CORNELL UNIVERSITY
Center for Radiophysics and Space Research

ITHACA, N. Y.

CRSR 382

VENUS HALO: PHOTOMETRIC EVIDENCE FOR

ICE IN THE VENUS CLOUDS

Brian O'Leary

CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY
ITHACA, NEW YORK

April 1970

CRSR 382

VENUS HALO: PHOTOMETRIC EVIDENCE FOR

ICE IN THE VENUS CLOUDS

Brian O'Leary

VENUS HALO: PHOTOMETRIC EVIDENCE FOR
ICE IN THE VENUS CLOUDS

ABSTRACT. Photometric observations of Venus near the 1969 inferior conjunction indicate an anomalous brightening of about 0.07 magnitude at 158° phase angle. The width of the brightness maximum is about 3° and its peak is between 1.1 and 4.4 standard deviations, depending on color, from the expected background phase curve. These results tend to confirm earlier observations which marginally showed the same brightness maximum. This is precisely the behavior expected if the Venus cloud tops were to contain a small abundance (a few percent) of hexagonal water-ice crystals, producing a halo effect analogous to the common terrestrial 22° halo phenomenon. Proof of such a halo effect causing Venus' brightening cannot be considered as unequivocal, but the observations are certainly provocative enough to conclude there is strong evidence that some of the Venus cloud tops contain hexagonal ice.

VENUS HALO: PHOTOMETRIC EVIDENCE FOR

ICE IN THE VENUS CLOUDS

The question of whether H_2O ice exists in the Venus
clouds has perhaps generated more debate, controversy and
frustration than any other topic in modern planetary
astronomy. The history of the debate is too involved to
discuss each event in this report, so I shall only mention
the high points. In 1964, Bottema, Plummer, Strong and
Zander (1) obtained a near-infrared spectrum of Venus from
a high-altitude balloon and concluded that the clouds are
composed of H_2O ice. Because this contradicts previous
observations that H_2O ice was not detected (2), many anal-
yses have been performed since then, but they too have led
to conflicting conclusions, both pro (3) and con (4).

Still there are some general thoughts upon which most
investigators seem to agree:

1. There is, as yet, no definitive evidence either
pro or con.

2. If ice is the main constituent of the Venus clouds,
then it is fairly clear, from the lack of an absorption fea-
ture at 1.5μ, that the predominant particle sizes are very
small ($\lesssim 2\mu$), unlike the case of terrestrial cirrus clouds.

3. The photometric properties of the Venus clouds in
the visible are similar to those of ice. From the phase

curve, Arking and Potter (5) concluded, "one may consider the cloud particles on Venus to be close to water droplets, ice particles, or particles of transparent minerals such as quartz." They derive particle sizes around 4μ which, with a little stretching, may be reconciled with the infrared observations.

4. The polarimetric properties of Venus are perhaps incompatable with ice as the major cloud constituent. Coffeen (4) derived a range of indices of refraction of 1.43 to 1.55, whereas ice is 1.31. However, Sagan (3) responds that an admixture of dust particles can bring the results into accord and may explain the yellow color of Venus. Coffeen's mean particle size is 2.5μ.

5. It is difficult, though perhaps not impossible, to reconcile spectroscopic observations of the low abundance of water vapor on Venus with the formation of water clouds on Venus. Belton, Hunten and Goody (4) have argued that the water vapor mixing ratio is some three orders of magnitude too low for water cloud formation. On the other hand, Sagan and Pollack (3) believe that the data can be brought into accord in view of the uncertainties of the observations and models. Moreover, they point out that if the Soviet Venera measurements of water vapor are correct, then the mixing ratio is sufficient for the formation of water clouds.

In 1966, I searched for ice in the Venus clouds by an entirely different method than those attempted by other observers: a halo effect (6). The common terrestrial halo phenomenon is a luminous ring located 22° from the Sun or Moon, and is due to the presence of hexagonal ice crystals in cirrus-type clouds.

The reason for the enhancement of light in the halo is based on the principle of the "angle of minimum deviation" used in the study of prisms. As shown in Fig. 1, parallel light entering hexagonal prisms which are randomly oriented suffers two refractions and tends to favor going in the direction of minimum deviation (7). The angle of minimum deviation, d, can be calculated from the familiar formula

$$n = \frac{\sin \frac{1}{2}(a+d)}{\sin \frac{1}{2}a} \qquad (1)$$

where n is the index of refraction of the crystal and a is the prism angle. For $n_D = 1.31$ (ice) and $a = 60^O$, d becomes 22°. It is also noted that because of the wavelength dependence of the index of refraction, the angle of minimum deviation is less for red light than for blue light; this causes the red band which often appears inside a halo. Most haloes are about 2 to 3 degrees in width and tend to disappear if the particle sizes are too small ($\lesssim 2\mu$) because of diffraction. Fresnel's Laws predict a polarization minimum at halo brightness maximum (6).

When applied to Venus, the approach is simply to monitor the brightness and polarization in various colors as Venus passes through $180^\circ - 22^\circ = 158^\circ$ phase angle. My 1966 results indicated a marginal Venus halo effect ∼0.05 magnitude brighter than the background phase curve. Similarly, there was suggestion of a polarization minimum of depth ∼0.3% from earlier observations by Dollfus (8). In both cases, however, the error scatter was as large as the apparent effect. At the time I was forced to conclude that, "at most, a small fraction (a few per cent) of the tops of the Venus clouds would consist of halo-producing crystals, i.e. hexagonal ice with sizes somewhat greater than a wavelength of light."

Caution is necessary in the interpretation: When we are observing a Venus halo, we are looking down into the clouds, where much of the reflected sunlight is multiply-scattered. In the ideal terrestrial case, the halo stands out several magnitudes greater than the background because single scattering dominates. Using a semi-empirical model, I estimated that about 15 percent of the incoming solar radiation is singly-scattered by the Venus clouds at 158° phase angle (6). This would suggest that if the Venus cloudtops were composed entirely of hexagonal ice with sufficiently large particle sizes, then one would observe a halo which is about one magnitude brighter than the background phase curve.

Diermendjian (9) has taken exception to this. He wrote, "The possible existence of a halo effect in diffuse reflection, suggested recently by O'Leary as an indication of the presence of ice-crystal clouds, is physically and theoretically untenable." In other words, he contends that looking into an optically thick cloud would completely wash out the halo.

I do not agree. The observation of 22° haloes from aircraft flying above optically thick cirrus clouds is a common sight; I once observed such a halo which was about one magnitude brighter than the cloud background. Moreover, theoretical phase function calculations of water clouds at various optical depths show that the rainbow, which in this discussion can be considered as a reasonable analogy to the halo, does not completely disappear even at very large optical depths; it is somewhat weakened by the increased component of multiple scattering and remains unshifted (10).

The purpose of this report is to present more recent photometric observations which I believe strongly suggest the existence of the Venus halo. I made the observations during two halo opportunities near the 1969 inferior conjunction at the Kitt Peak Number 4 16-inch telescope. The instrumentation and procedure were similar to those used in the earlier work (6), except that I used an infrared-sensitive photomultiplier tube (RCA 7102), a radium source for

calibration, and the narrow-band filters (100 $\overset{o}{A}$ width) to further cut down the light intensity and eliminate the effects of second-order extinction (11).

Figure 2 shows the results in 5 colors. The brightness of Venus, reduced to unit distance from the sun and earth, is the ordinate in units of relative magnitudes <u>per unit area</u> of the crescent. The dashed curve drawn through the points represents a fourth-order least squares fit calculated by computer (12). The standard deviation, σ, of the points from the curve is listed for each color in Table 1. It is immediately apparent that, besides the data in the blue wavelength, the error scatter in the 1969 observations is considerably less than ±0.05 magnitude obtained in 1966 (6). This improvement is primarily due to the fact that the largest source of error in the earlier observations, photomultiplier tube fatigue, has been removed. The largest sources of error in the 1969 observations were fluctuations in the daytime sky brightness and extinction, but the errors were small enough to bring the threshold of halo detection well below 0.05 magnitude, particularly in the near-infrared where the sky brightness and extinction are low.

The next step in the reductions was to construct the expected background phase curve if the halo were not present. One method is to attempt a least squares fit on those points which lie outside the halo region, i.e., outside $156\overset{o}{.}5 \leq \alpha \leq 160\overset{o}{.}0$. A third-order fit is shown as solid curves in

Figure 2 (13); from this comparison it is immediately appar-
ent that there is a brightness maximum near 22°. The maxi-
mum deviations, D, of the fourth order dashed curves from the
expected background curves are listed in Table 1. The next
column of the table shows values of D/σ, and we see that the
two curves are separated by as much as 4.4 standard devia-
tions in the near-infrared observations (Fig. 2b).

However, there are no background points either within
the halo region and far from the halo region, making it
difficult to assert that the solid curves are the most
plausible ones. The non-linear surge of the background
curve toward smaller scattering angles is obviously due to
forward scattering, but the exact nature of the bend does
not depend so much on mathematical models as on physical
realities. In fact, the solid curves seem to demonstrate
a stronger halo than the eye would estimate.

Unfortunately our knowledge of the behavior of the
Venus phase curve near inferior conjunction is too poor to
know the exact nature of the forward-scattering break of the
curve. However, fitting the points for $\alpha > 160°$ and $< 156°.5$
by eye and a French curve provides a useful alternative to
the cubic polynomial fit; these are shown as dotted-dashed
curves in Figure 2. In this case, the value of the maximum
deviation from the dashed curve is $D = 0.06$ magnitude for
all colors. Table 1 lists the values of $0.06/\sigma$, and, again,

there is a significant separation between the curves: the
deviations go up to 2.9σ for the near-infrared.

Inspection of the curves at 0.85 and 1.05μ (Fig. 2b)
indicates that the separation of the dashed curve from the
background curve must be at least D = 0.04 magnitude for any
reasonable method used to define the background curve; other-
wise the background curve itself would show a local maximum
near α = 158°. There is little question, therefore, that
Venus brightened anomalously to a maximum deviation D =
0.07 ± 0.03 magnitude for a 3° interval near α = 158°; this
is precisely as expected for a weak halo effect.

Since the index of refraction of ice is wavelength-
dependent, the halo position should shift with the wave-
length of observations. The arrows in Figure 2 indicate
those phase angles corresponding to the angles of minimum
deviation for each wavelength calculated from equation (1);
we see that the halo position should shift from 22°.2 in the
blue to 21°.2 at 1.05μ (14). Note these positions do not
correspond to the halo maximum, but rather to the theoretical
inner boundary of the halo (15). However, the sun subtends
nearly a degree of arc at Venus which tends to smear out the
halo. Therefore, the halo maximum should be located at a
phase angle about a half a degree less than each arrow loca-
tion.

This behavior is generally observed in Figure 2, although any actual shift of the halo with color is not apparent. In view of the uncertainties, particularly at shorter wavelengths, I do not consider the lack of a color effect to be a serious argument against the presence of a Venus halo effect.

It is conceivable that there are other interpretations of the anomalous brightening of Venus at $\alpha = 158^{\circ}$. For example, it may be caused by a meteorological quirk in the Venus clouds. Or perhaps there are crystals of other constituents whose shapes and indices of refraction fortuitously combine to produce a 22°-halo. Finally, it is possible that the transparency of the atmosphere over Kitt Peak, both before and after inferior conjunction, suddenly improved by ~ 0.05 mag. per unit air mass near $\alpha = 158^{\circ}$.

In my opinion, any of these alternative interpretations is unlikely. I therefore conclude that there is strong evidence for a small fractional abundance (a few percent) of hexagonal pure H_2O-ice crystals with sizes greater than a few microns in the Venus cloud tops. This does not preclude the possibility of large abundances of water ice in other forms — impure, nonhexagonal or small particle sizes (16). I urge confirmation of these observations over a wider range of phase angles during the next opportunity in November 1970.

One interesting byproduct of the observations is to compare the photometric properties of Venus near $\alpha = 158^{\circ}$ after inferior conjunction with those for the same geometry before inferior conjunction. Table 1 shows the shift, Δ, necessary to bring the two sets of observations into accord (12).

It is apparent that Venus is fainter and appreciably redder after inferior conjunction. The color effect is particularly interesting, because it confirms observations made near the 1966 inferior conjunction (6, 17). It is tempting to suggest that there is a systematic change in the scattering properties of the cloud tops between early Venus morning and late afternoon.

Finally, the observations show that the brightness surge of forward scattering is greater in the red than blue, again in the same sense as the 1966 results (6).

Future earthbased photometry and imagery from the 1974 flyby of Venus should add important new components of our understanding of the Venus clouds (18).

Brian O'Leary[*]
Laboratory for Planetary Studies
Center for Radiophysics and Space Research
Cornell University, Ithaca, New York 14850

Table 1

Wavelength	Standard deviation from fourth order fit σ (mag.)	Maximum deviation from background cubic fit, D (mag.)	D/σ	0.06 mag./σ	Δ (mag.)[a]
0.45μ	0.056	0.062	1.1	1.1	0.185
0.55	0.030	0.090	3.0	2.0	0.175
0.70	0.030	0.095	3.2	2.0	0.155
0.85	0.025	0.100	4.1	2.4	0.135
1.05	0.021	0.092	4.4	2.9	0.080

[a] Δ = the brightness which must be added to the observations before inferior conjunction to match observations after inferior conjunction (12).

REFERENCES

1. M. Bottema, W. Plummer, J. Strong and R. Zander, Astro-
   phys. J. 140, 1640 (1964); -----, J. Geophys. Res. 70,
   4401 (1965).

2. G.P. Kuiper, Commun. Lunar Planetary Lab. 1, 83 (1962);
   V.I. Moroz, Soviet Astron-AJ, English Transl., 7,
   109 (1963).

3. C. Sagan and J.B. Pollack, J. Geophys. Res. 72, 469
   (1967); J.E. Hansen and J. Cheyney, J. Atmospheric
   Sci. 25, 629 (1968); -----, J. Geophys. Res. 73, 6136
   (1968); J.B. Pollack and C. Sagan, ibid 73, 5943
   (1968); W.T. Plummer, J. Geophys. Res. 74, 3331 (1969);
   C. Sagan, Proc. I.A.U. Symposium No. 40, "Planetary
   Atmospheres", D. Reidel, Holland, in press (1970).

4. J.W. Chamberlain, Astrophys. J. 141, 1184 (1965); D.G.
   Rea and B.T. O'Leary, J. Geophys. Res. 73, 665 (1968);
   D.M. Hunten, M.J. Belton and R. Goody, in Atmosphere
   of Venus and Mars, Gordon and Breach (1968); D.L.
   Coffeen, Astron. J. 74, 446 (1969); G.P. Kuiper, Commun.
   Lunar Planetary Lab. 6, 229 (1969).

5. A. Arking and J. Potter, J. Atmospheric Sci. 25, 617
   (1968).

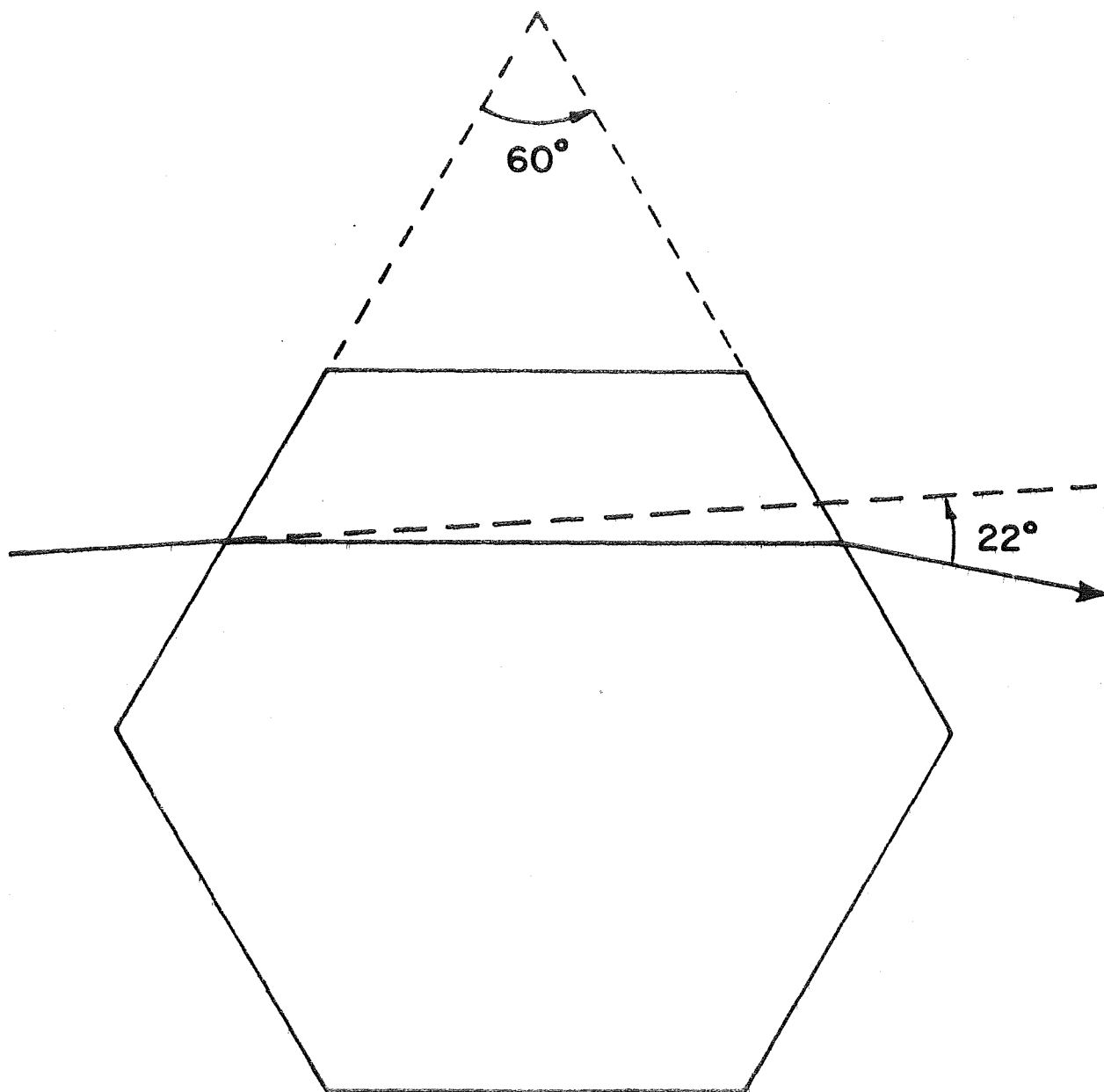6. B.T. O'Leary, Astrophys. J. 146, 754 (1966).

7. M. Minnaert, The Nature of Light and Color in the Open Air, Dover Publishers, N.Y., pp. 190-208 (1954).

8. These observations were privately communicated to me and are reported in Ref. 6.

9. D. Diermendjian, Electromagnetic Scattering on Spherical Polydispersions, Elsevier Press, N.Y., p. 131 (1969).

10. J. Pollack, private communication; and J.E. Hansen and J.B. Pollack, J. Atmospheric Sci., ___, (1970).

11. The observations were made in the daytime and there were no comparison stars which were bright enough or close enough to Venus to make reasonable calibrations. For extinction, I used Kitt Peak mean values.

12. The brightness per unit area of Venus at a given phase angle after inferior conjunction was different than that for the same phase angle before inferior conjunction. The same fourth-order least squares program was used to bring the two sets of data together.

13. Attempts were also made for second, fourth, and fifth-order fits. They were all roughly similar, but third order gave the most reasonable fit.

14. The color dependence of the index of refraction of ice are given in H.E. Merwin, International Critical Tables 7, 17 (1930) and N.E. Dorsey, Properties of Ordinary Water-Substance, p. 485 (Reinhold, 1940).

15. The sharp inner boundary and relatively diffuse outer
    boundary of most terrestrial halos is due to the
    fact that, with the geometry in Fig. 1, none of the
    light can be dispersed at angles less than the angle
    of minimum deviation; this often leads to a bright-
    ness <u>minimum</u> between scattering angles 20° and 21°.
    The minimum is not apparent in any of the Venus
    observations, and photometric profiles of terres-
    trial haloes often do not show the minimum. Many
    factors such as forward scattering and the angular
    size of the sun tend to smear out the sharp inner
    boundary and the minimum.

16. Impurities in the ice may change the index of refrac-
    tion enough to shift or obliterate the halo. Very
    small particle sizes imply that diffraction replaces
    geometric optics in the scattering process and the
    halo disappears. Work is underway in this laboratory
    to determine quantitatively the relation between
    particle size and halo properties.

17. The B-R color index difference in 1966 was ~ 0.1 mag.,
    but the error scatter was large ($\pm$ 0.05 mag). Table
    1 shows that difference to be 0.03 mag. for the
    1969 observations, although it reached 0.1 mag. for
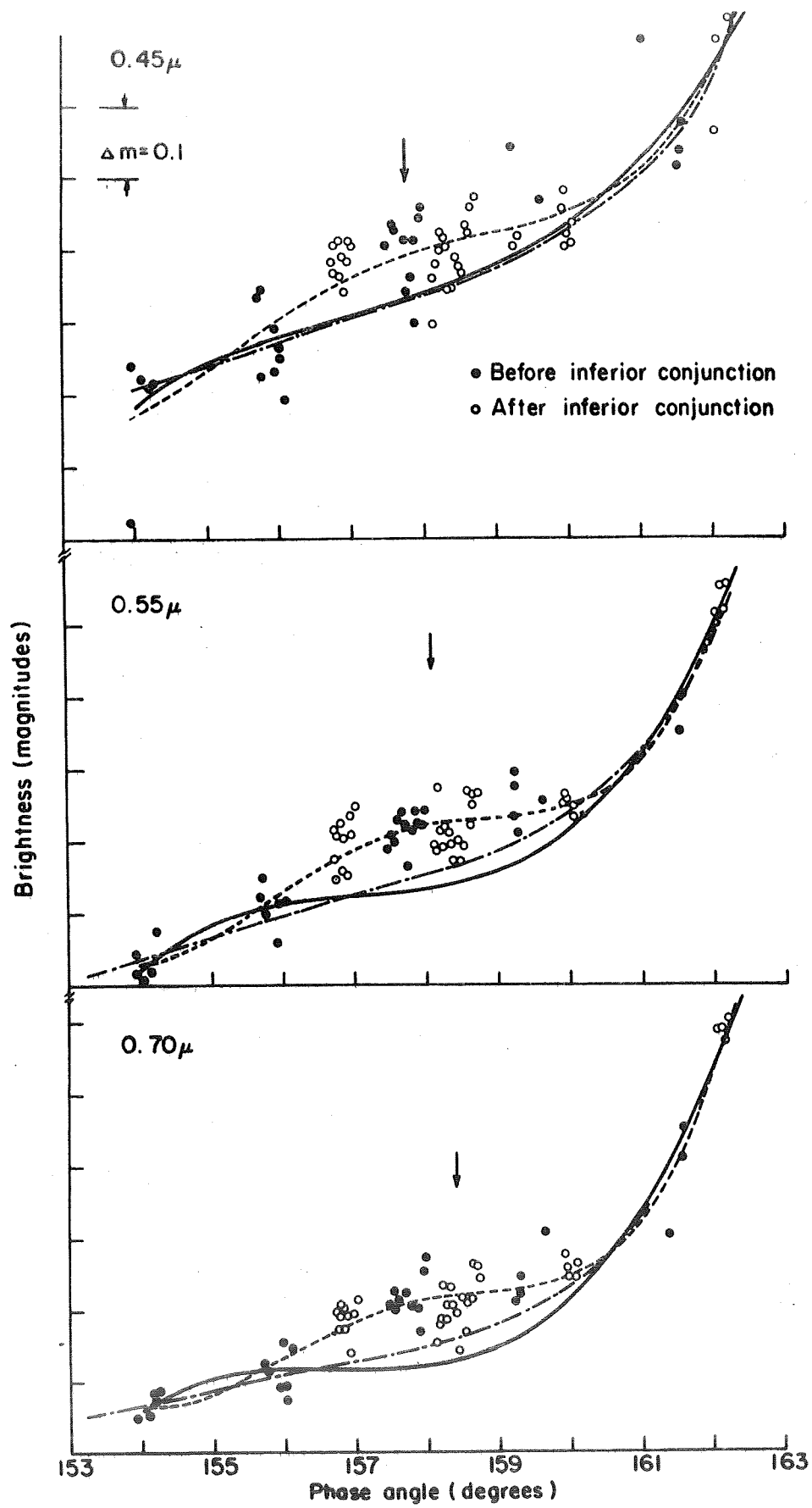   B-I' (1.05μ).

FIGURE CAPTIONS

Figure 1   Geometry of the 22° halo. When parallel light
enters a randomly-oriented hexagonal ice crystal
as above it tends to travel in the direction of
minimum deviation.

Figure 2   (a) and (b): Relative magnitudes of Venus and
per unit area of the crescent reduced to unit
distance from the sun and Earth, plotted against
phase angle α near inferior conjunction 1969.
Wavelengths of observation, in microns, are in-
dicated next to each set of curves. Each dashed
curve represents a fourth order fit to all
points, each solid curve a cubic fit to the
"background" points at $\alpha < 156^O.5$ and $> 160^O.0$,
and each dashed-dotted curve as eye and french
curve fit to the background points. Each arrow
indicates the angle of minimum deviation for each
color (see text).
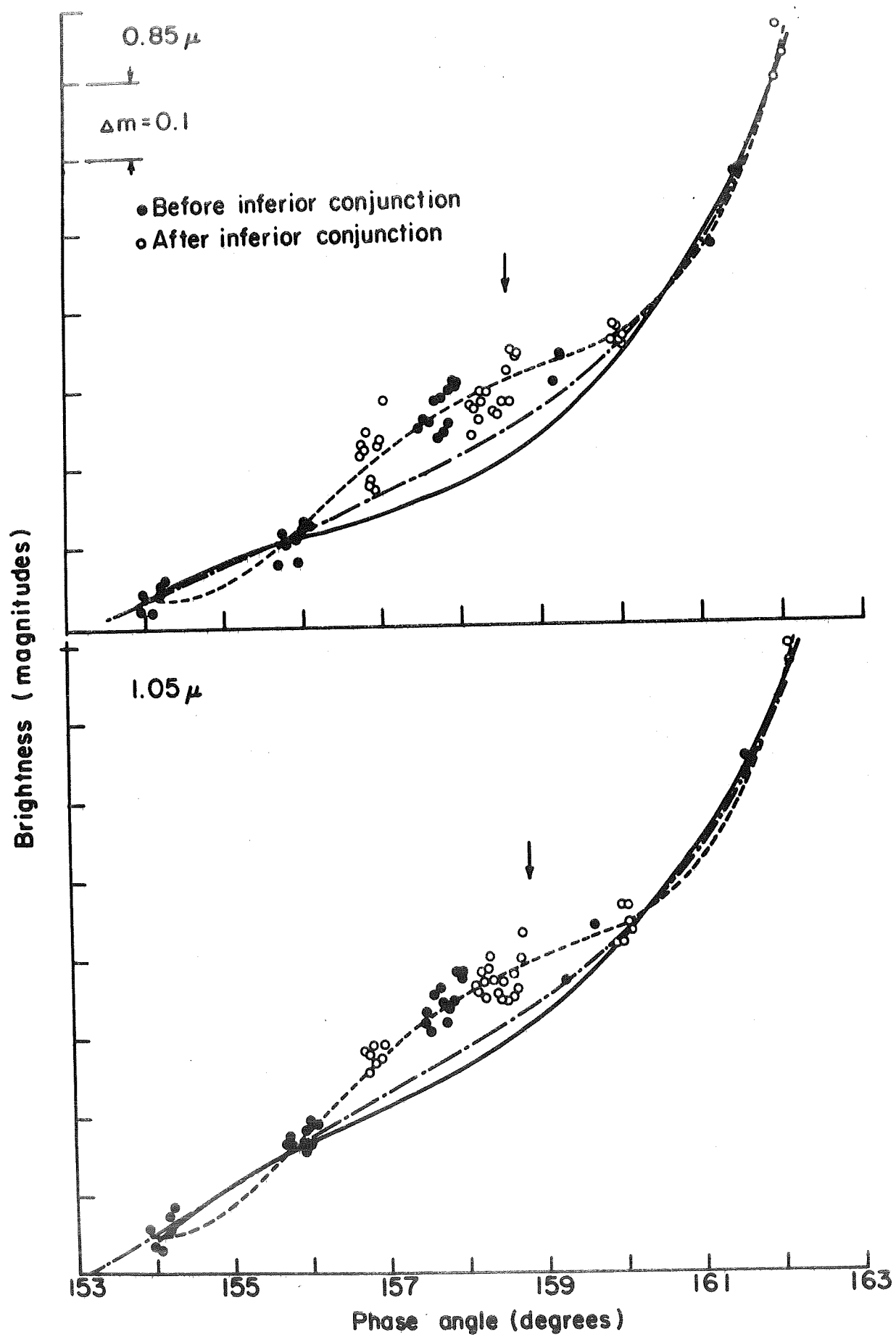
60°

22°

ICE: $n_D = 1.31$

Figure 1.

Figure

Figure 2'