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The atmospheres of the terrestrial planets

It has been known since the end of the nineteenth century that the Earth's nearest planetary neighbours, Venus and Mars, have extensive atmospheres. However, the nature of these atmospheres was not at all well understood until the advent of planetary missions by robot probes, beginning with Mariner 2 which encountered Venus in December 1962. Since then, the spurts of new information from missions like Pioneer Venus, and Mariner and Viking to Mars, plus radically improved Earth-based techniques including the use of infrared, microwave and radar sensing, have revealed most of the important basic atmospheric properties such as composition, temperature, surface pressure, cloud properties, dynamics and general circulation. Conditions on these planets are now known to be, for the most part, very different from even the most informed speculation that took place in the last few decades of the nineteenth century.

The bright and featureless aspect of Venus showed early observers that the planet was cloudy, and it was perhaps natural to assume that these were water clouds like those on the Earth, made more copious by the increased evaporation of surface water due to the greater proximity of Venus to the Sun. From this it seemed logical to expect rain and a swampy, tropical surface environment with carbonated-water oceans and at least a good chance of life. The searing temperatures and crushing pressures that we now know lie under clouds of concentrated sulphuric acid were recognized only after the dawn of the space age, and only fully accepted by some after the first landing on the planet by Venera 7 in 1970.

Mars has long enjoyed a reputation as a habitable sort of place. As early as 1774, Herschel concluded from his observations that it had a 'considerable' atmosphere containing clouds; Flammarion in 1896 noted the existence and variability of the polar caps. However, as late as the 1950s theoreticians analysing the carbon dioxide lines in the Martian spectrum were writing of the surface pressure in terms that were more than a factor of 10 too high. It was only with the development of high-resolution ground-based spectrometers and the arrival of Mariner 4 in the early 1960s that the surprisingly low value of around 6 mbar was derived and the composition of nearly pure carbon dioxide confirmed.

Mercury has always been elusive because its position close to the Sun means that telescopic observations from the Earth and spaceflight in its vicinity are both relatively difficult. Some putative spectroscopic evidence for a dense atmosphere was obtained in the nineteenth century, but this was later called into question on theoretical grounds when it was recognized that gases on such a small, hot body would readily escape to space. A thin atmosphere like that of Mars was still considered a possibility, for example by those who thought they could discern the occasional obscuration of surface features by airborne dust, well into the second half of the twentieth century. The arrival at Mercury of Mariner 10 in 1973 finally demonstrated that the surface pressure on the planet is less than the most perfect vacuum that can be created in laboratories on the Earth.

The fact that the terrestrial planet atmospheres are now well characterized in general terms does not of course mean that we fully understand them. The curious dynamics of Venus's cloud layers, the vivid evidence for massive climatic change on Mars and the possible existence of ice deposits near the poles on Mercury are just the tip of an enormous iceberg of ignorance and curiosity concerning our planetary neighbours. The flotilla of scientific probes being aimed towards Mars in the first decade of the twenty-first century is one testament to the fact that the magnificent journey of discovery that essentially began in the twentieth century is set fair to reach its zenith in the next.

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Table 1 Physical data for the terrestrial planets

	Mercury	Venus	Earth	Mars
Orbital and rotational data				
Mean distance from Sun (km)	5.79×10^7	1.082×10^8	1.496×10^8	2.279×10^8
Eccentricity	0.2056	0.0068	0.0167	0.0934
Obliquity (deg)	0	177	23.45	23.98
Siderial period (d)	87.97	224.701	365.256	686.980
Rotational period (h)	1407.5	5832.24	23.9345	24.6229
Solar day (d)	115.88	117	1	1.0287
Solar constant ($kW\,m^{-2}$)	See text	2.62	1.38	0.594
Net heat input ($kW\,m^{-2}$)	See text	0.367	0.842	0.499
Solid body data				
Mass (kg)	3.302×10^{23}	4.870×10^{24}	5.976×10^{24}	6.421×10^{23}
Radius (km)	2439	6051.5	6378	3398
Surface gravity ($m\,s^{-2}$)	3.70	8.60	9.78	3.72
Atmospheric data				
Composition	He, Na	See Table 2		
Mean molecular weight	—	43.44	28.98 (dry)	43.49
Mean surface temperature (K)	~400	730	288	220
Mean surface pressure ($N\,m^{-2}$)	$<10^{-12}$	92	1	0.007
Mass (kg)	$\sim 8 \times 10^3$	4.77×10^{20}	5.30×10^{18}	$\sim 10^{16}$

Table 2 Composition of the terrestrial planet atmospheres (for Mercury, see Table 4). Values are given as fractional abundances or as parts per million (ppm)

	Venus	Earth	Mars
Carbon dioxide	0.96	0.0003	0.95
Nitrogen	0.035	0.770	0.027
Argon	0.00007	0.0093	0.016
Water vapour	~0.0001(?)	~0.01	~0.0003
Oxygen	0.0013	0.21	~0
Sulphur dioxide	0.00015	0.2 ppb	~0
Carbon monoxide	0.00004	0.12 ppm	0.0007
Neon	5 ppm	18 ppm	2.5 ppm

Physical data for Mercury, Venus, Earth and Mars are given in Table 1, and data for the atmospheres of Venus, Earth and Mars are given in Tables 2 and 3.

MERCURY

Having already described the atmosphere of the innermost planet as resembling a perfect vacuum, it is perhaps capricious to go on at length about its interesting properties. Nevertheless, there are a few, and the story of how we got to our present understanding of this wispy envelope, and its associated mysteries, is engaging.

Most of the early observations of Mercury concentrated on trying to resolve details on the surface and on determining thereby the period of rotation. Maps were drawn, and features thought to be permanent were assigned romantic names. Maps by Schiaparelli in 1889 and Lowell in 1896 showed narrow, linear features reminiscent of those on their charts of Mars and probably of the same chimerical origin. Antoniadi, who published a book about Mercury in 1934 and made many observations of his own, was convinced that Mercury exhibited synchronous rotation, with the same face always directed at the Sun. He deduced that Mercury possessed an atmosphere thick enough to support dust storms, which seemed sometimes to obscure the dark markings he saw on the planet. In fact, he was viewing different parts of the disk, as Mercury rotated once every 58.6 days, rather than the 88 days that would have matched its annual journey around the Sun.

Table 3 Properties of clouds and dust in the terrestrial planet atmospheres*

	Venus	Earth	Mars
Fractional coverage	1.00	0.40	0.05 (cloud) 0–1.0 (dust)
Typical optical depth	25–40	5–7	0.2–6 (dust)
Composition	$H_2SO_4 \bullet H_2O$	H_2O	Magnetite etc. (dust); H_2O, CO_2
Number density (cm^{-3})			
liquid	50–300	100–1000	0
solid	10–50	0.1–50	30–1000
Mass loading ($g\ m^{-3}$)	0.01–0.1	0.1–10	0.0002–0.1
Main production process	Chemistry	Condensation	Windblown (dust)
Equivalent depth (mm)	0.1–0.2	0.03–0.05	1–100
Effective radius (μm)	2–4	10	0.4–2.5 (dust)
Main forms	Stratiform, cumulus	stratiform, cumulus	stratiform, mixed (dust)
Temporal variability	Slight (haze), high (deep)	High	High

* The equivalent depth is the estimated thickness of the cloud material if it were deposited on the surface. The effective radius is the radius of the spherical particles having most nearly the same scattering properties as the cloud at visible wavelengths. After Esposito *et al*. (1983), with changes and additions

Table 4 Properties of the atmosphere of Mercury, from Mariner 10 results

Surface pressure	$<10^{-12}$ bar
Average surface temperature	440 K (590–725 K, sunward side)
Atmospheric composition	Detected compounds 42% oxygen, 29% sodium, 22% hydrogen, 6% helium, 0.5% potassium Possible trace constituents Argon, carbon dioxide, water, nitrogen, xenon, krypton, neon

Another way to detect an atmosphere is by analysing the polarization of light reflected from the planet. Summarizing the evidence from a long sequence of such observations at several wavelengths, Dollfus in 1961 concluded that there was evidence for a pressure at the surface of up to about 1 mbar, one thousandth of that on Earth. Ingersoll in 1971 revised this to an upper limit of 0.28 mbar (for carbon dioxide; the value depends on the composition assumed). These researchers recognized that their analysis depended on the assumption that the surface itself does not contribute to the polarization of the reflected light; if it does, their values get smaller. In fact, the surface pressure is less than one billionth of a millibar.

Reviewing in 1988 the question of surface markings on Mercury, and the various maps that had been drawn over the years, Patrick Moore wrote ‘My own conclusion is that although it is probable that a few albedo features were glimpsed occasionally, the errors in observation were so unavoidably large that, without the spacecraft, we would never have learned anything definite about Mercury's features.’ The spacecraft he refers to is, of course, Mariner 10, the only one to visit Mercury to date.

It is to Mariner 10 that we also owe the resolution of the question of the surface pressure on Mercury. During three encounters, on 29 March 1974, 21 September 1974 and 16 March 1975, two ultraviolet spectrometers recorded atmospheric data. The first observed at a selection of wavelengths chosen to correspond to the emission lines of several candidate atmospheric species, specifically helium, neon, argon, xenon, hydrogen, carbon and oxygen. The second observed the Sun, and detected absorption by the atmosphere in four wavelength bands as the Sun went behind the limb of the planet. This is the so-called occultation technique, which is very sensitive to the presence of small traces of gas. The results are summarized in Table 4.

The total mass of Mercury's atmosphere has been estimated at only about 8 tonnes. The low surface pressure means that the atoms and molecules can escape from the planet, or collide with the surface, before they collide with each other: by analogy with the outermost layers of the thicker atmospheres of the other planets, this is called an exosphere. It follows that the atmosphere is transient; to exist at all, it must be constantly replenished. Since mixing is ineffective, the composition, and the density, may vary considerably over the globe, depending on the local balance between sources and sinks for each molecule.

Oxygen, sodium, and potassium in the atmosphere are probably baked out or otherwise derived from the minerals in the surface or the crust of Mercury. The hydrogen and helium come in as the solar wind and are temporarily trapped. It seems likely that trace amounts of argon, carbon dioxide, water, nitrogen, xenon, krypton and neon are also present.

The metallic ions sodium and potassium are probably produced by sputtering at the surface caused by micrometeorites, solar wind particles or ions from Mercury's magnetosphere. There is observational evidence for localized concentrations which may imply venting from subsurface sources or some other mechanism. Accumulations of radar-bright material in craters in the polar regions are thought by many to be deposits of water ice. They occur in locations that are permanently sheltered from sunlight that will, in the absence of a substantial atmosphere, be very cold. If substantial amounts of ice are indeed present (and it remains to be shown that the features are not due to some other radar-bright volatile, such as sulphur or even sodium) their origin is probably in meteoritic bombardment, although again outgassing from a source within the planet cannot be ruled out.

Mercury is a prime target for an orbiter mission in the first decade of the new century. NASA has announced plans for the Mercury Surface, Space Environment, Geochemistry and Ranging mission (Messenger), while the European Space Agency (ESA) has definite plans for a 'cornerstone' mission in 2008 or there abouts, albeit with an unfortunately puerile name 'Bepi Colombo'. ESA recently completed a technical and scientific study of a mission to return dust, rock and a core sample from the surface of Mercury, although no date has been set for this very ambitious mission. While primarily directed towards understanding the origin and evolution of Mercury as a planet, key atmospheric science questions can also be addressed. Firstly, better spectrometers can be used to confirm the composition given in Table 4, and to search for trace species like water vapour and carbon dioxide. Secondly, the variation in space and time of these species can be mapped, and any low-pressure 'volcanoes', fissures, or other regions where gases are issuing from the interior, located. Finally, the question of the nature and origin of the reflective deposits near the poles can be investigated with observations that include infrared temperature measurements. For a planet with a vacuum for an atmosphere, Mercury will remain an interesting place for many decades to come.

VENUS

The twentieth century was more than 60 years old before the technology was in place to probe beneath the all-enveloping cloud veil on Venus. Measurements of emission from the planet at microwave (centimetre) wavelengths, which penetrate all but the most massive clouds, showed a source temperature of more than 600 K, a value so high that most planetary scientists assumed at first that the source must be something other than the surface of the planet. It could, among other possibilities, be emission by some unidentified process in the planet's ionosphere, or from sustained lightning activity in the clouds. However, it was pointed out by Carl Sagan and others that the visible diameter of Venus is several tens of kilometers larger than its radar diameter, so the atmosphere below the cloud tops must be correspondingly deep. In an optically thick atmosphere, the vertical temperature gradient cannot deviate much from a value known as the adiabatic lapse rate, which on Venus is about $10\,\mathrm{K\,km^{-1}}$. The temperature at the cloud tops is relatively easy to measure, with infrared sensors on ground-based telescopes, and was known to be around 240 K. Thus, if this temperature was, say, 50 km above the ground, the latter had to be around 740 K, in agreement with the microwave emission temperatures. Sagan and colleagues also went on to show that it might, under certain conditions that remained to be proven, be possible to sustain such a high temperature by the greenhouse effect, a well-known atmospheric phenomenon without which our own planet would be an icy wasteland.

Still, the idea of as much as 500 K of greenhouse-induced heating was hard to believe at first. On the Earth, the effect is only about 35 K; the larger amounts of carbon dioxide on Venus and it being closer to the Sun imply a larger value but not, in most people's minds, so much. For one thing, the clouds of Venus are so reflective that about 80% of the Sun's heat is reflected back into space: the amount absorbed is less than that of the Earth and actually about the same as that of the relatively distant, dark and icy planet Mars.

The ensuing controversy was resolved only by the flight of Mariner 2, the world's first successful interplanetary probe. It had on board a microwave radiometer similar to those that had detected the hot emission from Venus, the difference being that, carried close to the planet, it could resolve the difference between heat emission from the surface and from the upper atmosphere or ionosphere. The results showed the intensity of the emission falling off from the centre of the planet to the limb, clear support for a source at the surface. Direct temperature sensors on the first successful Venera entry probe provided the final confirmation in 1967.

There followed a flurry of Venus investigation, led by the spacecraft of the Mariner, Venera and Pioneer programmes. Altogether there were 9 instrumented flybys, 15 landers

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