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CURRENT PROBLEMS IN RESEARCH

The Space Environment

As man looks forward to flight into space, he finds the outer regions not completely unknown.

Homer E. Newell, Jr.

Man will go out into space. The powerful modern rocket provides the means for achieving the age-old dream of leaving the earth. Already the first space pioneer is being trained for that first trip. It is reasonable, therefore, to ask what man will encounter out in space, and to take stock of what we already know about the space environment.

There are two aspects of the environment of space to consider: first, the natural environment of the earth's outer atmosphere and space; and second, the environmental conditions peculiar to flight through space.

The Earth's Environs

Extent of the earth's atmosphere. In considering outer space and space flight, it is natural to inquire how far the earth's atmosphere extends—that is, where does outer space actually begin? This is not as simple a question as it might at first seem. There are so many different approaches to it, and so many reasonable answers to it, that no single answer can be given. If one uses the term *atmosphere* strictly in the sense of its original meaning—namely, "breathsphere"—and says that the atmosphere ends at the altitude at which man can no longer obtain adequate breath, then the atmosphere ends at an altitude of about 6 kilometers above the earth's surface. Yet this is hardly an acceptable definition, since there is weather activity at altitudes as high as 20 kilometers, and one certainly thinks of the atmosphere as extending at least as far out as the earth's weather.

Taking a different approach, it might be possible to fix the extent of the earth's atmosphere in terms of the total amount of gas above a given altitude as compared to the total amount below. Thus, 90 percent of the atmospheric gases lie below an altitude of 16 kilometers (10 miles) and 99 percent lie below 30 kilometers (20 miles). Perhaps, then, one might say that outer space begins at about 30 kilometers. All but one one-millionth of the total amount of atmospheric gas lies below 100 kilometers, so that this again might be a convenient altitude to take as the beginning of outer space.

Still another approach to the question is to suggest that the atmosphere ends when it is no longer capable of sustaining aerodynamic vehicles in flight. The difficulty with this approach, however, is that it is not specific, since the height at which the atmosphere can support a vehicle depends upon the vehicle's characteristics, particularly its speed of flight. A variant of this approach might be to consider that outer space begins at that level below which an artificial earth satellite cannot be established in a circular orbit, due to the drag of the earth's atmosphere. This height turns out to be 160 kilometers (to within 10 km), and this is probably a more reasonable criterion to adopt than any of the others.

Even this last definition, however, has its drawbacks, for it excludes a large portion of the earth's ionosphere, which consists of ionized particles high above the earth. It is known that the ionosphere extends from 60 or 70 kilometers out to many thousands of kilometers above the earth. Thus, if the outermost edges of the ionosphere are taken as the threshold to outer space, this would place the beginning of space at an altitude on the order of one earth's radius above the ground.

Composition of the earth's atmosphere. Up to an altitude of about 80 kilometers, the composition of the earth's atmosphere is essentially the same as it is at sea level (N_2, 78 percent; O_2, 21 percent). However, water vapor, which is so prominent at sea level, is present in at most very small quantities in the upper atmosphere. Due to the action of ultraviolet light from the sun, ozone forms in the stratosphere, but its maximum concentration, which occurs at about 30 kilometers, is not greater than 10 parts per million. Thorough mixing of the atmospheric gases appears to occur up to 100 kilometers.

Above 80 kilometers the action of ultraviolet and x-radiations from the sun causes the formation of numerous ions and the dissociation of oxygen into atomic form. The lighter O atoms rise above the heavy N_2 molecules, and above 120 kilometers there is more O than N_2. Above 150 kilometers most of the atmospheric oxygen is in atomic form.

Above an altitude of 100 kilometers mixing appears to be no longer effective, and diffusive separation takes place. This has been shown experimentally with regard to the separation of argon from the remaining atmospheric gases. It may be expected, therefore,

The author is deputy director of space flight programs, National Aeronautics and Space Administration, Washington, D.C. This article is adapted from a paper presented at a symposium of the American Psychological Association, 8 September 1959.

that in the outermost reaches of the atmosphere, hydrogen and helium predominate.

Pressure and density. Both the pressure and density of the earth's atmosphere fall off exponentially with increasing altitude. There is a convenient mnemonic that one can use to estimate the pressure or density at a specified altitude: the pressure or density is divided by 10 for roughly every 10-mile (16-kilometer) increase in altitude. The rule holds good up to about 110 kilometers. At higher altitudes the rate of decrease of pressure and density is appreciably lower than at the lower altitudes. By the time one reaches 300 kilometers, the pressure and density have fallen about 10^{-11} times the value at sea level.

The variation of density with altitudes is shown by the curves in Fig. 1, which were obtained from rocket and satellite measurements. The spread in the data shows the considerable amount of variation in density with geographic position, season, and time of day.

The mean free path of air molecules at an altitude of 100 kilometers is about 10 centimeters. Above 220 kilometers, however, the mean free path must be measured in kilometers.

The density of molecular and atomic particles in outer space has not yet been measured. On the basis of theoretical considerations of the sun's corona, however, some conclude that the density just outside the earth's atmosphere may be 1000 particles per cubic centimeter. This is to be compared with the total of 10^{19} molecules per cubic centimeter in the atmosphere at sea level.

Temperature. In speaking of the temperature of the gases and particles in the earth's upper atmosphere and outer space I mean specifically the average kinetic energy per particle. In the lower atmosphere this is also equivalent to the equilibrium temperature that can be established between the atmospheric gases and an ordinary thermometer, but in the outermost atmosphere and space this equivalence no longer holds.

The temperature of the earth's upper atmosphere is shown in Fig. 2 as a function of height above sea level. Between 30 and 150 kilometers there are only small variations between daytime and nighttime temperatures. Above 200 kilometers, rather large diurnal variations occur.

The temperature of atmospheric gases in the very high atmosphere has, however, very little effect on the heating of objects such as satellites and space craft traversing those regions. This is due to the fact that the atmospheric density is so small. Because of the low atmospheric density, radiations from the sun and the earth, and radiation from the object to outer space, predominate in controlling the temperature of the object.

Beyond the atmosphere, in the regions of space around the earth, it is believed that the particles of the sun's corona have a temperature of about 10^5 degrees. Here again, however, the particle density is so low (about 10^3 per cubic centimeter) that radiation

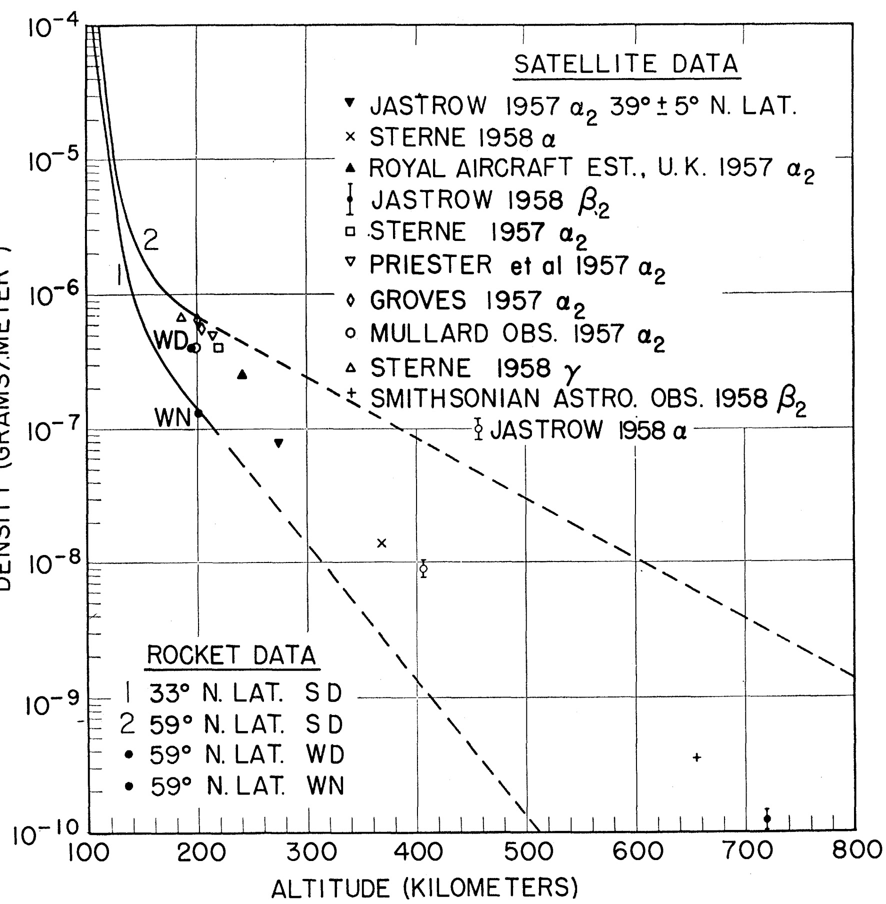

Fig. 1. Air densities, from data obtained with rockets and satellites.

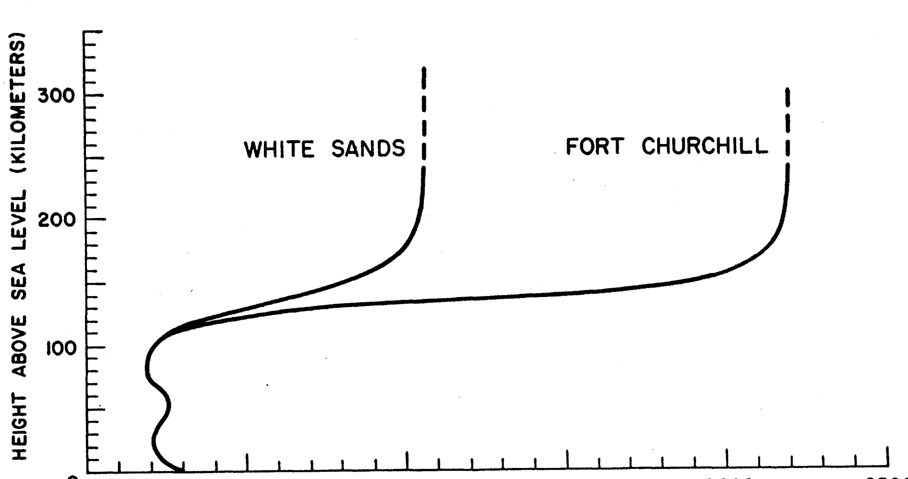

Fig. 2. Atmospheric temperature, as calculated from pressure and density data obtained with rockets.

exerts the greater control on the temperature of satellites or space stations.

Ionosphere. The earth's ionosphere is that portion of the upper atmosphere which is electrified, primarily by electromagnetic radiations from the sun. The concentration of electrons in the upper atmosphere is shown in the curve of Fig. 3, prepared by J. E. Jackson of the National Aeronautics and Space Administration's Goddard Space Flight Center. The plot presents conditions for summer noon at middle latitudes during a sunspot maximum. The electron densities vary with geographic latitude and phase of the sunspot cycle. At the equator the maximum of the curve would be about 100 kilometers higher, while at a time of sunspot minimum, the maximum intensity would be lower by a factor of 10. Note that the scale in the curve is logarithmic, and that appreciable electron densities extend out to many thousands of kilometers above the earth.

In addition, the ionosphere contains heavy ions in numbers roughly equivalent to the number of electrons. For example, above Fort Churchill, Canada, it was found that as altitude increases from 100 to 150 to 200 kilometers, the order of relative abundance of positive ions during the daytime changes from (O_2^+, NO^+) to (NO^+, O_2^+, O^+) to (O^+, NO^+, O_2^+). These observations have been supported by Soviet rocket and satellite observations, which indicate that the principal positive ion in the region from 250 to 950 kilometers is atomic oxygen, O^+.

The principal effects that the ionosphere may be expected to have upon satellites and space vehicles are the charging of those vehicles; the effects on radio communications to and from the vehicles; and the increased drags created by the charging effects.

Magnetic fields. The main magnetic field of the earth is that of a dipole with the axis inclined at an angle of about 11.5 degrees to the axis of rotation of the earth. The principal effect of the earth's magnetic field, as far as space travel is concerned, is the trapping of charged particles to form the radiation belt about the earth. In the regions of outer space there are probably moving clouds of charged particles carrying with them trapped magnetic fields. When such clouds impinge upon the earth's magnetic field, they probably distort the earth's field, producing the magnetic storms and the accompanying interference to radio communications which are observed at the surface of the earth.

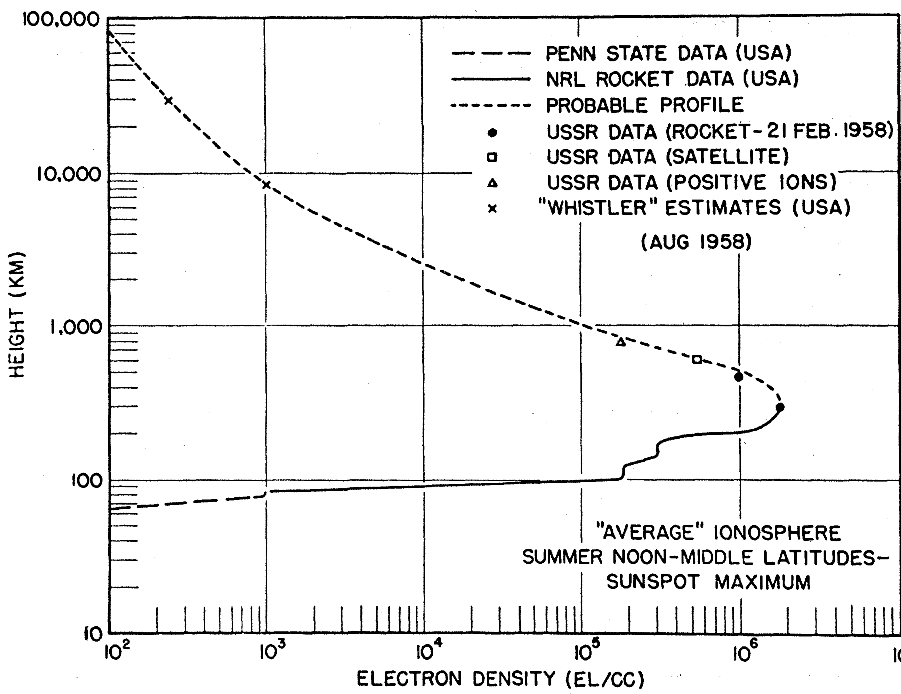

Fig. 3. Electron densities of the ionosphere as a function of altitude and extrapolation to include estimates for "whistlers."

Radiation belt. On 1 May 1958, J. A. Van Allen and his colleagues announced the discovery of a belt of radiation surrounding the earth. This discovery was made by means of the first Explorer satellite. Since then the radiation belt has been investigated further by means of later Explorer satellites and the Pioneer probes (Fig. 4), and by the U.S.S.R. with their satellites and space probe.

It appears that the radiation belt consists of at least two separate zones, as shown in Fig. 5. The particles in the belt carry energies of from approximately 20 thousand electron volts to several million electron volts or more. It has been determined that the particles occur in appreciable quantities at altitudes above 300 kilometers in northern latitudes and above 1000 kilometers over the equator. Their maximum density is about 1 particle per cubic centimeter. The maximum intensity of the inner zone occurs at an altitude of 4000 kilometers; that of the outer zone, at 16,000 kilometers. The outer zone extends out into space to a distance of about 55,000 kilometers. The extent of the outer zone, however, has been shown to vary markedly with activity in the sun.

It is probable that by far the greater portion of the particles are electrons, the remainder being protons. The more energetic particles in the inner belt have been identified as protons.

Particles from the radiation belt are now presumed to be the immediate cause of the earth's aurora. It is also thought that these particles coming into the auroral regions provide the energy that accounts for higher upper-air temperatures in the northern latitudes.

The radiation trapped in the Van Allen radiation belt may be a serious radiological hazard to the crews of future space craft or space stations. There is not yet available enough detail on the particles to provide a full answer to the question of how great this hazard is. The data presently at hand indicate that exposure levels would be in the range from 2 to 50 roentgens per person in the case of a rocket flying directly through the radiation belt to outer space. These radiation levels are well below the lethal dosage for human beings and may be further reduced by appropriate shielding. Moreover, it may be possible to launch a craft into outer space through the funnel-shaped region around the magnetic poles, thereby avoiding passage through the radiation belt. This cannot, however, be done in the case of orbiting satellite stations; if these are too high, they will continually enter and leave the radiation belt. In this case, the accumulated exposure might well become so great as to prohibit the use of the station. Thus, it may be necessary for manned satellites, at least the early ones, to be placed in orbits around the equatorial belt and to remain at relatively low altitudes—say, below 600 kilometers. It should be noted, however, that Winckler and his co-workers, in recent balloon flights, detected heavy fluxes of protons of 100-million-volt energy at low altitudes at the time of a major solar flare. It appears that the radiological hazard in space flight may be serious for limited periods during times of unusual solar activity.

Cosmic rays. Pervading the regions of outer space is the cosmic radiation, which consists of the nuclei of protons, alpha particles, and heavier elements up to, at least, iron. The composition appears to be roughly as follows: 85 percent protons, 14 percent alpha particles, and 1 percent heavier nuclei. The total intensity in space at a distance from the earth such that the earth itself provides little shielding is about 3.6 ± 0.8 particles per square centimeter per second from all directions. Close to the earth this intensity is divided by 2. Also, in the vicinity of the earth an additional component is introduced by backscatter of secondary radiation produced through collisions of primary cosmic rays with air molecules. Within the earth's atmosphere the primary radiation interacting with the molecules of the air generates secondary particles. Below 40 kilometers the total intensity of cosmic radiation begins to increase because of the production of secondary radiation, reaching a maximum total intensity at what is called the Pfotzer maximum at an altitude of 19 kilometers. Below the Pfotzer maximum the total intensity decreases but the numbers of primary rays are very small relative to the total intensity. The cosmic rays show some variation with solar activity, particularly in the lower energies.

The primary hazard which would be presented by cosmic rays to personnel in space craft or orbiting stations is probably to be found in the possibility of a destructive hit in a particularly sensitive region—for example, in the retina of the eye.

Meteors. The skin of a space vehicle, unprotected by the earth's atmosphere, is subjected to the action of meteoritic particles. The effects of these particles is either to cause punctures or to erode the surface by gouging out a crater. The range of possible damage to the space vehicle is broad, since meteoroids may consist of only a few molecules or may be large enough to destroy the entire vehicle. Punctures are significant in manned space flight, since pressure levels must be maintained in the cabin of the vehicle.

Information about the rate of impact of meteoroids has been obtained from measurements of meteors by optical methods and radar. Direct measurements of micrometeorites have been made with microphones and abrasion detectors on rockets and satellites. The total amount of data so far obtained through direct measurement is quite

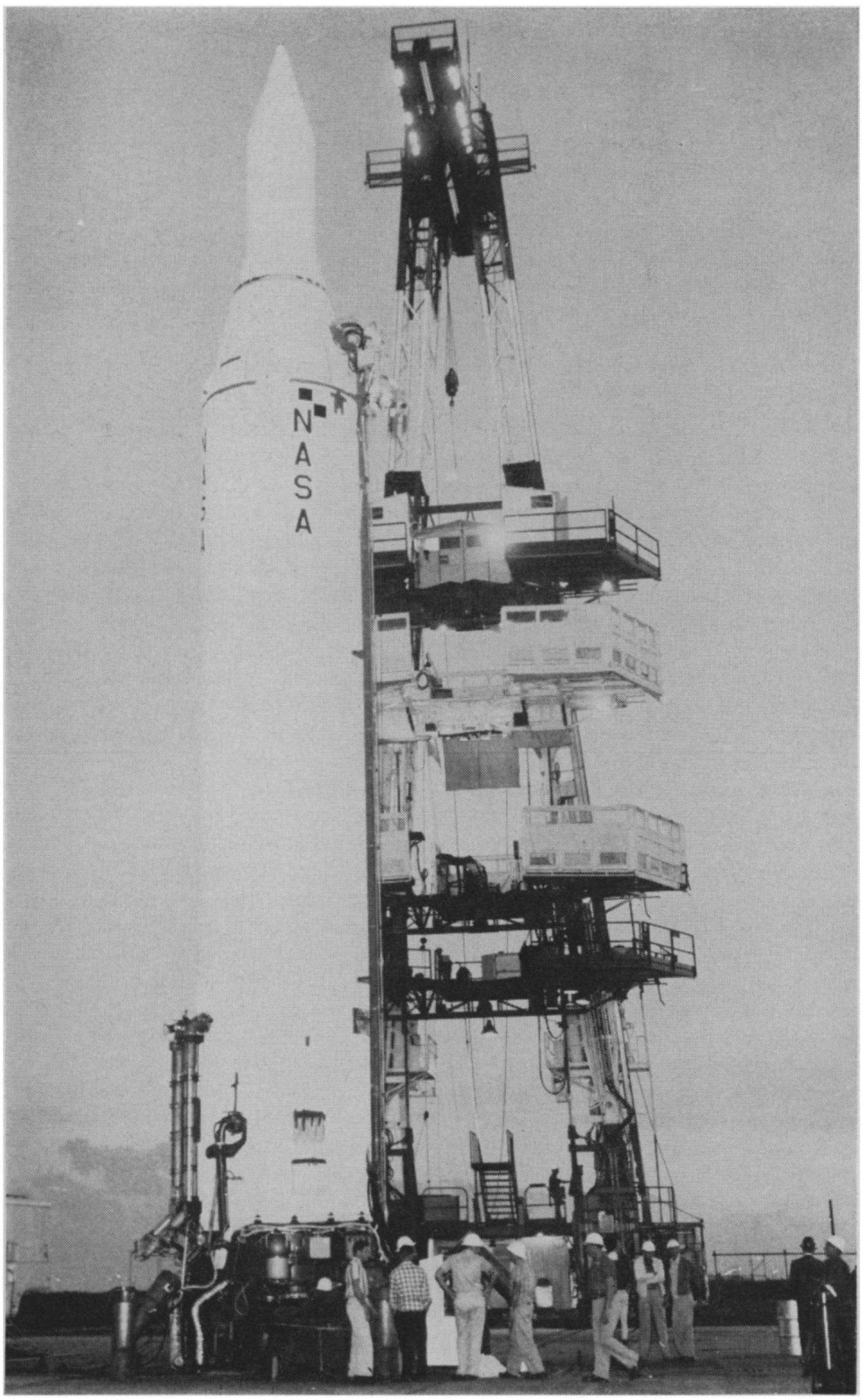

Fig. 4. Pioneer IV prior to launching.

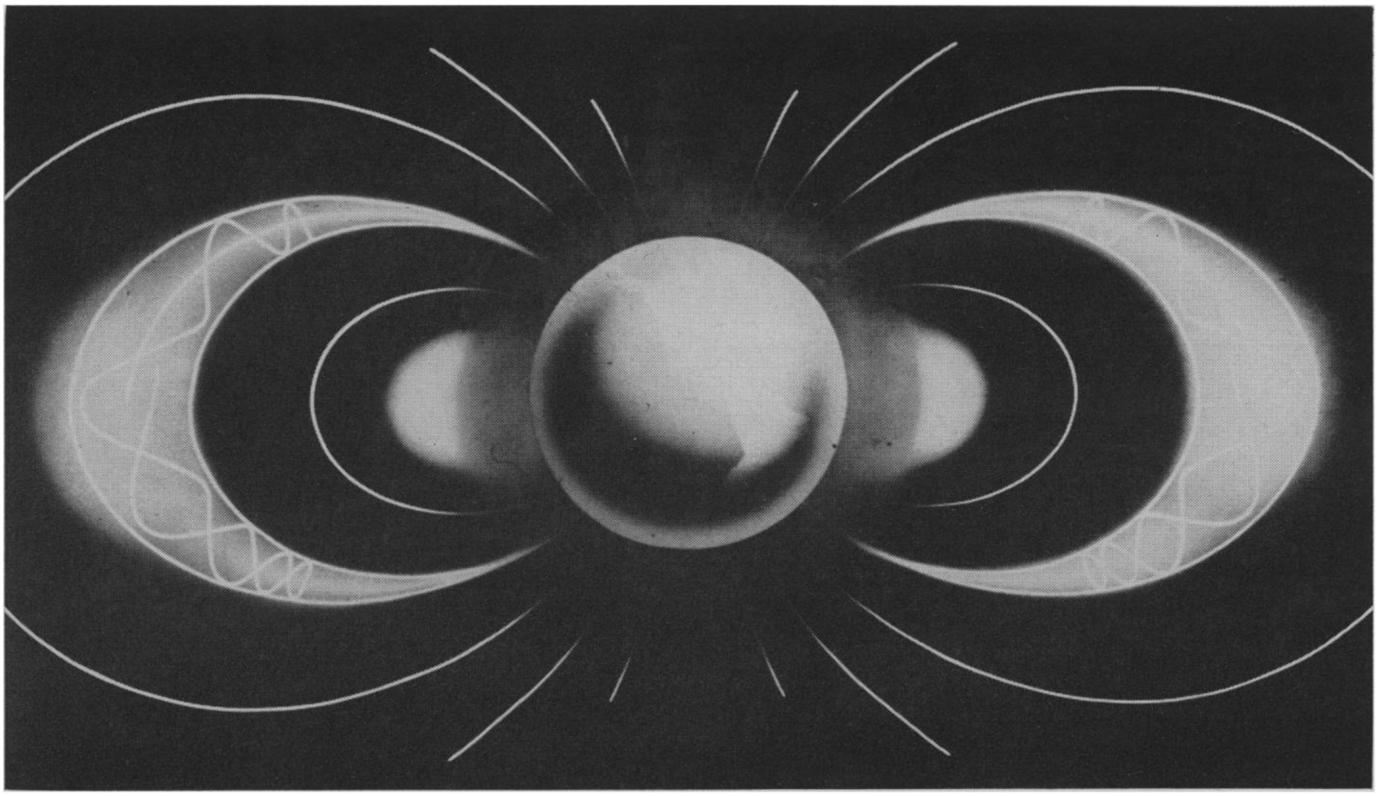

Fig. 5. Schematic representation of the great radiation belts.

small, but more data should be obtained from a micrometeorite detector presently in operation on the Explorer VI satellite.

Although at this time no direct measurements have been obtained to indicate the risk to space vehicles from the impact of meteoroids, estimates of this risk have been made. Damage from the impact of solid particles at meteor velocities of about 100,000 kilometers an hour has not been measured directly, but present estimates indicate that a surface of aluminum 1 centimeter thick would be punctured by a meteoroid with a mass of 0.001 gram. A spherical space ship 3 meters in diameter might be punctured in this way about once a year. Data from the micrometeorite experiment in Explorer I indicate that particles of 10^{-9}-gram mass and larger would hit the space ship at a rate of one every 10 seconds. The pilots of the space ship may actually hear the meteoroids striking the ship. These audible meteor pings would occur on a random basis at an estimated rate of about one per day. During a shower this rate may increase by a factor of 100.

Electromagnetic radiations. The electromagnetic radiations encountered in the earth's outer atmosphere and the space beyond are primarily solar. The total energy brought in by this solar radiation amounts to about 2 calories per square centimeter per minute, or 0.14 watt per square centimeter per second. This radiation is mostly in the visible wavelengths. However, the total radiation intensity in the ultraviolet between 2000 and 4000 angstrom units amounts to about 0.01 watt per square centimeter, while in the neighborhood of the Lyman alpha line at 1216 angstrom units, the total intensity is about 6×10^{-7} watt per square centimeter. Intensities in the soft x-ray wavelengths of 10^{-8} watt per square centimeter have been observed. This radiation extends into the harder wavelengths at the time of marked solar flares. The amount of gamma radiation appears to be negligibly small, as far as its possible effect on space craft and the occupants of space craft is concerned.

For a satellite or space craft operating in the vicinity of the earth, the earth itself will also be a source of radiation. Much of the earth's radiation will be in the infrared, and it will amount to 0.06 watt per square centimeter on the average. In addition, the earth reflects incoming solar radiation with an albedo of 0.4. At night the airglow and the auroras will be visible. The total radiation in the airglow in the visible and ultraviolet spectra amounts to about 5 times the radiation of starlight; the radiation in the airglow in the infrared is greater by several orders of magnitude. That in the auroras may be 1000 times more intense, but it is localized in the northern and southern auroral regions.

Space Flight Environment

In addition to the natural environment that man will encounter in the upper atmosphere and outer space, there will be the environment of his vehicle. Within that vehicle it will be necessary to create livable conditions. To do this, it will be natural to make those conditions as nearly like conditions on the earth as possible. From an engineering point of view, however, many compromises may have to be made. In addition, there are certain aspects of space flight that will be necessarily different from conditions on the earth.

Accelerations. The accelerations experienced during the launching of a space craft from the surface of the earth may be tailored to the tolerances of the personnel. Thus it becomes nec-

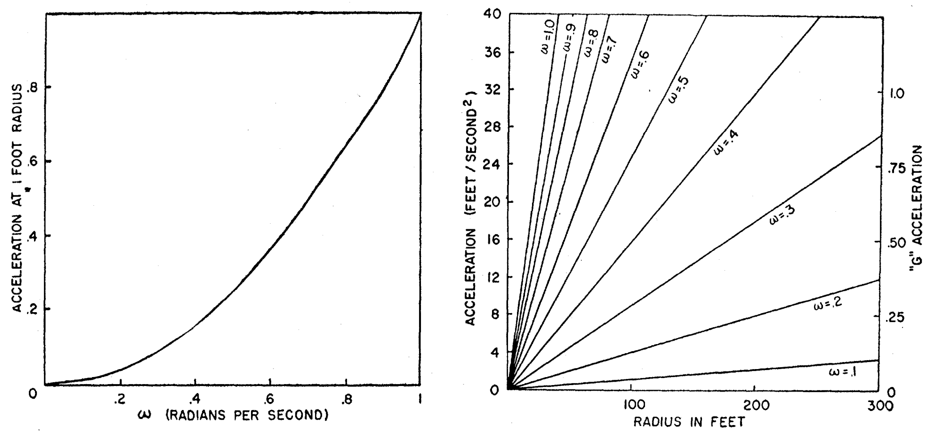

Fig. 6. Acceleration produced by rotation.

essary for the medical people to prescribe those tolerances. The more stringent the prescribed acceleration limits, the more difficult the engineering of the launching vehicle; thus, from the engineer's point of view it is desirable to set the limit as high as possible. In the case of the unmanned flights that are being conducted at present, accelerations vary from less than 1*g* at takeoff to as much as 50*g* during the final rocket stage.

In the return to earth from a flight in outer space, very high accelerations will be experienced unless an appropriately designed trajectory is followed. For a space craft plunging directly toward the earth, the decelerations could amount to as much as 100*g*. By varying the angle of approach and the rate of descent, these decelerations can be reduced, for example, to 8*g* for a 2-degree angle of descent. Also, by the use of appropriate braking rockets, these decelerations can be reduced to acceptable values.

In the case of a vehicle coasting in outer space the palpable effects of gravity are removed, and the occupants find themselves in a weightless condition. If it is desirable to remove this condition of weightlessness, that can be done by introducing an artificial gravity by rotating the vehicle. Figure 6 shows the number of *g*'s obtained by rotating the vehicle at a specified angular velocity, given as a function of radial distance from the axis of rotation.

Heating. A space craft will be subjected to aerodynamic heating during the launching phases and during its return to earth through the lower atmosphere. Since the launching velocities will be considerably smaller than the return velocity, the heating during the return stage will be considerably greater. From an engineering point of view there is no great difficulty involved in protecting the occupants of a space craft from the aerodynamic heating that occurs during the launching. On the return phase, however, skin temperatures of the vehicle will rise to many thousands of degrees centigrade, and it will become necessary, through the use of heat shields and heat sinks, oblation techniques, and judicious use of the radiation of excess heat, to prevent the occupied cabin from becoming excessively hot. Although this presents some difficult engineering problems, it probably can be done.

Any craft in space will also be subjected to heating by the incoming solar and earth radiations. For a craft at great distances from the earth, the solar heating will predominate, and the final equilibrium temperatures will result from achieving a balance between the input of solar radiation and reradiation from the craft to space. To provide acceptable temperatures in living quarters is simply a matter of engineering.

When a vehicle is close to the earth, the effect of the earth will be appreciable. This will be particularly true when the craft is so close that the earth eclipses the sun periodically. In this case, during the daytime portion of the orbit, skin temperatures may rise to 100° or 200°C, while during the nighttime portion of the orbit the surface temperatures may fall to 40° or 50° below 0°C. The equilibrium temperature then will become a function of the absorptive and radiative properties of the vehicle, its internal heat capacity, and the internal heat generated by equipment and occupants. Experience so far has indicated that there should be no problem, however, in maintaining temperatures appropriate for equipment. The requirements for human occupants are more stringent, and this problem requires additional careful engineering.

Visual background. The visual background for an observer looking out into space from a vehicle well away from the earth will consist of a black sky, bright stars, and a sun whose brilliance is unmitigated by diffuse light from a light sky. Sharp contrasts will be the primary feature. The earth also will be a bright object against a dark sky, since the earth's albedo is 0.4. At nighttime there will be a much fainter light from the earth, from airglow and auroral radiations.

Aural background. The noise background within the space ship will come from sources within the space craft itself. The only possible source from outer space would be meteors and micrometeors. Micrometeors are in general too small and their impact is too infrequent to provide any continual background noise. The larger micrometeors and meteors whose impacts can be heard would be so widely spaced as to be noted as discrete pings or thumps rather than as part of a background noise.

Psychological environment. The psychological environment is of course built up as a combination of the physical setting and the man himself. The contributing factors from the natural environment are indicated above. In addition, solitude and separation from the natural abode of man will be primary factors in the psychological environment. Since I am no expert on these matters, I will leave it to the psychologists to discuss them in detail.

Conclusion

Of great interest in all considerations of manned flight into space is the new environment that man will encounter. During such flights we may expect to learn more about the environment itself. But we may also expect to learn more about man, as he faces and copes with that environment. In the course of time, we may expect to learn how to live with the new environment or, rather, to live in spite of it (*1*).

Note

1. I am grateful to R. Jastrow for helpful discussions and assistance in the preparation of this article.