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Harry Davis (A'44–SM'49–F'55) was born in New York, N. Y., on December 2, 1909. He received the Bachelor of Science degree in physics in 1931 and the electrical engineering degree in 1933 from the College of the City of New York. In 1948 he received the Master's degree in electrical engineering from the Polytechnic Institute of Brooklyn where he has done further graduate work leading to the Doctorate degree, in conjunction with courses taken at Syracuse University.

After engaging in various commercial activities, Mr. Davis joined the government service in 1940 as a project engineer, advancing later to Division Chief, and Laboratory Chief. His work in these capacities included electronic research and development, particularly in the fields of navigation, guidance, and radar. In 1952 he was appointed Scientific Director of the Rome Air Development Center at Griffiss Air Force Base, Rome, N. Y. He is responsible for the technical direction of a large-scale program in the development of ground electronic equipment and systems.

During 1955 he was an instructor in graduate courses in electrical engineering at Columbia University, New York. He is now a member of a study group which assists the staff of the Secretary of Defense in special studies involving the evaluation of weapon systems.

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Guest Editorial

AFTER publication of two excellent issues of the PGMIL TRANSACTIONS, the editors decided to prepare an edition which would stress Space Technology, covering those aspects which might be of general interest to all members of the IRE and, more specifically, to those who because of their interest in Military Electronics joined the PGMIL.

Not that it is necessary to stress the Space Age. A dramatic illustration of this was noted recently in a local essay contest held for teenagers. The topic of the essay was "The Space Age and What It Means to Me." I considered this to be not quite the most original topic and, acting as a judge, was prepared for the usual type of essay that such an imaginative subject would produce. Quite surprisingly, therefore, I and the other judges found, buried among run-of-the-mill papers containing fanciful ideas and trite generalities, several essays expounding ideas which may, with considerable hazard, be termed exceedingly delightful fantasies. Other contestants concentrated upon the realities of life on this earth and stressed the fact that old Mother Earth will be our home and, by far, our most important home for a very long time.

The lesson we can learn even from these children is that although we may venture mentally into space at a pace faster than is permitted by our present hardware, the bulk of our work will remain in a region surrounded by and permeated with our earth fluids of various physical characteristics. True, military electronics will lead the way into an expanding space technology, but even in military electronics there is much to be done "on earth as it is in heaven."

Why, then, a Space issue? Primarily, it is felt that the military engineer must be and is the most versatile among scientists. Secondly, in his daily activities, he may not be exposed to newer concepts in other technologies which may affect his future work. A knowledge of the dynamics of satellites and planets and of the solar system and the universe is and will continue to be important to the military engineer. Finally, in recognition of the innate curiosity of the electronic engineer and, to the satisfaction of that curiosity, that thirst for knowledge beyond his own specialty, this issue is dedicated.—Harry Davis.

Our Interest in Space and Its Technology*

H. GUYFORD STEVER†

Summary—The urge to learn more about the space surrounding the earth has been strong throughout mankind's recorded history, the incentive coming sometimes from primitive religion, sometimes from scientific curiosity, and ofttimes from a love of natural beauty. Today we can add to these the incentive of our newly acquired capability of penetrating into this space with instrumented and manned vehicles. We already know much about the solar system and a little about the universe beyond. We have some knowledge of the physical existence and the motion of the planets and their satellites, the asteroids, the comets and the meteors; the composition of these bodies is also somewhat known. The nature of the electromagnetic and particle radiations from the sun and extra solar system sources are less completely known and will be the continuing objective of some of our early scientific explorations of solar space.

IN this first year of successful space flight, a large number of people, scientists and nonscientists alike, have studied enthusiastically the space surrounding the earth and, in fact, the entire cosmos. Much of what they have learned is knowledge inherited from the past, and not knowledge acquired during this first year of space technology nor even in recent decades. They have realized that this generation is not distinguished by a greater interest or by a disproportionately large contribution to knowledge about the space around our earth. We are, however, the first to possess the capability to explore it by inhabited or uninhabited vehicles under our control.

The beauty and inspiration of the heavens have been shared by all men in the past. Possibly the heavens were more important to the past than to the present. Certainly early man's attention to the heavens in relation to his primitive religion gave him a motivating interest which we do not have today. Early man assigned his primitive gods to homes on the planets, the wanderers, in the heavenly skies. The urge to observe, to record, and to predict the motion of the planets was a strong one because it pertained to religion in early civilizations, particularly those in the eastern Mediterranean, Babylonia and Egypt, and this motivation persisted through the middle ages until the postulation of the heliocentric theory of the universe and the birth of modern science.

The beauty and the mystery of the cosmos fired man's creative imagination; ancient literature and folklore is rich in the ideas and stories of space flight and space travel. In ancient days, when the space between heavenly bodies was thought to be filled with air, space flight was just an extension of bird flight. One of the early examples of this type of tale is the legend of Daedalus and his son Icarus, who flew on wings constructed of wax and bird feathers in their attempt to escape from imprisonment on Crete to return to their home on Sicily. Icarus flew too close to the sun, melted the wax holding his wings, and fell to his death into the sea off Greece. Another story was of King Bladud, tenth legendary king of England, founder of Bath, and father of the King Lear of Shakespeare's tale, who was said to have been killed in a flying attempt. Other authors, particularly Lucian, a second-century Greek satirist, wrote of very imaginative trips among the planets and stars. Cicero, the great Roman lawyer and statesman, in his book "Die Somnium Scipionis," described in a dream of Scipio a trip which started in the ancient city of Carthage and ended with a completely cosmic view of the universe. It is interesting to note that the great nonscientific minds of those days were well informed of the latest concepts of the universe, which were held by the natural philosophers; it is particularly interesting that Cicero mentions a "milky circle" which has in it "stars which we will never see from the earth, all larger than we have ever imagined." Also, Plutarch, best known as a great biographer, wrote a description of the physiognomy of the moon in his "De Facie in Orbe Lunare."

Tracing the many threads of man's interests in the cosmos from the early child-like curiosity of simple people to the more complicated observations, calculations, and predictions of stylized religions, on to the disciplined theorizing of the early Greco-Roman natural philosophers, to the unification of the basic principles during the Renaissance and the birth of modern science, to the deepening understanding of astrophysicists of the present day, we see that one of the most compelling and constant reasons for learning more about the space surrounding the earth is so that it could be used as an extraordinary scientific laboratory. The fund of observational data, which started with the ancient religions, was carried on by the astrologers and by the early astronomers, including Copernicus, Kepler, and Brahe, was inherited by those great physicists, Galileo, Newton, and others, and served for them as superb scientific data. The roots of the laws of motion and the law of gravitation are in those studies. The early development of scientific instruments, such as the telescope and the spectroscope, owe much to their use in the studies of the motion and the nature of the heavenly bodies.

Our current interest in space technology, or at least that part of space technology which has to do with space flight, is of course the solar system. To be true, the solar system is a minute part of the universe, but we will concentrate on it, for it can now be reached by vehicles designed on the basis of our current technology.

Now that mankind has this capability, there is a

* Manuscript received by the PGMIL, September 8, 1958. Many of the ideas and descriptions in this article are to be published in less abbreviated form as a chapter in the forthcoming book, "Space Technology," Howard Seifert, ed., John Wiley and Sons, Inc., New York, N. Y.

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whole new set of reasons why man will push into outer space. Many of these have nothing to do with science. One motivating force is curiosity, which is strong in scientists, but another more universal motivation is a love for adventure Some men have a love for adventure and a natural desire, which they cannot explain but only must satisfy, to explore new things. Often what they explore eventually proves to be of great importance to mankind, but that is not the reason they explore it. They are challenged simply because it is something to do which satisfies them. When this exploration of the solar system has taken place, and when men are able to travel to outer space, who knows what mankind will do with this capability? If one takes a very long-term view, there is a certainty of the eventual use of other parts of the solar system for gainful purposes; our generation cannot foresee these uses in detail.

What is the state of our knowledge of this cosmos which we have inherited from these thousands of years of studies by men? Most of us who were trained in modern science and engineering have a rather stand-pat concept of the solar system and the universe beyond the solar system. It is well to reexamine this, for already in this first year of space exploration some new data have been changing and adding to our ideas about the space around us.

The Solar System

Normally we think of the solar system in terms of the sun and the nine planets, together with their various moons. These planets in their almost circular, elliptical trajectories around the sun, together with the sun itself, account for most of the material of the solar system. The sun itself, with its diameter of 865 thousand miles, contains more than 99 per cent of all the matter of the solar system. Most of the rest of the matter is contained in the planets, particularly Jupiter and Saturn. Uranus and Neptune are respectable, medium-sized planets, while Earth, Venus, Mars, Mercury and Pluto are assigned to the smaller group. In numbers, however, there are many more bodies, including the asteroids, the comets, the meteors, and interplanetary dust. In addition, there is a great deal of electromagnetic and particle radiation which is an important part of the content of the solar system.

The Sun

The sun, with its more than 99 per cent of the mass of the solar system, naturally falls at the center. It is the source of a great deal of energy radiated primarily in the form of electromagnetic energy but, in part, in the form of particle radiation. This radiation greatly affects all that happens in the solar system, with the exception of the mechanical motion of the planets and other bodies about the sun, which is, of course, determined primarily by the universal law of gravitation and Newton's laws of motion, and depends upon the inert mass and the velocities of the bodies.

The sun has a diameter more than 100 times that of the earth, is 93 million miles away, and has a third of a million times more mass than the earth. The center of the sun had a density seven times that of lead, and in the center there is a pressure possibly of a billion tons per square inch and a temperature of 20 million degrees Centigrade. In this atomic furnace the nuclei collide with such velocities that transformation from atomic species to others is made. There are complex nuclear reactions which in their total use up the most plentiful element in the sun, hydrogen. From hydrogen, heavier nuclei are built and there is, as a result of this fusion, a release of enormous energies. A calculation has been made that 564 million tons of the sun's hydrogen are transmuted every second into 560 million tons of helium and 4 million tons of energy. This energy flows out to the surface and is radiated primarily in the form of electromagnetic radiation. Here on earth that radiation keeps life going, yet we intercept of the order of a billionth part of all the sun's radiated energy.

The surface of the sun, the so-called photosphere, is a gaseous envelope perhaps 200 miles thick. In the outer portions of this atmosphere the gases shine only faintly; at the bottom of the atmosphere they are intensely bright. The density of this thick atmosphere is not great, possibly a millionth of the density of air at sea level here on the earth. The pressure, in fact, is only about one-fifth of our sea level pressure, but of course the temperature is very high, 6300 degrees Centigrade. At the top of the photosphere the temperature drops probably to 1400 degrees and the density and pressure are decreased correspondingly. Furthermore, the gas at the top is quite transparent to the radiations from the lower levels of the photosphere.

Outside the photosphere is the chromosphere which is a turbulent, rarified atmosphere extending 5000 miles or more above the photosphere. It is in this chromosphere that the great solar storms and prominences, which appear like great protruding flames, occur. Outside this chromosphere is a very faint corona reaching millions of miles off in some directions. The speed of molecules in this corona is very great, indicating temperatures possibly 500 thousand degrees absolute. As viewed from a great distance, this corona might even be considered to stretch out to beyond the closest few planets.

The electromagnetic and particle radiation from the sun is not entirely steady; irregularities of this radiation cause perturbations in many phenomena throughout the solar system.

A good example of this can be seen from the effects which occur when a large solar flare occurs on the surface of the sun. These solar flares seem to be associated with sun spots, which are the black spots on the face of the sun, the great vortical motions within the sun's atmosphere; the sun spots cross the sun from east to west and vary from year to year in intensity and number, apparently with an eleven-year half-cycle.

Solar flares dissipate immense energies in a few minutes. Almost immediately after a solar flare occurs, the shortwave radio communication blacks out on the earth, at least on the daylit hemisphere of the earth. Also, solar radio noise increases. In a few minutes the solar flare will have generated light which is many times as bright as the surrounding regions of the sun; then the flare will die down in a few hours.

There are also some delayed effects of solar flares. About a day after the occurrence of a solar flare, a magnetic storm will occur which will disrupt the magnetic field of the earth. It will trouble wireless communications for days thereafter. Also, about a day after a solar flare the auroral activity will increase greatly.

The current theory concerning the nature of the sudden release of energy in solar flares is that in the tenuous gas in the sun's chromosphere the moving electrically-charged particles of gas distort the magnetic field lines and store energy in the twisted lines, the pressures of which are resisted by the pressures in the gas, until finally a great amount of energy is stored. Suddenly an instability sets in and all this energy stored in the electromagnetic field is dissipated in a short time and radiated primarily in the form of electromagnetic energy but partially in the form of ionized particles and electrons.

Terrestrial Space

Clearly from the above description the particle and electromagnetic radiations from the sun have a great influence on the space immediately surrounding the earth. Many of the particles and radiations are absorbed in the upper reaches of the earth's atmosphere. This atmosphere acts as a protective blanket for the plant and animal life on the earth. The harmful X rays and ultraviolet rays from the sun are absorbed, as are most of the cosmic rays and meteors. Many of the effects of the solar flare result from a change in the electrical layers in the upper atmosphere which in turn change radio transmissions. In addition, the circulating electric currents outside the denser portion of the atmosphere which are responsible for part of the earth's magnetic field are changed. The incoming particles from the sun, as they spiral in around the earth's magnetic field lines, also cause ionization in the upper atmosphere leading to the radiations which are associated with the earth's aurora.

Asteroids

There are thousands of asteroids, or little planets, which have already been detected. The first and largest one, Ceres, was discovered by Piazzi on the first and second days of the nineteenth century. A few years later Pallas, Juno, and Vesta had also been found and plotted. By the middle of the twentieth century more than fifteen hundred of these asteroids were tabulated and registered.

The typical orbit of an asteroid is almost circular and is located part way between Mars and Jupiter. The numerous asteroids which occur in this region seem to indicate they were formed by the violent destruction of a planet or, possibly, they are evidence of a planet which never quite coagulated. Modern theory seems to indicate that the latter is more likely. There are some asteroids, however, with orbits quite different from the typical asteroidal region. Hidalgo, for example, has a highly eccentric orbit in which its perihelion is closer to Mars than the typical asteroid orbit, and its aphelion stretches almost out to the orbit of Saturn.

There have been many estimates of the number of asteroids which have existed, and attempts have been made to determine the range of sizes. There seem to be about two hundred with an absolute magnitude of seven or less and the estimates range up to 30 thousand to 80 thousand with magnitudes greater than 19. Possibly there is as much matter in the form of asteroids as there is matter in the earth, though more likely the mass of the moon is a good comparison. The large asteroid Ceres has a diameter of almost 500 miles which, as you see, makes it not very different from the size of the moon, Ceres being one-fifth of the diameter of earth's moon and, in fact, one-seventh the diameter of the planet Mercury. Only one of these asteroids, Vesta, is visible with the naked eye; this is not because it is larger than Ceres, but because it has a greater surface reflectivity.

Some of the more recently discovered asteroids have orbits passing reasonably close to the earth. One such asteroid, Eros, actually passed inside the oribit of Mars and, in its closest approach, came within 15 million miles of the earth. Apollo, Adonis, Hermes, Icarus, and others have actually come closer, with Hermes passing within 500 thousand miles of the earth, or just about twice the distance from the earth to the moon. Asteroids which come close to the earth, however, are rather small in size.

Comets

Comets in recorded history have occasionally been spectacular. Our generation has not yet been treated to the most spectacular comets as have previous generations, but even the less impressive ones are interesting. Comets have been recorded for centuries. For example, Halley's comet was recorded in Japan and China every time except once since 240 B.C., appearing at approximately seventy-five year intervals. Apparently Halley's comet is the one pictured in the ancient Bayeux tapestry; it was also considered to be an ill omen for the Saxons in the battle of Hastings in 1066 A.D.

The orbits of comets vary greatly, both in their eccentricity and the angle between their orbital plane and the ecliptic, and even in the direction of motion about the sun. Some comets have almost circular orbits while others have orbits of great ellipticity going from perihelion close to the sun to aphelion far, far out beyond the farthest planet. Some have orbits which are almost hyperbolic; in fact, some orbits can be perturbed by a proper combination of gravitational influences by the planets, particularly Jupiter and Saturn, to change their orbit slightly from elliptical to hyperbolic, and so become lost to the solar system.

In appearance comets vary a great deal, but a typical comet appears first in the sky as a diffused spot of light. As it comes closer to the sun it seems to grow a tail pointing away from the sun. Some of these tails are extremely long. For example, the tail of Halley's comet in 1910 was about 30 million miles long when it passed perihelion and reached a maximum length of about 100 million miles somewhat later. This distance is greater than the distance from the sun to the earth. There is usually a bright nucleus in the center of the coma which is a diffused area about the nucleus. Tails are varied in shape and size; sometimes they have multiple structures.

The composition and structure of comets, in a theory which is of relatively recent origin and due largely to Whipple, is a mass of material loosely amalgamated, the material consisting of small solid particles frozen together in an ice of water, methane, ammonia, and possibly cyanogen and carbon dioxide. The nucleus of comets is not necessarily very large, Halley's having been estimated to be as low as 1500 feet in diameter and certainly not more than a mile. When these comets are far away from the sun they consist of the loosely amalgamated particles in the frozen ice. Possibly in the farthest reaches of the solar system they pick up additional matter by collision with particles and gaseous clouds. As they approach quite close to the sun, the sun's heat melts the ice and soon it evaporates; vapors are emitted in a very irregular process. Presumably the emitted vapors and particles make up the coma and tails of these comets. The reason why the tails are always away from the sun is not completely understood, but is due probably to a combination of light pressure, the collision of the tail particles with particle emanations from the sun, as well as electromagnetic forces.

Meteors

There are many solid bodies in the solar system which are much smaller than the comets and asteroids. In fact, many of the small particles which make up comets are in the class of these smaller bodies. When these particles hit the atmosphere they form the typical meteor trail. Possibly a billion meteors strike the earth's atmosphere each day; most of them are small specks of material which burn up in the air rapidly and are not visible. A very small number are large enough to penetrate the atmosphere and hit the earth somewhere. Once in a great while a very large one hits the earth, causing a great deal of damage, creating a great crater, and destroying things far away from the crater by the blast caused by high-speed passage through the air. The speed of these meteors varies a great deal, the average being 30 miles per second. Most of them vaporize completely while up in the atmosphere near the ionosphere, some 40 to 60 miles above the earth. The incandescent gas in the trail of the meteor is often spectacularly visible.

Many meteors are independent of meteor showers, but a large number of them are associated with showers which in turn are associated with comet orbits. Apparently the meteors associated with comet orbits are the loose solid particles which have been separated from the comet. Some comets which have completely disappeared still have associated with their orbits a number of particles which, when the earth's orbit crosses that of the comet, creates a meteor shower. A very spectacular meteor shower occurred in 1833, the Leonid. It was also spectacular in 1866, but in 1899, the next time that the orbit of the earth crossed the orbit of the comet in a position where many particles normally were, the showers seemed to have been deflected by the gravitational pull of other planets. There are other well known meteor showers, the Perseids, the Lyrids, the Andromedes, and others.

Interplanetary Dust

There is a great deal of material in the solar system which is best described as interplanetary dust. This can be observed by spectroscopic and optical observation. It creates a very faint glow in the night sky and is particularly concentrated in the plane of the ecliptic. It is thought that much of this dust, possibly supplied from the outer regions of the solar system and carried in by comets, is falling in toward the sun.

Life in the Solar System

Throughout history there has been great hope of finding life within the solar system on planets other than earth. In ancient days the gods were thought to live on the planets. Great men dreamed and wrote of civilizations on the planets and stars. Even as late as 1877 when Schiaparelli discovered the canals, the straight-line markings, on the face of Mars, there was a flurry of excitement which lasted for decades over the possibility of finding intelligent life on Mars.

Today we are much less expectant. The conditions which we know from observations to exist on the various planets leads us to expect that intelligent life does not exist on other planets. Possibly on Mars there is a very simple plant life. Other than that, conditions are not very good. With respect to space travel, this is one of our greatest disappointments, because the possibility of meeting other forms of animal life would be a tremendous spur to the imagination, and a driving force to achieve manned space flight quickly.

The Universe

The universe stretches far beyond the solar system. Our sun is out toward the rim of an average spiral nebula, the Milky Way, which is made up of possibly 100 billion stars and great dark clouds of interstellar dust and gas. We are about 26 thousand light years (a light year is about 6×10^{12} miles) from the center, and we will rotate about it in 200 million years. The whole diameter of the Milky Way is from 100 thousand to 300 thousand light years and it is 25 thousand to 40 thousand light years thick.

Beyond our galaxy there are countless galaxies and clusters of galaxies stretching out at least to the limit of vision with the largest telescope, about two billion light years.

When one considers that we are now straining to get our space vehicles out a few hundred miles from the earth, it becomes clear that mankind will not soon run out of incentive. In fact, to travel to the nearest star is a job far beyond our current capability. That star, Proxima Centauri, is about four and one third light years away. The current obstacle to man's travel to such a distance seems to be a limited life span and the limiting speed of travel, the velocity of light. There are some practical rocket motor problems, as well as the problem of storing sufficient energy per unit mass of fuel to attain anywhere near the velocity of light. Perhaps when we achieve nuclear reactions which result in 100 per cent conversion of fuel mass into energy, instead of the one per cent efficiency of the fusion process and the 0.1 per cent efficiency of the fission process, our prospects for travel to the nearest stars will be sufficiently improved for a try.

In the meantime here within the solar system there is first the challenge to learn more about it by scientific and manned exploration. Not far behind such a challenge comes that of putting our space capabilities to use. Along this line the only nonmilitary proposal which so far has evinced considerable interest is that of establishing communication relay stations on satellites. Fortunately this practical application is attainable with relative ease.

Beyond the scientific, military and simple nonmilitary applications of our space travel capability, most of us are confident that as we further the development of the capabilities we inherited from past generations of science and technology, there will unfold many practical uses which we can will to the future.

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Some Aspects of Astronautics*

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EDITED BY P. SWERLING†

Summary—This paper is mainly concerned with four general topics of importance in astronautics:

1) Basic laws of celestial mechanics. The subjects covered are: Kepler's laws and their Newtonian redevelopment, the orbital elements, and perturbations.

2) Lunar and interplanetary flights. A typical earth-moon transit trajectory, computed by automatic machine, is discussed. Guidance accuracies required for lunar impact are illustrated. Circumlunar flights, lunar satellites, and interplanetary flights are also briefly discussed.

3) The space environment. Among the subjects covered are: the distribution and characteristics of dust and meteoric material in the solar system; asteroids; comets; molecular, atomic, and subatomic particles in space; the possible lunar atmosphere and ionosphere; extraterrestrial radio noise; and the magnetic fields of the earth and sun.

4) Scientific experimentation in space. Useful subjects for experimentation are: refinement of our knowledge of basic constants such as the value of the astronomical unit; observation of the atmospheric and surface conditions of the moon and of our neighbor planets; increased observation of matter and radiation in space.

INTRODUCTION

THOSE who first venture into space will, unlike earlier navigators pushing across unexplored seas, find that much of the region to be traversed has already been charted and something of the character of both space itself and potential destinations in space is known. But there is always the difference between indirect knowledge and first-hand experience, and this difference undoubtedly will show up trenchantly on the first flights into space.

Before entering into details, a few important basic differences between space environment and terrestrial environment should be mentioned and kept in mind in our discussions of space. First, the configurations of bodies in space are never static; relative distances are always changing. Second, the description of the solar system in terms of distances alone is inadequate. The astronaut must think also in terms of all the orbital elements: the eccentricities, the inclinations, the nodes, the epochs, and the perihelions as well as the semimajor axes. The third general difference is the relation between energy expended and distance traversed. In space this will be completely unlike anything in terrestrial experience. Fourth is the matter of the scale of space. It is always most difficult to visualize the tremendous distances involved. A fifth difference is that space travel will be performed in vehicles which are intermediate in size between the small particles in free space and the massive planets. While the motions of the latter are influenced only by gravitational forces (Newtonian and relativistic), the small particles are, in addition, subject to magnetic, electrical, and radiation forces. It is to be expected that future space ships will, as intermediate-sized bodies, experience to some extent the effects of all of these forces.

There are many possible ways to classify space-flight activities, such as powered and ballistic, manned and unmanned, scientific and military, etc. One of the most useful of these ways is to order space flights by flight mission.

The main categories of activities of general interest are earth satellites, lunar flights, and interplanetary flights. Let us first consider the gross dimensions of these flight classes.

In the case of satellites the distance parameter of interest is orbit altitude. This can range from about 100 miles to about 1,000,000 miles. Beyond about 1,000,000 miles from the earth, the sun's field will disturb the vehicle to such an extent that the term "earth satellite" tends to lose its meaning. The time parameter of interest is orbit period; this will range from about $1\frac{1}{2}$ hours to about 8 months.

Lunar flight distances are, of course, roughly the distances from earth to moon—about 240,000 miles. Flight times will range generally from about one day to one month or more.

The interplanetary theater starts at a distance from the earth of about 1,000,000 miles and extends to the orbit of Pluto, nearly 5,000,000,000 miles at maximum displacement. Flight times would fall roughly in the range of one month to 50 years.

In the category of satellites we have two principal types: nonrecoverable satellites, and recoverable satellites.

The nonrecoverable earth satellite is now a familiar system. Its feasibility has been established beyond any reasonable doubt.

The recoverable satellite is so contrived that all or part of the satellite is perturbed by an on-board rocket so that it returns to the surface of the earth.

The lunar flight category can be broken down into the following principal missions:

1) Impacts on the moon.
2) Nondestructive landings on the moon.
3) Artificial satellites of the moon.
4) Circumlunar flights.

Interplanetary flight would, in turn, involve execution of the following:

1) Impact on the planetary surface. (Impact here has its usual meaning—a destructive collision.)
2) Land intact on the planetary surface.

* Manuscript received by the PGMIL, July 23, 1958.
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3) Set up an artificial satellite of the planet
4) Orbit around the planet and return to earth.
5) Set up interplanetary space buoys.

Basic Laws of Celestial Mechanics

Celestial mechanics, which is the basis for the determination of orbits or trajectories in space, is usually thought of as beginning with the publication of the "De Revolutionibus," by Copernicus, in 1543, although the subject has important roots nearly two thousand years before this date.

A second major step was made by Kepler in his discovery of the laws of planetary motion (see Fig. 1):

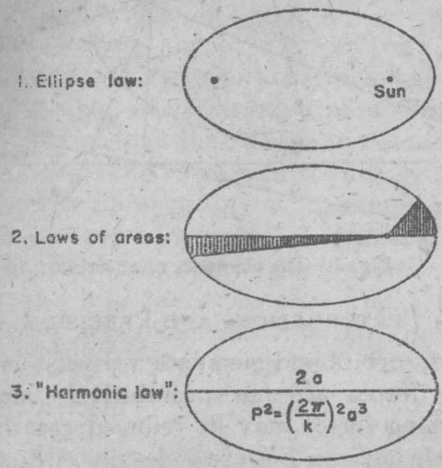

Fig. 1—Kepler's laws.

1) The orbits of the planets are ellipses with the sun at one focus.
2) The line joining the planet to the sun sweeps over equal areas in equal intervals of time.
3) The square of the period (P) of a planet is proportional to the cube of its mean distance (a).

In Kepler's third law the period, usually designated by P, is the length of time it takes the planet, comet, or today, satellite, to travel around its orbit. The mean distance, a, is sometimes called the semimajor axis (see Fig. 1) and is in fact the average of the greatest and least distances, the perihelion and the aphelion distances in heliocentric orbits, or the perigee and apogee distances in geocentric orbits.

With his law of universal gravitation and his laws of motion, Newton was able to rederive the Keplerian laws of planetary motion. In doing so he found it necessary to modify them in significant ways.

1) Kepler's laws define the motion of a planet exactly only if it is alone with its sun in the universe. Every other object in the universe will disturb the simple Keplerian motion, producing what we call perturbations. In Fig. 2 we see the effect of an extremely large perturbation. A comet or minor planet is traveling around the sun in Keplerian orbit A. One time, when it is crossing the orbit of Jupiter, it finds Jupiter nearby, at J. Jupiter's attraction is momentarily very large, causing the disturbed object to be hurled off toward the sun in a new direction. After it is safely past Jupiter the sun's attraction again becomes predominant, and the object thereafter travels in orbit B. Of course the attraction of Jupiter is never negligible, and so is progressively changing the orbit, though more gradually than in the illustration.

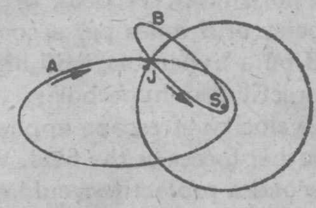

Fig. 2—Perturbations.

2) Newton showed also that Kepler's laws would be exact for a two-body system only if the two bodies were homogeneous in spherical concentric layers. Because of its rotation, the earth is not perfectly spherical, but bulges out at the equator. The bulge will introduce perturbative forces on the moon or an artificial satellite. These cannot be resolved into a single force acting from the center of the earth. The bulge perturbations of the orbit of an artificial satellite are much larger than those caused by the sun or the moon.

Other forces that may be treated as perturbations, when they are not too large, include thrust, drag, and other aerodynamic forces, and possibly electromagnetic forces, radiation pressure, and the modifications introduced into the gravitational field by Einstein mechanics.

3) Kepler's laws, in Newton's redevelopment, emerge as integrals of the two-body problem. There are many other useful integrals, of course, and at least one of them has such a simple form as to be especially useful in the solution or interpretation of orbit problems. It is the *vis-viva*, or energy integral, which expresses the fact that the sum of the kinetic and potential energies is constant:

$$V^2 = k(m_1 + m_2)\left(\frac{2}{r} - \frac{1}{a}\right).$$

In this equation, k is the gravitational constant, m_1 and m_2 are the masses of the two bodies, a is the semimajor axis, V is the velocity, and r is the distance from the focus.

4) Newton found that in the two-body problem the ellipse was not the only possible orbit. Parabolas and hyperbolas were also possible orbits. The addition of parabolas made it possible for Newton to show that the comets, which travel in nearly parabolic orbits, obey the same laws as the planets.

For illustration, let us suppose that a circle is the orbit of a satellite somewhat above the surface of the earth, with a velocity just under 5 miles per second. If the velocity were cut to 3 miles per second, the satellite would fall inward on a smaller ellipse until it encountered the surface of the earth. Conversely, if we increased the velocity of our projectile to 6 miles per second, we would find that it would rise up on a larger ellipse. If next we think of the velocity as increased to 7 miles per second along the same horizontal tangent, we find that the object will travel off on a parabola, never slowing down enough to return. This critical velocity, approximately 7 miles per second, is called the "velocity of escape." It is the same whether the direction of projection is horizontal, vertical, or some angle in between. A velocity of 8 miles per second would carry the projectile off on a hyperbola; still higher velocities, on more nearly rectilinear hyperbolas.

The so-called velocity of escape applies strictly only if we neglect all other forces in the field. With a velocity of 7 miles per second a projectile would escape, at least temporarily, from the earth, but not from the sun. As it receded from the earth, in any direction, its velocity would quickly drop off nearly to zero. But with its geocentric velocity nearly zero, its heliocentric velocity would be nearly the same as that of the earth, *i.e.*, $18\frac{1}{2}$ miles per second in a direction approximately at right angles to the direction of the sun. And so the escaped vehicle would take up a nearly circular orbit around the sun closely approximating that of the earth.

The Orbital Elements

A two-body orbit, as illustrated in Fig. 3, is specified by six constants, called the "elements" of the orbit. Three of these elements have to do with the orientation of the orbit in space, and require that we specify arbitrarily a reference plane, and in that plane a reference direction. For geocentric orbits we use the plane of the earth's equator and the direction of the vernal equinox. (For heliocentric orbits the reference plane is usually the ecliptic plane, *i.e.*, the plane of the earth's orbit.) The intersection of the orbit plane and the equator plane, in the geocentric case, is called the line of nodes. The ascending node is the point at which the object passes from the south side to the north side of the equator, and the descending node is the point at which it passes from north to south. Three angles that may be used for orientation elements are, then:

Ω = the longitude of the node, or the angle between the directions of the vernal equinox and the ascending node,

i = the inclination, or the angle between the two planes,

ω = the argument of perigee, or the angle in the orbit plane between the direction of the ascending node and the direction of perigee.

The remaining elements specify the size and shape of the orbit and the time at which the orbit is at some specified point. These may be:

a = the mean distance or semimajor axis.

e = the eccentricity, which may be defined as the distance from the center of the ellipse divided by the semimajor axis.

T = the time of perigee passage.

These six constants often are replaced by others in part or altogether. For example, orientation unit vectors, ***P***, directed to perigee, ***Q***, parallel to velocity vector at perigee, and ***W***, perpendicular to the orbit plane and making up a right-handed system with ***P*** and ***Q***, often are used as orientation elements in place of Ω, i, ω.

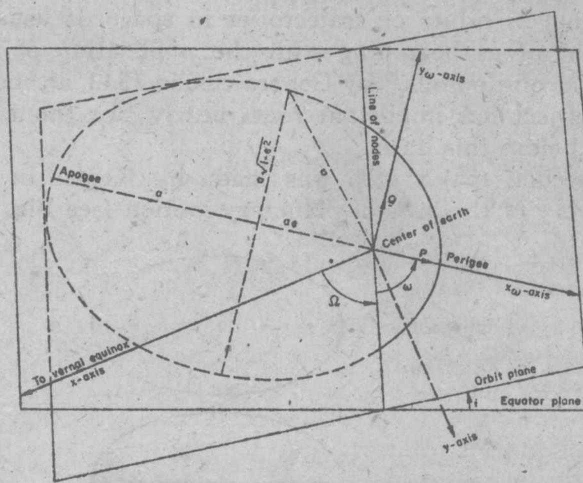

Fig. 3—The elements of an orbit.

Perturbations and Precision

Two-body orbits and elements are very useful if the perturbing forces are not prohibitively large. Often the perturbing forces may be reduced greatly by relatively simple devices. For example, the attraction of the sun on the moon is approximately twice that of the earth. If the earth and the moon were stationary, the sun would quickly pull the moon away from us. But most of the sun's attraction is used up in pulling the moon into approximately the same curvilinear orbit as that of the earth. What is left over is only about 1/100 of the earth's attraction. Consequently, as the first approximation, the moon's orbit around the earth is approximately a Keplerian ellipse. A perturbation as large as 1/100th of the primary acceleration, however, is extremely large, and the accurate determination of the moon's orbit is a very complicated matter.

Two well-known perturbations of satellite orbits due to an equatorial bulge of the central body are 1) regression of the nodes, and 2) advance of the perigee. That is, the nodes gradually move in a direction opposite to that of the orbital motion, while the perigee gradually moves in the same direction as the orbital motion. Perturbations due to drag cause a gradual decrease in the eccentricity and semimajor axis of an orbit. In many cases, the magnitude of these "secular" perturbations can be calculated to a good degree of approximation.

There are several different methods for handling perturbations. In one of them we make no reference whatsoever to auxiliary ellipses, but simply integrate the total acceleration, in order to follow the path. This process, used with numerical integration, is called Cowell's method. It has been used in lunar trajectory work almost exclusively. A second way to handle perturbations is to calculate from the position and velocity at any point in the actual path the elliptic orbit that would be followed if at that point all perturbations were suddenly to cease. The differences between the actual accelerations and the "two-body accelerations" in this "osculating" ellipse are then integrated to find a correction to a position in the two-body orbit that will give the position in the actual orbit. When numerical integration is used, this method is referred to as Encke's method. It is especially effective when the perturbations are small. After a time, however, the perturbations are likely to build up to such a point that a new osculating reference orbit must be determined from integrated position and velocity.

Instead of making abrupt changes from one reference orbit to another, we can make the changes gradually by the method of variation of parameters. In this method the parameters that define the osculating two-body orbit are allowed to vary progressively so that the osculating orbit will always give the same position and velocity as the two-body orbit. The effect will be to cause one of the osculating ellipses gradually to change until it merges into the other one. The variations of the parameters are determined directly from the perturbations and may be integrated numerically, or, alternatively, by series expansions.

When the perturbations are very large, neither Encke's method nor the method of variation of parameters offers any advantage over Cowell's method, and the last should be used because it requires less calculation. When the perturbations are small, however, and especially when the two-body motion is very rapid, Cowell's method is disadvantageous and may even be incapable of handling the problem.

When perturbations are handled by numerical integration, the process is called special perturbations. When the perturbations are represented by series and integrated term by term, the process is referred to as general perturbations. Today we refer to such series as "Fourier series." Actually the process antedates Fourier by more than two thousand years. In the Ptolemaic system the complex motions of the planets were represented by systems of circles that were equivalent to Fourier series.

It is desirable, at this point, to distinguish clearly between two kinds of trajectory work: "preliminary (or feasibility) trajectories" and "precision trajectories." By preliminary trajectories, we mean qualitative trajectories that are useful in preliminary studies, in which only rough estimates of the amount of fuel, the duration of flight, required guidance tolerances, or similar questions are desired. Precision trajectories, on the other hand, are necessary for accurate space navigation.

The lunar flight trajectory illustrates one of the important distinctions between preliminary and precision work. In preliminary studies of lunar and circumlunar trajectories it is possible to suppose that the moon is moving with uniform velocity in a perfect circle, or that it is a fixed point in a rotating framework. In precision work, however, the rotating framework ceases to be useful. In fact there are no simple mathematical expressions that will represent the moon's position for more than a very brief interval. We must turn to tables of the moon's position, such as those given in the various national ephemerides or almanacs.

Another important consideration in precision orbit work is the following. At the present time refined values of the basic constants are definitely required before an interplanetary ballistic flight to intersect another planet could be successful. This may seem odd, since centuries of astronomical observations have contributed to plotting the elements of the orbits of planets and satellites to six-place accuracy or better, and to determining the mutual perturbations of these orbits caused by the several bodies in the solar system. However, one dominant factor makes these elements unsuitable for successful planet-to-planet navigation. This factor is that while planetary orbital dimensions are known to six-place accuracy or better when expressed in terms of the astronomical unit (the semimajor axis of the earth's orbit), the astronomical unit (au) itself is known to only about one part in 1500 when expressed in terms of meters or feet, the units in which flight design must be made. (Specifically, 1.495×10^{8} km $\leqq 1$ au $\leqq 1.496\times10^{8}$ km.)

As a simple example of the effect of this uncertainty in the scale of the solar system on a problem in space navigation, consider the trip from the Earth to Venus along a minimum-energy orbit. Making several simplifying assumptions regarding the eccentricities and inclinations of the orbits of the Earth and Venus, we find that the uncertainty in the semimajor axis of the minimum-energy orbit would be about 172,000 km or 15 diameters of Venus; and this neglects the timing error introduced. One of the first tasks of a flight into interplanetary space should be the measurement of the fundamental astronomical unit of distance in terms of laboratory standards of length. Another basic constant, the gravitational constant, is known to only about three significant figures when expressed in the cgs system or any other laboratory system of units.

Lunar and Interplanetary Flights

A typical preliminary ballistic earth-moon transit trajectory computed by automatic machine is shown in Fig. 4. It is plotted in rotating coordinates so arranged that the earth-moon line appears to stay fixed. This scheme shows the trajectory about as it would appear to an observer standing on the moon. This same trajectory is plotted in inertial coordinates in Fig. 5.

It can be seen in Fig. 5 that the vehicle in this particular transit trajectory will move in a counterclockwise direction in the initial phases of flight; *i.e.*, the advance of vehicle angular position will be in the same direction as the orbital motion of earth and moon. Such

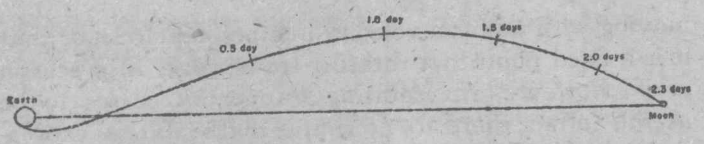

Fig. 4—Moon-rocket trajectory in rotating space.

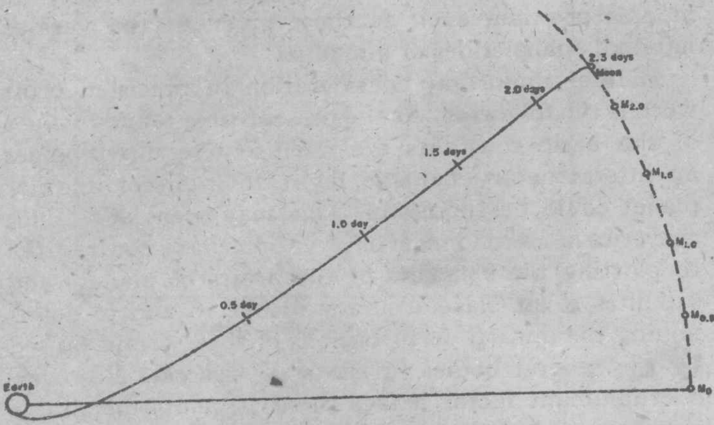

Fig. 5—Moon-rocket trajectory in inertial space.

an orbit is referred to as a direct orbit. An advantage of such an orbit is the fact that one can capitalize on the orbital motion of the earth (in earth-moon space) as well as the rotation of the earth in building up the initial velocity of the vehicle.

In Fig. 5 the attraction of the moon can be seen near the terminal end of the trajectory. The direction of approach has become almost a straight line to the moon's center.

The time required for an earth-moon passage is strongly dependent upon initial velocity. A plot of transit time as a function of initial velocity is shown in Fig. 6. The exact time-vs-velocity curve is, of course, somewhat dependent also upon the direction of projection, but the dependence is relatively slight.

This marked decrease in flight time for a moderate velocity increase in the low-speed regime suggests that the efficiency of some flight missions can be enhanced by sacrificing some payload to increase projection velocity. This would be true, for example, in missions requiring the expenditure of large amounts of electrical energy during transit, or in manned flight where the demands of nutrition and a livable environment grow with flight duration.

A lunar-impact flight consists simply of projection of a vehicle from the earth to crash on the surface of the moon unchecked. Such a flight would typically involve traversal of a trajectory, like that in Figs. 4 and 5. The speed of the body at impact, relative to the moon's surface, will be no less than lunar escape velocity, and typically would be around 10,000 feet per second. It is conceivable that some sort of instrument package could be made to survive such an impact, but the possibilities are only of a speculative sort.

A particularly interesting payload possibility for an impact flight is a source of visible light to signal arrival.

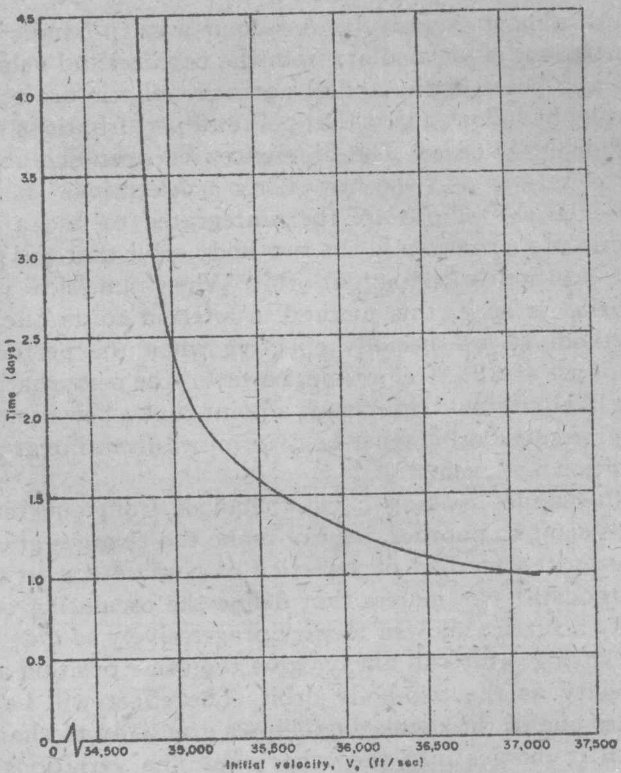

Fig. 6—Transit time from earth to moon.

It has been estimated that something like 10 pounds of flash power exploded on the dark half of the half-illuminated moon would be observable in a 21-inch reflecting telescope.

The accuracy required in the projection process to produce an impact on the visible side of the moon must be determined by trial and error, *i.e.*, simply by computing a great number of trajectories, noting locations of impacts and miss distances. The values of allowable errors in speed and direction of projection are dependent upon the speed, direction, and position at the initial point in the unpowered trajectory. A coordinate arrangement for defining projection conditions is shown in Fig. 7. Combinations of initial conditions that result in hits passing through the moon's center are shown in Fig. 8. For nominal values

$$V_e = 35{,}000 \text{ feet per second}$$
$$\gamma = 14.2 \text{ degrees}$$
$$\phi = 108 \text{ degrees}$$
$$r = 4300 \text{ statute miles,}$$

marked in Fig. 8, we find that allowable errors in speed or direction for impact on the visible face of the moon are about

$$\delta V = \pm\ 40 \text{ feet per second}$$
$$\delta\gamma = \pm\ 0.25 \text{ degree.}$$

The exact band of conditions for impact, around the nominal point selected, is shown in Fig. 9. Generally

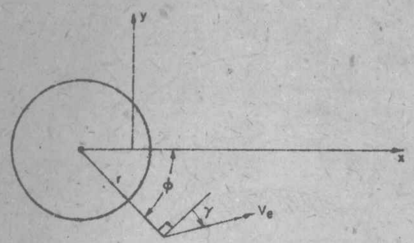

Fig. 7—Parameters used to describe initial conditions.

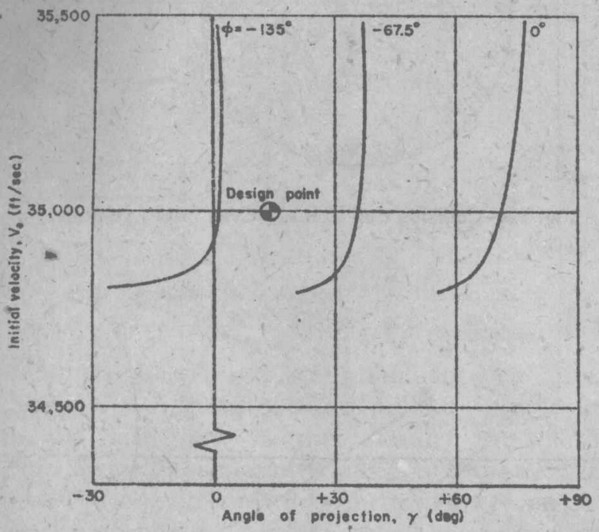

Fig. 8—Combinations of V_e and γ required to hit the moon from various initial positions.

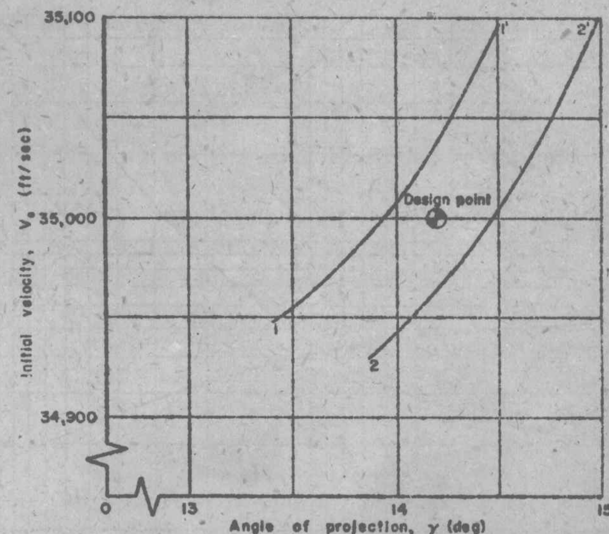

Fig. 9—Hit-band region around design point.

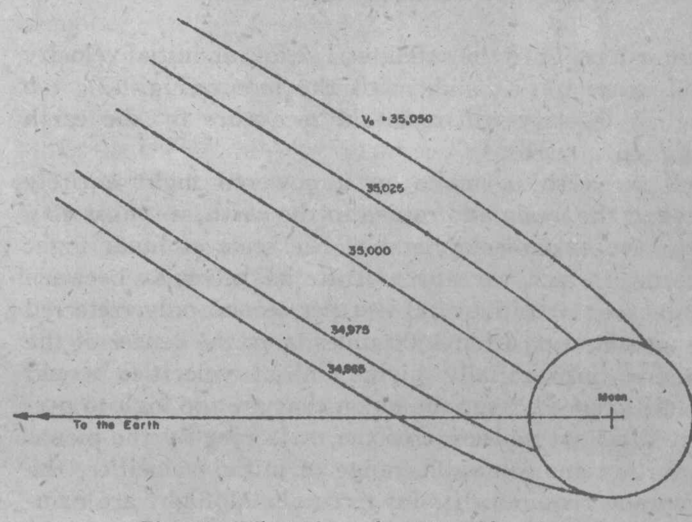

Fig. 10—Effect of varying V_e on hit point.

speaking, higher values of V_e lead to larger allowable δV, while smaller values of V_e allow greater values of $\delta\gamma$. Effects of velocity errors are illustrated in Fig. 10.

We must also recognize the existence of another kind of flight tolerance that does not figure in purely terrestrial flight activities—that of launch time. In addition to a fairly close tolerance on the instant of launch, it must be recognized that the calendar dates on which launching is feasible are dependent upon the latitude of the launch site, the range of firing azimuth available, and the inclination of the moon's orbit relative to the earth's equatorial plane. These general observations about launch-time tolerance apply more or less directly to all of the lunar flight types listed.

For most equipments, a nondestructive landing on a solid surface implies an approach to the surface at a rather low speed—a good deal less than 10,000 feet per second. Since the moon has no appreciable atmosphere, deceleration must be accomplished by rocket propulsion in the final phase of approach.

The trajectory requirements for lunar landing are essentially the same as those for impact, except perhaps for some closer specification of accuracy tolerances if a nearly perpendicular hit on the lunar surface is needed to accommodate the particular landing-gear arrangement employed. Landing does, however, involve another extension of the problem beyond the impact case. It introduces a requirement for control of the orientation of the vehicle so that the decelerating-rocket thrust is properly aligned relative to the lunar approach velocity.

Another flight mission that requires rocket deceleration at the moon, and, hence, altitude stabilization, is that of establishing an artificial satellite of the moon. For this operation we must proceed along a transit trajectory that misses the moon, to pass by it at an altitude equal to the desired satellite altitude.

The period and orbital velocity of a lunar satellite as a function of orbit altitude is shown in Fig. 11. It is seen that for reasonably close satellites, orbital velocity falls in the vicinity of 5000 feet per second. Since the velocity of the vehicle in its transit trajectory will be of the order of 10,000 feet per second near the moon, it is apparent that a velocity reduction of around 5,000 feet per second is required to set up a lunar satellite.

The projection accuracy required in this operation does not differ markedly from that required to lunar impact. The limiting accuracy requirements are derived from consideration of two possible catastrophies

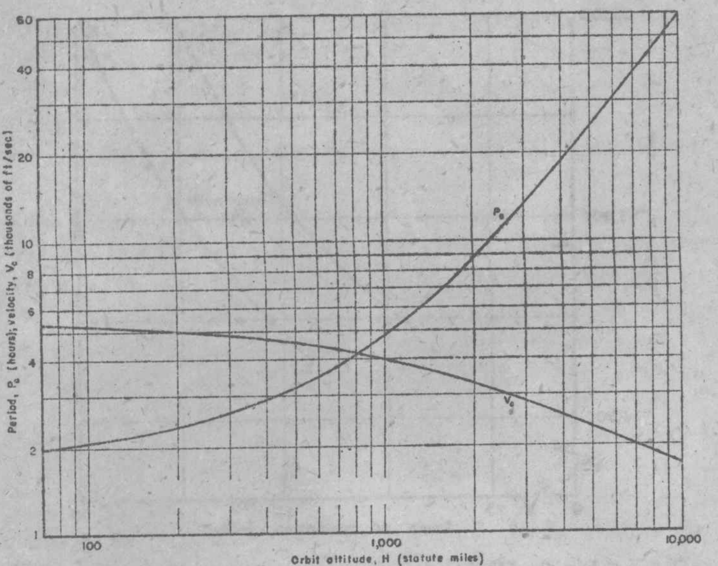

Fig. 11—Period and velocity in circular orbit.

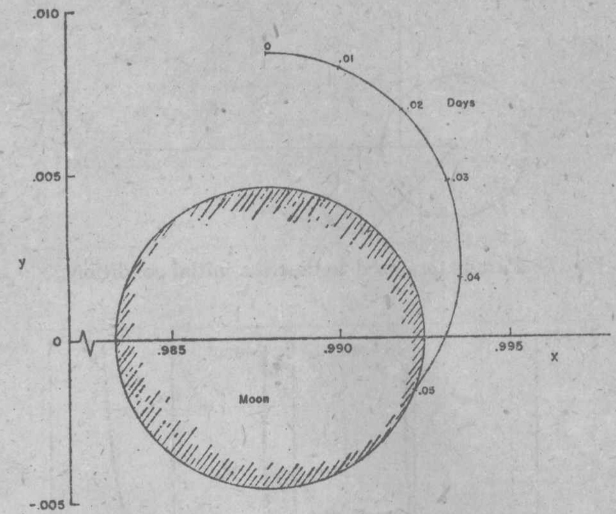

Fig. 12—Collision due to insufficient initial velocity.

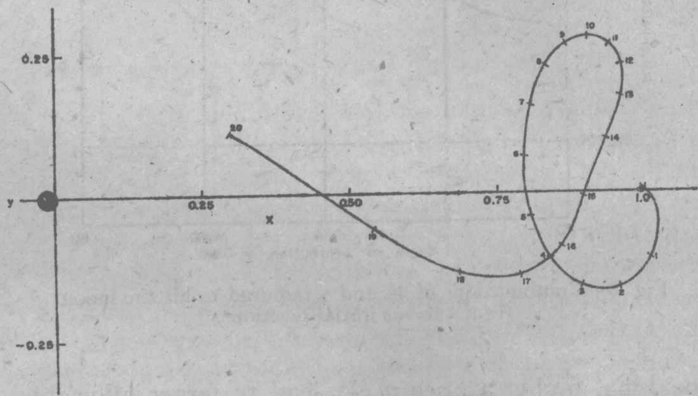

Fig. 13—Recapture of lunar satellite by the earth.

that can occur to the satellite. Too low an initial velocity will cause it to collide with the moon (Fig. 12); too high a velocity will result in recapture by the earth (Fig. 13).

If we wish to make an unpowered flight entirely around the moon and return to the earth, we must stay near the extreme low end of the scale of lunar flight speeds. In fact, we must operate in the region between about 34,800 and 35,100 feet per second only (referred to an initial position 4300 miles from the center of the earth). Substantially higher initial velocities would result in speeds near the moon that are too high to permit sufficient deflection of the trajectory by the moon.

Within the allowable range of initial velocities, the accuracy requirements for circumlunar flight are comparatively modest if all we ask is return to the earth: typically ± 75 feet per second in velocity or ± 5 degrees in direction. These large tolerances are, however, associated with fairly large variations in the distance of closest approach to the moon and in total flight time. A variation of 10 feet per second in initial velocity would change the distance of closest approach by about 1000 miles and the total flight time by about 25 hours. Because of this sensitivity of flight time to initial velocity, the velocity would have to be controlled to within about ± 0.5 foot per second if a returning circumlunar vehicle were to be recovered within the continental United States. These values of sensitivity apply to a trajectory with an initial velocity of about 34,900 feet per second which passes the moon at a nearest approach distance of about 4000 miles. The sensitivities for other trajectories could differ from these by as much as an order of magnitude depending upon the exact values of the initial conditions.

There are five special points in earth-moon space, called "libration centers," at which a vehicle might "float at anchor" as a sort of space buoy. The arrangement of these points in the (x, y) plane is shown in Fig. 14. Approximate solutions to the equations of motion can be developed in the neighborhoods of these centers of libration.

We find from this solution that the motion near the straight-line centers of libration (I, II, and III) is unstable; because of the presence of the hyperbolic functions, a particle initially near a center of libration will eventually move indefinitely far away.

For the equilateral-triangle points only oscillatory terms appear in the solution to the equations of motion, so it would seem that we could establish space buoys at the triangle points that would stay at anchor in earth-moon space for an indefinite period, until displaced by external disturbances.

In treating lunar flight, we have been concerned with a space environment dominated by the fields of two massive bodies—the earth and the moon—revolving in circles about their common center of mass. When we consider interplanetary flight, the main features of the problem are determined by a similar kind of flight environment. The difference is that the interplanetary flight has more major phases.

Let us run through these phases in a flight, say, from earth to Mars. The first phase takes place in earth-moon space. This phase soon blends into the second

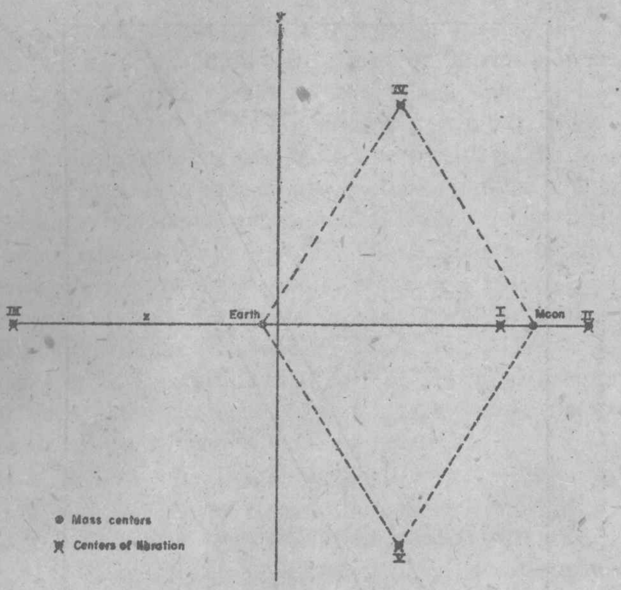

Fig. 14—Relative positions of libration centers.

phase, where the main sources of influence are the earth and sun. At a distance of a few million miles from the earth, the third phase begins, in which the sole influence of substantial consequence is due to the sun. As we approach Mars, we enter the fourth flight phase, where the bodies of chief concern are Mars and the sun. In the terminal, or fifth phase very near Mars, only the field of Mars itself is important.

The computation of an interplanetary flight trajectory is very complex, because of the multiplicity of flight phases with the attendant requirements for changing reference frames, equations of motion, accuracy scales, etc. However, the major characteristics of an interplanetary trajectory can be summarized as follows. The initial leg of the trajectory (phase one) approximates a hyperbola with focus at the earth's center; this leg (through phase two) blends into a large ellipse with focus at the sun's center (phase three); near the end (through phase four) this ellipse blends into a hyperbola with focus at the center of the target planet (phase five).

Landing on Mercury would be similar to landing on the moon; there is no atmosphere, so deceleration must be accomplished by rocket. Landings on Venus, Mars, or the earth can make use of aerodynamic drag for deceleration. Landings in the usual sense are not likely on the other planets, since they do not have (or probably do not have) clearly defined solid surfaces.

Establishment of an artificial satellite of another planet involves the same possible sources of failure as establishment of a lunar satellite—too little velocity will result in collision with the planet; too much will lead to capture by the sun. A round trip around, say, Mars with subsequent return to the earth is possible by proper trajectory arrangements.

Libration centers in interplanetary space are produced by the fields of the sun and a planet, just as they are produced in earth-moon space by the fields of the earth and moon. Thus we should also be able to establish interplanetary space buoys. In fact such buoys already exist in natural form as the Trojan asteroids (see below) at the equilateral-triangle points relative to the sun and Jupiter.

For all of these interplanetary missions the guidance accuracy requirements are far more stringent than for analogous lunar missions. Representative velocity tolerances are on the order of 0.1 foot per second.

Another type of interplanetary mission is that of establishing an artificial asteroid (artificial solar satellite).

The Space Environment

One of the most important aspects of the space environment deals with the material content of space. Let us first consider bodies in the range from cosmic dust to chunks of rock (*i.e.*, say 20 microns to a few meters) commonly called meteoroids. Fig. 15, based upon the observational and theoretical results of the Harvard Meteor Program, gives the mass and size of meteoric particles as functions of the visual magnitude. Fig. 16 indicates the number of such meteoroids striking the earth per day, and the number striking a 3-meter sphere in the neighborhood of the earth per day.

It is estimated by Whipple that a meteoroid of magnitude 17, moving with a velocity of 18 km/second, of which about two per day will strike a 3-meter sphere, will penetrate an aluminum skin of 0.01 cm; whereas a meteoroid of magnitude 5, one of which will strike the sphere every hundred years, would penetrate 4.5 cm. of aluminum. About every 50 days a particle capable of penetrating 0.5 cm of aluminum would hit the sphere.

But the probability of striking meteoroids depends upon where the vehicle is in space. Fig. 16 applies to the immediate neighborhoood of the earth. At greater distances good data are lacking. What is known, however, is that 1) the smallest dust particles (micrometeoroids) are concentrated in the ecliptic or plane of the earth's orbit, and 2) most meteoritic material is cometary refuse and is consequently largely distributed along the orbits of comets.

Let us review some of the evidence for the ecliptic concentration of cosmic dust. After evening twilight, especially near March 21 in northern latitudes, a faint tapered band of light can be seen extending up from the horizon centered along the ecliptic. This band of light, which can be photoelectrically traced through the complete night sky, is called the zodiacal light. The color of the zodiacal light is nearly the same as that of the sun, but shows approximately 20 per cent polarization. These observational facts suggest that the zodiacal light is caused for the most part by sunlight scattered from small dust or meteoroidal particles at least 20 microns in diameter. Since light scattered by free electrons is strongly polarized, it is probable that free electrons represent a fraction of the particles present. This

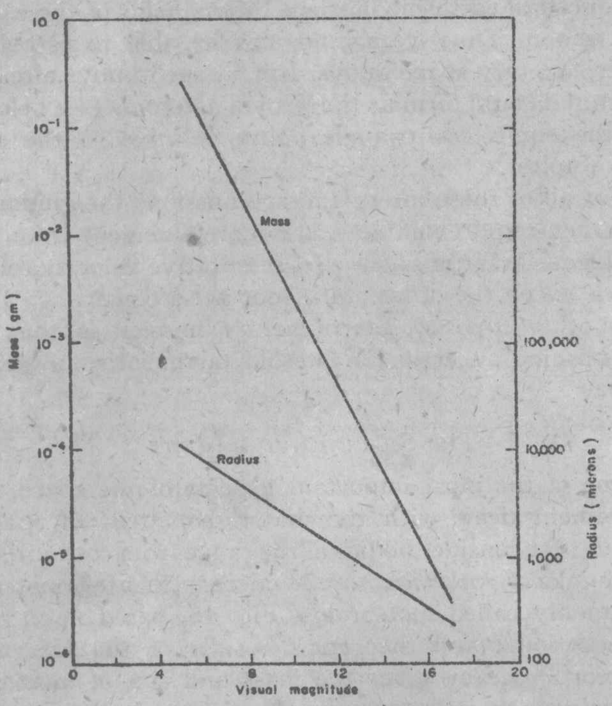

Fig. 15—Meteor brightness vs size.

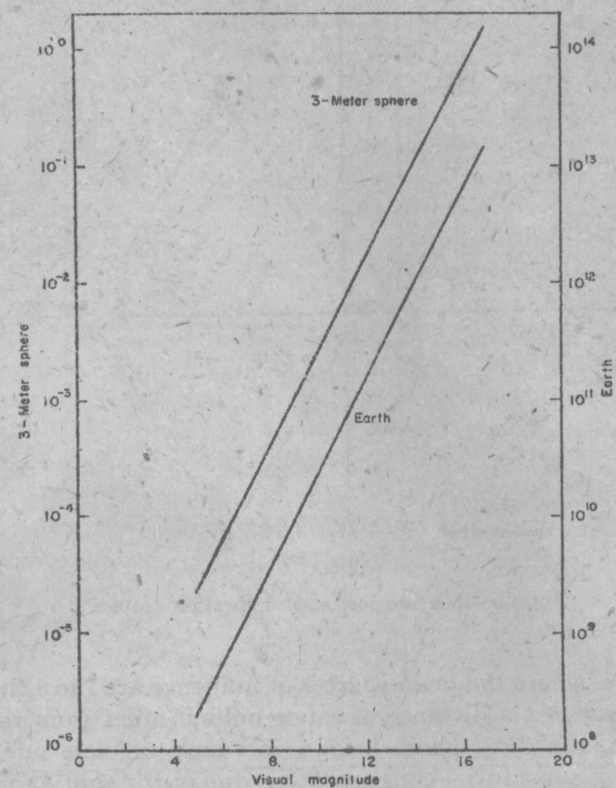

Fig. 16—Meteor impacts per day.

is also substantiated by the fact that the total light present seems to vary with solar activity, being least when ionizing radiations from the sun are at a minimum. However, since scattering by gas atoms and molecules alters the color of the light, it must be concluded that the zodiacal particles (except for the free electrons) are much larger than molecules.

It has been suggested that the zodiacal light is an extension of the outer solar corona. This idea is reinforced by the fact that the corona has a color and continuous spectrum agreeing with the zodiacal light. But most interesting is the comparison of the brightnesses, as shown in Fig. 17.

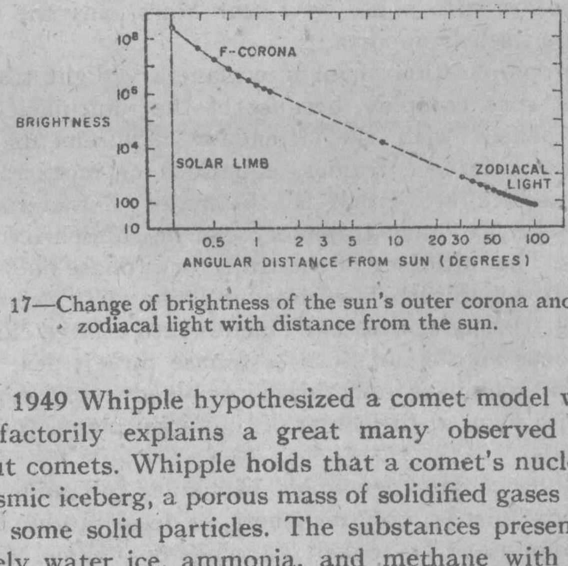

Fig. 17—Change of brightness of the sun's outer corona and the zodiacal light with distance from the sun.

This layer of small meteoroidal particles must extend from the sun well beyond the orbit of the earth, being concentrated toward the ecliptic or fundamental plane of the solar system.

The major concentration of the smallest meteoric material (producing no visual effects when striking the earth) is in the ecliptic, but other oncentrations are intimately associated with comets and other bodies. The visible meteors, or shooting stars, are of two types—those associated with showers and those which are sporadic. The shower meteors are of cometary origin; the sporadics are proably traceable to asteroids.

Let us review a few facts concerning comets and meteor showers. No accurate masses of comets have been determined, since they are not massive enough to exert any measurable perturbative forces on other bodies. But it is estimated that typical masses are of the order of 10^{12} tons (earth = approximately 10^{21} tons), and the densities are such that in a thousand cubic miles of a comet's tail there is less matter than in a cubic inch of air.

In 1949 Whipple hypothesized a comet model which satisfactorily explains a great many observed facts about comets. Whipple holds that a comet's nucleus is a cosmic iceberg, a porous mass of solidified gases or ice plus some solid particles. The substances present are largely water ice, ammonia, and methane with some carbon dioxide and cyanagen.

But what is of special interest is that on each trip near the sun, the comet is partially disintegrated and leaves a "wake" of small solid particles and ices. So the regions of space where an astronaut is likely to find higher than average densities of meteoric material are along the orbit of comets, either "live" comets or old disintegrated comets.

Whenever the earth passes through one of these cometary wakes, a meteor shower results. Hundreds of shooting stars are observed to emerge from a small area of the sky called the radiant, the direction being determined by the orbit of the comet wake in space. In