ENVIRONMENT FOR MANNED PLANETARY MISSIONS*

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Abstract

The radiation hazard in space is discussed in terms of Van Allen radiation and solar flare proton radiation; radiation presents a significant hazard but it is apparently tolerable if shielding is as great as 10 g cm^{-2}. The meteorite hazard is comparable; penetration is unlikely if the wall thickness corresponds to mass densities as high as those required for radiation shielding. Neither Mars nor Venus has a magnetosphere like that of earth, and hence no radiation belt; however, both have induced magnetospheres. The atmosphere of Mars is so thin as to complicate the landing problem there. The atmosphere of Venus is very thick; recent observations in Mariner 5 and Venus 4 permit a more detailed description of the atmosphere of Venus than that of Mars.

I. Introduction

The environment that will be encountered on a manned planetary mission can be conveniently divided into three segments -- the near-earth environment, the interplanetary environment, and the planetary environment. In this presentation, major emphasis will be devoted to the last of these, since problems associated with the first two will have been met in earlier manned lunar operations. Further, the treatment here will be highly selective with regard to those elements of the environment which are judged to provide some degree of risk; elements of the environment that are straightforward and pose no special problems -- such as gravity and heat balance -- will be ignored.

II. Radiation Belt

The main problem in the near-earth environment results from the Van Allen radiation belt. This has a complicated structure involving both high and low energy electrons and protons trapped in the geomagnetic field; only the high energy components are of much significance from the standpoint of radiation exposure inside a spacecraft.

The inner zone of the radiation belt has as its most penetrating component protons with energies in excess of 35 Mev. The maximum flux occurs at an altitude of about 3000 km above the geomagnetic equator, and it has a value of about 5×10^4 protons cm^{-2} s^{-1}. Figure 1 shows an approximate representation of the high-energy proton belt[1]. The flux contours vary in altitude with longitude because of the off-set location of the earth's magnetic dipole; the 10^3 protons cm^{-2} s^{-1} contour varies in altitude from about 1800 km at 90°E to about 900 km at 60°W,

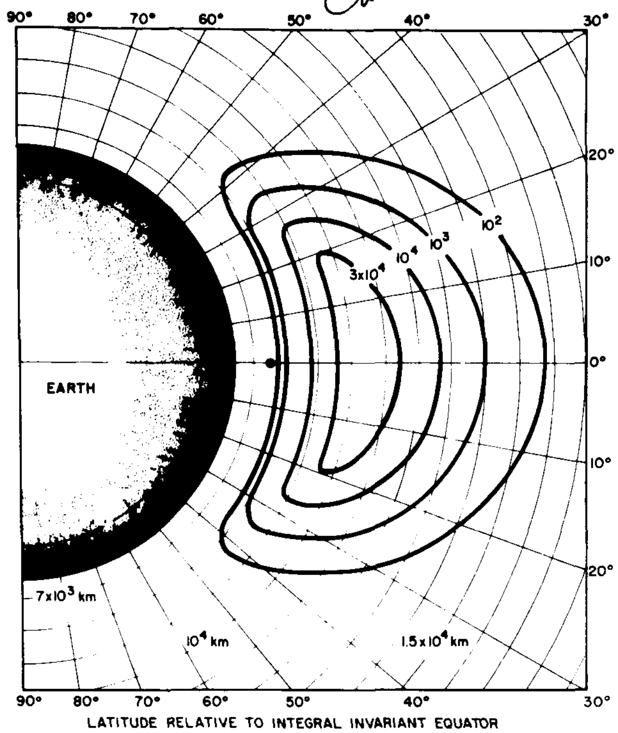

Figure 1. Energetic proton flux (inner zone) of the Van Allen radiation. The numbers identify flux contours of protons with energies greater than about 35 Mev in protons/cm^2-sec. As shown, the altitude of the belt is appropriate for 210° E longitude. The proton flux beyond about 1.3×10^4 km undergoes time variations.

and the 10^2 protons cm^{-2} s^{-1} contour is about 300 km lower. These particles can penetrate more than 1 g cm^{-2} of aluminum, and will give rise to similar fluxes but in the 1-10 Mev range inside such a shield. This would give rise to radiation dosages of about 10 rads hr^{-1}, but only near the surface of an astronaut's body, as most of the radiation is not energetic enough to penetrate deeply. However, spacecraft shielding will probably run more like 10 g cm^{-2}, which can be penetrated by protons only if their energies exceed about 100 Mev. The flux of particles with energies this high is very small, probably less than 10 cm^{-2} s^{-1} except in a small area near the center of the belt[2]. Further, exposure to this radiation can be minimized by orbiting below the intense radiation and then passing through the zone rather quickly on leaving the earth; for example, in about one-half hour, as will be done in Apollo lunar operation. The outer edge of the zone is normally near 6000 km altitude, but it may raise to about 10,000 km at times[3].

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The penetrating component of the outer zone of the radiation belt is electrons with energies greater than 1.5 Mev. The flux values between 10,000 and 30,000 km vary from 10^3 to 10^6 electrons cm^{-2} s^{-1}, the latter high values being associated with magnetic disturbances. Electron energies only rarely exceed 5 Mev. The fluxes are highly variable, sometimes changing by a factor of 100 in a few minutes. The radiation dosage may at times run quite high behind a 1 g cm^{-2} shield, even in excess of 100 rads hr^{-1}. Virtually all the electrons can be stopped with a 10 g cm^{-2} shield, but this does not eliminate the radiation problem with electrons, because of the phenomenon of bremsstrahlung. This radiation is more penetrating than the electrons that produce it by a factor of 100 or 1000, so it is more difficult to shield against. Radiation with photon energies greater than 300 kev can penetrate a 10 g cm^{-2} shield with a fractional transmission larger than 1/e. The efficiency of production of bremsstrahlung is greatest for electron impact on heavy nuclei, so the problem could be minimized by the use of a two-layer shield -- an outer layer consisting mainly of low atomic mass materials to minimize bremsstrahlung production, and an inner layer consisting of high atomic mass materials to maximize absorption of photons. However, in the practical problem of space flight, the duration of exposure during a mission would normally be small, as the spacecraft will probably pass through the region rapidly. If necessary, periods of high magnetic activity and associated high electron flux levels might be avoided if the launch windows are not too restrictive, or a trajectory leaving the atmosphere at a latitude in excess of 45° might be chosen to avoid most of the radiation belt.

III. Solar Flare Protons

Solar flare protons are potentially a serious hazard to manned space flight. Many solar flares emit energetic protons with energies exceeding 10 Mev, but in most cases the energy spectrum is steep, and for most flares there are few particles if any with energies in excess of 30 Mev. However, a few flares emit much more energetic radiation. About 50 flares during one eleven-year sunspot cycle emitted particles with energies in excess of 30 Mev, which are capable of penetrating a shield of 1 g cm^{-2}. The flares that emit >30 Mev radiation are grouped around the maximum of the sunspot cycle; for three or four years near the minimum, only one or two such flares are to be expected. The peak frequency near sunspot maximum is about one per month. About one third of these events may be classified as large events in which the total flux of particles with energies exceeding 30 Mev is greater than 10^8 particles cm^{-2}. The data on energy spectra for solar flare protons are not very reliable, because it has been necessary to use indirect observations, such as ionospheric effects, in their derivation. Relatively few data have been obtained in spacecraft with instrumentation designed to accurately measure the energy spectra in the critical energy range and the time history of the spectra.

Some of the solar flare proton events involve particle energies greater than 10^3 Mev. These events, which may be described as relativistic, can be observed at ground level by neutron monitors. Such events occur about once every two years on the average, with no obvious correlation with solar cycle, although the statistics on frequency of occurrence are poor. During the last two solar cycles, none of these relativistic events occurred in a three-year period around the maxima or a four-year period around the minima of the cycles. This has lead to the conjecture that such events are not to be expected at sunspot maximum or minimum, but only on the sharply rising and falling portions of the solar activity curve. However, in view of the poor statistics, it may well be that this was just a random variation of no real significance, and relativistic events may be as likely at the maximum as immediately preceding it and following it.

Frier and Weber[4] have calculated that a radiation dosage of 885 rads from protons and 430 rads from alpha particles would have been encountered under 1 g cm^{-2} of shielding during July, 1959, when three large events occurred. The Space Radiation Study Panel of the Space Science Board give 1540 rads as the surface dose behind a 1 g cm^{-2} shield for the same series of flares, and 144 rads as the internal dosage four centimeters below the skin of an astronaut[5]. Behind a 10 g cm^{-2} shield, the internal dosage falls to 30 rads, which is also the calculated dosage for an event that occurred in February, 1956, and for a pair of events in November, 1960. Further, there is no assurance that larger events might not be encountered than those seen during the last period of activity.

Man can usually survive a dosage of 100 to 200 rads, and can possibly survive in the range 200 to 500; but over 500 is very likely to be lethal (the Space Science Board report indicates a median lethal dosage of about 250 rads or 450 roentgens, with 10% death rate at about 90 rads and 90% at about 400 rads). Shielding of 10 g cm^{-2} therefore appears to provide adequate protection -- protection such that 30 rad doses would have been obtained during the past twenty years only in February 1956, July 1959, and November 1960. Even if two such events occurred during an interplanetary mission, the dosage would probably be tolerable, especially when the great shielding that must exist in some directions due to massive portions of the spacecraft is taken into account.

IV. Meteorites

Probably the greatest meteoric hazard to manned planetary flight is that presented by uncharted meteor streams in space. Only those that cross the earth's orbit have been charted, and there is little evidence concerning streams that miss the earth's orbit, although they are a reasonable expectation. One might take as a first indication of their probability the number of streams that are encountered by the earth in its orbit, an average of several a month, most of which do not produce dangerous impact rates. There is also the prospect that the probability of encountering meteor streams may increase as one approaches the asteroidal belt. Mariner 4 observed a five-fold increase in impact frequency for microscopic particle in passing from earth orbit to Mars, but these data have been thrown into some doubt by the discovery that the microphone detectors emit noise pulses when they undergo a temperature change, and these pulses appear like meteorite impacts[6].

The most relevant data on rates of meteorite impact were obtained in Explorers 16 and 23 and Pegasus 1 and 2[7]. On Explorer 16 over a 7 1/2 month interval, there were 44 penetrations of 1 mill and 11 penetrations of 2 mil beryllium-copper foils, and on Explorer 23 there were 43 penetrations of 1 mil and 54 penetrations of 2 mill foils. On Pegasus, capacitor type penetration detectors were used with aluminum outer plates of 40, 200, and 400 micron thickness (approximately 1.6, 8, and 16 mil). The resulting rates vary from about 2×10^{-6} penetrations m^{-2} s^{-1} for 10^{-2} cm aluminum foils to 3×10^{-8} for 4×10^{-2} foils. These data extrapolate to 3×10^{-9} penetrations m^{-2} s^{-1} for 10^{-1} cm walls and 10^{-11} for 1 cm walls. These latter figures correspond to average penetration times for 1 m^2 surfaces of 10 years and 3000 years for 1 mm and 1 cm thick walls.

Pegasus data showed about a 25% increase in impact rate during the peak of a meteor shower; the increase was recognized only on the 40 micron (1.6 mill) foil detectors.

V. Induced Magnetospheres

Neither Mars nor Venus possesses an intrinsic magnetic field strong enough to produce a magnetosphere like that of the earth. However, both possess ionospheres whose conductivities are sufficient to give rise to induced magnetospheres[8]. One can think of this in terms of the solar wind bringing magnetic field up to the ionosphere, while currents are induced in the ionosphere to stop the rapid passage of the magnetic field through it. The magnetic field piles up to the point where it is strong enough to divert the solar wind; this then limits the further build up of magnetic field[9], and a shock wave is then formed in the solar wind.

If the conducting obstacle in the solar wind were solid, the magnetic field would pile up in front of it producing a transition region just thick enough to turn back the solar wind. The thickness of the transition layer required to do this is roughly the geometric mean of the electron and proton gyroradii in the stagnation field, or about 4 km. Once these minimum conditions are fulfilled, the further pile up of magnetic field would be eliminated by the diversion of the flow of the solar wind around the obstacle, the flow being turned aside by the stagnation field[10]. However, when the conducting obstacle is an ionosphere, the conditions are different. The magnetic field will pile up and reach the stagnation value near the ionization peak in the ionosphere, where the conductivity is high and the resistance to the passage of magnetic field is greatest. However, the thickness of the region in which a stagnation field piles up may be quite large, as it will continue to build in thickness until it reaches such a level in the atmosphere that the diverted solar wind can pass around the planet relatively unhindered by collisions with atmospheric particles. As long as collisions with atmospheric particles seriously interfere with the flow of the solar wind, field will continue to pile up in the transition layer; as the solar wind cannot pile up magnetic field to a strength greater than the stagnation value, the transition layer can only thicken. The point at which the solar wind can proceed relatively unhindered around the planet will be where the atmospheric particle concentration has fallen to about 10^6 or 10^7 cm^{-3}. The thickness of the transition layer is about 400 km on Mars or Venus, and it can be regarded as an induced magnetosphere.

The induced magnetosphere is very small by comparison with the earth's magnetosphere, but otherwise it bears some considerable resemblance to the latter. The outer boundary of an induced magnetosphere may be referred to as a magnetopause, and the solar wind cannot penetrate it. A shock front with a standoff distance of about three tenths of the radius of the magnetopause forms ahead of it.

The induced magnetosphere protects the planetary atmosphere from bombardment by the solar wind and also greatly limits the action of the solar wind in the sweeping away of atmospheric particles. The loss of atmospheric particles depends upon their becoming ionized while on ballistic trajectories above the magnetopause, after which they are swept away by the electric field associated with the motion of the solar wind. The trajectory lifetime of a particle above the magnetopause is of the order of a few minutes, whereas the ionization lifetime is about a month or 40,000 min, so a fraction of the order of 10^{-4} of the particles that pass through the magnetopause will be lost. The average velocity of atmospheric particles is of the order of 4×10^4 cm s^{-1}, and at a concentration of 10^6 cm^{-3}, the upward flux is about 10^{10} cm^{-2} s^{-1}. The loss is therefore about 10^6 cm^{-2} s^{-1}, which is a modest number -- about equal to the rate of loss of helium on earth and less than a tenth of the rate of hydrogen loss. The total loss from a planet over geologic time would be a few tens of meters at STP, which is rather trivial.

VI. Martian Atmosphere

The pressure at the Martian surface is now generally accepted as lying in the range 4 to 8 mb, mainly on the basis of Mariner 4 observations[11] but also on the basis of spectroscopic evidence[12]. It is probable that surface topographic differences are large enough to cause a variation which is greater than the factor of two uncertainly identified above. There are light and dark areas on the planet, and one reasonable supposition is that the light areas are lowlands (deserts) and the dark areas are mountainous highlands; the elevation difference might easily be in excess of ten kilometers, which could give a factor of two or three variations in surface pressure. The first priority need for new data on the Martian atmosphere is topographic data and surface pressures at a few reference points. The topographic data could be most efficiently gathered by radar techniques, but it could also be obtained, though at a slower rate, by repeated occultation of radio signals from spacecraft.

The Martian atmosphere consists mainly of CO_2. A reasonable expectation for other constituents is 3% N_2 and 0.03% A[13]. The atmosphere is very dry, as should be expected for such a cold planet; the average temperature is about 230°K, and the temperature at the winter polar region is near 170°K. It is claimed on the basis of observation that the water content of the atmosphere is about 14×10^{-4} g cm^{-2} [14]; however, Johnson[13] claims that unmistakable white clouds should be seen if the atmosphere were that moist, and suggests that about a factor of ten less water is more reasonable. Johnson also suggests that the polar caps consist of very thin deposits of hoar frost. Leighton and Murray[15], on the other hand, claim that the polar caps consist mainly of solidified carbon dioxide.

Not much is known of the atmospheric structure. Mariner 4 data indicate a scale height near the surface of about 10 km. Calculations of atmospheric temperature for the thermosphere indicate a temperature of about 400°K[16, 17] but little is known of the crucial hundred km nearest the surface. One indication of the average temperature below 100 km is given by the required low atmospheric density in the ionosphere, which according to Mariner 4 data has its maximum at an altitude of 125 km. However, this has been variously interpreted as analgous to an F2 region[13, 18], an F1 region[19], and an E region[16], indicating atmospheric concentrations of about 10^9, 10^{11}, or 10^{13} particles cm^{-3}, respectively, at 125 km. The atmosphere would have to be relatively warm to agree with the E region interpretation and relatively cold to agree with the F2 region interpretation. Radiative equilibrium calculations are probably in best agreement with the F1 region interpretation if one takes into account the probable effects of eddy heat transport in the atmosphere. The effectiveness of eddy heat transport has been questioned by McElroy[20] on the grounds of rapid radiative relaxation. McElroy's consideration of rapid radiative relaxation compares this with the time required to achieve complete mixing, whereas the appropriate comparison is with the average lifetime of individual eddies. For reasonable size eddies, eddy heat transfer can be expected to cause a considerable reduction of the temperature below 100 km; this is accomplished by eddy transfer downward of heat into a region where radiative heat losses are relatively large and well able to dispose of the heat that has been transfused downward.

Because of the low surface density of the Martian atmosphere, strong winds are to be expected as a result of unequal solar heating over the planet. This results simply from the low heat capacity, which means that the heat imbalance cannot be compensated by a slow wind. High winds occasionally raise dust on Mars.

VII. Cytherian Atmosphere

A lot of new data are available from Venus. The Russian Venus 4 probe measured a temperature of 313°K and a pressure of 1 atm at 25 km, and 553°K and 15 atm at the surface. There is some question as to whether the probe actually reached the surface, or, if it did, if it was on an elevated area, such as a mountain. The highest temperature observed, 553°K, is in reasonable agreement with the microwave measurements made on the dark side of the planet, where the Venus 4 spacecraft landed. The composition measurements indicated the presence of oxygen, about 0.4%, and water, less than 1.6%. They indicated no nitrogen, but the threshold for detection was greater than 5%, where 3% is a reasonable expectation. Most of the atmosphere, more than 92%, is of carbon dioxide.

Mariner 5 measurements complemented the Venus 4 measurements very nicely. A low scale height, about 5.4 km, was deduced from the data-link occultation measurements at a pressure level of about a millibar[21]. Furthermore, the ionosphere was observed in some detail[22] and the magnetic and solar plasma flow perturbations near the planet[23] were also observed. A photometer detected hydrogen Lyman-alpha radiation in the outer atmosphere, and from this an exospheric temperature of about 700°K was deduced[24]. Atomic oxygen was not observed, but not much could be expected with the exospheric temperature that prevails.

A highly tentative model of the Cytherian atmosphere is shown in Figure 2.

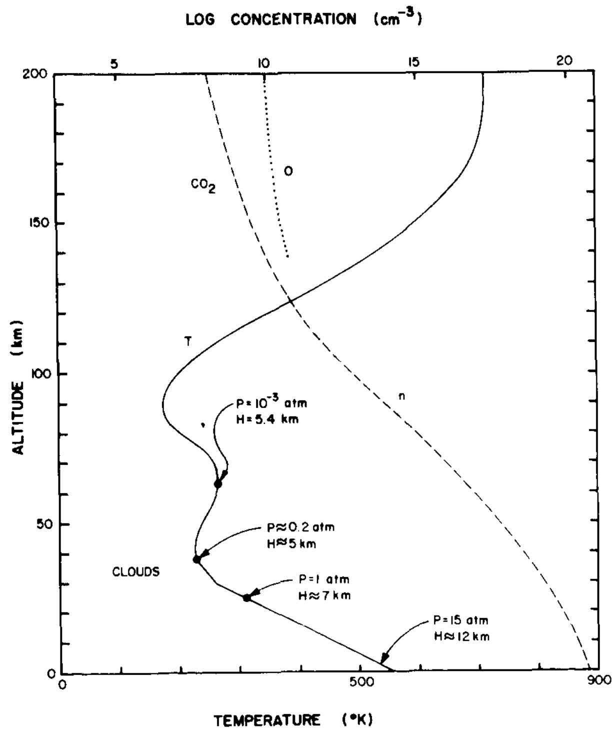

Figure 2. Tentative model of the temperature and particle concentration distribution in the atmosphere of Venus.

The temperature profile measured in Venus 4 is shown below 25 km, and this is very close to the dry adiabatic lapse rate. The temperature distribution shown for the region above 70 km is close to that calculated by McElroy[25], and it is in good agreement with the exospheric temperature determined from the hydrogen corona. The temperature minimum near 90 km is indicated by McElroy's calculations. The warm region at 60 km is based upon the scale height determination from the occultation experiment; it appears analgous to the warm region near 50 km in the earth's atmosphere, which is due to absorption of solar ultraviolet radiation by ozone.

An important question relates to the quantity of water on Venus. The Venus 4 measurements indicate less than 1.6%, but there is no indication of how much less it might be. However, even this figure provides some useful limits on clouds. At 40°C, the water content could run as high as 8% without condensation; the fact that the content lies so significantly below this means that a cloud base could exist no lower than about 3 km above the 1 atm pressure level where the measurements commenced. Extrapolation of the adiabatic lapse rate is therefore appropriate to a temperature of approximately 10°C at 28 km, where condensation would occur with 1.6% water. A cloud base could exist there, and the temperature distribution above that point would likely be moist adiabatic, which has a somewhat lesser slope than the dry adiabatic lapse rate. Infrared radiation measurements indicate a temperature of about 230°K at a haze layer or cloud top. If the cloud base were at its lower limit, the measured temperature at the cloud top would indicate a pressure (using a moist adiabatic temperature distribution) there of about 150 mb, and an altitude of about 34 km; if the cloud base were much higher than its lower limit, the cloud top temperature would be reached at a pressure of about 200 mb (using the dry adiabatic lapse rate for estimating), which would occur at an altitude of about 33 km. Thus the clouds might be fairly dense rain clouds or very thin clouds without much affecting the conclusion that the temperature falls to about 230°K near 34 km, and the pressure there is about 0.2 atm.

Also shown in Figure 2 are some concentration figures for carbon dioxide. At high levels, some light constituent or constituents can be expected to predominate, probably H, He, or O. The curve labeled O suggests possible concentrations.

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