetic disturbances associated with a sudden ionospheric disturbance.

The inner zone appears to be comparatively stable. Very little, if any, change in radiation intensity in the inner zone has been observed during a magnetic storm.

There is general agreement on how the particles remain trapped, spiralling around the lines of force and being reflected back and forth between northern and southern hemisphere mirror points. It has been established that the protons in the inner zone are products of the decay of neutrons which move outwards from the top of the atmosphere. These neutrons are produced in nuclear disintegrations caused by cosmic ray interactions in the outer atmosphere. The low energy electrons, found primarily in the outer zone, are assumed to be of solar origin. This requires a disturbance of the earth's magnetic field which will allow the solar particles to become trapped. A detailed theory of this disturbance is still lacking.

The high-energy electrons in the outer belt are too energetic for solar particles, so that if they are of solar origin, a subsequent acceleration is required to account for the observed energies. No satisfactory mechanism has yet been proposed, but there are indications that the acceleration must take place near the earth.

It is an unhappy fact that the total corpuscular radiation near the earth as a function of position, direction, and time is not well known. Data on the time fluctuations, and particles with kinetic energy below 1 Mev, are especially needed.

During the last sunspot cycle, extensive systematic observations of cosmic radiation proved that at least the low energy part of the spectrum is strongly modified by the sun's action. Recent balloon flights have indicated a diurnal variation in the heavy primary component, which is a flux of nuclei completely stripped of their electrons.

The lower limit of kinetic energy is between 30 and 1 Mev, depending on time. The upper limit is at least 10^{10} Mev. Only particles with energy below 50 Mev seem to have a time variation of intensity. Different nuclei have roughly the same distribution of momentum per unit charge. The relative abundance in the primary flux is about 85 percent protons, 13 percent helium, and 2 percent heavier nuclei.

Observations made at the surface or even at great heights in the atmosphere do not provide unambiguous measurements of the primary cosmic rays, due to the presence of secondary radiation, produced by interactions with the atmosphere.

Cosmic ray intensity usually decreases greatly as solar activity increases. However, large anomalous increases also occur. Thus a sharp increase in intensity at high latitudes may follow a solar flare. This increase occurs from a few minutes up to about one and one-half hours after the flare, depending upon the particular flare, its position on the solar disk and its location with respect to the Earth. Although a large increase in intensity occurs at some high latitudes, little or none is found at low latitudes. The increase is apparently due to a large additional flux of solar particles, most of which have energy less than a few Mev.

During a solar flare, the neutron flux increases much more than does the charged particle flux. Even small solar flares produce a flux of penetrating particles which is estimated to be as much as 10^4 times that of the cosmic radiation. Thus the radiation from solar activity can at times be more important than the primary cosmic rays.

Corpuscular radiation can produce thermal effects by impact with the surface of a space vehicle. In regions of high particle densities and velocities, the contribution to the thermal input may be comparable to that of the solar thermal radiation in the vicinity of earth. For example, during times of high solar activity, solar winds of 10^5 particles/cm^3 with radial velocities of 1500 km/sec have been postulated. If such a flux of protons strikes the vehicle the thermal input from absorption of their kinetic energy alone would be about 20 percent of the mean solar constant. This could seriously upset the thermal balance in the interior.

Measurements from Explorer X in March 1961 confirmed the existence of a solar wind. Preliminary analyses of data indicate a solar wind of 10 protons/cm^3 traveling at speeds of about 275 km/sec during a quiet period, with the speed increasing to 1600 km/sec after a solar flare which occurred on 26 March 1926. On this basis, the thermal inputs would be on the order of 10^{-7} and 10^{-5} cal/cm^2/min respectively.

Solar Electromagnetic Radiation

A value of 2 cal/cm^2-min is generally accepted as the mean total energy of solar electromagnetic radiation at the earth's orbit, and the energy distribution is considered to be similar to blackbody emission at 6000°K.

It is difficult to determine the true spectral distribution of this radiation. Infrared spectra recently obtained indicate that at wavelengths beyond 5 microns, the radiation more closely approximates that of a blackbody at 5000°K. However, for the purpose of specifying the environment, radiation of wavelengths longer than 2000 Å is reasonably well known. For wavelengths of the extreme ultraviolet and the soft x-ray region, space experiments are just now providing necessary measurements of spectral distributions and intensity above atmospheric absorption. Compilations of solar radiations for wavelengths shorter than 3000 Å have been prepared, but these continue to require revision as additional and better experimental results become available.

Although less than 2 percent of the mean solar electromagnetic energy lies in the region below 3000 Å, we need more accurate information about these radiations because of their strong ionizing effects. The photoionization of any material exposed to direct solar ultraviolet and x-rays will depend strongly on the wavelengths as well as the total intensity. For example, the Helium II emission line at 304 Å has a great effect on the ionosphere, where it is almost entirely absorbed in the 150 to 200 km region by photoionizing the atmosphere. Recently, large daily variations in the density of the upper atmosphere have been discovered which are attributed to the energy supplied by absorption of this helium line.

Measurements of the quiet sun indicate that the average solar radiation at different radio wavelengths varies by a factor of three or more in a cycle similar to the sunspot cycle. Tremendous increases in the radio emission from small areas of the sun (up to hundreds of times the corresponding emission from the whole solar disk) are observed from regions associated with flares.

Fields

The general intergalactic field, in which the solar system is embedded, appears to have a strength of 10^{-5} to 10^{-6} gauss.

On a cosmic scale, the dipole field of the earth attenuates rapidly. Thus the magnetic field in interplanetary space will be governed by the field of the sun and the magnetic effects produced by solar corpuscular streams. These streams modify the sun's main field drastically, since the outward flowing ionized gas draws out the lines of force of the solar magnetic field in a radial direction. Also, components which are perpendicular to the velocity may be "frozen in," and carried radially out with the streams. Thus it is possible for the magnetic field to vary in time through a range of 10^{-2} to 10^{-8} gauss or more.

Our experimental knowledge of the geomagnetic field within and beyond the magnetosphere is meager. The magnetometer measurements on Explorer VI agreed with values predicted from calculations of the dipole moment up to about 5 radii from the center of the earth. Beyond this, however, systematic deviations began to appear which can be accounted for by postulating that at 7 to 10 earth radii there is a ring current of several million amperes which modifies the predicted magnetic field. Results from Pioneers I and V confirm the onset of systematic deviations at 5 radii. On the basis of space-probe data, the earth's field is now believed to terminate at 14 or 15 earth radii.

It is postulated that hydromagnetic waves are generated by changes in the pressure of the solar wind, and by instabilities at the boundary of the magnetosphere. In addition, changes in the size of the magnetosphere will also generate hydromagnetic waves.

When complete data from Explorer X becomes available, we will have a better understanding of these phenomena. Preliminary findings, released in April 1961, confirm the solar-wind hypothesis of the interplanetary magnetic field. This satellite detected disturbances in the interplanetary magnetic field for several hours before the appearance of a large solar flare. Field strength during the flare varied from 5 to 40 x 10^{-5} gauss. The sequence of magnetometer disturbances and positions of Explorer X, and the records of the sudden commencement geomagnetic disturbance on earth, seem to prove that the sudden commencement was caused by particles speeding from the sun at 1000 km/sec.

Drag and Sputtering

As an object moves through the earth's upper atmosphere at orbital velocities, it experiences various phenomena caused by interaction with ambient particles. A charge accumulation will result due both to the photoelectric effect and to collisions with electrons and positively charged ions. Phenomena such as recombination, surface accommodation, and the secondary emissions and sputtering caused by impacting ions, atoms, and molecules will also contribute to changing the condition of the satellite's surface.

Calculations substantiate the generally accepted opinion that sputtering erosion will probably never cause a structural failure of a space vehicle. It is entirely possible, however, for enough damage to be done to the vehicle's surface that its emissivity and absorptivity characteristics will be changed sufficiently to disturb the temperature control, and ultimately cause thermal damage.

Sputtering of the surface of a satellite largely depends upon the parameter causing drag. Except in the low atmosphere, the charged particle drag is comparable to the neutral drag on an object.

As a vehicle travels through an ionized medium, the surface assumes a negative potential because thermal velocities of the electrons are over 50 times greater than the velocities of the ions, hence the electron flux is greater than the ion flux. Although this tends to be counteracted by the photoelectric effect on the day side, its magnitude is not believed sufficient to overcome the charge due to the collection of electrons on the night side. Thus, a net negative charge will result.

It was calculated that a vehicle could obtain a potential of several thousand volts during each pass through the Van Allen zones. The calculation is in doubt, however, since it is based on an assumed energy distribution of electrons greater than is shown by recent measurements. However, if these potentials occur, they would in turn cause an increase in the effective radius of the vehicle by a factor of 10, and in the effective cross-sectional area by a factor of 100. In the case of Vanguard I, the pass through the inner radiation belt resulted in a two-fold increase in the mean drag.

The drag on a satellite is also dependent on particles resulting from solar flares. From correlations of orbital data, and radio wave charts of the sun, it appears that particles reaching the Earth about 24 hours after a solar flare, cause an increase in the charge on the satellite, thus increasing the effective cross-sectional area and hence increasing the drag.

It should be noted that at sufficiently high altitudes the pressure of solar radiation acting upon a vehicle may be equal to or greater than the atmospheric drag. This was evidenced in the case of Echo I.

In addition to thermal effects already mentioned, a satellite will experience an erosion process called sputtering, due to the bombardment of the surface by particles of reasonably high energy. The amount of sputtering that occurs depends on number and energies of the particles.

Bombarding ions gain additional energy due to the charging of the vehicle. Prior to the discovery of the Van Allen belts, the vehicle charge was thought to be 10 to 60 v. However, revised calculations indicate that a vehicle could reach a potential as high as 1000 v. Although it is true that such a potential would be maintained only while passing through regions with large numbers of high-energy particles. The 1000-volt value must be considered in estimating the amount of sputtering.

Calculations of sputtering have been based on the assumption that the particles strike the surface at normal incidence. Recently quantitative data have been obtained indicating that impact at oblique angle of incidence can increase the sputtering rate as much as 16 times that which would occur at the normal angles of incidence. There is considerable speculation about the values of the threshold energy for sputtering. Until recently the accepted values were in the range of 30 to 100 ev. However, recent experimental work indicates that sputtering occurs for energies as low as 5 to 10 ev. According to these measurements, impacts having the energies associated with orbital velocities should be expected to produce erosion due to sputtering. The exact quantitative effects cannot be predicted at this time because of insufficient data.

Although it is not likely that vehicles will be flown continuously at altitudes as low as 120 km, the amount of material sputtered during their periodic trips through low altitudes will be significant. Moreover, there may be other areas where the sputtering rate is greater than anticipated.

Meteorites

Studies of the nature and number of small aggregate particles is interplanetary space preceded the era of rockets and satellites. Visual and radio meteor-observation, measurements of solar light-scattering, zodiacal light, and other techniques, as well as examination of meteoritic specimens which reached the earth's surface, provided fairly accurate information on the influx rate and velocities of particles larger than 1 cm.

Meteor observations established that the maximum heliocentric velocities of most particles is less than 42 km/sec at the earth's distance from the sun, and that meteoritic particles travel in orbits which are randomly distributed with respect to the plane of the earth's orbit. The size, mass, and densities remained uncertain.

Although recent direct measurements have been made from rockets and satellites, the sampling area and time available are small compared to that available to meteor observers. For example, if the entire surface of a satellite could be used as a measuring area for one year, the total exposed area-time integral would be on the order of 10^7 m^2/sec, while from the ground 10^9 m^2/sec of sky can be observed in one second. It is also difficult with rocket and satellite measurements to determine the particle size from the interaction with the detecting unit. Present methods allow instrument calibrations for velocities up to 7 km/sec, whereas actual impact velocities must range from 11 to 70 km/sec.

Considering all the uncertainties, estimates obtained by various investigators are in fair agreement with the few direct measurements available. For example, for particles of 10^{-8} grams, the fluxes measured by Explorer VI and Vanguard III were 10^{-5} particles/cm^2/sec and 10^{-3} particles/cm^2/sec respectively. Whipple's estimated value for particles of this mass was 10^{-4}. Similarly, for particles of approximately 3 x 10^{-10} grams, Explorer VI and Midas II measurements are 10^{-4} and 10^{-2} respectively, whereas Whipple's estimate was 10^{-3} particles/cm^2/sec.