

Proceedings of the
NATIONAL ACADEMY OF SCIENCES

Volume 54 • Number 6 • December 15, 1965

*SOME NEW METHODS FOR PLANETARY EXPLORATION**

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*Presented before the Academy, October 12, 1965, by invitation of the
Committee on Arrangements for the Autumn Meeting*

For many centuries the planets of our solar system have been objects of study by astronomers. Before the invention of the telescope, these studies were restricted to an attempt to understand and predict their motion. Telescopes and accurate clocks allowed more precise observations to be made. By the 19th century, minor perturbations of the motions of the planets were being analyzed. By the end of this century, however, astronomers were becoming more interested in stellar and galactic problems, and the group interested in celestial mechanics and planetary observations appeared to be decreasing to a vanishing point in the mid-20th century. Then came the space program, and the possibility of performing experiments on, or at least near, other planets encouraged interest in the solar system to a remarkable degree.

New Tools for Planetary Investigations.—Since World War II, many devices other than rockets have extended our capability for planetary research; for example, telescopic observations have been improved by the use of better photographic film, including color film, and by various electronic instruments. Outside of the visible, more sensitive infrared detectors have become available. Spectroscopy has taken advantage of improvements in the art. Radio telescopes have become sensitive enough to make planetary measurements.

Within the past few years, still greater steps have been taken. Telescopes have been lifted above the sensible atmosphere with balloons; radar signals have been returned from the planets. And finally, spacecraft have been sent to the vicinity of Venus and Mars. In the near future, an astronomical observatory will be orbiting the Earth. Spacecraft will be sent to orbit nearby planets and will send capsules to land on the surfaces.

This paper will be concerned primarily with two of these new tools for planetary research, namely, ground radar systems and unmanned spacecraft.

Planetary Radar.—The first radar echo observed from an extraterrestrial body was in January 1946, when a group of U.S. Army Signal Corps engineers succeeded in detecting a signal returned from the Moon.¹ By 1961, echoes had been detected from the planet Venus.² Considering that the distance to Venus is more than 100 times as great as that to the Moon, and that the radar equation involves a term in

the inverse fourth power of the distance, this is an indication of the remarkable development in radar technology during this period of 15 years.

As a part of its Deep Space Net development program, the Jet Propulsion Laboratory is conducting planetary radar experiments with a system whose pertinent parameters are: transmitted power of 100 kw, wavelength of $12\frac{1}{2}$ cm, antenna with 330-m² effective area (28-m parabola), and a receiving system temperature of 37°K. In the near future, a new antenna 65 m in diameter will be in operation as a part of the Deep Space Tracking Network. It may also be used for some radar observations.

It is not sufficient merely to detect an echo from a planet. Useful scientific information requires measurement of the properties of the echo. The time at which the echo occurs will give the range to the target. Echo power will provide information on the scattering properties of the target. Frequency shift will measure the relative velocity of target and receiver. Frequency dispersion will measure the rotation of the target, relative to a line perpendicular to the direction of the receiver.

The actual mechanization of a system to make these measurements requires a careful analysis of the precise nature of the returned signal in the presence of thermal noise, and an appropriate selection of the transmitted signal. Discussion of these problems can be found in a number of references.³⁻⁵ Actual results obtained by these methods have proved that radar is an exceedingly valuable new tool for planetary exploration.

The range to the planet Venus has been measured to a precision of about 25 km, and the range rate to about 0.1 m/sec.⁴ These data supplement positional data from astronomical observations in a useful way. Astronomical data consist of angle measurements versus time, and since an angle is a nondimensional quantity, all distance measurements are computed. By adding precise range and range-rate data to the astronomical data, the geometry and motions of the planets can be calculated to a very much greater precision than formerly.

An index of this accuracy improvement is the determination of the astronomical unit. The best value calculated from conventional astronomical observations was that of Rabe in 1950. Using the perturbation of the motion of the asteroid Eros, he obtained the value $149,530,000 \pm 10,000$ km. Calculations made from radar data on the planet Venus give the value $149,598,640 \pm 250$ km. Unpublished calculations by Muhleman, using an extensive series of radar data while Venus traveled over most of its orbit, give a value $149,598,388 \pm 50$ km. These last calculations use the radar data to solve for the orbital parameters of the Earth and Venus, rather than taking the optically determined ephemeris for Venus and using radar to make a small correction. The difference between Rabe's value and that of Muhleman is far outside the quoted probable error. This is believed to be due to an improper accounting of the effect of Mars in the calculations of Rabe. (It should be mentioned that these radar measurements are actually measurements of planetary range in terms of light-seconds and not kilometers. To convert to kilometers, a value of c of 299,792.5 was used.)

The return power in an echo is a measure of the back-scattering of the target. For a target planet illuminated by a beam of larger dimensions than the planet itself, the echo will be extended in time as the signal returns from different areas of

the planet surface. Hence, a measure of return power as a function of time will give the back-scattering from different areas of the planet. An example of such data is in Figure 1, showing the signal return from Venus for a series of zones around the sub-Earth point, each 46 miles deep. Note that the signal is plotted as return power versus frequency. The rotation of the planet gives rise to the frequency spread as the zones move away from the sub-Earth point. Zones 2 and 3 show marked asymmetries. These are presumably related to topographic features on the planet.

Frequency dispersion of the echo, as the reflecting zone moves out toward the limb of the planet, is a means of measuring the rotation rate of the planet. Venus is a particularly interesting case because astronomical observations had not been able to establish any definite rate, since no visible fixed surface features were available. Spectroscopic observations indicated a very slow rotation but the data contained large uncertainties. The radar data, expressed most simply as band-

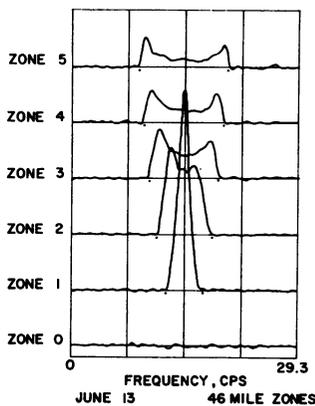


FIG. 1.—Power-frequency spectrum of radar return from Venus.

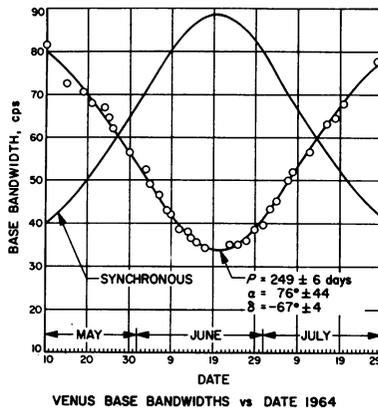


FIG. 2.—Bandwidth of radar return from Venus showing rotation of the planet.

widths for reflections near the limbs, showed unequivocally that Venus does indeed rotate slowly. A long series of observations (Fig. 2) also shows that because of the relative motion of Earth and Venus, the direction of rotation can be obtained. The surprising result is that Venus rotates with retrograde motion at a period of about 250 days.

Planetary radar observations of Mercury and Mars have also yielded useful information. Jupiter has been detected both by the Jet Propulsion Laboratory (JPL) and by a USSR group. Because of the great distance and the large frequency dispersion due to rotation of the planet, Jupiter turns out to be a very difficult target. The JPL data gave the surprising result that the only statistically significant echo was detected from a region centered about Jovian longitude 32 degrees.⁶

Planetary radar offers many opportunities for extended research activities. Systems are becoming more sensitive as transmitter power and antenna diameters increase while receiver temperatures go lower. Other than the Moon, Venus will continue to be the most attractive target. Continuing study will provide a radar map of the planet. Amplitude and polarization studies will give some clues to the nature of the surface.

Spacecraft for Planetary Studies.—Within the past five years, the possibility of sending instruments to the planets has advanced from speculation to reality. The United States has successfully sent two spacecraft to other planets: Mariner II to Venus and Mariner IV to Mars. The Soviets have made a number of unsuccessful attempts. In the immediate future, both countries can be expected to continue their experiments.

These flights clearly open up a whole new era in planetology. At the same time, it should be remembered that they are exceedingly costly, and therefore the scientific missions should be conducted in such a way as to yield the maximum return. This requires a realization on the part of the scientific community of the problems involved in conducting experiments at another planet and of the general scope of future plans.

Some Constraints on Planetary Journeys.—As a practical matter, the energy available from a booster rocket is finite. Hence, on most missions, the spacecraft will fly to another planet along an orbit which is close to the minimum energy. This will be a heliocentric elliptical path with a perihelion (or aphelion) near the

	62	63	64	65	66	67	68	69	70	71
VENUS.....										
Encounter.....										
MARS.....										
Encounter.....										

FIG. 3.—Dates for launching spacecraft to Venus and Mars.

Earth and an aphelion (or perihelion) near the target planet. To come near the target planet, it will be necessary to launch at a specified time when the Earth and the planet are in the correct relative positions. Figure 3 shows the timetable for Mars and Venus. This means that launch and arrival at the planet occurs at times determined by solar system geometry. If, therefore, an experiment requires observations at some particular season on Mars, a flight will be possible only at certain launch periods.

Because the orbits of the planets are not co-planar, the energy required to send a spacecraft to another planet varies with the launch date. For example, in the case of Mars the lowest minimum energy orbit will occur in 1969 and the highest in 1973 with the cycle repeating in a 15-year period. The 1969 launch requires that the spacecraft leave the Earth's gravitational field with a velocity of 2.8 km/sec. In 1973, this will have risen to 4.0 km/sec. The size of spacecraft which can be launched with a given booster will vary accordingly.

Data sent back to Earth from spacecraft in the vicinity of a planet must travel vast distances. Hence, the communication system must be designed so that the maximum data rate is kept as low as possible. The instrumentation selected for the spacecraft, therefore, must be designed to satisfy the low data rate requirement, or must provide a data storage system able to collect data over a short period of time and send it over the communication link sufficiently slowly to meet the rate specification. The Mariner IV television system required a record-to-playback ratio of 1200.

Instruments designed to fly on a spacecraft must, of course, operate in the spacecraft environment. This environment can be divided into three categories: launch, free-fall in the vacuum of space, and landing on another planet or re-entry and land-

ing on the Earth. Each category has its problems. The launch is characterized primarily by severe vibration and acceleration. Coasting in space presents problems due to the long exposure to a very hard vacuum. The landing or re-entry period presents further vibration and acceleration problems, possibly complicated by the gaseous constituents of a planetary atmosphere. While instruments have been built to operate properly in each of these environs, it is not an easy task. The worst environment is usually the vibration at launch. The effects of a hard vacuum, however, should not be minimized. These may include evaporation of instrument materials; problems of lubrication of bearing surfaces; and thermal problems caused by the disappearance of convective cooling. Electrical problems may arise due to the passage through the atmosphere from sea-level pressure to the vacuum of space or from leakage of sealed compartments, or possibly from outgassing in the vicinity of a high-voltage circuit.

In addition to the environmental constraints, the instrument designer must live with weight, volume, and power consumption specifications. On most spacecraft to date, these constraints have been quite stringent. However, looking into the future when larger boost vehicles become available, they should be relaxed.

A spacecraft designed to land instruments on another planet introduces a new constraint, namely, the requirement for biological sterilization. One of the very interesting experiments which will be conducted on the surface of Mars is the search for life. Therefore, all space flight hardware which has any finite probability of landing on Mars must be sterile to ensure that life forms found on the planet are not transported from Earth. The methods by which a large spacecraft can be made completely sterile and maintained in that condition through the launching are currently being developed. One possibility is a requirement that the complete spacecraft be sterilized by heating above the boiling point for an extended period of time. In this case, of course, instruments would have to be constructed out of materials and components which could stand such treatment.

Finally, there is the question of reliability on the long journey through space. Some instruments are required to work continuously for many months; others are needed only in the vicinity of the planet. These must turn on reliably, with the correct calibrations, after the long exposure to space vacuum and radiations. All equipment aboard the spacecraft must operate perfectly the first and only time a completely realistic test is given. Once the launch button has been pushed, there will be no opportunity to make an adjustment or to replace a component.

Examples from Mariner IV, which flew past Mars on July 14, 1965, may be used to illustrate the scientific instruments aboard a planetary spacecraft.⁷ Figure 4 is a sketch of the spacecraft showing the location of these instruments. Figure 5 is the Mariner magnetometer. This is a triaxial metastable helium device with a sensitivity of better than 1 gamma. It weighs 7.5 lb and consumes 7.3 w.

Figure 6 shows the television system mounted on a platform beneath the Mariner. The platform was designed to scan the sky near the planet until a photoelectric device locked onto the planet and pointed the camera in the proper direction. The platform remained fixed while the motion of the spacecraft across the planet allowed the camera to take a series of photographs of the surface. These were stored on a magnetic tape and later played back to Earth. The television system weighed 11.3 lb and required 8 w of power.

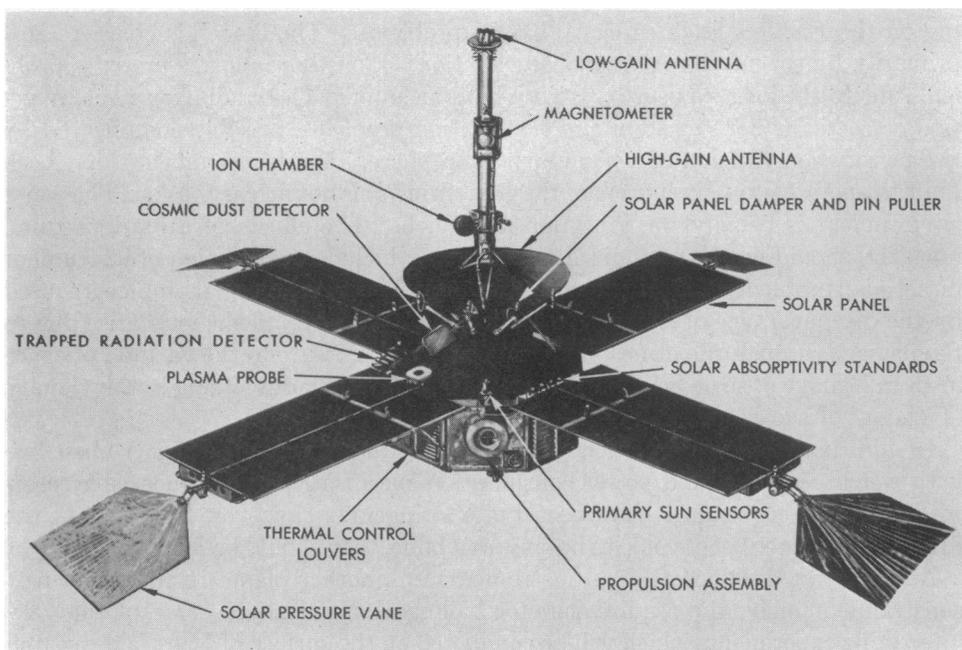


FIG. 4.—Mariner spacecraft showing location of scientific instruments.

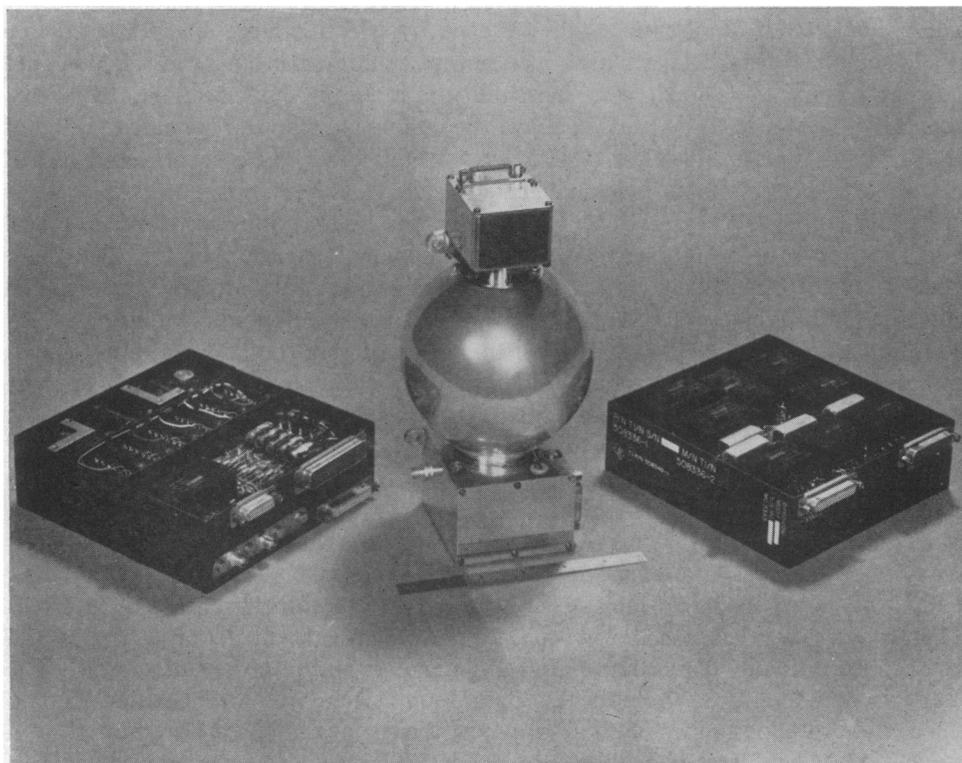


FIG. 5.—Mariner magnetometer.

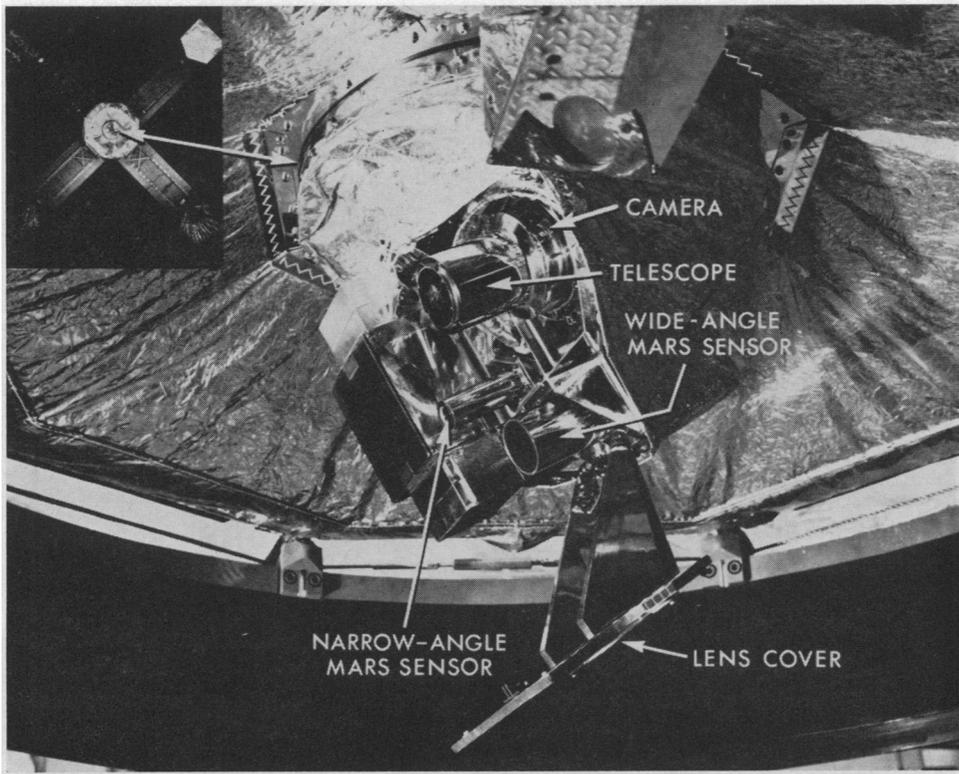


FIG. 6.—Television system on Mariner.

Figure 7 (frame 11) is one of the photographs returned from Mars. Taken through a green filter, it covers an area 170×150 miles, centered on latitude 31°S , longitude 197°E . The Sun is 47° from the zenith and is in the north, or top, of the photograph.

Data from these instruments and from 90 others measuring spacecraft performance were collected in a data automation system, processed into digital form, and routed to the transmitter in the correct sequence. The data automation system contained about 11,000 components. It weighed 12 lb and required 6.5 w of power.

The large amount of data received from Mariner was processed at the Space Flight Operations Facility in Pasadena. Within 5 min of receipt of the telemetry signal, both scientific and engineering data were reduced and displayed for initial evaluation. Approximately 24 hr later, scientific data were available for preliminary analysis.

Weekly summary reports and tapes were made available to each experimenter. The final data are being collected into a master data library which will contain the "best" record of Mariner transmitted data organized into digital form for computer processing by the experimenters.

Mariner IV represents the most sophisticated planetary spacecraft the U.S. has yet launched. It performed very well, but its capability was limited by the 575-lb total weight constraint. The next generation of spacecraft, the Voyager series, will weigh more than ten times as much and will be capable of missions considerably

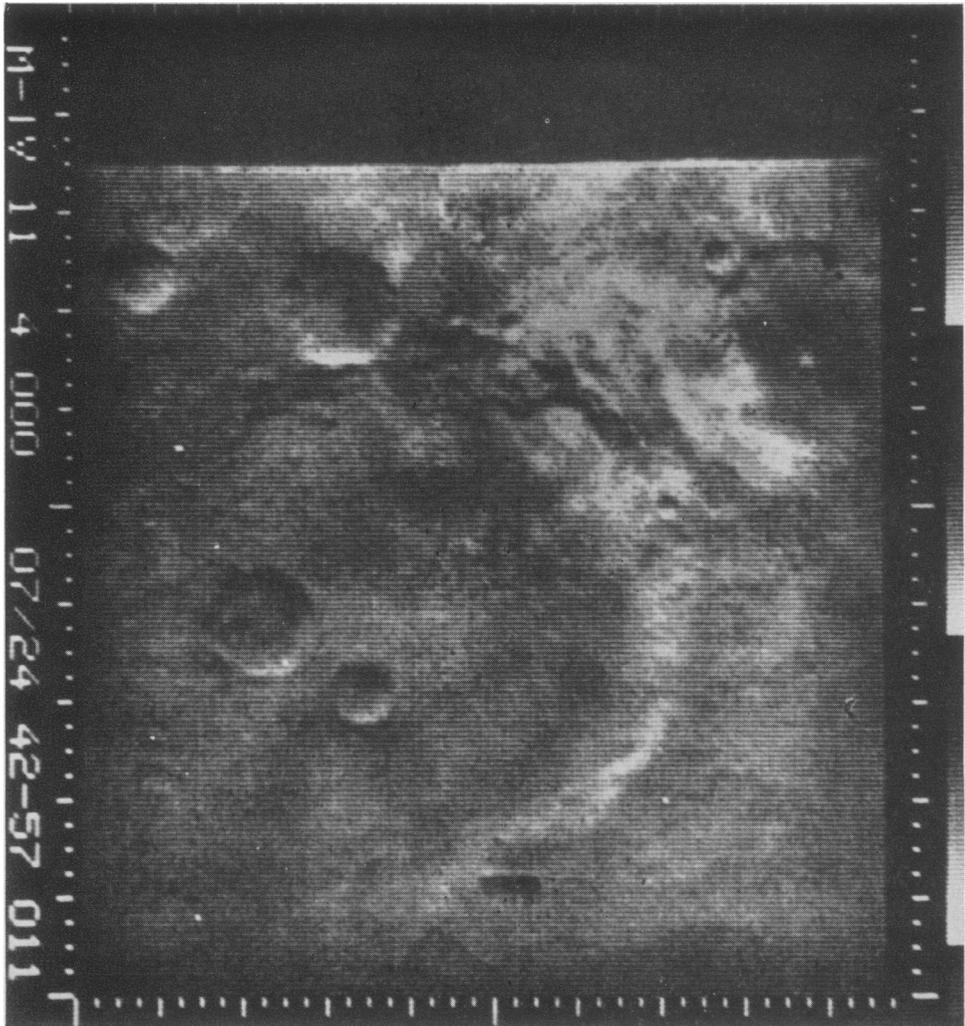


FIG. 7.—Mariner photo of Mars (frame 11).

more extensive. Present plans call for both orbiting and landing versions of Voyager, starting in 1971, for Mars exploration. Later, Voyager will be used for a Venus mission and possibly for others. The detailed plans for the first Voyager are not yet firm. Many experiments have been proposed to NASA which are now under consideration.

Conclusions.—Exploration of the solar system has indeed entered a new era. The two examples discussed—namely, planetary radar experiments from the Earth and spacecraft experiments at other planets—offer spectacular opportunities for investigating our neighboring planets.

Radar experiments have shown: (1) that solar system geometrical relationships can be determined with extreme accuracy, and (2) that extensive new information on planetary surfaces can be obtained to supplement that from observations with visible or infrared light.

Unmanned spacecraft traveling to the planets have demonstrated that complex experiments can be operated successfully at planetary distances. Information which can be obtained includes: (1) detailed trajectory analysis which makes possible more precise determinations of solar system parameters, such as the masses of the planets; (2) actual close-up observations of the planets with television and other instruments; and (3) data from instruments landed on a planet. Although this last has not yet been demonstrated, the results from Mariner give us every confidence that Voyager will indeed succeed in making surface observations of Mars.

* This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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⁶ Goldstein, R., "Radar observations of Jupiter," *Science*, **144** (1620), 842-843 (1964).

⁷ Schutz, F. L., *et al.*, in *Mariner/Mars Science Subsystem*, IEEE Convention, Session 4, San Francisco, California, August 24, 1965.

THE RELATION BETWEEN PROMPT AND DELAYED EMISSION IN PHOTOSYNTHESIS*

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Communicated by Bryce L. Crawford, Jr., October 19, 1965

Following the discovery of delayed light emission from photosynthetic tissues by Strehler and Arnold in 1951,¹ a considerable attempt has been made to correlate this emission with the quantum-conversion process in photosynthesis.^{1-6, 13} The attempt has been successful in so far as it has been possible to establish a clear parallelism between some parameters of photosynthesis and long-lived emission. Determinations of the quantum yield of the delayed light, however, have resulted in values as low as 10^{-6} for the emission in the time range between 0.0015 and 30 sec after the excitation had ended.⁷ The possibility of an increase of the yield at shorter times could not be completely excluded. It has not been shown, so far, what fraction of the total emission actually consists of delayed light. Knowledge of this fraction is of considerable importance, since it provides the basis for a judgment as to whether or not charge separation and trapping or other metastable electronic states play a major role in primary quantum conversion.

Arnold and Davidson⁸ have recently presented data for the decay of delayed light emission covering the wide range from 10^{-1} sec to 5×10^{-5} sec. Extrapolation of