The Mapping of Venus

Presidential Address, 1984

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INTRODUCTION

In the first of my two Presidential Addresses [*Journal,* **94** (2), 45 (1984)] I dealt with the mapping of Mars. That was a fairly straightforward account, because the Martian markings are visible with a small telescope when the planet is best placed, and of course they are permanent; Huygens saw the Syrtis Major as long ago as 1659, and it has not altered much (if at all) since then. But Venus is a different proposition. Its surface is permanently hidden by its obscuring atmosphere; the weather on Venus is always cloudy. Therefore, mapping the features on the surface of the planet itself is impossible by ordinary visual observation; all we can see is the uppermost part of the cloud-layer. It is only in recent times, with the advent of radar and space-research methods, that we have found out what Venus is really like.

In this Address I propose to confine myself, as I did in the case of Mars, to attempts at mapping—with the full appreciation that most attempts before the 1960s were of little true value, though they were far from being devoid of interest.

Venus is almost a twin of the Earth in size and mass, with an atmosphere made up chiefly of carbon dioxide (as we knew as long ago as the 1930s). The sidereal period is 224·7 days; the phase ranges from New to Full—though as the phase increases, the apparent diameter decreases, so that Venus is decidedly awkward to observe. Galileo saw the phases with his early telescopes, and used them as a conclusive disproof of the Ptolemaic theory as opposed to the Copernican, but that was all he could make out.

EARLY DRAWINGS AT THE TELESCOPE

So far as I know, the first attempt at making a telescopic drawing of the markings on Venus was due to the Neopolitan lawyer Francesco Fontana, in 1645. His telescope was probably no better than Galileo's, and the dark patch he showed on the crescent was purely optical. Huygens, who had been so successful with Mars, saw nothing on Venus. In 1666–7 G. D. Cassini, at Bologna, recorded dusky patches and produced the first estimate of the rotation period: 23h 21m, but when he left Italy for the less clear skies of Paris he saw the markings on Venus no more. His son and successor J. J. Cassini also failed. So we come to the first real attempt at a map—by Francesco Bianchini of Rome in 1726, using a 66mm (2·6-inch) refractor with a focal length of 20 metres and a power of 100. This was one of the "aerial telescopes" common at the time. I have always wondered how anybody managed to see anything at all with them! However, Bianchini did—or thought he did. He recorded dark patches which he believed to be permanent, and interpreted them as continents. In 1727 he went on to produce a map, and published it in a book, *Hesperi et Phosphori Nova Phaenomena.* He derived a rotation period of 24d 8h, which was accepted for a long time, and his map was regarded as authentic.

Can we dismiss Bianchini's "oceans" and "continents" as obsolutely illusory? Probably; it is hard to see how he can have recorded anything real. After that there were no more developments until the time of Schröter, later in the eighteenth century.

A word or two about Johann Hieronymus Schröter, amateur astronomer and Chief Magistrate

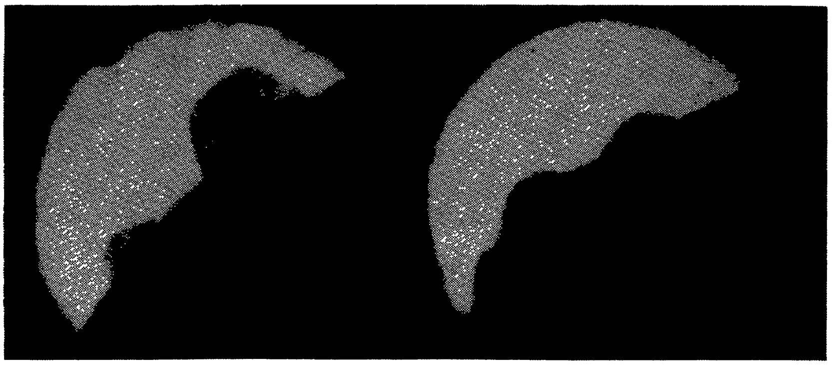

Figure 1. Two drawings of Venus by Francesco Bianchini made in 1726 February 9 (*left*) and February 14 (*right*).

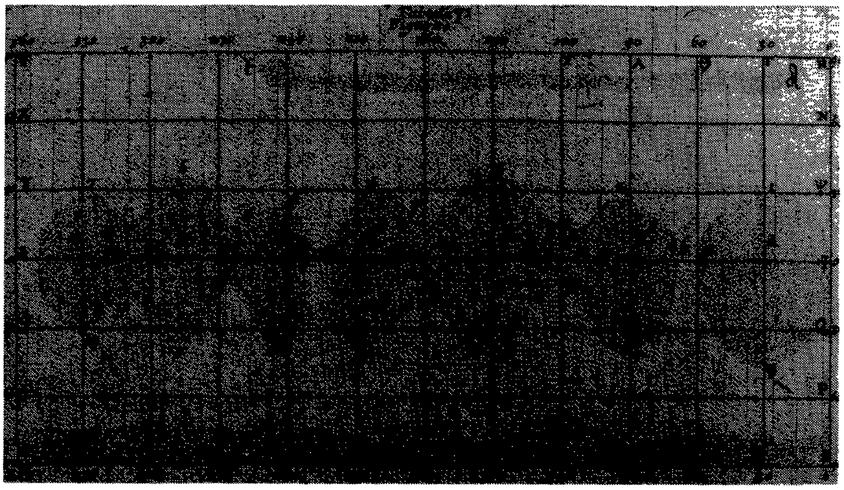

Figure 2. Bianchini's map of Venus, 1727.

of the little town of Lilienthal, near Bremen. I have always felt that historians of astronomy tend to treat him harshly. He was the real founder of selenography; his drawings of Mars were much better than any previously made, though admittedly he misinterpreted them and regarded them as showing atmospheric rather than surface features; and though he was a somewhat clumsy draughtsman, he was not inaccurate. His largest telescope, a 480mm reflector by Schräder of Kiel, may have been imperfect, but he also used telescopes made by William Herschel, which were unquestionably as good as any instruments of the time. (*En passant,* it seems that the only Herschel telescopes ever used for serious work were those used by William, Caroline and John Herschel, and those which were sold to Schröter.)

Schröter did not find Venus an easy object. Between 1779 and 1788 he saw no markings at all, but he made drawings showing a terminator shading which he knew to be optical. Then, on 1788 February 28, he "perceived the ordinarily uniform brightness of the planet's disk to be marbled by a filmy streak". Subsequently he saw other markings, but all were so ill-defined and diffuse that he classed them—correctly, this time—as atmospheric. He did his best to derive a rotation period, and gave a value of 23h 21m 7s·977 in 1811. Giving a value to a thousandth of a second seems rather curious, but it is only fair to add that Schröter was well aware of the difficulties, and commented on them. He gave the axial tilt as 15° to the perpendicular, and in 1789 began a series of observations which he believed to indicate the existence of high mountains; he recorded a luminous speck beyond the southern cusp which he took to be a peak catching the sunlight.

William Herschel was observing Venus during this period, and in 1780 June he had commented that the markings "would not give me the time of rotation of Venus. For the spots often assumed the appearance of optical deceptions, such as might arise from prismatic affections; and I was unwilling to lay any stress upon the motion of spots, that were either extremely faint and changeable, or whose situation could not be precisely ascertained. However, that Venus has a motion on an axis cannot be doubted, from these observations; and that she has an atmosphere is evident, from the changes I took notice of, which surely cannot be on the solid body of the planet".

Schröter, however, was sure of his "enlightened mountains". In 1790 he wrote: "The bright prolongation of the southern cusp, seen on the 10th and 12th of March, must be ascribed to the solar light illuminating a high ridge of mountains situated in this region. . . . Considering the immense height of the mountains, and the great inequalities of the surface of Venus, it is natural to suppose that at the times of the greatest elongations, one cusp frequently appears pointed and the other blunt; owing to the shadow of some mountain darkening the extremity of the latter, the same appearance may often take place in the falcated phase of the planet.... The shadows of mountains will, no doubt, at times occasion an uneven, ragged appearance.... Though we cannot suppose a smaller but rather a greater force of gravity on Venus than on our globe, nature seems, however, to have raised on the former such great inequalities, and mountains of such enormous height, as to exceed four, five and even six times the perpendicular elevation of Cimboraco, the highest of our mountains."

Herschel was not impressed, and published a criticism of Schröter's work, asking "by what accident I came to overlook mountains in this planet which are said to be of such enormous height". He added that "probably the mirror of his telescope, which was a very excellent one, was by that time considerably tarnished", and gave his opinion that "as to the mountains in Venus, I may venture to say that no eye, which is not considerably better than mine, or assisted by much better instruments, will ever get a sight of them".

That sort of tone was atypical of Herschel, but fortunately Schröter's reply was calm and courteous;

he wrote that "I should indeed be surprised that the celebrated author had not, in all the time since 1777, perceived any inequality in the boundary of light, or any other appearance of that kind, tending to confirm the existence of very high mountains . . . were it not that his bold spirit of investigation has been chiefly employed in making much more extensive observations in the far distant region of the heavens, where he has gathered unfading laurels. In fact, the observations which he has communicated from his journals are *much too few* to prove a negative against old and recent astronomers."

NINETEENTH CENTURY OBSERVATIONS

The next important observations were made almost a century after Schröter began his work. They were due to Étienne Trouvelot, a Belgian astronomer, first from Harvard and then from Meudon. Trouvelot recorded the white cusp-caps which were (correctly) regarded as polar, and showed himself to be a supporter of the high-mountain theory. In February 1878 he wrote*: "The polar patches are distinctly visible, the southern one being the more brilliant. Their surface is irregular and seems like a confused mass of luminous points, separated by comparatively sombre intervening spaces. This surface is undoubtedly very broken, and resembles that of a mountainous district studded with numerous peaks. . . . The polar spots seem to be bristling with peaks and needles."

It is worth noting here that the mountain-top theory was still supported as recently as 1947 by Henry McEwen, then Director of our own Mercury and Venus Section. It is ironical that today we know that there are indeed mountains on Venus—but they bear no relation to those reported by Schröter or Trouvelot.

Trouvelot made hundreds of drawings of Venus. He saw vague features, from which he derived a rotation period of 23h 49m 28s, but he was under no delusions, and wrote: "I cannot pass over one curious fact which emerges from an examination of the patches on Venus drawn by different observers; none of the patches drawn by one observer resembles those drawn by others!"

The series of observations by Trouvelot are of special interest in the light of recent events. On 3 September 1876 he recorded what he called "the great grey patch". It "occupied almost a third of the illuminated disk, bordering on to the side of the terminator, which seemed to cut it at the west; to the east, spreading out north and south, it formed a kind of large greyish oval bay. . . . Whether the patch was at a lower level than the whitish bands, or whether it were due to irradiation, it seemed that it caused an irregularity in the terminator. . . . It was not of uniform tint; it was darker toward the south." Trouvelot saw the patch again on September 5, 6

*My translation from the French.—P.M.

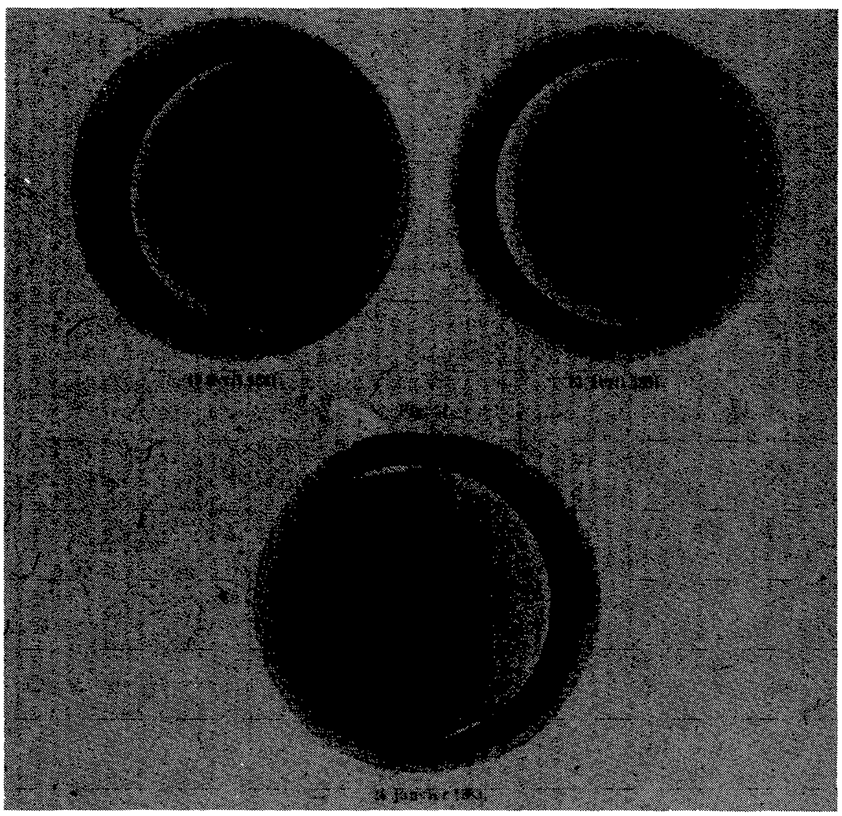

Figure 3. Three drawings of Venus by Etienne Trouvelot made in 1883, 1884 and 1890.

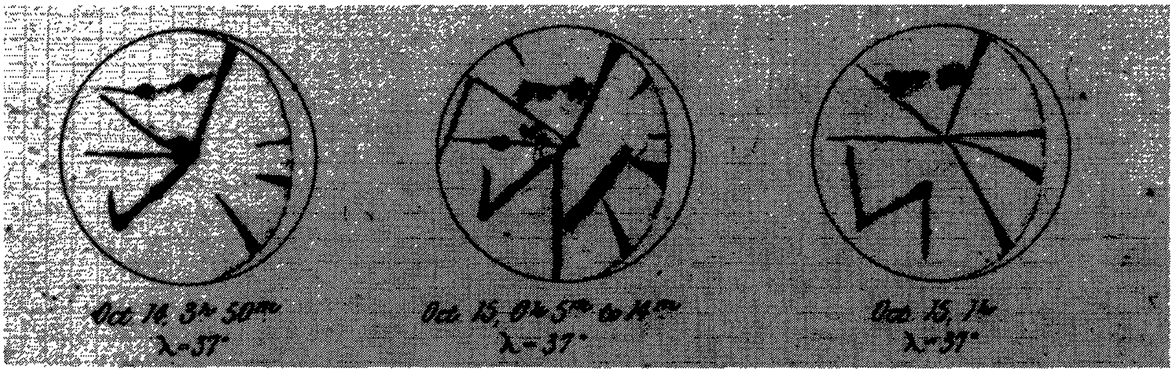

Figure 4. Three drawings of Venus made by Percival Lowell in 1896.

and 10, though with decreasing ease. Fourteen years later, in 1891 February, he recovered it, and wrote: "The resemblance was so striking that it is scarcely possible to avoid the conclusion that they were one and the same patch. Moreover, the conditions were the same." He concluded; in his view "these two features were the same, even permanent patch which, hidden for most of the time by the ordinarily opaque atmosphere, can become visible when there is a temporary clearing in the atmosphere above it."

Of course this is wrong. But it seems that there has been very recent and violent vulcanism on Venus (I will return to this later), and I wonder whether Trouvelot's "great grey patch" can have been produced in such a way? Trouvelot himself certainly believed in vulcanism there, and regarded the polar caps also as elevations. "The mountain massifs of Venus, isolated at opposite poles and with steep, high walls, form peaks and needles which strongly reflect the sunlight, and are certainly of volcanic origin. It is among these high mountains that we find the poles of rotation of the planet—the mountains themselves being simply the polar caps of Venus. The axis of rotation is only 10° to 12° away from the perpendicular to the orbital plane, so that the seasons on Venus are not well marked."

Many other drawings were made around this time (for instance by Lihou in 1885–6, using a small refractor). Meanwhile, G. V. Schiaparelli had entered the lists. We remember Schiaparelli chiefly for his studies of the Martian *canali*; but with Venus he was concerned mainly with the polar caps, and he came to the conclusion that the rotation must be synchronous, so that the same face was always turned toward the Sun. This idea was accepted for many years. Indeed, in 1955 Audouin Dollfus, one of the greatest of all modern planetary observers, still supported it.

Mention of the Martian *canali* brings me on to another controversy, which was not finally settled until our own time. And nor surprisingly, the main character in the story is Percival Lowell. From Flagstaff, using his great refractor, he made studies of Venus as well as Mars, and here too he saw well-defined streaks. His drawings are frankly strange. In 1897 he produced a map, even naming the features which he believed he had seen. From a dark central patch, Eros, he drew well-defined radial strips which were given mythological names; he was sure that the rotation was synchronous. He wrote:

"The markings themselves are long and narrow; but unlike the finer markings on Mars, they have the appearance of being natural, not artificial. They are not only permanent, but permanently visible whenever our own atmospheric conditions are not so poor as to obliterate all detail on the disk. They are thus evidently not cloud-hidden at any time. . . . The markings, which are of a straw-coloured grey, bear the look of being ground or rock, and it is presumable from this that we see simply barren rock or sand weathered by aeons of exposure to the Sun. The markings are perfectly distinct and unmistakable, and conclusive as to the planet's period of rotation. There is no certain evidence of any polar caps."

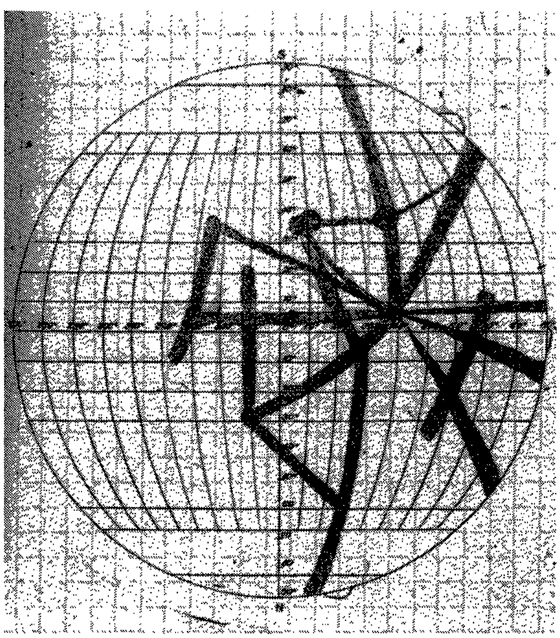

Figure 5. Map of Venus by Lowell.

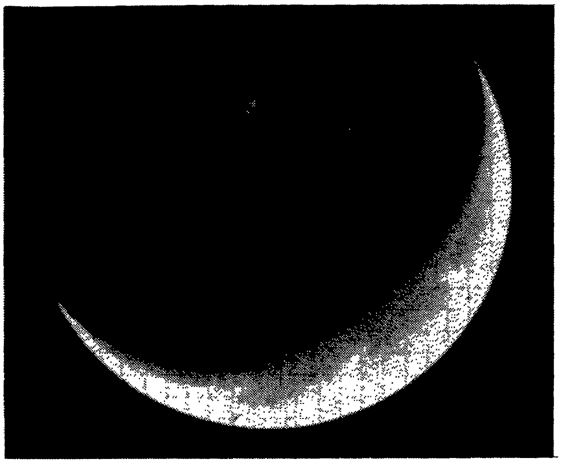

Figure 6. Drawing of Venus made by E. E. Barnard observing with a 160m (12-inch) refractor on 1889 May 29.

Lowell drew similar streaks on Mercury, and on the Galilean satellites of Jupiter. Not surprisingly, he met with criticism. E. M. Antoniadi, once Director of the BAA Mars Section, commented that some people, "forgetting that Venus is decently clad in a dense atmospheric mantle, cover what they call the 'surface' of the unfortunate planet with the fashionable canal network, dividing it into clumsy melon slices having their radiant now on the cusps and then on the visual ray." Another sceptic was E. E. Barnard, renowned for his keen eyesight. Using the Lick Observatory 910mm refractor, he wrote: "Venus has been examined on a number of occasions with the 36-inch, when the planet was beautifully defined. . . . Nothing was seen of the singular system of dark narrow lines shown in recent years by observers to cover the surface of the planet. Every effort was made to show them, by reducing the aperture and by the use of solar screens and various magnifying powers. They were also looked for with the 4-inch finder. Previous attempts with the 12-inch here also failed." He added: "Surface markings were nearly always present, but they were always very elusive, and at no time could a satisfactory drawing be secured."

A. E. Douglass, who worked at the Lowell Observatory and had recorded 'canals', was quick to come to Lowell's defence. In 1898 he wrote:

"In the last six years many thousands of hours have been spent by us at telescopes of 13, 18 and 24 inches aperture and their smaller finders, when the seeing was sufficiently good for profitable work on the finest known planetary detail. . . . The markings on Venus are absolutely certain. Under proper conditions they are to me about as easy or difficult to see as the irregularities in the terminator of the Moon when it is near first quarter, viewed by the naked eye. . . . At the best seeing the markings are visible at the first glance. To say that no markings save M. Antoniadi's symmetrical shadings of atmospheric contrast exist, or that the detail seen here is due to the pressure on our objective . . . is to offer suggestions too absurd to be taken seriously." Douglass then went on to make a comment which seems to be most peculiar: he claimed that other observers had not seen the canals on Venus because they were using telescopes of too great an aperture! "I decided long since that in planetary work the greatest efficiency is obtained with the smallest aperture which supplies the required illumination. There is a limit to this, however; a 1½-inch lens shows the markings on Venus nicely, but they are not so well defined as in a lens of 3 inches, which in our atmosphere is a very satisfactory size to use. When the seeing is bad, an aperture of less than 3 inches will become necessary."

I know the Lowell refractor well; I have used it many times, both for mapping the Moon in the pre-Apollo period and for planetary work. And the idea that it is less effective than a 3-inch portable telescope, such as the one I obtained around the time when I first joined the BAA at the age of eleven, is frankly ridiculous.

VISUAL OBSERVATIONS IN THE TWENTIETH CENTURY

Not many others saw the features as clearly as the Flagstaff obervers. For example Fournier, using a 290mm Merz refractor in 1909, could see nothing except diffuse shadings which were vaguely streaky.

It is interesting to look back at the observations made in 1924 by W. H. Steavenson—how well many

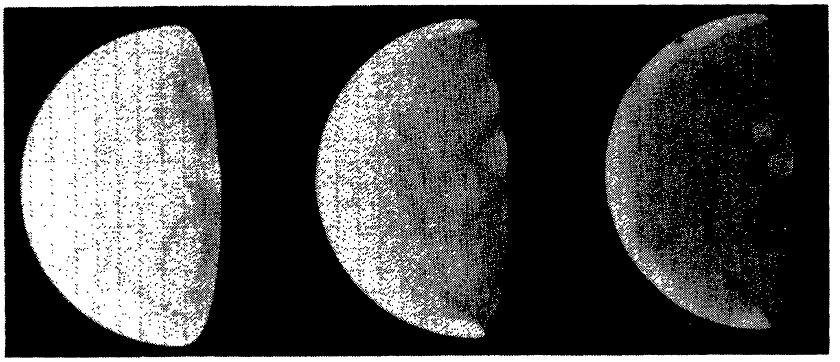

Figure 7. Three drawings of Venus in 1909 by M. G. Fournier, made (*left*) on October 16 and (*centre and right*) on October 19, 2h 15m apart.

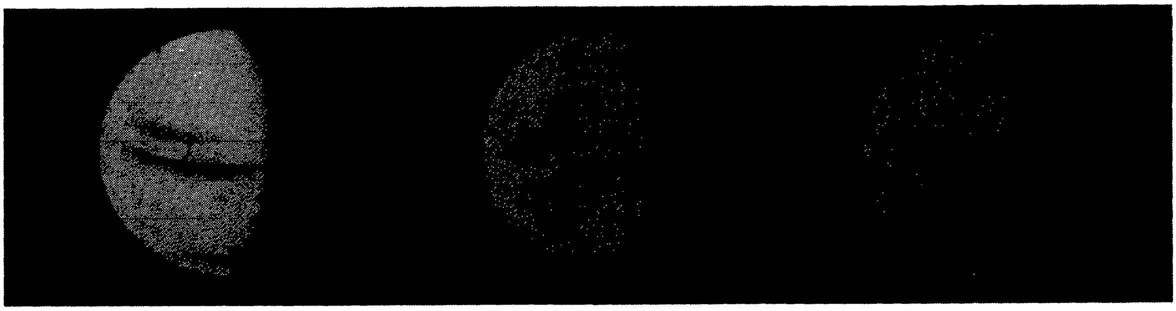

Figure 8. Three drawings of Venus by W. H. Steavenson made in 1924 March 9 (*left*), March 11 (*centre*), and March 12 (*right*).

of us remember him! Using ×280 on a 152mm refractor, he wrote: "I at once saw a marking which was much more prominent than any I have seen before. Its most conspicuous portion took the form of a broad dusky band stretching westward toward the limb from just south of what would be the centre of the disk.... It should be visible in any telescope over three inches aperture." And he added: "The streaks and patches observed in 1924 were unusually long-lived, while their changes of form were sufficiently gradual to enable them to be identified with a reasonable amount of confidence on several (sometimes successive) nights." Steavenson derived a rotation period for the planet of 8 days.

What about photographs? White-light pictures showed nothing definite. Using the Mount Wilson 1·5 metre reflector, F. E. Wright showed vague patches in ultraviolet, but these clearly referred only to high-level clouds.

The 'spoke-system' refused to die. It was recorded again by F. E. Seagrave in 1919, with a 210mm reflector, who wrote: "I am very sure that I could see faint traces of the spoke-like markings near the centre of the disk. They were very much like those seen and described many years ago by the late Dr Percival Lowell." Then, in 1932, Robert Barker published a paper in our own *Journal* which appeared to confirm Lowell's findings. He wrote:

"I have been able to secure records of markings, some of which were very distinct and if not permanent, were of lasting duration. These included Lowell's named features such as Astoreth, Ashera and Hero." Barker, using a 320mm Calver reflector (an excellent one; I have used it myself) generally employed a power of 325. He supported the synchronous rotation period, and followed up his first paper with another in 1934. Undoubtedly he regarded the streaks as surface features rather than clouds.

In 1951 the controversy was re-opened. P. Cluff, using ×121 on a 150mm reflector, drew streaks which were near-Lowellian. In the same year drawings were made by R. M. Baum, the present Director of our Inner Planets Section, using ×100 on a 76mm refractor—the aperture advocated by Douglass. At once we were back to the central patch and the radial spokes. I could see no trace of them, using large telescopes as well as small ones. Indeed, whenever I saw shadings I had to exaggerate them on drawings for the sake of clarity. On the other hand O. C. Ranck, using a 100mm reflector, and H. Squyres, with a 150mm, supported Baum in principle. It seemed that small apertures would show the spoke-system while larger ones would not, and I was from the start convinced that the whole system was an optical effect.

Richard Baum—a very valued friend of mine—and I had quite an argument in print (in the American periodical *The Strolling Astronomer*). Our views were diametrically opposed. Baum maintained

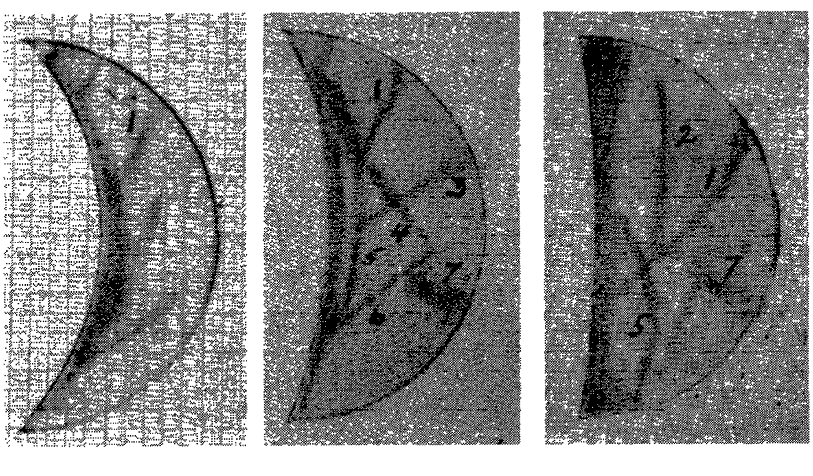

Figure 9. Three drawings of Venus by Robert Parker made in 1932 March 31 (*left*), April 20 (*centre*) and May 2 (*right*) using a power of 210.

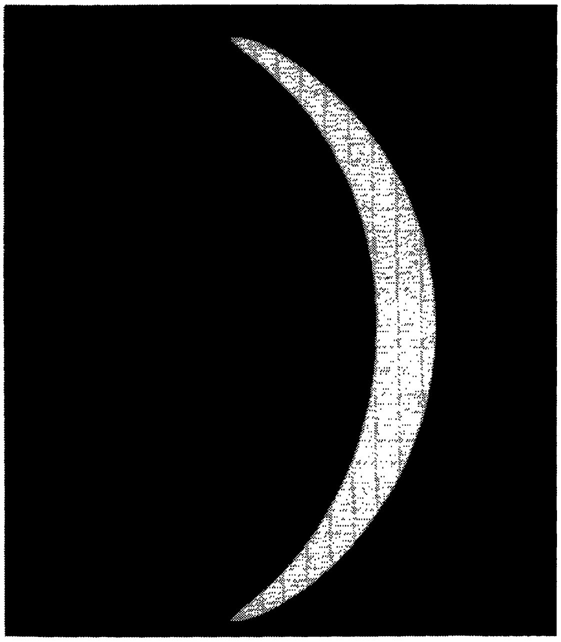

Figure 10. Venus photographed at Palomar Observatory with the 5-metre (200-inch) reflector.

that "Mars, we know, exhibits canals; hence Lowell's work is accurate". He also maintained that Douglass was right in claiming that under most conditions Venus was best observed with a small telescope. Baum wrote:

"Unfortunately Moore, though an experienced observer, reveals a deplorable lack of knowledge respecting this question both historically and theoretically. . . . Many have refuted Lowell's work simply because of his trend toward the canaliform in planetary features, and have stood by their rejection without bothering to investigate the matter any further than the use of hackneyed argument allows. While recognizing the ingenuity of many explanations, I personally regard them as being too little and too superficial to be employed as statements of authoritative negation. . . . When I first saw the spokes in 1951, they seemed to be narrow smokelike features definitely linear and symmetrically placed around the subsolar point like the spokes of a wheel. As my experience broadened so did my delineation of the spokes; instead of being the narrow features of first sight, comparatively broad diffuse bands were being recorded. . . . The use of large apertures is strictly limited to those climes where seeing is usually above the average. In other regions the poor seeing is so magnified by the large aperture that any markings, especially faint ones as those of Venus are, will be effaced or so masked as to look entirely different from what they really look like. Thus though a small aperture does not have the resolving power, it does nevertheless reveal a general light and shade impression which is better than any other for correct evaluation purposes."

In 1955 Baum was essentially supported by Dollfus, who found that the dusky markings of Venus often showed the pattern of a radial system with its centre at the subsolar point. Both Baum and Dollfus are considerably better observers and infinitely better draughtsmen than I will ever be. Yet in this particular case I think that in view of what we now know, we must admit that the spoke-system does not exist; it is as unreal as the canal network on Mars.

The work carried out at Meudon in 1961 by Boyer and Guèrin was different. They had no faith in the radial spokes, but they did record a persistent Y-shaped feature, clearly atmospheric, from which they derived a retrograde rotation period of 4 days. At the time I was sceptical; most people agreed with G. P. Kuiper that the rotation period was probably about a month (the idea of its being longer than the revolution period had not then been considered). I was completely wrong. The Boyer–Guèrin Y-feature has been confirmed by the spaceprobe results, and so has the 4-day rotation period of the upper clouds. It was an outstanding piece of careful, accurate observation.

SPECULATIONS ABOUT THE SURFACE OF VENUS

So—what was Venus really like?

There had been many suggestions. In 1918 Svante Arrhenius, a Swede whose work was good enough to

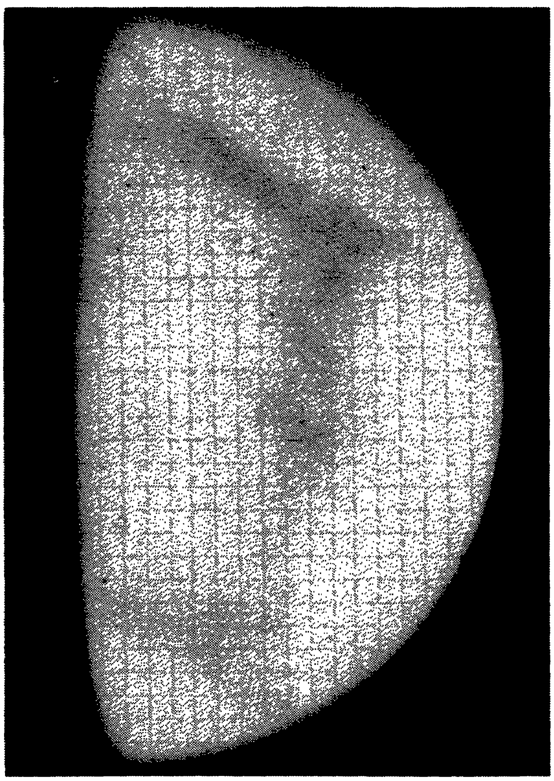

Figure 11. Drawing of Venus by Patrick Moore using a 317mm (12½-inch) reflector.

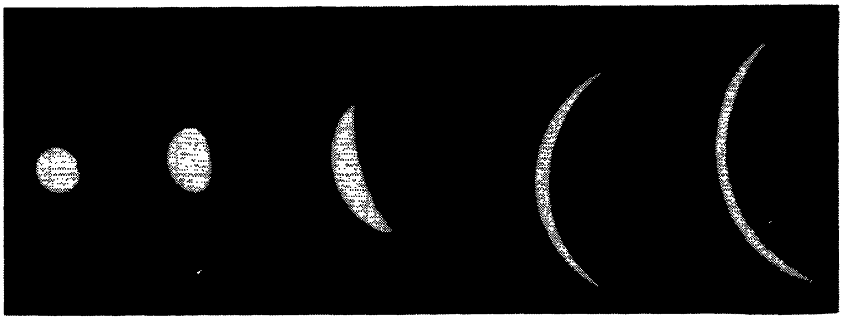

Figure 12. Photograph of the phases of Venus.

win him a Nobel Prize, published a vivid description of the kind of world he imagined Venus to be:

"The average surface temperature there is calculated to be about 47°C. . . . The humidity is probably about six times the average of that on the Earth, or three times that in the Congo, where the average temperature is 26°C. The atmosphere of Venus holds about as much water vapour 5km *above* the surface as does the atmosphere of the Earth *at* the surface. We must therefore conclude that everything on Venus is dripping wet. The rainstorms, on the other hand, do not necessarily bring greater precipitation than with us. The cloud-formation is enormous, and dense rain-clouds travel as high up as 10km. The heat from the Sun does not attack the ground, but the dense clouds, causing a powerful external circulation of air which carries the vapour to higher strata, where it condenses into new clouds. Thus, an effective barrier is formed against horizontal air-currents in the great expanses below. At the surface of Venus, therefore, there exists a complete absence of wind both vertically, as the Sun's radiation is absorbed by the ever-present clouds above, and horizontally, due to friction. Disintegration takes place with enormous rapidity, and violent rains carry the products speedily downhill, where they fill the valleys and oceans in front of river mouths.

"A very great part of the surface of Venus is no doubt covered with swamps, corresponding to those on Earth in which the coal deposits were formed, except that they are about 30°C warmer. No dust is lifted high into the air to lend it a distinct colour; only the dazzling white reflected from the clouds reaches the outside space and gives the planet its remarkable, brilliantly white lustre. The powerful air-currents in the highest strata of the atmosphere equalize the temperature difference between poles and equator almost completely, so that a uniform climate exists all over the planet.

". . . The temperature on Venus is not so high as to prevent a luxurious vegetation. The constantly uniform climatic conditions which exist everywhere result in an entire absence of adaptation to changing exterior conditions. Only low forms of life are therefore represented, mostly no doubt belonging to the vegetable kingdom; and the organisms are of nearly the same kind all over the planet. The vegetation processes are greatly accelerated by the high temperature. Therefore, the lifetime of organisms is probably short. Their dead bodies, decaying rapidly if lying in the open air, will fill it with stifling gases; if embedded in the slime carried down by the rivers, they speedily turn into small lumps of coal which later, under the pressure of new layers combined with high temperature, become particles of graphite. . . . later, the temperature will sink, the dense clouds and gloom disperse, and some time, perhaps not before life on Earth has reverted to its simpler form or even become extinct, a flora and fauna will appear, and Venus will then indeed be the 'Heavenly Queen' of Babylonian fame, not because of her radiant lustre alone, but as the dwelling-place of the highest beings in our Solar System."

In the same year the Russian 'astrobotanist' G. A. Tikhoff wrote: "Owing to the high temperature, the planet must reflect all the heat rays, of which those visible to the eye are the rays from red to green inclusive. In addition, the plants must radiate red rays. With the yellow, this gives them an orange colour. . . . Thus we get the following gamut of colours: on mars where the climate is rigorous the plants are blue. On Earth where the climate is intermediate the plants are green, and on Venus where the climate is hot the plants have orange colours."

Sir Fred Hoyle had different views, expressed in 1955. He believed Venus to have oceans of oil! "In writing previously about the clouds I said that the only suggestion that seemed to fit the observations was that the clouds are made up of fine dust particles. To this suggestion we must now add the possibility that the clouds might consist of drops of oil—that Venus may be draped in a kind of perpetual smog. . . . The slowing-down of the rotation of Venus can be explained by the friction of tides—if Venus possesses oceans, but not I think otherwise. Previously the difficulty was to understand what liquid the oceans were made of. Now we see that the oceans may well be oceans of oil. Venus is probably endowed beyond the dreams of the richest Texas oil-king."

F. L. Whipple and D. H. Menzel also believed in oceans—but of water, not oil. The alternative theory was that Venus must be a fiercely-hot dust-desert,

Figure 13. Mosaic of photographs of Venus taken by *Mariner 10* in 1974.

Figure 14. Capsule of the Russian *Venera 7.*

without a trace of moisture anywhere. But nobody really knew; and there matters remained until first radar, and then spacecraft came to the rescue. Early radar proved that the rotation was not synchronous. Definite features were recorded, some of which appeared to be craters. The modern age was at hand.

OBSERVATIONS OF VENUS FROM SPACE

This Address has been primarily historical. In my Mars address last year I more or less ended where the Space Age began. I must today say a little more about studies of Venus in very recent times, because it is only now that we have any reliable maps, but I will be relatively brief.

The first attempt to rendezvous with Venus was a Russian one. *Venera 1* was launched on 1961 February 12, but contact with it was lost at a distance of less than 8 million km, and was never regained. In 1962 July America's *Mariner 1* was even less successful; it plunged into the sea, apparently because someone had forgotten to feed a minus sign into the computer (a slight mistake which cost approximately £4,280,000). But *Mariner 2*, sent up from Cape Canaveral on August 27, more than compensated. On 1962 December 14 it passed within 35 million km of Venus, and though it sent back no pictures it cleared up many of the outstanding problems. The surface temperature really was intolerably high; gone were Arrhenius' swamps, the Whipple–Menzel ocean and Hoyle's oil. The desert theory was right. In fact, Venus as a potential colony was ruled out. In 1967 *Mariner 5* passed Venus at 4000km, and confirmed the earlier results. The next American probe was *Mariner 10*, which by-passed Venus on 1974 February 5 on its way to Mercury, and sent back excellent pictures of the cloud-tops, finally killing off Lowell's canals and the spoke-system. The clouds at the equator were obvious; so was the south polar cap—and as an old observer I am glad that we were right in that respect at least. Perhaps most importantly, the 4-day rotation period for the upper clouds was confirmed, though the planet itself takes 243 Earth-days to make one rotation.

The Russians were more concerned with soft landings, which the Americans had originally dismissed as being too difficult. *Veneras 3, 4, 5* and *6* transmitted while descending through the planet's atmosphere, but were literally squashed by the immense pressure before arrival at the surface. *Venera 7* was more successful, and transmitted for 23 minutes after touch-down before being put permanently out of action by the hostile conditions. *Venera 8*, of 1972, also came down safely, transmitting for 30 minutes and showing that the surface windspeeds were less than 1 metre per second and that the temperature profile on the day-side was

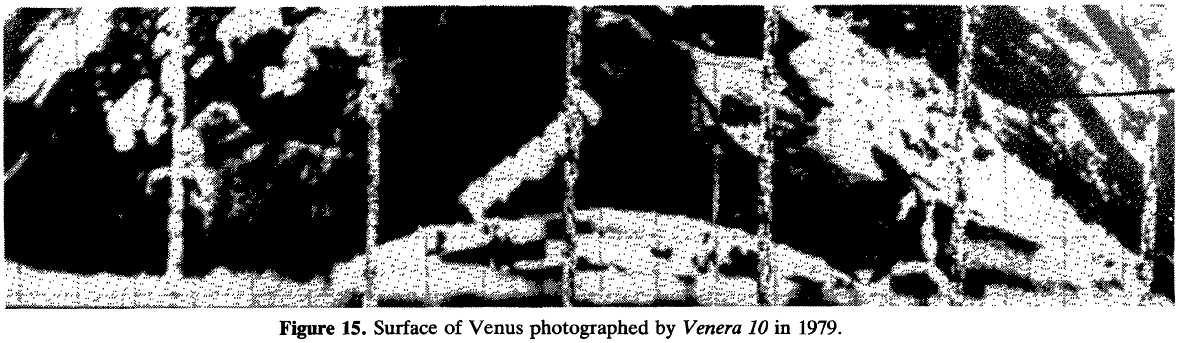

Figure 15. Surface of Venus photographed by *Venera 10* in 1979.

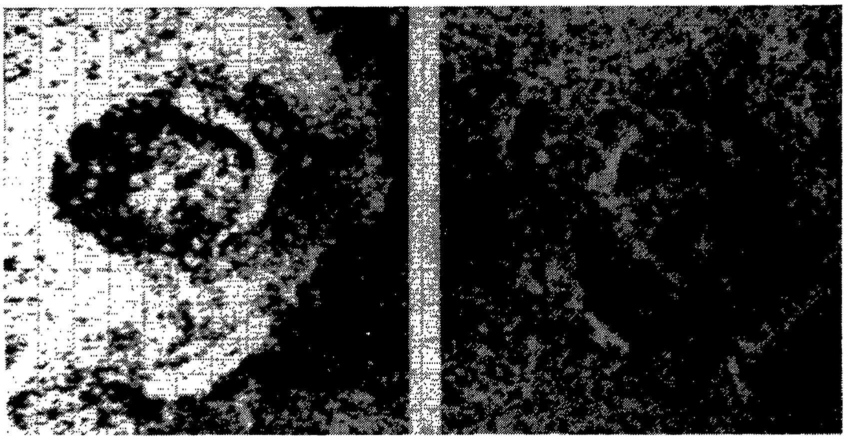

Figure 16. Craters 100 to 200km in diameter, photographed by *Venera 15* in 1983.

much the same as that on the night-side, where *Venera 7* had come down. On 1975 October 21 *Venera 9* obtained the first surface picture; it showed a gloomy, rock-strewn landscape—the light-level was compared with that in Moscow at noon on a cloudy winter day. Less than a week later *Venera 10* repeated the success. The landing areas were not identical, but were of the same general type. In 1982 came *Veneras 13* and *14*, which even sent back colour pictures; the sky of Venus is bright orange, and the rocks glow under the scorching heat. *Veneras 15* and *16* were made up of orbiters plus landers. The radar equipment carried by the orbiters sent back high-resolution pictures, good enough to show craters down to 100km in diameter. There are ray-craters, and the latest 'strips' show lava-flows with a resolution down to a mere 3km. Unlike the soft-landing lunar and Martian probes, the Venus lenders can hardly have survived for long, particularly in view of the great quantity of corrosive sulphuric acid.

The Americans were far from idle. The *Pioneers* were launched in 1978 August, and reached Venus in December. The lander was a multi-probe vehicle, consisting of a "bus" and four smaller probes; they were not designed to survive impact on Venus, though in fact one of the smaller probes did so and transmitted briefly after arrival. In the long run the orbiter was more valuable. It began mapping the planet by radar, and is still doing so (1984 October).

Predictably, the first *Pioneer* picture showed a featurelsss crescent. Close-range images showed the now familiar Y-feature. But above all, *Pioneer's* radar provided the first true map of Venus' surface, and by now we have a detailed knowledge of 80% of it, from latitude 75° north to 63° south. There are highlands, lowlands, and a huge rolling plain covering 60% of the total. The two largest highlands (continents, if you like) are Ishtar Terra in the north and Aphrodite Terra straddling the equator. Ishtar is about the size of Australia; to its eastern side are the Maxwell Mountains, the highest points on Venus, rising to 10·3km above the mean level and 8·2km above the adjoining plateau. Aphrodite measures 9700 × 3200km, and consists of east and west mountains separated by a lower region. There are also rift valleys, one of which dwarfs our Grand Canyon and rivals the Valles Marineris on Mars.

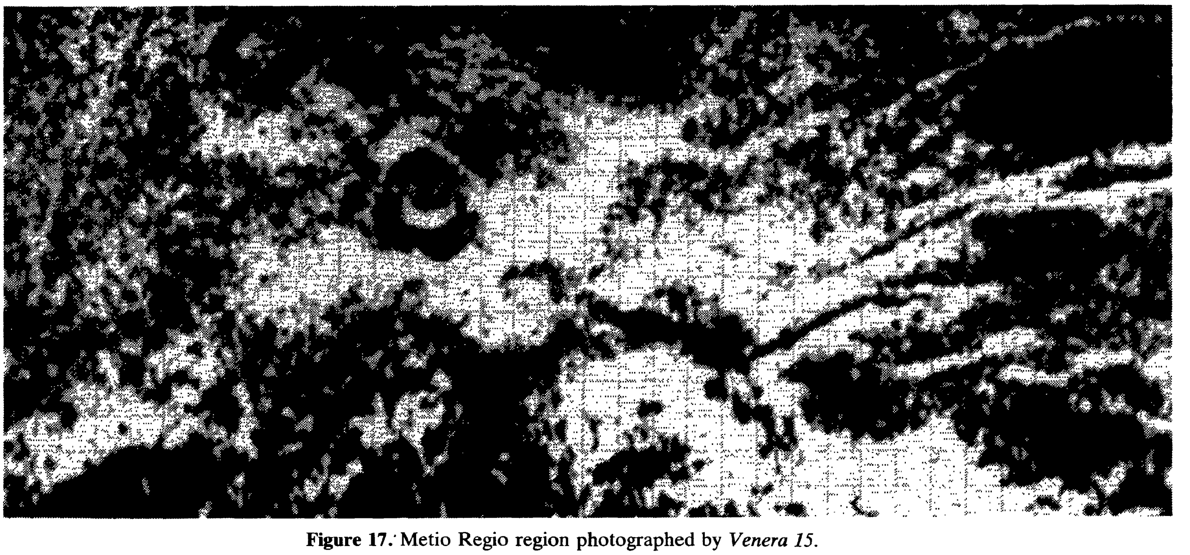

Figure 17. Metio Regio region photographed by *Venera 15*.

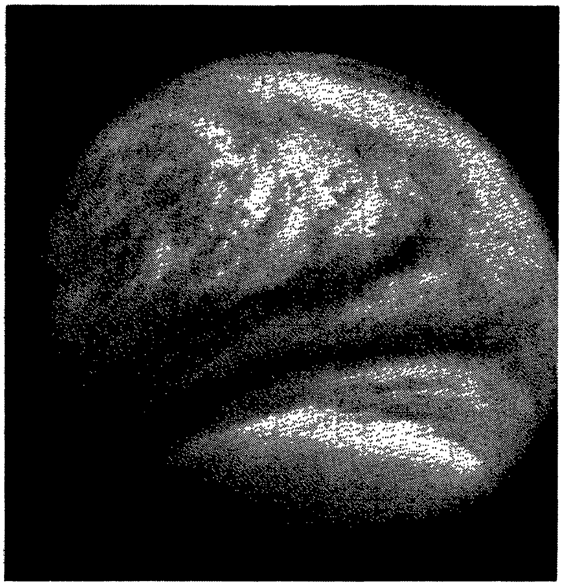

Figure 18. Ultraviolet photograph by the *Pioneer* Venus orbiter in 1979.

Beta Regio, a smaller highland, is perhaps the most interesting area on Venus. It seems to consist of two vast shield volcanoes, Rhea Mons and Theia Mons, both of which rise to 4km; basically they are very much like our Hawaiian volcanoes of Mauna Kea and Mauna Loa, but are more massive. Also, there is every indication that they are extremely active. On Earth, a volcano arises over a 'hot spot' or plume in the mantle, and when the plate moves on the volcano dies; this has happened to Mauna Kea, while Mauna Loa is now over the plume. The new science of plate tectonics has revolutionized all our ideas. Venus, however, seems to be a one-plate planet, so that a volcano will stay over a plume and remain active for a very long time indeed—as with Rhea and Theia. The other main volcanic area is Atla Regio, in the so-called "Scorpion's Tail" of Aphrodite. Clusters of lightning bolts provide extra evidence.

Moreover, we have the data collected by L. Esposito and F. Scarf in America. They find that in 1978 the amount of sulphur dioxide in Venus' atmosphere increased by a factor of over fifty, and suggest that this was due to a vast eruption sending huge amounts of sulphur dioxide and haze particles into the atmosphere to a height of at least 70km. (Do you recall Trouvelot's "great grey patch"?) The volcanoes of Venus may be far more devastating than ours. The Earth's sulphur dioxide level after the recent El Chichón eruption in Mexico was only 10% of the 1978 levels on Venus. Since 1978, the amount of sulphur dioxide in the atmosphere of Venus has been falling again. Maxwell Montes, the highest on Venus, are more probably genuinely extinct, or at least dormant.

In a way I suppose that Venus has been a disappointment. We now know that it is hopelessly hostile. The carbon dioxide atmosphere has a ground pressure 90 times that of our air at sea-level; the clouds contain sulphuric acid; the ground temperatures are not far short of 1000° Fahrenheit. As I have commented, anyone who goes there and ventures unprotected on to the surface will be at once fried,

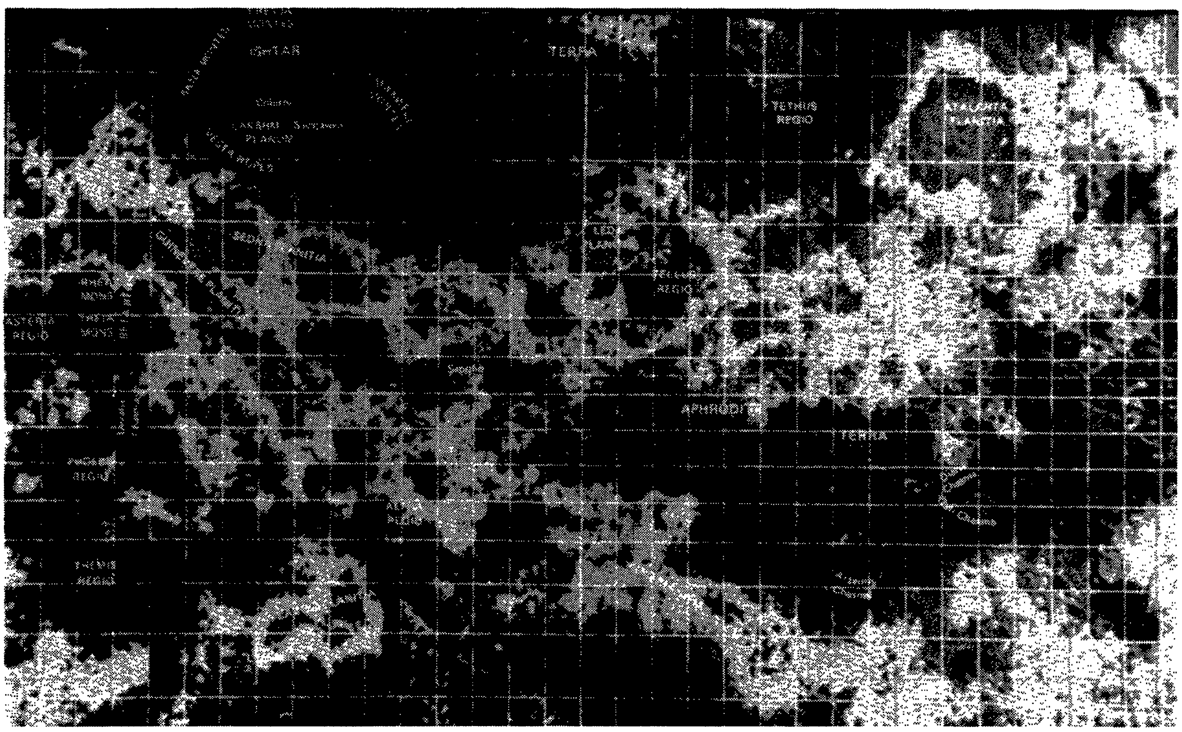

Figure 19. Map plotted by radar from the *Pioneer* Venus orbiter.

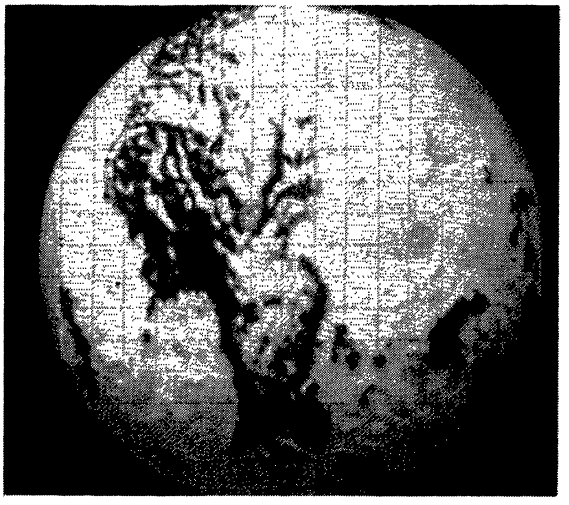

Figure 20. Global view of Venus showing Aphrodite; obtained by radar from the *Pioneer* Venus orbiter.

squashed, poisoned and corroded. It may not always have been so; in the early days of the Solar System, when the Sun was 30% less luminous than it is now, Venus and the Earth may have begun to evolve along similar lines, with the same types of atmospheres and oceans, and perhaps primitive life. But as the Sun grew more powerful, the oceans of Venus boiled away; the carbonates were driven out of the rocks, and as a runaway greenhouse effect transformed Venus into the furnace-like environment of today any life there was ruthlessly snuffed out. If so, then Venus is a tragic world. It is rather sobering to reflect that if the Earth had been a mere twenty million miles closer to the Sun, it might have suffered the same fate—and you and I would not be here.

Future exploration? The Russians plan to drop landers on to Venus from their *Vega* probes *en route* to Halley's Comet, and even a balloon to float about and send back information from different levels in the atmosphere. Another American radar mapper is scheduled for the later 1980s. But I do not foresee that men will go there—at least in the foreseeable future, perhaps never. Carl Sagan's plan for 'seeding' the atmosphere and terraforming the planet seems very remote, if it is possible at all. For now, we must accept Venus as it is. But though it is so hostile, and so remarkably like the conventional picture of hell, it retains its fascination for us, and there is a great deal about it which we still do not know.

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