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t. "Scientific Results of the Mariner II Voyage to Venus"

Mariner II was launched on August 27, 1962, passed at a distance of only 41,000 km from the center of Venus on December 14, and transmitted its last scientific and engineering data to earth on January 2, 1963. It was remarkably successful for the first vehicle of its type whose launching was satisfactory. A large part of the emphasis on this first flight was engineering and a great amount of important technological information was obtained from it. The history of this voyage, including a discussion of the engineering and scientific problems and results, is surveyed by J. N. James(1). My discussion this morning will be restricted to the scientific results obtained to date by the seven groups of experimenters. The emphasis given each experiment will be governed by my own interests and what I happen to know.

A very interesting scientific by-product of the engineering technology is information on the scale of distances and some of the masses in the solar system. Radio signals sent from the earth and received by Mariner were rebroadcast back to give a very accurate Doppler measurement of its radial velocity relative to the earth. The 22,000 Doppler observations, together with the simultaneous radar observations of Venus made by the Goldstone tracking station, will enable an exceedingly accurate computation to be made of the astronomical unit, abbreviated A.U., which determines the scale in cm. of all distances in the solar system. From the deflection of the trajectory as it passed Venus, preliminary calculations have shown that the previous value for the mass of Venus, 0.8148 ± 0.0004 times the mass of the earth, can be refined to 0.81485 ± 0.00004. The Doppler radial velocity is

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affected also by the motion of the earth around the center of mass of the earth-moon system and from this a refined value of the mass of the moon can be obtained. This work was carried out by T. W. Hamilton, J. F. Koukol, N. A. Renzetti, D. W. Trask and J. D. Anderson.

During the encounter period,[2] Venus was scanned by a microwave radiometer at wavelengths of 13.5 and 19 millimeters and by an infrared radiometer at wavelengths of 8.4 and 10.4 microns. There were three scans, one on the dark side, one nearly along the line separating the light and dark sides, and one on the light side. The microwave radiometer showed that the surface temperature was about 700°K and the infrared radiometer showed that the temperature at the top of the clouds was about 250°K. Thus it is now definite that the high radio frequency temperatures previously recorded are at the surface rather than in the ionosphere, and the greenhouse model for the Venusian atmosphere gains added support. There were no temperature differences detectable between the light and dark sides. The cloud cover in the regions scanned seems quite continuous with no breaks detected as wide as a few percent of the diameter of the disk. There was no significant amount of CO_2 in the upper clouds. The experimenters for the infrared radiometer were L. D. Kaplan, G. Neugebauer, and C. Sagan; the experimenters for the microwave radiometer were A. H. Barrett, D. E. Jones, J. Copeland, and A. E. Lilley.

The experiment of W. M. Alexander for the observation of interplanetary dust grains yielded only a couple of definitely confirmed impacts, many fewer than had been expected.[3] No thorough analysis of the results in terms of particle density is available.

An ion chamber and three Geiger counters were used by H. R. Anderson, H. V. Neher, and J. A. Van Allen to observe energetic particles.[2],[3],[4] From their observations it may be concluded that there is no great flux of

protons in the range from 10 to 100 Mev since the observations in space are about what would be expected from the flux of particles observed above 100 Mev by ion chambers flown on balloons. On several occasions low energy cosmic rays were observed, enabling us to extend our knowledge of the time constants for their appearance and escape to the lower energies observable in space. Several Forbush decreases in the galactic cosmic ray flux were observed both by Mariner II and on earth, confirming and extending the earlier proof by Pioneer V that on such occasions cosmic rays are screened out from a very large volume of space in the solar system. Aside from such transient increases and decreases in the cosmic ray flux associated with solar disturbances, the general level remained constant to with 2 percent between the orbit of earth and the orbit of Venus. You will recall that the flux of low energy galactic cosmic rays, those with energies in the neighborhood of 1 Bev, varies over the 11 year sun spot cycle. Presumably this is due to some screening mechanism outside the orbit of earth which excludes low energy particles more effectively when the sun is active than when it is quiet. It is tempting to conclude that this absence of change in the cosmic ray flux between the earth and Venus means that the entire screening mechanism is located outside, perhaps far outside, the orbit of the earth. However, it is just possible that there is some further screening between the earth and Venus, but that during the four months of the flight the general level of cosmic rays at any fixed distance from the sun increased a bit, as expected at this phase of the sun spot cycle, and that this increase just compensated for the decrease due to the additional screening. Unfortunately, observations of the low energy cosmic ray flux at the earth adequate to check this point do not seem to be available.

In my opinion, the most important result of the Mariner II experiment was the conclusive demonstration[3] that, at least at this stage of the solar cycle, the solar wind flows out from the sun all the time essentially as in Parker's well-known model, although with a considerably lower density than was popular a few years ago. The plasma detector of Mariner II measured the current due to charged particles coming along directions lying within about 5° of the line to the sun and having energies in a narrow band. An electrostatic analyzer selected in succession 10 energy bands that correspond to proton velocities distributed in a geometric series between 231 and 8224 km/sec. The main conclusions to be drawn from a preliminary analysis of the data are that a measurable solar wind blew essentially radially outward from the sun at all times, that most of the time the velocity lay between 350 and 750 km/sec, and typical densities were a few per cm^3 (perhaps ranging from less than 1 to as much as 30). Particles were present simultaneously in several channels; if this is interpreted as a manifestation of the temperature of the gas, values of the order of 2×10^5 $^{\circ}K$ are usually obtained. A less orthodox alternative is that this is in part the manifestation of waves with frequencies greater than about 1 sec^{-1}. There is also clear evidence for the presence in the solar wind of alpha particles as well as protons. The density ratio seems to fluctuate and the relative abundance of alpha particles seems to be lower than in the photosphere. A very striking feature of the plasma data is the fact that the velocity showed a series of peaks, each lasting from 2 to 4 or 5 days, that the level of geomagnetic disturbance correlated well with the solar wind velocity, and that the peaks showed a strong tendency to recur at approximately 27-day intervals. The experimenters for the plasma probe were M. M. Neugebauer and C. W. Snyder.

A triaxial fluxgate magnetometer was used to measure the vector interplanetary field at intervals of 37 sec. throughout most of the voyage(3).

Unfortunately the space craft magnetic field shifted during launch from the prelaunch value by an amount that is not known accurately and showed substantial later shifts. Thus there is always some uncertainty in the zero from which the interplanetary field is measured and, while I believe that a reasonable interpretation of the data can be presented, anyone is free to modify it by making a different estimate of the space craft field. Much of the time the interplanetary field has a general order of magnitude of 5 gamma and shows relatively little change over periods of many minutes. There are many periods of disturbance when the field varies much more rapidly, time constants ranging from fractions of an hour through a few minutes to perhaps only a few seconds being apparent. On these occasions the field changes may be as much as 5 or 10 gamma and the field itself may sometimes be even larger in magnitude. If one looks at individual hourly averages of the field components, no particular structure of the interplanetary field is apparent. If one averages over periods of 10 to 20 hours, there is an indication that the field may have a basic spiral structure in the plane of the ecliptic, the field making an angle of about 45° with the radius from the sun. Superposed on this regular field are fluctuations or waves that deflect the field in a random way from its mean direction. Typically the deflection may be through 20° to 40°; it is made up of a superposition of waves with periods ranging from several hours down to fractions of an hour in quiet times and down to only a minute or less in disturbed times. I must emphasize that this model is still very tentative. It appears somewhat more certain that the component of the field along the radius from the sun seems to have one typical average value during one-half of the solar rotation and another average value, most likely of equal magnitude but opposite sign, over the other half of

the solar rotation. This pattern shows a rough 27-day periodicity. No effects ascribable to the presence of a Venusian magnetic field could be detected in the neighborhood of Venus. This requires that the magnetic moment of Venus be less than 1/10th, or perhaps only 1/20th that of the earth. It is by no means excluded that Venus has essentially no magnetic field. This result is consistent with the recently established low rotation rate of Venus; but considering our uncertain quantitative knowledge of dynamo theory, neither result can be said to require the other. The magnetometer experimenters were P. J. Coleman, Jr., Leverett Davis, Jr., E. J. Smith and C. P. Sonett.

Next let us consider a tentative model in terms of which some of these observations may be discussed. Some parts of this model may be novel, but some have been borrowed from others. It must be emphasized that the model is provisional and many details are likely to be wrong. But it is the best I can do at the moment.

Consider first the region within 10 or 20 solar radii of the sun. Near the sun the magnetic field dominates the plasma flow; the field must be essentially force-free except for oscillations and waves whose velocity of propagation is much faster than the expansion that becomes the solar wind. The gas can move freely only along the tubes of force. Hence there is likely to be a tendency for the gas to well up from the photosphere into the upper corona in places where the magnetic field extends to large radii in a relatively regular, nearly vertical pattern. The entire upper corona may be filled by gas that spreads out from a few such sources and in quiet times the entire solar wind will come from them. The magnetic field in interplanetary space is drawn from only a few regions and its radial component changes sign much less

frequently than would be the case if all the irregular fields of the photosphere were sampled as the sun rotates. There may be some tendency for the alpha particles to settle relative to the protons in this welling-up region, which might account for a low density of alphas in the solar wind.

As one goes out to the region where the plasma momentum begins to become more important than the more rapidly decreasing magnetic field stresses in determining the motion, the tubes of force may form nozzles out of which the gas is ejected. The flow will not be quite radial, as in Parker's familiar model of the solar wind, but will be modified by the field. This may explain the high velocity,relatively narrow jets of low density wind observed near the earth by the Mariner II plasma probe. If there were merely a local hot spot on the sun, the angular width of the jet might be expected to be greater and there might be a stronger tendency for the density to increase more rapidly than the velocity. If the cross-sectional area of the nozzle is not merely proportional to the square of the distance from the center of the sun, it should be possible to vary density and velocity independently. The appearance of the same jet on several successive rotations of the sun indicates that the field patterns in the upper corona are quite stable. Near the sun the field and gas must co-rotate with the sun as they expand provided the tubes of force remain connected to the sun. At intermediate distances the interaction between the field and the angular momentum of the wind is complicated and it is not clear how co-rotation shifts over to the essentially radial flow that should be present near the earth. But there do seem to be good possibilities for angular motions near the sun that will complicate the calculation of radial velocities based on the time lag between central meridian passage of a photospheric or chromospheric feature and arrival at the earth of a disturbance supposedly associated with

the feature. If propagation is not radial, the disturbance may originate from the feature at some time other than central meridian passage.

Near the earth — in fact, starting inside Mercury's orbit — the momentum of the solar wind dominates the magnetic forces, which can no longer influence the average motion significantly. If the field maintains any continuity as it expands, it should be stretched out and sheared into the well-known spiral when conditions are steady. Near the earth it would be expected that if the wind has a velocity in the 400 to 500 km/sec range, the spiral would make an angle of about 45° with the radius from the sun. There may, of course, be superposed waves and oscillations. The magnetometer observations suggest that during quiet times these have characteristic lengths in a frame moving with the wind of from 10^{5} to $10^{6.5}$ km, and that during disturbed conditions there are many fluctuations with a scale of only $10^{4.5}$ km. or less. There appears to be rough equipartition between the magnetic energy density and the kinetic energy density associated with the fluctuations about the average of the mass motion.

As one goes farther out in the solar system, the spiral should tend to become very flat so that the average direction of the field is nearly normal to the radius vector. Here the energy density of the magnetic field and the kinetic energy density both vary inversely as the square of the distance from the sun and if there is equipartition, the waves in the field lines should continue to make angles of 20° to 40° with the average direction of the field lines. As the solar wind comes to the point where its momentum can not further push back the galactic magnetic field, the wind must pass through a shock transition in which its velocity decreases and its field strength increases. As layer after layer of flattened spirals pile up, the fact that the lines of force

originate at different points on the sun and hence have different senses means that they cannot merge into a simple uniform field. Instead the field is likely to be quite irregular as in the region just outside the earth's magnetosphere where the solar wind piles up and forms a stagnant region as its flow is impeded by the geomagnetic field. This region at the interface between the solar wind and the interstellar region will not continue to increase in thickness indefinitely. The irregular field structure will decay because of its finite conductivity. Its outer layers will be swept away by the relative motion of the solar system and the interstellar gas. As its field lines merge with the interstellar field, the plasma contained in the tubes of force in the transition region may drain out of the tubes into the interstellar region, leaving the field essentially alone to maintain the pressure balance. This will further increase the field strength in the transition region. It is tempting to think that this irregular thatch of field lines forms the barrier that tends to keep low energy galactic cosmic rays out of the solar system and thus produces the eleven-year cycle of cosmic ray intensity.

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November 26, 1963

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