New Possibilities for Solar-System Exploration

By H. J. STEWART
Jet Propulsion Laboratory

Solar electropropulsion developments and recent astrodynamic analyses raise new prospects for sending spacecraft throughout the solar system on scientific explorations

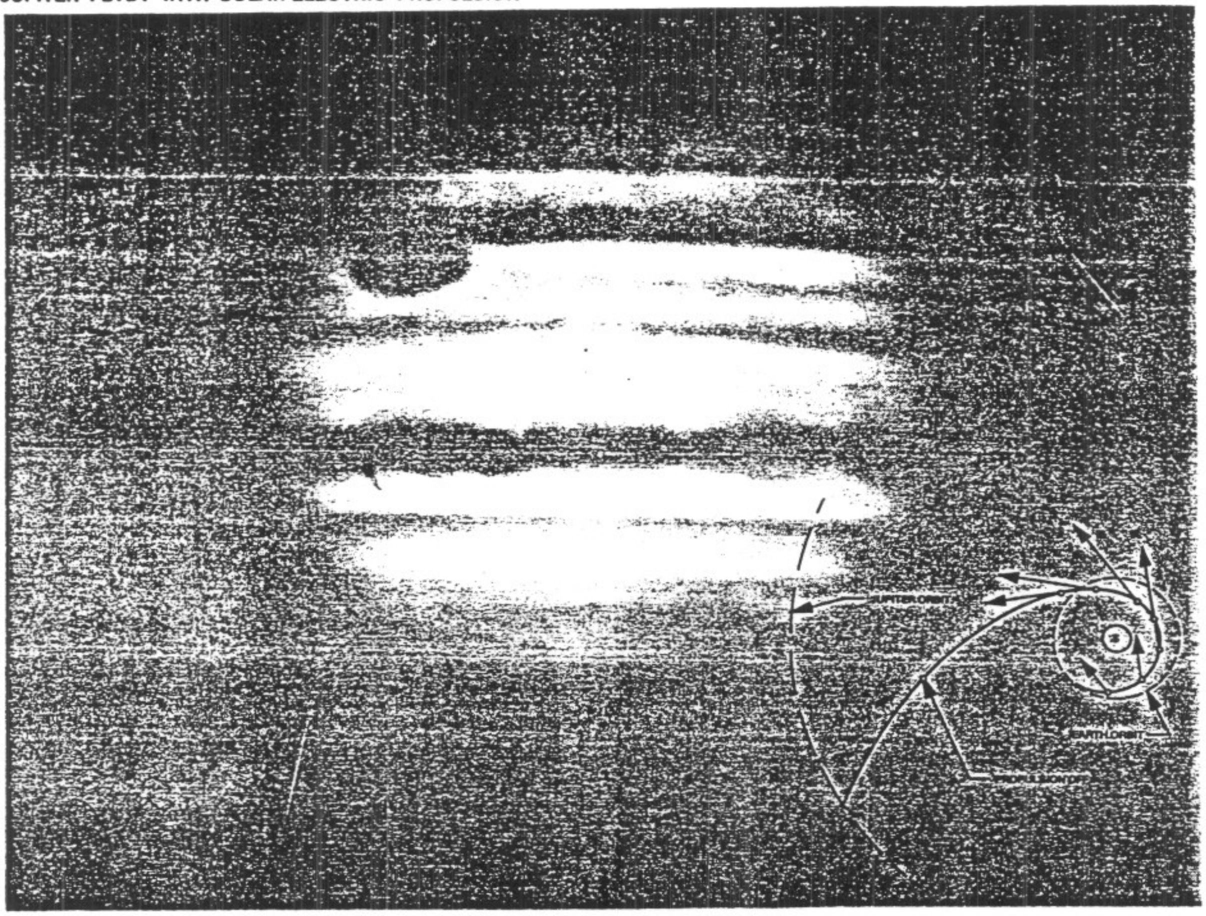
Two propulsion developments, now emerging from engineering research, may well open Jupiter and the outer planets, Mercury, regions outside the solar system, and even the Sun itself to close-up inspection during the decade of the 1970s. Of course, any of these objectives could be achieved with multistaged conventional rocket systems. However, the approximately 56,000-fps minimum "ideal" velocity requirement for a direct flight to Neptune, together with a 30-year flight-time, presents extremely formidable system and operational requirements.

The first of the two developments is the use of a planetary gravitational field in a flyby mission to change the energy and direction of the spacecraft's heliocentric trajectory to a secondary mission objective. The second is electric propulsion, with its 5000-10,000-sec specific impulse and the now-recognized possibility of efficient small systems based on solar (photo-voltaic) power.

H. J. STEWART (F) manages JPL's Advanced Studies Office and is Professor of Aeronautics at CalTech, where he has been a member of the faculty since 1938, except for a two-year leave of absence (1958-60) while he served as Director of the NASA Office of Program Planning and Evaluation. Dr. Stewart contributed to the pioneering in rocketry at CalTech and JPL in the '40s, was active in missile development in the 1950s, and participated in the Explorer I development.

The effect of a moving planetary gravitational field in changing the heliocentric trajectory of a third body has been known from the earliest days of classical astronomy. It forms the basis of the theory of perturbations of planetary orbits. The concept of using the effect to guide and propel spacecraft appears to be relatively recent. Crocco's suggestion of an orbit continuously repeating an Earth-Venus-Mars-Earth circuit was an intriguing early example.

The physical basis can readily be illustrated in the "patched-conic" approximation by considering a two-dimensional planetary flyby. Near the planet, the motion relative to the planet (if solar and other perturbations are neglected) will be a hyperbola, as shown by the sketch on page 28. At points P_1 and P_2 equidistant from the planet, the magnitudes of the relative velocities V_{R1} and V_{R2} will be equal. Adding the velocity of the planet V_P vectorially gives the heliocentric velocities V_{H1} and V_{H2}. If the outgoing asymptote is more nearly in



the direction of V_P, as the sketch indicates, the magnitude of V_{H2} will be greater than that of V_{H1}, and energy will have been added to the spacecraft. If, on the other hand, the spacecraft were to pass in front of the planet and to be deflected away from the direction of the planet's motion, the heliocentric energy would be decreased. Both the speed change and the direction change are effects equivalent to free-space propulsive maneuvers.

To date, the most dramatic example of this classical astronomical three-body effect on a spacecraft has been the perturbation of the Mariner IV trajectory in its passage by Mars in July 1965. In this case, the geometry of the planetary passage was adjusted to meet the desires of the scientific investigators. The perturbation was of no particular significance in the over-all operation; but the effect was equivalent to a free-space propulsion maneuver of over 3000 fps and resulted in sufficient energy increase to raise the perihelion distance by about 10 million mi.

Much larger effects could be achieved in a Venus flyby, partly because of that planet's greater mass and partly because of its higher orbital speed.

NON-PLANETARY SECONDARY JUPITER MISSIONS

Characteristic	Mission		
	Solar escape	Solar probe	Out-of-the ecliptic
Launching hyperbolic excess velocity, km/sec	11.0	11.0	11.0
Launch date	April 14, 1973	April 12, 1973	April 14, 1973
Closest approach to Jupiter, km	46,177	193,186	397,267
Performance	20.8 km/sec heliocentric excess velocity.	2.6-yr trip to photosphere.	1.4 AU above ecliptic with 90 deg inclination.
Primary mission's Earth-launch hyperbolic excess velocity, km/sec	33	30	44

PLANETARY SECONDARY JUPITER MISSIONS

Mission	Saturn	Uranus	Neptune	Saturn, Uranus, and Neptune (Grand Tour)
Launching hyperbolic excess velocity, km/sec	11.0	11.0	11.0	11.0
Launch date	Oct. 1, 1978	Oct. 1, 1978	Nov. 8, 1979	Oct. 7, 1978
Mission time, yr	2.8	5.9	8.1	8.9
Primary-mission minimum hyperbolic excess velocity, km/sec	10.4	11.2	11.6	—
Corresponding mission time, yr	6.0	16.0	30.7	—

The strongest effects can be achieved on a Jupiter flyby in spite of its low orbital speed; its mass (317 times that of the Earth) has such a strong gravitational field that large deflections are possible, and an energy change many times greater than that corresponding to the hyperbolic approach velocity can be obtained.

Because the effects can be so large, the analysis of possible secondary missions following a Jupiter flyby has received much attention in recent years. The table on page 27 gives a brief summary of some of the results of Minovitch,[1] who studied not only Jupiter flyby missions but also Mars, Venus, and even lunar missions. The examples chosen all use a launching from Earth with an 11.0-km/sec hyperbolic excess velocity, corresponding approximately to a 500-day Jupiter mission and a trajectory which one would probably prefer even if there was no secondary mission. Such a trajectory requires about 1 km/sec more than the minimum "ideal" velocity from the launching vehicle, but reduces the mission time by more than a year. In these circumstances the two extra stages of high-performance rockets required, if the objectives were to be obtained as primary missions, would be provided at no cost except for guidance and control by the Jupiter field.

Secondary Jupiter missions to the outer planets also appear very attractive. Flandro has computed the characteristics of the trajectories for the late 1970s.[2] Almost every year one or more interesting possibilities occur. In particular, the year 1978 offers the possibility of a "Grand Tour" of the outer planets, passing Jupiter, Saturn, Uranus, and Neptune. All planetary secondary missions terminate with conditions suitable for escape from the solar system. The table just above shows some results of Flandro's calculations. For comparison, all the examples shown have an 11.0-km/sec hyperbolic excess launching trajectory.

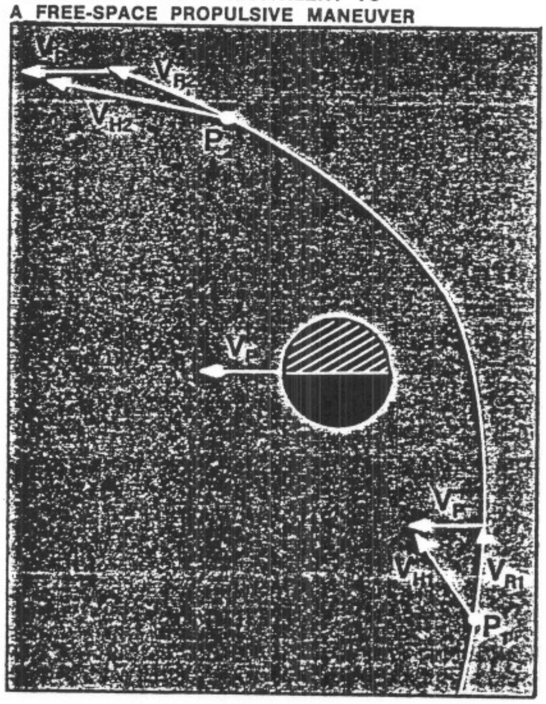
In these cases, the interesting factor is not the reduction in the required launch-vehicle performance; indeed, the 11.0-km/sec trajectory has slightly greater energy than that required for a primary mission to Saturn. The interesting factor is the drastic reduction in trip time. Even shorter trip times are possible with higher launching velocities. The management problems in organizing and carrying out a direct 30-year mission to Neptune (sheer boredom on the part of the participants) look great enough to deter even the most determined explorer. In comparison, the eight-year trip by way of Jupiter seems quite tractable, particularly since we now have had a number of spacecraft with useful life of over a year.

These examples show clearly that the three-body effects generate significant secondary mission trajectories, and others could be cited.

The question then arises, would this technique be practical from an over-all engineering standpoint? More precisely, the question is whether it is practical to solve the guidance and control problem for the heliocentric path approaching a planet so that a satisfactory approximation to desired interaction is obtained.

This question has not been examined in depth

PLANETARY FLYBY—EQUIVALENT TO A FREE-SPACE PROPULSIVE MANEUVER



for Jupiter secondary missions; but an apparently more difficult problem, concerning a Venus-Mercury mission, has been critically analyzed by Cutting and Sturms for a hypothetical flight with a 1970 launching (favorable periods occur two or three times per decade).[3] They found that Mariner-type systems—using the Deep Space Net for tracking, communications, and the basic guidance information, in association with inertial-guidance equipment in the spacecraft for controlling execution of the guidance command—provide a satisfactory solution to the Venus-Mercury problem. They found it necessary to use three midcourse maneuvers, one about a week after launching, a second a few days before Venus passage, and a third about a week after Venus passage. Midcourse corrections of this type have been carried out with the required precision many times on the Ranger, Mariner, and Surveyor flights. Cutting and Sturms showed that a total midcourse propellant allowance of about 700 fps would provide a margin of three over the expected value (based on the variance of the error parameters).

Two conclusions can be deduced from these various results. First, use of a flyby perturbation to generate a secondary mission is a practical engineering concept. Jupiter secondary missions have not yet been examined in as great detail as the Venus-Mercury mission; but qualitative considerations make it seem likely that analysis will show the Jupiter secondary mission requirements to be less rigorous. Then, it follows that it is not necessary or even desirable to develop launching systems with a capacity greater than that required to examine Jupiter in order to explore the outer reaches of the solar system in a flyby mode. It should be noted, however, that a short flight-time trajectory to Neptune, for example, either direct or by way of Jupiter, has to approach the terminal planet with a high speed. This characteristic is of relatively little importance for a flyby mission but would make planetary capture more difficult.

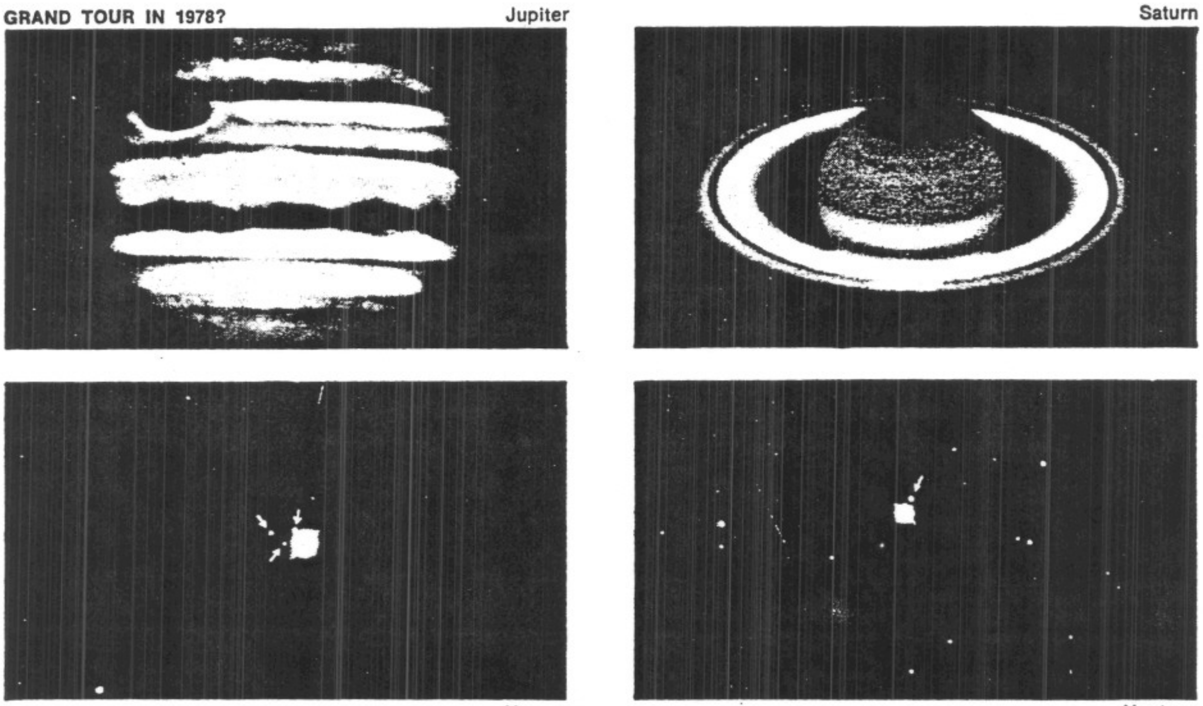
Now let us examine these same problems in terms of electric propulsion. Electric propulsion received attention initially because of the possibility of utilizing a very high specific impulse. The past decade has seen many different laboratory models of electric-propulsion systems demonstrated. Two problem areas, however, raised important questions concerning the applicability of the systems for high-energy planetary missions. First, it was apparent that very long operating periods would be essential with a high electrical efficiency. Steady progress was made toward the solution of this problem. Second, and more critical, it was apparent that very light and very long-lived power generation systems were required. The maximum weight that could be permitted and still retain a competitive advantage over chemical rocket systems was about 100 lb/kwe.

The early electric-propulsion-system studies all assumed that lightweight power-generation systems in space would be based on nuclear reactors. Theoretical analysis showed the required weight ratios to be achievable, at least for fairly large systems generating some hundreds of kilowatts. The technological problems involved, however, remained many and difficult. Consequently, al-

GRAND TOUR IN 1978?

Jupiter

Saturn



Uranus

Neptune

though steady progress has been achieved, the technology is still in the research phase.

While the nuclear-reactor work has been progressing, an alternative based on the still newer solid-state technology, has rapidly developed. When Mariner IV was designed, engineers noted that its solar panels (at a sub-kilowatt level) were generating power at a weight ratio of only a little over the critical 100 lb/kwe. It appeared likely that somewhat larger panels could be used to power scientifically useful electric-propulsion spacecraft. Accordingly, in 1964, NASA and the U.S. Air Force, with the Jet Propulsion Laboratory as an administrative agent, organized a joint research program to demonstrate the feasibility of solar-powered electric-propulsion spacecraft.

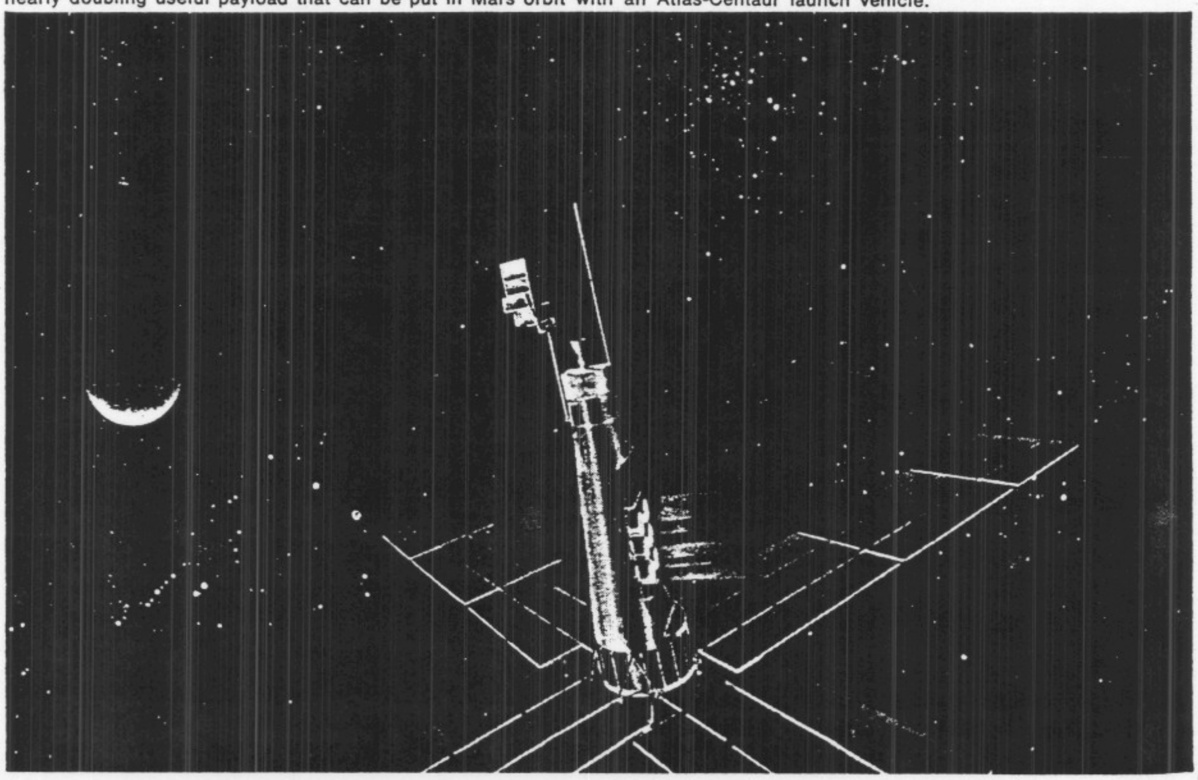
This joint program had several elements. The first element was an experimental program—carried out primarily at Electro-Optical Systems, Inc., and at Hughes Aircraft Co.—to demonstrate, by vacuum operation for extended periods, that suitable thrustors and power-conversion equipment have been developed. A second element was a design study, carried out at The Boeing Co., of the structural problems of solar panels large enough to generate from 20 to 50 kwe at the Earth's distance from the Sun. The general objective of these first two elements was to demonstrate the feasibility of electric-propulsion systems (sized to fit an Atlas-Centaur or a Saturn IB-Centaur) with a total propulsion-system weight (less propellant) of not more than 75 lb/kwe.

By the end of 1965 all of these objectives had been achieved. Several thrustors had exceeded 2000 hr of operation in a vacuum. Power-conditioning equipment approximately designed for flight environment had operated for over 500 hr in vacuum. Engineering studies showed that reasonably conservative design concepts could make solar arrays at 50 lb/kwe in units as small as 20 kw. The work is continuing. By last June, one thrustor (still under test) had already exceeded 4000 hr of vacuum operation. A contract has been initiated at Boeing to fabricate a sample solar panel to demonstrate the practicality of their design concepts.

A third element of this program has been a number of mission analyses and conceptual spacecraft design studies. These considered a Mars-orbiter mission, the simplest planetary mission for which electric propulsion shows a substantial advantage. An artist's rendition of the Hughes version of such a spacecraft,[4] sized for an Atlas-Centaur launching vehicle, appears at bottom. The mission profile was based on chemical-rocket launching to Earth-escape velocity (optimization shows that a slightly greater velocity should be reached), electric propulsion for the heliocentric arc, and chemical-rocket capture at Mars to a highly eccentric orbit.

The advantage of electric propulsion for the Mars-orbiter mission does not come primarily from the high specific impulse, although this is a significant factor, but rather from the reduction

Solar electro-propulsion spacecraft (concept shown based on Hughes Aircraft design studies) now present the prospect of nearly doubling useful payload that can be put in Mars orbit with an Atlas-Centaur launch vehicle.



in approach velocity to Mars—an effect of the low level of acceleration in the heliocentric arc. Typical results showed that an all-chemical rocket system has to allocate 60% of the spacecraft weight to propulsion for capture at Mars, but the electric-propulsion system needs only 20% for capture. The extra weight of the large solar panels should be nearly balanced by the increase in weight that can be launched and by the elimination of a separate midcourse propulsion system. Electric-propulsion spacecraft thus offer the prospect of nearly doubling the useful payload that can be put in Mars orbit.

From continuing analytical work has come some preliminary results on the application of solar-electric propulsion for a Jupiter flyby mission. Here high specific impulse represents the primary advantage. Trajectory problems have been only partially explored, but some sample solutions have been obtained to illustrate the feasibility of the concept. The drawing on page 27 shows an optimized heliocentric arc solution for launching from Earth at escape velocity.[4] Somewhat surprisingly, the initial portion of the electric-propulsion phase is used to decrease the heliocentric energy, so that, in falling in toward the Sun, a higher power level is available to produce the required energy increase for the transfer to Jupiter.

The next level of analysis, varying the initial conditions, still remains to be done. But the basic point, that a solar-electric spacecraft could fly to Jupiter, has already been established. Furthermore, it appears that even as small a launch vehicle as an Atlas-Centaur could launch a large enough spacecraft to support a scientifically significant mission. This possibility will be explored in more detail.

It is highly significant that problems no longer are centered on the feasibility of developing useful propulsion hardware. Now problems chiefly concern trajectory design, orbit determination, generating appropriate guidance information, and integrating the interests of the experimenter.

References

1. Minovitch, M. A., "Utilizing Large Planetary Perturbations for the Design of Deep-Space, Solar Probe and Out-of-Ecliptic Trajectories," Jet Propulsion Laboratory Technical Report No. 32-849, Dec. 15, 1965.

2. Flandro, G. A., "Utilization of Energy Derived from the Gravitational Field of Jupiter for Reducing Flight Time to the Outer Solar System," Jet Propulsion Laboratory Space Programs Summary No. 37-35. Vol. IV, Oct. 31, 1965.

3. Sturms, F. M. Jr. and Cutting, E., "Trajectory Analysis of a 1970 Mission to Mercury via a Close Encounter with Venus," *Journal of Spacecraft and Rockets*, Vol. 3, No. 5, page 624, May 1966.

4. Stearns, J. W. and Kerrisk, D. J., "Solar Powered Electric Propulsion Systems—Engineering and Applications," AIAA Paper No. 66-576, June 1966.

Single-copy reprints of this article may be obtained free of charge by writing on your organization's letterhead to Dept. MG, *Astronautics & Aeronautics*, 1290 Sixth Avenue, New York, N.Y. 10019. Multiple copy rates will be sent on request.