and are much more regular than their counterparts, the familiar travelling cyclones and anticyclones of terrestrial mid-latitudes. J. Barnes presented results of efforts to understand the wave properties theoretically[7]. The high martian static stability and the zonally aligned topography both tend to stabilize these disturbances relative to their terrestrial counterparts, and may be the causes of the great observed regularity. More generally, the scales of the observed waves and those on the other planets seem to fit in with a general scaling for planetary waves similar to that for the Hadley circulations. (See the photograph).

Aspects of the climatic history of Mars are discussed in detail in the preceding article by Fanale. The regolith and CO_2 polar ice caps seem to have had crucial roles in buffering atmospheric CO_2 pressure since the time of regolith formation. The regolith and polar caps also serve as reversible reservoirs of H_2O. Viking Orbiter measurements of atmospheric water vapour may provide an indication of the relative roles of seasonal adsorption in the regolith and condensation in the polar cap, but the interpretation of these data remains controversial. B. Jakosky and C. Farmer[8] believe that the seasonal variations of H_2O are dominated by adsorption, whereas D. Davies and L. Wainio consider exchange with the polar cap to be more important[9].

An important new result relevant to the earliest period of atmospheric history was a careful recalculation of the escape flux of nitrogen by J. Fox and A. Dalgarno[10]. Viking measurements showed an enrichment of ^{15}N with respect to ^{14}N by a factor of 1.7. Fox and Dalgarno were able to show that their calculated escape is consistent with this enrichment and an initial N_2 endowment of as few as ten^{22} N_2 molecules per cm^2, much more than the current value but substantially lower than the early post-Viking estimate of McElroy *et al.*[11]. The escape flux predicted by Fox and Dalgarno is sensitive to assumed details of the ionospheric structure which have not yet been measured, and to certain other assumptions. If the assumptions are correct, and if the N_2/CO_2 ratio of Mars is in line with that of the Earth and Venus, the Fox–Dalgarno calculation suggests a total evolved CO_2 mass equivalent to as little as 50 mbar, but it does not demand such a low value. □

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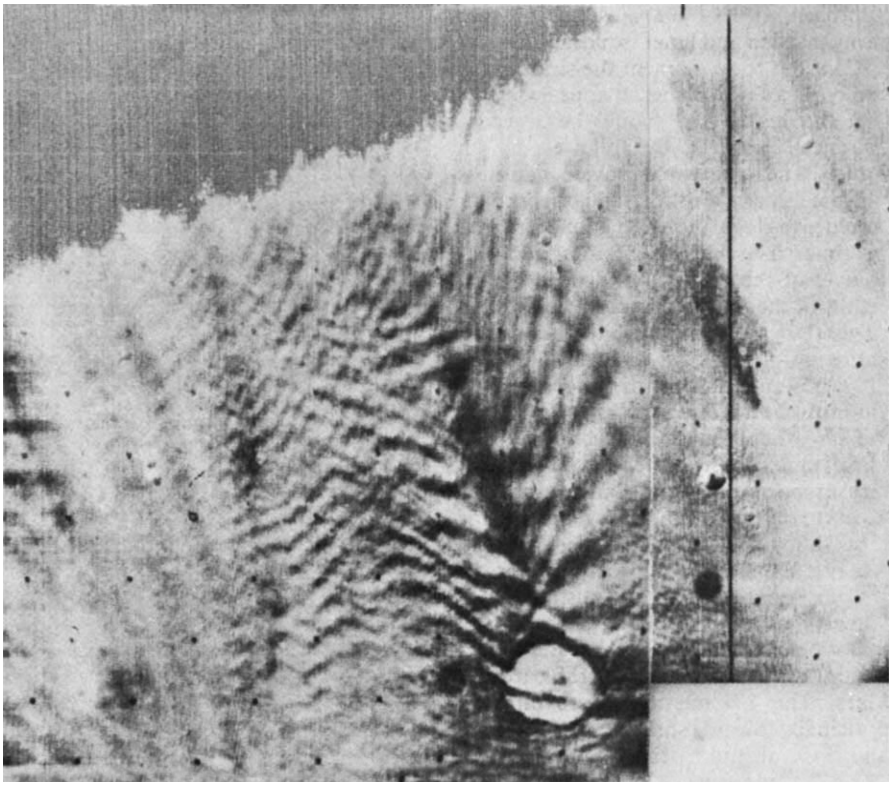

Mariner 9 photograph showing a lee wave system produced by crater Milankovic, a 100-km diameter crater at 53°N, 148°W. The lee waves extend 800 km downstream to the evening terminator with a wavelength of about 60 km.

Exploration of the upper atmosphere and ionosphere of Mars

from C.T. Russell and A.F. Nagy

STRATEGIES for the exploration of the Solar System and its individual planets have been prepared by a number of different committees and boards. In recent years, the major factor restraining the pursuit of such plans has not been lack of suitable technology but of money or, more specifically, the willingness to spend that money on any particular objective. To establish a logical strategy, the sophistication of the planned investigation and the accessibility of the planet play important roles. Whether sophistication is measured in terms of the type of mission — flyby, orbiter, lander, rover or manned — or in terms of scientific objectives, the ranking of a particular mission remains roughly the same. Again, whether the accessibility of a planet is measured in terms of the required launch vehicle capability or in engineering considerations such as thermal and power requirements and mission lifetime or in available telemetry rate, one will obtain roughly the same ranking.

The cost of a mission depends on both sophistication and accessibility. For roughly the same cost one could choose to fly a very sophisticated mission to the Moon, a modest mission to Jupiter or a very simple mission to Pluto. The total money available for the planetary program, is, however, limited and choices have to be made. It is sensible to choose a mixture of sophisticated and simple missions, because detailed data obtained from the more accessible bodies can help us to understand the behaviour of the more inaccessible objects, and comparisons between less sophisticated and more fragmented data obtained about a group of planets can be used to learn more about the generalities of planetary evolution. This approach is usually adopted because budgets are tight, and mission planners must seek missions that provide new and exciting data at the minimum cost. However, there are exceptions to this

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approach, two of the most major ones being martian and lunar exploration.

Consider for a moment the strategy for exploring a single planet. It appears logical that the initial step should be a reconnaisance with a flyby followed by an orbiter. The flyby would provide snapshots of some characteristics, and the orbiter would give global data over a longer period of time. The instrumentation and objectives of the orbiter will depend on the results of the flyby. It is not obvious that a single flyby or a single orbiter can do the entire job — orbits suited for one objective may be unsuitable for another, for example. Orbiters certainly provide increased observation time, but may also make more sophisticated and/or global measurements possible. Landers provide access to the surface and a longer period for observation and analysis, although at only one site. Sample return provides access to yet more sophisticated analysis as well as allowing longer time for analysis.

Both the United States and the Soviet Union have orbited spacecraft around Mars. The US missions were directed principally towards surface, photogeology and low altitude atmospheric science objectives. The Soviet missions looked at the solar wind interaction with Mars but telemetered little data and had relatively high minimum altitudes that did not penetrate the upper atmosphere and ionosphere of Mars. Hence there is only very limited information on the nature of the upper atmosphere and ionosphere of Mars, little geophysical or geochemical data, only a rough idea of the topography and an essentially unresolved controversy on the existence of an intrinsic planetary magnetic field. Furthermore, the proper global geochemical and geophysical data to plan an intelligent surface exploration strategy are not currently available. The US skipped a stage of exploration in order to be first to return data from the surface. The US and European scientific communities have become aware of this void and are coming forward with proposals to fill the gap. An ESA mission, KEPLER, has been proposed but unfortunately it competes with the Polar Orbiting Lunar Observatory (POLO), also in the planning process at ESA, which is designed to fill the analogous gap in our lunar knowledge. In the US, a Pioneer class Mars Orbiter mission, in many ways similar to KEPLER, has been discussed, but the chances for such a mission are very uncertain given the present tight financial situation at NASA.

In view of this lack of data there was little discussion of martian aeronomy or the solar wind interaction at the conference. J.A. Slavin (UCLA) addressed the existence of a planetary magnetic field. The few cases in which the Soviet Mars orbiters were claimed to enter either a martian magnetosphere or magnetotail are subject to varying interpretations. How far does the bow shock stand off of the planet and what size object would be necessary to create a bow shock in this position? Slavin showed that a size slightly larger than the planet plus its ionosphere is necessary and thus he feels there is a weak intrinsic field with a moment of about 1.4×10^{22} G cm^{-3}, about 5,000 times smaller than the Earth's moment. Examining available ionospheric data, principally from radio occultations, he finds no evidence for a Venus-type interaction. On the other hand, at altitudes above the ionosphere there are similarities in that heavy ions are found to be carried away by solar wind from both planets.

Photograph of Mars taken from a distance of 419,000 km by Viking 2. Near the top is the volcano Ascraeus Mons, with a white water-ice cloud to the north-west. The Valles Marineris is visible below the volcano, and the impact crater of the Argyre Basin, covered with winter frost, at the bottom of the photograph. The picture below shows the horizon of Mars with clouds, thought to be crystals of CO_2, 25–40 km above the surface. Taken 11 July 1976 by Viking Orbiter 1.

The lack of martian aeronomical data is particularly intriguing to planetary scientists because of the contrasts between Venus, Earth and Mars. Earth and Mars have similar rotation periods. Venus and the Earth have similar gravitational fields. Mars and Venus have similar atmospheric composition. Venus has no — or at least no detectable — planetary magnetic field while Mars has at most a weak one. In view of these contrasts, will the martian thermospheric temperature be controlled by solar EUV like the Earth's or be rather insensitive to solar EUV like that of Venus? Does Mars have a strong upper atmospheric wind system like Venus?

The ionosphere of Mars is similarly an enigma. Is there a solar wind source of heat as on Venus? What maintains the nightside ionosphere revealed by radio occultation? The terrestrial ionosphere is partially maintained at night by the large reservoir in the magnetosphere that fills with plasma during the day and empties at night. On Venus the night ionosphere is maintained by rapid flows from the dayside and by energetic particle bombardment from the wake of Venus. Finally, the chemistry of the martian ionosphere is a virtual unknown. The neutral atmospheric composition and hence the ionospheric composition are expected to be similar to that of Venus. However, the reaction rates are temperature and velocity dependent and therefore quite a few surprises may be in store.

Venus was found to have an extended non-thermal hydrogen and oxygen corona even though it has a very low exospheric temperature; the presence of this corona is due to dissociative recombination and charge-exchange reactions. On the other hand the Earth has an extensive hydrogen corona caused by the Jean's escape flux and charge-exchange processes, but it does not have a significant oxygen corona. The solar wind is deflected by the terrestrial magnetosphere so there is little significant interaction with the geocorona, but in the case of Venus, with no intrinsic field, the situation is very different, in that there is significant absorption by the corona through ionization in and charge-exchange with the flowing solar wind. In this regard Venus acts very much like a comet. Does Mars behave the same way, or is its corona shielded from the solar wind by a small magnetosphere?

These questions and many more must wait until we get back to a logical series of explorations, for despite the sophistication of some of our knowledge about Mars we are completely ignorant about some of its basic features. Our best hope is ESA's KEPLER or NASA's Pioneer Mars Orbiter missions. The realization of either of these missions would provide a big step forwards in our knowledge of Mars, as well as exposing many areas of ignorance to stimulate further progression in our exploration of the planets. □

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