The Unacceptable Phase of Venus

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It is proposed that the discrepancy between the observed and predicted phases of Venus is caused mainly by the Venusian atmosphere. The photochemical production of sulphuric acid droplets by solar radiation results in an atmospheric profile 'inflated' on the day side of the planet. Consequent shadowing near the terminator will contribute towards the observed phase anomaly.

INTRODUCTION

We can be pretty sure about when the Moon will show an exact half-phase, or dichotomy. But the Moon is not the only object that can show a 50% phase. Venus can also. Can we be equally sure about exactly when our nearest planetary neighbour will exhibit this phase? The answer is certainly no.

It is a well-known fact that not only does the time of Venusian dichotomy not arrive according to plan, but the general phase value misbehaves also. The difference between the observed phase and the calculated phase is known as the phase anomaly.

The anomaly manifests itself in the observed phase always being smaller than the calculated phase. As a result of this, during evening (eastern) elongations, when the phase is decreasing, dichotomy occurs early, and during morning (western) elongations, when the phase is increasing, dichotomy is late (see figure 1).

HISTORY

The phase anomaly was discovered by Schröter in 1793 when he found a difference of eight days between observed and calculated dichotomy. (The phase anomaly of Venus is sometimes referred to, after its discoverer, as the Schröter Effect.) The Rev. T. W. Webb[1], without realizing it, verified Schröter's observations in 1833 March; Beer and Mädler recorded an anomaly of some six days in 1836, while in 1839 De Vico recorded an anomaly of three days.

Obviously, for any real understanding of the anomaly, a long series of observations is necessary. Probably the first such series was instigated by McEwan[2] between 1919 and 1927. Only four elongations were covered, the results of which were summarized by Ellis[3]. M. B. B. Heath[4] was next to make an extended study of the planet, covering 15 elongations between 1927 and 1955. It is worth noting that Heath's work consistently revealed a smaller anom-

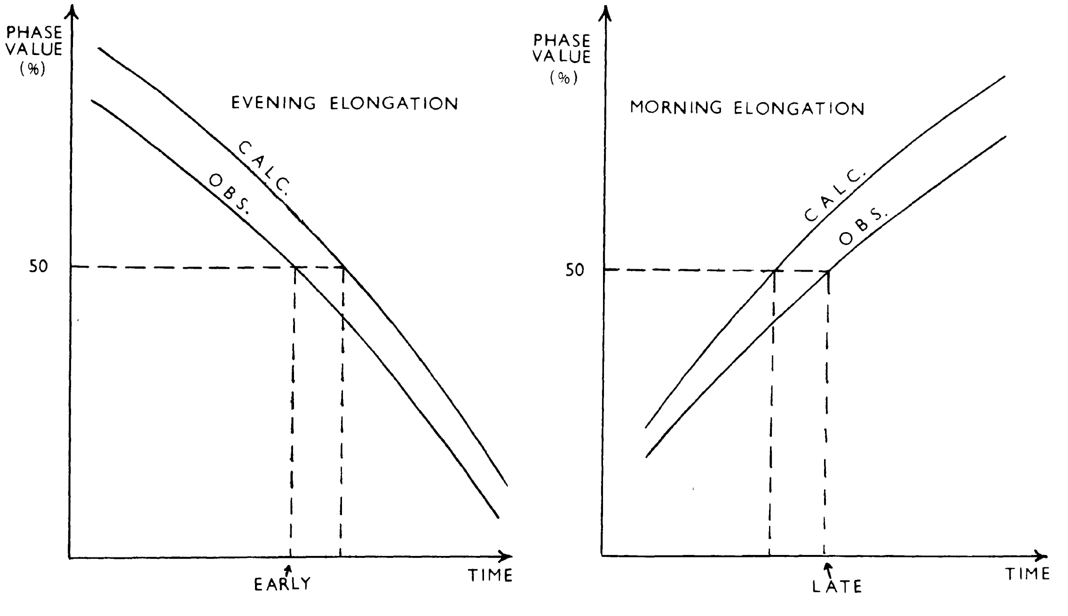

Figure 1

aly (three days or less) than has generally been found since by BAA members.

The most recent study[5] of Venus was initiated by Patrick Moore in 1955 with a view to making observations over an eight-year period (eight terrestrial years approximate to 13 Venusian years, during which time the planet goes through a complete cycle of events).

These studies of this most unusual astronomical phenomenon have led to several suggestions explaining why it happens.

THEORIES

So far, the following explanations have been put forward for the unacceptability of the calculated phase of Venus:

(*a*) An explanation based on the use of an artificial model[6].

(*b*) The effect of sky brightness on the phase value[7].

(*c*) The effect of magnification on the observed phase due to resolution limitations[8].

(*d*) The effect of refraction in the upper atmosphere of Venus[9].

(*e*) The possible contribution of atmospheric tides[10].

(*f*) The effect of cloud towers formed in the planet's upper atmosphere[11].

Surprisingly, none of the above theories consider the possible role of photochemistry in the phase anomaly. We believe that photochemical reactions in the cloud-top region of Venus' atmosphere, caused by ultraviolet radiation from the Sun, play a part in causing the anomaly.

PHOTOCHEMISTRY

The *Mariner 10* Venus probe suggested the importance of photochemistry in the upper atmosphere of the planet[12]. Subsequent *Venera* and *Pioneer* results confirmed this photochemistry and added to our knowledge of it[13]. The results of the *Mariner 10* probe support the view that the visible clouds are composed mainly of concentrated sulphuric acid (H_2SO_4). The presence of sulphur (S) in an elemental form in these clouds would explain their yellow colour. *Pioneer* verified the presence of this elemental sulphur[14].

The photochemical reactions, powered by the Sun's ultraviolet light, occur above the visible cloud tops. Four principal reactions appear to be involved in the formation of sulphuric acid and elemental sulphur. To begin with, carbon dioxide is liberated from the surface rocks. In the cloud-top region, this is converted by ultraviolet radiation into carbon monoxide (CO) and oxygen (O_2). The oxygen so formed reacts with hydrogen from the solar wind to produce water (H_2O). Carbonyl sulphide (COS), produced from a reaction of carbon dioxide and sulphur in the lower atmosphere, is dissociated by ultraviolet light to produce carbon monoxide and sulphur. The oxygen and sulphur produced in the above reactions react together to produce sulphur dioxide. This reacts with more oxygen to give sulphur trioxide, which now combines with water to produce sulphuric acid. These reactions can be summarized as follows:

(1) $CO_2 \xrightarrow{UV} CO + O$

(2) $O_2 + H \longrightarrow H_2O$

(3) $COS \xrightarrow{UV} CO + S$

(4) $O_2 + S \longrightarrow SO_2 + O \longrightarrow SO_3 + H_2O \longrightarrow H_2SO_4$

The sulphuric acid and elemental sulphur so produced settle towards the planetary surface. The result of this is not a definite cloud top but rather a gradual thickening of the sulphuric acid aerosol, as it is called, down to the cloud tops proper[15].

With the sulphuric acid being formed photochemically in this way, powered by the Sun's ultraviolet light, would it not be reasonable to assume that, in the absence of the Sun's ultraviolet light on the night side of Venus, the sulphuric acid aerosol will not be produced there and the hazy cloud-top level will be lower?

Evidence for a difference in cloud-top levels between the day and night side of Venus has been given by Crisp and Young[16], and by Taylor[17]. The height difference measured by them is of the order of 2–3 km. Waller [18] and O'Leary[19] have even described two distinct, and possibly three, haze layers, altogether about 30 km thick, situated above the cloud-top level and dominated by sulphur particles and droplets of sulphuric acid. This figure is further supported by Beatty[20], from *Pioneer* measurements. This 'smog' appears and disappears over periods of several years and may well be partly to blame for the erratic nature of the phase anomaly. Young also has spectroscopic evidence of higher clouds near the sub-solar region. This would be expected if the cloud tops are formed photochemically; higher amounts of ultraviolet radiation being incident per unit area at the sub-solar point resulting in greater photochemical activity.

How does all of this tie in with the phase anomaly? In the terminator region the incidence of sunlight is such that the photochemical process ceases and an area of lower cloud results. The region of higher cloud preceding this casts a shadow. (See figure 2.) This shadow extends beyond the terminator into what would be the day side of the atmosphere. Thus the phase appears to be less than it would normally be. This general effect would cause some earliness of dichotomy during evening elongations and lateness in the morning elongations, as explained by figure 1.

Numerically, the authors calculate, using an elliptical model for the atmosphere (a method suggested by Dormand and Gadian of Teesside Polytechnic), that a height difference of 3 km between the day and night cloud levels would contribute about one day to

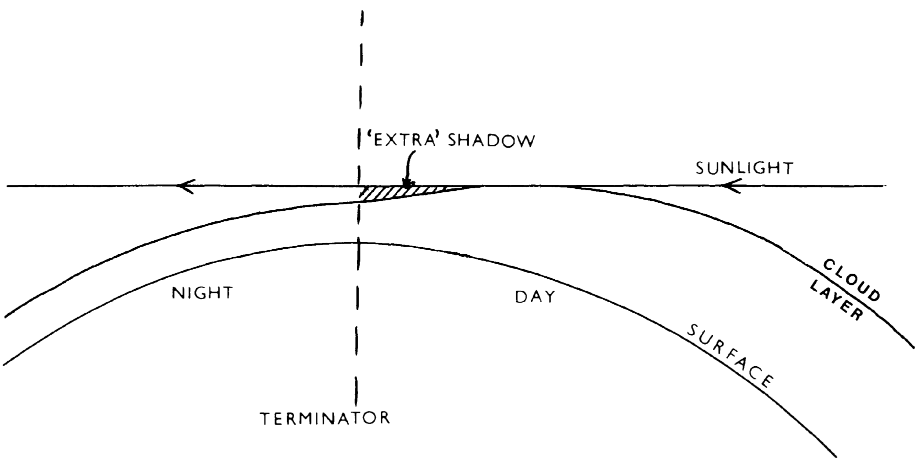

Figure 2

the observed average phase anomaly, which is about seven days for the evening elongation and five days for the morning elongation[5] (see Appendix). Winick and Stewart[21], using *Pioneer* results, give the photochemical reactions in great detail. Note, though, that SO_2 is proposed as the mechanism for the supply of sulphur instead of COS as in this article. Winick and Stewart, however, give the region of photochemical activity as extending from an altitude of 58 km (just below the visible cloud tops) up to 96 km. Does this band indirectly support the figures already given (references 15–19) regarding the day/night height difference? They also point, significantly, to a "reduced level of radical chemistry at night".

This smooth step in the upper atmosphere exists on the morning and evening terminators and is a dynamic effect of the Venusian meteorology. The morning step forms when the rotation of the atmosphere brings the upper cloud tops into the region of grazing incidence with the Sun's ultraviolet light. The sulphuric acid aerosol then begins to form. The evening step forms by the reverse of this process as the atmospheric rotation takes the cloud tops over onto the night side. The overall changing situation can, indeed, be visualized in terms of a stationary atmosphere and the Sun revolving around this in four days (the upper atmosphere rotates once in about four days[22,23]). The expansion and contraction of the atmosphere can be pictured in this way, if need be, using this relative model.

PROBLEM OF GREATER EVENING ANOMALY

BAA observations have revealed a consistently larger anomaly during evening (eastern) elongations[5]. This may also be related to the photochemical process. As the cloud tops reach the evening terminator they have been exposed to ultraviolet for about two days. This could result in a higher region of cloud tops on the evening terminator than on the morning terminator. The higher region of clouds would, perhaps, reach the ultraviolet cut-off point sooner than on the morning terminator so producing a greater anomaly.

It has been rightly pointed out by J. Hedley Robinson[5] that smaller instruments give consistently smaller phase estimates because of their lower ability to collect light from the hazy, delicate terminator region. Could it be that a greater use of small instruments during the more convenient evening elongations might contribute to the larger evening anomaly? Alas, average aperture sizes used on past elongations by BAA observers who reported their results (calculated by the authors from BAA reports supplied by Richard Baum and shown in Table I) suggest that there is no significant difference in the size of instrument used.

OBSERVATIONS WITH FILTERS

The use of filters in observing Venus, proposed by J. Hedley Robinson in 1956, also lends support to the above model[5]. The W15 yellow filter was originally introduced to help reduce the scatter of individual observations due to varying colour sensitivity of the eyes of different observers, but subsequent studies

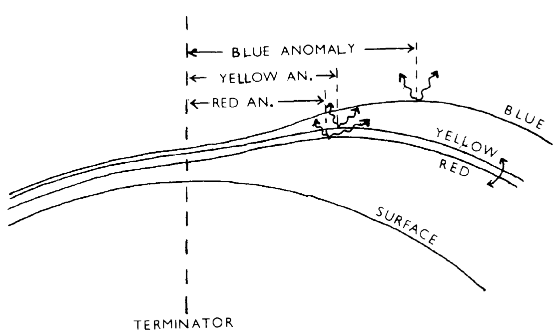

Figure 3

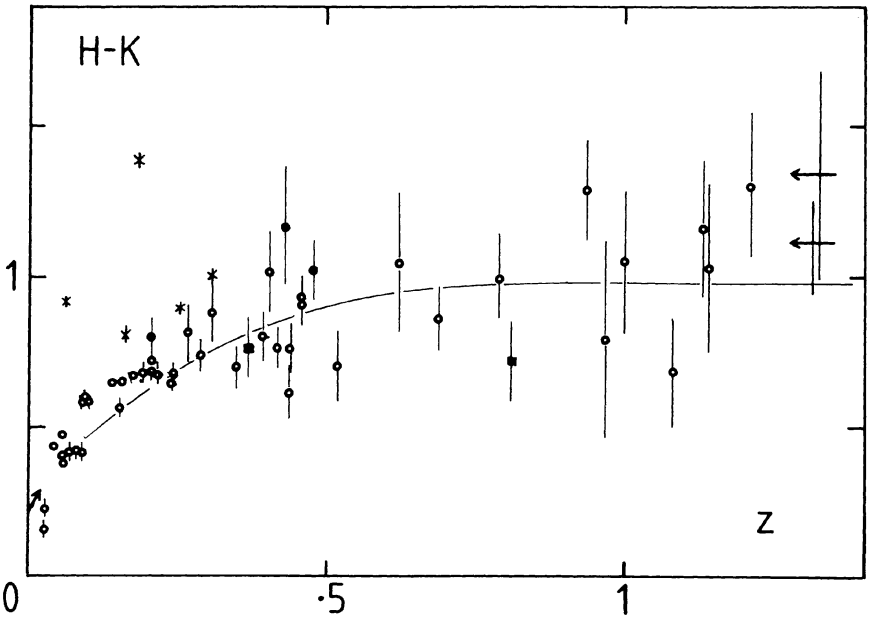

Figure 5. The variation of the (H-K) infrared colour of radio galaxies as a function of redshift. The points indicated by stars are galaxies whose colours are contaminated by non-stellar radiation from an active nucleus. The solid line is the predicted relation for a giant elliptical galaxy spectrum as observed at different redshifts.

objects, the astrophysics of which are poorly understood. In the case of objects whose light is dominated by starlight, we should be able to model the evolution of the stellar population and thus obtain clues about the evolution of galaxies in general. Another fortunate feature of using radio galaxies is that they often possess strong emission lines and so very large redshifts can be measured. The largest so far measured by Dr Hyron Spinrad is 1·62 for the galaxy associated with the radio source 3C241. Just how difficult this task has been is indicated by the fact that we only completed identifying about 96% of the brightest 173 sources in the northern sky with optical objects last year, it being necessary to identify 23·5 magnitude objects to find the faintest of the identifications. Because of concentrated efforts by Dr Spinrad and our group, we have been able to find redshifts for about 90% of the galaxies in this sample. These are the most distant galaxies known in which the light is dominated by starlight.

INFRARED OBSERVATIONS OF DISTANT RADIO GALAXIES

Dr Simon Lilly and I have made a detailed optical and infrared study of 81 of the radio galaxies found in the above survey. We were able to observe all of them with the UK Infrared Telescope in Hawaii and supplement the infrared data with optical observations taken at Palomar and Kitt Peak. The technicalities of how we made our observations and the advantages of using this particular sample need not trouble us here. Suffice to say that we have been able to use the most powerful optical and infrared facilities in the world in these studies and that this is the most complete sample of the most distant galaxies ever studied.

The most convenient way of presenting the results of these studies is in terms of the optical and infrared colours of the galaxies as a function of redshift. First of all, let us look at the difference in magnitude between the H and K wavebands, *i.e.* the infrared colour H-K, as a function of redshift (figure 5). The solid line which runs rather nicely through all the points is not a best fit to the data but is a theoretical prediction of what the (H-K) *versus* redshift relations would look like if the rest-frame spectrum of the radio galaxies was unchanged with redshift. In other words, so far as we can tell the shape of the spectrum in the infrared part of the spectrum remains unchanged back to the largest redshifts we can measure. This strongly suggests that we are dealing with basically the same type of stellar populations in the most distant systems, although we have not yet addressed the question of the relative numbers of the stars in these distant systems.

A second important colour-redshift diagram is shown in figure 6, the optical-infrared colours (V-K) or (r-K) *versus* redshift. The reason for the smaller number of points is that we must take special care about the homogeneity of the data. In contrast to the (H-K)–redshift relation, there is no simple fit to the data from any of the models. The line marked NE shows the relation expected if the spectrum of the galaxies was unchanging with cosmic time. The line marked C shows what would be expected if all the stars in the galaxy formed very early in its history and the subsequent evolution has simply consisted of this stellar population growing older. The line marked 0·5 shows what would be expected if the star formation rate has decreased exponentially with cosmic time, half of the stars having been formed very early in the

14 *Sky & Telesc.*, **58**, 13 (1979).
15 Gehrels, T. *et al.*, *Astron. J.*, **85**, 682 (1980).
16 Crisp, D. and Young, A. T., *Icarus*, **35**, 183 (1978).
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18 Waller, P., *Solar System Today*, 50 (1981 June).
19 O'Leary, B., *J. Atmos. Sci.*, **32**, 1091 (1975).
20 Beatty, J. K., *Sky & Telesc.*, **63**, 134 (1982).
21 Winick, J. R. and Stewart, A. I. F., *J. Geophys. Res.*, **85**, 7849 (1980).
22 Schubert, G. *et al.*, *ibid.*, **85**, 7995 (1980).
23 Rossow, W. B. and Williams, G. P., *J. Atmos. Sci.*, **36**, 377 (1979).
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25 Lane, W. A., *Astron. J.*, **84**, 683 (1979).
26 Dollfus, A. *et al.*, *ibid.*, **84**, 1419 (1979).

APPENDIX

The day-side atmospheric 'bulge' is modelled by an ellipse centred on O'; YY' is 'normally' where the terminator would be, so figure 4 represents theoretical dichotomy. Because of the morning and evening steps the observed phase, shown by YO'Y', is seen to be less than 50%. Taking R as 6052 km + 60 km, *i.e.* 6112 km, the following calculation can be made:

If ΔP is the difference between observed and theoretical phases then

$$\Delta P \simeq \left(\frac{\epsilon}{2R} \times 100\right)\,\%$$

The rate at which the atmosphere can 'blow-up' is very difficult to estimate but is clearly important because it imposes an upper limit on γ. The high winds[22,23] of 100 m/s mean that the atmosphere only has a very short time to form a smooth step. The average updraught in the Earth's atmosphere is about 1 m/s. Although atmospheres can move a lot more quickly, it is unlikely to be more than 1 m/s in the high-altitude layers of Venus. Several values of ΔP were tried and the one that matched the limitation on γ was 0·5%, as follows:

Putting $\Delta P = 0{\cdot}5\%$,

$$\epsilon \simeq \frac{R}{100} = 61{\cdot}12\,\text{km}.$$

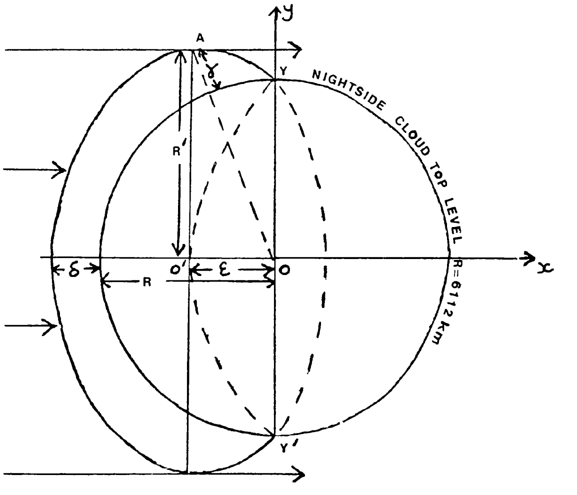

Figure 4

The equation of the ellipse is therefore

$$\frac{(x+61{\cdot}12)^2}{(6053{\cdot}9)^2} + \frac{y^2}{R'^2} = 1, \text{ taking } \delta = 3\,\text{km}.$$

But the ellipse passes through (O,R)

$$\therefore \frac{(61{\cdot}12)^2}{(6053{\cdot}9)^2} + \frac{(6112)^2}{R'^2} = 1$$

giving $R' = 6112{\cdot}3$ km.

From the triangle OO'A,

$$(\gamma+R)^2 = R'^2+\epsilon^2$$

$$\therefore (\gamma+6112)^2 = 6112{\cdot}3^2+61{\cdot}12^2$$

$$\therefore \gamma \triangleq 600\,\text{m}.$$

Does the atmosphere have time to reach this height difference at A? At a wind speed of 100 m/s, the atmosphere takes $\frac{60\,000}{100\times60}$, *i.e.* 10 mins to cover a distance of ϵ, *i.e.* about 60 000 m. This gives an updraught of $\frac{600}{10\times60}$, *i.e.* 1 m/s.

Thus, with a day/night height difference of 3 km between the cloud levels, a phase anomaly of about 0·5%, corresponding to a time difference of about one day, should result.

Additional Notice

LUNAR SECTION PHOTOGRAPHIC COMPETITION

At the Exhibition Meeting on May 19 the Lunar Section will again hold a photographic competition which will be open to all members of the Association who are of amateur status. Entries should be recent photographs of the Moon and should be accompanied by the entrant's full name and address. All entries must be sent to Mr M. Mobberley, 'Denmara', Cross Green, Cockfield, Bury St Edmunds, Suffolk, IP30 0LQ, by May 12 at the latest. The competition will be judged by a panel of Lunar Section photographers. A book prize will be awarded to the winning entrant.