Chapter 1
The dawn of Venus exploration

The Evening Star and the Morning Star

Everyone has seen Venus, as a bright, starlike apparition in the evening sky, following the Sun down towards the horizon and setting a few hours later. At various other times of the year, there comes a brief season where an early bird can see Venus rise brilliantly before the Sun, climbing higher until it seems to dim and vanish as the sky brightens after sunrise. When it rises before the Sun, people have long called Venus the Morning Star; half an orbit later, when on the other side of the Sun so that the Sun sets first, Venus is the Evening Star. Before Copernicus promoted the idea that planets orbit the Sun, it was not obvious that these two phenomena were the same body, and early civilisations had distinct names for them. To the Greeks, they were Phosphoros and Hesperos.

For much of the year, Venus sets and rises so near the Sun that we tend not to notice it. During the day, like the true stars at vastly greater distances, Venus is still overhead and just as bright, of course, but it is hard to see because the contrast with the dark sky is lost when the Sun is up. It can be studied during the day if a telescope is used to shut out most of the sunlight, and even with ordinary binoculars if you know where to look.[1] In any observations made over a period of a few months, Venus can be seen to exhibit lunarlike phases (Figure 1.1).

As viewed from the Earth, Venus traces a flattened ‘figure eight’ pattern with the Sun at the centre (Figure 1.2). Sometimes, but rarely, Venus travels across the disc of the Sun when at its closest to the Earth, or behind the Sun when at its farthest, and we witness a transit.

At closest approach to the Earth (inferior conjunction), not only is Venus near the Sun in the sky, making viewing difficult, but also the side facing us is dark (Figure 1.2). A fully illuminated disc can be seen, again with difficulty, only when Venus is on the far side of the Sun, at so-called superior conjunction.

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[1] There are also reports of Venus seen with the naked eye during the day. The most famous of these involved Napoleon Bonaparte, whose attention was called to the phenomenon while he was delivering an open-air, midday address to a crowd in Luxembourg in 1796. A similar apparition was reported in Washington DC on the day of Abraham Lincoln’s second inauguration in 1865.

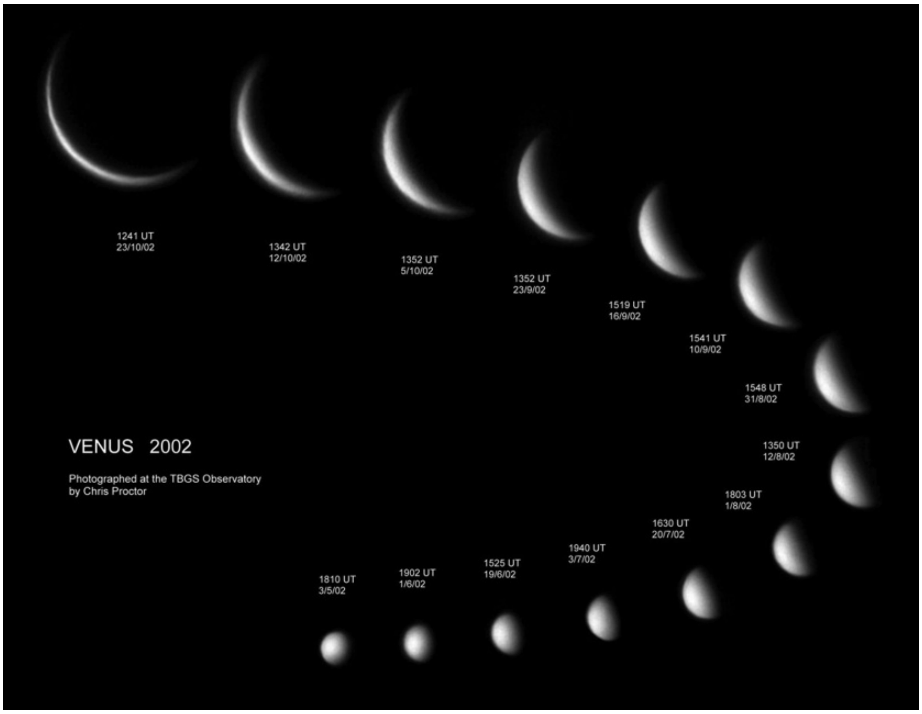

Figure 1.1 Venus at different points in its orbit, showing the phases from near superior conjunction (beyond the Sun, at bottom) to near inferior conjunction (closest to Earth, top).

The time between sunset and Venus's disappearance below the horizon, and vice versa, is greatest when it appears at its greatest separation from the Sun, called opposition, and viewing conditions are usually best then. However, the time when Venus appears brightest to us is not in fact exactly at opposition, but halfway between opposition and inferior conjunction, when the trade-off between size of the disc and the portion illuminated, what astronomers call the phase, is optimum.

Because it is at times such a brilliant object, Venus has been observed since the earliest times and used as an object of veneration[2] and as a celestial calendar by many early civilisations, most notably the Mayans in South America. There has been some interesting debate as to whether pre-telescopic observers could see the crescent shape of Venus with the naked eye. Written references to 'horned Venus' and implications that some symbolic crescents in art and heraldry might relate to Venus rather than the Moon would seem to support this idea, but the difficulty we have in achieving the feat today suggests otherwise (Plate 2).

The angle between a line from the observer on Earth to the centre of the Sun, and the corresponding line to Venus, is never more than 47.5 degrees (Figure 1.2). So, when the Sun is just set and our eyes are shielded from most of its light, allowing Venus to appear

[2] Nowadays of course most frequently associated with the Roman goddess of love, from whom the planet takes its modern name (Plate 1).

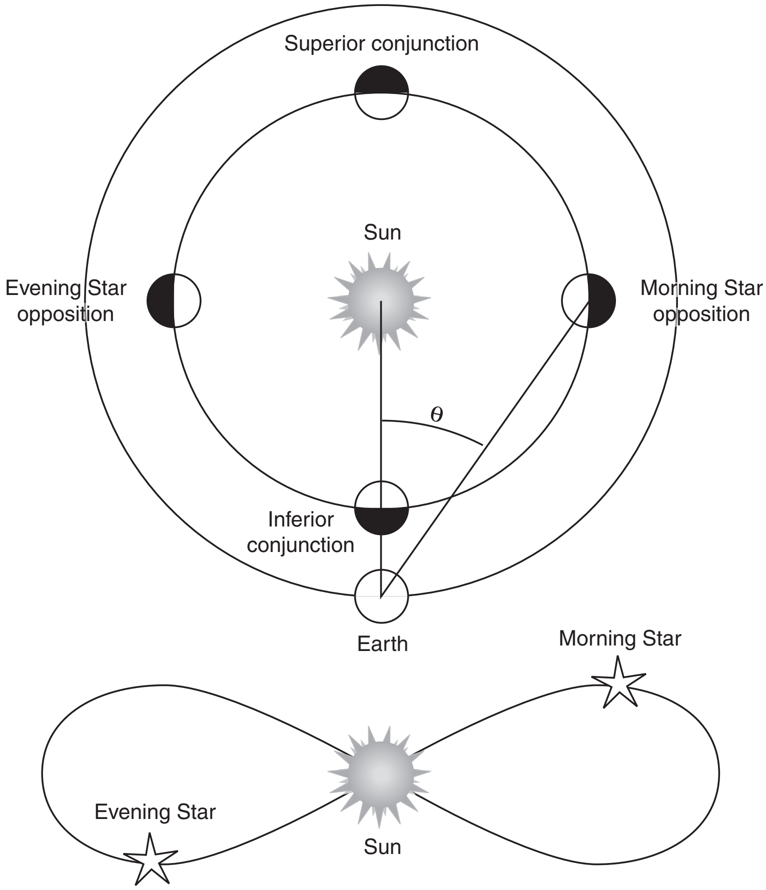

Figure 1.2 The orbits of Venus and Earth seen from above (top), and the apparent motion of Venus in the sky as viewed from Earth (below). It appears brightest at the points marked by stars, while approaching maximum elongation (i.e. the greatest apparent distance from the Sun). At that time, through a telescope it has the appearance of a crescent, as illustrated in Figure 1.1.

brightly, the planet is never more than halfway between the horizon and the zenith, that is, its elevation is always in the lower half of the sky. Mercury rises only half as far as Venus. The earliest recorded interpretation of these easily and much observed facts as meaning that Venus and Mercury orbit the Sun, and not the Earth, was made by Heraclides around 350 BC. Also in Greece, around 70 years later, Aristarchus surmised that the Earth, and everything else in the Universe, did the same.

The idea that the Earth was not the centre of the universe was too radical in those days, especially for the clerics, and of course was reluctantly accepted only much more recently. The breakthrough came in the early 1600s when the arrival of even very crude telescopes soon had Galileo following Copernicus and proclaiming the phases of Venus as a Moonlike phenomenon ('Cynthiae figuras aemulatur mater amorum') and making the heretical deduction that Venus must orbit the Sun. Not only that, but the 'Morning and then Evening' Star behaviour and the crescent phases must occur because Venus, and the much-dimmer and less well-observed Mercury, orbit closer to the Sun than the Earth. The other planets, which behave quite differently in the sky, lie outside the Earth's orbit.

In particular this must be true of the fourth member of the inner planet family, Mars. Mars is our second-nearest planetary neighbour, but Venus is larger (nearly as large as the Earth, see Plate 3) and significantly closer. Venus also has more cloud cover than the other three inner planets, not excluding the Earth, which makes its visible surface more reflective.[3] These three factors – size, proximity and albedo – explain why Venus can appear so bright.

Once it became an accepted principle for heavenly bodies to orbit the Sun and each other, it also became logical to wonder whether Venus had any satellites. It has been pointed out that if Venus had a moon on the same scale as the Earth's, it would be easily visible to the naked-eye observer here, including, of course, the ancients.[4] Under optimum conditions, the Venusian moon as seen from the Earth would be separated by more than a solar diameter from its parent in the night sky, and would be as bright as Saturn. Asimov points out that this obvious demonstration of one planetary-sized object orbiting another would have had a profound effect on the philosophers who pondered the nature of the universe, comparable to that after Galileo's observation of four large moons of Jupiter following the invention of the telescope. The Copernican revolution might have come thousands of years sooner, and Galileo might have been spared persecution, amongst many other consequences.[5]

Transits: Venus crosses the disc of the Sun, but rarely

If Earth and Venus orbited in exactly the same plane, we would see the disc of Venus as a dark spot crossing the Sun (a 'transit') every time the planet reached inferior conjunction, that is every 1.6 years, and then passing behind it 288 days later. However, the two orbital planes are tilted with respect to each other at an angle of 3.4 degrees, and this, plus the timing of the alignments of the three bodies in a straight line, means that transits are actually quite infrequent phenomena. Most of the time, Venus passes above or below the solar disc as seen from Earth.

About once a century, however, the path traced by Venus does cross the Sun, and then it does so twice in eight years, once in the upper and once in the lower solar hemisphere, as it moves from above the Sun to below, or vice versa. The pattern repeats every 243 years, with pairs of transits 8 years apart separated by gaps of 121.5 years and 105.5 years, the most recent pairs being in June 2004 and June 2012 (Plate 4). Before that, they were in December 1874 and December 1882, while the next will not take place until December 2117 and December 2125.

[3] Cloudy Venus has an albedo (from the Greek meaning 'whiteness') of about 0.76, which means it reflects all but 24 per cent of the sunlight that falls on it. Mars, by contrast, has little cloud cover and most of the reflected radiation comes from the relatively dark, rocky surface. The result is an albedo of only about 0.2. Earth is somewhere in between, with partial cloud, ice and ocean cover which together deliver an albedo in the region of 0.3.

[4] By Isaac Asimov, for example, in *The Tragedy of the Moon* (London, 1975).

[5] By an unusually, for him, arcane argument, Asimov suggests that these consequences would also mean that mankind nowadays 'may well be approaching the end of its days as a technological society' (ibid., pp 15–26).

The reason for this somewhat bizarre pattern of events has to do with the orbital periods of both planets, as well as their inclinations. It takes 243 years for Earth and Venus to return to the same relative positions because Venus travels around the Sun exactly 395 times in that many Earth years. A second orbital resonance, also probably coincidental, has thirteen Venus orbits in almost exactly eight Earth years, giving the eight-year separation of transits when the line from Earth to Venus at inferior conjunction intersects the Sun.

Other factors, such as the eccentricity[6] and precession[7] of both orbits, complicate the calculation, so the task of determining the timing of transits accurately is best done on a computer. Johannes Kepler attempted some predictions as early as 1627, but although he got the year of the next Venus transit right (1631), he did not realise that it would not be visible in Europe, nor that another was to come eight years later that would be. Improved calculations by Jeremiah Horrocks led him to make observations of the transit in 1639, from which he estimated the size of Venus and computed the first modern value of the distance from the Earth to the Sun,[8] allowing a scale to be put on the rest of the Solar System using Kepler's laws of planetary motion.

Later observers, most famously those travelling with Captain Cook on his first voyage around the world at the time of the transit of 1769, used the method derived by Edmond Halley (Figure 1.3) to get an improved value for the astronomical unit by simultaneous measurements from widely separated baselines on Earth.[9] Cook's observations (Figure 1.4)

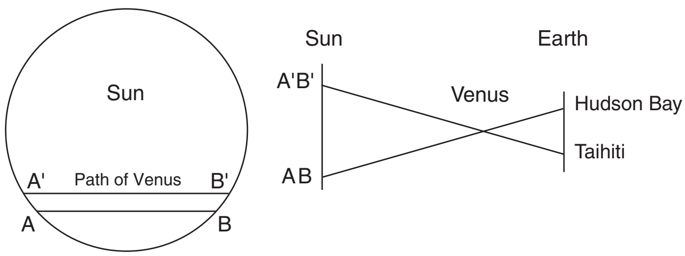

Figure 1.3 Halley's method for determining the Earth–Sun distance (1 AU) by observations of the transit of Venus across the solar disc from two widely separated locations on Earth. The observers measure the separation AB to A'B' as accurately as possible from the time taken for Venus to cross the solar disc in both cases, and use the fact that the Sun–Venus distance is 0.723 AU as determined from Venus's orbital period using Kepler's third law.

[6] The eccentricity of an orbit is a measure of its departure from a perfect circle, something which changes slowly over long periods of time. The current values for Earth and Venus are 0.0167 and 0.0068, while a circle is of course 0.0000.

[7] 'Precession' refers to how the alignments of the two non-circular orbits vary with respect to each other under the influence of gravitational perturbations from other large bodies, especially the Sun and Jupiter.

[8] Horrocks's result for the Earth–Sun distance, published after his premature death in 1641 aged only 22, was 'at least 15,000 semidiameters of the Earth'. This corresponds to a lower limit of about 60 million miles, much larger than generally believed at the time, and highly controversial, but still about 30% smaller than the modern value.

[9] The mean Earth–Sun distance is known as the Astronomical Unit (AU), so called because the scale of the Solar System could be estimated in AU well before the distances between the planets were known in absolute terms.

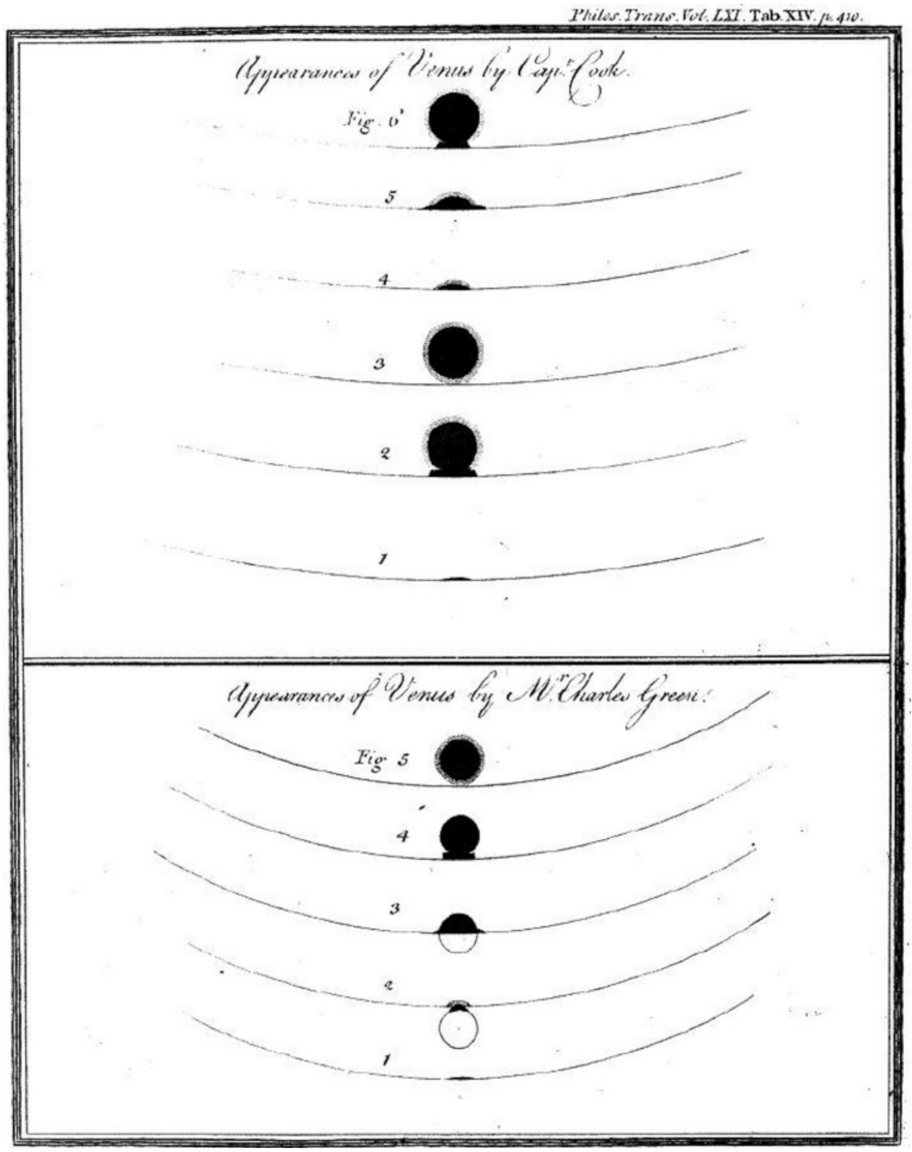

Figure 1.4 Captain Cook's drawing of the Venus transit of 1769.

from his base at Venus Point (still so called) in Tahiti, combined with others in Norway and Canada, yielded a value for the Earth-Sun distance of '93,726,900 English miles', which is correct to better than 1 per cent.

Early observations: another planet with an atmosphere

Dark, blotchy features on the disc of Venus had been reported by Cassini as early as 1666, and by other astronomers at various times since. When they thought they had seen something, it was generally assumed that these features were on the surface, or perhaps the combined effect of patches of cloud moving over the visible surface. Today, credit for discovering the atmosphere of Venus is generally given to a Russian observer, Mikhail Lomonosov, who recorded in the journal of the observatory at St Petersburg that the disc of Venus showed a halo during the solar transit of 1761. From this he deduced that the planet 'is surrounded by a considerable atmosphere, equal to, if not greater than, that which envelops our earthly sphere'.

At various times in the 1790s, the German astronomer Johann Schroeter reported observations of diffuse and variable markings on Venus, which he attributed to atmospheric phenomena. These markings may not have been real, but the limb darkening and the extension he saw of the 'horns' of the crescent Venus right around the planet probably were, and are also indications of a substantial atmosphere. Writing in 1793, William Herschel reported from his own observations of 'faint and changeable spots' that it was evident that Venus 'has an atmosphere'. These changes led him also to report that the fact that 'Venus has a motion on an axis cannot be doubted', although they 'surely cannot be on the solid body of the planet'. Indeed they are not.

Observations of surface features

As telescopes got better, and observers strained to see features on Venus that could tell them something about the nature of the nearest planet, reports of various phenomena filtered into the journals of professional scientific societies around the world. In the second half of the nineteenth century, these included occasional bright spots that were sometimes inferred to be snow-covered mountain peaks catching the sunlight. Bright polar caps were also seen by a large number of highly reputable astronomers using the latest instruments, and generally assumed to be icy like those on Earth and Mars. Today, transient bright clouds are seen on Venus from orbiting spacecraft and also from the Earth, and there is a spirited debate as to their cause, the two most popular theories being volcanic plumes or some as yet unexplained meteorological phenomenon. The polar caps are certainly present as well, but as semi-permanent features in the cloud cover, rather than ice on the surface. Whether the Victorian astronomers actually saw these through their telescopes is debatable; nowadays we require special photographic observing techniques not available before the 1920s.

In the summer of 1886, Percival Lowell, soon to become notorious for his interpretation of features seen on Mars as canals built by an intelligent civilisation, turned his new, state-of-the-art 24-inch refracting telescope on Venus. He had used his considerable wealth to build this facility on Mars Hill near Flagstaff, Arizona, in order to make better observations of the red planet and the civilised artefacts that excited him so much. However, when the new observatory was commissioned, Mars was not well located in the night sky over Arizona, so he looked at Venus instead. The markings he saw (Figure 1.5) seemed sufficiently reproducible for him to become convinced that he was observing features on the surface, providing 'evidence for slowness of rotation'. Unlike his vision for Mars, he did not claim the features looked artificial, describing them as 'perfectly natural' and the result of 'rock or sand weathered by aeons of exposure to wind and sun'.

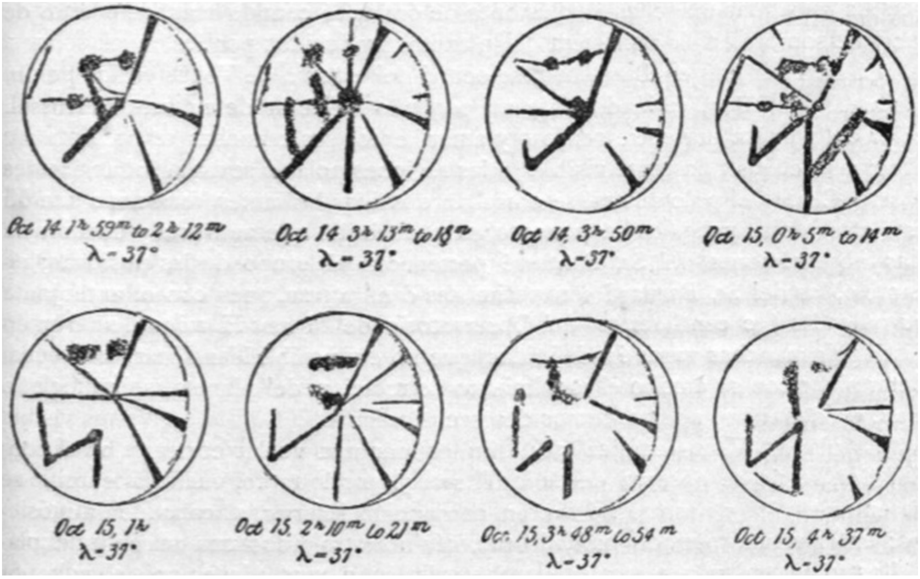

Figure 1.5 Sketches of Venus obtained by Percival Lowell from his observatory in Flagstaff, Arizona in August 1896, showing what he took to be surface features viewed through the 'brilliant straw-color veil' of Venus's atmosphere[10].

Other astronomers, including some of Lowell's own assistants using the same telescope, were sceptical, and reported that they could not see the features which Lowell described as 'perfectly distinct'. A plausible theory has been advanced which suggests that Lowell was observing the blood vessels in his own eye, reflected in the lenses of his telescope. He suffered, and in 1916 died suddenly, from high blood pressure, a condition that most likely made his retinal arteries more prominent than normal. This, plus his ambitious and excitable nature, may account for why Lowell thought he saw features on Venus that were invisible to others, and that we can now be certain do not exist.

The ashen light

One of the earliest discoveries about Venus was that the night side is not completely dark. Many observers, since the Jesuit priest Giovanni Riccioli of Bologna as long ago as 1643, have reported the emanation of a mysterious glow from the main disc when observing the planet at times when the sunlit side presents itself as a narrow crescent (Figure 1.6). The purported glow, which became known as the ashen light, is extremely faint and not always present even under good observing conditions. Some astronomers say they have

[10] This quote is from an article Lowell wrote in the German journal *Astronomische Nachrichten*, in 1897. There he went on to state emphatically that the markings on Venus were to him as distinct as those on the Moon, that they 'disclosed the rotation period unmistakably', and 'are not obscured at any time by clouds. In other words there are no clouds on the planet'.

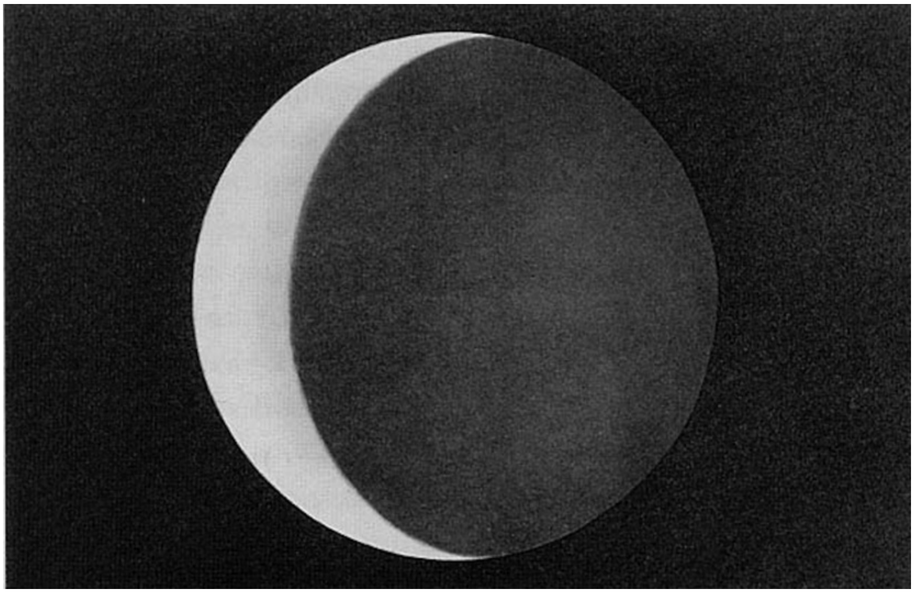

Figure 1.6 A sketch of Venus by Patrick Moore, using a 15-inch reflector, showing the ashen light (his observing notes say that its brightness is exaggerated for clarity).

never been able to see it, and doubt its existence,[11] but they are far outnumbered by those who have. The latter describe it as being dark red or brownish in colour, patchy and changeable in shape and coverage, and variable in brightness.

There has been much discussion over the years as to what could be the source of this light, but there is still no general agreement. In the nineteenth century, there were imaginative suggestions involving celebratory bonfires and fireworks by hypothetical inhabitants of Venus. The 'leakage' of sunlight from the dayside, via scattering processes in the clouds, was a more realistic idea, but the bright regions are not concentrated near the terminator,[12] and it is hard to produce a model for the process responsible if this is the cause. More recently, it has become popular to posit that either some sort of auroral or airglow effect, or possibly frequent, widespread lightning discharges, must be responsible. However, close-up examination using television cameras on various spacecraft has failed to find the necessary evidence for this.

Some of the most recent investigations, from Earthbound telescopes and from instruments on spacecraft, have revealed initially surprising properties of the surface and the clouds that offer a new explanation for the mysterious emissions, probably the right one at last. We now know that the cloud layers on our sister planet, although extensive, are translucent at visible and near-infrared (IR) wavelengths, and it follows that we are seeing

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[11] E. E. Barnard (1857–1923), who was professor of astronomy at the University of Chicago and who, among numerous other achievements, was the first since Galileo to discover a satellite of Jupiter (Amalthea), was one of those undoubtedly meticulous observers who were sceptical about the existence of the ashen light on Venus (and canals on Mars).

[12] The terminator is the day-night boundary line.

through them to the surface, which is glowing faintly with a dull red heat. The many reports of the colour of the night side of Venus as being a dim rusty shade lend further support to this idea. If it is correct, the observed patchiness and variability are both attributable to the large-scale structure of clouds in the deep atmosphere.

In order not to get too far ahead of the story, we will return to the topic of the ashen light and discuss this theory in more detail later, after covering more of the historical and scientific background. The implications turn out to be almost as exciting as observing Venusian firework displays from Earth.

The ultraviolet markings

Modern observing methods in the visible part of the spectrum show no markings on Venus that could be associated with surface features. Instead, with rare exceptions, most notably Lowell, a few visual observers have reported only subtle and ephemeral markings on the disc, and most see no contrast at all.[13] Some very faint streaks in the clouds, and slight 'scalloping' of the terminator line which separates the day and night sides, are the only irregularity commonly seen through the telescope with the naked eye (Plate 5).

Even the television cameras on the spacecraft *Mariner 10*, which observed Venus from a distance of 10,000 kilometres in 1973, were unable to detect significant contrasts over the brilliantly reflective disc of the planet when observing at visible wavelengths. Cameras, however, can image the planet at wavelengths to which the human eye is not sensitive, and they do not have to move very far into the ultraviolet (UV) spectrum, or in the other direction in wavelength to the near infrared, before the story changes completely.

The pictures of Venus that one usually sees, with prominent markings in the clouds, are taken photographically through a UV filter (Figure 1.7). At these short wavelengths,[14] the sulphur compounds in the clouds absorb sunlight, and differences in their density distribution within the upper cloud layers show up in the images as dark markings. Even these are quite subtle, and the contrasts are often stretched by a computer before the picture is released to the public.

The UV markings were first observed in the 1920s, but it was not until the mid-1980s, well into the era of space exploration, that it was discovered that striking contrasts can also be observed on the night side at certain wavelengths in the near-IR spectrum.[15] The UV observations are of course seen on the side of the planet that is illuminated by the Sun,

[13] However, Patrick Moore, probably the best and certainly the most famous amateur observer of recent times, states categorically (in 'Venus', London 2005) that 'it is wrong to say that nothing whatsoever can be seen on Venus using ordinary telescopes', and has reported his own observations of bright spots, polar caps and 'vague, elusive' shadings on many occasions.

[14] In planetary observations, wavelengths are usually measured in micrometres (one millionth of a metre), often abbreviated to microns or micron. Ultraviolet pictures of Venus are typically at about 0.35 micron, where visible light has wavelengths from about 0.4 to 0.8 micron.

[15] 'Infrared' means wavelengths longer than red light, i.e. lower in frequency than the lowest the eye can detect. The 'near' infrared is the part of this that is nearest to the visible in wavelength, typically from 0.8 micron, out to about 4.0 microns where the 'mid' infrared begins. The 'far' infrared corresponds to wavelengths from 20 microns, out to 1 millimetre where the microwave spectrum takes over. This

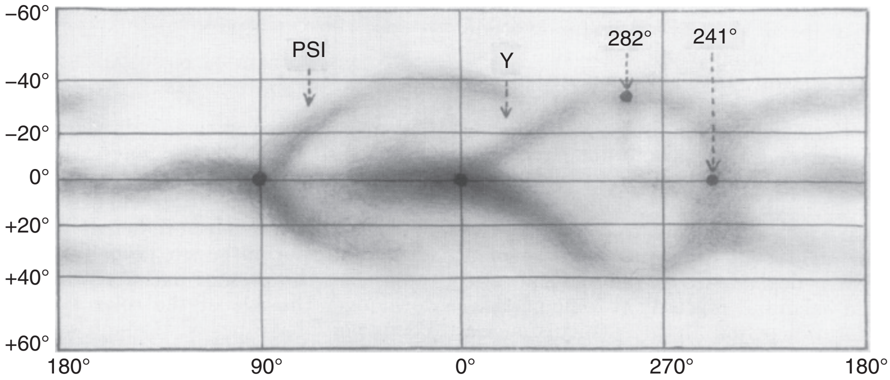

Figure 1.7 A sketch map of real quasi-permanent markings in the clouds on Venus, produced from ultraviolet photographs.

while the near-IR features are emissions from the planet itself and so dim that they can be seen only on the dark side. In this respect they are obviously related to the ashen light phenomenon, but were discovered at longer wavelengths, using IR detectors rather than the human eye. The cloud patterns that they reveal are different from those in UV images obtained at about the same time, even allowing for the time it takes for features to travel from the day to the night side (about two days). This suggests that the two types of observation are sensitive to different cloud layers at different heights in the atmosphere, which does seem to be the case, as we discuss later in Chapter 6. We will also see that we can, at last, get glimpses of the surface through the clouds by observing in the near infrared under certain conditions.

Speculation on the nature of the clouds and conditions at the surface

Long before Earth-based telescopes first revealed the ultraviolet markings in Venus's clouds, it had been realised that the brightness of Venus in the morning and evening skies, and the general lack of visible features, must be a result of a thick, uniform and permanent covering of clouds. The idea was consistent with the understandable supposition that Venus was much like the Earth in most ways, but with more evaporation from its presumed oceans because of the stronger solar heating, and therefore more cloud. Svante Arrhenius, in his book *The Destinies of the Stars* published in 1918, started with the fact that Venus's distance from the Sun is 72 per cent that of Earth. Using observational estimates of the reflectivity or albedo of the cloudy globe, he then worked out that the mean temperature at equatorial latitudes would be about 47°C, compared with 26°C for the tropics on Earth. Extrapolated to the poles, this sort of temperature would not be compatible with polar ice caps, which suggested to some astronomers that Venus could be entirely covered with oceans of water.

terminology is largely historic, having to do with the different technologies required to detect infrared radiation in these regions, but is still used extensively.

Others proposed that Venus might be dry and desertlike, in which case the clouds might be windblown dust or sand. The argument in this case was that, being close to the Sun, Venus had dried out over the aeons, like the once-fertile Sahara on Earth. If the clouds were dust, this could explain the slight lemon-yellow coloration that apparently distinguishes the Venusian clouds from their terrestrial counterparts.

However, until the space age began in the 1960s, the commonest picture of the surface of Venus in popular astronomy was one that resembled the primitive Earth, with some seas but also rain-soaked landmasses (Plate 6). It did not seem unreasonable to go on to invoke swamps, tropical vegetation, animal life and even humans. These might be cavemen fighting dinosaurs, or advanced civilisations living in cities and using technology. Both of these scenarios were popular in the fiction of the time, of which the best known today are the John Carter series of Edgar Rice Burroughs and the Pellucidar novels of C. S. Lewis.

The search for water vapour in the atmosphere

By the 1930s, it had become possible to make useful observations of the nearby planets using a spectrograph, an instrument that breaks light into its constituent wavelengths, like a rainbow but with finer detail and the ability to work at wavelengths beyond the range of sensitivity of the human eye. When attached to a good-sized telescope, these devices offered the possibility to detect the characteristic absorption features of common atmospheric gases, including water vapour. Percival Lowell and his team at Flagstaff had made strenuous attempts to show that the Martian atmosphere had a measurable humidity, as it would have to if there were open canals carrying liquid water across the surface. They came up with several false detections, but it was not until the 1950s that the Martian water vapour was definitely found, and at a much lower concentration than Lowell had hoped for.

If the clouds on Venus were similar to those on Earth and composed mostly of water droplets, then there ought to have been plenty of vapour for the early spectroscopists to detect there, too. In the United States, Walter Adams and Theodore Dunham were among the first to look, in the 1930s, and they did find interesting features in their spectra, although when they studied them in detail, the absorption lines turned out to belong to carbon dioxide.

Later observers, with gradually improved instrumentation and high-altitude observatories on aircraft, found many more bands of carbon dioxide lines at progressively longer wavelengths, and by the 1960s it was apparent that this gas was a major component of the overall atmospheric composition. At this time observers were also reporting water vapour detections, but these showed confusingly high levels of variability and were mostly at levels too small to be consistent with clouds made up of water droplets or ice, which was what most astronomers expected (Figure 1.8).

By 1972, Andrew Young and others had proposed that the spectrum of the clouds was best matched not by water but by sulphuric acid, and this was confirmed by the middle of the decade by the use of polarimetry, which allowed the refractive index of the cloud material to be inferred. It was consistent with a mixture of about three parts H_2SO_4 to only

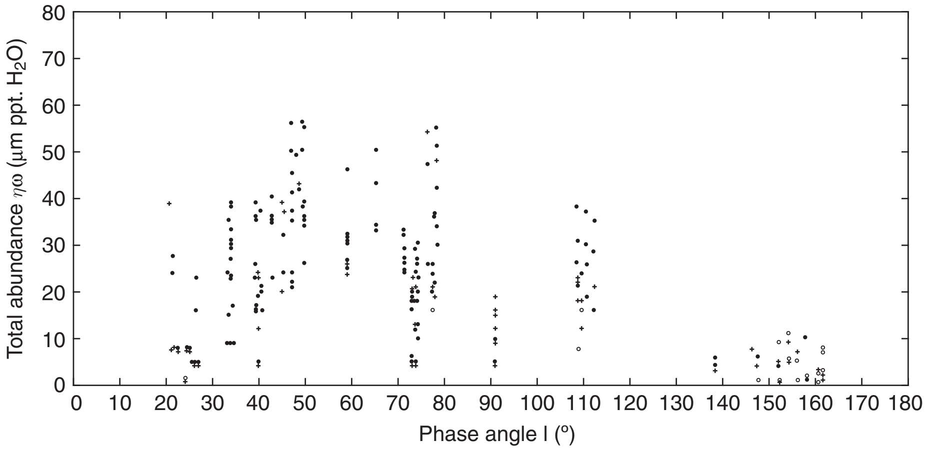

Figure 1.8 Earth-based observations of the column abundance of water vapour above the clouds as a function of phase angle (the angle between the Earth–Venus and Sun–Venus directions). The amounts are very small, and remarkably variable.

one part of H_2O – a very strong acid solution. Experience in the laboratory on Earth readily shows such a solution to be highly corrosive for many common materials that might be exposed to it, including, of course, human tissue. As if this were not enough by way of a slap in the face for the tropical paradise image of Venus, evidence was also building that the surface is almost unimaginably hot.

A hot and arid surface?

The first indications that the surface conditions on Venus might be inhospitable to human explorers came in the 1950s with the advent of the first large radio telescopes. In the passive mode normally used in astronomy, the large dishes tune in to microwave radiation – consisting of short radio waves with wavelengths typically measuring a few centimetres – emitted from the surface of the planet. Unlike the shorter-wavelength visible and infrared radiation, microwaves pass almost unaffected through the cloud layers, and the intensity of the emission from the surface can be measured on Earth. The intensity is related to the temperature of the emitting surface in a known way, through Planck's radiation formula. The early results for Venus, made in 1956 using a 50-foot dish at the US Naval Research Laboratory in Washington to observe at wavelengths in the range from 3 to 10 centimetres, corresponded to a source at a temperature of more than 300°C, much too hot for free water or plant life, let alone dinosaurs (or humans).

At first, such high temperatures for the surface of Venus did not seem reasonable; after all, the solar intensity is only twice that of the Earth, and most of that is reflected away by the bright clouds, back into space. In fact, because of the high albedo, the solar heating of Venus is actually *less* than Earth, and about the same as distant, chilly Mars.

Even if the atmosphere of Venus were much thicker than Earth's, it seemed at first incredible that it could trap enough heat to elevate the temperature that much through the greenhouse effect. Alternative explanations were sought, the most promising of which was that the microwave emission from Venus was not from a hot surface, but instead produced by non-thermal emission from electrons in Venus's ionosphere, approximately 100 kilometres above the surface.

Calculations soon showed that the ionosphere would have to be implausibly dense to match the observations, leaving the choice between two scenarios, both of which were seen as rather unlikely by most scientists. An exception was the young Carl Sagan, who was grappling with the problem as part of his doctoral studies at the University of Chicago. Sagan made calculations that convinced him, at least, that the greenhouse effect was responsible, and began to look for ways to gain experimental proof.

As the debate about Venus raged on in astronomical circles, the space age began with the launch of *Sputnik 1* on 4 October 1957. Both the Americans and the Soviets were keen to achieve successful flights to the nearby planets. The closest, Venus, was high on the list, along with Mars, rather farther and harder to reach but full of mystery and promise. Investigating the possible high temperatures on Venus made an obvious scientific goal for a mission, and would enhance the achievement of simply getting there.

There were basically two ways of doing this. The first was to fly a small microwave radiometer all the way to Venus, to investigate the emission phenomenon close up and verify whether the radiation being picked up from Earth really was from the surface. The other was to dive into the atmosphere, land on the surface and measure the temperature directly. Better still, do both. The race was on.