A PHOTOMETRIC STUDY OF
PLUTO AND SATELLITES OF THE OUTER PLANETS

by

Leif E. Andersson

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I. INTRODUCTION

The purpose of the present study is to collect new photometric data in a standard photometric system for several bodies in the outer solar system; to discuss selected older series of observations of these objects; and to subject the data to preliminary interpretation and treatment, particularly considering the axial rotation of these satellites and planets. The original inspiration for this work came from the frequently encountered statement that all satellites in the solar system have synchronous rotation. In fact, the observations published up to a few years ago lend firm support to that claim only for the Moon, the four Galilean satellites of Jupiter, Saturn's eighth satellite (Iapetus), and, with somewhat less strength, Rhea (Saturn V). The unexpected results of the determinations of the rotation rates of Mercury and Venus, and the theoretical work following these discoveries, suggested to this student that the satellite systems of the planets may well contain other examples of spin-orbit resonances. The absence of published magnitudes and colors in the UBV system (or other modern photometric system) for some satellites was an additional incentive for the start of a program of UBV photometry of satellites of the outer planets. The satellites of Mars were removed from consideration for this observing program at an early stage because they would only be observable during a short time interval near each opposition, and then only with large instruments; besides, it was expected that the Mariner missions to Mars would soon settle the question of the rotation of Phobos and Deimos, as indeed they did (Burns 1972). When some incidental observations of Pluto showed that the present photometric behaviour of the planet differs from that reported previously (Walker and Hardie 1955, Hardie 1965), it was decided to include Pluto in the program, which in any case seems appropriate considering the well-known suggestion that Pluto is an escaped satellite of Neptune.

The choice of the UBV system as the photometric system for this investigation was dictated by two major circumstances: several satellites are too faint to be measured with narrowband filters, except perhaps with the largest existing telescopes, and the V magnitudes correspond closely to the visual and photovisual magnitudes in common use in the past. The widespread use of the UBV system means that suitable equipment is available at most observatories, so that opportunities for observing at various telescopes could be seized upon at short notice and with no complications caused by the photometric system used. The principal drawback of the UBV system is the notorious difficulty in reducing the U-B colors (e.g., Hardie 1966), but the satellites and almost all comparison stars used are photometrically well-behaved in this respect (having F, G, and K type spectra), and no major problems were encountered in establishing the U-B colors for the program objects. Nevertheless some effort was made to design reduction procedures that would reproduce the standard U-B colors better than Johnson's method (Johnson 1963) will do at a low-altitude observing site such as southern Indiana; these efforts are described in chapter IV.

The principal observational difficulty in satellite photometry is the strong and (spatially) highly variable sky background due to the planet. While this investigation used conventional photoelectric photometers with single, stationary, fixed-size, circular diaphragms in the focal plane of the telescope, it is clear that specially designed photometers may offer significant advantages. The most promising approach is probably area scanning; the first area scanning photoelectric photometer used for satellite work was devised by Rakos (1965), and the technique is in active and very successful use at the Lowell observatory (Franz et al. 1971, Franz and Millis 1973). However, it is felt that the present study demonstrates that useful photometry can be made with conventional equipment on even rather close satellites if proper care is taken and the properties of the sky brightness distribution are reasonably well known.

Some mention should be made of photographic photometry here. For the purposes of this investigation photography offers no advantage for bright satellites not too close to the primary; such satellites can be measured photoelectrically with little effort to an accuracy not easily attained in photographic photometry. For close satellites the corrections for the scattered light from the primary require much effort, whether one works photoelectrically or photographically; the accurate data which will hopefully be available in the future on such satellites will probably be obtained by area-scanning techniques. For faint distant satellites photography may be competitive, but the reduction work remains considerable; the accuracy will probably be low, and the possibility of systematic errors in the magnitudes, particularly due to trailing, is rather serious.

It is appropriate here to briefly summarize the information that can be more or less directly obtained from UBV photometry of satellites (and related bodies, such as asteroids). The primary data, after correction for atmospheric extinction and transformation to the standard system, are usually stated as a magnitude, V, and two color indices, B-V and U-B, for the object observed. As the distance from sun and earth varies continually for any solar system object, the magnitude is physically meaningful only after distance normalization, for example by reduction to mean opposition. Thus we have as the result of a complete UBV observation of a satellite or planet the following data: V_o, B-V, and U-B. By collecting such data over an interval of time we can determine how these vary with time and solar phase angle. The variation with time, if regular and periodic, can usually be attributed to the rotation of the object around its axis, and is for satellites often correlated with position in the orbit around the primary and having the same period as the orbital motion, thus indicating synchronous rotation. The character of this variation (amplitude and shape of lightcurve) may be different at different times or in different parts of the sky, because of differing aspect of the object relative to its axis of rotation or because of physical libration. The phase function (magnitude versus solar phase angle) gives indications about the surface roughness of the body; what other information it contains is a matter of some debate and will require further work for full clarification. The variation of color with phase angle is usually small; it is unclear what information it carries. The mean colors are at the present stage mostly useful as classification criteria and are presumably determined by the mineralogy and texture of the surface (for atmosphereless bodies such as most objects studied in this work). The current activity in narrow-band colorimetry of asteroids (Chapman et al. 1973) should lead to increased understanding of this in the near future, particularly when combined with results of polarimetric studies. Finally, the magnitude of the object allows the size to be calculated if the albedo is known by other means (Bowell and Zellner 1974), or conversely, the albedo can be determined if the size is known. If the mass is known, as is frequently the case entirely independently of any photometry, it can be combined with the size to give the density which is of course the fundamental datum for models of the interior structure of the body. This array of photometrically derived physical parameters of the satellite or planet, together with further parameters derived by other techniques (polarimetry, narrow-band photometry, spectroscopy), and information that may be obtained by future flybys and orbiting or impacting space probes, constitutes the physical description of the body to be accounted for by any theory for the origin or evolution of the solar system.

II. PHOTOMETRIC AND GEOMETRIC PARAMETERS

The terminology used in discussions of photometry of solar system objects has a fair degree of universal acceptance as regards definitions of terms and symbols for the quantities and parameters involved. Introductions to this terminology are available in several sources (e.g., Harris 1961, de Vaucouleurs 1970, Sharonov 1964). In the following I will briefly state definitions of some terms used frequently in this work and in a few cases somewhat modify the conventional terminology to improve the precision or usefulness of the definition. The sources used to obtain actual numerical values of various quantities needed for the reductions will also be indicated.

A. Reduction to standard distance and phase angle.

The observed (apparent) magnitude, m, of a planet or satellite is a function of its distance from the sun, r, its distance from the earth, Δ, and the solar phase angle, α, which is the angle at the planet between the earth and the sun. r, Δ, and a (used below) are expressed in astronomical units. The observed magnitude is also dependent on the rotational phase of the body and the earth's angular distance from the equatorial plane if the body is not spherical or if its albedo varies over its surface. The magnitude may also be influenced by changes in the planet's atmosphere or surface features. Neglecting for the moment any variations not dependent on distance or solar phase angle we have:

$$m = m(1,0) + 5 \log r\Delta + F(\alpha)$$

where $F(\alpha)$ is the phase function or the difference between the magnitude at phase α and the magnitude at zero phase angle (here a conventionally defined zero-phase magnitude may be used rather than the actual magnitude at zero phase; see next section). The quantity $m(1,0)$ depends on the size of the body and on its geometric albedo (see below); we will call it the absolute magnitude. The symbol m in the absolute magnitude may be replaced by any specific type of magnitude; the two arguments in parentheses are intended to indicate $r = \Delta = 1$ and $\alpha = 0$. The symbol $m(1,\alpha)$ may be used for magnitudes reduced to unit distance but uncorrected for phase variation. For outer planets it is convenient to reduce observations to mean opposition distance ($r = a$, $\Delta = a - 1$, where a is the semimajor axis of the planet's orbit); the resulting magnitude, m_o, is not only directly comparable with other observations reduced in the same manner, but gives a rough indication of the actual observed magnitude. Subtracting $F(\alpha)$ from m_o gives the mean opposition magnitude, $\overline{m}_o$.

m_o and $m(1,\alpha)$ are thus possible forms in which to report individual observations. Combining many observations permits a phase function to be derived for the object, and a representative quantity, $\overline{m}_o$ or $m(1,0)$, can be obtained. When quoting $\overline{m}_o$ or $m(1,0)$ as parameters describing the planet or satellite in question, it is usually understood that rotational and other intrinsic variations have been corrected for, to the extent to which they are known.

In this work the magnitudes given are usually the V magnitudes of the UBV system. The following relations apply (neglecting rotational variation, etc.):

$$\begin{aligned} V - 5 \log r\Delta &= V(1,\alpha) \\ &= V(1,0) + F(\alpha) \\ &= V_o - 5 \log a(a-1) \\ &= \overline{V}_o - 5 \log a(a-1) + F(\alpha) \qquad (1) \end{aligned}$$

If the phase function is linear, the average V_o for a series of observations is equal to the V_o that would be derived from an observation at the phase angle equal to the average phase angle $\langle\alpha\rangle$ for the observation series, subject only to the observational errors. Thus its value does not depend on the phase coefficient β (see next section); if the phase function is not linear, this will still be approximately true if the range of phase angles of the individual observations is not too large. The error of $V_o(\alpha = \langle\alpha\rangle)$ may be estimated as the m.e. of the mean of the individual V_o values reduced to phase angle $\langle\alpha\rangle$, using an approximate value for β. If the observational errors are comparable to the extent of the variation with phase angle (as is frequently the case for observations reported here) the thus estimated m.e. of $V_o(\alpha = \langle\alpha\rangle)$ is only weakly dependent on how good an approximation to β was used. Thus $V_o(\alpha = \langle\alpha\rangle)$ is necessarily better determined from a given set of observations than

$\overline{V}_o$ is, and will be frequently used in ch. VII.

$\overline{V}_o$ (or V(1,0)) as a parameter of the physical description of a planet or satellite has a somewhat undesirable property connected with the phase function: the shape of $F(\alpha)$ near $\alpha = 0$ is not very accurately known for most bodies. The phase function for many objects in the solar system, including several of the principal planets as well as probably all asteroids and many of the satellites, has its greatest slope and curvature for very small phase angles (disregarding phase angles >90°). It is thus hardly appropriate to represent $F(\alpha)$ by a power series in α, as is frequently done. In all but the most recent literature (preceding and including Harris' review (1961)) this problem is not fully appreciated.

B. Characteristics of observed phase functions.

For any solar system object outside the orbit of the Earth the range of solar phase angles under which it may be observed extends from zero to a maximum value which is mainly determined by the semi-major axis of the orbit; for example, the maximum phase angle is 47° for Mars, around 30° for most asteroids, and 12° or less for the Jovian planets. Over most of this range it is generally found that a linear function is a close approximation of $F(\alpha)$; the slope of this linear function is called the phase coefficient, β. For atmosphereless bodies its value is usually in the range, 0.02 mag/deg to 0.06 mag/deg. The deviation from linearity appears for phase angles less than about 10° and has the form of a steep brightness surge which at $\alpha \leq 1°$ may differ by a few tenths of a magnitude from the linear function extrapolated to small α. The presence of this so-called opposition effect is generally considered indicative of a rough surface with intricate structure, in which the individual particles making up the surface layer have strong backscattering properties and low reflectivity. Objects having this type of phase curve and for which good observations over the observable range of phase angles are available in the literature include the Moon, several asteroids, and the rings of Saturn (e.g., Gehrels et al. 1964; Gehrels 1970; Bobrov 1970; Cook et al. 1973).

Theoretical models of surfaces having such phase curves have been constructed by several authors (Hapke 1963; Irvine 1966; Lumme 1971). Gehrels (1970) gives a "mean asteroid phase curve" obtained from several well-observed asteroids and issues a plea for the use of this function in correcting an observed magnitude for phase (unless a more accurate curve is known for the object in question). His phase curve consists of a linear part with slope 0.023 mag/deg and a superposed opposition effect beginning at 8° and reaching 0.40 mag. brighter than the extrapolated linear relation at 0°. He recommends a reduction to zero phase with the absolute magnitude defined by the linear phase function only (thus an actual observation at zero phase will take a positive correction); this seems to be a satisfactory way of reducing in a uniform manner magnitudes of photometrically asteroid-like objects without necessarily having detailed knowledge of the phase curve at very small phase angles. Because it seems possible that the opposition effect at the smallest phase angles (say, <1°) may be strongly varying from object to object and may be much larger than indicated by extrapolation from slightly larger values of α, a procedure such as that of Gehrels is preferable to one of attempting to extrapolate to $\alpha = 0$ by including the opposition effect.

It would be desirable to have a physically reasonable two- or three-parameter numerical description of any observed phase function of the type discussed. One possibility would be to use the following two-parameter photometric function:

$$F(\alpha) = \beta\alpha + \phi f(\alpha) \qquad (1)$$

where β is the usual (linear) phase coefficient and ϕ is a factor for scaling the opposition effect, f, in Gehrels' asteroid function. Thus $\beta = 0.023$ mag/deg and $\phi = 1$ gives Gehrels' function, shown in Fig. 1.

C. Albedo.

The albedo (or reflectivity) of a planet or satellite can be defined in several ways (Harris 1961, de Vaucouleurs 1970). In this work reference will be made to the geometric albedo, p. It is the ratio of the amount of light reflected from the body, observed at zero phase angle, to that reflected from a Lambert disk (perfect diffuse reflector) in the plane of the sky, of the same angular size as the body, and at the same distances from sun and earth. Because of the previously discussed complications with phase functions at very small phase angles, the generally quoted values of p for various solar system objects refer to an extrapolation from moderately small

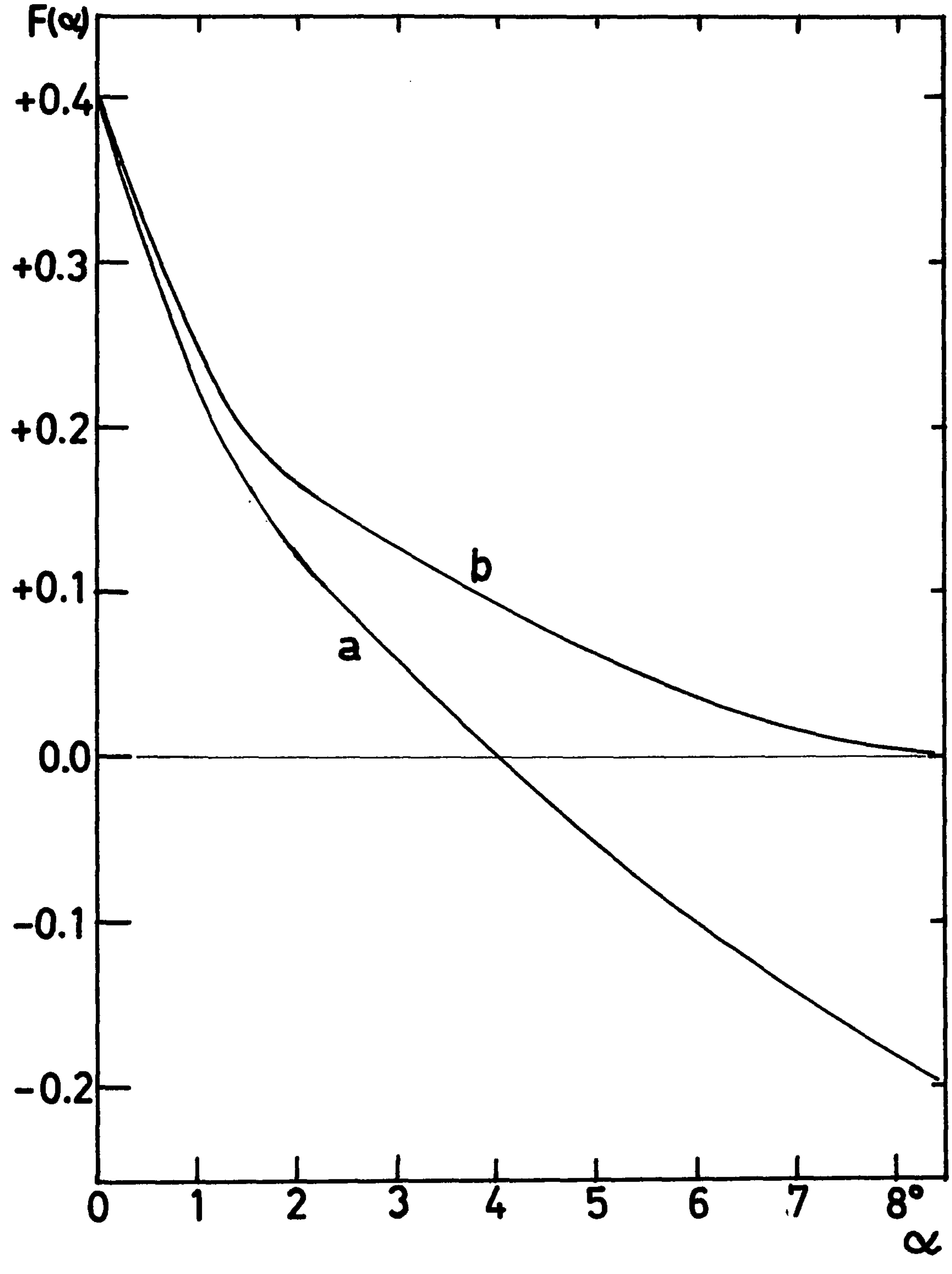

Figure 1. Gehrels' standard phase function for asteroids (curve a). The opposition effect is plotted separately as curve b.

phase angles to $\alpha = 0$, taking only partial account of the opposition effect. p is related to the absolute magnitude and the radius, R, of the body by:

$$m(1,0) = m_{\odot} - 2.5 \log p - 5 \log \frac{R}{1\ AU} \qquad (1)$$

Here $m_{\odot}$ is the magnitude of the sun. In planetary photometry the following UBV data for the sun are frequently adopted (Gehrels et al. 1964): V = -26.77, B-V = +0.63, U-B = +0.10.

D. The reflection effect.

A small fraction of the light received from a satellite has been reflected by both the primary and the satellite. An exhaustive theoretical treatment has been given by Schoenberg (1929). Here will only be shown that the contribution of this doubly reflected light is not measurable with present photometric techniques for any natural satellite except the Moon. (The earthshine is measurable because the Moon can be observed at nearly 180° solar phase angle, while the Earth-Moon-observer angle is necessarily close to 0°.)

If all light reflections involved (sunlight reflected by satellite; sunlight reflected by primary towards satellite; and light from primary reflected by satellite) took place at zero phase angle, the ratio of twice reflected light to directly reflected sunlight would equal the ratio, N, of the brightness of the primary, as observed at its opposition as seen from the satellite, to the brightness of the sun, seen from the same vantage point. If $R \ll r$, where R is the radius of the primary and r the distance of the satellite from the primary, the ratio is easily shown (using eq. (1) of the previous section) to be

$$N = p(R/r)^2 \qquad (1)$$

where p is the geometric albedo of the primary. For obvious geometrical reasons all reflections can not take place at zero phase angle, and the appropriate phase functions must be included in the singly and doubly reflected light fractions. Let the Sun-satellite-observer angle be α, the Sun-primary-satellite angle α', and the primary-satellite-observer angle α''. Denote the phase function of the primary by F' and that of the satellite by F. Then the ratio, N', of doubly to singly reflected light received by the observer becomes

$$N' = p(R/r)^2 \Phi'(\alpha')\Phi(\alpha'')/\Phi(\alpha)$$

where

$$F(\alpha) = -2.5 \log\Phi(\alpha)$$

and similarly for Φ' and F'. If the size of the satellite orbit is negligible compared to the distance to Sun and Earth, we have

$$|\alpha' + \alpha'' - 180°| \leq \alpha$$

and since Φ and Φ' decrease with increasing phase angles,

$$N' \leq p(R/r)^2 \Phi'(\alpha')\Phi(180° - \alpha_{max} - \alpha')/\Phi(\alpha_{max}) \qquad (2)$$

where α_{max} is the maximum solar phase angle observable for the planet in question.

The satellite of any of the outer planets for which N' is expected to be largest is Jupiter V, since its R/r is larger than for any other satellite. The phase functions for it and for Jupiter are of course not well known for phase angles greater than $\alpha_{max} \approx 12°$; for this application it will be assumed that the well-known phase functions of the Moon and Venus (Harris 1961) may be used for Jupiter V and Jupiter. It is found that for all values of α',

$$N' \lesssim 0.003$$

in V and less in B and U. To detect this effect one would thus have to measure Jupiter V to an accuracy of $0\overset{m}{.}003$ or better. In view of the many approximations entering in (2), the effect may actually be substantially larger than $0\overset{m}{.}003$, but Jupiter V can hardly be measured even to $0\overset{m}{.}05$ with existing photometric equipment (indeed, no photometry has ever been published). The satellite for which accurate photometry exists and for which R/r is largest is Io (Jupiter I); the reflection effect probably contributes less than $0\overset{m}{.}001$ to its magnitude.

The reflection effect will be neglected in the rest of this work.

E. Orbital and rotational phase for a synchronously rotating satellite.

For a satellite known or suspected to rotate synchronously one frequently plots photometric data versus <u>orbital phase</u>, Θ, which could be defined as the angular distance (at the satellite) from the projection of the earth on the satellite's orbital plane to the primary, counted in the direction of the orbital motion. However, it may also be considered defined by the formula by which it is usually calculated:

$$\Theta = 360° \times \frac{t - t_{SC}}{t_{SC_1} - t_{SC}} \qquad (1)$$

where t is the time of observation, and t_{SC} and t_{SC_1} are the times of the preceding and following superior conjunctions with the primary, respectively. Alternatively, if times of eastern elongation (EE) are given in the ephemeris,

$$\Theta = 360° \times \frac{t - t_{EE}}{t_{EE_1} - t_{EE}} + 90° \qquad (2)$$

For a retrograde satellite the sign of the last term will be negative. In principle one should make allowance for the finite size of the satellite orbit; this would add the angular separation from the primary to the right side of (2). The elongation times are usually not given in the ephemeris to an accuracy requiring a correction for the orbit size in (2), but for Iapetus the effect amounts to nearly 1^h in the time of EE or $0\overset{\circ}{.}2$ in Θ; it is negligible for other satellites for which elongation times are given in the AE.

The idea behind plotting magnitude, etc. versus Θ is, of course, that Θ identifies the face of the satellite observed, i.e., the rotational phase; however, for several reasons the orbital phase as calculated by (1) or (2) is only an approximation to the rotational phase as defined in the next paragraph: 1) the eccentricity of the satellite orbit makes the actual orbital motion nonuniform; 2) the reference direction (the Earth-planet line) does not rotate uniformly in an inertial frame; 3) if the reference direction is not in the plane of the satellite equator there will be projection effects analogous to the obliquity part of the Equation of Time, familiar from elementary astronomy; and 4) the rotation of the satellite may not be uniform (physical libration). The physical libration of the Moon is extremely small (amplitude $<0\overset{\circ}{.}1$). The angle between the axis of rotation and axis of the orbit, i.e. the obliquity, is $6\overset{\circ}{.}7$ for the Moon. For other synchronously rotating satellites it is probably also small but generally not zero, since the rotation of these satellites may be expected to be governed by analogues of Cassini's laws (Peale 1974). Obliquity and physical libration will be disregarded in the rest of this chapter. If the obliquity is small, item 3 above concerns mainly the angular distance of the Earth from the plane of the satellite's orbit. The satellite's period of rotation is in all cases very much shorter than the period in which the Earth makes a full revolution in a coordinate system fixed to the satellite orbit (the latter period is roughly the period of revolution of the planet around the Sun, differing from it only because of precession of the satellite orbit). Therefore, the projection effect of the inclination on θ can be ignored.

The coordinates in a system fixed to the solid surface of a planet or satellite are called <u>planetographic longitude</u> and <u>planetographic latitude</u>, and the poles and equator of the system are defined by the axis of rotation. The zero meridian of a synchronously rotating satellite will be defined as the meridian of the mean center of the disk of the satellite as seen from the center of the primary. (This definition could run into difficulties if the obliquity approaches 90°. However, it is doubtful whether the rotation of a satellite with an obliquity of 90° could be considered synchronous.) The <u>rotational phase</u>, Θ', is defined as the planetographic longitude of the center of the apparent geometrical disk of the satellite (seen from Earth); the longitudes are taken to increase in such direction on the surface of the satellite that the rotational phase increases with time for a distant stationary observer. For objects observed under large solar phase angles it would perhaps be more appropriate to use the center of the <u>illuminated disk</u>, as more representative of the parts of the object reflecting light towards the observer. The distinction is of little practical importance for any object considered in this work because of the small phase angles involved. The difference in longitude between the center of the geometrical disk and the center of the illuminated disk (the latter taken to be the midpoint of the symmetry axis of the illuminated disk) is, for zero inclination of the equator to the line of sight, easily shown to be

$$C = \arcsin\left(\tfrac{1}{2} - \tfrac{1}{2}\cos\alpha\right)$$
$$(\approx \alpha^2/4 \text{ if } \alpha \text{ small})$$

where α is the solar phase angle. For Jupiter the maximum value of the correction is about 0°6, and for Saturn less than 0°2.

Because of the eccentricity of the satellite orbit the rotational phase is not zero at superior conjunction unless the satellite is at pericenter or apocenter at that time. Instead, Θ' is then equal to the difference between mean and true anomaly in the satellite orbit at the time of conjunction:

$$\Theta'_{SC} = M_{SC} - v_{SC} = -2e \sin M_{SC} + \text{terms in } e^2 \text{ and higher}$$

Here M and v are the mean and true anomalies, e is the eccentricity, and the subscript SC refers to superior conjunction. Θ'_{SC} can amount to 14° for Hyperion and over 3° for Titan and Iapetus. The need for a correction would be eliminated if the conjunction times in (1) were exchanged for times of "mean superior conjunction" (MSC), meaning the time when a fictitious "mean satellite" (whose true anomaly equals the mean anomaly of the actual satellite) is at SC. It is easily shown that to an accuracy (in Θ) of the order of e^2, MSC falls midway in time between the western elongation (WE) preceding and the EE following SC (for retrograde satellites reverse WE and EE). This provides a quick and easy way to calculate Θ free of the eccentricity effect for satellites for which all elongations are given in the ephemeris.

To evaluate the effect mentioned under 2) above, we first note that the rotational phase of the satellite as seen from the Sun is uniform to a very good approximation because the planet's revolution period is longer than that of the satellite by at least two orders of magnitude in all cases of interest. Call the rotational phase (or orbital phase corrected for eccentricity) as seen from the Sun Θ_s. Also let the projection of the solar phase angle on the plane of the satellite orbit be y. y is negative before and positive after opposition. Because of the general near-coplanarity in the solar system, y is numerically practically equal to α except near opposition. It is easily seen that the rotational or orbital (eccentricity effect eliminated) phase of the satellite seen from Earth is

$$\Theta = \Theta_s \pm y \tag{3}$$

where the negative sign applies to retrograde satellites. The error made in linear interpolation of Θ with time as argument, such as is in fact done in eq. (1), is proportional to $\frac{d^2\Theta}{dt^2} = \pm \frac{d^2y}{dt^2}$. For an outer planet one can to first approximation set the projected phase angle $y = \frac{1}{r}\sin(\lambda_o - \lambda_p)$, where λ_o and λ_p are the heliocentric longitudes of Earth and planet and r is the planet's distance from the Sun in AU. From Taylor expansion of (3) one then finds that the error (from this cause) made in using (1) to find the orbital phase is at most

$$\Delta\Theta_{max} \approx \frac{P^2}{8r}\left(\frac{d\lambda_o}{dt} - \frac{d\lambda_p}{dt}\right)^2 \approx 0^\circ\!.002\ (\text{day}^{-2})\ \frac{P^2}{r}$$

where P is the period of revolution of the satellite (i.e., $t_{SC_1} - t_{SC}$ in (1)). The error can amount to 1°.3 for Iapetus, 0°.1 for Callisto and Hyperion, and less for all other satellites likely to be in synchronous rotation.

The AE gives mean orbital longitudes, L, at 5^d intervals for Saturn's satellites; these combined with the geocentric longitude U of Saturn referred to the ringplane (given in the AE ephemeris for the rings of Saturn), are the simplest as well as most accurate means of obtaining Θ' for these satellites. For the first seven (Mimas through Hyperion) the orbital inclination to the plane of the rings is small, and the rotational phase is given to good approximation by

$$\Theta' = L - U \quad .$$

Because the tabulated L is uncorrected for lighttime it must be obtained from the table with the time of observation minus the lighttime as argument. For Iapetus the orbit is inclined appreciably to the ringplane and a correction for projection effects must be applied:

$$\Theta' = L - U + \delta\Theta$$

where $\delta\Theta$ is defined by

$$\tan(U-\eta-\delta\Theta) = \cos\gamma \tan(U-\eta) - \tan B \sin\gamma \sec(U-\eta) \quad \text{and} \quad |\delta\Theta| < 90° \quad . \tag{4}$$

γ is the orbit inclination, B is the saturnicentric latitude of the Earth, and η is the longitude of the ascending node of the orbit. γ, B, and η are given in the AE (η is called Θ there). The same formula can be used for other Saturn satellites if high accuracy is desired. Approximate expressions for $\delta\Theta$ are easily derived from (4).

In addition to the rotational phase it is also of interest to know the latitude (planetographic), ϕ, of the sub-earth point on the satellite. For satellites of the outermost planets ϕ varies slowly and can be considered constant during one observing season. An approximate value can be obtained from the shape of the apparent orbit ellipse of the satellite from the AE:

$$\sin|\phi| = \frac{\text{minor axis of app. orbit}}{\text{major axis of app. orbit}}$$

The sign of ϕ is given by the apparent sense of revolution of the satellite. For the Galilean satellites of Jupiter, $\phi \approx D_E$ (from the physical ephemeris of Jupiter), and for the inner satellites of Saturn $\phi \approx B$ (from the ring ephemeris). For Iapetus

$$\sin\phi = \sin B \cos \gamma + \cos B \sin \gamma \sin (U-\eta)$$

where B, γ, and η are defined above.

Much of the material in this section can be modified to apply to all satellites, not only synchronously rotating ones. For the case of general rotation there is of course no connection between orbital and rotational phase; the planetographic longitude must be defined in some other way than for the synchronous case.

F. Correction of magnitude and phase angle for finite size of satellite orbit.

The satellite orbit is in most cases so small compared with the distance to the Sun that the reduction to V_o can be done using distances of the primary from Sun and Earth as taken directly from the AE. Likewise, the solar phase angle for the satellite can usually be considered the same as that of the planet. For some satellites treated here the differences in magnitude correction and phase angle between satellite and primary can exceed one unit in the last decimal usually quoted ($0^m.01$ and $0^\circ.01$). The maximum differences are about $0^m.1$ and $0^\circ.2$ for Jupiter VI, VII, and X, $0^m.2$ and $0^\circ.5$ for the outermost four Jupiter satellites, $0^m.012$ and $0^\circ.02$ for Iapetus, and $0^m.05$ and $0^\circ.1$ for Phoebe. The following approximate correction formulae have been derived:

$$(V_o-V)_s - (V_o-V)_p = -\frac{8.7\rho}{r+\Delta}\cos\left(\pm\Theta + \frac{\alpha_p}{2}\right) \quad (1)$$

$$\alpha_s - \alpha_p = \frac{\rho}{r\Delta}\sin\left(\lambda_p-\lambda_o\mp\Theta\right) \quad (2)$$

ρ is the distance of the satellite from the primary, r and Δ are the primary's distances from Sun and Earth, Θ is the orbital phase of the satellite (lower signs apply to retrograde satellites), and λ denotes heliocentric longitude. Subscripts s, p, and o refer to satellite, primary, and Earth, respectively. The phase angle α is to be taken with positive sign after and with negative sign before opposition. In (2) $r\Delta/\rho$ must be expressed in AU. The formulae neglect the orbital inclination of the satellite orbits; the approximations $\rho \ll r$ and $r \gg 1$ are implied. In practice, the corrections calculated by (1) and (2) are probably good to a few per cent.

G. Sources of data for magnitude reductions.

Most of the ephemeris data needed for reduction of observed magnitudes to standard distance and phase angle may be taken directly from the AE. In recent volumes of the AE, Δ is given daily for the major planets (4^d interval for Pluto), and r is given at 10^d intervals for Jupiter and Saturn and at 40^d intervals for the three outermost planets. Ephemerides for Pluto were not given in the AE before 1950; the reduction of older Pluto observations were made using the heliocentric rectangular coordinates in Eckert et al. (1951). The tabulated r and Δ are geometric distances at the tabular times, thus not the distance traveled by the light measured in the photometric observations. However, the error in the reduced magnitude introduced by this planetary aberration effect is always less than $0^m.001$ for all planets.

The solar phase angle is given in the AE (the symbol ι is used instead of α) for Jupiter and Saturn at 4^d intervals (in the Physical Ephemerides section); for Saturn it has only been so given since 1960. For the other outer planets α has been calculated from the heliocentric and geocentric ephemerides; for Pluto before 1950 the tables of Eckert et al. (1951) were employed. For Saturn before 1960 the ring ephemeris (which includes saturnicentric longitudes and latitudes of Sun and Earth) is convenient for calculating α.

Reduction to mean opposition requires the mean distance a of the planet from the Sun. The a's adopted in this thesis are: Jupiter 5.203 AU, Saturn 9.54, Uranus 19.22, Neptune 30.06 and Pluto 39.5. The corresponding values of the frequently used quantity, $5 \log a(a-1) = \overline{V}_o - V(1,0)$, are: Jupiter $6^m.70$, Saturn $9^m.555$, Uranus $12^m.72$, Neptune $14^m.71$, and Pluto $15^m.91$.

III. ROTATION OF SATELLITES: SOME THEORETICAL CONSIDERATIONS

Interest in planetary rotation and its evolution by tidal energy dissipation has intensified following the establishment of the rotation periods of Mercury and Venus by radar techniques in the early 1960's. An excellent review (in spite of a number of misprints) is that of Goldreich and Peale (1968). The formalism developed there and by Goldreich and Soter (1966) will be used in the following to make estimates of the rate of despinning of satellites. Such estimates will give a rough idea of whether a particular body has had its spin appreciably changed by tidal effects during the age of the solar system or whether it may be expected to retain essentially the spin rate acquired during its formation.

The effect of tidal friction on the evolution of the rotation of the Earth and the orbit of the Moon was developed in a classical series of papers by Darwin (1908); several more recent calculations follow in principle Darwin's method (Kaula 1964, Goldreich 1966a). Since we are here concerned with the changes in the rotation of a satellite because of the tides raised on it by its primary, we will in the following call the disturbing body the "planet" and the body on which the tides studied are raised, the "satellite."

The discussion will be restricted to approximately spherical bodies even though many of the smaller satellites almost certainly deviate strongly from spherical shape. The smallest (and thus most likely nonspherical) satellites orbiting Jovian planets are the outermost satellites of Jupiter and Saturn, and it will be seen that for the spherical case these satellites are being tidally despun so slowly that the age of the solar system is, by several orders of magnitude, insufficient time to affect their rotation appreciably. It appears likely that this conclusion will still hold if their shape is taken into account.

The planet, of mass M, raises a tide on the satellite, and the deformation of the satellite gives rise to a disturbing potential in addition to the one causing the original tidal deformation. If internal friction (imperfect elasticity) is present in the satellite, then there will be a time lag between variations in the original tide-raising potential and in the secondary potential; and if the satellite rotates with respect to the radius vector there will thus also be a geometric lag. In other words, the tide-raising body will be asymmetrically located in the secondary potential, and a net torque will result.

In the Darwinian treatment (e.g. Kaula 1964), the tidal potentials are expressed in terms of spherical harmonics, e.g., for the tide-raising potential U:

$$U = \frac{GM}{r} \sum_{\ell=2}^{\infty} \left(\frac{\rho}{r}\right)^{\ell} P_{\ell}(\cos S)$$

where ρ is the distance from the center of the satellite to the field point considered; r is the distance of the planet from the satellite;

S is the angle between the radius vectors of the field point and the planet; P_ℓ is the Legendre polynomial of order ℓ; and G is the constant of gravitation. The potential, U', caused by the tidal deformation itself is of the form

$$U' = \frac{GM}{r} \sum_{\ell=2}^{\infty} k_\ell \frac{R^{2\ell+1}}{\rho^{\ell+1} r^\ell} Y_\ell$$

where R is the radius of the satellite; k_ℓ is a constant (the potential Love number) depending on elastic properties of the satellite; and Y_ℓ represents a combination of surface spherical harmonics of order ℓ (actually, $P_\ell(\cos S)$ displaced by the geometric lag angle). Actual numerical calculations in the references mentioned have been restricted to the terms of lowest order (ℓ=2); for the present situation in the Earth-Moon system this is probably adequate, and as $\frac{R}{r}$ (ratio of the radius of the body whose tides are considered to the distance to the tide-raising body) is smaller by a factor of at least 3 for all satellites in the solar system than it is for the Earth, it is probably safe to claim that the terms of higher order than ℓ=2 have been unimportant for the evolution of the rotation of all satellites. (For the Earth during earlier stages of its history, and perhaps for some other planets, this may not be true). Considering, then, only the terms of order 2, one obtains (Goldreich and Peale 1968) for the component T along the satellite's rotational axis of the time-averaged tidal torque acting on the satellite:

$$T = \frac{2Gk_2M^2R^5}{a^6} \sum_{m=1}^{2} m\frac{(2-m)!}{(2+m)!} \sum_{p=0}^{2} \sum_{q=-\infty}^{\infty} (F_{mp}(i)G_{pq}(e))^2 \sin\varepsilon_{mpq} \qquad (1)$$

where

$$\operatorname{sgn} \varepsilon_{mpq} = \operatorname{sgn}(n(2-2p + q) - m\omega); \qquad (2)$$

a is the semimajor axis of the satellite orbit; n is the mean motion in the satellite orbit; and ω is the angular spin velocity of the satellite. $F_{mp}(i)$ are trigonometric polynomials in the obliquity i (angle between satellite's equatorial and orbital planes), and $G_{pq}(e)$ are power series in the orbital eccentricity e. The F_{mp} and G_{pq} of lowest orders are listed by Kaula (1964) and Goldreich and Peale(1968); in the latter reference the lists contain a few misprints. Because of the obliquity i and the eccentricity e the tides are best expressed as a sum of Fourier component tides, each characterized by a set of integers m,p,q. The phase lag of the (m,p,q) tidal component is denoted ε_{mpq}.

The obliquity i is not known accurately for any satellite except the Moon. It seems reasonable, however, to assume that it is small for all satellites which are affected strongly by tidal action. Setting i = 0 makes the obliquity polynomials F_{mp} with m = 1 equal to zero. Furthermore, $F_{21}(0)$ and $F_{22}(0)$ are both equal to zero, so that we are left only with the terms containing $F_{20}(0)$, the numerical value of which is equal to 3. Eq. (1) then reduces to

$$T = \frac{3Gk_2M^2R^5}{2a^6} \sum_{q} (G_{0q}(e))^2 \sin \varepsilon_{20q} \qquad (3)$$

and

$$\mathrm{sgn}\ \varepsilon_{20q} = \mathrm{sgn}\ (n - \omega + \frac{nq}{2}) \quad . \tag{4}$$

If the eccentricity is small, the G_{0q} with $q \neq 0$ are negligible; and $G_{00}(0) = 1$. We find that if i and e are small, and $n \neq \omega$ (ε vanishes if $n=\omega$ and $p=q=0$), then the dominant tidal component is $(l,m,p,q) = (2,2,0,0)$ which is the familiar semidiurnal tide.

The phase lag ε_{mpq} is related to the dissipation factor Q by the relation $1/Q = |\tan \varepsilon_{mpq}|$, provided $Q>>1$ (MacDonald 1964). Q is defined as $2\pi E/\Delta E$, where E is the maximum energy stored in the tidal deformation (or, in general, the peak energy in an oscillating system) and ΔE is the energy dissipated during one cycle. Thus a large Q is characteristic of a weakly damped oscillator or a relatively nondissipative medium. Goldreich and Soter (1966) examined orbits and rotational rates of bodies in the solar system for the purpose of making estimates of or setting limits to the effective Q for tides in these bodies. The Jovian planets have enormous Q values, probably $>10^4$; other bodies probably have Q's in the range 10 to 10^3. Experimental determinations of Q involve in general much higher frequencies than the tides (Knopoff 1964), and in any case a value determined for a homogeneous substance is not necessarily applicable to a large body with complicated (and generally unknown) internal structure such as a planet. In the case of the Earth, a variety of methods give Q's ranging from 10 to 40 for the energy dissipation at tidal frequencies. Unfortunately, it is still unclear where precisely in the Earth most of the dissipation takes place. Among the principal suspects are the shallow parts of the oceans, the interfaces between various layers in the Earth or between crustal blocks, and in the body of the mantle (Kaula 1968, p. 199). While the oceans are usually thought to be the main energy sinks, dissipation in the solid parts of the Earth could be more important if Q depends in certain ways on the frequency and/or strain amplitude. The dependence of Q on frequency or amplitude is virtually unknown for low frequencies, which is unfortunate because the evolution of a planet-satellite system may differ drastically among models with different frequency or amplitude dependences of the dissipation factor. Laboratory experiments (at acoustic frequencies) indicate that Q is independent of frequency for solids, but $Q \propto (\text{frequency})^{-1}$ for liquids (Knopoff 1964). Greenberg (1973) has pointed out that the pairs of resonant satellite orbits in the Saturn system provide some constraints on the dependence of frequency and amplitude of Saturn's tidal Q.

The Love numbers are dimensionless constants describing the response of a body to disturbing potentials (Munk and MacDonald 1960). Of interest here is the potential Love number of order 2, called k_2. For a homogeneous sphere of radius R, density ρ, surface gravity g, and rigidity μ, it is

$$k_2 = \frac{3}{2} (1 + 19\mu/2g\rho R)^{-1}. \quad (5)$$

For a small body, where rigidity of the material completely dominates over self-gravitation in determining the degree of sphericity, k_2 will be small, while for a very large planet and for fluid (μ=0) spheres k_2 will approach a maximum value of $\frac{3}{2}$. The tidal Love number for the Earth is found to be about 0.3 by a variety of methods; for other planets and satellites it must be calculated using an assumed value for μ.

Now consider a satellite with radius R, mass m, and spin rate ω. Its (scalar) rotational angular momentum is $H = cmR^2\omega$, where c depends on the density distribution in the body. The constant c can be determined from observations of precession of the axis of rotation, or may be calculated from models of the interior of the body. If the rotation only changes because of tidal effects, the time derivative of H is simply the previously derived torque T. The moment of inertia, $C = cmR^2$, may be regarded as constant, so we have

$$T = cmR^2\dot{\omega} \quad . \tag{6}$$

For a homogeneous sphere, $c = \frac{2}{5}$; even for the Earth, for which the central density is about twice the mean density, the value of c is 0.33, i.e. not much less than for the homogeneous case. For any satellite in the solar system c may therefore be set equal to $\frac{2}{5}$ with an error unlikely to be as large as 10%. Next, T from eq. (3) will be substituted in (6), retaining only the q = 0 term from the sum in (3). The result is

$$\frac{3Gk_2M^2R^5}{2a^6} \sin \varepsilon = \frac{2}{5} mR^2\dot{\omega} \tag{7}$$

where the subscripts of the phase lag angle have been dropped. As

Q>>1 and $1/Q = |\tan\varepsilon|$, ε is a small angle and $1/Q = |\sin \varepsilon|$ is a good approximation. Thus

$$|\dot{\omega}| = \frac{15Gk_2M^2R^3}{4ma^6Q} \qquad (8)$$

In table I are collected mechanical data for all satellites of the solar system (except for some of Jupiter's outer satellites for which no accurate physical data are available and for the orbits of which JVI and JVIII are representative). Observationally determined radii and masses are taken from recent review articles (Morrison and Cruikshank 1974, Kovalevsky 1970, Dollfus 1970). The mass of Titania has been determined by Dunham (1971), and the masses and densities of the four large satellites of Jupiter are preliminary results of the Pioneer 10 mission (Anderson, quoted by Gehrels 1974). The uncertainties in the directly determined radii range from very small (Moon, Io, Ganymede) to about 40% (Triton). The majority of the observational masses are good to several per cent, but may be wrong by a factor of two or more for Rhea, Iapetus, and Titania. For satellites without directly determined radii, a radius was calculated from the V magnitude (this thesis, where applicable; otherwise Harris (1961)) and an assumed visual geometric albedo p. The latter is given in the table. Where no mass determination was available the mass was estimated using the radius and an assumed density ρ, also given in the table. The assumed albedoes and densities are necessarily rather arbitrary and no detailed justification will be offered for the values chosen. For JVI and Phoebe the very low p applies to Ceres, an asteroid similar in color to the two satellites.

The estimate of the Love number k_2 utilizes the assumed value of the rigidity μ given in the table for each satellite. The value $\mu = 10 \times 10^{11}$dyn cm^{-2} for several of the smallest satellites is typical of the rigidity in the earth's mantle, and the now available seismic velocity data from the Moon (Lammlein et al. 1974) indicate that this rigidity is also representative for the outer layers of the Moon; it seems a reasonable guess for bodies that may be of asteroidal origin. The smaller value used for other satellites, 0.3×10^{11}dyn cm^{-2}, is characteristic of ice (Goldreich and Soter 1966) and should be appropriate for medium-sized satellites according to the models of Lewis (1971). For the larger satellites of the outer planets, much of the bulk of the body will be liquid (consisting of ammonia-rich water); for such a satellite the effective rigidity must be much less than the above-mentioned value, and may be practically zero if the solid crust is very thin. However, this situation occurs only for satellites which would have a relatively large value for k_2 anyway, $\gtrsim 0.2$, so making $\mu = 0$ would change the Love number by less than a factor of ten.

For estimates of the tidal torque on despinning satellites, the greatest source of uncertainty may be Q. In table I the value Q = 100 has been adopted throughout, and is probably within one order of magnitude of the correct value for all bodies that are solid throughout. For a purely liquid satellite Q will depend on the viscosity of the liquid and will be extremely large if the

Table I.

Satellite data for tidal despinning.

Satellite	Distance from planet (10^3km)	Radius (km)	Mass (10^{24}g)	k_2	Assumed density (g cm^{-3})	Assumed geom. albedo	Assumed rigidity (10^{11}cgs)	Spin-down time scale (yr)
Moon	384	1738	74	0.015			10	2×10^8
Phobos	9.4	12	2×10^{-5}	6×10^{-6}	3.0		10	1×10^5
Deimos	23.5	6	3×10^{-6}	1×10^{-6}	3.0		10	1×10^8
Jupiter V	181	160	0.05	0.0001	3.0	0.07	10	3000
Io	422	1829	89	0.4	3.48		0.3	130
Europa	671	1550	48	0.3	3.07		0.3	3000
Ganymede	1071	2635	148	0.3	1.94		0.3	3×10^4
Callisto	1884	2500	108	0.2	1.65		0.3	1×10^6
Jupiter VI	11 500	60	0.003	1×10^{-5}	3.0	0.07	10	1×10^{15}
Jupiter VIII	23 500	15	5×10^{-5}	1×10^{-6}	3.0	0.07	10	5×10^{17a}
Janus	160	140	0.01	0.0003	1.0	0.60	0.3	2000
Mimas	186	260	0.037	0.0003		0.60	0.3	3000
Enceladus	238	340	0.085	0.0005		0.60	0.3	7000
Tethys	295	600	0.63	0.002		0.60	0.3	6000
Dione	378	575	1.16	0.01			0.3	1×10^4
Rhea	528	800	1.5	0.005			0.3	1×10^5
Titan	1223	2500	140	0.3			0.3	7×10^5
Hyperion	1484	200	0.04	0.0006	1.0	0.15	0.3	6×10^8
Iapetus	3563	900	1.5	0.003			0.3	1×10^{10}
Phoebe	12 950	100	0.014	4×10^{-5}	3.0	0.07	10	1×10^{16}

continued

Table I (cont'd)

Satellite	Distance from planet (10^3km)	Radius (km)	Mass (10^{24}g)	k_2	Assumed density (g cm^{-3})	Assumed geom. albedo	Assumed rigidity (10^{11}cgs)	Spin-down time scale (yr)
Miranda	130	300	0.3	0.01	2.6	0.15	0.3	2000
Ariel	192	780	5	0.06	2.6	0.15	0.3	3000
Umbriel	267	520	1.5	0.03	2.6	0.15	0.3	5×10^4
Titania	439	940	9	0.08		0.15	0.3	3×10^5
Oberon	569	860	7	0.07	2.6	0.15	0.3	2×10^6
Triton	354	1880	140	0.7			0.3	1×10^4
Nereid	5510	270	0.2	0.01	3.0	0.15	0.3	1×10^{11} [a]

Masses of the planets:

Earth	6.0	$\times 10^{27}$g
Mars	0.65	"
Jupiter	1900	"
Saturn	570	"
Uranus	87	"
Neptune	103	"

[a] correction for orbital eccentricity applied; see text.

viscosity is of the order of that of water. For a Lewis-type body with a thin (a few km) crust of solid ice, some dissipation must take place in the crust or at its interface with the liquid mantle, but Q will be difficult to estimate for such a case.

The rate of despinning for each satellite was calculated by eq. (8); for the satellites with very large orbital eccentricity (JVIII and Nereid) the tidal terms with $q \neq 0$ have been included. The factor $\sum_q (G_{0q}(e))^2$, with which $\dot{\omega}$ from (8) was multiplied for these satellites, amounts to ≈ 3 for JVIII and 120 for Nereid; for the other satellites it differs by at most 30% from unity. The time scale for despinning a satellite to its final spin state, usually synchroneity with the orbital mean motion, from its primordial rate may be estimated by dividing an estimate of the original spin rate by $\dot{\omega}$. For the original spin the value $\omega = 2 \times 10^{-4} s^{-1}$ was adopted for the purposes of table I. This corresponds to a rotation period of 9^h which is within a factor of about three of all rotation periods of planets and asteroids which are not thought to have had their spin greatly modified since the early history of the solar system.

When comparing the spin-down time scales with each other and with the age of the solar system, it must be kept in mind that because of the numerous and very large uncertainties involved the spin-down rates are only order-of-magnitude estimates, although the results of the calculations are given in the table to one-digit accuracy. For a satellite without observationally determined radius or mass, the dependence of the spin-down rate on the quantities for which only guesses are available, is:

$$\dot{\omega} \propto \rho/\mu p^2 Q \quad . \tag{9}$$

Also, the assumptions made (zero obliquity; spherical shape; only the principal tidal term included) may have a large effect on the results. Particularly for the small satellites their nonsphericity must affect the tidal spin-down strongly. No attempt to evaluate this effect will be made here; however, nonsphericity is of great interest in connection with spin-orbit resonances, which will be considered below. Finally, the tidal evolution of the satellite orbit means that the present-day orbit could be quite different from the orbit when the satellite's spin was most strongly affected by tides. The influence of the orbital evolution on the spin history is not considered here but may have been important for some satellites.

For satellites whose mean orbital motion is much slower than the original spin rate, the time scale given in table I will be a satisfactory estimate of the time actually required for the body to reach synchronous rotation, <u>if</u> the spin-down is uniform. The discoveries of the remarkable rotation rates of Mercury and Venus showed that the orderly progress towards synchroneity may well be thwarted by various circumstances, leading to non-synchronous final spin states. Peale and Gold (1965) showed that for certain models for tidal friction, the tidal torque averaged over the orbit will be zero for a value of the rotation rate between the orbital mean motion and the pericenter motion, if the orbit is non-circular. For instance, if $Q \propto (\text{frequency})^{-1}$ such a rotation rate (> the mean motion) exists whenever the orbital eccentricity is $\neq 0$. If Q is independent of frequency the eccentricity must be larger than a minimum value for the final spin rate to be larger than the mean motion. Goldreich and Peale (1968) and Bellomo et al. (1967) developed the theory of spin-orbit coupling for planets with all three moments of inertia different ($A<B<C$, where C is the moment about the spin axis). A stable non-synchronous spin may be possible either because of the eccentricity of the orbit or because of the presence of a third body. The first situation is called a "spin-orbit resonance of the first kind" by Goldreich and Peale; Mercury is almost certainly an example of this, as was first suggested by Colombo (1965). The three-body situation is called a "spin-orbit resonance of the second kind" and is possibly exemplified by Venus (with the Earth as the third body locking the rotation of Venus). The satellites in the solar system may well offer additional examples of resonances involving the spin. The most obvious possibility is Nereid, whose eccentricity is so large (0.75) that a resonance of the first kind seems almost unavoidable, given enough time. Very high order resonances are probably stable in this case, and a determination of just which one the satellite came to occupy might prove a valuable constraint on the possible choices of frequency and amplitude dependence for Q. Hyperion, in a rather eccentric orbit heavily influenced by Titan, is a candidate for either kind of spin-orbit resonance.

The rotation of Titan may still offer surprises. While markings on Titan's disk have been seen (Dollfus 1961), no rotational variation has ever been convincingly demonstrated by photometry. The expected rotation is synchronous, but a rate slightly larger than the synchronous rate would require observation over an extended period of time to be recognized as such. If the satellite is effectively liquid throughout most of its volume, as suggested by the models of Lewis (1971), no permanent deformation in the equatorial plane can be sustained, and because the orbital eccentricity is 0.03 it becomes necessary to consider the possibility of an asymptotic rotation rate of the type suggested by Peale and Gold (1965). If Titan's effective tidal Q is extremely high the satellite may rotate rapidly, but the presence of an atmosphere of considerable density (Hunten 1974) suggests that the structure of Titan is complex enough to offer some possibilities of dissipation mechanisms which would reduce Q. Even if Q is as high as 10^5, the satellite would be despun in less than the age of the solar system. The final spin can be predicted if the dissipation is assumed to be due to viscosity only; then Q is inversely proportional to frequency and the rotation rate at which the average tidal torque over one revolution is zero can be calculated by eq. (1). For zero obliquity the simpler (3) applies, and

$$T = K\sum_{q}(G_{oq}(e))^2(n-\omega+\frac{qn}{2}) = 0 \tag{10}$$

where K is a constant and the approximation $\sin \varepsilon = \tan \varepsilon = \varepsilon$ (i.e., ε small) is implied. Neglecting terms in e^4 and higher and solving for ω obtains

$$\frac{\omega}{n} = 1 + 6e^2 \tag{11}$$

For Titan, e = 0.03 so the asymptotic rotation rate is ½% larger than the orbital mean motion. Note that this is independent of the precise value of Q. On the other hand, the permanent deformation required to ensure that the despinning doesn't stop until synchroneity is reached is very small. The criterion derived by Goldreich (1966b) yields a required asymmetry of about

$$\frac{B-A}{C} > 4\times10^{-8}$$

where $A<B<C$ are the principal moments of inertia.

The rotation of Iapetus has long been known to be synchronous. Table I gives a spin-down time scale comparable to the age of the solar system. This likely implies that the rigidity is smaller than the value given, or that Q for Iapetus is <100, or both. The satellite is large enough to be extensively melted in the interior if it is composed largely of ices, so a low μ is quite to be expected. On the other hand, a permanent asymmetry must be present of the same size as that required for Titan to be synchronous, because the orbital eccentricity of Iapetus is the same as Titan's, and observations of Iapetus' unusual light variation date back 300 years, ensuring that the spin is synchronous to within 1 part in 10^4.

The Neptune-satellite Nereid has a spin-down time in table I of ~10 times the age of the solar system. However, the assumed albedo, rigidity, and Q, may quite possibly all be too large, comfortably allowing the spin-down time to be contained within the age of the solar system. Thus it is impossible to predict whether Nereid's rotation has changed much from its original state.

IV. EARLIER PHOTOMETRIC STUDIES OF SATELLITES

A brief review of the then existing photometric observations of satellites was given by Graff (1929), at about the same time as pioneering work in photoelectric photometry was performed by Stebbins, giving the first high-precision magnitudes of Jupiter's Galilean satellites (Stebbins 1927, Stebbins and Jacobsen 1928). These remained the only photoelectric (PE) data for satellites until a systematic program of photometry of planets and satellites was undertaken by Kuiper and Harris at the McDonald Observatory in 1950. These new observations, which were made on the UBV system (R and I measures were made by Hardie), formed the basis for an extensive review of the photometric properties of planets and satellites. That review article (Harris 1961) will be frequently referred to in this thesis. Unfortunately, the individual observations are not detailed in the article and were never published elsewhere; the original records of these observations are apparently lost. A review by de Vaucouleurs (1970) provides excellent updating for the planets but does not treat the satellites.

Several pre-PE observers were experienced and careful in the use of visual photometry or visual estimates and reported a large number of observations; in some cases the work is reported in such a form that a meaningful rediscussion is readily performed (usually after PE photometry of the comparison stars used by the visual observer). Particularly for Titan and Iapetus such data turn out to be very valuable. (The term "visual photometry" will here be taken to imply use of a visual photometer, the various types of which have been described by Hassenstein (1931); for direct visual comparison with nearby stars in the field of view of the telescope the term "visual estimates" will be used.)

The first program of systematic visual photometry of most of the satellites in the solar system appears to be that initiated by E. C. Pickering at Harvard in 1877 (Pickering 1879). The observations were made using various types of photometers, and compared the satellites variously with stars, with each other, and with their primary. The internal accuracy seems to be rather low. Twenty years later Wendell (1913) observed Titan and Iapetus at the same observatory. The observations show good internal consistency and are reported in full detail, identifying the comparison star used for each observation. Wendell's observations are discussed in detail in ch. VII.

During 1905-08 Guthnick (1914) carried out numerous measurements of the Galilean satellites of Jupiter and the six brightest Saturn satellites with a visual photometer. The results clearly show (in the light of modern results) the effects of insufficient allowance for the scattered light from the planet, in that the light curves show minima at the conjunctions and maxima at the elongations. The mean magnitudes are in substantial agreement with recent PE values;

the Titan and Iapetus data will be briefly considered in ch. VII.

Graff (1920, 1924, 1939) also observed Jupiter and Saturn satellites with an improved photometer of his own design. His observations appear to be relatively reliable, although suffering to some extent from the "conjunction effect" just mentioned. The observations are given individually but the comparison stars used are only given in a master list, not identified for each observation. Widorn's (1950) Iapetus observations in 1949 were made in the same manner as those of Graff. Both sets of observations are discussed in ch. VII.

Visual estimates of magnitudes of variable stars, satellites, etc., have long been popular with amateur astronomers because of their simplicity (in principle, at least) and because no special photometric equipment is necessary. For stars in the field and with suitable comparison stars nearby, visual estimates by an experienced observer may be good to about 0.1 mag.; but the strong and uneven background of scattered light from the primary makes satellite estimates difficult and very prone to systematic errors. In addition, if other satellites are used as comparison objects, the variations that may be present in the latter can introduce additional errors. Thus visual estimates of satellites must be considered with caution. Major series of visual estimates include those by Wirtz (1912) and Barnard (e.g. 1912, 1927). Neither is suitable for rediscussion here. More recently British and American amateurs have devoted considerable attention to the mean magnitudes and variations of the satellites of Saturn, reporting estimates or photometry mostly in the Journal of the British Astronomical Association and the Strolling Astronomer. One notes that the glare from the planet is an outstanding complication when making visual estimates, a fact rarely appreciated fully (Hodgson 1972). Some recent series of visual estimates will be mentioned in ch. VII, notably Steavenson's observations of Uranus satellites in 1950.

Photographic magnitudes (visual estimates directly from the plate or measurements by iris photometer) are frequently by-products of astrometric photography of satellites. This is the principal source of magnitudes for most of the fainter satellites in the solar system. Examples are the magnitude determinations for the outer Jupiter satellites reported in many short communications by Nicholson. An interesting example of careful reduction of microdensitometric data on satellites deeply immersed in the scattered light of the primary is the determination of the magnitudes of the Martian satellites by Pascu (1973).

In the last few years a variety of electronic devices have come into use, in which the primary image in the focal plane of the telescope is intensified or magnified by electronic means and then registered, e.g. on a photographic plate. While their use for photometry is as yet experimental, in the future they may well provide the best possible magnitudes for the fainter satellites in the solar system.

The first photoelectric satellite observations (not counting work on the Earth's moon) reported in the literature since Harris' review (1961) concerned the discovery of a short-lived brightening of Io as it reappeared from eclipse by Jupiter (Binder and Cruikshank 1964). The many observational studies of this phenomenon have been reviewed and a model proposed by Cruikshank and Murphy (1973). UBV observations yielding information on mean magnitudes and colors and their variation with orbital phase have been reported for various Saturn satellites by Blanco and Catalano (1971), Millis (1973), Franz and Millis (1973), Blair and Owen (1974), and Franklin and Cook (1974). The preliminary reports on Phoebe and Jupiter VI (Andersson and Burkhead 1970, Andersson 1972) are superseded by the detailed discussion in the present work. Broadband photometry of the Martian satellites has been reported by Zellner and Capen (1974), and uvby photometry of the Galilean satellites and Saturn's major satellites by Morrison et al. (1974b) and Noland et al. (1974). Spectrophotometry with narrowband filters by Johnson (1971; Galilean satellites) and McCord et al. (1971; satellites of Saturn) was mainly performed for the purpose of establishing the spectral reflectivities but allowed some conclusions about the variations with orbital phase. A number of infrared observations have also been reported during the last several years. The status of research on the physical nature of the natural satellites in the solar system, as of late 1973, has been well summarized by Morrison and Cruikshank (1974).

Because some satellites are likely to be physically similar to some asteroids, the current activity in the physical study of asteroids is of great interest from the point of view of the satellites. For instance, the classification of asteroids by their spectral reflectivity curves from narrowband photometry (Chapman et al. 1973) should aid in the interpretation of the colors of satellites like Jupiter's outer ones, since these may be captured asteroids. A good overview of recent research on the asteroids is provided by the I.A.U. 12th colloquium proceedings edited by Gehrels (1971).

V. NEW OBSERVATIONS AND THEIR REDUCTIONS

A. Instrumentation.

Observations for this program were made in 1970-73, during more than 100 nights on nine telescopes. Some of these are partial nights, kindly relinquished by other observers assigned to the telescopes in question. The observing runs outside of Indiana are listed in Table II; the observing time at the Indiana University 16-inch (41 cm) telescope, at the Morgan-Monroe Station of the Goethe Link Observatory, is summarized in Table III. Only nights which actually yielded useful observations are included. A scheduled observing run on the 42-inch (107 cm) telescope of the Lowell Observatory in 1973 Jan produced no data because of bad weather. Likewise, scheduled nights in 1971 Apr on the 36-inch (91 cm) reflector of the Goethe Link Observatory were unproductive because of instrumental difficulties. A number of nights in the spring and summer of 1971 at the Morgan-Monroe 16-inch were devoted to experimental photometry (mostly involving area scanning photometry of Jupiter's Galilean satellites and other objects); data from these nights have not been reduced and the nights are not included in the tables.

All photometry was done with conventional single-channel photoelectric photometers equipped with RCA 1 P21 photomultipliers cooled by dry ice. Exceptions are two nights of the 1972 May run at the LPL (Catalina) Observatory, when the photometer had an EMI 6255 photomultiplier tube. The photometer used for all observations on the Indiana 16-inch and McDonald 82-inch telescopes is manufactured by Boro-Spotz Co. and has an offset-guider; it was operated in conjunction with a General Radio DC amplifier, and the amplified signal was recorded by a Brown strip chart recorder. During the various observing runs at Kitt Peak National Observatory standard Kitt Peak photometer heads, cold boxes, DC current integrators, and offset-guiders were employed; the results of the integrations were usually both recorded on strip chart and punched on paper tape (together with time, filter, and gain information). The observations at the Catalina 61-inch reflector on 1972 Jun 20 were also made with a Kitt Peak photometer, while the 40-inch observations one month earlier utilized photometers belonging to the Lunar and Planetary Laboratory. In both cases the output consisted of punched paper tape; in addition, the results were printed. The 1972 Jan observing run at the McDonald 36-inch utilized a McDonald photometer with offset-guider and a pulse counting system (RIDL). The digital display on the pulse counter was written down by hand after each integration.

The filters used were in all cases such that their natural system (together with p.m. tube and optics) was close to the UBV system of Johnson and Morgan (1953). In addition to the three main filters an ultraviolet-plus-red filter combination was usually

Table II.

Observing runs in Texas and Arizona.

Observatory	Telescopes (inches / cm)	Period (UT dates)	No. of nights	Principal program objects
McDonald Obs.	82 / 208	1970 Dec 24 - 31	3	Saturn + Uranus satellites
Kitt Peak Nat'l Obs.	#2-36 / 91	1971 Nov 5 - 18	2	Saturn sat.
"	50 / 127	1971 Nov 7 - 13	5	" "
McDonald Obs.	36 / 91	1972 Jan 10 - 21	9	" " Uranus " Pluto
"	82 / 208	1972 Jan 11 - 21	3	Saturn sat.
Catalina Obs.	40 / 102	1972 May 6 - 10	5	Jupiter VI, Pluto
Kitt Peak Nat'l Obs.	#2-36 / 91	1972 Jun 13 - 16	4	Jupiter VI, Uranus sat. Triton
"	#4-16 / 41	1972 Jun 17	1	standard star tie-ins
Catalina Obs.	61 / 155	1972 Jun 20	1	Triton
McDonald Obs. *	82 / 208	1972 Dec 30 - 1973 Jan 12	4	Phoebe
Kitt Peak Nat'l Obs.	#3-16 / 41	1972 Dec 30 - 1973 Jan 1	3	standard star tie-ins
"	50 / 127	1973 Jan 3 - 4	2	Saturn sat.

*observer M. S. Burkhead

Table III.

Observing at the Goethe Link Observatory 16-inch (41 cm) telescope.

Period (UT dates)	No. of nights	Principal program objects
1970 Apr 5 - 10	3	Jupiter VI
1970 Sep 11 - Dec 7	16	Saturn satellites
1971 Feb 2 - Aug 1	18	Widorn's and Wendell's stars
1971 Sep 22 - Dec 19	9	Saturn sat. and standards
1972 Feb 15 - Apr 26	11	Saturn sat., Pluto standards
1972 May 20 - Aug 6	4	Uranus standards, Jupiter standards, Neptune standards
1973 Apr 6 - Jul 12	7	Graff's stars, Uranus standards, Neptune standards, Pluto standards

The star sequences identified above as Widorn's, Wendell's, and Graff's stars are described in the Titan and lapetus sections of ch. VII.

employed to check the redleak of the U filter. The filters used in Indiana observations (and McDonald observations in 1970) through 1971 Aug were of the types and thicknesses specified by Johnson (1963) for the original UBV system. However, the U and B passbands were dislocated somewhat towards the red, relative to the "standard" locations, so that, for instance, the instrumental B-V color required a transformation coefficient of about 1.2. Also, the redleak of the U filter was rather large. New U and B filters were adopted in 1971 Sep (U: 2mm Schott UG-2; B: 3mm Schott GG-13 + Corning 5030), with much improved color transformations resulting. The "new" filter set was also used on subsequent observing with the McDonald 82-inch. All KPNO observations and the observations with the LPL 61-inch were made with the same UBV filter set (KPNO filters #315, 233, 232; the first of these is 1 mm UG-2, the others as specified by Johnson). The observing with the McDonald 36-inch telescope used standard UBV filters; the filters used at LPL in 1972 May are unidentified but the transformations are nearly ideal. Transformation coefficients for various observing periods are given in Table IV.

Because of the importance of the scattered light from (in this case) the bright planet, it should be mentioned that all photometry was done at the Cassegrain focus of the respective telescope. All the telescopes have secondaries supported by four struts, which are oriented North-South-East-West in the McDonald 36-inch, the LPL 61-inch, and the Kitt Peak #2 36-inch, and at 45° angle to that configuration in the McDonald 82-inch and Kitt Peak 50-inch telescopes. In the Indiana 16-inch the struts had the horizontal-vertical configuration until 1971 Dec, when they were turned by 45°. As for the state of the mirror coatings the records are incomplete; the primary of the Indiana 16-inch reflector was re-coated in 1971 Dec, otherwise all observations probably involved mirror coatings from a few months to two years old.

B. Observing routine and photoelectric reductions.

One "observation", as used in this thesis, means the result of a number of consecutive deflections or integrations, in each of the various colors, of a single object and the sky near it. The pattern usually followed for comparison stars and program objects with uncomplicated sky background was: star V - star B - star U - star redleak - sky U - sky B - sky V - star U - star B - star V. If the sky level was high, a UBVVBU pattern was usually followed for the sky. (For observing procedures for close satellites, see section C of this chapter.) When pulse counting or current integrators were used, the number of separate integrations in each color varied from three or four for bright objects on steady nights, to ten or more for faint or difficult objects. Redleak was only taken for the redder objects. On many nights no U observations were made. Dark current measurements were made as necessary. V and B deflections (both star and sky) were always taken with the same gain setting on the amplifier.

Table IV.

Transformation of instrumental systems to UBV

Observatory	Time	ε	μ	ψ	ζ_{BV}	ζ_{UB}
KPNO	1971 Nov	+0.03	1.01	0.95	1.0	-0.9
"	1972 Jun	+0.01	0.99	0.99	1.2	-1.0
"	1972 Dec	+0.02	0.98	1.00	1.0	-1.1
McD (36")	1972 Jan	-0.02	1.04	0.96	1.3	-0.9
LPL	1972 May	+0.05	1.02	1.00	0.7	-1.0
Link	1970 Sep-Dec	-0.04	1.19	0.86	1.2	{-0.9 -1.2
"	1971 Feb-Sep	-0.02	1.20	0.84	{1.2 1.0:	{-0.4: -0.6
"	1971 Sep-Dec	-0.02	1.03	1.00	0.8	-3.0
"	1972 Feb-Aug	-0.03	1.04	1.01	0.9	{-2.5: -2.9

For definitions of quantities tabulated see sec. B of this chapter.

Values shown are means of independent determinations during periods indicated, and are close to but not necessarily identical with the "adopted mean values" (used on nights when transformations were not solved for).

Colon (:) indicates large variations from night to night.

The net deflections (sky, redleak, etc. removed, and corrections for nonlinearity, if any, applied), gains, star identification, declination, and hour angle were punched on cards (one card per observation). The computer program used to perform the reductions was UBVLSQ, written by Dr. M. S. Burkhead in 1966 and revised by the author. In UBVLSQ conventional procedures, as described by Hardie (1962), are followed in determining the constants of the transformation and the extinction by least squares from the observed deflections of standard stars and then calculating the magnitude and colors on the standard system for each observation of each standard and program object.

Let the deflections through the V, B, and U filters be D_v, D_b, and D_u, and let the amplifier gains in magnitudes (from an arbitrary zero level) be G (same for b and v) and G_u. Then the raw magnitude and colors are

$$\begin{aligned} v &= G - 2.5 \log D_v \\ b - v &= 2.5 \log (D_v/D_b) \\ u - b &= G_u - G + 2.5 \log (D_b/D_u) \quad . \end{aligned} \tag{1}$$

The raw magnitude and colors are related to outside-the-atmosphere values, v_o, $(b-v)_o$, and $(u-b)_o$, by

$$\begin{aligned} v_o &= v - k'_v X \\ (b-v)_o &= b - v - (k'_{bv} + k''_{bv} (b-v))X \\ (u-b)_o &= u - b - (k'_{ub} + k''_{ub} (u-b))X \end{aligned} \tag{2}$$

where X is the airmass. Finally, the outside-the-atmosphere values on the instrumental system are transformed into values on the standard UBV system by

$$V = v_o + \varepsilon(B-V) + \zeta_V$$
$$B - V = \mu(b-v)_o + \zeta_{BV} \qquad (3)$$
$$U - B = \psi(u-b)_o + \zeta_{UB} \quad .$$

The equations (2) and (3) can be combined into

$$B - V = \mu(b-v)(1-k''_{bv}X) - \mu k'_{bv}X + \zeta_{BV}$$
$$U - B = \psi(u-b)(1-k''_{ub}X) - \psi k'_{ub}X + \zeta_{UB} \qquad (4)$$
$$V = v + \varepsilon(B-V) - k'_vX + \zeta_V$$

where the V equation is placed last because B-V must be available for calculating V.

Thus the following constants are needed for converting raw photometry to the standard system:

transformation coefficients	μ	ψ	ε
zero shifts	ζ_{BV}	ζ_{UB}	ζ_V
principal extinction coefficients	k'_{bv}	k'_{ub}	k'_v
second-order extinction coefficients	k''_{bv}	k''_{ub}	

Of these, k''_{bv} and k''_{ub} are customarily considered constant for a given instrumental set-up and need thus only be determined once. Instead of determining k''_{ub}, this constant is often set equal to zero, following Johnson (1963), because the atmospheric extinction in the U band depends in a complicated way on the energy distribution in the spectrum of the measured star. The complications arising from this will be discussed below.

The UBVLSQ input deck includes adopted mean values for the eleven quantities above, and for each night to be reduced it must be decided which quantities should be solved for and for which mean values are to be used. In option 1, all transformation, zero shift, and (principal) extinction coefficients are solved for; in option 2, zero shifts and extinction; in option 3, zero shifts only; and, in option 4, transformation coefficients and zero shifts. Mean values for the second-order extinction are always used. In the versions of UBVLSQ actually used for the final reductions of the nights of the present observing program it is possible to apply an empirical time or hour angle dependence of the extinction coefficients.

For the purposes of this work, the UBV system was considered defined by the following sets of stars:

1) the primary and secondary standard stars listed by Johnson (1963). Magnitudes and colors derived from the photometry by Johnson et al. (1966) and supplied by M. Jerzykiewicz (priv. comm., 1973) were used; these differ in general by small amounts (rarely exceeding 0.01 mag.) from the values originally given by Johnson;
2) the Ten-Year Standards of the Lowell Observatory solar variability program (Jerzykiewicz and Serkowski 1967);
3) a few stars from Cousins (1971): μ Cet, 17 Eri, 10 Tau, o^1 Eri, τ Vir, ι Vir, ω^2 Sco, and τ Sgr.

In addition to these standards, the clusters designated by Johnson and Morgan (1953) as UBV secondary standard regions (the Pleiades, Praesepe, and IC 4665) were used to determine transformation coefficients on various occasions. The stars used as comparison stars for Pluto and the satellites of the various planets were tied in with the standard system on numerous nights. They are mentioned with the appropriate planet in ch. VII and are also found among the stars listed in the Appendix.

The reduction of ultraviolet magnitudes and colors poses special problems in broadband photometry. When defining the UBV system (Johnson and Morgan 1953, Johnson 1963) the variation of the U-B extinction coefficient with the type of star was ignored; as a result, the U-B values for the standard stars are not outside-the-atmosphere values. Their physical meaning is neither simple nor well defined. While it is widely acknowledged that less simplistic procedures must be adopted for correcting U-B observations for extinction, there is no agreement as to which features of the original UBV system should be retained. Gutierrez-Moreno et al. (1966) argue for the concept of extra-atmospheric colors, and their U-B colors differ substantially from those of Johnson. Others argue that the original U-B values are in such widespread use that a major revision would obsolete a large body of existing work, and therefore procedures should be developed which reduce the observations to "original UBV circumstances" rather than to zero airmass (Hardie 1966). In this thesis the second view is taken.

With comparison stars reasonably similar to the Sun the U-B extinction may be expected to be a simple function of U-B. However, the need to deal at least occasionally with a wider range of star types, and the large airmasses often involved prompted some experimentation with a two-parameter representation of the U-B extinction coefficient of the type

$$k_{ub} = k'_{ub} + k''_1 (u-b) + k''_2 (b-v).$$

Also, since the U-B values for the standard stars are not extra-atmospheric, the observations were reduced to a "standard U-B airmass", X_o. The third equation in (4) becomes:

$$U-B = \psi(u-b)(1-k''_1(X-X_o)) - \psi(k'_{ub} + k''_2(b-v))(X-X_o) + \zeta_{UB} \qquad (5)$$

It was not possible to find a combination of k''_1, k''_2, and X_o, which would satisfactorily reduce all Indiana "old filters" observing nights. Perhaps the k'' vary substantially from night to night at a low-altitude site such as the Goethe Link Observatory. The sets of constants finally adopted give a rather poor representation of many nights, with numerous residuals $>0\overset{m}{.}05$. The nights using the "new" filter set were successfully reduced using (5); even observations at large airmass have small residuals. The observations in Texas and Arizona were reduced according to Johnson's precepts; sometimes a small non-zero k''_{ub} coefficient was allowed. The adopted mean extinction coefficients for various periods are listed in Table V. Since k'_{ub} is, formally, the extinction coefficient for a hypothetical star with b-v = u-b = 0, and no real stars have such colors, the last column gives the approximate extinction coefficient for a solar type star. This number is approximately equal to the k'_{ub} which would have been appropriate if $k''_1 = k''_2 = 0$ had been adopted instead of the values given.

Table V

Extinction coefficients.

Observatory	Time	k'_v	k'_{bv}	k'_{ub}	k''_{bv}	k''_1 (k''_{ub})	k''_2	X_o	d(u-b)/dX (G0 star at X=1)
KPNO	1971 Nov	0.12	0.10	0.35	-0.020	0	0	0	--
"	1972 Jun 13-16	.16	.12	.35	- .040	0	0	0	--
"	1972 Jun 17	.125	.094	.277	- .040	0	0	0	--
"	1972 Dec-1973 Jan	.16	.10	.30	- .040	0	0	0	--
McD	1972 Jan	.14	.065	.29	- .039	0	0	0	--
LPL	1972 May	.16	.10	.30	- .032	0	0	0	--
Link	1970 Sep	.25	.12	.70	- .032	-0.140	+0.120	0.3	0.45
"	1970 Oct-Dec	.25	.12	.70	- .032	- .140	.120	1.0	.45
"	1971 Feb-Sep	.15	.12	.70	- .032	- .140	.120	-1.0	.45
"	1971 Sep-Dec	.27	.15	.53	- .040	- .065	.060	3.3	.40
"	1972 Feb-May	.29	.14	.53	- .040	- .065	.060	3.3	.40

For definitions of quantities tabulated, see text.

Values shown are the "adopted mean values" for the periods indicated.

C. Sky corrections for close satellites.

In photometry of close planetary satellites the principal observational complication is the bright background of instrumentally and atmospherically scattered light from the primary. The scattered light included by even a small diaphragm is often comparable to the light contributed by the object to be measured. Furthermore, the surface brightness gradient of the background is high and (spatially) variable, making it impossible to measure sky in the usual manner. In this section will be developed formulae for sky corrections, based on a simple model for distribution of scattered light in the telescopic image of a star.

A star image in the focal plane of the telescope has several parts (King 1971). Most of the light is concentrated in a central part with a radius of the order of a few seconds of arc. The finite extent of the central image is usually determined by the atmospheric seeing. Other circumstances that cause a point source to have a finite-size image are diffraction and imperfections of the telescope optics; they were unimportant for all nights and telescopes involved in making observations of close satellites reported here. The central image is separated from the "aureole" or "halo" by a transitional region with large brightness gradient. The aureole extends outwards from about ten arcsec from the center and is detectable (for bright objects) several degrees away. Finally, in addition to these radial-symmetric components some light from the star is, in a reflector, channeled into "diffraction spikes" (usually four in number) by the vanes or struts supporting the secondary mirror.

For our purposes the most important part of the scattered light profile is the aureole. Its exact origin is unclear but both the atmosphere and the telescope optics contribute; the state of the reflecting surfaces appears important (Piccirillo 1973). The surface brightness in the aureole approximately follows an inverse square law over a large range of distance (r) from the center. The data compiled by King (1971) suggest that the r^{-2} law holds very accurately over a tremendous range of r ($\sim 10''$ to $\sim 10°$), but other data from the literature and my own observations indicate that the exponent in the power law may range from perhaps -1.4 to -2.5 and is not necessarily constant over the whole range of r (Zellner 1970, Kormendy 1973, Piccirillo 1973, Shechtman 1974). The sky correction formulae derived here assume a model with an r^{-2} brightness distribution law in the aureole. The exponent may be slightly color dependent but no such effect is included in the model; this will be discussed later.

Let the flux of scattered light per unit area in the focal plane of the telescope, as a function of distance, r, from the central image, be:

$$\imath(r) = A\ r^{-2} \quad . \tag{1}$$

In practice, distances in the focal plane will be expressed (via the scale of the telescope) in seconds of arc. The constant A depends on the brightness of the star and, presumably, the scattering properties of the atmosphere and the telescope.

The simplest method of obtaining the sky to be subtracted from the deflection of object + sky is to measure sky at two points equidistant (say, at distance d) from the program object (satellite) and on opposite sides of it. Let the two deflections be D_{-1} and D_1. If they are taken on the line through the center and the satellite, we have

$$D_{-1} = \pi\rho^2 A(r-d)^{-2}$$
$$D_1 = \pi\rho^2 A(r+d)^{-2} \qquad (2)$$

where ρ is the radius of the (circular) diaphragm used, and the deflections are expressed in such units that the conversion factor from light flux to deflections is unity. The pure sky deflection D_o that would be measured at the location of the satellite is

$$D_o = \pi\rho^2 A r^{-2} \qquad (2a)$$

which is readily obtained from D_{-1} and D_1:

$$D_o = 4\left[(D_{-1})^{-\frac{1}{2}} + (D_1)^{-\frac{1}{2}}\right]^{-2} \quad . \qquad (3)$$

If D_{-1} and D_1 are not taken along the radius vector, (3) must be substituted by a more general expression in which d/r and the orientation of the sky measures enter. It is suggested that skies be measured on the radius vector, both because the reduction is simpler and because the influence of any angular dependence of the brightness distribution (e.g. diffraction spikes) is minimized.

The diaphragm through which the deflections are taken has a finite size, and it may be necessary to take this into account. By Taylor expansion of $I(r)$ about the center of the diaphragm and integration over the diaphragm* one finds that the deflection through a circular diaphragm of radius ρ at a distance r from the central image is

$$D = \pi\rho^2 A r^{-2}\left(1 + \frac{\rho^2}{2r^2} + \frac{\rho^4}{3r^4} + \ldots\right) =$$

$$= \pi\ A\ \ln(1/(1 - \frac{\rho^2}{r^2})) \quad . \tag{4}$$

Likewise, the finite size of the central image (planet, in this case) may be non-negligible. If the planet's disk is a circle of radius R, D is obtained by substituting R for ρ in (4). The corrections for finite central image and finite diaphragm thus have the same form. If both are included we have (neglecting higher

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*The integral of a function $f(x,y)$ (defined in the cartesian x,y plane) over the area of a circle with radius R and center at (x_o,y_o) is

$$\int_R f(x,y)\ dxdy = \pi R^2 f(x_o,y_o) + \frac{\pi}{8} R^4 \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) f$$

$$+ \frac{\pi}{192} R^6 \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)^2 f + \ldots$$

The derivatives are to be evaluated at (x_o,y_o).

terms in the series expansion)

$$D = \pi A \frac{\rho^2}{r^2} \left(1 + \frac{\rho^2+R^2}{2r^2}\right) \quad . \tag{5}$$

The same formula for an arbitrary power law, r^{-n}, is easily shown to be

$$D = \pi A \frac{\rho^2}{r^2} \left(1 - \frac{n^2}{8} \frac{\rho^2+R^2}{r^2}\right) \quad . \tag{5a}$$

Finite R and ρ can be allowed for in (3) by first correcting D_{-1} and D_1 by factors $\left(1 + \frac{R^2+\rho^2}{2(r-d)^2}\right)^{-1}$ and $\left(1 + \frac{R^2+\rho^2}{2(r-d)^2}\right)^{-1}$, respectively (thus reducing them to "center of diaphragm values"), then calculating a "center of diaphragm value" for D_o by (3), and finally correcting D_o to its "real" value by multiplying by $\left(1 + \frac{R^2+\rho^2}{2r^2}\right)$. However, the error made in using (3) directly is small.

The method of sky measurement described, with one sky setting between the satellite and the primary and another at the same distance from the satellite but on the opposite side, will be called the "symmetrical skies" method. The influence of various error sources will be considered following the description of another sky measurement method which will be called the "concentric diaphragm" method. It consists of measuring the satellite through two diaphragms of different size, both centered on the satellite. The ratio of the areas of the two diaphragms is known; let it be a (>1). Let the measured deflection through the smaller diaphragm be D_1, and the deflection through the larger, D_2. D_1 is the sum of a sky contribution D_s and a star or satellite contribution D_*. D_2 consists of an a times larger sky contribution and a slightly larger star contribution, cD_*, than for the smaller diaphragm (because of the extent of the star's brightness profile). The constant c depends on the diaphragm sizes and the seeing, and is evaluated observationally by measuring a bright star (so that the sky contribution to the total deflection is negligible) through both diaphragms.

$$D_1 = D_s + D_*$$

$$D_2 = aD_s + cD \qquad (6)$$

which leads to

$$D_* = \frac{aD_1 - D_2}{a-c} \quad . \qquad (7)$$

Allowance for finite size of central image and diaphragms according to (5) leads to

$$D_* = \frac{LaD_1 - D_2}{La-c} \qquad (7a)$$

where

$$L = \frac{1 + (R^2+\rho_2^{\,2})/2r^2}{1 + (R^2+\rho_1^{\,2})/2r^2} \approx 1 + (a-1)\rho_1^{\,2}/2r^2 \quad . \qquad (8)$$

ρ_1 and ρ_2 are the radii of the two diaphragms and r and R have the same meanings as in (5).

c is here treated purely as an empirically determined quantity. It should be possible to give a formula of the form $c = c(\rho_1,\rho_2,s)$, where s is a parameter describing the seeing, using a realistic model for star profiles as function of the seeing. Possible starting points are the analytical approximations of seeing profiles by Moffat (1969) and Franz et al. (1971). As examples of typical measured values of c, we mention that during the 1972 Jan McDonald Observatory run c varied from 1.02 on nights of average seeing (~2'') to 1.05 or more when the seeing was poor (~5''), using diaphragms of 8'' and 16'' diameter. The nights with poor seeing are usually also the ones when the seeing is most variable, and c determinations then show considerable scatter with consequent uncertainty in the application of eq. (7).

To illustrate the influence of various error sources the compilation in Table VI is given. The second column gives an approximate expression for the error due to the cause given on the same line in column one. It is assumed that eqs. (3) (as modified by (5)) and (7a) are used in the reductions, and that the sky brightness follows an inverse-square law, except where otherwise stated in the first column. No derivations of the tabulated expressions will be given here, but they can all be obtained by elementary methods using information given in this chapter.

The last column in Table VI gives the effect of the error source in question on a typical actual observation, for which the circumstances were as follows. Oberon (Uranus IV) was observed on 1972 Jan 18 (UT) in V and B through the 8'' and 16'' diaphragms, with the following results (in counts per second):

	V	B	No. of 5^s integrations
8'' diaphragm	145	230½	18, 10
16'' - '' -	232	391½	20, 10

Sky was measured with the smaller diaphragm ~8″ North and South of the satellite (which was located at distance 32″ and position angle 163° with respect to the planet):

	V	B	No. of 5^s integrations
sky N	56½	108½	7, 4
sky S	19	31	7,5

These include a uniform sky component of 9 counts/sec in V and 11½ in B; an estimated contribution by dark current of 10 counts/sec has already been subtracted from all figures above. The ratio of the areas of the two diaphragms was determined (on another night) by measuring moonlit sky and was found to be a = 3.83. Measurements of a comparison star through both diaphragms yielded c = 1.03 ± 0.01. From $\sqrt{N}$ considerations, the mean errors in the satellite measures above due to pulse count statistics are between 0.5% and 1%, and the mean errors of the skies 2% to 4%. The symmetrical skies method gives satellite signals of D_V = 117 and D_B = 182, while concentric diaphragms give D_V = 116 and D_B = 177. The agreement between the two methods is about as good as the statistical considerations would lead one to expect. The ratio between the inner and outer skies is larger than expected from an r^{-2} sky brightness law; the ratio observed would be explained if a much steeper law ($\sim r^{-3}$) applies, or if the skies were in fact measured ~11″ from the satellite rather than ~8″ (the setting accuracy was estimated as 2″ according to the observing log for the night). An over-estimate of the dark count or the constant sky contribution would work in

Table VI.

Error estimates for satellite photometry

Error source	Error in D_*	Error in sample observation (V magnitude)
Symmetrical skies method		
1. Finite size of diaphragm neglected (i.e., p = 0 implicitly assumed)	$-\frac{p^2}{4}\frac{d^2}{r^2-d^2}D_s$	+0.0001
2. Subtraction of constant sky background (D_{cs}) neglected	$-3\frac{d^2}{r^2}D_{cs}$	+0.016
3. Satellite measurement displaced from midpoint between sky measures by amount Ed (positive away from primary)	$-2E\frac{d}{r}D_s$	+0.09 E
4. True sky brightness follows $r^{-(2+m)}$ law	$+\frac{1}{4}m(2+m)\frac{d^2}{r^2}D_s$	-0.003 m(2+m)
5. Inner sky measurement in error by fraction E	$-E\frac{r-d}{2r}D_s$	+0.07 E
6. Outer sky measurement in error by fraction E	$-E\frac{r+d}{2r}D_s$	+0.12 E

Table VI (cont'd).

Error source	Error in D_*	Error in sample observation (V magnitude)
Concentric diaphragms method		
7. Finite size of diaphragm neglected	$+\frac{ap^2}{2} D_s$	-0.008
8. Constant sky D_{cs} neglected	$+\frac{ap^2}{2} D_{cs}$	-0.003
9. Center of small diaphragm displaced from center of large diaphragm by Eρ (positive away from primary)	$-2E \frac{ap}{a-1} D_s$	+0.06E
10. True sky brightness follows $r^{-(2+m)}$ law	$-\frac{ap^2}{8} m(2+m) D_s$	+0.0013 m(2+m)
11. Incorrect diaphragm ratio used (a + Δ instead of a)	$+\frac{\Delta}{a-1} D_s$	-0.07 Δ
12. Incorrect seeing factor used (c + Δ instead of c)	$+\frac{\Delta}{a-1} D_*$	-0.4 Δ
13. Large diaphragm measurement in error by fraction E	$-E \frac{a}{a-1} (D_s + \frac{1}{a} D_*)$	+0.7E
14. Small diaphragm measurement in error by fraction E	$+E \frac{a}{a-1} (D_s + D_*)$	-1.7E

a = ratio of diaphragm areas (>1)

c = seeing factor

p = ratio of radius ρ of smaller diaphragm to distance r of satellite from primary

2d = distance between inner and outer sky settings

D_s = sky deflection (aureole contribution) through smaller diaphragm, at satellite

D_* = satellite deflection through smaller diaphragm (sky removed)

E and Δ are defined in the first column for each item where they appear.

the same direction. Probably several of these reasons contribute to the large difference between inner and outer skies, but it is also seen from Table VI that neither would introduce an error in the satellite's magnitude of as much as $0^{m}.02$. It is concluded that this observation yielded the V and B magnitudes of Oberon with an estimated mean error (from pulse count statistics and sky brightness model dependent sources) of about $0^{m}.03$.

Photometry of satellites of Saturn requires special consideration because of the very complicated sky background near the planet. During the period of observation (1970-72) the ring system presented its greatest opening towards the Earth and contributed as much light as the disk of the planet itself. For the purpose of reducing photometry of the inner Saturn satellites the following model was devised (Fig. 2a): the planet is considered to consist of a circular central disk of radius R_1, which has a fraction k of the total light of the system, and two smaller disks (representing the ansae of the ring system) located at a distance d from the center and on opposite sides of it; these smaller disks have radii R_2 and contribute each $\frac{1}{2}(1-k)$ of the total light. If the surface brightness around a point source of light follows eq. (1), then the surface brightness in the vicinity of the Saturn model is obtained at a point P (see Fig. 2a), located at distance r from the center and at a position angle ζ with respect to the long axis, as the sum of these components:

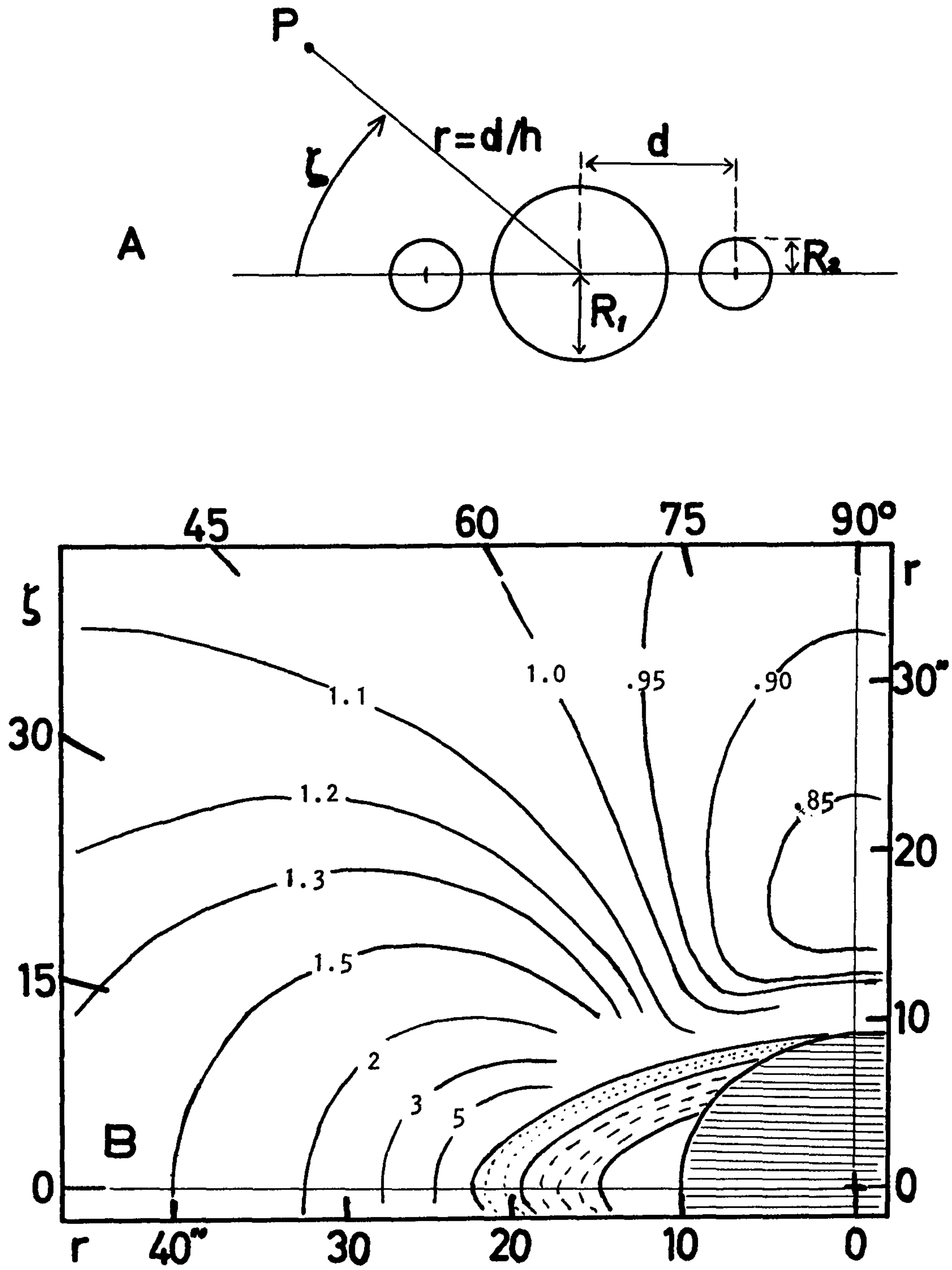


Figure 2 A. Structure of the Saturn model.
Figure 2 B. Map of the sky brightness correction factor $K(h,\zeta)$ for the vicinity of Saturn; the numerical values of the parameters d, R_1, R_2, and k are given on p. 71. The outline of Saturn in Nov 1971 is superposed.

$$I(\text{central disk}) = \frac{Ak}{r^2}\left(1 + \frac{R_1^{\,2}}{2r^2}\right) \tag{9a}$$

$$I(\text{nearer ansa}) = A\frac{\frac{1}{2}(1-k)}{r^2+d^2-2rd\cos\zeta}\left(1 + \frac{R_2^{\,2}}{2(r^2+d^2-2rd\cos\zeta)}\right) \tag{9b}$$

$$I(\text{distant ansa}) = A\frac{\frac{1}{2}(1-k)}{r^2+d^2+2rd\cos\zeta}\left(1 + \frac{R_2^{\,2}}{2(r^2+d^2+2rd\cos\zeta)}\right) \tag{9c}$$

where the lowest order term of the correction for finite size of the light source is included. The following constants (at mean opposition distance) were adopted for the model:

$$d = 18''$$
$$R_1 = 10''$$
$$R_2 = 4''$$
$$k = 0.46 \quad .$$

The value of k was deduced from Müller's empirical formula for the total magnitude of Saturn as a function of the inclination of the ringplane to the line of sight (Harris 1961). For observing periods when the ring system is seen more nearly edge-on, a larger k and a smaller R_2 would be appropriate. With $h = \frac{d}{r}$ and the above numerical values the following expression results:

$$I(r,\zeta) = \frac{A}{r^2}K(h,\zeta) =$$
$$= \frac{A}{r^2}\left[0.46 + 0.07h^2 + 0.54\,\frac{1+h^2}{1-2h^2\cos2\zeta+h^4} + 0.013h^2\,\frac{1+2h^2(2+\cos2\zeta)+h^4}{(1-2h^2\cos2\zeta+h^4)^2}\right] \quad . \tag{10}$$

Fig. 2b illustrates how $K(h,\zeta)$ varies around Saturn. In applying the symmetrical skies method to inner Saturn satellites, each sky measurement is reduced to its "point source Saturn" equivalent by dividing by the appropriate $K(h,\zeta)$ (calculated by (10) or estimated from a map similar to Fig. 2b). Eq. (3) is then applied, and the resulting sky is multiplied by its proper $K(h,\zeta)$. Finite size of the diaphragm (radius ρ) can be allowed for by substituting R_1^2 by $(R_1^2+\rho^2)$ in (9a), and similarly in (9b) and (9c). For use in the concentric diaphragm method a formula analogous to (8) may be derived.

The great majority of the satellite observations can be reduced without any detailed knowledge of the light distribution along the diffraction spikes. Sky measurements made in the course of this study, as well as the data of Piccirillo (1973), suggest that the brightness of a unit length of a spike is roughly proportional to $\frac{1}{r^2}$, where r, as usual, is the distance from the star. While no special procedure was designed for dealing with observations seriously contaminated by diffraction spikes, all such observations were reduced with full attention to the geometry of the individual case, and the error estimates for such data are believed to be realistic.

Sky measurements (from symmetrical-skies-type observations) from several nights on different telescopes were examined to check for any r dependence of the color of the light in the aureole. It was found that $\frac{d(B-V)}{dV}$ and $\frac{d(U-B)}{dV}$ are predominantly negative (scattered light bluer with increasing r or V); the amounts are typically 0.01 to 0.1 and are apparently different for different telescopes. The errors in the satellite colors because of this effect are probably $\lesssim 0\overset{m}{.}01$ for practically all satellite observations reported here.

Because the colors of most satellites do not differ greatly from those of the background of scattered light, error sources of a geometrical nature (such as most items in Table VI) will affect the reduction of the V, B, and U deflections to about the same extent, and the errors will be largely cancelled in taking the B-V and U-B colors. For this reason colors from some observations have been accepted even though the magnitude determination appears affected by some error.

It should be pointed out that this observer's sophistication in performing and reducing observations of close satellites increased greatly during the progress of this investigation, from a start at a rather naïve level. The records for the nights of the fall of 1970 are incomplete in various respects; for instance, observations specifically for the purpose of determining the seeing factor c were not made, and for only a few of these nights do the available data allow a reliable determination of c. For other nights a full range of possible values had to be allowed. The large estimated error quoted for many observations during that season reflect such circumstances.

D. Determination of the orientation of the axis of rotation.

A body which has an asymmetric shape or surface albedo distribution and which rotates on an axis fixed in space will present light variations whose amplitude and light curve shape depend on the direction to the observer. In the solar system, the light curve of a satellite, asteroid, etc., will thus change because of the orbital motions of the Earth and the body. This offers a possibility of determining the orientation of the axis of rotation by obtaining light curves of the object when it is at different locations in the sky. For objects in the outer solar system these possible locations are restricted practically to a great circle (the plane of the orbit around the Sun) and an ambiguity will remain in the axis orientation. Vesely (1971) has reviewed such work pertaining to asteroids. The discussion given here is substantially the same as that in Andersson and Fix (1973).

The general problem of interpreting the light curve of a rotating planetary body in terms of its albedo distribution or shape has been discussed by Russell (1906). First, we note that it is in principle not possible from light curves alone to distinguish between variations due to shape and due to albedo variations over the surface. For asteroids the variations are usually assumed to be due to shape, while for much larger bodies they must be ascribed to uneven albedo. The apparent brightness (i.e., the light curve in intensity units, rather than magnitudes) can be expressed as a Fourier time series:

$$H(t) = C_o + C_1 \cos \omega t + D_1 \sin \omega t + C_2 \cos 2\omega t + D_2 \sin 2\omega t + \ldots$$
$$= K_o + K_1 \cos(\omega t - \psi_1) + K_2 \cos(2\omega t - \psi_2) + \ldots \qquad (1)$$

where t is time, ω is the synodic rotation rate of the body, and C_i, D_i, K_i, and ψ_i are constants (for the light curve at a given time), which are themselves functions of the albedo distribution and the angle, Θ, between the axis of rotation and the line of sight. Strictly speaking, they also depend on the solar phase angle; this is a serious complication in asteroid work, but for outer solar system objects the phase effects are always small and an attempt to include them formally in the equation appears unjustified. Of course, the actual observations used in the light curve should be corrected for phase in the usual manner (ch. II). The coefficient K_o is the mean brightness, and K_1 is (approximately) the amplitude. The C and D coefficients as trigonometric series in Θ may be written in the form:

$$C_m = \sum_{k=m}^{\infty} c_k^m P_k^m (\cos\Theta) \qquad m = 0,1,2,3\ldots$$
$$D_m = \sum_{k=m}^{\infty} d_k^m P_k^m (\cos\Theta) \qquad m = 1,2,3\ldots \quad . \qquad (2)$$

Summation is over even values of k only, except that k = 1 is included. $P_k^m (\cos\Theta)$ are the associated Legendre polynomials. Note that $K_o = C_o$.

The coefficients c_k^m and d_k^m are determined uniquely by the albedo distribution and/or shape. Unfortunately, the reverse is not true: the inversion of the light curve to derive the surface spottiness or shape is not unique, in that the surface spherical harmonics of odd order >1 do not affect the C's and D's and thus cannot be determined.

Because of the absolute convergence of the series (1) (Russel 1906) it is permissible to rearrange it by powers of sin Θ and cos Θ, and this suggests one practical way of approximating the Fourier coefficients. Retaining only the lowest term beyond the constant term, and introducing $K_m = (C_m^2+D_m^2)^{\frac{1}{2}}$ in accordance with (1), we obtain

$$\begin{aligned} K_o &= a_1 + a_2\cos\Theta \\ K_1 &= a_3\sin\Theta \\ K_2 &= a_4\sin^2\Theta \quad . \end{aligned} \tag{3}$$

The procedure for the axis determination used in our paper on Pluto (Andersson and Fix 1973) was to Fourier-analyze the available Pluto light curves, thus obtaining one set of K's for each light curve, and then for each point of a grid over the celestial sphere solve by least squares for the a_k coefficients in (3). For certain grid points the residuals of the K's were all smaller than pre-set limits selected from considerations of the accuracy of the light curves; these grid points, then, defined the range of possible pole positions.

It is convenient to consider this problem in a coordinate system with the orbital plane of the outer solar system object in question as fundamental plane (except for Pluto, this means roughly longitude and latitude referred to the ecliptic). Let the geocentric longitude of the object in this system, at the time of a given light curve observation, be λ; the corresponding latitude β is small (always <1° for the Jovian planets and Pluto) and will be assumed zero here. Let the coordinates of one of the poles of the object be (λ_o, β_o). From elementary spherical trigonometry we have

$$\cos \Theta = \cos \beta_o \cos(\lambda - \lambda_o)$$

which, substituted into (3), gives

$$\begin{aligned} K_o &= a_1 + b_1 \cos(\lambda-\lambda_o) \\ K_1^2 &= b_2 - b_3 \cos 2(\lambda-\lambda_o) \\ K_2 &= b_4 K_1^2 \end{aligned} \qquad (4)$$

where

$$\begin{aligned} b_1 &= a_2 \cos \beta_o \\ b_2 &= a_3^2(3-\cos 2\beta_o)/4 \\ b_3 &= a_3^2(1+\cos 2\beta_o)/4 \\ b_4 &= a_4/a_3^2 \quad . \end{aligned} \qquad (5)$$

Clearly, if light curves have been obtained at well-distributed points along the orbit around the sun, inspection of a plot of K_o versus λ will directly give λ_o, in that the pole longitudes are at the extrema of the curve (the maximum in the plot corresponds to the pole of the hemisphere on the object which has the lower mean albedo). In the plots of K_1^2 and K_2 versus λ the minima are at the pole longitudes λ_o and λ_o + 180°. The pole latitude is determined from the K_1^2 plot:

$$\cos 2\beta_o = \frac{3b_3-b_2}{b_3+b_2} \qquad (6)$$

or in like manner from the K_2 plot. Whether the pole at λ_o is north or south of the orbital plane remains undetermined by this analysis.

The physical meaning of a nonzero a_2 (or b_1) in the expression for K_o is a higher mean albedo in the northern hemisphere than in the southern, or vice versa. However, for several bodies in the solar system, notably the Jovian planets, there is a latitude dependence of the albedo which is symmetrical with respect to the equator. This suggests that an additional trigonometric term in K_o may be necessary for a realistic representation of the observed mean brightness. From (2) one finds that the next term contains $\cos^2\Theta$:

$$K_o = a_1 + a_2\cos\Theta + a_5\cos^2\Theta$$

where a_5 is a constant. If $a_2=0$, K_o as a function of the longitude λ is

$$K_o = b_5 + b_6\cos 2(\lambda-\lambda_o) \quad . \qquad (7)$$

If the object is brighter at the poles than at the equator, K_o will be a maximum when the object is observed at the pole longitudes (λ_o and λ_o + 180°), while it will be a minimum at these longitudes if the object has dark polar caps.

If limb darkening is present, the coefficients in eqs. (2) - (7) depend on the limb darkening law in addition to the albedo distribution.

The case of limb darkening is briefly mentioned by Russell (1906). It is well-known that the full Moon has the same surface brightness over the whole disk, except for intrinsic albedo variations (Minnaert 1961), i.e. it has no limb darkening. It seems likely that this is the case also for other objects with no atmosphere.

VI. PLUTO

The light variation due to rotation of Pluto was first described by Walker and Hardie (1955), on the basis of observations obtained by Kuiper, Walker, and Hardie in 1952-55. A period of rotation of $6\overset{d}{.}39$, an amplitude of about $0\overset{m}{.}11$, and a mean opposition magnitude (without any reduction for phase) of $\overline{V}_o = 14.9$ were derived. The light curve was found to be asymmetric with the descending branch much steeper than the ascending branch. The B-V color was found to be +0.79 with no indication of variation with rotational phase. Further observations by Hardie (1965) showed a slightly larger amplitude and a somewhat fainter mean magnitude; the reality of the difference between the 1964 results and the earlier ones was considered doubtful, partly because of a recognized zero-point discrepancy between different years in the early observations.

Pluto was observed on 9 nights in 1972 Jan, at the McDonald Observatory, mainly with a view towards improving the period. The planet was found to be fainter than expected and showing a larger variation than previously. That this was the case was further verified on five nights in 1972 May, at the Catalina Observatory of the Lunar and Planetary Laboratory. The phase of the variation was in perfect agreement with predictions using the period of Hardie (1965). A search of the literature from the years immediately following the discovery of the planet in 1930 revealed a few visual and photographic observations (Table IX) which suggested a value between 14.6 and 14.8 for $\overline{V}_o$. The observations of Baade (1934) were reduced using the known period, but did not form a light curve (in spite of their range of $0^m.2$), suggesting that the apparent variation pointed out by Baade was due to observational errors. The available data thus suggest a trend towards fainter $\overline{V}_o$ and larger amplitude from 1930 to the present. Five magnitudes obtained by Kiladze (1967) in 1966 have a mean $\overline{V}_o$ = 14.9, but no details of reductions are given, and since Kiladze only used them to support the light variation elements of Hardie, he may have simply normalized the magnitude scale so that Pluto's magnitude would conform with Walker's and Hardie's data. It appears justified to exclude Kiladze's observations from this discussion.

The new observations are listed in Table VII. For the reduction to V_o Pluto's mean distance from the sun is taken as 39.5 AU. No B-V variation is indicated, so the V_o is calculated using a weighted mean of the observed V and B, assuming the true B-V is constant and equal to the mean of the observed B-V values:

$$V_o = qV + (1-q)\ (V + (B-V) - (\overline{B-V})) + \Delta V$$

where ΔV is the correction to mean opposition and q is a weighting factor to allow the difference of the sizes of the B and V signals to be taken into account. $(\overline{B-V})$ is the adopted mean color.

The comparison stars are given in Table VIII. The table includes various stars used by earlier observers; they are discussed

Table VII

New observations of Pluto.

UT date	JD 2441000 +	V_o	B-V	U-B	Solar phase angle
1971					
31 Mar	041.62	15.18:	0.77:	0.29:	0°.63
1972					
10 Jan	326.99	15.09::	0.97::	-	1.72
11 Jan	327.92	15.19	0.84	-	1.72
12 Jan	328.90	15.25	0.79	-	1.71
14 Jan	330.96	15.13	0.80	-	1.69
15 Jan	332.01	15.06	0.82	-	1.68
16 Jan	332.95	15.01	0.79	0.32	1.67
18 Jan	334.91	15.26	0.83	-	1.64
20 Jan	336.92	15.09	0.80	-	1.61
21 Jan	337.96	15.04	0.75	0.24	1.60
6 May	443.73	15.22	0.76	0.40::	1.38
7 May	444.71	15.17	0.82	0.28	1.40
8 May	445.70	15.10	0.84	0.30	1.42
9 May	446.70	15.03::	-	-	1.44
10 May	447.68	15.10::	0.78:	-	1.46
30 Dec	682.02	15.12:	0.84	0.44:	1.80
31 Dec	683.01	15.05:	0.87	-	1.80
1973					
3 Jan	686.00	15.27:	0.82:	0.37:	1.79

Magnitude reduced to mean opposition distance using a = 39.50 AU. Estimated m.e. of V values marked :: is ± $^m\!.05$ or more; of values marked :, ± $^m\!.03$; of others, ± $^m\!.015$. For B-V and U-B about twice these error estimates apply.

Table VIII

Pluto comparison stars.

Star	V	B-V	U-B	Source of photometry	Year of Pluto observation
a	13.75	0.42	-	App.	1930
b	13.85	0.72	-	"	1930
c	14.22	0.52	-	"	1930
A	13.14	0.84	-	Walker and Hardie (1955)	1954
B	12.03	0.62	-	"	1954
C	12.76	0.62	-	"	1955
D	12.42	0.95	-	"	1955
+20°2578	10.59	1.112	-	Hardie (priv comm. 1973)	1964
+20°2580	9.71	0.336		"	1964
+16°2362	6.49	1.02	0.82	App.	1971
+14°2523	7.22	1.18	1.27	"	1972-73
+14°2528	9.23	0.25	0.13	"	1972-73

App. = Appendix, this thesis

below. The last two stars in the table were used for the new observations, except that on 1971 Mar 31 the comparison was +16°2362. The magnitudes and colors of +14°2523 and +14°2528 are fairly well determined, however, the magnitudes (not colors) from three nights in 1972 Dec and 1973 Jan are discrepant ($\sim 0^{m}.05$ too bright). There is some indication of irregular magnitude extinction during these nights and therefore the magnitudes are viewed with suspicion and are not included in the adopted magnitude values. If included they would lower the magnitudes by 0.02.

The photometric material from 1930-33 consists of one visual photometric observation by Graff and photographic determinations by Baade and others. The old Pluto observations are listed in Table IX. Graff's comparison stars were measured photoelectrically in 1972 Dec and 1973 Jan. The accuracy of this photometry is low but adequate for this purpose. For the photographic magnitudes the following conversions were used:

$B = m_{pg} + 0.11$ for the North Polar Sequence (Allen 1963);

$B = m_{pg} + 0.1(m_{pg} - 12.5)$ for Selected Area comparisons.

The second relation has been derived from a comparison of recent PE photometry in SA 50 and 51 by Purgathofer (1969) and Priser (1974) with the photographic magnitudes in the Mount Wilson Catalogue (Seares et al. 1930). It holds for $15<m_{pg}<17$ with an average error of about $0^{m}.1$. A number of additional magnitude estimates in 1930-33 can be found in the Astronomische Nachrichten, mostly incidental to positional observations; they are given to one decimal

Table IX

Early photometric observations of Pluto.

1	2	3	4	5	6	7
1930 Sep 20	1	$14.88m_V$	Tab. VIII	-0.14	14.74	Graff (1930)
1930 ?	1?	$15.5\ m_{pg}$	NPS	-0.9	14.6	Nicholson and Mayall (1930)
1930 ?	5	$16.04m_{pg}$	NPS	-0.9	15.1	Münch (1931)
1931 Mar 21	1	$15.76m_{pg}$	SA 75	-0.68	15.08	Baade (1930)
1933 Mar 19-20	2	$15.56m_{pg}$	SA 50,51	-0.65	14.91	Baade (1934)
1933 Oct 14 - Nov 17	5	$15.59m_{pg}$	SA 50	-0.64	14.95	Baade (1934)

Column headings:
1 Date(s) of observation
2 Number of nights observed
3 Magnitude of Pluto (mean of nights) and type of magnitude
4 Comparison stars. NPS = North Polar Sequence
SA = Selected Area
5 Reduction to V_O. Includes conversion from original kind of magnitude to V, and correction to mean opposition
6 V_o
7 Reference

Solar phase angle for all dated observations: $1\overset{\circ}{.}3$.

only (or none) and vary mostly between m_{pg} - 15 and 16, corresponding to V_o = 14.6 ±.5. The comparison stars used in 1954, 1955, and 1964 were reobserved in 1972 Dec and 1973 Jan, but the photometry is poor and the magnitudes listed in Table VIII are those given by the original observers. The largest discrepancy appears for star "B" used in 1954; the V magnitude measured in 1972-73 is $0^m.08$ fainter than the one used by Walker and Hardie. The 1954-55 stars should be remeasured. The 1972-73 results for all Pluto comparison stars are given in the Appendix.

The mean B-V color of Pluto from the data in Table VII (excluding the very poor Jan 10 data point) is +0.81 with a mean error of the mean (assuming constant color) of 0.01. Since the accuracy of the individual observations is unexceptional, no strong statement can be made about B-V variations with rotational phase. A variation with an amplitude of $0^m.02$ could easily be present. The U-B color was measured on about half the nights; the scatter is rather large. Excluding only the very poor observation of May 6 gives the mean U-B = +0.31 ±.03 with half weight given to observations marked with a colon in the table. The four observations of highest weight alone give +0.28 ±.02. The colors quoted by Harris (1961) are B-V = +0.80, U-B = +0.27; Walker and Hardie (1955) give +0.79 and +0.26, respectively. The colors thus may have become very slightly redder since 1954, but the reality of the change would be difficult to establish.

No previous attempt appears to have been made to determine the phase coefficient of Pluto. The present range of phase angle during an apparition is from about $0^\circ.5$ to $1^\circ.8$. The only series of observations involving an appreciable part of this range is the 1955 data by Walker and Hardie (1955), with a range in solar phase angle from $0^\circ.95$ to $1^\circ.50$ represented. In that paper an internal probable error of less than $0^m.01$ is claimed for most of the 1955 observations, while a plot of the data versus rotational phase gives a distinct impression of larger scatter (Fig. 3 of Walker and Hardie (1955)). Plotting the deviation of the points from a smooth light curve (such as in Fig. 5 of Harris (1961)) versus solar phase angle reveals a trend in the direction expected from a phase effect. The phase coefficient β implied is between 0.03 and 0.05 mag/deg. We note as a curiosity that this is similar to the phase coefficient at 2° phase angle found by O'Leary (1967) for Mars, a planet to which Pluto is probably similar in size and albedo. Replotting the 1955 observations reduced to a common phase angle, using β = 0.05 mag/deg, allows a smooth light curve to be drawn from which no point deviates as much as $0^m.015$.

If a phase coefficient of about 0.05 mag/deg is accepted the observations in 1954 are systematically fainter than in 1955 by $0^m.04$. The 1954 observations were made in V and B, while the 1955 work was carried out in integrated light (only the UV was filtered out). The magnitude calibration was probably somewhat better in 1954. Kuiper's 1953 observations agree with the 1954 magnitude zero point. We will assume that the 1954 data have the correct zero point. The principal data for the various series of observations of Pluto are given in Table X. The 1954-55, 1964, and 1971-73 observations are plotted versus rotational phase in Fig. 3.

It is suggested that the gradual increase in amplitude and the decrease in mean brightness are due to a change of aspect of the planet relative to its axis of rotation. If the obliquity is large, the planetographic latitude of the sub-earth point will gradually change because of orbital motion of the planet, and in the extreme case of 90° obliquity the aspect will go through all configurations, from a pole-on view to one where the planetary equator bisects the apparent disk. Pluto's amplitude increase is interpreted to indicate that the sub-earth point has moved towards the planetary equator during recent decades; the decline in mean brightness then implies a higher average albedo for the polar regions facing the Earth in 1954 than for the equatorial regions.

A search for an axis orientation for Pluto which is compatible with the available photometry has been reported on by Andersson and Fix (1973). The method has been described in chapter V. In terms of the described model, acceptable agreement with the photometry was found for poles in a region near orbital longitude 280°, or ~320° with the new V_o for 1930-33 in Tables IX and X. The latitude of the pole is less well determined but is at most ±40°, so the obliquity implied is larger than 50° (Fig. 2 in Andersson and Fix (1973)). There is, of course, an identical region containing the

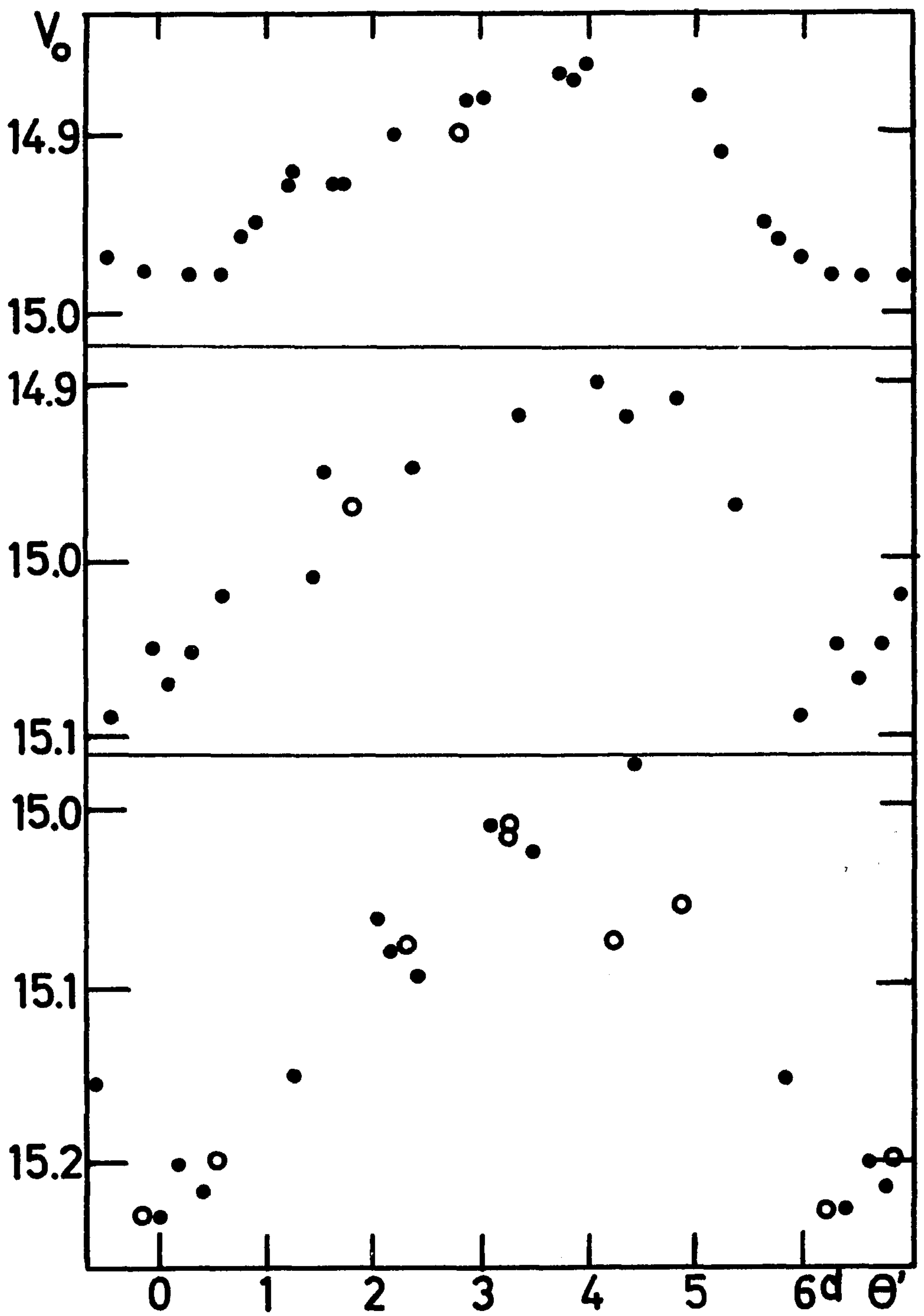


Figure 3. Pluto light curves in 1954-55 (top), 1964 (center), and 1971-73 (bottom), reduced to $\alpha=1°$ with $\beta = 0\overset{m}{.}05$/deg. Open symbols indicate observations of lower weight. Note that the rotational phase is given in days.

Table X

Pluto photometry: principal series of observation.

Date	$\bar{V}_o$	Amplitude	Range of phase angle	λ	Remarks
1933.8	14.95:	-	1°.3	113°	1,7
1953.3	14.92:	-	1°.3 - 1°.4	144	2
1954.2	14.92	$0^m.11$	0.4 - 0.7	145	2
1955.3	14.88	0.11	0.9 - 1.5	147	2,3
1964.4	14.99	0.16	1.7 - 1.8	165	4
1966.3	14.90:	-	1.2 - 1.4	169	5
1972.0	}15.12	0.22	1.6 - 1.7	181	6
1972.4			1.4 - 1.5	182	6

$\bar{V}_o$ has been reduced to 1° phase angle using $\beta = 0^m.05$/deg.

λ is Pluto's approximate celestial longitude (heliocentric).

Remarks: 1 Baade (1934). See Table IX.

2 Walker and Hardie (1955)

3. $\bar{V}_o$ should probably be adjusted by +0.04; see text.

4 R. Hardie, private communication, 1973

5 Kiladze (1967)

6 this thesis; also Andersson and Fix (1973)

7 this $\bar{V}_o$ is $0^m.2$ fainter than the value given by Andersson and Fix because of improved transformations of SA magnitudes.

opposite pole 180° away in longitude. Because the photometric axis determination method does not give the sign of the latitude (with respect to the orbit) of the pole, it is not possible to say which of the two pole regions contains the North pole (in the IAU sense). If the motion (due to rotation) of the photocenter of the image of Pluto on astrometric plates can be detected, the sense of rotation could be determined. Polarimetric observations (Kelsey and Fix 1973) suggest that the position angle of polarization of Pluto deviates slightly but probably significantly from the expected value (equal to the p.a. of the intensity equator). If real, the effect may lead to a polarimetric determination of the sense of rotation and also resolve the latitude ambiguity for the pole.

A large number of astrometric plates of Pluto from the years following the discovery of the planet exist at various observatories. If a sufficient number of these are of a quality suitable for photographic photometry, the amplitude of variation at that time might be determined, allowing a much improved axis orientation to be found. Also, Pluto passed through the plane of the ecliptic in 1930; near opposition in any of several years preceding or following 1930 the planet would have been seen under a much smaller solar phase angle than is possible at present. In 1930 and 1931 the phase angle at opposition was less than 0°01, and several early observations (lists in Cohen et al. 1967) were made at less than 0°1 phase angle. It may thus be possible to obtain a nearly complete phase function for the range of phase angle observable from the Earth (0 to 2°).

Using the new photometry and the upper limit for Pluto's radius, 3400 km, derived by Halliday et al. (1966), yields a geometric albedo at present of 0.07 at minimum light and 0.09 at maximum. The albedo in 1954 was then about 0.10. Because the radius is an upper limit the actual albedo may be higher. The scanty polarimetric data available are consistent with these albedo values (Kelsey and Fix 1973).

VII. SATELLITES OF THE JOVIAN PLANETS

A. Generalities.

This chapter contains the individual observations made of satellites in 1970-73, as well as results of re-reductions of various older satellite photometry. The available observational material for each satellite is discussed. The following satellites are not discussed because no new photometric material has become available since Harris' review (1961): Jupiter V; Mimas; Miranda, Ariel, and Umbriel; and Nereid. Plates of all of these have been taken and measured for positions in recent years, and photographic magnitudes could probably be obtained from some of them. Janus, the Saturn satellite discovered by Dollfus in 1966, is unlikely to be observed again until the ring system approaches its edge-on aspect in 1980. Jupiter's Galilean satellites were observed on nine nights near opposition in 1971, using a simple area scanning technique (letting the objects drift through the diaphragm at the sidereal rate) on the Goethe Link Observatory 16-inch telescope. These data will be reduced at a later time.

Because of the varying degree of difficulty in observing different satellites, and because a few different techniques for removing the sky background were used (see ch. V:C), the errors quoted for individual observations are of varying reliability.

They were estimated by a variety of methods. Considerations entering for a given observation usually included the agreement between different measurements of the satellite during the night; the scatter among the deflections or integrations in an observation; the photometric quality of the night as judged from observations of standard stars; and the plausible errors in the sky corrections (Table VI). In view of this diversity, caution is urged against attaching too much significance to any one individual value. Inspection of numerous light curves in this chapter indicates that the deviations of the data points from the curves are on the average close to the "estimated mean errors" for the observations. In the tables the est.m.e. are always given in units of $0\overset{m}{.}01$.

The following abbreviations are used for the methods of observation of close satellites (ch. V:C):

ss = symmetrical skies,

cd = concentric diaphragms,

ms = multiple skies (symmetrical skies with additional sky measurements),

scan = drift scans.

Mean opposition magnitudes ($\overline{V}_o$, i.e., reduced to $\alpha = 0$), or magnitudes reduced to mean opposition distance and some representative solar phase angle (e.g., $V_o(\alpha=4°)$), are used throughout this chapter. The corresponding absolute magnitudes ($V(1,\alpha)$) can be found in the summary in the next chapter.

Satellite measures with est.m.e. $\geq 0\overset{m}{.}20$ and a few obviously erroneous observations are not included in this chapter.

B. Jupiter VI.

The first attempt to observe Jupiter VI photoelectrically was made in 1970 April (Andersson and Burkhead 1970). The mean opposition magnitude was found to be $\overline{V}_o = 14.7$; the B-V color given in the 1970 publication was too blue by $0\overset{m}{.}1$, due to a reduction error, and corrected data for these observations are given in the following.

Jupiter VI was observed again on 1972 May 8 with the 40-inch telescope at the Catalina Observatory, and on three nights in 1972 June, with the No. 2 36-inch at Kitt Peak. The nightly mean magnitudes and colors for 1970 and 1972 are given in Table XI. A few photographic magnitude estimates of Jupiter VI by other observers are given in sec. C of this chapter, together with such estimates for other outer satellites of Jupiter. The comparison stars to which the PE photometry is tied are listed in Table XII.

At the time of the observations in 1972 Jupiter was in Sagittarius. The extreme density of stars in the field and the southern declination made the observations difficult, and the individual observations show considerable scatter during each night. The path of the satellite was checked for contaminating stars to $m_{pg} \sim 17$ on a plate taken by M. S. Burkhead with the 36-inch telescope of the Goethe Link Observatory, but the unrecognized inclusion of an 18^m field star in a measurement would introduce an error of $0\overset{m}{.}05$ in the magnitude of J VI; many of the observations are probably affected in this manner. In this area of the sky, near the galactic center, individual faint stars are not resolved on the Palomar Sky

Table XI

Jupiter VI photometry.

1	2	3	4	5	6	7	8
1970 Apr 5.3	14.90	0.64	-	3 3 -	10	3°41	-0.22
8.3	14.85	0.67	-	1 1 -	10	2.84	- .20
1972 May 8.5	15.05	-	-	2 2 -	4	8.68	- .21
Jun 14.4	14.84	0.71	-	3 2 -	5	2.29	+ .01
15.4	14.78	0.61	0.47	12 2 1	3	2.09	+ .02
16.4	14.77	0.76	0.44	14 2 1	3	1.89	+ .02

Column headings: 1 UT date

2 V_o

3 B-V

4 U-B

5 No. of observations in V, B, and U

6 Estimated m.e. of single V observation (units of $0^m.01$)

7 Solar phase angle of J VI

8 Reduction to mean opposition (V_o-V)

Mean opposition distance: a = 5.203 AU, Δ = 4.203 AU.

Table XII

Comparison stars for Jupiter VI.

Observing period	Star	V	B-V	U-B	Photometry reference
1970	ι Vir	4.08	0.52	0.02	Cousins (1971)
1972 May	CD-23°14580	6.73	0.64	-	Appendix
1972 Jun	CD-23°14320	9.33	1.28	1.10	Appendix

Survey prints. On June 15 and 16 the satellite was observed for about four hours; the individual observations are plotted in Fig. 4. The second of these nights seems to show a light curve minimum, but it is not possible to state anything conclusive about the light variation.

The nightly mean V_o is plotted versus solar phase angle in Fig. 5. The distribution of observations over the possible range of α is too spotty to allow a clear separation of the opposition effect from the linear phase dependence. Using the two-parameter representation of ch. II:B, the points in Fig. 5 can be fit by combinations of β and ϕ ranging from ($\beta = 0^m.04$/deg, $\phi = 0$) to ($\beta = 0$, $\phi = 1.5$). The extrapolation to zero phase angle of the linear part of the phase function is consequently uncertain; using Gehrels' phase function the mean opposition magnitude $\overline{V}_o$ is about 14.90 (the disagreement with the 1970 publication is only apparent, since a linear phase function was assumed there). $V_o(\alpha{=}2.5°)$ is well determined from all observations in the range $1^\circ.8 < \alpha < 3^\circ.5$ as 14.82; the dispersion of the individual observations is about $0^m.10$, presumably partly due to the unknown rotational light variation.

The mean B-V color is 0.68. The scatter among individual values is somewhat larger than expected and possibly partly real. The U-B color is 0.46, the mean of only two (but mutually agreeing) measurements and thus rather uncertain. The colors are somewhat similar to those of a few asteroids, such as 1 Ceres; however, the satellite is outside the upper left edge (blue B-V, red U-B) of the asteroid

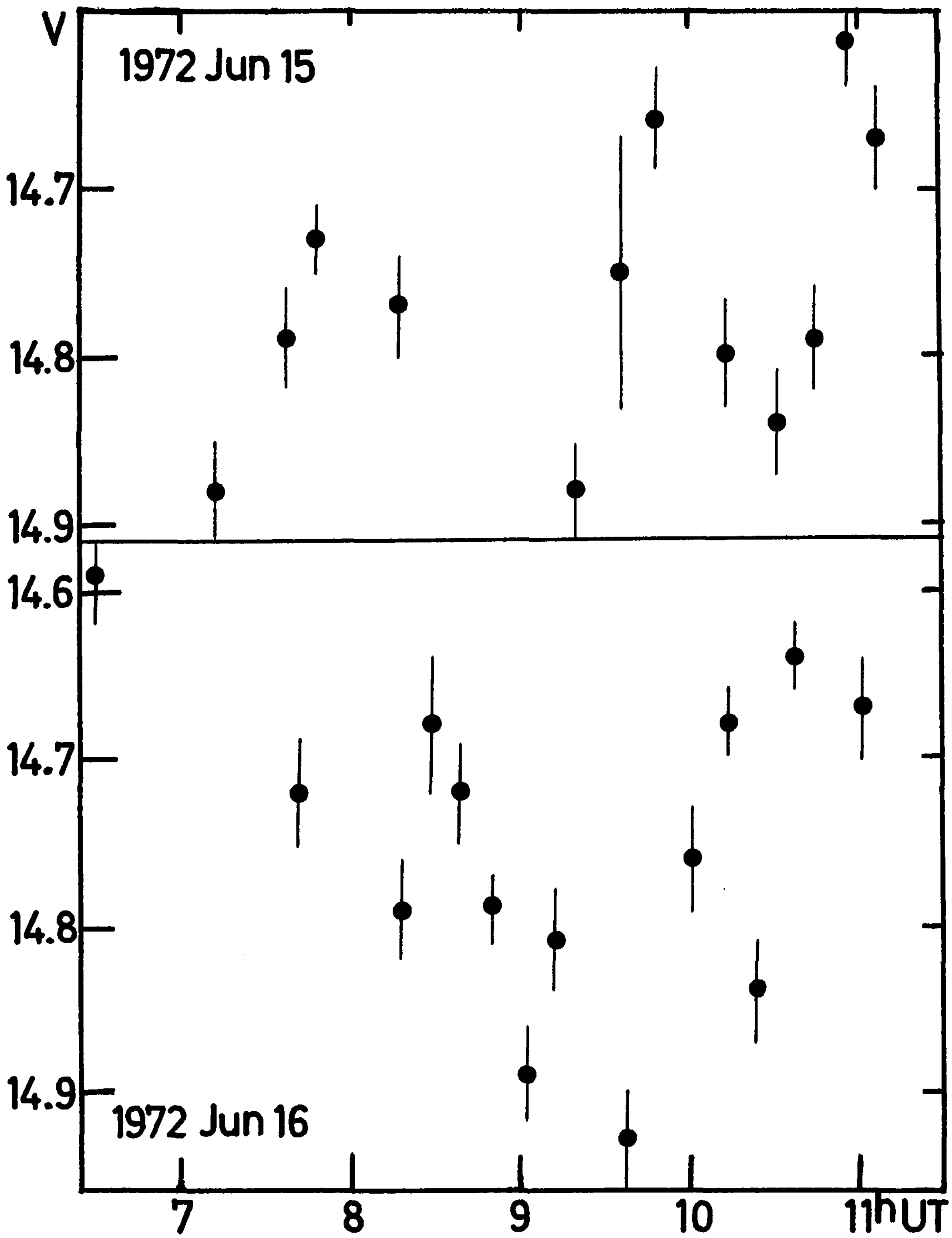


Figure 4. Observations of Jupiter VI on two nights in 1972 Jun, made at Kitt Peak. The observed magnitudes are plotted, not corrected to mean opposition distance or common phase angle.

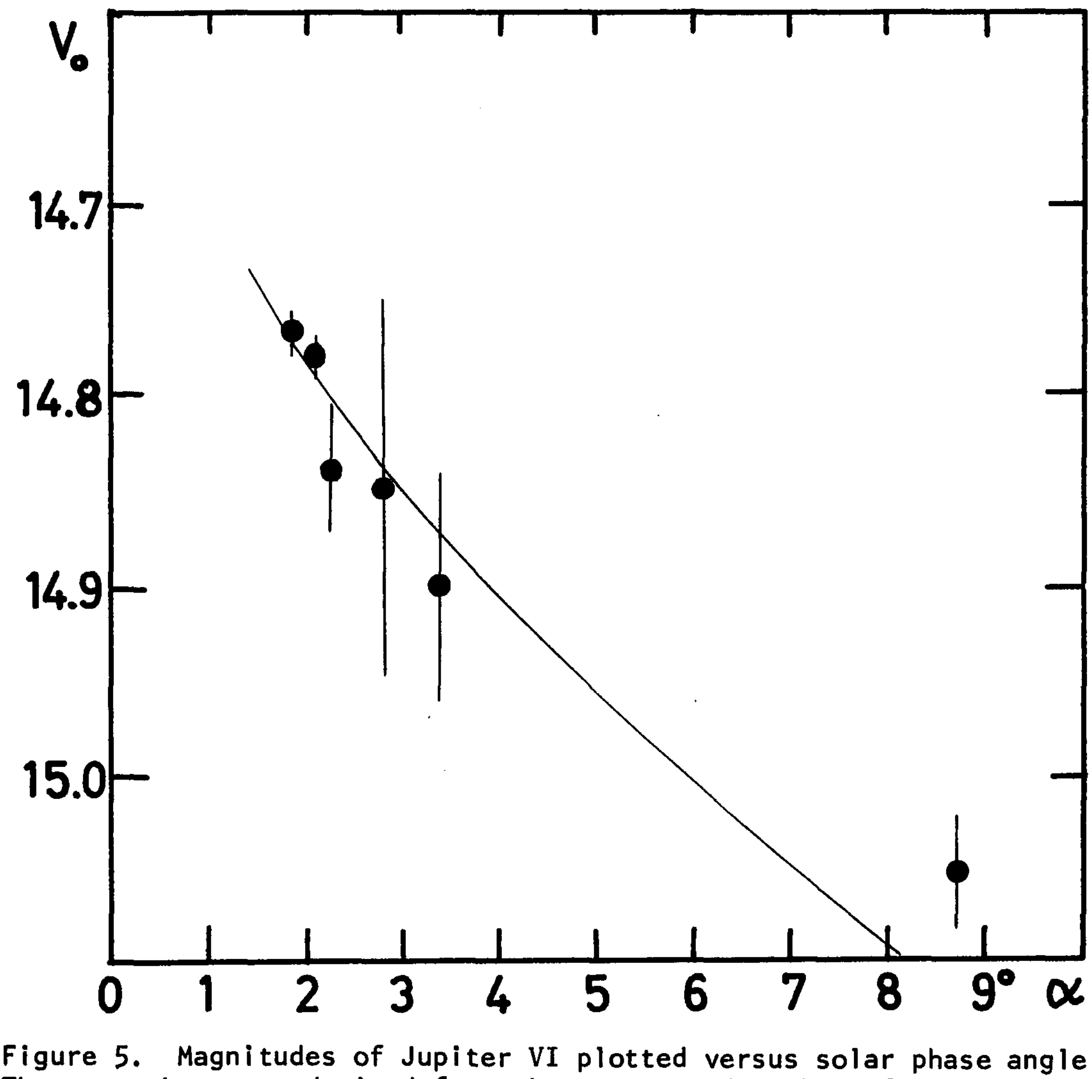


Figure 5. Magnitudes of Jupiter VI plotted versus solar phase angle. The error bars are derived from the errors and number of observations in Table XI. The solid line is Gehrels' phase function for $\overline{V}_o$ = 14.91.

distribution in the U-B vs. B-V diagram (Fig. 6). It is of interest to note that the two Trojan asteroids in the diagram (624 Hektor and 1437 Diomedes) are both found in the extreme lower part (blue U-B) of the diagram. If these two are representative of the Trojans in general, then the dissimilarity between J VI and the Trojans speaks against Kuiper's (1956) theory of the formation of both the Trojan asteroids and the irregular satellites of Jupiter as satellites of proto-Jupiter.

C. The outer satellites of Jupiter.

The usually quoted magnitudes for Jupiter VIII-XII are photographic and due to Nicholson (Harris 1961). No photoelectric observations of these satellites seem to exist. As a check on Nicholson's magnitudes a number of other magnitude estimates have been reduced to mean opposition and zero phase angle. A few are from Kuiper (1961); most were kindly made available by E. Roemer, and are visual estimates by Dr. Roemer from astrometric plates (unfiltered 103a-O or IIa-O) using similarly exposed plates of Selected Areas for comparison. The standard sequences in the SA's are from unpublished photoelectric photometry by W. A. Baum. The observations reported here include some of J VI and J VII; for the latter satellite this may be the only credible photometric information available.

The observations are given in Table XIII. The correction to mean opposition and the solar phase angle were calculated for the

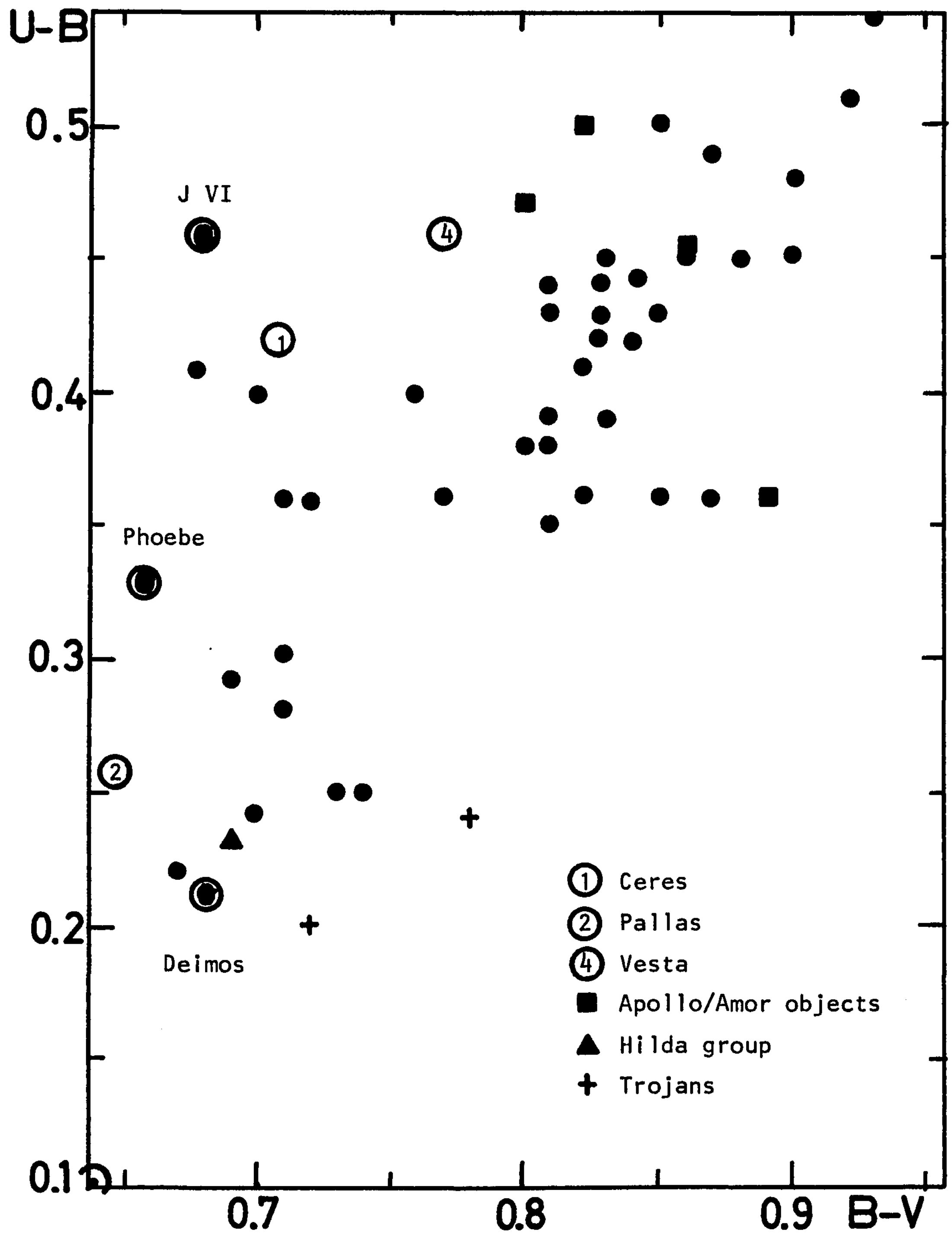


Figure 6. Two-color diagram for asteroids and small satellites. Note that the orientation differs from that used in stellar astronomy. The Sun is at the lower left corner. The asteroid colors (at $\alpha=5°$) are from Gehrels (1970) with some data from Zellner et al. (1974) and other recent publications by LPL staff members. Deimos is plotted from Zellner and Capen (1974) and J VI and Phoebe from this thesis. A few very red asteroids fall outside the diagram at the top and right.

Table XIII

Photographic observations of Jupiter satellites.

Satellite	UT date	Tel.	m_{pg}	α	$m_o - m$	$\overline{m}_o - m_o$	$\overline{m}_{pg_o}$
VI	1952 Feb 5	82	(14.0)	9°6	-0.38	-0.22	(13.4)
	1956 Mar 6	82	15.4	3.8	- .26	+ .01	15.2
	1969 Jun 14	61	16.9	10.6	- .61	- .25	16.0
	1970 Mar 13	90	16.2	7.3	- .35	- .15	15.7
VII	1956 Mar 6	82	17.1	4.1	- .12	+ .00	17.0
	1969 Jun 14	61	18.0	10.6	- .62	- .25	17.1
	1970 Mar 13	90	17.8	7.2	- .37	- .15	17.3
VIII	1963 Aug 25	40	18.6	8.7	+ .10	- .20	18.5
	1964 Aug 16	40	18.9:	11.7	- .24	- .27	18.4:
	1964 Dec 10	40	18.0	5.8	+ .12	- .09	18.0
	1965 Oct 2	40	19.0	11.2	- .26	- .26	18.5
IX	1969 May 17,18	61	19.7	9.6	- .43	- .22	19.0
X	1968 Mar 23	61	19.3:	6.0	- .30	- .10	18.9:
	1969 Apr 19,20	61	19.7	5.4	- .28	- .08	19.3
XI	1969 Jun 13	61	19.3	10.6	- .50	- .25	18.6
	1969 Jun 14	61	19.5	10.6	- .50	- .15	18.8
XII	1968 Mar 24	61	20.3:	6.1	- .34	- .11	19.8:
	1970 May 8	90	19.4	3.7	- .16	+ .02	19.3

The 1952 observation of J VI (in parentheses) is photovisual. Telescopes and observer references: 82-inch, McDonald Obs. (Kuiper 1961); 40-inch, U.S.N.O. Flagstaff (Roemer et al. 1966); 61-inch, Catalina Obs., 90-inch, Steward Obs. (Roemer, priv. comm.)

satellite itself, except for J VIII where m_o-m and α refer to Jupiter, because no suitable ephemeris data for the time of observation were available for this satellite. The necessary data for the calculations were taken from the Explanatory Supplement to the AE (1961) for J VI and J VII, and from Herget (1968) for the other satellites. The neglected corrections from Jupiter to J VIII could possibly amount to 0.2 in the magnitude and $0\overset{\circ}{.}6$ in the phase angle. The correction to zero phase uses Gehrels' asteroid function, which was previously shown to describe the variation of J VI with phase quite well.

The agreement between different observations of the same satellite is generally satisfactory, considering the uncertainty inherent in the method of observations (because of seeing differences between the satellite and SA exposures, etc.). For J VI there is conspicuous disagreement: Kuiper's observation in 1952 is 1½ magnitude brighter than expected from the PE photometry, while Roemer's magnitudes are faint by half a magnitude. Comparing with the values in Harris (1961) one finds good agreement for J IX-XII; J VIII is clearly made too faint by Harris. Subtracting $0\overset{m}{.}7$ from $\overline{m}_{pg_o}$ gives the following approximate mean opposition V magnitudes:

J VII	$\overline{V}_o$ = 16.4
VIII	17.7
IX	18.3
X	18.4
XI	18.0
XII	18.9

Because of the faintness of Jupiter's outer satellites, PE data will be difficult to obtain, but is necessary for determining their degree of similarity as regards colors, phase coefficients, and rotational variations. Comparisons of such physical data for these satellites will be important arguments for their mode of origin: if they are fragments from a collision of two parent bodies (Colombo and Franklin 1971), one should find not more than two groups of mutually similar objects among the seven satellites; if they were originally formed as satellites of proto-Jupiter, escaped, and were recaptured (Kuiper 1956), then they are probably all rather similar to each other; and if they are a (possibly transient) population of individually captured asteroids (Bailey 1971), they should be individually distinct but within the range of photometric characteristics of asteroids.

D. Comparison stars for Saturn satellites.

The stars to which the photometry of the satellites of Saturn is tied are listed in Table XIV. The two bright stars used in the fall of 1970 seem in retrospect a rather poor choice, particularly because their colors are not very similar to those of the Sun. The U-B colors obtained in the fall of 1970 for some Saturn satellites are therefore considered separately from U-B measures from the following season. +17°703 was observed on all nights of the 1971-72 Saturn apparition except for a few nights in 1971 Sep and Oct; +18°623 was measured on these latter nights and on many

Table XIV

Comparison stars for Saturn satellites.

Observing period	Star	V	B-V	U-B
1970	HR 1036	6.54	0.165	0.07
1970	HR 1110	6.15	0.965	0.74
1970 Dec 31	+13°494	7.835	1.05	0.79
1971 Sep - 1972 Jan	+18°623	7.43	0.56	0.065
1971 Nov - 1972 Mar	+17°703	7.515	0.685	0.225
1971 Nov	a	11.655	0.855	0.50
1972 Dec - 1973	+20°863	7.97	0.74	0.25

[a] $\alpha = 4^h11^m25^s$, $\delta = +18°55'.4$ (1950.0)

All photometry from the Appendix.

later occasions. The $11^{m}.6$ anonymous star was included to allow frequent measurement of Phoebe without having to move directly to that 16^{m} object from a comparison star nine magnitudes brighter, during the Kitt Peak run in 1971 Nov.

On about half of the nights when Saturn satellites were observed, UBV standards (see ch. V:B) and/or stars in the Pleiades or Praesepe were also observed. The stars listed in Table XIV are well tied in with the UBV system and with each other. However, it should be pointed out that for the Hyades members +17°703 (van Bueren 23) and +18°623 (vB 31) the magnitudes given in the table are a few hundredths brighter than in the Hyades photometry of Johnson and Knuckles (1955). The possibility that for this reason my magnitudes for Saturn satellites are systematically too bright by about $0^{m}.02$ is discussed in detail in the Titan and Iapetus sections.

E. The inner Saturn satellites.

Photometry of Mimas, Enceladus, Tethys, Dione, and Rhea is hampered by their closeness to the bright planet, aggravated by the complicated sky background due to the ring system. Rhea is brightest and also furthest from Saturn, and all photometry of this satellite agrees in making its $V_o \approx 9.7$ and in noting that the leading side (presented at eastern elongation (EE)), is brighter than the trailing side by approximately $0^{m}.2$ (Pickering 1879, Guthnick 1914, Graff 1924, Harris 1961, McCord et al. 1971, Blair and Owen 1974, Noland et al. 1974). The existing photometry of Dione is also fairly accordant (same ref. as for Rhea; also Franz and Millis 1973); $V_o \approx 10.4$ and the light curve again has a maximum at EE and an amplitude at least as large as that of Rhea. Tethys (ref. as for Dione) is slightly brighter than Dione, with $V_o \approx 10.2$, but, being closer to Saturn, is more difficult to observe; like Rhea and Dione it is probably slightly brighter at EE than at WE. Enceladus, still fainter and closer to the planet, was observed photoelectrically by Harris on two nights and by Franz and Millis on several nights. The latter find the satellite brighter by about $0^m.4$ at WE. This surprising result finds some support in older visual photometry (Pickering 1879, Lowell 1914). No reliable photometry of Mimas is available.

Enceladus was measured by the writer on two nights in 1971 Nov (Table XV). On both occasions the symmetrical sky method was used, supplemented by further sky measures in the vicinity of the satellite. The repeatability of the deflections was good and the uncertainty in the result is largely due to the modeling of the sky background, for which the procedures outlined in ch. V:C were employed but found at the limit of their usefulness. It is difficult to give meaningful m.e. estimates; the approximate maximum errors compatible with any physically reasonable sky distribution fit to the sky observations are given. It is unlikely, however, that the actual errors are larger than $0^m.2$ unless some mistake

Table XV

New Enceladus photometry.

UT date	V_o	B_o	U_o	max. V errors	α	Θ'
1971 Nov 8.20	11.40	12.11	12.39	+0.40 -0.40	2°.07	107°
Nov 10.28	11.55	12.23	12.52	+1.5 -0.25	1.85	277

Mean colors: B-V = 0.70 ± .02

U-B = 0.28 .01

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU

was made during the observations (such as recording erroneous coordinates for a sky measurement). The colors are relatively insensitive to the sky model, and since the agreement is good between the two nights, the UBV colors of Enceladus are probably satisfactorily determined. The very blue B-V = 0.62 given by Harris is not substantiated.

The agreement of V_o is poor among the reported PE photometry of Enceladus. Exact dates of Harris' observations are not known; only the years are given (1951 and 1956). His V_o = 11.77 is somewhat fainter than the minimum (at EE) according to Franz and Millis, which is at $V_o \approx 11.65$. Perhaps the northern hemisphere of the satellite has lower albedo than the southern; the Earth was north of Enceladus' orbital plane in 1951 and 1956. The observation at EE in Table XV is $0^m.15$ brighter than the observation at WE, but the uncertainty is large. However, my WE observation can only with difficulty be contrived to be as bright as the $V_o \approx 11.25$ of Franz and Millis. More observations will be needed to settle the question of Enceladus' light curve.

Usable observations of Tethys were obtained on eight nights; some are of very low accuracy. The observations are given in Table XVI. The material is clearly too small for a determination of the light curve, since most observations are clustered near EE. The distribution with solar phase angle is satisfactory. From Fig. 7 it is seen that β_B is well determined at $0^m.03$/deg, while β_V and β_U are more uncertain but of the same order as β_B. Observations in

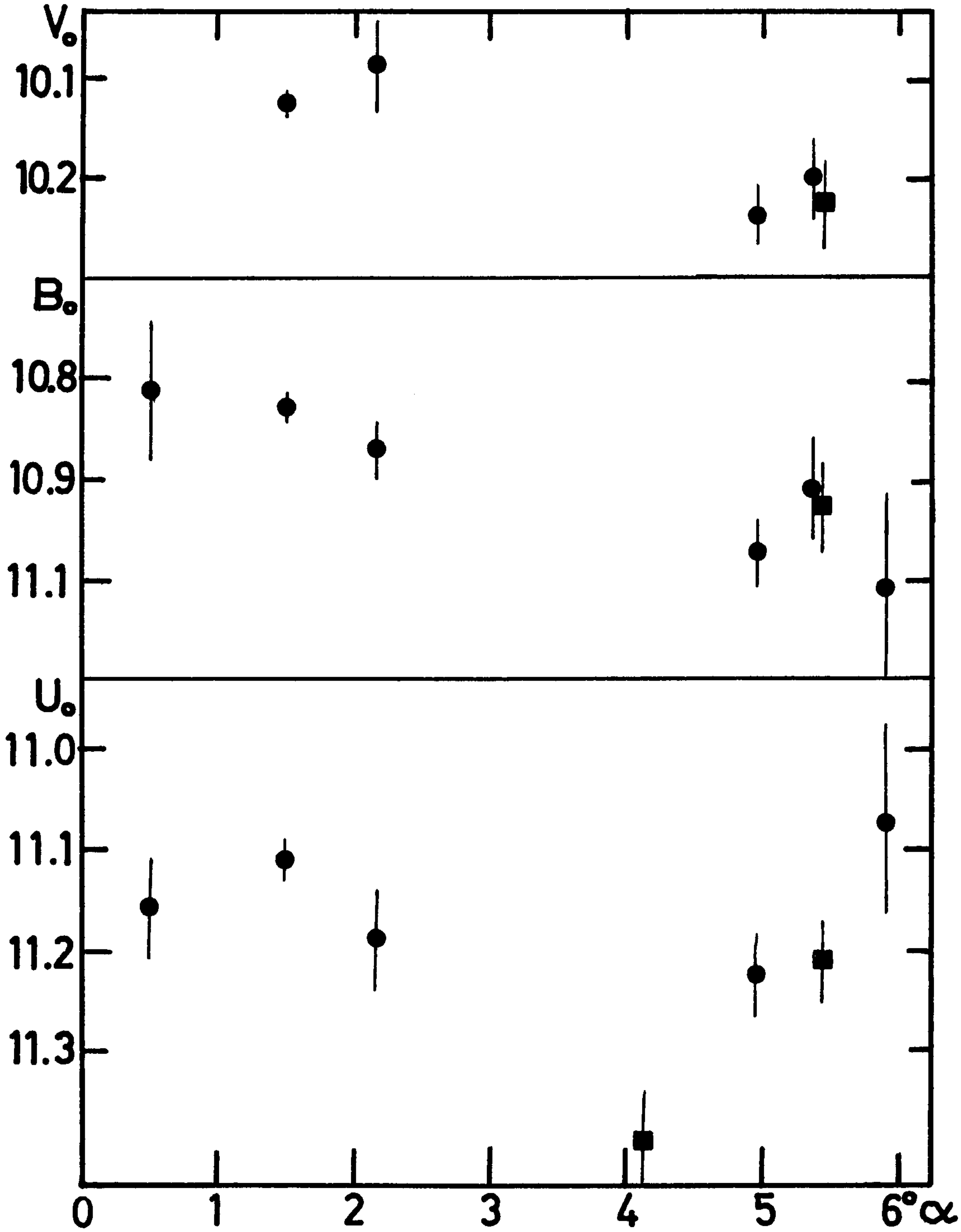


Figure 7. Magnitudes versus phase angle for Tethys. Open symbols indicate very uncertain observations (est. m.e. ⩾ 0^{m}15). Circles are data from the western half of the orbit, squares data from the eastern half.

Table XVI

New Tethys photometry.

UT date		V_o	B_o	U_o	est. m.e. V	B	U	α	θ'	Method
1970	Oct 4.31	--	--	11.39	-	-	5	4°13	259°	cd
	Nov 8.30	10.02	10.81	11.16	18	7	5	0.51	93	cd
	Dec 31.12	10.24	10.97	11.23	3	3	4	4.94	90	ss, scan
1971	Sep 21.40	10.16	11.01	11.07	15	10	9	5.91	65	ss,cd
	Nov 7.44	10.09	10.87	11.19	4	3	5	2.16	38	ss
	Nov 13.33	10.13	10.83	11.11	1	1	2	1.50	82	ss
1972	Jan 20.20	10.20	10.91	-	4	5	-	5.37	69	cd
	Jan 21.10	10.23	10.93	11.21	4	4	4	5.42	241	cd

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU all three colors, reduced to $\alpha = 0$ using $\beta = 0^m.03$ deg, are combined into the fragmentary light curve in Fig. 8. The prominently discordant points are from 1970 Oct 4 and 1971 Sep 21 (both in U); they were obtained with the Indiana 16-inch telescope, with which this close satellite is difficult even under good conditions. No variation with orbital phase is suggested by Fig. 8, but in view of the few points in the western half of the orbit a variation of small amplitude is certainly not excluded, particularly if the extrema are not at the elongations. A rotation rate slightly higher than the orbital rate was found by Franz and Millis to give a somewhat better fit to their observations than the light curve based on the synchronous rate, but the scatter of their points is appreciable in either case. Noland et al. (1974) find an amplitude of about $0^m.15$ with maximum at EE.

Tethys' mean opposition magnitudes (assuming the rotational variation to be negligible, giving lower weight to the poorest observations, and excluding the above-mentioned discrepant measurements) are $\overline{V}_o = 10.06$, $\overline{B}_o = 10.79$, $\overline{U}_o = 11.09$, and thus the colors B-V = 0.73 and U-B = 0.30. The magnitudes are about $0^m.1$ brighter than the values of Harris and Noland et al., possibly because my data are concentrated around EE. If included, the U observation on 1970 Oct 4 would increase $\overline{U}_o$ and U-B by $0^m.03$.

The new observations of Dione are listed in Table XVII. Plotting the magnitudes versus rotational phase reveals a variation with amplitude $\sim 0^m.4$; the maximum is near $\theta' = 90°$. The solar phase

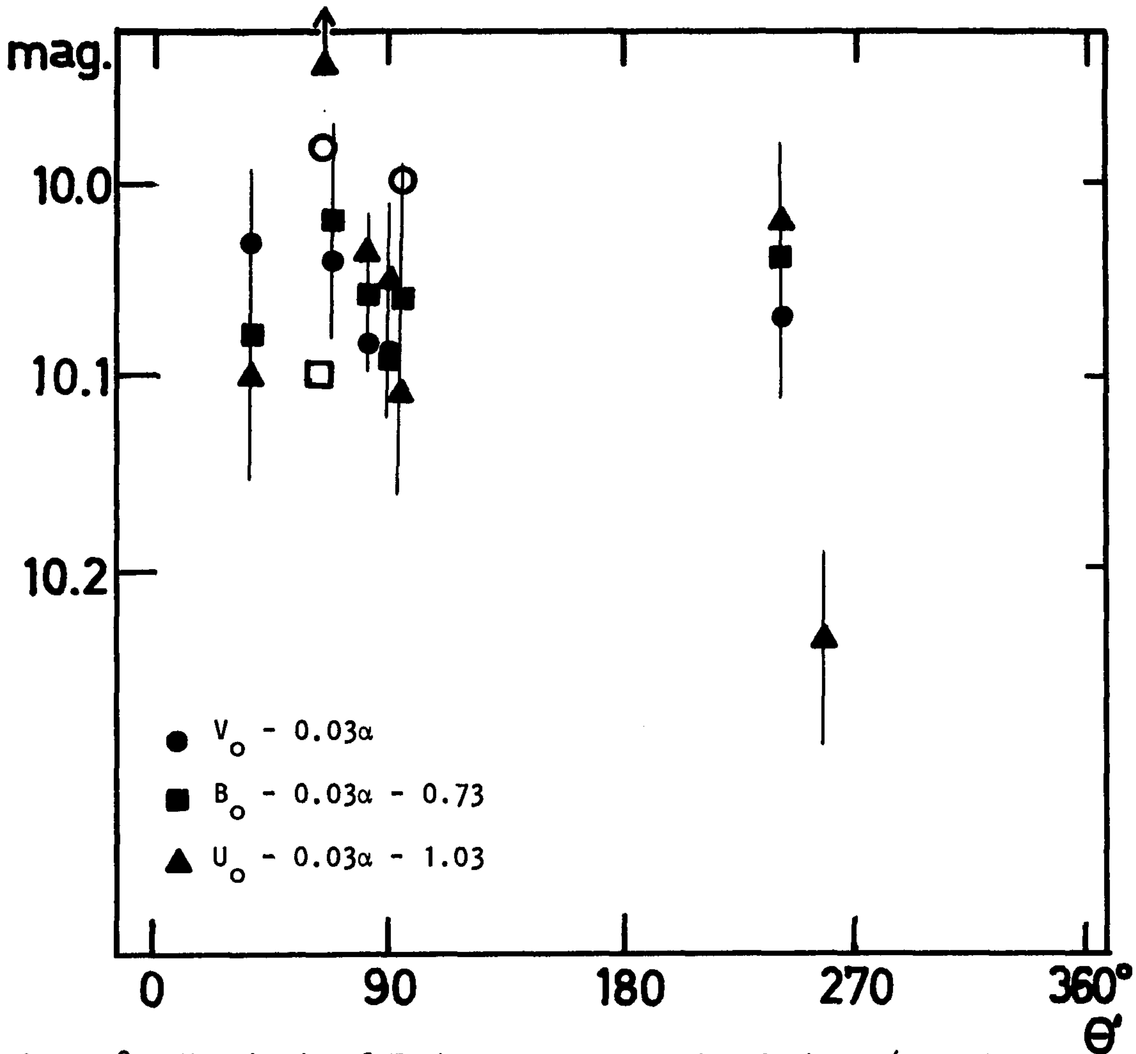


Figure 8. Magnitude of Tethys versus rotational phase (assuming synchronous rotation). Open symbols indicate observations with est. m.e.$\geq 0^{m}.10$.

angle coverage is good except for an empty interval $2\overset{\circ}{.}2 < \alpha < 4°$. Magnitudes ($V_o$,$B_o$,$U_o$) are plotted versus solar phase angle in Fig. 9; the magnitudes have been approximately compensated for the rotational variation by adding $+0\overset{m}{.}20 \sin \Theta'$. Both the low α ($< 2\overset{\circ}{.}2$) and the high α ($>4°$) groups of observations in both V and B contain about equally many data points from the eastern ($0<\Theta'<180°$) and western ($180°<\Theta'<360°$) halves of the satellite orbit. Unfortunately, in U all the points near EE have small α, and all but one of the points near WE have large α. Therefore it is not possible to completely separate the variations in U due to rotation and due to solar phase angle. The phase coefficients as calculated by least squares from the observations in Table XVII are given in Table XVIII. The reality of the surprising increase of β from U to V is rather doubtful.

Because of the interval with no data in the middle of the accessible range of α, it is not clear whether the phase function is in fact a straight line over this range or whether a strong opposition effect at less than $\alpha \sim 3°$ is responsible for the brightness difference between the $\alpha < 2°$ data and those at $>4°$. The latter is the case for Saturn's rings (e.g. Morrison and Cruikshank 1974), whose phase function fits the present Dione data about as well as the linear fit.

Since data from the eastern and the western halves of the orbit are shown with different symbols in Fig. 9, it can be seen that β does not differ noticeably between the two sides of the satellite. All observations have been reduced to $\alpha = 0$ and

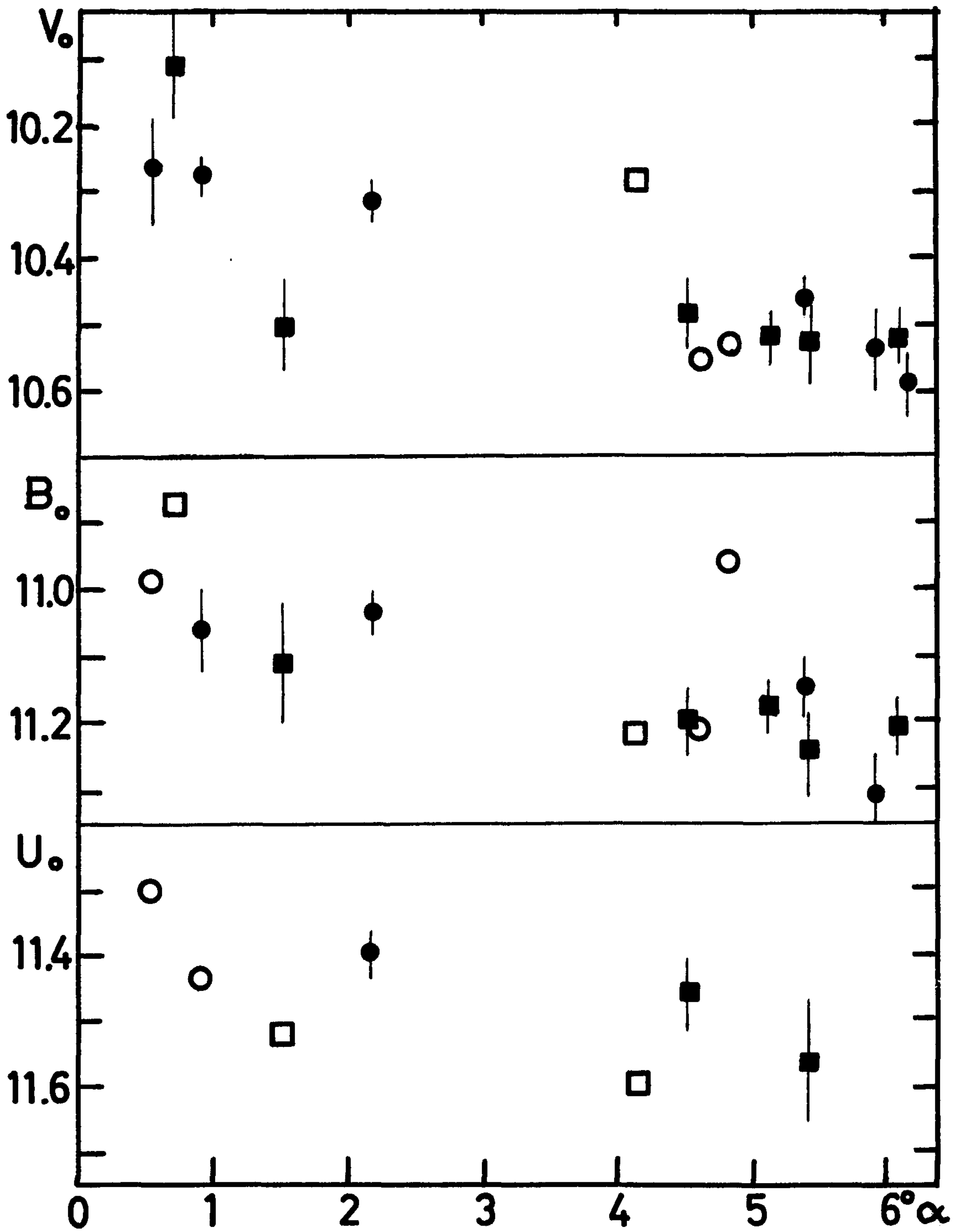


Figure 9. Magnitudes (corrected for rotational variation) versus phase angle for Dione. Open symbols indicate observations with est. m.e. ⩾ $0^{m}_{.}10$. Circles are data from the western half of the orbit, squares are data from the eastern half.

Table XVII

New Dione photometry.

UT date		V_o	B_o	U_o	est. m.e. V	B	U	α	θ'	Method
1970	Sep 28.32	10.71	11.36	-	12	15	-	4°61	312°	ms, cd
	Sep 29.30	10.28	11.00	11.26	5	5	5	4.54	81	cd
	Oct 4.30	10.22	11.15	11.46	15	12	15	4.13	19	cd
	Nov 6.31	9.97	10.73	-	8	10	-	0.72	44	cd
	Nov 8.32	10.43	11.15	11.46	8	12	10	0.52	308	cd
1971	Sep 21.40	10.71	11.48	-	6	6	-	5.92	236	ss
	Nov 7.36	10.50	11.22	11.58	3	3	3	2.17	296	ss
	Nov 13.44	10.45	11.10	11.46	7	9	12	1.50	16	ss
	Nov 18.51	10.40	11.18	11.56	3	6	15	0.91	324	ss
1972	Jan 12.22	10.66	11.08	-	15	15	-	4.85	324	cd
	Jan 16.14	10.35	11.01	-	4	4	-	5.12	120	ss, cd
	Jan 20.21	10.64	11.33	-	3	4	-	5.37	295	ss, cd
	Jan 21.09	10.37	11.09	11.40	6	6	9	5.41	51	ss, cd
	Mar 1.10	10.79	-	-	5	-	-	6.81	273	ss
	Mar 5.13	10.32	11.01	-	4	4	-	6.10	83	ms

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU

Table XVIII

Dione phase functions

Magnitude	β ± s.e.		$\bar{m}_o$ ± s.e.		Observations included (Tab. XVII)
$V_o + 0\overset{m}{.}20 \sin \Theta'$	0.054 ±	.012	10.23 ±	.05	all
	.054	.006	10.22	.03	m.e. < $0\overset{m}{.}07$
B_o + 0.20 sin Θ'	.043	.012	10.97	.05	all
	.033	.010	11.04	.05	m.e. < 0.10
U_o + 0.20 sin Θ'	.036[a]	.017	11.37[a]	.06	all

[a]U unreliable because of correlation between α and Θ'.

combined into the light curve in Fig. 10. The average deviation of points from the fitted sine curve is about $0^m.07$, which is also typical for the estimated m.e. of individual observations. The amplitude of the fitted curve is $0^m.40$. This amplitude is in agreement with Franz and Millis (1973) but is larger than found by Noland et al. (1974) and smaller than reported by Blair and Owen (1974). It is particularly disturbing that Noland et al. find both a much smaller amplitude and a much smaller β than I do, even though the size and phase distribution of their observational material is about the same as mine.

The mean opposition magnitudes are given in Table XVIII, but because of the change of β from V to U the colors obtained from $\overline{V}_o$, $\overline{B}_o$, and $\overline{U}_o$ are redder than the B-V and U-B actually observed. The mean B-V is 0.71. There is a suggestion of variation of B-V with rotational phase; excluding the poorer observations (m.e. of B or V $\geq 0^m.10$), the leading side has B-V = 0.69 ± .02 (m.e. of mean; mean solar phase angle for the five observations included is $4^\circ.5$), while the trailing side has 0.74 ± .02 (four observations; mean α $3^\circ.6$). The three best U-B observations give a mean of 0.31; the mean of all U-B measurements is 0.33 ± .02. The agreement with the colors measured by Harris (1961) is excellent. Blair and Owen (1974) find a much redder B-V (0.82) but the scatter in their data is large, and their photometry is not exactly on the UBV system. My magnitude for Dione is in good agreement with all available PE photometry if allowance is made for the large β found here.

Good observations of Rhea were obtained on 26 nights, and are

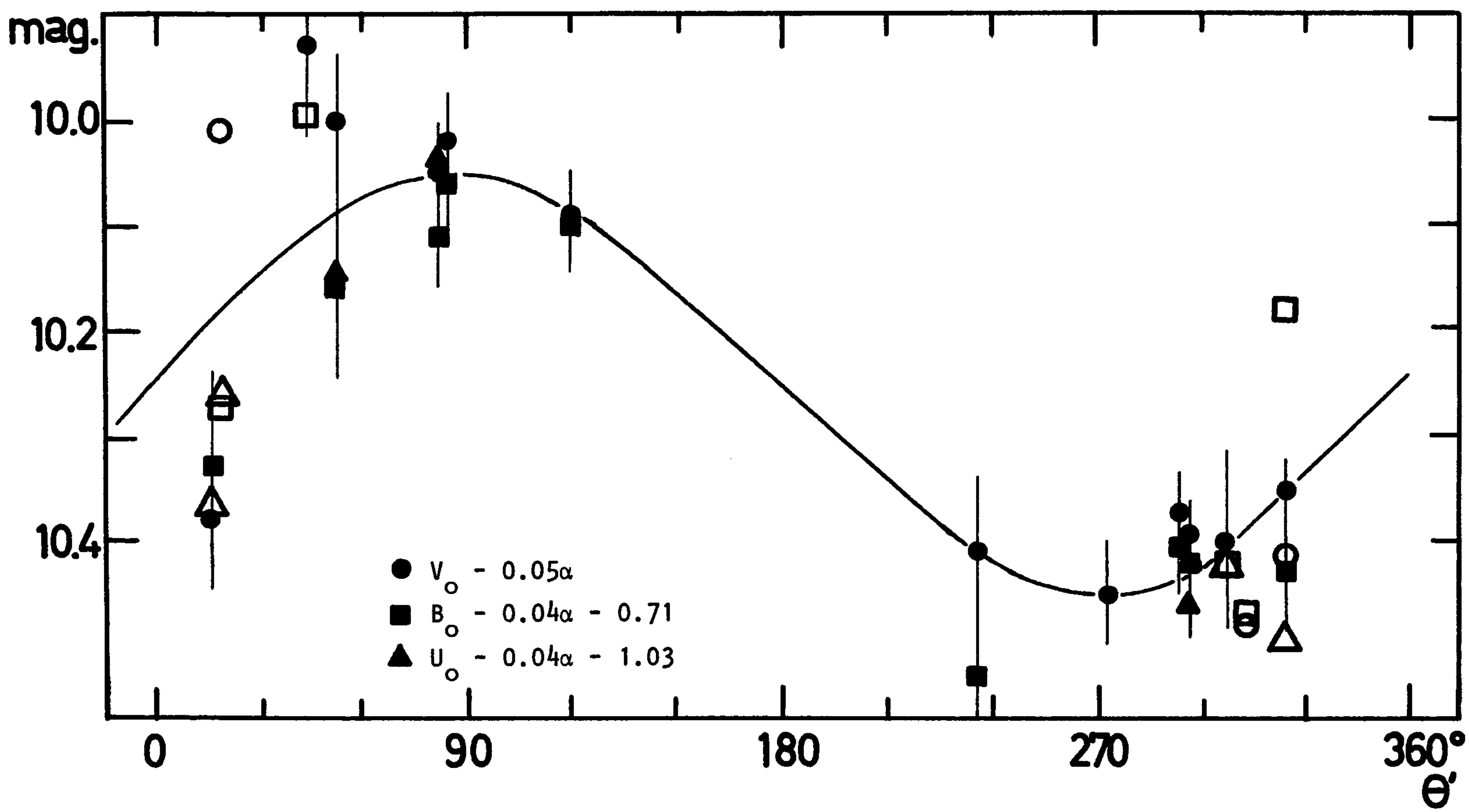


Figure 10. Magnitude of Dione versus rotational phase. Open symbols indicate observations with est. m.e. $\geq 0^m.10$.

Table XIX

New Rhea photometry.

UT date		V_o	B_o	U_o	est. m.e. V	B	U	α	Θ'	Method
1970	Sep 11.36	9.83	10.62	11.00	4	4	4	5°69	314°	ms
	Sep 12.33	9.74	10.44	10.80	4	6	7	5.64	31	ms
	Sep 29.30	9.74	-	10.92	12	-	10	4.54	304	cd
	Sep 30.42	9.73	10.42	11.02	11	3	10	4.46	34	cd
	Oct 1.34	9.57	10.37	-	9	10	-	4.38	107	cd
	Oct 4.36	9.87	10.62	11.11	8	6	6	4.12	348	cd
	Oct 5.28	9.78	10.48	10.88	10	7	5	4.05	61	cd
	Oct 30.30	-	10.51	-	-	4	-	1.50	257	cd
	Nov 6.24	9.39	10.15	10.52	4	4	8	0.72	91	cd
	Nov 8.32	9.54	10.38	-	10	7	-	0.50	256	cd
	Nov 17.16	9.59	10.38	10.81	5	6	8	0.68	242	cd
	Nov 21.25	9.59	10.37	10.82	10	9	11	1.13	208	cd
	Dec 6.15	9.86	10.68	11.16	4	3	5	2.76	316	cd, ss
	Dec 7.16	9.71	10.42	10.84	6	4	5	2.86	36	cd, ms
1971	Sep 21.40	9.82	10.60	10.90	3	3	5	5.91	307	cd, ss
	Oct 8.42	9.90	10.66	11.00	2	2	5	4.96	223	ms
	Nov 7.30	9.62	10.39	10.75	2	2	3	2.18	86	ss
	Nov 13.38	9.69	10.45	10.82	2	2	3	1.50	211	ms
	Nov 18.52	9.71	10.51	10.96	2	2	4	0.91	261	ss

(continued)

Table XIX

(cont.)

UT date	V_o	B_o	U_o	est. m.e. V	B	U	α	Θ'	Method
1972 Jan 11.18	-	10.70	-	-	10	-	4°.76	222°	ss
Jan 12.20	9.76	10.55	10.93	2	2	3	4.84	303	ss, cd
Jan 16.15	9.83	10.62	-	1	1	-	5.12	257	ss, cd
Jan 18.13	9.67	10.44	-	2	2	-	5.25	55	ss
Jan 20.23	9.78	10.52	-	2	3	-	5.37	223	ss, cd
Jan 21.07	9.83	10.62	11.02	2	2	3	5.42	289	ss
Mar 1.10	9.88	-	-	4	-	-	6.18	238	ss

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU

listed in Table XIX. The light variation found by several earlier observers is clearly indicated, with the leading side (seen at EE) the brighter by $\sim 0^m_.2$. The magnitudes, corrected for rotational variation by adding $+0^m_.10 \sin \theta'$, are plotted versus α in Fig. 11. As for Dione, it is not clear whether the phase function is linear over the range covered, or whether it is curved in the manner of the phase curve of Saturn's rings. The argument for the latter interpretation depends strongly on the observations at very small phase angle made in 1970 Nov; while some of these are of low accuracy their accordance is striking. The least-squares linear fits are given in Table XX. The β values determined from the high-accuracy observations made at Kitt Peak and McDonald are much smaller than those determined from the whole observational material, but include only one observation at $\alpha < 1°$. In any case the scatter of the points is dismayingly large, suggesting that the errors are generally larger than the estimates in Table XIX. The best that can be said about the phase coefficients is that β_V, β_B, and β_U are all of the order of $0^m_.03$/deg if the phase function is linear.

The mean opposition magnitudes from the least squares fits are found in Table XX; if instead $\beta = 0^m_.03$/deg is used, $\overline{V}_o = 9.59$, $\overline{B}_o = 10.36$, and $\overline{U}_o = 10.78$, using all observations, and practically the same if data with m.e. > $0^m_.03$ are excluded. The mean colors are B-V = 0.77 ± .01 (m.e. of mean) and U-B = 0.42 ± .01 using all observations listed except the very discrepant 1970 Sep 30; excluding those for which estimated magnitude errors exceed $0^m_.03$ yields

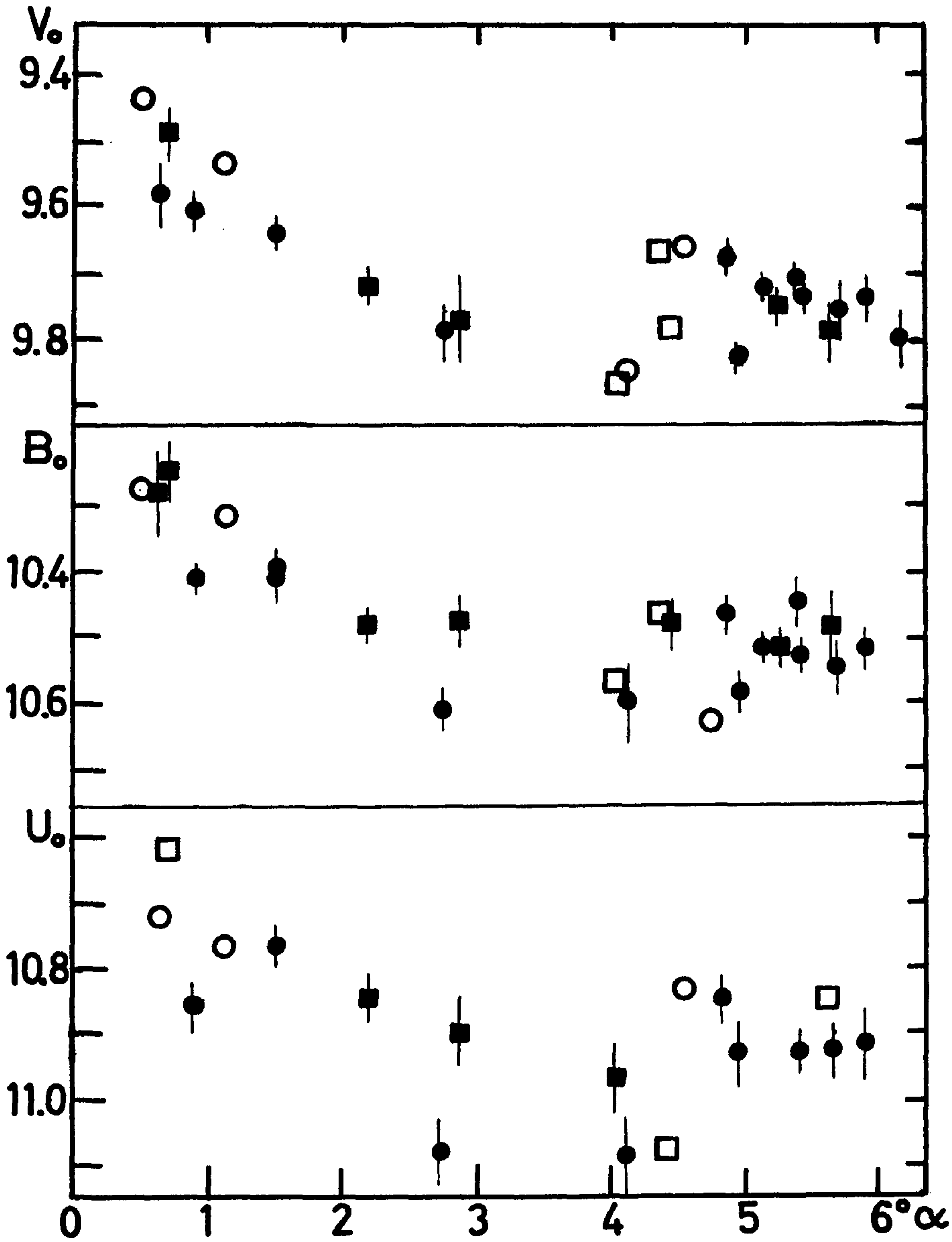


Figure 11. Magnitudes (corrected for rotational variation) versus phase angle for Rhea. Open symbols indicate observations with est. m.e. $\geqslant$ $0\overset{m}{.}07$. Circles are data from the western half of the orbit, squares data from the eastern half.

Table XX

Rhea phase functions

Magnitude	β ± s.e. (mag/deg)		$\overline{m}_o$ ± s.e.		Observations (Tab. XIX)
$V_o + 0\overset{m}{.}10 \sin \Theta'$	0.044 ±	.009	9.54 ±	.04	all
	.021	.006	9.62	.03	1971 Nov, 1972 Jan (excl. Jan 11)
$B_o + 0.10 \sin \Theta'$	0.041	.008	10.33	.03	all
	.019	.007	10.40	.03	1971 Nov, 1972 Jan (excl. Jan 11)
$U_o + 0.10 \sin \Theta'$	0.036	.014	10.76	.03	all
	.018	.012	10.80	.04	1971 Nov, 1972 Jan (excl. Jan 11)

0.78 ± .01 and 0.38 ± .01. The Indiana U-B observations give a larger U-B than the out-of-state observations, and since they are generally of lower accuracy the figure U-B = 0.38 is adopted here. Agreement is good with all other published mean UBV colors for Rhea.

There is no discernible dependence of colors on α in this material. The color versus Θ' plots of Fig. 12 suggest that B-V is slightly bluer at EE than at WE. The amplitude of the B-V variation may be about $0\overset{m}{.}05$. No variation of U-B is apparent, but the scatter is large and a variation of $0\overset{m}{.}05$ could certainly remain undetected. Magnitudes versus Θ' are also plotted in Fig. 12. Because of the possible presence of an opposition effect only observations at $\alpha > 1°$ are plotted. The scatter is large, there are few high-quality observations in the eastern half of the orbit, and the amplitude is not well defined. The curves drawn in the figure have amplitudes of $0\overset{m}{.}15$ (V) and $0\overset{m}{.}20$ (B), in reasonable agreement with other determinations.

It is clear that the photometric behavior of the inner Saturn satellites requires more observations of good accuracy for a fully satisfactory description. The compilation in Table XXI shows, however, that there is substantial agreement about the mean magnitude and colors for Rhea, Dione, and Tethys. The principal disagreeing datum is Blair and Owen's (1974) determination of B-V for Dione. I have one observing date in common with Blair and Owen (1971 Nov 18); on this date I obtained B-V = 0.78 ± .06. Except for this observation and a few other low-accuracy ones, my data are plainly incompatible

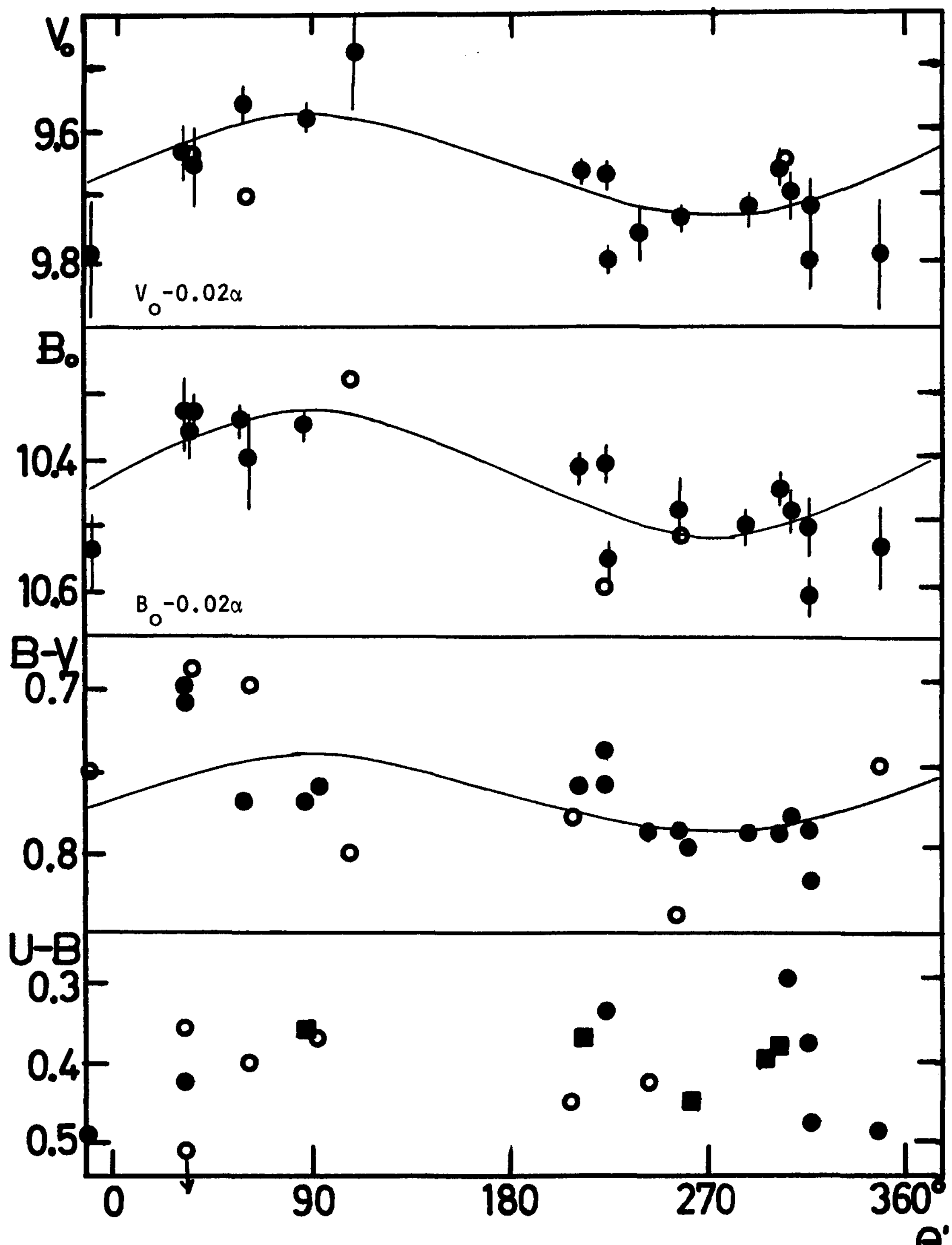


Figure 12. Magnitudes and colors of Rhea versus rotational phase. Magnitudes at $\alpha<1\overset{\circ}{.}2$ are not plotted. Open symbols indicate for magnitudes est. m.e.≥$0\overset{m}{.}10$ and for colors est. m.e.≥$0\overset{m}{.}07$ in one of the magnitudes involved. In the U-B plot squares indicate observations from McDonald or Kitt Peak.

with B-V as large as 0.80. Since my B-V for Dione also agrees with that obtained by Harris, the data of Blair and Owen are probably in error. The magnitudes according to McCord et al. (1971) are taken from figures in that reference, and the details of the transformation to the UBV system are unknown. Observations of Rhea and Titan in 1968/69 by Blanco and Catalano (1971) and Veverka (1970) suggest that a correction of about $+0\overset{m}{.}15$ will transform the magnitudes of McCord et al. to V_o. The photometry of Blanco and Catalano as given in their paper suffers from minor reduction errors (Blanco and Catalano, private communication 1974); revised values are given in the table. (See the Appendix for comments on their comparison stars.)

The amplitude of Rhea's rotational light variation is fairly well determined, while there is still some uncertainty for Dione and more so for Tethys and Enceladus. If the axes of rotation of these satellites are perpendicular to the ring plane, the amplitude would be roughly proportional to cos B. Since $0.9 \lesssim \cos B \leq 1$, the amplitude will vary by $\sim$10%. With better photometry this effect should be detectable for Rhea and Dione.

The phase coefficients over the range $1° < \alpha \lesssim 6°$ are of the order of $0\overset{m}{.}03$/deg for Tethys, Dione, and Rhea. Dione's are largest, in conflict with the findings of Noland et al. (1971) who find smaller β for Dione than for Rhea. Since only phase angles $\lesssim 6°$ are accessible for Saturn, it is not possible to say whether these rather large phase coefficients reflect the slope of the linear part of the phase function, or whether they are influenced by an opposition

Table XXI

Saturn's inner satellites: photometry summary.

Reference Obs. Year(s)	Enceladus V_o ΔV	 B-V U-B	Tethys V_o ΔV	 B-V U-B	Dione V_o ΔV	 B-V U-B	Rhea V_o ΔV	 B-V U-B	B range
Harris (1961)	11.77	0.62	10.27	0.73	10.44	0.71	9.76	0.76	+ 2°
1951, -53, -56	-	-	-	0.34	-	0.30	-0.20	0.35	+25
Blanco & Catalano (1971, priv. comm. 1974)							9.68	0.77	-11
1968, -69/70							-0.23	0.37	-18
McCord et al. (1971)			10.15[a]	-	10.27[a]	-	9.56[a]	-	-11
1968			-0.2:	-	-0.2:	-	-0.2	-	-18
Blair & Owen (1974)			10.30[b]	0.75[b]	10.4[b]	0.82[b]	9.71[b]	0.78[b]	-24
1971/72			0.0:	0.32[b]	-0.6	0.27[b]	-0.2	0.38[b]	-25
Franz & Millis (1973)	11.55	-	10.2	-	10.4	-			-24
1971/72, -72/73	+0.4	-	-0.1:[c]	-	-0.4	-			-27
Noland et al. (1974)			10.28[d]	-	10.41[d]	-	9.74[d]	-	-26
1972/73			-0.16	-	-0.2	-	-0.19	-	-27
this thesis	11.5:	0.69	10.15	0.73	10.38	0.71	9.68	0.78	-21
1970, -71/72	-	0.28	0.0:	0.30	-0.40	0.31	-0.15	0.38	-25

(continued)

V_o is reduced to $\alpha = 3^\circ$ where the phase angles of the observations are known. ΔV is the amplitude of the rotational light variation, negative if the maximum is in the eastern half of the orbit.

[a]narrowband photometry; probable correction to $V \approx +0^{m}.15$.

[b]photometric system close to but not identical to UBV.

[c]possibly non-synchronous with $\Delta V \sim 0^{m}.4$.

[d]y of Strömgren uvby system, approximately transformed to V.

Last column = approximate extremes of Earth's saturnicentric latitude B referred to the ringplane.

effect extending past $\alpha = 6°$. There is some indication of additional brightening at $\alpha < 1°$ for these three satellites, but this statement depends largely on the observations in 1970 Nov, which are mostly of very low accuracy.

F. Titan.

The new photometry of Titan is given in Table XXII. It is immediately evident from the near-constancy of V_o that both the rotational variation and the phase coefficient must be small. Fig. 13 shows magnitude and colors plotted versus rotational phase (assuming synchronous rotation). No variation is discernible. Plots were also made of V_o versus Θ' (not shown) for time intervals of about a month each to check for short-lived rotational variations. None were evident. Since faint and probably non-permanent markings have been seen on Titan's disk (the diameter of which is about one arcsec) by the French observers (Dollfus 1961), measurable variations in magnitude or colors might be expected; the observations show that any such variation has an amplitude $\lesssim 0\overset{m}{.}02$ if permanent and $\lesssim 0\overset{m}{.}05$ if lasting through at least two or three revolutions of Titan.

Titan's phase coefficients are very small; Noland et al. (1974) give values ranging from $0\overset{m}{.}001$/deg in the near infrared to $0\overset{m}{.}014$/deg at 3500 Å. Least squares solutions for the β's from my photometry are given in Table XXIII. The material was for this purpose divided into three groups; viz., Indiana observations with the "old" filter

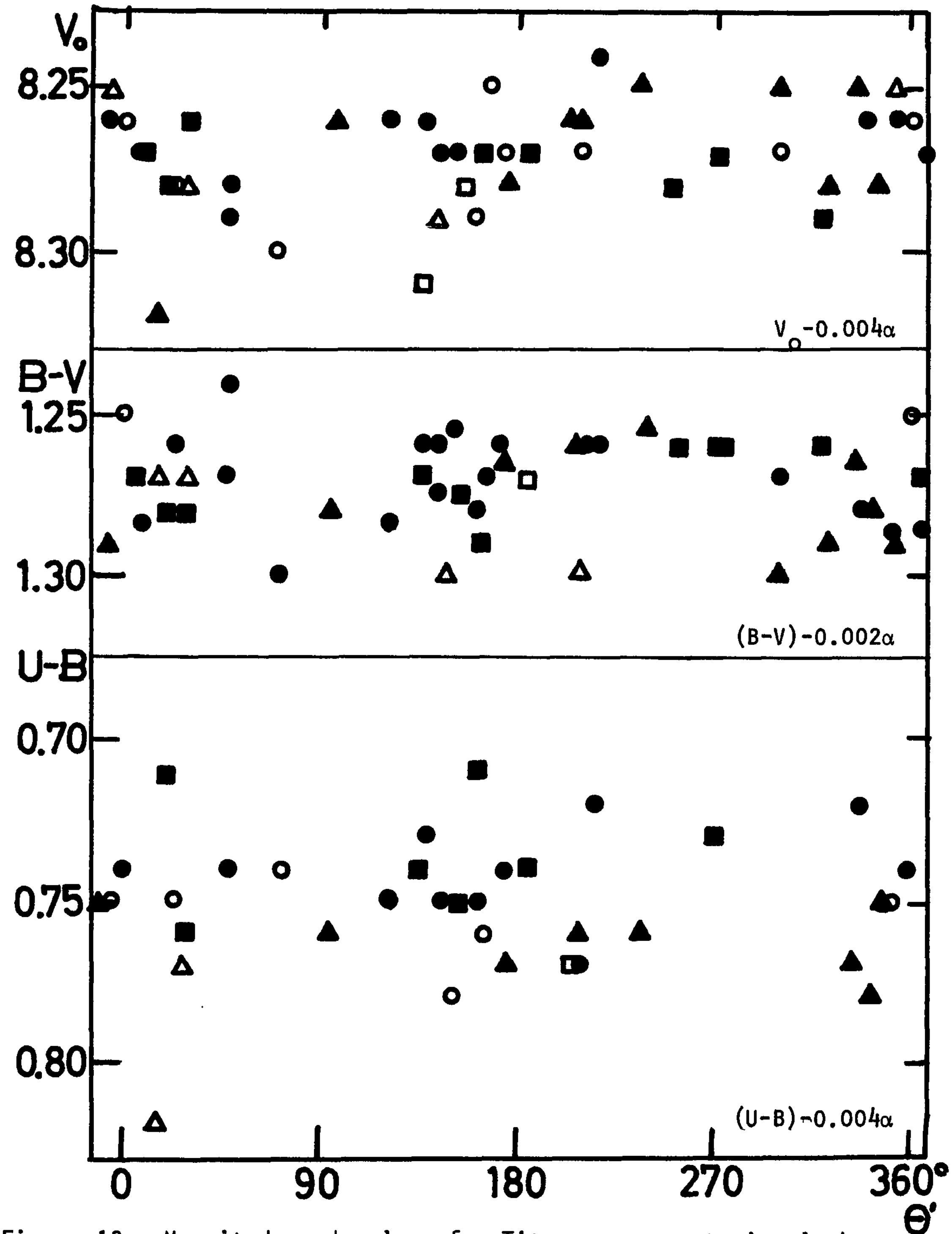


Figure 13. Magnitude and colors for Titan versus rotational phase (synchronous rotation assumed). Open symbols indicate observations with est. m.e. ≥ $0^m_.03$. Circles: Indiana data obtained with the "old" filter set; triangles: Indiana data with "new" filters; squares: Texas and Arizona data.

Table XXII

New Titan photometry.

UT date		V_o	B-V	U-B	est. m.e. V	B-V	U-B	α	Θ'	Obs.
1970	Sep 11.33	8.28	1.29	0.74	2	1	2	5°.69	338°	Go
	Sep 12.32	8.28	1.26	0.76	3	3	2	5.64	0	Go
	Sep 29.25	8.30	1.27	0.77	3	2	4	4.54	23	Go
	Sep 30.42	8.31	1.25	-	2	2	-	4.46	49	Go
	Oct 1.30	8.32	1.31	0.76	3	2	4	4.38	70	Go
	Oct 4.34	8.28	1.27	0.75	2	2	2	4.13	139	Go
	Oct 5.25	8.31	1.29	0.77	3	2	2	4.05	159	Go
	Oct 27.26	8.28	1.275	-	3	1	-	1.83	298	Go
	Oct 30.28	8.28	1.29	-	2	2	-	1.50	6	Go
	Nov 6.24	8.25	1.27	0.76	3	2	3	0.72	164	Go
	Nov 8.19	8.27	1.26	0.77	5	2	2	0.50	208	Go
	Nov 17.09	8.28	1.27	0.74	2	1	2	0.67	49	Go
	Nov 21.24	8.27	1.26	0.75	2	1	2	1.13	143	Go
	Dec 6.10	8.27	1.29	0.76	1	1	1	2.75	120	Go
	Dec 7.12	8.28	1.28	0.76	2	2	2	2.85	143	Go
1971	Sep 14.40	8.28	1.30	0.77	2	2	5	6.16	353	Go
	Sep 21.43	8.29	1.265	0.80	2	1	4	5.91	151	Go
	Sep 22.42	8.29	1.27	0.76	3	2	2	5.85	174	Go, n
	Sep 24.31	8.26	1.27	0.74	2	2	2	5.79	216	Go, n
	Sep 25.23	8.27	1.265	0.78	3	1	2	5.75	237	Gn
	Sep 30.32	8.27	1.30	0.77	3	2	2	5.47	352	Gn
	Oct 1.27	8.34	1.28	0.84	2	3	5	5.41	14	Gn
	Oct 8.41	8.30	1.275	0.79	1	1	2	4.96	175	Gn
	Oct 31.28	8.26	1.27	0.78	2	2	2	2.93	333	Gn
	Nov 7.48	8.32	1.275	0.75	3	1	2	2.16	136	K
	Nov 8.32	8.29	1.28	0.76	4	1	2	2.07	155	K
	Nov 13.35	8.28	1.265	0.74	1	1	1	1.50	269	K

(continued)

Table XXII

New Titan photometry.

(cont'd.)

UT date	V_o	B-V	U-B	est. m.e. V	B-V	U-B	α	Θ'	Obs.
1971 Nov 18.24	8.28	1.28	0.71	1	1	2	0°94	20°	K
Dec 12.32	8.27	1.265	0.78	1	1	3	1.93	205	Gn
1972 Jan 11.16	8.29	1.30	0.73	2	2	2	4.76	161	M
Jan 12.22	8.29	1.28	0.76	2	3	2	4.85	185	M
Jan 15.14	8.30	1.27	-	1	1	-	5.05	251	M
Jan 16.12	8.29	1.27	-	1	1	-	5.12	273	M
Jan 18.13	8.31	1.27	-	1	1	-	5.25	318	M
Jan 20.19	8.29	1.28	-	1	1	-	5.37	5	M
Jan 21.09	8.28	1.29	0.78	1	1	1	5.42	26	Mn
Feb 20.06	8.30	1.29	0.80	2	2	2	6.26	342	Gn
Feb 27.12	8.31	1.31	-	3	3	-	6.22	141	Gn
Mar 1.08	8.28	1.31	0.78	2	2	1	6.18	208	Gn
Mar 5.12	8.27	1.31	-	2	2	-	6.10	299	Gn
Mar 6.13	8.30	1.30	-	2	1	-	6.07	321	Gn
Mar 9.04	8.30	1.28	0.79	3	3	4	5.99	27	Gn
Mar 12.05	8.28	1.29	0.78	2	1	2	5.90	95	Gn

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU.

Obs.: Observatory and filter set (cf. ch. V:A)

- G Goethe Link Obs.
- K Kitt Peak Natl. Obs.
- M McDonald Obs.
- o "old" Indiana filter set
- n "new" " " "

Table XXIII

Titan: magnitudes, colors, phase coefficients

Quantity	Reduced to α=0±s.e.	β ± s.e. mag/deg		Zero point corr. to Indiana data "old"	"new"	n
V_o	8.275±005	0.0036 ±	0012	$+0^m.005$	$+0^m.01$	41
B_o	9.542 008	.0054	0016	+0.005	0.00	42
U_o("old")	10.287 012	.0085	0029	-	-	14
U_o(other)	10.276 021	.0125	0043	-	-0.01	16
B-V	1.268 006	.0023	0012	0.00	-0.005	45
U-B ("old")	0.755 009	.0011	0020	-	-	16
U-B (other)	0.760 011	.038	0024	-	-0.025	17

Data excluded:

V_o	1971 Oct 1, Nov 7
B_o	1970 Oct 1; 1971 Oct 1, Nov 7
U_o	1970 Oct 1; 1971 Sep 24, Oct 1
B-V	none
U-B	1971 Oct 1

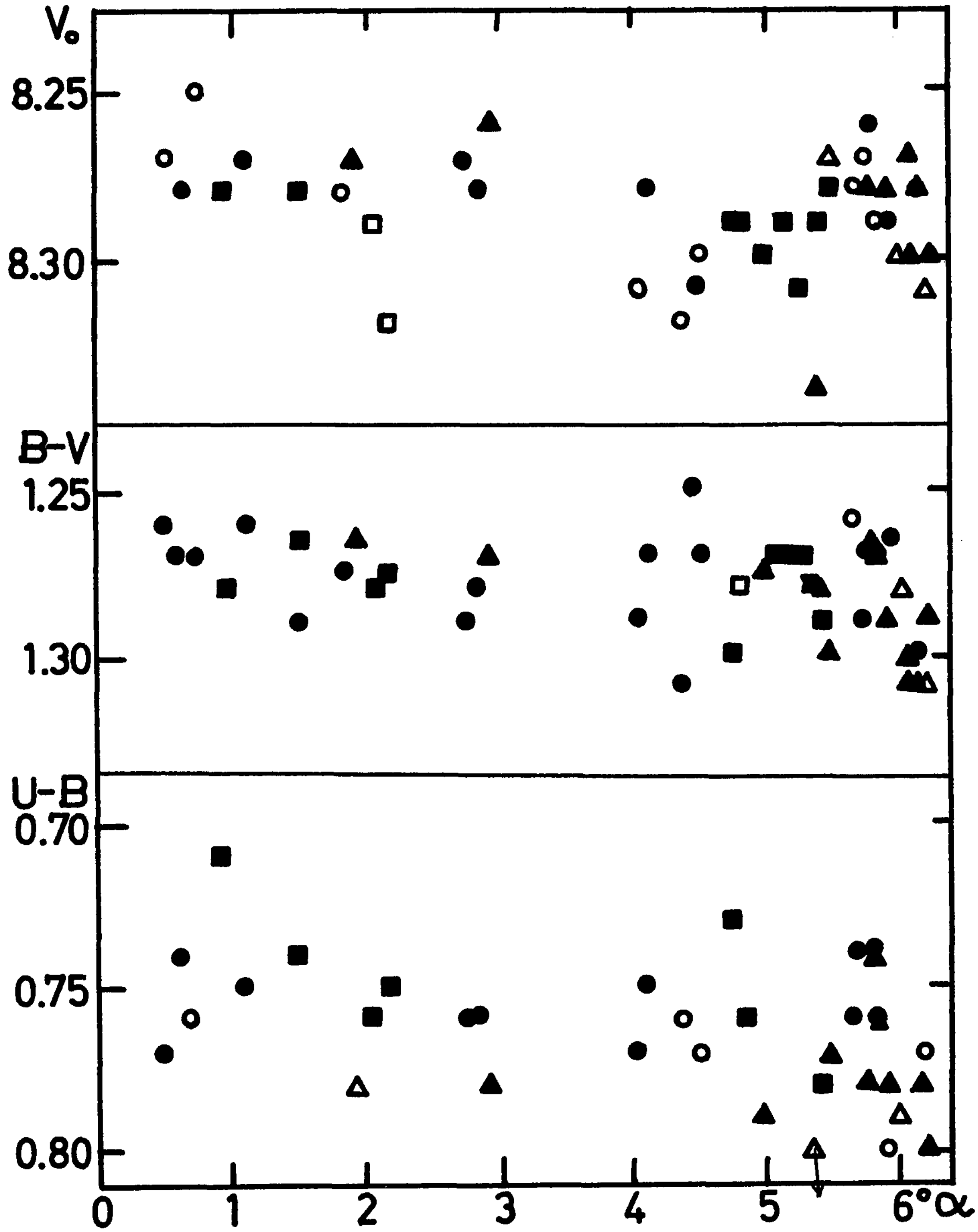


Figure 14. Titan magnitude and colors versus solar phase angle. The symbols have the same meanings as in Fig. 13. The corrections in Table XXIII have not been applied.

set, Indiana observations with the "new" filter set, and Texas and Arizona observations. (For details of filters and photometers, see ch. V:A.) Mean magnitudes and colors and approximate phase coefficients were derived for each group and zero point differences between the Indiana data and the out-of-state group were determined. After applying the zero point corrections to the Indiana data, phase coefficients were determined for the combined material. The "old filter" U-B and U were not combined with the other two groups of U-B and U data because of the somewhat larger effective wavelength of the "old" U filter than the standard U wavelength, and the relatively strong wavelength dependence of Titan's β in the ultraviolet. All the quantities in Table XXIII were treated independently and the number of data points entering in the least squares solution was not the same for all the quantities (column headed n), so the results do not exactly "add up"; $\beta_V + \beta_{B-V}$ is not equal to β_B, for example. A solution for the β's with the constraint equations $\beta_V + \beta_{B-V} = \beta_B$ and $\beta_B + \beta_{U-B} = \beta_U$ would perhaps have been preferable, but the results would certainly not differ from the values in the table by as much as the standard errors listed there. It should also be emphasized that because of the strong dependence of β on wavelength at the shorter wavelengths, not too much significance should be attached to the exact value of any broadband (e.g., UBV) determination of β_U; the β's for Titan reported here serve mainly to confirm the narrowband results of Noland et al. as regards the behavior of β with wavelength.

The magnitude and colors at $\alpha=4°$ are very well determined: $V_o(\alpha=4°) = 8.290\pm002$ (formal m.e. of mean), $B-V = 1.277\pm002$, and $U-B = 0.75\pm01$. The formal errors are so small that the true uncertainty of V_o and B-V is determined by the errors of the adopted magnitudes and colors of the comparison stars. There is no indication of any difference between the 1970 and 1971/72 apparitions, an important point in view of the following.

It was evident already after the first few observations of Titan in 1970 Sep that Titan was brighter than the $V_o = 8.39$ given by Harris (1961). However, PE photometry by various investigators (Veverka 1970, Blanco and Catalano 1971) made from 1967 to early 1970 confirmed Harris' magnitude. In view of this previously unknown long term variability of Titan, all available quality photometry of Titan was reexamined, beginning with Wendell's (1913) photometry of Titan and Iapetus in 1896-1900. PE observations of his comparison stars were obtained in 1971 and are reported in the Appendix (stars identified by "13" in the Remarks column).

The 1896-1900 observations of Titan are listed in Table XXIV. Wendell usually made two observations per night (each consisting of four settings); they are combined into one entry in the table. Titan's rotational phase was recalculated for each observation and should be accurate to better than 2°. The V_o magnitude was calculated from

$$V_o = m_o + (V_{star} - m_{star}) + k((B-V)_{star} - (B-V)_{Titan}) + \\ +\ell(m_{star} - m_{Titan}) \qquad (1)$$

where m_o is the satellite's magnitude at mean opposition as derived by Wendell (column 13 in his table XXII), m_{star} the magnitude for the comparison star adopted by him (column 4 in his table), and V_{star} and $(B-V)_{star}$ the photoelectric data for the star, taken from the Appendix. The value of the color coefficient k was adopted as 0.30, taken from a plot of $(V_{star} - m_{star})$ versus $(B-V)_{star}$ for all the stars used by Wendell. The plot is shown in Fig. 15a. However, since Wendell adopted m_{star} values from measurements with another photometer than the one used for the satellite measurements, the color coefficient was also determined from the Titan observations themselves under the assumption that Titan was constant at least during the individual years. The plot of $m_o + (V_{star} - m_{star})$ versus $(B-V)_{star}$ in Fig. 15b, which uses the observations in 1899, suggests that k is somewhat less than 0.3; similar results are obtained from the other years. The value k = 0.30 was retained although the best value may be a few hundredths smaller. The coefficient, ℓ, of the magnitude scale term is poorly determined but its amount must be quite small ($\lesssim 0.05$) since there is no perceptible correlation between the magnitude of the comparison star and the V_o of Titan in Table XXIV, where ℓ was assumed to be zero. The by far faintest star with which Wendell compared Titan is -19°4374; the single observation using this star gives a V_o which is $0^m.2$ fainter than average, but the star is very red and the discrepancy could be due, e.g., to variability in the star. On two nights Wendell compared Iapetus with two different stars of widely

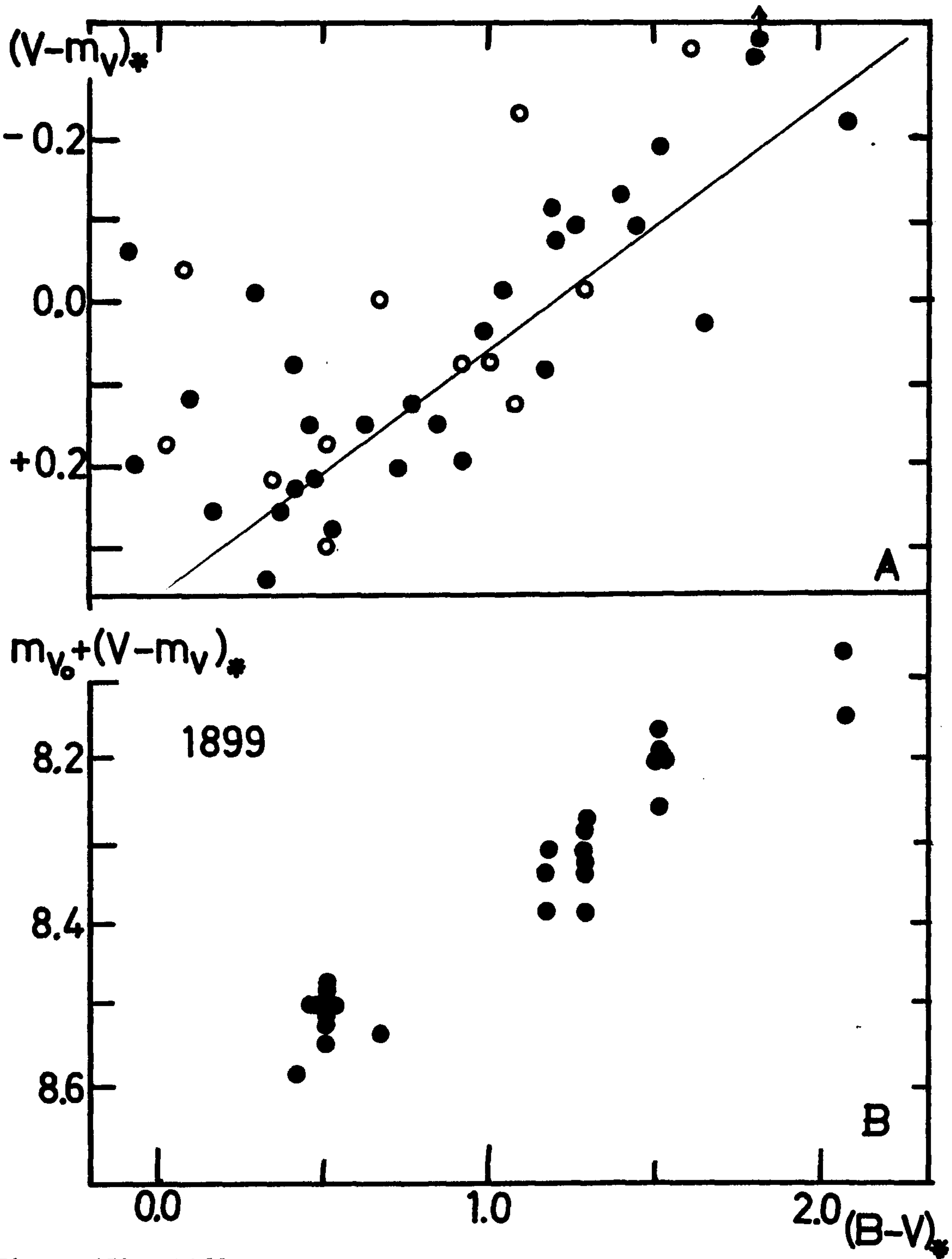


Figure 15A. Difference between photoelectric magnitude and magnitude adopted by Wendell, versus B-V color of star, for Wendell's comparison stars. Open symbols indicate single V measurement, or est. m.e.$\gtrsim$ 0^m.04 for V. The solid line has a slope of 0.30.

Figure 15B. Magnitude (m_V) of Titan, corrected for the difference V-m_V, versus B-V color of the star. 1899 data only; very uncertain observations (:: in Table XXIV) excluded.

Table XXIV

Wendell's Titan photometry

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1896	3672.74	-14°4118	8.20	8.29	1°.3	230°	
	3680.71	-14 4095	8.29	8.34	0.5	50	
	3691.75	-14 4085	8.43	8.36:	0.7	301	3
	3721.66	-13 3994	8.33	8.23	3.7	257	
1897	4091.62	-17 4395	8.43	8.42:	2.9	319	3
	4099.69	-16 4122	8.32	8.29	3.6	140	
	4150.57	-16 4120	8.42	8.32	5.8	208	
1898	4448.68	-19 4381	8.27	8.21:	0.9	83	2,4
	4455.70	-19 4375	8.34	8.34	1.6	243	
	4456.71	-19 4375	8.28	8.28	1.7	267	
	4462.72	-19 4374	8.66	8.52:	2.3	42	4
	4486.68	-19 4368	8.25	8.30	4.3	224	
	4487.70	-19 4368	8.21:	8.26:	4.4	248	1
1899	4790.69	-21 4648	8.54	8.35:	2.6	230	3
	4792.66	-21 4641	8.36	8.33	2.4	275	
	4805.70	-21 4605	8.37:	8.38:	1.1	210	1,3,4
	4807.67	-21 4605	8.29	8.30:	0.9	255	3,4
	4812.70	-21 4605	8.56::	8.57::	0.4	8	1,3,4
	4819.64	-21 4594	8.26	8.23::	0.3	167	3
	4822.66	-21 4594	8.26	8.23::	0.6	235	3
	4825.70	-21 4594	8.24	8.21::	0.9	303	3
	4827.64	-21 4594	8.28:	8.25::	1.1	346	1,3
	4833.67	-21 4564	8.40	8.28:	1.7	125	3
	4835.66	-21 4564	8.46	8.34:	1.9	169	3
	4836.68	-21 4564	8.36	8.24:	2.0	192	3
	4837.65	-21 4564	8.40	8.28:	2.1	214	3

continued

Table XXIV

(cont'd.)

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1899	4839.68	-21°4564	8.40	8.28:	2°.3	260°	3
	4846.72	-21 4554	8.40	8.39:	2.9	58	3
	4847.68	-21 4554	8.34	8.33:	3.0	81	3
	4849.68	-21 4554	8.28	8.27:	3.2	126	3
	4850.68	-21 4554	8.33	8.32:	3.3	149	3
	4851.68	-21 4554	8.30	8.29:	3.4	171	3
	4854.62	-21 4554	8.34	8.33:	3.7	237	3
	4862.68	-21 4540	8.20	8.27	4.2	60	
	4863.67	-21 4539	8.23	8.31	4.3	83	
	4864.69	-21 4539	8.20	8.28	4.4	106	
	4867.62	-21 4539	8.28:	8.35:	4.5	172	1
	4875.61	-21 4540	8.21	8.28	5.0	352	
	4881.58	-21 4540	8.17	8.24	5.3	129	
	4884.57	-21 4540	8.21	8.28	5.4	197	
	4902.55	-21 4540	8.20	8.27	5.8	241	
	4903.56	-21 4540	8.25	8.32	5.8	264	
	4904.56	-21 4540	8.23	8.30	5.8	287	
	4905.56	-21 4540	8.22	8.29	5.8	309	
	4911.55	-21 4540	8.19	8.26	5.7	84	
1900	5147.73	-22 4722	8.76	8.30:	4.4	357	4
	5162.71	-22 4702	8.68	8.28:	3.2	337	2,5
	5175.71	-22 4655	8.58	8.29:	1.9	271	2
	5180.71	-22 4648	8.45	8.24:	1.5	24	2,4
	5191.69	-22 4613	8.36	8.11:	0.2	273	5
	5194.71	-22 4619	8.67	8.36:	0.1	341	5
	5201.75	-22 4597	8.36	8.26	0.8	139	
	5206.63	-22 4581	8.27	8.07:	1.3	253	2,5

continued

Table XXIV

(cont'd.)

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1900	5208.78	-22°4581	8.44	8.24:	1°.5	301°	2,5
	5214.70	-22 4555	8.35	8.16:	2.1	74	5
	5220.71	-22 4555	8.34::	8.16::	2.6	210	1,5
	5228.71	-22 4511	8.39	8.31:	3.3	31	5
	5231.66	-22 4511	8.28	8.20:	3.6	99	5
	5275.58	-22 4480	8.52:	8.42:	5.7	11	1
	5285.55	-22 4480	8.38	8.28	5.8	236	

$V_o = m_o + (V_{star} - m_{star}) + 0.30(B-V)_{star} - 0.39$

Remarks: reason for uncertainty; see text differing magnitude (see sec. H) with results suggesting that $\ell \approx -0.07$. The value $\ell = 0$ is assumed in the tables; if $\ell = -0.10$, then some individual Titan V_o magnitudes are in error by $\sim 0^m.1$. The observations followed by a colon (:) are uncertain for some of the following reasons:

1) large discrepancy between Wendell's two observations on one night ($>0^m.10$). Two extreme cases have double colon (::).
2) comparison star measured photoelectrically on only one night. The corresponding Titan observations are probably good in most cases.
3) the estimated m.e. of the V magnitude of star, as given in the Appendix, is $\geq 0^m.04$. In most cases the large scatter is observational, and further measurements of the star will fix the magnitude, but it is possible that some of these stars are variable. Observations tied to the very poorly determined star $-21°4594$ are marked with double colon (::).
4) the B-V of the star is >1.6. Such a red color makes it probable that the star is at least slightly variable.
5) the B-V of the star is $\lesssim 0.30$. These stars seem to deviate systematically from the linear relation in Fig. 15a, and the observations in which Titan was

compared with such stars (all made in 1900) are on the average $0^{m}.08$ brighter than other Titan observations in the same year.

These sources of uncertainty are identified by number in the Remarks column in Table XXIV.

Because of the southern declination of Wendell's stars the PE photometry had to be made at large airmass (usually >2), and it was necessary to tie the photometry to secondary standards near the program stars. These secondary standards are α^1Lib, 41 Lib, ψ Oph, ξ Oph, and 4 Sgr, for stars used in the five years 1896-1900, respectively. They all have published photometry. The adopted V magnitudes for these five stars are 5.16, 5.37, 4.49, 4.39, and 4.75, based on magnitudes in the literature and my own measures (see Appendix); it is unlikely that any of them is in error by $0^{m}.02$. These stars are of intermediate spectral classes and fairly similar to the average of Wendell's stars. 4 Sgr is an exception, in that it is much bluer than Titan or the Titan comparison stars. Since stars tied to 4 Sgr, used in 1900 by Wendell, were also often observed at particularly large airmass (both by him and by me), their magnitudes are somewhat more likely to be in error than the magnitudes of the 1896-99 stars.

Three error sources in the tying-in of Titan to the system of the comparison stars will now be considered. First, Titan shines by reflected light, which is therefore polarized. Since Wendell's photometer was of a polarizing type, this could seriously affect the photometry if the polarization is large. Fortunately, Zellner (1973) has shown that Titan's polarization is small, less than 0.5% in the visual at all phase angles, and therefore does not affect the photometry noticeably. Next, differential extinction between Titan and the comparison star is a source of error for individual observations, even though it will largely be cancelled out in taking the average of many observations. The airmass difference was calculated for numerous of Wendell's observations and was always found to be less than 0.15. With an extinction coefficient of $0^m.2$/airmass this would at most introduce an error in Titan's magnitude of 0.03. Since the random errors in Wendell's photometry are, on the average, about twice this, it is hardly worth the effort to correct the individual observations for differential extinction; it has not been done in Table XXIV. Finally, the spectral energy distribution of Titan is not the same as that of a star of the same B-V color; therefore, even if $V-m_v$ is a well-behaved function of B-V for normal stars, it is not necessarily true that Titan conforms to it. This possibility was investigated by studying magnitude corrections ($V-m_v$) obtained by numerical integration of the spectral energy distributions for representative stars and Titan, weighted by the appropriate filter passbands or sensitivity functions. The spectral distributions were taken from Willstrop (1965), with values shortward of 4000 Å adapted from Straižys and Sviderskiene (1972); the response functions for B, V, and the darkadapted human eye were taken from Allen (1963). (The

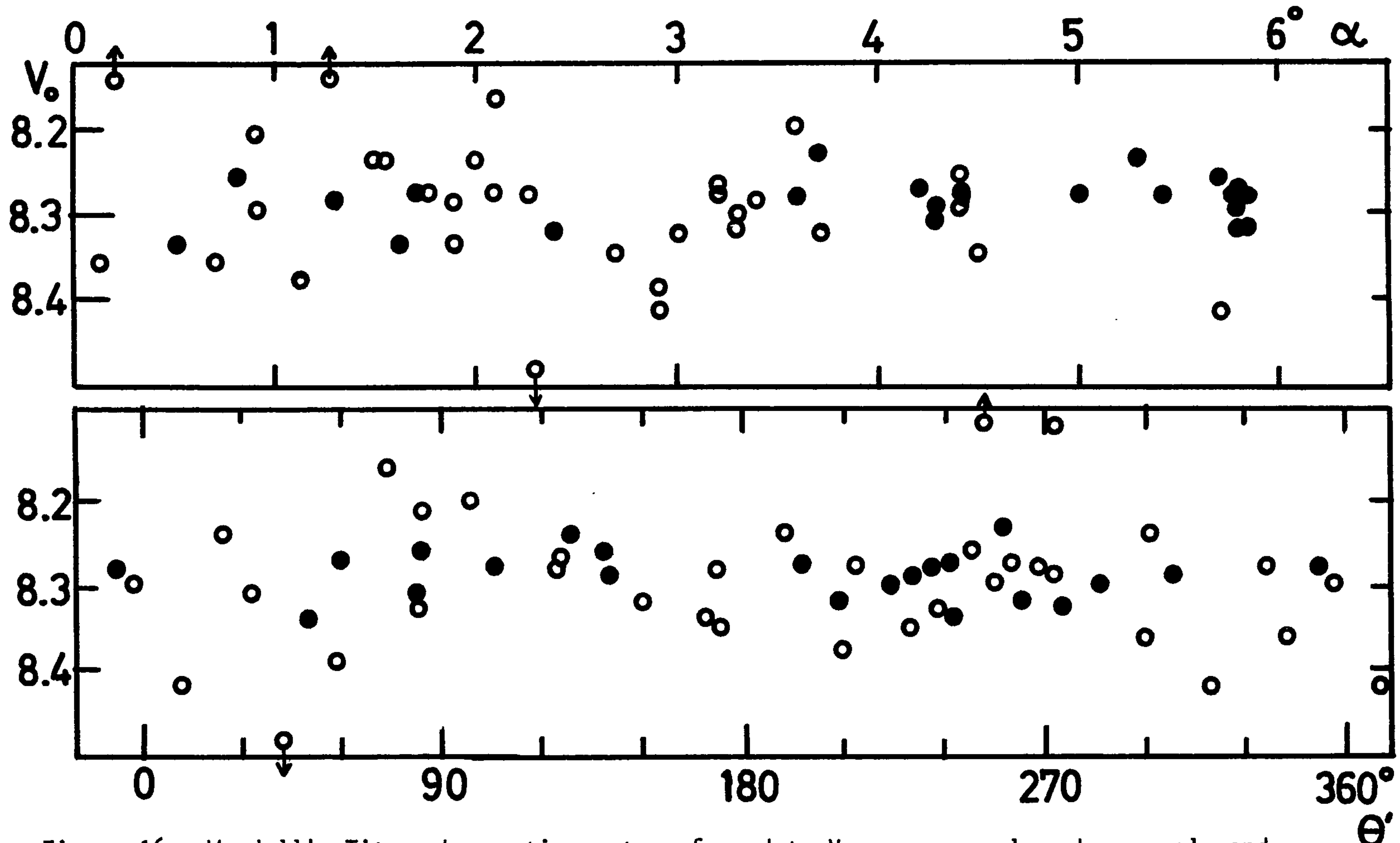


Figure 16. Wendell's Titan observations, transformed to V_o, versus solar phase angle and versus rotational phase. Open symbols indicate those observations followed by a colon (:) in Table XXIV; data with double colon (::) are not plotted.

darkadapted human eye was chosen instead of the usual lightadapted eye sensitivity function, because the value of k in eq. (1) suggested that the effective wavelength of Wendell's visual magnitudes was about 5100Å, nearly that of the darkadapted eye.) Titan's spectral distribution was taken as the product of its geometrical albedo as determined by Younkin (1974) and McCord et al. (1971) and the spectral distribution of a solar-type star (ζ^1 Ret) in Willstrop's catalog. Atmospheric extinction (λ^{-4} law) was allowed for. It was found that $V-m_v$ is a linear function of B-V, with a dispersion of about $0\overset{m}{.}01$. Titan departs only $0\overset{m}{.}01$ from the linear relation, in the sense that its $V-m_v$ is smaller than for stars of the same B-V. Since the correction is only marginally significant, it has not been applied to Wendell's data.

The annual mean magnitudes of Titan, as derived from Wendell's photometry, are given in Table XXV. It appears that the satellite was practically constant in light in 1896-1900, at $V_o = 8.29$. As previously mentioned a magnitude dependent correction may be necessary (i.e., the coefficient ℓ in eq. (1) may be non-zero). If $\ell \approx -0.05$, the mean V_o in 1898 becomes $0\overset{m}{.}04$ brighter, while the changes for the other years are small. The mean for 1896-1900 becomes $V_o = 8.28$. Wendell's observations are plotted versus rotational and solar phase angle in Fig. 16. It is clear that no persistent rotational variation of amplitude $\gtrsim 0\overset{m}{.}05$ was present; no significant variation with α is recognizable.

Table XXV

Wendell's Titan photometry: summary

Year	All observations (except ::)					Good observations (i.e., excl. :: and :)				
	n	mean V_o	$\pm\ \sigma$	$\langle \Delta m \rangle$	$\langle (B-V)_* \rangle$	n	mean V_o	$\pm\ \sigma$	$\langle \Delta m \rangle$	$\langle (B-V)_* \rangle$
1896	4	8.30	± .06	+0.27	0.96	3	8.29	± .05	+0.28	1.17
1897	3	8.34	.07	+ .07	0.65	2	8.30	.02	- .26	0.47
1898	6	8.32	.11	+ .83	1.05	3	8.31	.03	+ .71	0.75
1899	27	8.30	.04	+ .59	1.07	11	8.28	.03	+ .20	0.63
1900	14	8.25	.09	- .09	0.73	2	8.27	.01	- .24	1.24
All	58	8.29		+0.36	0.95	21	8.29		+0.20	0.77

n number of nights

$\langle (B-V)_* \rangle$ mean comparison star B-V

$\langle \Delta m \rangle$ mean magnitude difference, $m_{star} - m_{Titan}$

: and :: refer to observations so marked in Table XXIV

Other pre-photoelectric photometry of Titan include the observations by Guthnick (1914) in 1905-08 and Graff (1924, 1939) in 1921-22. I have measured the comparison stars used by Graff in 1922; they are discussed in detail in connection with Iapetus (sec. H of this chapter). All but one of the stars are bluer than Titan, and the color equation of Graff's magnitude system is poorly determined, so Titan's V_o magnitude is also poorly determined, even though its magnitude in Graff's visual system has a formal mean error of the mean of only $0^m.013$. The equation used to reduce the Iapetus magnitudes is

$$V - m_v = 0.12\ (m_v - 8.95) \tag{2}$$

Three of Graff's stars have B-V colors >1.0 and V magnitudes within $2^m.0$ of that of Titan. Applying (2) to them yields V values that are fainter than the photoelectrically measured V's by $0^m.01$, $0^m.11$, and $0^m.02$, respectively. Since Titan's B-V is almost equal to the mean B-V for the three stars, the satellite's $V - m_v$ will be derived from (2) with an adjustment equal to the mean error for the three Titan-colored stars, which is $-0^m.05$ (in the sense V(observed) minus V(calculated)). The result is $V - m_v = -0.11$; the resulting V_o for Titan is 8.21. Account has been taken of the facts that eq.(2) requires the actual observed m_v (i.e., not reduced to mean opposition), and that Graff adopted a slightly different semimajor axis for Saturn (a = 9.554 AU) than that used in this work. The error in the calculated V_o is difficult to estimate with confidence, but since the dispersion in the $V - m_v$ for the three red stars is about

$0\overset{m}{.}05$, this figure is adopted also for Titan. Better photometry of Graff's comparison stars may improve the situation somewhat.

Graff (1924) **also** made photometry of Saturn satellites in 1921. I have not measured the stars he used for comparison in 1921, but plan to do so. However, he used the same telescope and very probably the same photometer as in the following year, so the same reduction formula may be appropriate for both years. If so, one finds $V_o = 8.05$. This is so much brighter than the V_o derived for any other observing period that it must be viewed with great suspicion.

The photometry of Guthnick (1914) has not been studied in detail, but PE photometry of the comparison stars is contemplated.

Widorn (1950) observed other Saturn satellites, including Titan, in the course of his Iapetus photometry in 1949. In fact, he used their mean magnitude as an additional comparison star, arguing that their small variations would largely cancel out in taking the average. His adopted m_{v_o} for Titan is 8.40. As detailed further in the Iapetus section, there are no significant color or magnitude terms in $V - m_v$ for his comparison stars, but the scatter is large. $V_o = 8.40$ would be consistent with Harris' PE photometry two years later, but in view of the uncertainties in Widorn's magnitude scale Titan's V_o in 1949 cannot be considered well enough known to be useful in a study of Titan's long-term variability.

Since 1950, several workers have made PE observations of Titan.

Harris (1961) made UBV observations of Titan on 19 nights in 1951 to 1956 (his Fig. 10, which plots V_o versus Θ, contains only 17 points). As with his other satellite observations, the circumstances of the individual observations are not available. Since he did not observe any other satellite in 1954 or 1955, it is probable that the Titan observations were made in 1951, 1952, 1953, and 1956. From his V_o versus Θ plot it appears that he found the satellite to be at V_o = 8.36 on two occasions, 8.42 once, 8.43 also once, and at intermediate values on the remaining nights. Therefore, Titan's V_o was within $0^m.04$ of 8.39 for each of Harris' years of observation (presuming that no appreciable variation took place during any one season).

PE photometry of Titan has been made at all Saturn apparitions since 1967, and in several cases more than one observing team covered the satellite during one apparition. Therefore a fairly complete and reliable light curve from late 1967 to early 1974 can be constructed. The observations in 1967-74, as well as the earlier series just discussed, are summarized in Tables XXVI and XXVII. In the first table are given references, observing periods, the type of photometry, etc.; in the next table the mean magnitudes for each series and apparition (several times per apparition in the case of the major PE series) are listed chronologically, reduced to V of the UBV system and reduced to zero solar phase angle using a phase coefficient of $0^m.004$/deg. As usual the standard distances from Sun and Earth are a = 9.54 AU and Δ = 8.54 AU.

Table XXVI

Available Titan photometry.

References	Years of observation	Total number of nights	Type of photometry	Remarks
Pickering 1879	1877-78	18	visual	a
Wendell 1913	1896-1900	64	visual	1
Guthnick 1910, 1914	1905-08	92	visual	a
Graff 1924	1921	20	visual	a
Graff 1939	1922	38	visual	2
Widorn 1950	1949	36?	visual	a
Harris 1961	1951-56	19?	UBV	3,b
Franklin, priv. comm.	1967	3	BV	4
Payne 1971a	1968-69	18	visual	5
Blanco and Catalano, 1971 & priv. comm.	1968-70	21	UBV	6
Veverka 1970 & priv. comm.	1968-69	14	UBV	7
McCord et al. 1971	1968-69	?	narrowband 0.3 - 1.1μ	a
Andersson, this thesis	1970-72	43	UBV	9
Jerzykiewicz 1973; Lockwood, priv. comm.	1971-74	31	b y	9
Blair and Owen 1974	1971-72	9	UBV	a
Younkin 1974	1972	1	narrowband 0.50 - 1.08μ	a
Noland et al. 1974	1972-73	30	u v b y r i	10
Franklin and Cook 1974	1972-74	24	BV	11

Remarks: a not used in Table XXVII because of low accuracy and/or absence of satisfactory transformation to V.

b exact years unknown but including 1951 and 1956 and probably 1952 and 1953.

Numbers are used in Table XXVII as reference numbers.

Table XXVII

V_o magnitude of Titan, 1896-1974.

Ref.no.	Mean date	Nominal mag. ± σ	mean	n	<α>	Corr.	$V_o(\alpha=0)$	
1	1896.4	8.29 ±	0.05	3	1°8	0.	8.28 ±	0.05
1	1897.5	8.30	.02	2	4.7	0.	8.28	.03
1	1898.5	8.31	.03	3	2.5	0.	8.30	.04
1	1899.6	8.28	.03	11	5.5	0.	8.26	.03
1	1900.6	8.27	.01	2	3.3	0.	8.26	.03
2	1922.2	8.32	.11	34	3.5	-0.11	8.20	.05
3	1951 1952? 1953? 1956	8.39	.02	17	2.5[a]	0.	8.38	.02
4	1967.92	8.373	.016	3	5.4	0.	8.35	.02
5	1968.9	8.42	.09	18	3.6	-0.02	8.39	.10
6	1968.84	8.380	.010	7	3.1	0.	8.37	.02
7	1968.9	8.378	.008	6	4.4	0.	8.36	.02
6	1969.72	8.383	.015	6	4.1	-0.07	8.30	.02
6	1969.87	8.367	.015	3	1.8	-0.07	8.29	.02
6	1970.10	8.390	.021	5	6.0	-0.07	8.30	.02
8	1970.74	8.300	.017	7	4.7	+0.02	8.30	.02
8	1970.88	8.273	.010	8	1.5	+0.02	8.29	.02
8	1971.74	8.288	.025	8	4.7	+0.02	8.29	.02
8	1971.87	8.283	.021	6	1.9	+0.02	8.30	.02
9	1972.04	8.300	.007	7	5.0	+0.015	8.30	.02
8	1972.04	8.293	.010	7	5.1	+0.02	8.29	.02
8	1972.17	8.291	.015	7	6.1	+0.02	8.29	.02
10	1972.76	3.955	.021	19	5.8	+4.36	8.29	.02
9	1972.92	8.279	.015	8	2.1	+0.015	8.29	.02
10	1972.93	3.933	.011	11	1.6	+4.36	8.29	.02

continued

Table XXVII

(cont'd.)

Ref.no.	Mean date	Nominal mean mag. ± σ		n	<α>	Corr.	$V_o(\alpha=0)$	
11	1972.94	8.333 ±	0.020	7	0°.5	-0.03	8.30 ±	0.02
9	1973.08	8.288	.010	4	5.0	+0.015	8.28	.02
11	1973.13	8.335	.016	4	6.0	-0.03	8.28	.02
11	1973.81	8.302	.004	6	5.8	-0.03	8.25	.02
9	1973.82	8.255	.010	4	5.6	+0.015	8.25	.02
9	1973.95	8.262	.006	4	1.1	+0.015	8.27	.02
11	1974.04	8.286	.022	7	3.3	-0.03	8.24	.02
9	1974.08	8.262	.077	4	4.2	+0.015	8.26	.02

[a]assumed phase angle (none published).

Ref. no.: number in Remarks column of Table XXVI.

Nominal mean mag.: refers to the type of visual magnitude employed in original publication (m_V, y, V), except for Wendell's observations (Ref. no. 1) which are my reductions to V (Tables XXIV and XXV).

n: number of observations in mean. In some cases not all observations of the original publication are included (e.g., only Wendell's "good" observations (cf. Table XXV) are used).

<α>: mean solar phase angle.

Corr.: correction to refer observations to V system; see text for details.

$V_o(\alpha=0)$: mean opposition magnitude, assuming a linear phase function with $\beta = 0^m.004$/deg (even where a different phase function is derived in the original publication). The error quoted is the estimated mean external error with respect to the UBV system. The relative error of any two items after 1970.5 is about $0^m.01$.

Addendum: Blanco and Catalano (1974) report recent observations which lead to $V_o(\alpha=0) = 8.24$ at 1974.23.

The only non-PE Titan photometry since 1967 is the visual photometry by Payne (1971a). The internal accuracy is rather good, but the magnitudes are tied to a single star which is $0^{m}.5$ bluer in B-V than Titan; since no determination of the color dependence of m_v - V is available, an uncertainty of $0^{m}.10$ has been assigned to V_o from Payne's photometry, corresponding to a correction for color of 0.2(B-V). Photometry of the star (+7°258) is given in the Appendix; the V magnitude measured is $0^{m}.02$ brighter than the value adopted by Payne.

No corrections were applied to Franklin's (priv. comm. 1974) and Veverka's (1970; priv. comm. 1974) observations in 1967-69. As mentioned in connection with the inner Saturn satellites, the narrowband photometry of McCord et al. (1971) apparently requires a correction of about $+0^{m}.2$ for V_o, but since no accurate value is available, and since dates and other circumstances are not given, these observations are not used in Table XXVII.

The comparison stars used by Blanco and Catalano (1971) in their 1968 and 1969/70 photometry of Rhea and Titan were measured on two nights in 1972 Dec at Kitt Peak; results are given in the Appendix. The 1968 comparison stars are definitely bluer in U-B than the values given by Blanco and Catalano, and the V magnitudes of the 1969/70 stars are probably brighter than quoted in their paper. A re-examination of the observations (Blanco and Catalano, priv. comm. 1974) revealed some reduction errors; accordingly, I apply a correction of $-0^{m}.07$ to their published Titan magnitudes in

1969/70, while no correction is applied to their 1968 magnitudes. An independent check on the magnitudes and colors of the comparison stars of Blanco and Catalano is desirable.

Titan has been observed at Lowell Observatory since early 1972 as part of the Solar Variability Program (M. Jerzykiewicz 1973, priv. comm. 1974; G. W. Lockwood, priv. comm. 1974). The photometry is made in b and y of the Strömgren uvby system; since there are widely adopted standards only for colors, not magnitudes, in this system, the y magnitude scale is defined by a list of standard star magnitudes determined by the Lowell observers. There are three observing nights in 1972 Jan in common between my own Titan photometry and the Lowell observations. The magnitude differences (V_o-y_o) are -$0^m.004$, -0.001, and -0.010, respectively (although the third decimal is insignificant, since my magnitudes are only accurate to about $0^m.01$). A correction of -$0^m.005$ has been adopted here for converting Lowell y_o magnitudes to my V_o. Exceptional care is taken in the Lowell program to ensure the constancy of the photometric system used over several years, so the same correction applies to subsequent seasons of Lowell observations.

Blair and Owen (1974), in their photometry of the inner Saturn satellites, used Titan and two stars as comparison objects. They report their observations on the instrumental system, which is close to the UBV system. They adopted magnitudes and colors for their two stars from the Photoelectric Catalogue (Blanco et al. 1968) which gives one V value for one star and two for the other. While Blair and Owen have some nights in common with my photometry, they do not give nightly magnitudes for Titan. Their adopted V_o is 8.35, appreciably fainter than 8.29, my mean for the 1971/72 apparition. It seems proper to await confirmatory photometry of their standard stars and the accurate transformation of their photometry to the standard system before including their Titan magnitude here.

The Hawaii-Cornell photometry of Saturn satellites (Noland et al. 1974) utilizes the uvby system (plus two red filters). The magnitudes are referred to the star 37 Tau. Three nights in common with the Lowell photometry gives $(y_{o,Lowell} - y_{o,H-C}) = 4.340$, 4.350, and 4.351, respectively (again, the third decimal place is insignificant since only the Lowell data carries three decimals). The correction to obtain V_o on my system becomes 4.34, to be applied to the y_o referred to 37 Tau. Noland et al. also derive a transformation to the V system, and find for Titan $V_o = 8.34$. This is about $0\overset{m}{.}04$ fainter than implied by the correction above, but the V magnitudes for their standard stars are on the average $0\overset{m}{.}02$ fainter than representative V values for the same stars from the literature. Noland et al. estimate the uncertainty of their transformation to V at $0\overset{m}{.}02$.

The UBV photometry of Iapetus and Titan by Franklin and Cook (1974) has five nights of Titan observation in common with the Lowell photometry; the difference $(y_{o,\ Lowell} - V_{o,F\&C})$ is $-0\overset{m}{.}041 \pm .014\ (\sigma)$. The correction to obtain V_o on the system of my 1971/72 photometry becomes $-0^{m}.05$, a disturbingly large amount. A check is provided by Franklin and Cook's observations of Iapetus in 1972 Jan, with several dates in common with or adjoining my dates; a correction of $-0^{m}.03 \pm .01$ is suggested. A third check can be made by comparing Franklin and Cook with the Hawaii-Cornell photometry. Two points of comparison give, for the difference $(y_{o,H-C} - V_{o,F\&C})$, $-4^{m}.405$, and $-4^{m}.385$. This is consistent with a correction $+4^{m}.34$ for the Hawaii observations and $-0^{m}.05$ for those of Franklin and Cook. The latter figure is adopted for transforming Franklin and Cook's V_o to my system.

While the magnitude systems of Titan observations since 1970 are quite well tied in with each other, thanks to the numerous cases of observing dates in common, the reliability of the zero point of the chosen reference system (my 1971/72 observations) must be considered further. It purports to be that of the V magnitude of the UBV system, yet the photometry of Franklin and Cook, which is supposedly on the same system, requires a correction of $-0^{m}.05$, a figure probably not in error by more than $0^{m}.015$. The most obvious source of the discrepancy would be the tie in of my own standard stars to the UBV system. My standard stars for the Saturn satellite photometry were discussed in sec. D of this chapter; the principal anchor point is the star +17°703 (van Bueren 23). While I am confident that it is at least as bright as the V = 7.54 given by Johnson and Knuckles (1955) the difference need not be as much as the $0^{m}.025$ implied by my adopted magnitude for the star.

As a compromise it will be assumed, for the purposes of Tables XXVI and XXVII, that my magnitude of the star is $0^{m}.02$ too bright. Thus the revised correction for the photometry of Franklin and Cook becomes $-0^{m}.03$, and the other Titan observations in 1970-1973 take corrections that are $0^{m}.02$ greater (algebraically) than the corrections relative to my 1971/72 photometry that have been derived in the previous pages. The mean external error of the 1970-74 Titan magnitude system may be estimated at $0^{m}.015$; the tie-in between any two of the series of observations has an accuracy of about $0^{m}.01$. This last figure is also a reasonable estimate of the tie-in between the consecutive seasons of Franklin and Cook's photometry, as well as between my 1970 and 1971/72 seasons. The mean error (external) of the previous series of PE photometry has been set (somewhat arbitrarily) at $0^{m}.02$.

In Table XXVIII the data of the previous table are collected by apparition of Saturn, thus giving approximately annual mean V_o values. From Harris' data only the opposition times of the two years in which he definitely observed Titan are given. Data pertaining to the position of Saturn in its orbit and the orientation of the ring plane are also given. Lightcurves for Titan are shown in Fig. 17. It appears that Titan has brightened by $0^{m}.1$ since 1967 at an irregular rate. It probably rose by $\sim 0^{m}.05$ in 1969, but because of the uncertainty about the magnitude zero point for the 1969/70 apparition, when only one observing team made photometry of Titan, it is possible that much of the change took place in 1970.

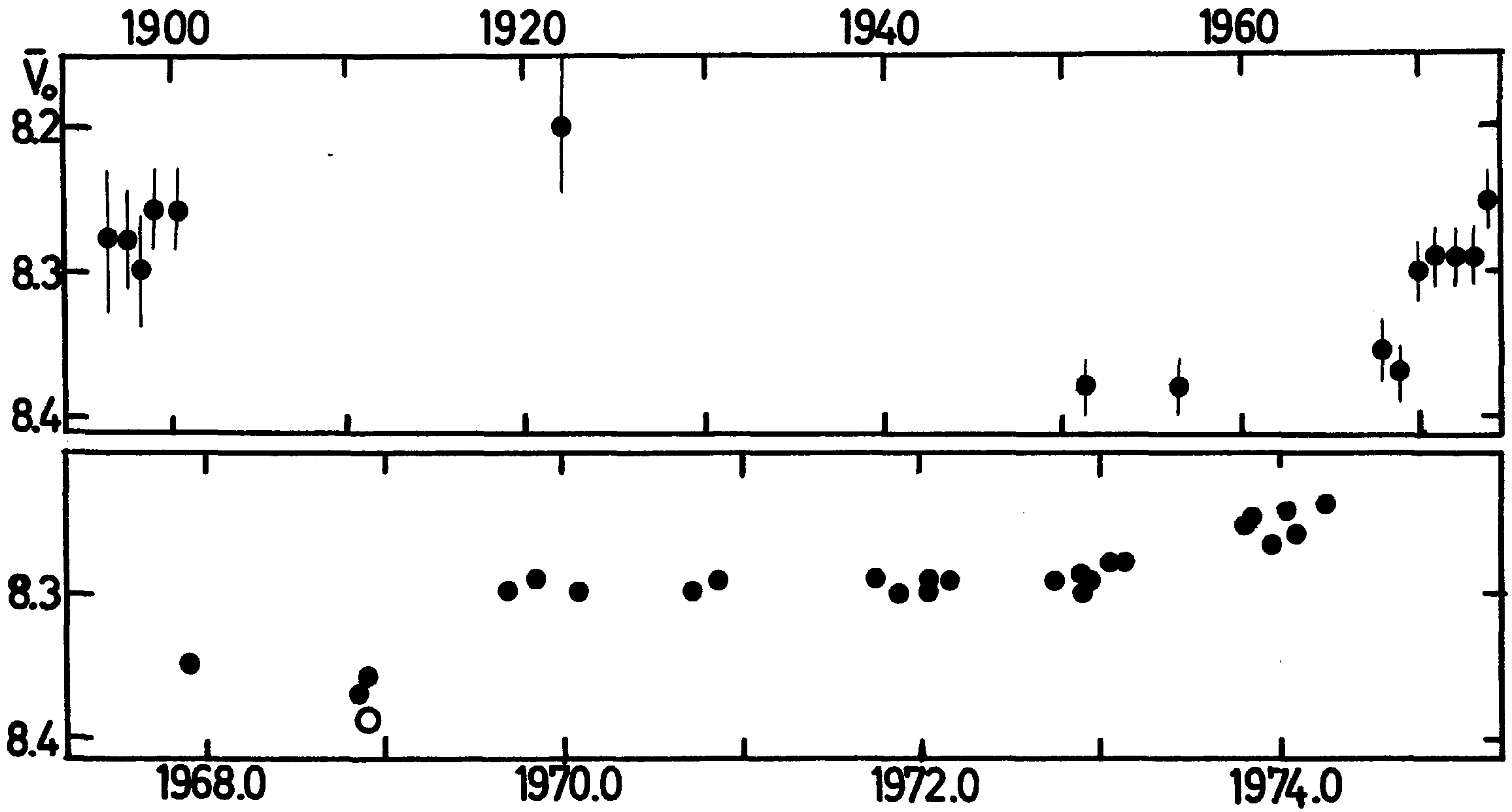


Figure 17. Magnitude of Titan, 1896-1974. The top figure is plotted from Table XXVIII. The bottom figure is plotted from Table XXVII; filled symbols have uncertainties of $0^m.02$, and the open symbol is $0^m.10$. The data from Blanco and Catalano (1974) is included.

Table XXVIII

Magnitude of Titan, by apparition

Mean date	$V_o(\alpha=0)$	Years after perihelion	r AU	B'
1896.4	8.28	10.8	9.90	+21°
1897.5	8.28	11.9	9.98	+24
1898.5	8.30	12.9	10.02	+26
1899.6	8.26	14.0	10.05	+27
1900.6	8.26	15.0	10.06	+26
1922.2	8.20	7.1	9.54	+ 5
1951.2	8.38	6.7	9.48	+ 3
1956.4	8.38	11.9	9.97	+24
1967.9	8.35	23.4	9.43	- 8
1968.9	8.37	24.4	9.32	-13
1969.9	8.30	25.4	9.22	-18
1970.8	8.29	26.3	9.15	-21
1972.0	8.29	27.5	9.07	-25
1973.0	8.29	28.5	9.03	-26
1973.9	8.25	29.4	9.02	-26

r distance from Sun

B' Saturnicentric latitude of Sun, referred to ring plane

Between late 1970 and early 1973 there was no perceptible change; but during 1973 the satellite brightened again, by $0^{m}.04$. This change is shown by both series of observations that included both the 1972/73 and 1973/74 apparitions. The time scale for measurable change, say $0^{m}.02$, thus seems to be around 0.5 yr. As pointed out earlier there is no indication of variations over time intervals comparable with Titan's orbital period, but it is possible that some of the small scatter (about $0^{m}.02$) during any one apparition is due to actual variations.

Considering the somewhat irregular character of the change in 1967-74, it is likely that Titan's variation is not periodic. However, the 1896-1974 light curve in Fig. 17 shows that if there is a periodicity, one possible period is about 75 yr. It is difficult to think of a physical mechanism consistent with such a long period.

It is evident from a comparison of the magnitudes in 1922 and 1951, and again in 1900 and 1956, that there is at least not a strict dependence on the position of Saturn in its orbit. Titan's V_o is plotted versus distance from the Sun and versus B' (Saturnicentric latitude of the Sun referred to the ring plane) in Fig. 18a. (Since B' reaches its minimum value very near Saturn's perihelion the two diagrams have been combined into one.) If the magnitudes in 1922 and 1956 are disregarded, the figure suggests that Titan is brightest when the Sun, and thus also the Earth, is well North or South of the ring plane. If this correlation is real it could

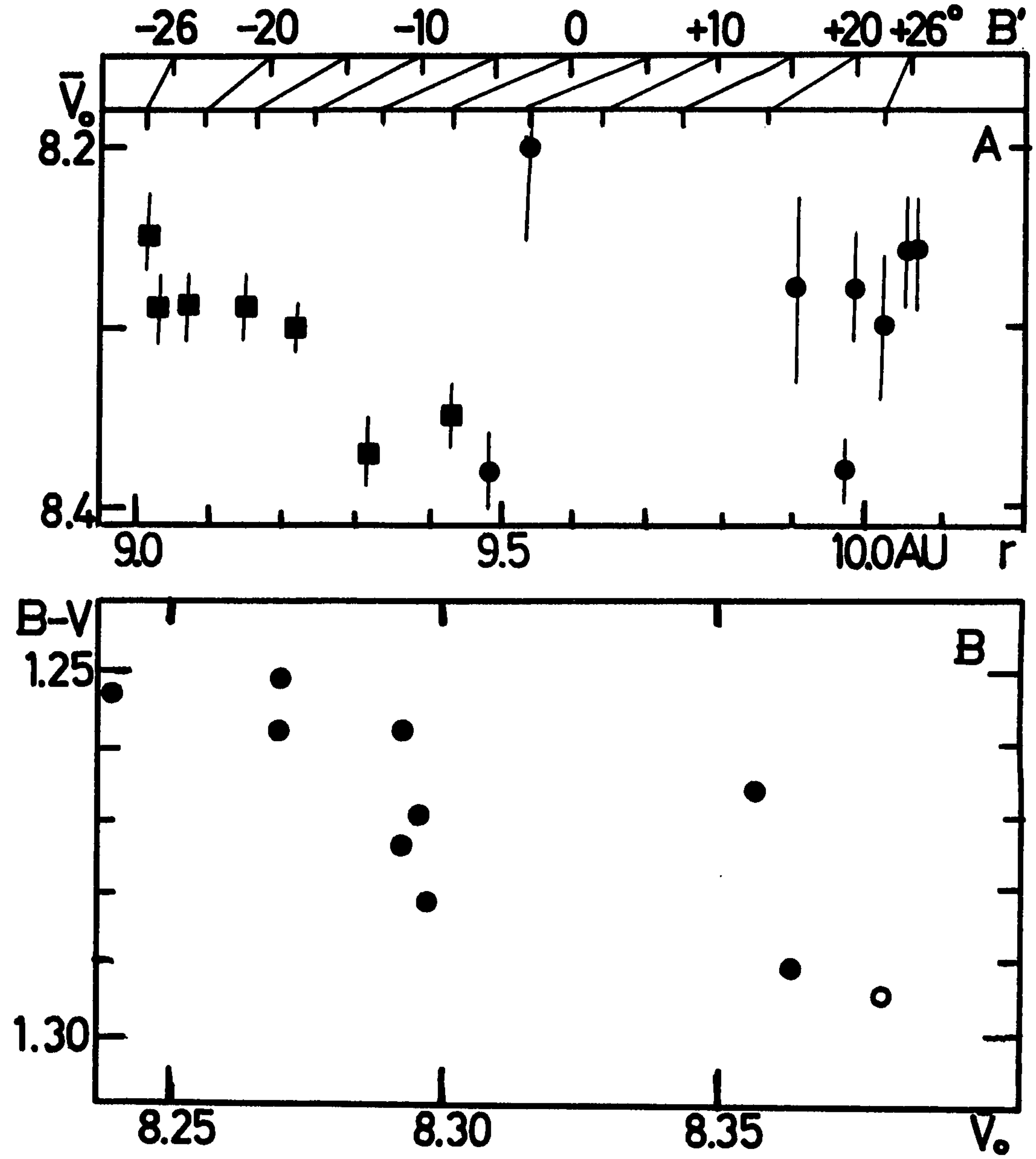


Figure 18A. Magnitude of Titan versus distance from the Sun (bottom scale) and Sun's saturnicentric latitude B' (top two scales). B' should be read on the upper B' scale for square symbols and on the lower B' scale for circles.

Figure 18B. B-V color versus magnitude for Titan. Sources for B-V: this thesis; Harris 1961; Franklin 1974 and priv. comm.; Blanco and Catalano 1971, 1974, and priv. comm.; Veverka 1970. B-V has been reduced to $\alpha=0$ using β_{B-V} = 0$^m_.$002/deg.

mean either that Titan has bright polar caps or that there is a seasonal variation of the satellite's albedo.

Clues about the nature of Titan's variations may be supplied by the variability (or absence thereof) of other properties of this body. Unfortunately, the records of Titan's behavior from the points of view of polarimetry, spectroscopy, spectrophotometry, and infrared photometry are even less complete than the V photometry. There is a suggestion of decreasing polarization in the visual region from 1968 to 1971 (Zellner 1973). B-V and U-B colors have been reported by Harris (1961), Blanco and Catalano (1971, revised in priv. comm. 1974), Veverka (1970), and Franklin and Cook (1974), in addition to my own observations. The differences between the colors reported are small and probably due to small errors or systematic effects in the transformation to the UBV system, although, taken at face value, B-V may become slightly redder with increasing V_o. This is shown in Fig. 18b.

G. Hyperion.

This rarely observed satellite was measured photoelectrically on 13 nights. The observations are listed in Table XXIX. Plotting the magnitudes versus rotational phase reveals no obvious variation due to synchronous rotation, but suggests that a few observations are affected by large errors. Fig. 19 shows V_o, B_o, and U_o plotted versus solar phase angle. With the exception of data from two nights (1970 Dec 24 and 1971 Nov 10) the figure suggests a linear

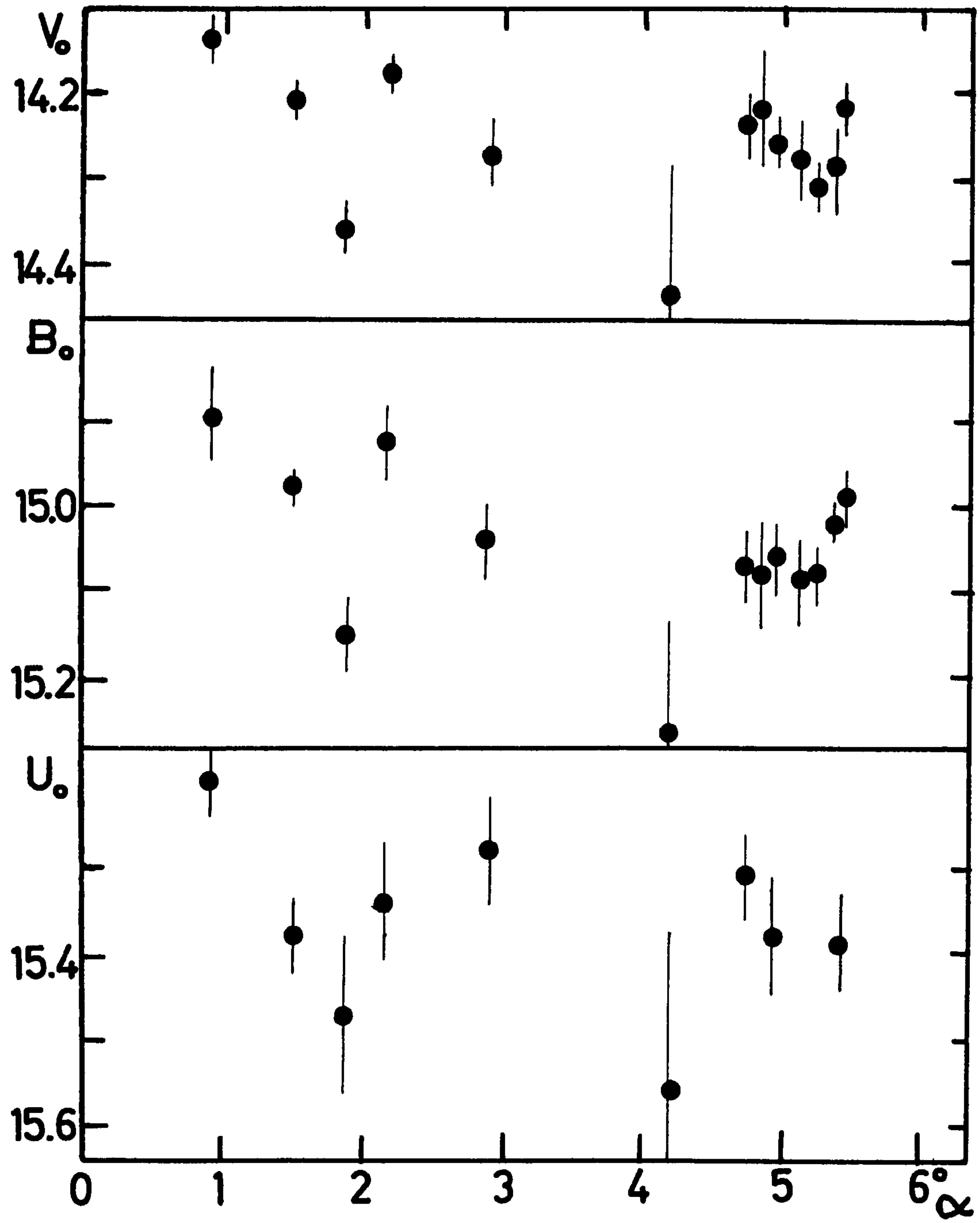


Figure 19. Magnitudes of Hyperion versus solar phase angle. No correction for rotational variation applied.

phase function with slope $0^m.02$/deg in V and slightly more in B. The slope in U is not well determined but seems to be of the same order as β_V and β_B. The first of the two discrepant nights is simply afflicted with very large random errors. No obvious reason for Hyperion's faintness on 1971 Nov 10 can be offered; the colors seem to be unaffected. In Fig. 20 the magnitudes, reduced to $\alpha = 0$ with $\beta = 0^m.025$/deg, are plotted versus rotational phase. It should be pointed out that the mean orbital longitude L for Hyperion in the **AE** includes periodic terms (librations) which have been removed in the calculation of the rotational phase. Thus Θ' in Table XXIX refers to an assumed uniform synchronous rotation of the satellite.

Fig. 20 is consistent with the satellite's brightness being constant (disregarding the abovementioned discrepant observations); if the 1973 Jan 3 V and B observations are slightly too faint there is perhaps a suggestion of a variation with amplitude about $0^m.1$ and minimum near superior conjunction. Because of the lack of observations in the half of the orbit centered at inferior conjunction, a variety of small-amplitude synchronous light curves remain possible.

Hyperion has a substantial orbital eccentricity (0.10) and its motion is very heavily influenced by Titan. The present data do not exclude the interesting possibility of non-synchronous and resonant spin for Hyperion. Assembling the observations on various submultiples of the orbital period yield the same result as the

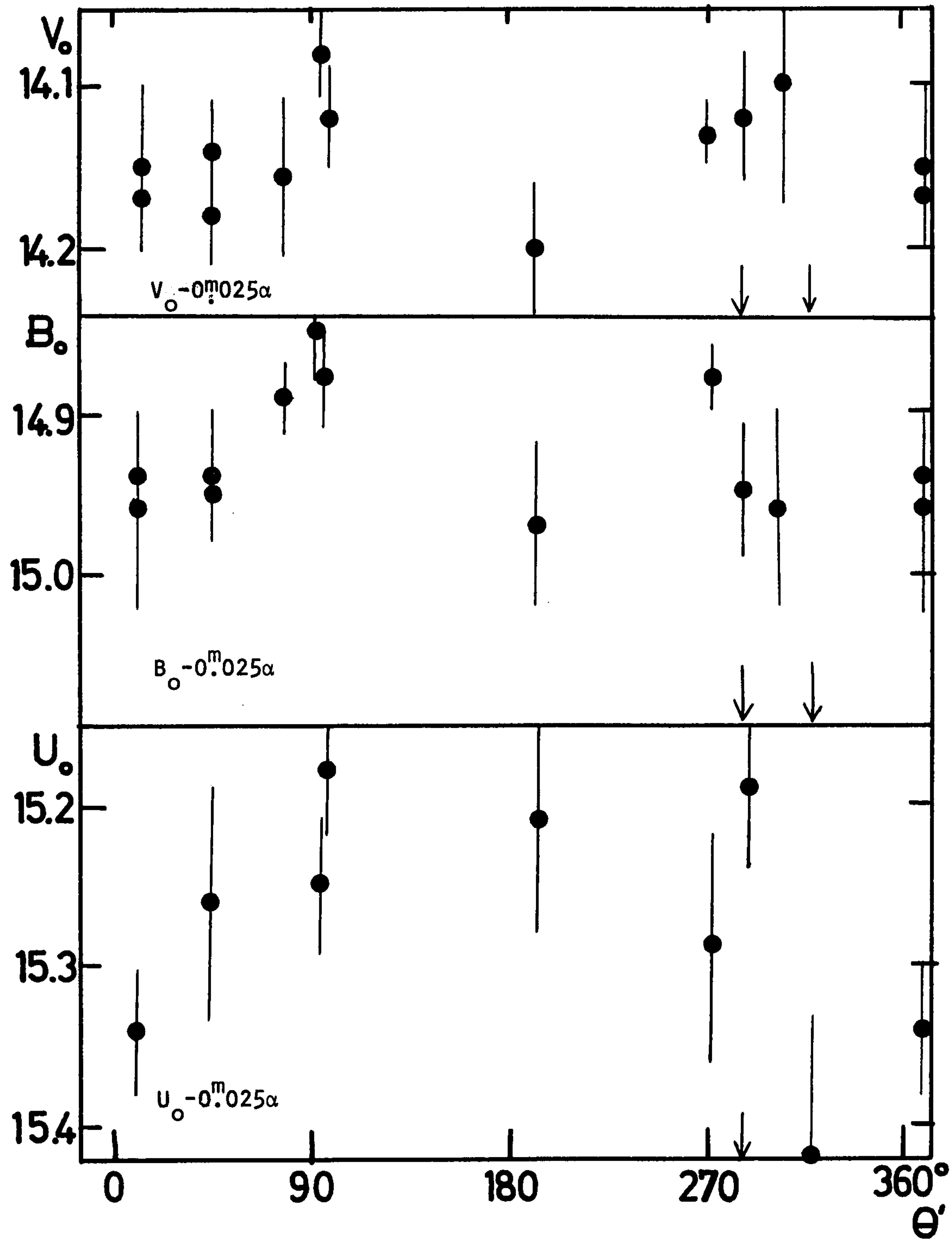


Figure 20. Magnitudes of Hyperion versus rotational phase (assuming uniform synchronous rotation).

Table XXIX

New Hyperion photometry.

UT date			V_o	B_o	U_o	est.m.e. V	B	U	α	Θ'	Method
1970	Dec	24.12	14.44	15.27	15.56	16	13	18	4°42	286°	ss
	Dec	31.11	14.26	15.06	15.38	3	4	7	4.94	44	ss
1971	Nov	7.51	14.18	14.93	15.34	2	4	7	2.15	272	ss
	Nov	10.22	14.36	15.15	15.47	3	4	9	1.86	318	ss
	Nov	13.28	14.21	14.98	15.38	2	2	4	1.51	10	ss
	Nov	18.41	14.14	14.90	15.20	3	5	4	0.92	98	ss
1972	Jan	11.27	14.24	15.07	15.31	4	4	5	4.77	287	ss
	Jan	12.24	14.22	15.08	-	7	6	-	4.85	304	ss
	Jan	16.21	14.28	15.09	-	5	5	-	5.12	11	ms,cd
	Jan	18.15	14.31	15.08	-	3	3	-	5.25	44	ss
	Jan	20.13	14.29	15.02	-	5	2	-	5.37	78	ss,cd
	Jan	21.08	14.22	14.99	15.39	3	3	4	5.41	94	ss
1973	Jan	3.27	14.27	15.04	15.28	4	5	6	2.89	192	ss

The rotational phase Θ' refers to synchronous rotation.

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU.

synchronous period: small variations, if any, and the same data points as before remain discrepant. Photometry of rather high precision will be necessary to establish the rotational state of Hyperion.

If synchronous rotation is accepted, phase coefficients can be derived without assumption of a negligible rotational variation by utilizing the pairs of observations that can be found in the table at practically the same Θ' but substantially different α. The pairs suited for this are at Θ' = 10, 11; 94, 98; and 272, 287°. Of these, only the last one is usable for β_U. The resulting phase coefficients are $\beta_V = 0\overset{m}{.}02$/deg, $\beta_B = 0\overset{m}{.}03$/deg, $\beta_U = 0\overset{m}{.}04$/deg. The formal error (from the m.e. of the individual observations in the table) is about $0\overset{m}{.}01$/deg for all three, so the increase of β from V to U is probably real. Using these values the mean opposition magnitudes are, $\overline{V}_o$ = 14.16, $\overline{B}_o$ = 14.90, and $\overline{U}_o$ = 15.19. The mean colors of the observations in Table XXIX (including 1971 Nov 10 but excluding the first entry in the table) are B-V = 0.78 and U-B = 0.33, or, reducing to α = 0, 0.74 and 0.30.

Harris observed Hyperion five times in 1953. His results are V_o = 14.16, B-V = 0.69, U-B = 0.42:. The discrepancy with my photometry is rather conspicuous, at least in the colors. The phase angles of Harris' observations are unknown, but their average would seem unlikely to be less than, say, 2°. If so, Harris found Hyperion at least $0\overset{m}{.}1$ brighter in B than I do. In 1953 the Earth was ~13° north of the plane of Saturn's rings while in 1970-73 it was 21° to 26° south of the ring plane. It is therefore possible that Hyperion's northern hemisphere has a somewhat higher albedo and bluer B-V color than the southern hemisphere; however, there is also the possibility that Harris' observations were all made very close to opposition, and that Hyperion has a strong opposition effect. Franklin and Cook (1974) recently reported two observations of Hyperion, made in 1972 Dec at very small phase angle (0°.3) and near eastern elongation. They found V_o = 13.9 which is ~0^m.25 brighter than my $\overline{V}_o$, suggesting an extremely strong opposition effect. Clearly, more observations are needed.

H. Iapetus.

This satellite was observed on 41 nights; more than three complete revolutions around Saturn are covered, including four minima. The observations are listed in Table XXX. The familiar light variation with an amplitude of about two magnitudes is clearly shown in Fig. 21. The phenomenon of unequal minima is conspicuous; it was ascribed by Millis (1973) to different phase coefficients on the bright and dark sides of the satellite. (That the large amplitude light variation is, in fact, due to albedo differences over the surface rather than an elongated shape of the satellite, as has sometimes been suggested (Dollfus 1970), was definitely established by Murphy et al. (1972) from 20μ radiometry and by Zellner (1972) from polarimetry.) By fortunate coincidence the photometry by Millis not only overlaps my photometry in time

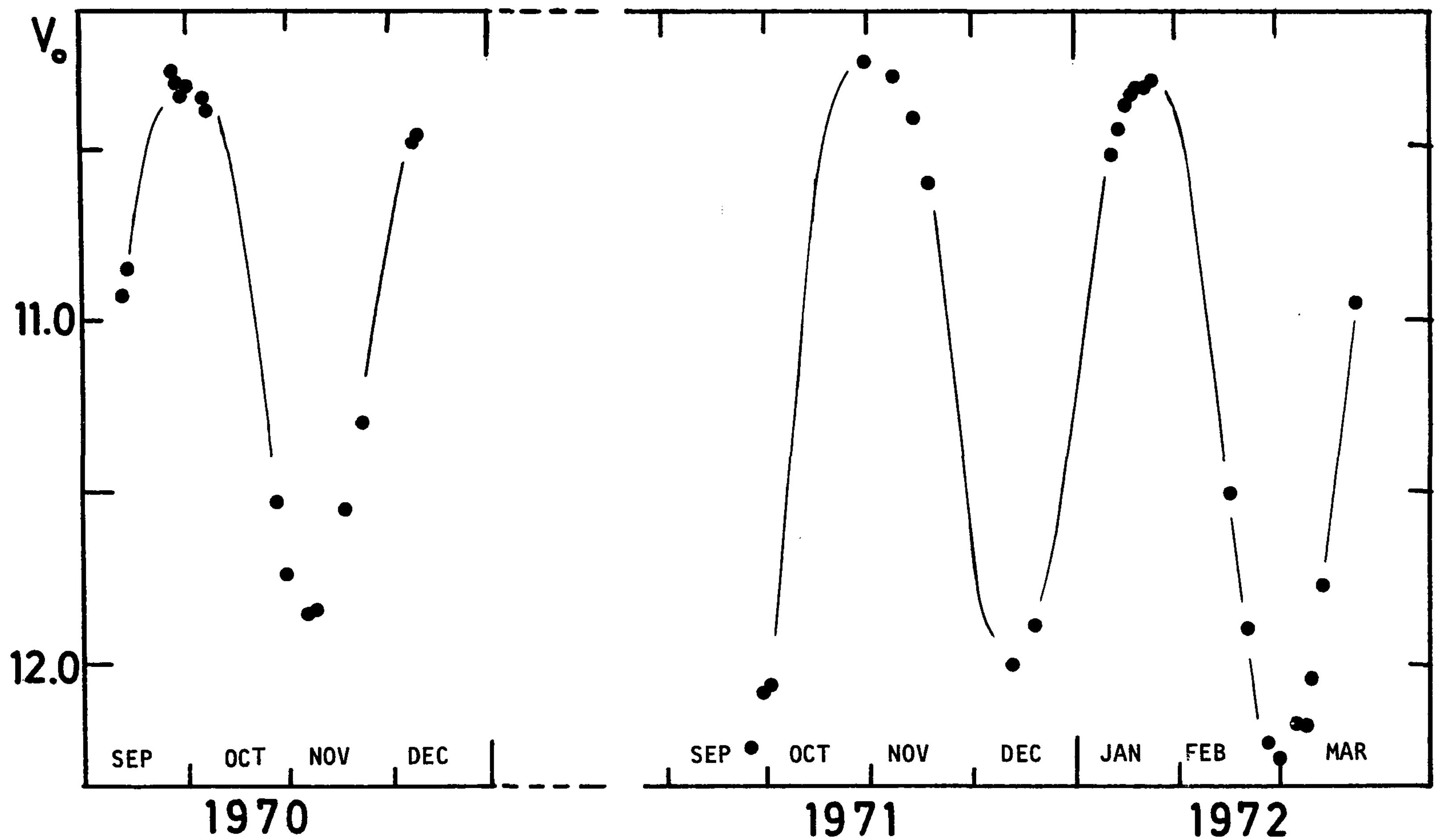


Figure 21. Iapetus light curve, 1970 Sep - 1972 Mar.

Table XXX

New Iapetus photometry.

UT date		V_o	B-V	U-B	est. m.e. V	B-V	U-B	α	Θ'
1970	Sep 11.35	10.92	0.71	0.29	2	2	3	5°69	189°3
	Sep 12.33	10.85	0.69	0.31	2	1	2	5.64	193.8
	Sep 28.24	10.29	0.69	0.33	3	2	3	4.62	266.4
	Sep 29.25	10.31	0.70	0.30	3	3	4	4.54	271.1
	Sep 30.41	10.36	0.74	0.29	2	2	3	4.46	276.4
	Oct 1.32	10.32	0.72	0.24	5	5	6	4.38	280.5
	Oct 4.27	10.36	0.72	0.32	2	2	3	4.14	294.1
	Oct 5.26	10.40	0.67	0.32	2	2	3	4.05	298.6
	Oct 27.28	11.52	0.78	-	4	3	-	1.83	40.0
	Oct 30.33	11.74	0.78	0.37	2	5	5	1.50	54.1
	Nov 6.27	11.86	0.74	0.39	4	3	6	0.73	86.2
	Nov 8.21	11.84	0.76	0.35	10	5	7	0.52	95.1
	Nov 17.08	11.55	0.74	0.35	2	2	4	0.67	136.2
	Nov 21.25	11.30	0.74	0.31	1	3	3	1.13	155.5
	Dec 6.13	10.49	0.70	0.33	3	2	5	2.75	224.2
	Dec 7.15	10.47	0.70	0.30	1	1	3	2.85	228.9
1971	Sep 25.21	12.24	0.75	0.31	5	5	8	5.75	94.2
	Sep 30.34	12.08	0.69	0.55	4	3	8	5.47	117.6
	Oct 1.28	12.07	0.69	0.19	3	2	5	5.41	121.4
	Oct 31.28	10.26[a]	0.67	0.27	2	1	4	2.93	259.5
	Nov 7.50	10.30	0.69	0.26	2	1	3	2.16	292.7
	Nov 13.50	10.42	0.68	0.23	2	1	3	1.49	320.4
	Nov 18.30	10.61	0.71	0.27	1	1	1	0.94	342.6
	Dec 12.33	12.00	0.75	0.32	1	1	5	1.93	93.6
	Dec 19.18[c]	11.89	0.73	-	2	1	-	2.67	125.2
1972	Jan 11.20	10.52[a]	0.70	0.24	2	1	2	4.77	231.0
	Jan 12.23	10.45	0.69	0.28	2	1	2	4.85	235.7
	Jan 15.15	10.39	0.71	-	1	1	-	5.05	249.0

continued

Table XXX

(cont'd.)

UT date	V_o	B-V	U-B	est. m.e. V	B-V	U-B	α	Θ'
1972 Jan 16.12	10.35[a]	0.68	-	1	1	-	5°.12	253°.5
Jan 18.11	10.34[a]	0.69	-	1	1	-	5.25	262.6
Jan 20.24	10.34[a]	0.67	-	2	2	-	5.37	272.3
Jan 21.16	10.32[a]	0.70	0.28	2	1	2	5.42	276.5
Feb 15.16	11.50	-	-	10	-	-	6.24	29.8
Feb 20.07	11.90[a]	0.75	0.32	2	1	3	6.26	51.9
Feb 27.10	12.23[a]	0.86	-	4	4	-	6.22	83.5
Mar 1.07	12.28	0.77	0.32	2	3	5	6.18	96.8
Mar 5.13	12.17	0.82	-	5	4	-	6.10	115.0
Mar 6.13	12.17	0.74	-	2	2	-	6.07	119.5
Mar 9.05	12.04	0.72	0.31	4	3	5	5.99	132.5
Mar 12.06	11.77	0.73	-	1	1	-	5.90	146.0
Mar 24.34	10.85[b]	0.75	0.25	10	6	6	5.37	200.7

[a]observing date in common with Millis (1973)

[b]magnitude tied to Titan. No standard star observed.

[c]Observation by M. S. Burkhead

V_o is corrected for the finite size of Iapetus' orbit.

α refers to phase angle of Saturn, not Iapetus. The difference may amount to 0°.02.

Mean opposition distance: a = 9.54AU, Δ = 8.54 AU.

and has many observing dates in common, but is tied to the same principal comparison star as I used in 1971-72 (+17°703 = van Bueren 23). Eight dates of common V observation of Iapetus yield the mean difference

$$V_o(\text{Millis}) - V_o(\text{Andersson}) = +0.035 \pm 0.020(\sigma)$$

and if one date (1971 Oct 31) is excluded, the difference becomes +0.029 ± 0.013. (On the discrepant date Millis' magnitude is $0^m.07$ fainter than mine; the B-V also differ more than usual.) The V_o difference is explained by the different V for the standard star assumed: Millis adopted the magnitude given by Johnson and Knuckles (1955), which (as discussed in sec. D of this chapter) is $0^m.025$ fainter than that measured by me. Allowing for this zero point difference, the two series of Iapetus observations are seen to be remarkably accordant, and the mean error of a single observation can hardly exceed $0^m.02$ in either series if the observations on common dates are representative. Many individual observations in my photometry have much lower accuracy than $0^m.02$, as seen in the estimated-error column in Table XXX, but they are not in common with Millis; the comparison with his photometry demonstrates that my error estimates are realistic.

Since three revolutions of Iapetus are fairly well covered by internally consistent photometry, there are numerous cases of observations at nearly the same rotational phase but different solar phase angles, allowing the phase coefficient to be determined at each such rotational phase. The relevant observations are listed in Table XXXI. Observations within about 5° of the same rotational phase were grouped together; a wider range was permitted near maximum light, where the slope of the light curve is small. Magnitudes were corrected to the mean Θ' for each group, using the slope dV/dΘ' from a preliminary light curve. Millis' observations were adjusted by $-0^{m}_{.}025$ for reasons mentioned, and, in addition, a correction for the finite size of Iapetus orbit (amounting at most to $0^{m}_{.}012$) was applied, since my data include such a correction. Rotational phases according to the definition used in this work were calculated for Millis' times of observation (the orbital phases used in his paper were presumably calculated directly from elongation times given in the AE). An estimated error of $0^{m}_{.}02$ has been assigned to Millis' magnitudes. All magnitude adjustments were carried to the nearest $0^{m}_{.}005$.

For most Θ' values in Table XXXI there are effectively two α values represented, one at $\lesssim 3°$ and one at >4°; at the latter phase angle there are usually several observations. β was calculated directly from the magnitude and α differences between the two points (for a point consisting of several observations the mean V_o and the mean α were used, and the formal m.e. of the mean V_o was adopted as estimated error for the point). At Θ' = 120°, 226°, and 257° there are many and fairly well distributed points, and least squares solutions were obtained. There are many points between 270° and 280°, but the solar phase angle range is less than 1°, and β is indeterminate; instead, the value obtained by Franklin and Cook (1974) is given in Table XXXI.

Table XXXI

Iapetus phase coefficients in V.

Mean Θ'	Θ'	V_o		V_o(mean Θ')	α	Ref.	β_V(mag/deg)
37°	40°.0	11.52	± 0.04	11.47	1°.83	1	0.035 ± 0.010
	34.1	11.575	.02	11.625	6.25	M	
53	54.1	11.74	± .02	11.725	1.50	1	.041 ± .006
	51.9	11.90	.02	11.915	6.26	2	
	52.1	11.91	.02	11.925	6.26	M	
85	86.2	11.86	± .03	11.86[a]	0.73	1	.064 ± .005
	83.5	11.935	.02	11.94	1.70	M	
	88.1	12.245	.02	12.25	6.21	M	
	83.6	12.225	.02	12.23	6.22	M	
	83.5	12.24	.04	12.245	6.22	2	
94	95.1	11.84	± .10	11.84[a]	0.52	1	.062 ± .008
	93.6	12.00	.02	12.00	1.93	2	
	94.2	12.24	.05	12.24[a]	5.75	2	
	96.8	12.28	.02	12.285	6.18	2	
	92.5	12.245	.02	12.245	6.19	M	
120	125.2	11.89	± .02	11.96	2.67	2	.051 ± .010
	121.4	12.065	.03	12.085	5.41	2	
	117.6	12.08	.04	12.05	5.47	2	
	123.9	12.08	.02	12.13	6.04	M	
	119.5	12.17	.02	12.165	6.07	2	
	115.0	12.17	.04	12.11	6.10	2	
135	136.2	11.55	± .03	11.57[a]	0.67	1	.063 ± .009
	134.3	11.765	.02	11.755	2.88	M	
	137.3	11.915	.02	11.95	5.96	M	
	132.5	12.04	.06	12.00[a]	5.99	2	

continued

Table XXXI

(cont'd.)

Mean Θ'	Θ'	V_o		V_o(mean Θ')	α	Ref.	β_V(mag/deg)
151°	155°.5	11.30	± 0.03	11.40[b]	1°.13	1	0.061 ± 0.009
	146.0	11.77	.01	11.69	5.90	2	
226	224.2	10.49	± .03	10.475	2.75	1	.036 ± .005
	228.9	10.47	.03	10.49	2.85	1	
	218.1	10.595	.02	10.53	3.82	M	
	221.5	10.595	.02	10.56	4.59	M	
	226.3	10.545	.02	10.545	4.69	M	
	230.5	10.51	.02	10.545	4.76	M	
	231.5	10.52	.02	10.555	4.77	2	
257	259.5	10.26	± .02	10.265	2.93	2	.028 ± .009
	259.7	10.305	.02	10.31	2.93	M	
	266.4	10.29	.03	10.30	4.62	1	
	244.2	10.43	.02	10.39	4.98	M	
	249.0	10.39	.01	10.37	5.05	2	
	253.3	10.37	.02	10.36	5.12	M	
	253.5	10.35	.01	10.34	5.12	2	
	258.4	10.335	.02	10.335	5.18	M	
	262.6	10.34	.01	10.35	5.25	2	
	262.6	10.365	.02	10.375	5.25	M	
270						FC	.026 ± .005
295	292.7	10.30	± .02	10.31	2.16	2	.031 ± .013
	298.6	10.40	.03	10.39	4.05	1	
	294.1	10.36	.03	10.365	4.14	1	
323	320.4	10.42	± .02	10.44	1.49	2	.022 ± .007
	321.6	10.525	.02	10.54	5.88	M	
	326.2	10.565	.02	10.535	5.92	M	

continued

Table XXXI

(concl.)

Mean Θ'	Θ'	V_o	V_o(mean Θ')	α	Ref.	β_V(mag/deg)
341°	342°.6	10.61 ± 0.01	10.625[b]	0°.94	2	0.021 ± 0.007
	339.8	10.715 .02	10.73	6.02	M	
352	351.5	10.685 ± .02	10.72[b]	0.72	M	0.029 ± .008
	353.5	10.895 .02	10.875	6.10	M	

[a]not used in calculation of β_V

[b]corrected for opposition effect by +0.03 ± 0.03

Ref.: 1 Table XXX, 1970 observations

2 Table XXX, 1971-72 observations

M Millis (1973)

FC Franklin and Cook (1974)

Points with uncertainties ≥ $0^m.05$ have not been used in calculation of β_V.

Points from the 1970 apparition (Ref. 1) have been assigned a minimum error of $0^m.03$.

An opposition effect is expected to be present, at least on the dark side. Franklin and Cook (1974) recently presented evidence that Iapetus exhibits an opposition effect on the bright side. Therefore the phase function is probably non-linear at all values of Θ', and it is not obvious that a linear fit is meaningful. However, the phase function for $\Theta' = 270°$ derived by Franklin and Cook can be fit very well by a linear function for $1° \lesssim \alpha \lesssim 6°$; points at $\alpha \sim 0\overset{\circ}{.}3$ lie $\sim 0\overset{m}{.}1$ above the linear function. I will assume that the structure of the phase function is approximately the same (except for the varying slope β of the linear part) at all values of Θ'. It is clear from the data at $\Theta' = 85°$, $94°$, and $135°$ in Table XXXI that the assumption is at least not grossly in error even near the minimum of the light curve. At these three rotational phases β can be derived without using the data point at $\alpha \sim 1°$, which instead can be used as a check. The small-α points lie a few hundredths of a magnitude above the linear fit to the remaining points, as expected in view of the opposition effect. At $\Theta' = 151°$, $341°$, and $352°$ the single small-α points must be used to obtain β, and have been corrected in Table XXXI for opposition effect by adding $0\overset{m}{.}03$; an estimated error of the same amount has been allowed for.

β_V as a function of Θ' is plotted in Fig. 22. Surprisingly, the curve is not symmetrical about $\Theta' = 90°$ as is the light curve. The best-fitting sinusoid (with equal weight for all points in the least squares solution) is

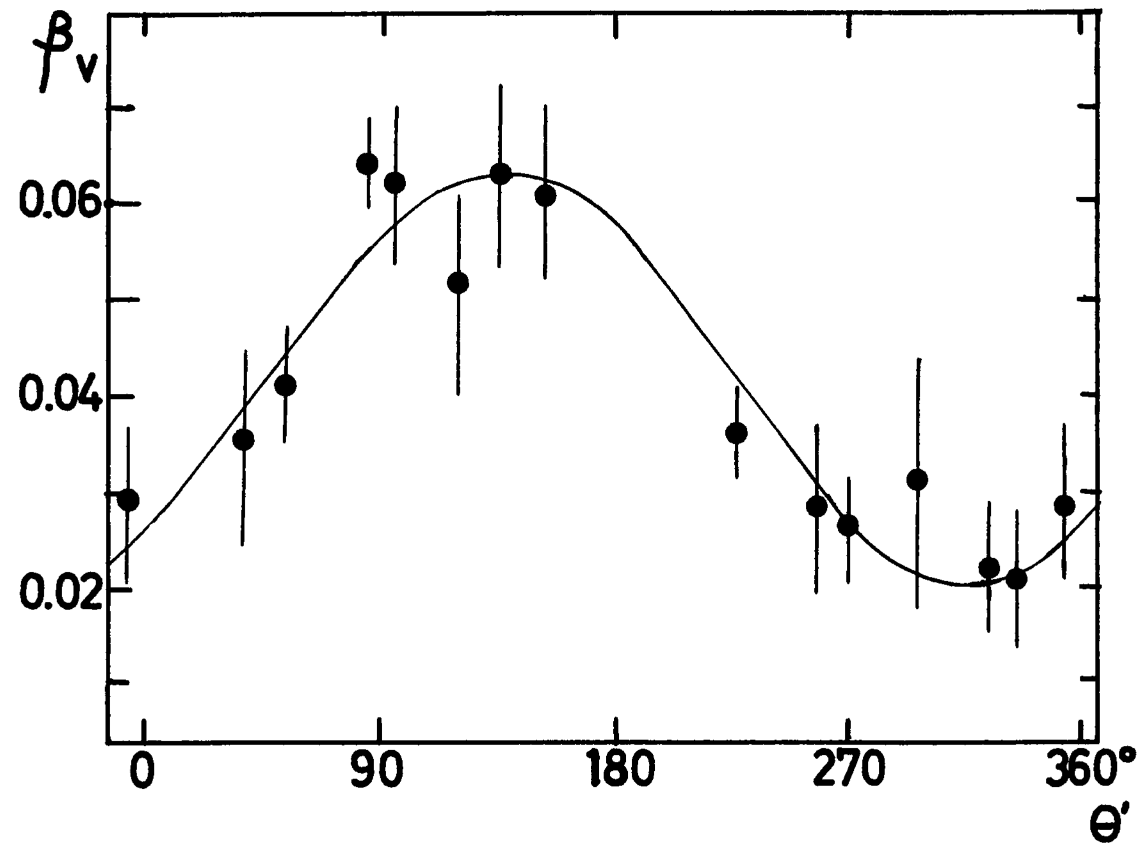


Figure 22. Iapetus' phase coefficient in V as function of rotational phase. The solid curve is

$$\beta_V = (0\overset{m}{.}042 + 0\overset{m}{.}022 \sin(\theta' - 45°))/\text{deg}$$

$$\beta_V = (0.041 + 0.018 \sin(\Theta' - 44°)) \text{ mag/deg} \quad . \tag{1}$$

With the constraint that maximum be at $\Theta' = 90°$, the best fit is

$$\beta_V = (0.040 + 0.015 \sin \Theta') \text{ mag/deg} \quad . \tag{2}$$

The fit of (1) is good; only one point (at $\Theta' = 85°$) deviates by more than its standard error in Table XXXI. Only five points deviate from (2) by <u>less</u> than their s.e.

Iapetus' light variations are usually interpreted in terms of two surface materials, one with high and one with low albedo, which cover the surface in varying proportions. The color variations (see below) are consistent with this model, in that color extrema occur at the same time as magnitude extrema. The expression (1) for the phase coefficient would then imply that the latter does not depend on the surface material. This seems rather unlikely. More observations are urgently needed. For reductions in the following, a modification of (1) will be used, which accomodates the most accurate data points in Fig. 22 somewhat better than (1), at the expense of the poorer points at $\Theta' = 120°$ and $295°$:

$$\beta_V = (0.042 + 0.022 \sin (\Theta' - 45°)) \text{ mag/deg} \quad . \tag{3}$$

Using this phase coefficient, my data and Millis' observations have been reduced to $\alpha = 4°$. This α is chosen instead of the customary $0°$ because it is near the average phase angle for all observations. Then the light curve is least sensitive to errors in the expression for the phase coefficient. The dispersion about a smoothly drawn curve (Fig. 23) is only $\sim 0\overset{m}{.}02$.

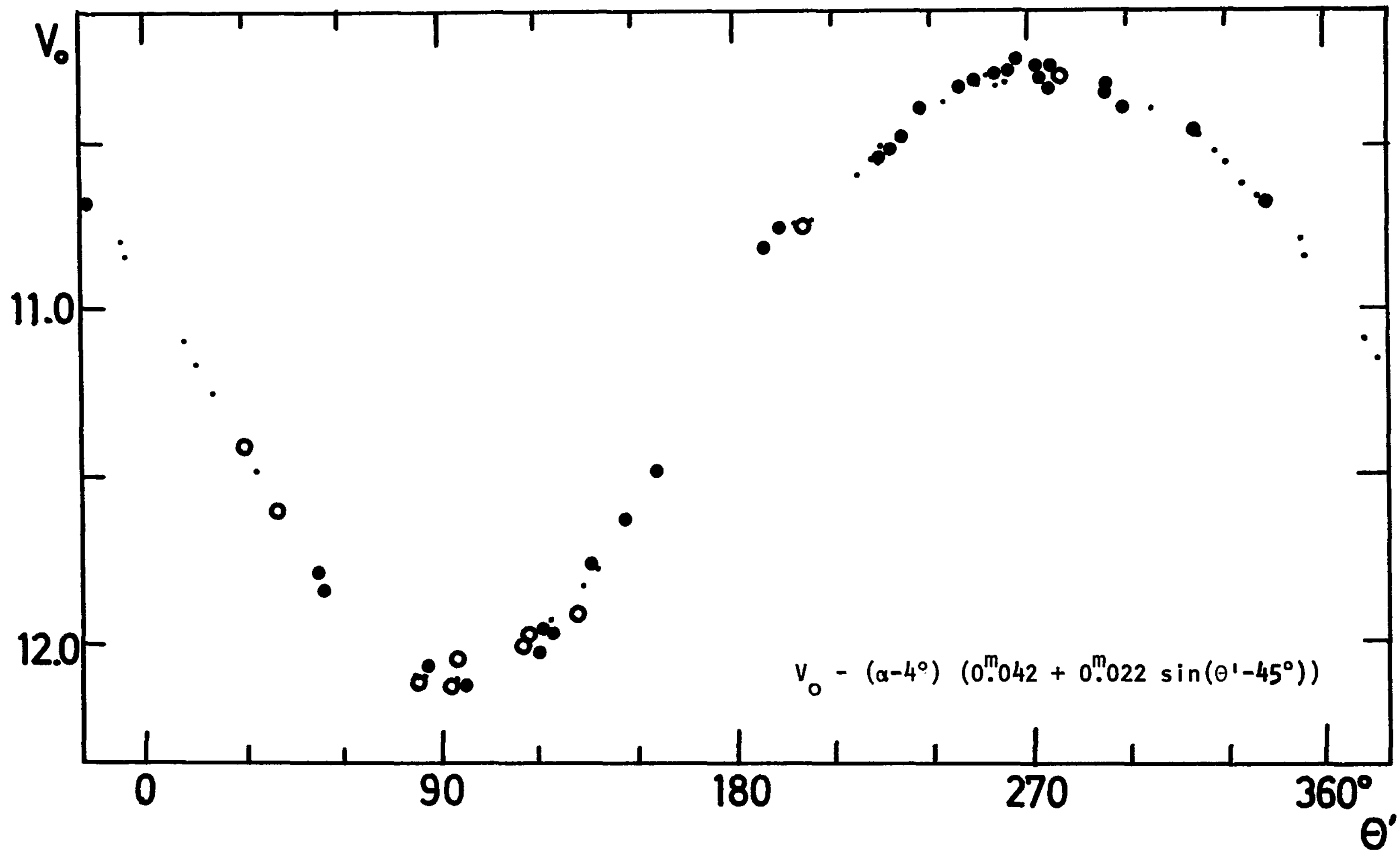


Figure 23. Magnitude of Iapetus versus rotational phase. V_o has been reduced to α=4° by eq. (3). Small dots are Millis' (1973) observations. Open symbols indicate observations with est. m.e. ⩾ $0^m.04$.

The colors (B-V and U-B) were shown by Harris (1961) and by Millis to vary by a few hundredths of a magnitude, being reddest near $\Theta' = 90°$. My observations, shown in Fig. 24 (excluding those of lowest accuracy), are in complete agreement with Millis' results. B-V ranges from 0.69 to 0.75, and U-B from about 0.27 to 0.32. The average error is larger in my data than in Millis', especially in U-B. The U-B colors measured in 1970 are slightly redder than the rest (as was also the case for, e.g., Rhea) and have in the figure been adjusted by $-0\overset{m}{.}03$. No dependence on solar phase angle is discernible in the colors, but because of the rather low accuracy of the observations phase coefficients as large as $0\overset{m}{.}005$/deg can not be excluded in either B-V or U-B. Phase coefficients of this order are suggested by the work of Noland et al. (1974) for the dark side of Iapetus.

The Iapetus observations by Wendell (1913) were converted to V magnitudes in the same manner as for Titan. They are listed in Table XXXII, and are plotted (reduced to $\alpha = 4°$) versus Θ' in Fig. 25. Wendell's magnitudes were reduced using eq. (1) in the Titan section. Since they are very easily calculated, the effects of Iapetus' varying B-V color and the finite size of its orbit were included, although these effects are hardly significant in this photometry where the typical error of one observation is about $0\overset{m}{.}1$. The errors due to the airmass differences between Iapetus and comparison stars are not included; they may amount to $0\overset{m}{.}03$ in a few cases. Uncertainty (due to color of comparison star, etc.)

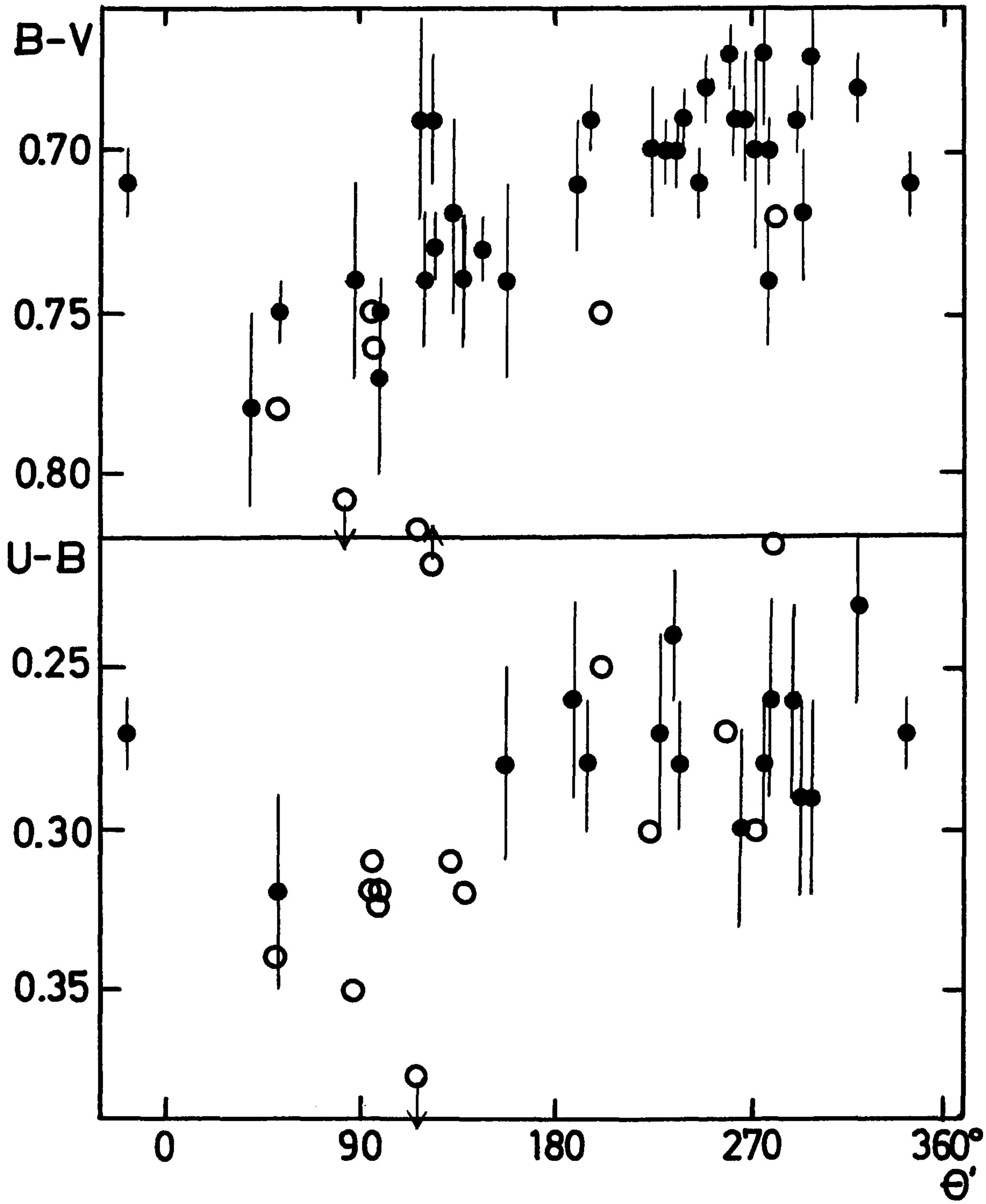


Figure 24. Colors of Iapetus versus rotational phase. U-B data from 1970 (measured with the Indiana "old" filters) have been adjusted by $-0^{m}_{.}03$. Open symbols indicate observations with est. m.e. $\gtrsim 0^{m}_{.}04$.

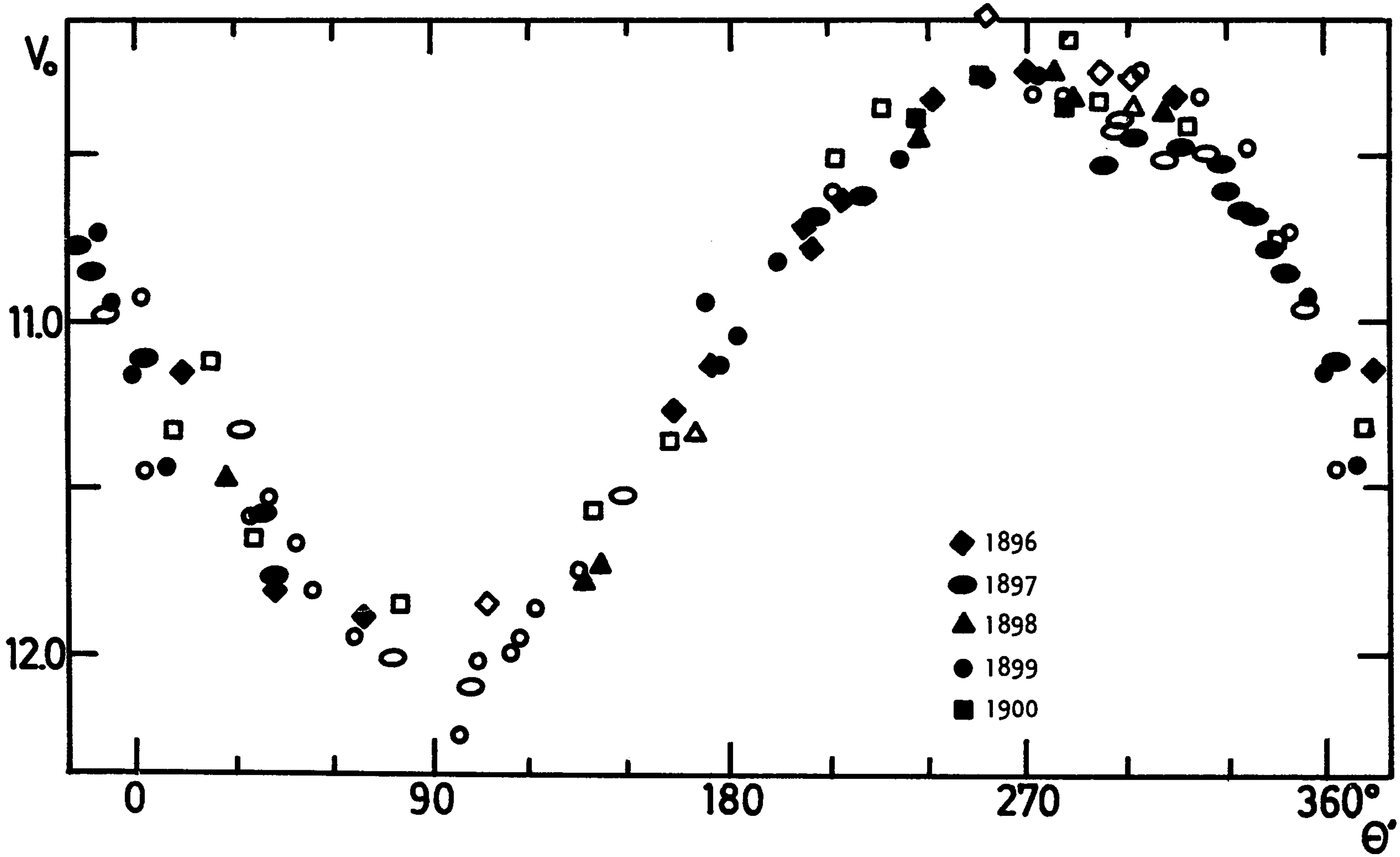
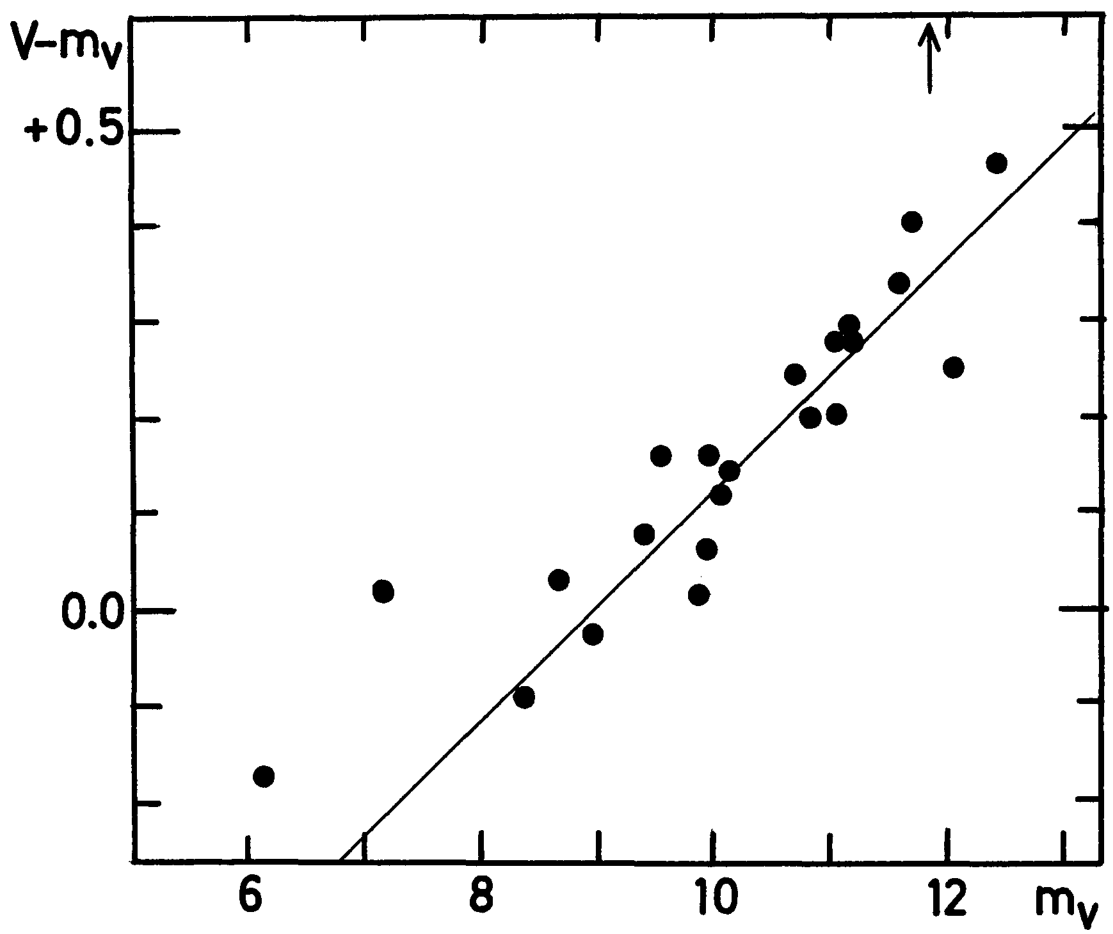


Figure 25. Wendell's Iapetus observations, reduced to $V_o(\alpha=4°)$, versus rotational phase. Open symbols indicate observations having a colon (:) in Table XXXII.

is indicated in the table in the same way as for Titan. In all but a few cases Iapetus was fainter than the comparison star, often by two or three magnitudes. Therefore, a small magnitude scale error could cause the magnitudes to be systematically in error, particularly at minimum brightness. The Titan data and two nights on which Wendell compared Iapetus with two stars of different brightness are consistent with a magnitude scale error coefficient, ℓ (see eq. (1) in Titan section), between zero and -0.10. Therefore the maximum and minimum in Fig. 25 could be too bright by up to $0^m.1$ and $0^m.3$, respectively; half these amounts are more likely estimates. The light curve of 1896-1900 is very similar to the 1970-72 curve (Fig. 23). Both the magnitude at maximum and the amplitude agree to within $0^m.1$ between the two curves.

The comparison stars used by Graff (1939) in 1922 are listed in the Appendix and are identified by "11" in the Remarks column. Most of the stars have been measured only once. The star +1°2692 was not measured, since it is double, with comparable components and separation about 10". For one star (with m_v = 11.90 in Graff's Table I) the photoelectric V is one magnitude fainter than Graff's adopted magnitude; this is possibly a case of misidentification. For the remaining stars $V-m_v$ is plotted against m_v in Fig. 26; a fairly tight, approximately linear relation appears. If the two stars which are much brighter than the rest are excluded, the best fitting straight line is

$$V-m_v = 0.12(m_v-8.95). \quad (4)$$



Figures 26. Graff's (1939) comparison stars: difference between photoelectric V and Graff's adopted m_V, versus magnitude of the star. The fitted line has a slope of 0.12.

Table XXXII

Wendell's Iapetus photometry.

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1896	3665.73	-14°4118	10.74	11.01	2°0	173°	
	3672.70	-14 4118	10.38	10.65	1.3	205	
	3674.72	-14 4118	10.24	10.51	1.2	214	
	3680.70	-14 4095	9.98	10.22	0.6	242	
	3687.71	-14 4095 -14 4085	9.89 10.06	10.15	0.3	270	
	3691.72	-14 4085	10.08	10.19:	0.7	293	3
	3696.67	-13 4022	10.06	10.28	1.2	315	
	3709.61	-13 4022	10.89	11.10	2.5	15	
	3715.67	-13 4003	11.65	11.76	3.1	42	
	3721.62	-13 3994	11.81	11.87	3.7	70	
	3729.71	-13 3994	11.80:	11.86:	4.2	107	1
	3741.62	-12 4141	11.25	11.34	5.0	162	
	3750.61	-12 4141	10.68	10.78	5.4	203	
	3762.59	μ Lib	10.36	10.12:	5.8	257	5
	3771.58	μ Lib	10.53:	10.28::	5.9	298	1,5
	3772.58	μ Lib -12 4141 μ Lib	10.45 10.24 10.46	10.33	5.9	302	6
1897	4074.70	-17 4413	10.36	10.50	1.3	220	
	4090.62	-16 4138	10.36	10.53	2.8	293	
	4091.60	-17 4395	10.22	10.38:	2.9	297	3
	4092.63	-16 4138	10.26	10.42	2.9	302	
	4094.70	-16 4129	10.34:	10.49:	3.2	311	1
	4097.60	-16 4122	10.34:	10.48:	3.4	325	1
	4098.66	-16 4122	10.48	10.62	3.5	330	
	4099.68	-16 4122	10.52	10.66	3.6	334	
	4100.62	-16 4122	10.54	10.68	3.7	339	
	4101.68	-16 4122	10.62	10.76	3.7	344	

continued

Table XXXII

(cont'd.)

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1897	4102.69	-16°4122	10.70	10.84	3°.8	348°	
	4112.60	-16 4120	11.28:	11.34:	4.5	33	1
	4113.67	-16 4120	11.54	11.60	4.6	38	
	4114.59	-16 4120 -16 4116	11.73	11.80	4.6	42	
	4122.60	-16 4116	11.93:	12.06:	5.1	79	1,3
	4127.60	-16 4116	12.04	12.17:	5.3	102	3
	4137.62	-16 4116	11.46:	11.61:	5.6	148	1,3
	4150.56	-16 4120	10.69	10.78	5.8	206	
	4170.53	-17 4388	10.34:	10.46:	5.6	296	1
	4171.54	-17 4388	10.33	10.44	5.6	300	
	4174.52	-17 4388	10.41	10.52	5.4	314	
	4177.52	-17 4388	10.45	10.56	5.3	327	
	4183.52	-16 4144	10.74	10.97:	5.1	354	3
	4185.50	-17 4413	11.03	11.14	5.0	3	
1898	4431.69	-19 4399	11.25	11.36	0.9	27	
	4455.69	-19 4375	11.45	11.64	1.6	137	
	4456.69	-19 4375	11.40	11.59	1.7	142	
	4462.72	-19 4374	11.20	11.24:	2.3	170	4
	4477.68	-19 4368	10.20	10.44	3.6	238	
	4486.67	-19 4368	10.06	10.29	4.3	279	
	4487.69	-19 4368	10.12	10.35	4.4	284	
	4491.69	-19 4368	10.14:	10.37:	4.6	302	1
	4493.70	-19 4362	10.18	10.40	4.7	312	
1899	4790.68	-21 4648	10.66:	10.66:	2.6	203	1,3
	4792.68	-21 4641	10.37:	10.54:	2.4	212	1
	4805.69	-21 4605	10.06	10.26:	1.1	272	3,4

continued

Table XXXII

(cont'd.)

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1899	4807.68	-21°4605	10.05	10.24:	0°.9	281°	3,4
	4812.69	-21 4605	10.01	10.20:	0.5	304	3,4
	4816.67	-21 4605	10.06	10.24:	0.2	322	3,4
	4819.66	-21 4594	10.28	10.40::	0.3	336	3
	4822.65	-21 4594	10.53	10.64::	0.6	350	3
	4825.68	-21 4594	10.70	10.81::	0.9	3	3
	4833.68	-21 4564	11.38	11.42:	1.7	40	3
	4835.65	-21 4564	11.54	11.59:	1.9	49	3
	4836.68	-21 4564	11.68	11.72:	2.0	54	3
	4839.66	-21 4564	11.82	11.86:	2.3	67	3
	4846.61	-21 4554	11.98	12.16:	2.9	99	3
	4847.66	-21 4554	11.78	11.95:	3.0	104	3
	4849.68	-21 4554	11.77	11.94:	3.2	113	3
	4850.66	-21 4554	11.74:	11.91:	3.3	118	1,3
	4851.66	-21 4554	11.65:	11.82:	3.4	122	1,3
	4854.59	-21 4554	11.56	11.73:	3.7	136	3
	4862.66	-21 4540	10.71	11.96	4.2	173	
	4863.65	-21 4539	10.90	11.16	4.3	177	
	4864.67	-21 4539	10.80	11.06	4.4	182	
	4867.60	-21 4539	10.60	10.86	4.5	195	
	4875.60	-21 4540	10.30	10.55	5.0	232	
	4881.56	-21 4540	10.08	10.32	5.3	259	
	4884.54	-21 4540	10.06	10.31	5.4	273	
	4902.53	-21 4540	10.74	10.98	5.8	355	
	4903.55	-21 4540	10.98	11.21	5.8	0	
	4904.54	-21 4540	11.28:	11.50:	5.8	4	1
	4905.54	-21 4540	11.26	11.49	5.8	9	
	4911.53	-21 4540	11.42:	11.65:	5.7	36	1

continued

Table XXXII

(concl.)

Year	JD 241000+	Comparison star	m_o	V_o	α	Θ'	Rem.
1900	5147.75	-22°4722	11.63:	11.33:	4°.4	11°	1,4
	5162.74	-22 4702	12.05	11.81:	3.2	80	2,5
	5175.72	-22 4655	11.56	11.45:	1.9	140	2
	5180.69	-22 4648	11.26	11.23:	1.5	162	2,4
	5191.67	-22 4613	10.40	10.34:	0.3	213	5
	5194.69	-22 4619	10.34	10.22:	0.1	227	5
	5201.76	-22 4597	10.11	10.19	0.8	259	
	5206.61	-22 4581	10.13	10.11:	1.3	282	2,5
	5208.76	-22 4581	10.34	10.31:	1.5	291	2,5
	5214.68	-22 4555	10.38	10.37:	2.1	319	5
	5220.68	-22 4555	10.74	10.73:	2.6	346	5
	5228.69	-22 4511	11.01	11.09:	3.3	23	5
	5231.63	-22 4511	11.55	11.63:	3.6	36	5
	5275.56	-22 4480	10.38	10.47	5.7	236	
	5285.53	-22 4480	10.30	10.38	5.8	281	

Remarks: 1 Wendell's individual observations discrepant (range > $0^m.10$)

2 comparison star measured only once (Appendix)

3 est. error of star's V magnitude ≥ $0^m.04$

4 B-V of star > 1.60

5 B-V of star ≤ $0^m.30$

6 only magnitude referred to -12°4141 used

$$V_o = m_o + (V_{star} - m_{star}) + 0.30\,(B\text{-}V)_{star} - 0.216 - 0.009 \sin \Theta' - 0.012 \cos \Theta',$$

where the sin Θ' term is due to the color variation of Iapetus and the cos Θ' term is due to the finite size of the satellite orbit.

The standard deviation of the points with $m_V > 8$ is $0^m.06$. There is no correlation between the deviation from (4) and the B-V color, but the reddest stars are all brighter than the average magnitude, so a small color term may be hidden in (4). Since Iapetus' B-V is nearly equal to the average for the stars, any color term is not expected to affect the Iapetus photometry.

Graff's observations of Iapetus are given in Table XXXIII. Graff usually made two or three observations per night, but only nightly means are given in the Table. The resulting light curve, reduced to $\alpha = 4°$, is shown in Fig. 27. The magnitude at maximum is well-defined and practically the same as in 1970-72. The minimum is decidedly asymmetric and very deep. The points near $\Theta'_i = 90°$ are mostly quite uncertain, the points on the rising branch are few, and most of the points on the descending branch have phase angles less than 1° and may be influenced by the opposition effect. The relation (4) may not hold very well at the faint end of the star sequence, where the magnitude is about the same as that of Iapetus at minimum. The information derived from Graff's light curve is thus rather uncertain, except for the magnitude at maximum.

The most widely quoted pre-photoelectric photometry of Iapetus is that of Widorn (1950). UBV photometry of his comparison stars is given in the Appendix ("9" in the Remarks column there). The V magnitude of the star +11°2239 is $0^m.5$ brighter than the m_V quoted by Widorn; a misprint in his paper is probable. The other

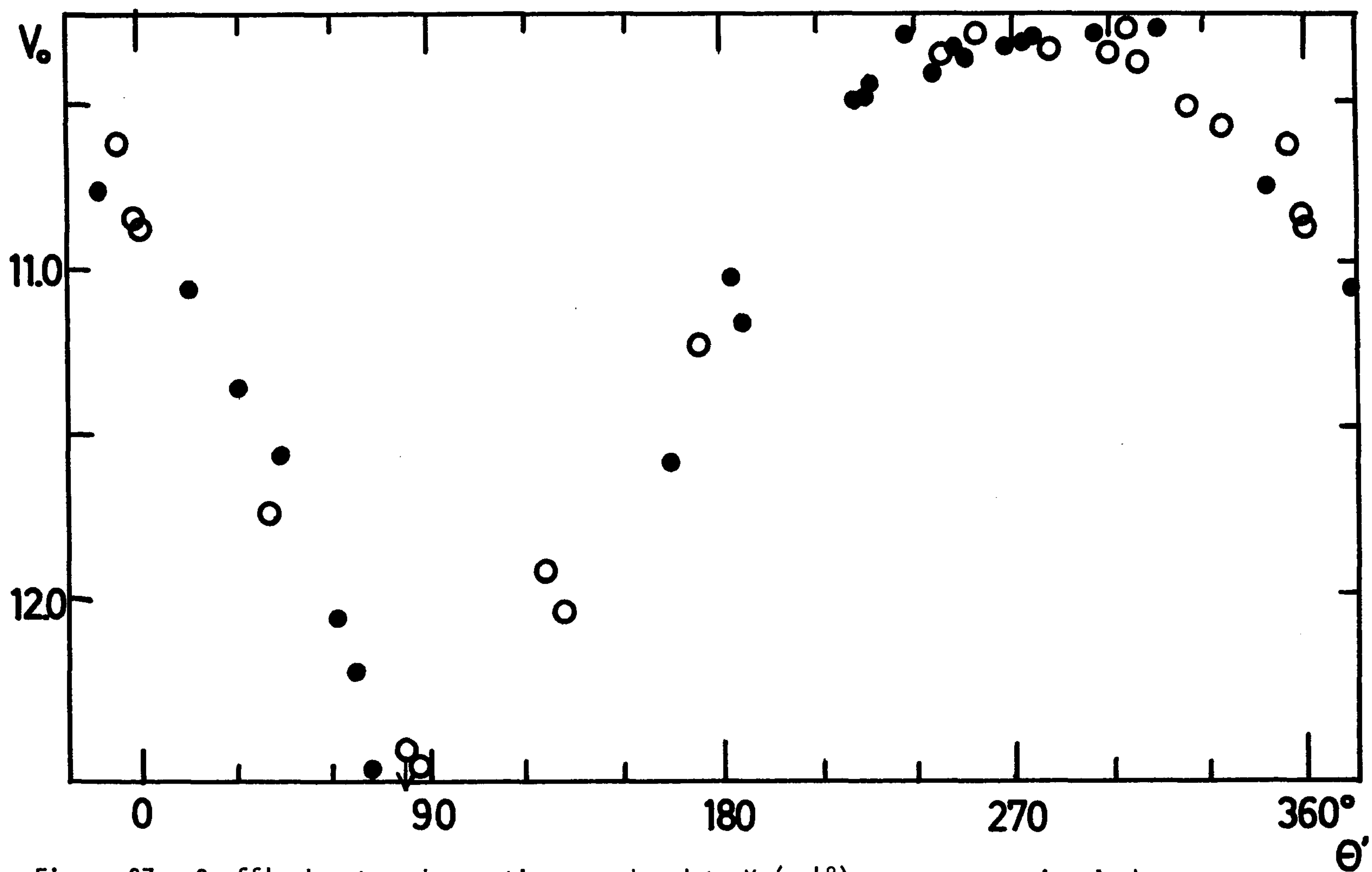


Figure 27. Graff's Iapetus observations, reduced to $V_o(\alpha=4°)$, versus rotational phase. Open symbols indicate observations having a colon (:) in Table XXXIII.

Table XXXIII

Graff's Iapetus photometry.

UT date 1922	m_o	V_o	α	Θ'	$m-m_o$
Feb 13.06	10.79	11.03	4°00	184°	0.07
21.08	10.29	10.46	3.32	221	.05
21.96	10.28	10.46	3.24	225	.05
28.05	10.15	10.30	2.65	253	.03
Mar 17.97	10.32:	10.48:	0.80	335	.01
20.98	10.49	10.66	0.50	349	.01
23.01	10.54:	10.72:	0.33	359	.01
26.96	10.72	10.92	0.38	17	.01
29.98	10.98	11.22	0.65	31	.01
31.90	11.32:	11.59:	0.85	40	.01
Apr 1.97	11.17	11.43	0.97	44	.01
5.90	11.71	12.03	1.38	62	.01
6.86	11.74	12.07	1.49	67	.01
7.92	12.01	12.37	1.60	72	.02
9.90	12.23:	12.62:	1.81	81	.02
10.87	12.02:	12.38:	1.91	85	.02
19.90	11.23:	11.84:	2.79	127	.03
20.88	11.62:	11.95:	2.89	131	.03
27.96	11.26	11.56	3.56	164	.05
29.95	10.95:	11.21:	3.73	173	.06
May 2.94	10.91	11.16	3.98	187	.06
11.93	10.29	10.47	4.65	228	.09
13.95	10.15	10.32	4.78	237	.09
15.90	10.28	10.45	4.92	246	.10
16.92	10.21:	10.38:	4.98	250	.10
17.89	10.24	10.41	5.05	155	.11
18.94	10.18:	10.34:	5.11	260	.11
20.98	10.21	10.38	5.22	269	.12

continued

Table XXXIII

(Cont'd.)

UT date 1922	m_o	V_o	α	Θ'	$m-m_o$
May 22.01	10.18	10.34	5°28	274°	0.12
22.86	10.17	10.33	5.32	277	.12
23.97	10.21:	10.38:	5.38	282	.13
26.90	10.18	10.34	5.52	296	.14
27.90	10.23:	10.39:	5.56	300	.14
28.88	10.15:	10.30:	5.60	305	.15
29.92	10.26:	10.43:	5.64	310	.15
30.92	10.16	10.32	5.68	314	.15
Jun 1.98	10.36:	10.54:	5.75	324	.16
8.94	10.48:	10.68:	5.94	355	.19
9.89	10.70:	10.92:	5.96	360	.19

$V_o = m_o + 0.12(m_o + (m-m_o) - 8.95) + 0.012 \cos \Theta'$

m_o is nightly mean of Graff's observations, reduced to mean opposition using a = 9.54 AU.

seven stars give for the difference between the photoelectric and Widorn's adopted magnitude:

$$V - m_V = 0.03 \pm 0.15\ (\sigma).$$

There is no obvious dependence of $V\text{-}m_V$ on either magnitude or B-V color, but because of the large scatter and small number of stars moderate such effects can not be ruled out. Since the mean B-V for the stars is about the same as that for Iapetus, any color term should not affect the Iapetus photometry anyway. Widorn's observations (nightly means) are listed in Table XXXIV, and the resulting light curve (reduced to $\alpha=4°$, using (3)) is shown in Fig. 28. As for Graff's curve, most points on the descending branch have $\alpha < 1°$ and are presumably affected by the opposition effect. The maximum is remarkably bright and broad; the minimum is narrow and at about the same magnitude as in the recent light curves. The possibility of a magnitude scale error makes the minimum magnitude very uncertain.

Of other early photometry of Iapetus, that reported by Pickering (1879) and that by Guthnick (1910) were made with Saturn in the same part of its orbit. One would expect the two light curves to be quite similar, but they are not. Guthnick carries through very elaborate calculations of fitting model albedo distributions to the two light curves, and discusses the striking difference between the curves in terms of an atmosphere on Iapetus. However, it is likely that there are large systematic errors in Pickering's photometry; the fact that he found Hyperion on the average barely

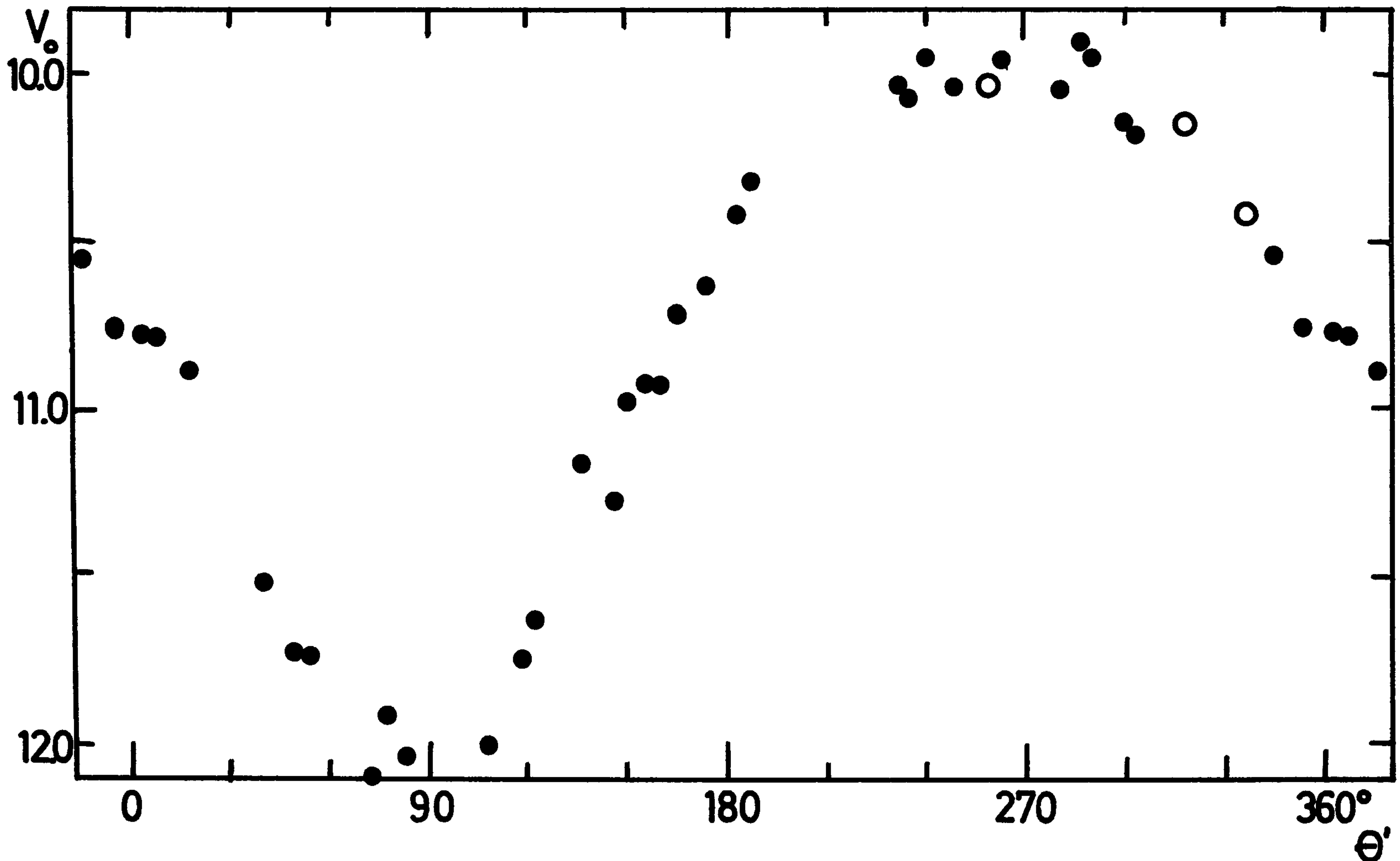


Figure 28. Widorn's Iapetus observations, reduced to $V_o(\alpha=4°)$, versus rotational phase. Open symbols indicate observations having a colon (:) in Table XXXIV.

Table XXXIV

Widorn's Iapetus photometry.

UT date 1922	m_o	V_o	α	θ'
Jan 22.90	9.97	10.00	3°23	231°
23.85	10.00	10.03	3.15	235
24.86	9.88	9.91	3.06	240
26.85	9.97	10.00	2.84	249
28.85	9.97:	10.00:	2.65	258
29.85	9.89	9.92	2.54	263
Feb 2.82	9.95	9.98	2.12	281
3.82	9.81	9.84	2.01	286
4.82	9.86	9.90	1.90	290
6.83	10.05	10.09	1.68	299
7.86	10.10	10.13	1.57	304
10.80	10.01:	10.05:	1.24	318
14.78	10.27:	10.31:	0.79	336
16.79	10.43	10.47	0.57	345
18.80	10.63	10.67	0.35	354
20.80	10.62	10.66	0.19	3
21.82	10.62	10.66	0.18	8
23.77	10.72	10.76	0.32	17
28.81	11.33	11.37	0.88	40
Mar 2.78	11.54	11.58	1.11	49
3.78	11.54	11.57	1.21	54
7.84	11.95	11.98	1.66	72
8.78	11.75	11.78	1.77	77
9.78	11.88	11.91	1.88	82
15.77	11.87	11.90	2.52	109
17.76	11.63	11.65	2.72	118
18.79	11.51	11.54	2.83	123
21.84	11.09	11.11	3.13	137

continued

Table XXXIV

(cont'd.)

UT date 1922	m_o	V_o	α	Θ'
Mar 23.72	11.21	11.23	3°32	146°
24.77	10.93	10.95	3.42	150
25.83	10.86	10.88	3.52	155
26.77	10.87	10.89	3.61	160
27.78	10.68	10.70	3.70	165
29.79	10.61	10.63	3.89	174
31.66	10.39	10.41	4.04	182
Apr 1.77	10.30	10.32	4.15	187

$V_o = m_o + 0.03 - 0.012 \cos \Theta'$

m_o is nightly mean of Widorn's observations, reduced to mean opposition using a = 9.54 AU.

three magnitudes fainter than Rhea, while the difference according to PE measurements is about $4\overset{m}{.}5$, suggests that a magnitude scale error is present. Guthnick's photometry seems more reliable, and PE photometry of his comparison stars is contemplated. The star magnitudes are tied to the HR system; the systematic errors are probably small, at least for magnitudes near Iapetus' maximum. Incidentally, Guthnick made the first attempt at determining a phase coefficient for Iapetus; he concluded that β is less than $0\overset{m}{.}01$/deg, which is much too small and shows that his individual observations are at least occasionally in error by $\sim 0\overset{m}{.}2$ or more.

The few PE observations by Harris (1961) in 1951-53 define a very fragmentary light curve; the solar phase angles of the observations are unknown. Since the phase coefficient is only $\sim 0\overset{m}{.}02$/deg at maximum light, his observations in the interval $260° < \theta' < 330°$ nevertheless give Iapetus' magnitude at maximum with an error unlikely to be as large as $0\overset{m}{.}1$.

Franklin and Cook (1974) have reported BV photometry of six Iapetus maxima in 1972-74. There are observing dates in common with both mine and Millis' photometry. As mentioned in the Titan section, the V magnitudes of Franklin and Cook are about $0\overset{m}{.}03$ too faint on my scale.

The rather fragmentary light curve of Noland et al. (1974), which is based on narrowband photometry, is in good agreement with the 1970-72 curve from mine and Millis' observations. The individual Iapetus observations are given as magnitudes relative to the star 37 Tau. From observing dates in common with Franklin and Cook it appears that V_o magnitudes (on my system) can be obtained from the y magnitudes of Noland et al. by adding +4.29; their V magnitudes for standard stars (which require a correction of $-0\overset{m}{.}02$) and their mean values of V_o and y for Iapetus yield the correction +4.35. The source of the $0\overset{m}{.}06$ discrepancy is unclear. For use in Table XXXV I adopt a correction of +4.32.

The visual photometric light curve of Payne (1971b) from observations in 1968-70 has a magnitude at maximum in rough agreement with the PE photometry, but has a fainter minimum. Since only one comparison star was used (+7°258; see Appendix) the magnitude scale term can not be determined.

The narrowband observations of McCord et al. (1971) define only a small part of the light curve. As previously noted not enough information is supplied to allow a reliable transformation to V magnitudes.

Data for various series of Iapetus observations are collected in Table XXXV. The magnitudes at maximum and minimum are reduced to $\alpha = 4°$ using $\beta = 0\overset{m}{.}020$ and $0\overset{m}{.}064$/deg, respectively. The error estimates are very approximate. K_o and K_1 are coefficients in the Fourier series representation of the light curve (in intensity units), as described in ch. V:D; the scale is such that a brightness of unity corresponds to $V_o = 12.5$. Since most of the light curves listed are not very accurate, K_o and K_1 were evaluated in the simplest manner possible (K_o was taken as the mean of the brightnesses

Table XXXV

Iapetus light curves.

Years	Mean date	V_o(max)	V_o(min)	λ_S	$\phi_\odot$	K_o	K_1	±
1896-1900	1898.5	10.35±0.05	12.1 ±0.2	252°	+15°	3.8	2.9	0.3
1905-08	1907.0	10.10 .15	11.9 .3	346	- 5	5.0	3.9	1.0
1922	1922.3	10.33 .05	12.5 .3	186	+10	4.0	3.2	0.4
1949	1949.1	10.00 .10	12.0 .3	155	+ 2	5.7	4.2	0.8
1951-53	1952.5	10.24 .05	-	196	+12	-	-	
1970	1970.8	10.31 .03	12.10 .05	48	-15	-	3.0	0.15
1971-72	1971.9	10.28 .03	12.16 .03	63	-15	4.3	3.2	0.15
1972-73	1972.9	10.26 .04	12.19 .05	76	-14	4.2	3.3	0.2
1973-74	1973.9	10.27 .03	-	90	-13	-	-	

V_o(max) reduced to α=4° with β = 0.020/deg

V_o(min) " " " " .064 "

The same error estimate applies to both K_o and K_1.

λ_S = heliocentric longitude of Saturn

$\phi_\odot$ = planetographic (Iapetus) latitude of subsolar point

Since the motion in λ_S amounts to 12°/year, and in $\phi_\odot$ up to 4°/year, the tabulated values should only be considered as representative values for the observing period in question.

For references, see text.

at $\Theta' = 0°$, $90°$, $180°$, and $270°$, and K_1 as half the difference between the maximum and minimum brightness), and higher terms were not calculated. Plots of K_o and K_1 versus λ_S (heliocentric longitude of Saturn) are shown in Fig. 29. It is obvious that more high-accuracy light curves from various parts of Saturn's orbit are required before a good solution for the orientation of Iapetus' spin axis can be obtained. From the best data points alone (the photoelectric light curves since 1970, the mean light curve from Wendell's observations, and perhaps Graff's data) it is not obvious that K_o and K_1 vary at all, but if the data of Widorn and Guthnick are to be taken seriously the variation is quite large, implying a large obliquity. In this case one pole is at longitude $\sim 50°$, because K_1 is a minimum there; and since K_o also has a minimum there and another minimum at the longitude 180° away, dark polar caps are implied.

The obliquity of a body which moves in a precessing orbit and whose spin evolves under the influence of bodily tides, will ultimately reach one of two possible stable states (Peale 1974). (Under certain circumstances a third stable state is possible.) In one of these "Cassini states" the obliquity is very small; in the other, the spin axis, the orbit normal, and the normal to the satellite's "proper plane" (e.g., Brouwer and Clemence 1961, p. 81) are coplanar, and the normal to the proper plane lies between the other two vectors. Mercury is an example of the first state and the Moon, of the second. The orbit of Iapetus precesses about its proper plane with a period of about 3000 years and an inclination

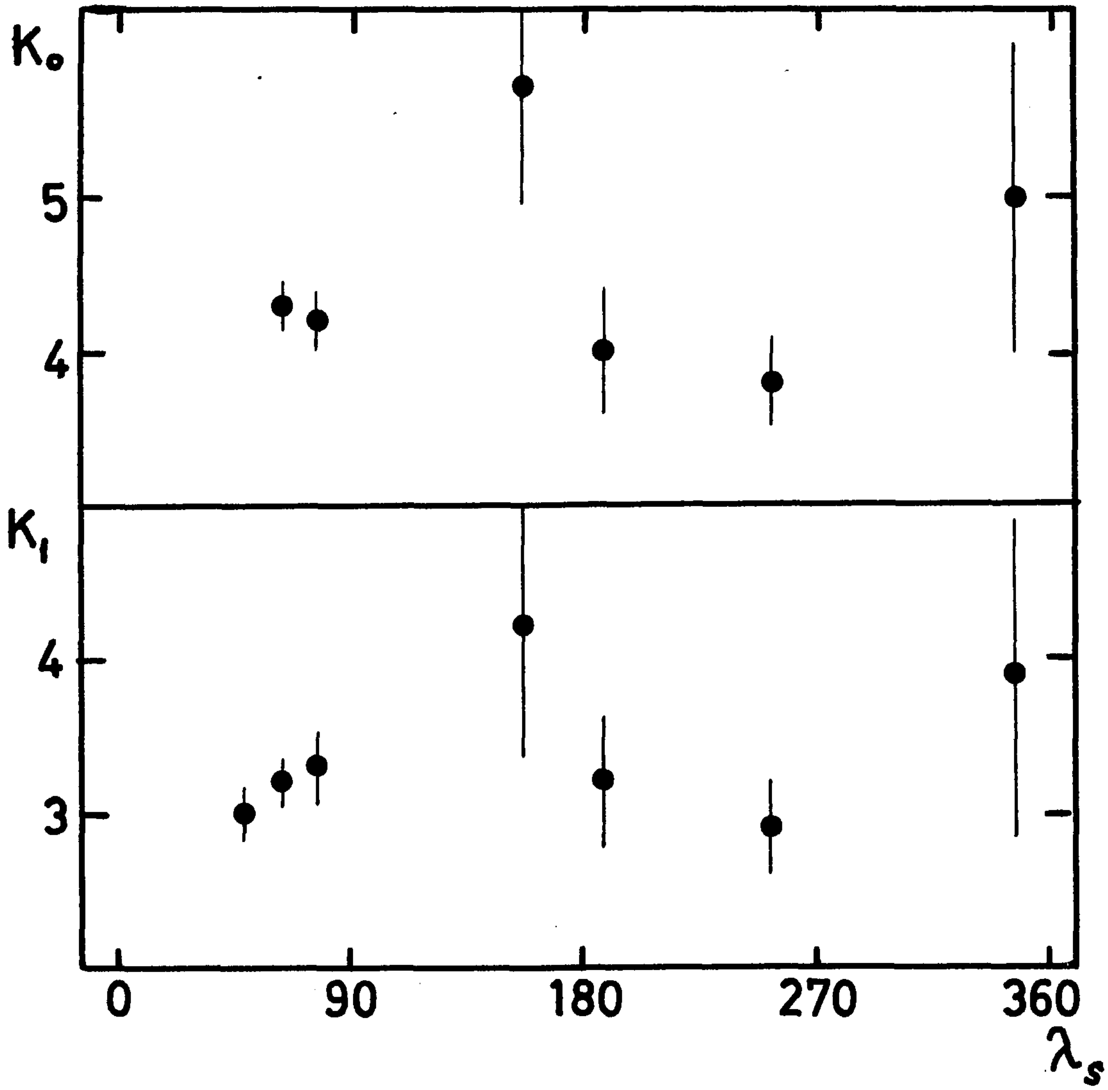


Figure 29. Fourier coefficients K_0 and K_1 of Iapetus light curves, versus heliocentric longitude of Saturn. See text for details.

of 8°. If Iapetus is in one of the two Cassini states mentioned, its obliquity is either close to zero or else $\gtrsim$ 8°. The inclination of the equator of Iapetus to the orbit of Saturn (which largely determines the range of aspects as seen from Earth) is, in the first case, 15° (in 1970; currently decreasing by 1°.5 per century), and in the second case $\gtrsim$ 11° (Fig. 30). Using the formulae of ch. V:D one finds for the first case that the observed amplitude (K_1) of Iapetus should vary by about 3% and have a minimum when the longitude of Saturn is $\lambda_S \approx 50°$. The second Cassini state encompasses a range of possible obliquities ε; if $\varepsilon \approx 8°$ the amplitude will vary by 2% and have one minimum near $\lambda_S = 80°$, and if $\varepsilon = 40°$ the amplitude will vary by ~14% and have a minimum near $\lambda_S = 160°$. Although the neglected higher terms in equations (3) to (7) in ch. V:D may modify these figures somewhat, the light curve of Widorn (taken at face value) is clearly incompatible with Iapetus being in one of the two Cassini states mentioned. Since the spin rate of the satellite has reached its final state, it would appear very unlikely that the obliquity has not reached one of its final states. Therefore I conclude that Widorn's magnitudes for Iapetus require a correction of at least +0.2; this is somewhat disturbing in view of his adopted mean magnitudes for Tethys, Dione, and Rhea, which are all slightly fainter than the photoelectric values.

Morrison et al. (1974a) use the PE photometry and Widorn's results to derive a model albedo distribution for Iapetus. From

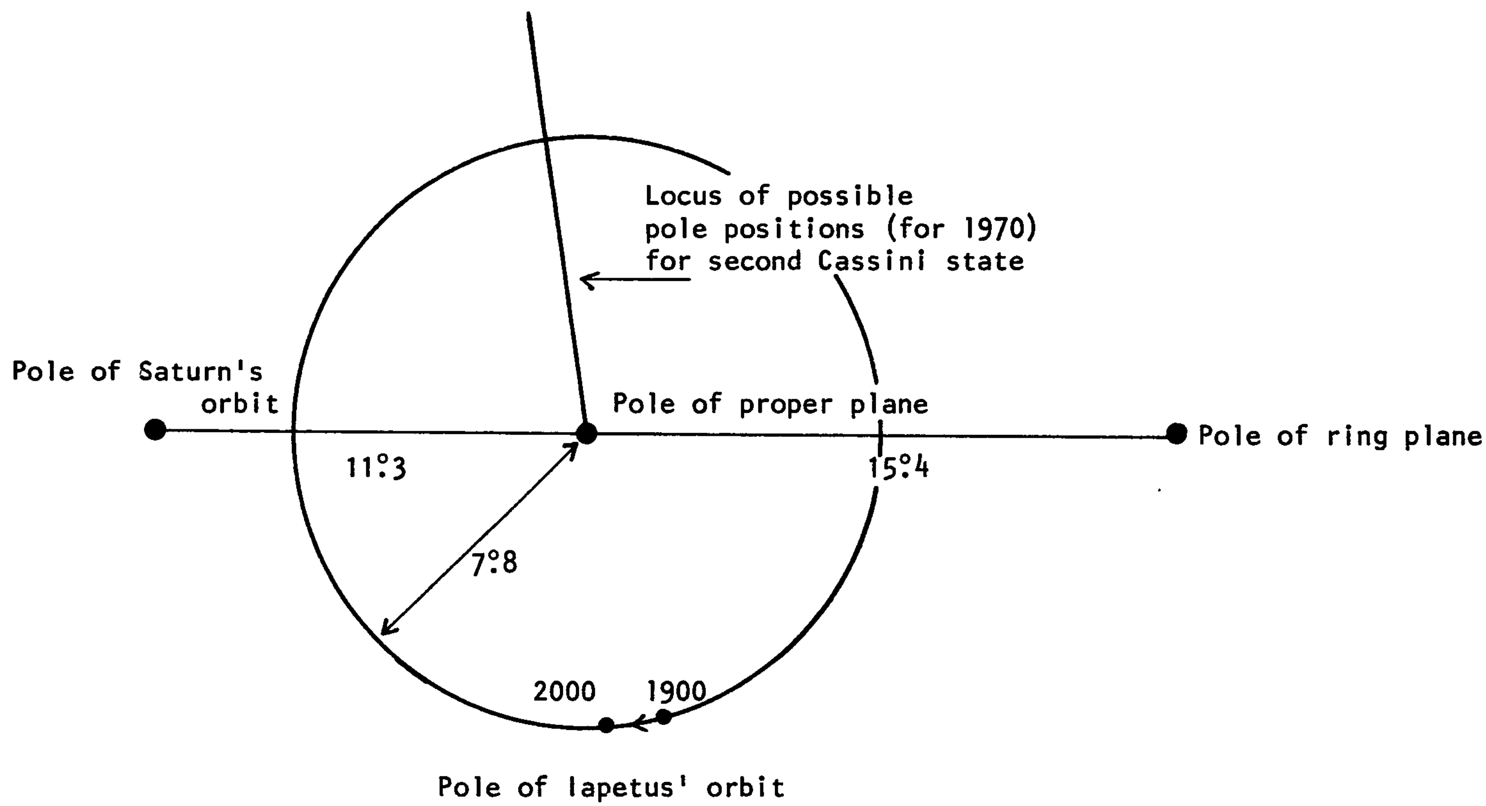


Figure 30. Geometric relations between the spin axis, proper plane, and orbital plane of Iapetus, Saturn's orbital plane, and the plane of the rings. Adapted from Kuiper (1956). See text for details.

the large amplitude of Widorn's curve they argue that the satellite has a bright southern polar cap; in essence, they assume that Widorn's data are free of any magnitude scale error, in which case the apparent difference in maximum brightness between 1949 and 1971-73 is due to a large zero point error in Widorn's photometry ($V - m_V \approx +0.4$). In view of the results in the previous paragraph the results of Widorn are probably too uncertain to justify their use in calculations such as those by Morrison et al. In any case, PE light curves during the next several apparitions of Saturn will allow a preliminary obliquity to be determined; in 1978 and 1979 Saturn will be in the same part of its orbit as in 1949.

J. Phoebe.

The outermost satellite of Saturn is much fainter than the value of V = 14 quoted in many textbooks. Phoebe was observed for the first time photoelectrically in 1970 Dec with the 82-inch telescope. Good photometry was further obtained in 1971 Nov with observations during several hours on each of four nights. In 1972 Dec and 1973 Jan Phoebe was measured on four nights by M. S. Burkhead, while a few poor magnitudes were obtained during the same period by the author. The PE photometry is summarized in Table XXXVI. One photographic magnitude determination by Kuiper (1961) and three communicated by E. Roemer are listed in Table XXXVII. These photographic determinations are in good agreement with the PE data.

The nightly means of V_o are plotted versus solar phase angle

Table XXXVI

Phoebe photometry.

1	2	3	4	5	6	7	8
1970 Dec 24.14	16.62	0.64	0.30	1 1 1	5	4°47	+0.12
31.14	16.61	0.71	0.27	1 1 1	6	5.00	+ .10
1971 Nov 9.2	16.30	0.67:	-	5 2	4	1.98	+ .17
10.3	16.40	0.58	0.41:	6 1 1	4	1.88	+ .17
13.4	16.30	0.70	0.37	5 1 1	3	1.52	+ .18
18.3	16.30	-	-	6	6	0.97	+ .18
1972 Dec 30.17[a]	16.52	0.59	-	1 1	4	2.40	+ .23
31.21[a]	16.49	0.67	-	1 1	4	2.51	+ .23
1973 Jan 3.2	16.40	-	-	3	10	2.83	+ .22
4.2	16.39	0.75:	-	3 1	10	2.92	+ .22
10.12[a]	16.49	0.67	0.34	1 1 1	4	3.53	+ .20
12.15[a]	16.59	0.67	-	1 1	4	3.73	+ .19

[a]Observation by M. S. Burkhead

Column headings
1 UT date
2 V_o
3 B-V
4 U-B
5 No. of observations in V, B, and U
6 Estimated m.e. of single V observation (units of $0^m.01$)
7 Solar phase angle of Phoebe
8 Reduction to mean opposition (V_o-V)

Mean opposition distance: a = 9.54 AU, Δ = 8.54 AU

Table XXXVII

Photographic observations of Phoebe.

UT date	Observer	m_{pg}	α	m_o-m	$\overline{m}_o-m_o$	$\overline{m}_{pg_o}$
1952 Feb 5	Kuiper	17.3:	5°.1	-0.09	-0.06	17.2
1968 Nov 24	Roemer	17.0:	4.0	+ .03	- .00	17.0
1969 Nov 4	"	17.0	0.8	+ .11	+ .26	17.4
1970 Nov 26	"	16.5	1.7	+ .20	+ .14	16.8

The correction to zero phase angle ($\overline{m}_o$ - m_o) uses Gehrels' asteroid phase function.

Observers and telescope: Kuiper, 82-inch, McDonald Obs.
Roemer, 61-inch, Catalina Obs.
" , 90-inch, Steward Obs.

in Fig. 31. The best-fitting straight line has a slope of $0^m.09$/deg. Clearly an opposition effect must be present, and the phase function is steeper than the standard asteroid function. Because of the small range of phase angle available for observation, one can not separate the linear phase function from the opposition effect; the acceptable combinations range from about $\beta = 0^m.10$/deg, $\phi = 0$, to $\beta = 0$, $\phi = 2$. The data at $\alpha > 2°$ reduced with Gehrels' function give a mean opposition magnitude of $\overline{V}_o = 16.58$, while the four nights at $\alpha < 2°$ give $\overline{V}_o = 16.48$. $V_o(\alpha = 2°)$ is fairly well determined at 16.38. In these averages the two poor nights of 1973 Jan 3 and 4 have been ignored.

The observations in 1971 Nov suggested that a rotational variation was present, although the amplitude and period was not immediately evident. The observations, which are listed in Table XXXVIII, were assembled on numerous trial periods ranging from 8^h to 50^h. The most promising periods are near $11^h.3$ and $21^h.5$; the exact values depend somewhat on what slope for the phase function is adopted for reducing the observations to a common phase angle. For a slope of $0^m.15$/deg (corresponding to, e.g., $\beta = 0^m.03$/deg and $\phi = 1.5$) the best fits are obtained for $P = 11^h.25$ and $21^h.2$, and the corresponding light curves are shown in Fig. 32. Assembling the 1972/73 data on these periods obtains rather unconvincing light curves of apparently somewhat smaller amplitude ($\sim 0^m.1$) than the 1971 observations ($\sim 0^m.23$). The above-mentioned periods refer to light curve intervals containing one maximum and one minimum;

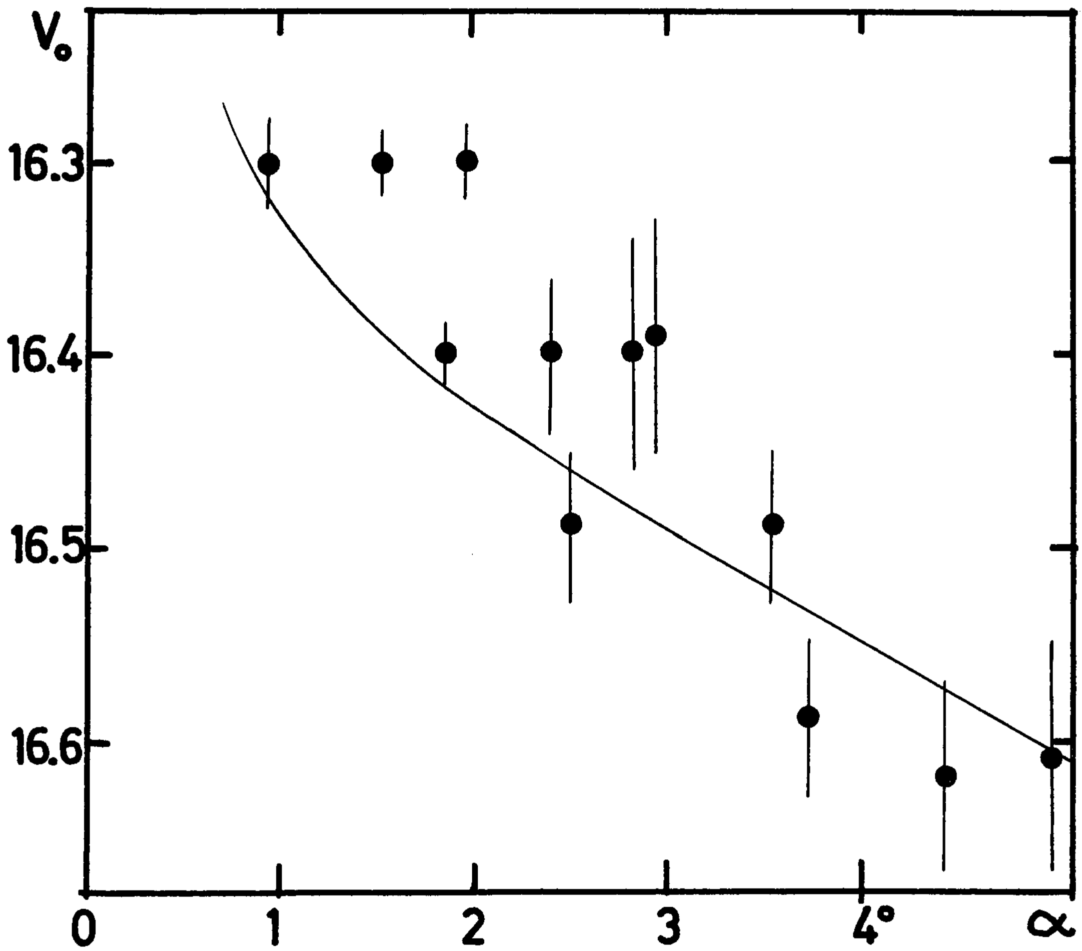


Figure 31. Magnitude of Phoebe versus solar phase angle. Error bars are derived from the est. m.e. and number of observations in Table XXXVI. The solid curve is Gehrels' asteroid function (cf. Fig. 1).

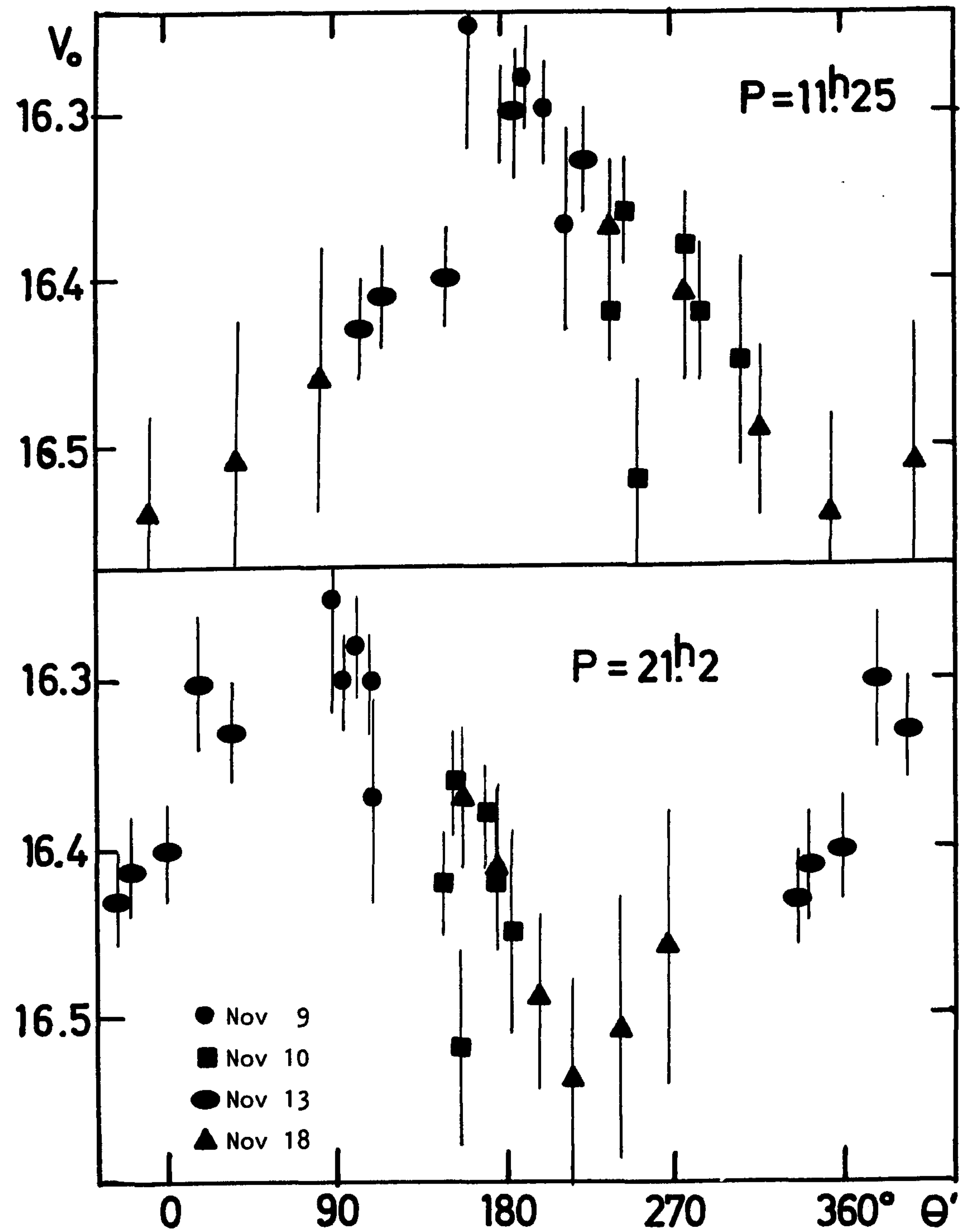


Figure 32. Light curves of Phoebe, assembled from observations in 1971 Nov, on periods $11^h_.25$ and $21^h_.20$. Reduced to $\alpha=2°$ using $\beta = 0^m_.15$/deg. Epoch of rotational phase: 1971 Nov 9.00 UT.

Table XXXVIII

Observations of Phoebe, 1971 Nov.

UT date	V_o	m.e. ($0^m.01$)	$V_o(\alpha=2°)$	Phase on period $11^h.25$	$21^h.20$
$9^d.21$	16.25	7	16.25	0.45	0.24
9.23	16.30	3	16.30	.50	.26
9.25	16.28	3	16.28	.53	.28
9.26	16.30	3	16.30	.56	.30
9.28	16.37	6	16.37	.59	.31
10.25	16.40	3	16.42	.66	.41
10.26	16.34	3	16.36	.68	.42
10.27	16.50	6	16.52	.70	.43
10.30	16.36	3	16.38	.77	.47
10.31	16.40	4	16.42	.79	.48
10.34	16.43	6	16.45	.85	.51
13.35	16.36	3	16.43	.29	.93
13.37	16.34	3	16.41	.32	.95
13.41	16.33	3	16.40	.41	.00
13.46	16.23	4	16.30	.51	.05
13.51	16.26	3	16.33	.62	.10
18.22	16.22	4	16.37	.66	.43
18.27	16.26	5	16.41	.77	.49
18.32	16.34	5	16.49	.88	.55
18.37	16.39	6	16.54	.98	.60
18.42	16.36	8	16.51	.11	.67
18.48	16.31	8	16.46	.23	.74

Correction to $\alpha = 2°$ uses a phase function slope = $0^m.15$/deg

Rotational phase equals zero at $9^d.00$

asteroids generally show two maxima and two minima per rotation, so it is likely that the photometric period should be doubled to give the actual period of rotation. Until further photometric data for Phoebe are available, these results on the satellite's rotation should be regarded as tentative.

Phoebe's colors are B-V = 0.66 ± .02 and U-B = 0.33 ± .03 (m.e. of mean). In the two-color diagram (Fig. 6) Phoebe lies at the extreme left edge (blue B-V) of the distribution of asteroids. The most nearly similar in color among solar system objects are some of Saturn's other satellites and a few asteroids, including 2 Pallas.

K. Satellites of Uranus.

The trustworthy photometric material on Uranus' satellites is very scanty. Harris (1961) reports PE measures of Titania and Oberon on three nights (but the dates of observation are not given); he also reports photographic magnitudes determined by Gehrels for Miranda, Ariel, and Umbriel. Among the visual estimates scattered in the literature, those of Steavenson (1964) in 1950 are given with sufficient details of circumstances of observation for re-reduction, and results of the rediscussion is presented here.

The new PE photometry of Titania is given in Table XXXIX, and that of Oberon in Table XL. The comparison stars used are listed in Table XLI. V_o is plotted versus orbital phase for both satellites in Fig. 33. If the error bars for Titania are realistic,

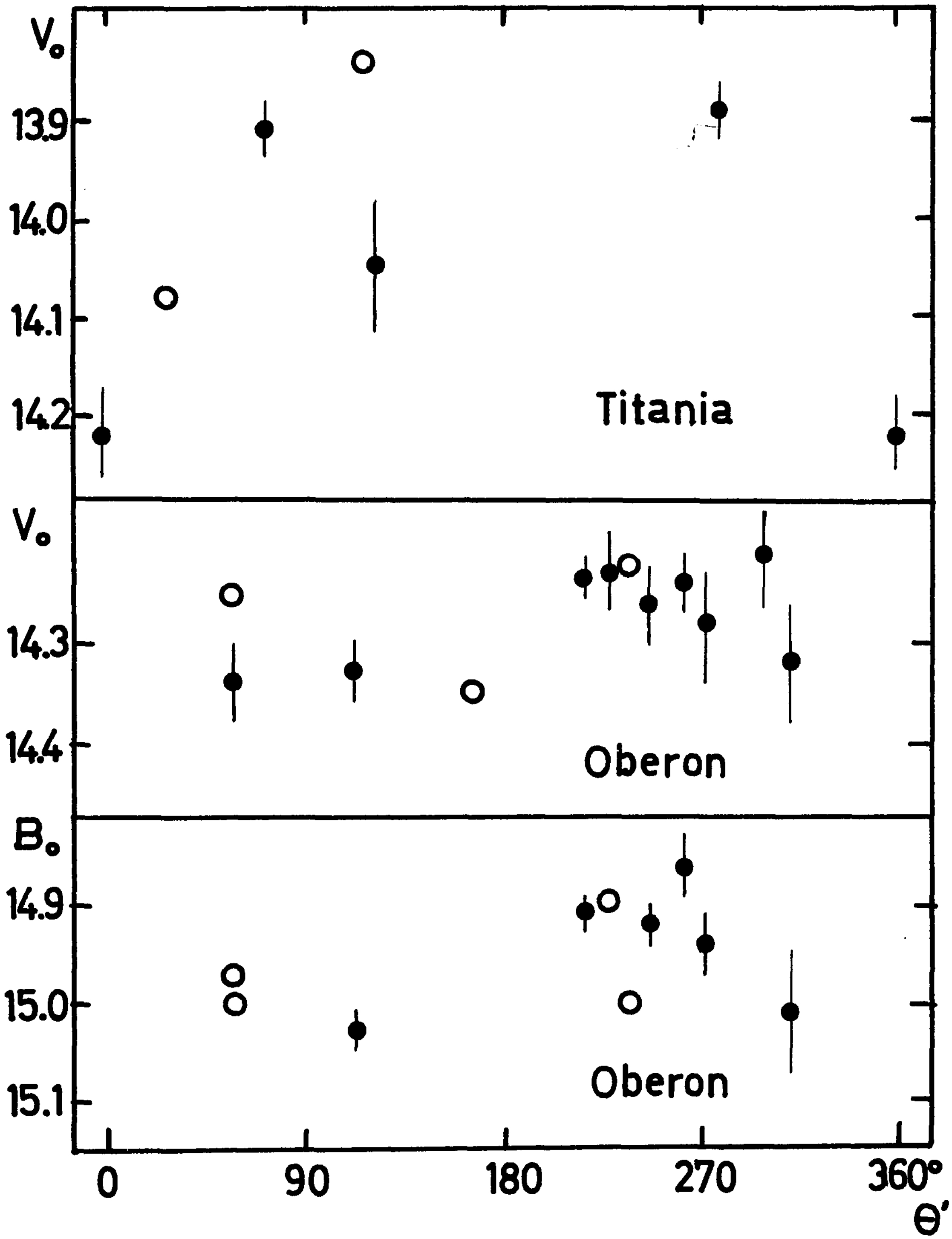


Figure 33. Magnitudes of Titania and Oberon versus rotational phase (assuming synchronous rotation). Open symbols indicate observations with est. m.e. $\gtrsim 0^{m}.07$.

Table XXXIX

New Titania photometry.

UT date	V_o	B_o	U_o	est.m.e. V	B	U	α	Θ'	Method	Star
1970 Dec 31.47	14.22	14.81	15.11	4	4	5	3°06	359°	scan	2
1972 Jan 16.52	13.89	14.59	-	4	3	-	3.05	277	cd ss	4
Jan 21.49	14.05	-	-	6	-	-	3.01	123	cd	3
Jun 15.21	14.08	14.82	-	10	7	-	2.97	28	cd	5
Jun 16.25	13.91	14.67	14.92	3	2	8	2.99	71	cd	5
1973 Jan 3.53	13.84	-	-	15	-	-	3.02	115	cd	4
Mean	14.01	14.72	15.02							
m.e. of mean	.06	.06	.10							

Method of measurement: scan drift scan
cd concentric diaphragms
ss symmetrical skies

Column headed "Star" gives comparison star used:

1 38 Vir
2 HR 4896
3 BD-5°3636
4 BD-6°3742
5 BD-4°3377

Mean opposition distance: a = 19.22 AU, Δ = 18.22 AU.

Table XL

New Oberon photometry.

UT date		V_o	B_o	U_o	est.m.e. V	B	U	α	Θ'	Method	Star
1970	Dec 24.48	14.23	14.90	-	4	10	-	3°01	229°	ss	1
	Dec 27.49	14.32	15.01	15.16	6	6	?	3.04	309	?	1
	Dec 31.46	14.25	14.97	15.21	?	?	?	3.06	55	?	2
1972	Jan 12.48	14.34	15.00	-	4	8	-	3.07	58	ss	3,4
	Jan 14.51	14.33	15.03	-	3	2		3.06	112	ss cd	3,4
	Jan 16.53	14.35	-	-	12	-	-	3.05	166	cd	4
	Jan 18.46	14.24	14.91	-	2	2	-	3.04	218	ss cd	3,4
	Jan 20.46	14.28	14.94	-	6	3	-	3.02	271	cd	3,4
	Jan 21.48	14.21	-	-	5	-	-	3.01	298	cd	3
	Jun 15.22	14.22	15.00	-	7	7	-	2.97	235	cd	5
	Jun 16.26	14.24	14.86	15.07	3	3	7	2.99	263	cd	5
1973	Jan 3.52	14.26	14.92	-	4	2	-	3.02	246	ss cd	4

	V_o	B_o	U_o
Mean	14.27	14.95	15.15
m.e. of mean	.01	.02	.04

Question mark (?) indicates data unavailable at time of writing.

Method of measurement: ss symmetrical skies
cd concentric diaphragms

Star: see Table XXXIX.

Table XLI

Comparison stars for Uranus satellites.

Star	V	B-V	U-B
38 Vir	6.125	0.48	0.03
HR 4896	6.45	1.08	1.08
-4°3377	9.25	0.74	0.22
-5°3636	9.22	0.585	0.06
-6°3742	8.37	0.96	0.59

The adopted magnitudes and colors are those reported in the Appendix.

then some variation of this satellite is indicated, but the small number of observations precludes any firm conclusions. For Oberon a variation of about $0^{m}_{.}1$ amplitude is suggested, with the trailing side (currently presented at southern elongation) the brighter. Unfortunately the observations near northern elongation are few in number, and one (of uncertain quality) is discrepant. If this light variation is confirmed Uranus' outermost satellite joins the outermost major satellites of Jupiter (Callisto) and Saturn (Iapetus) in being brighter on its trailing side, unlike the other cases of well-established synchronous rotation (Io, Europa, Ganymede, Dione, and Rhea) where the leading side is brighter.

No information on variation with solar phase angle is provided by the new PE material, since all observations were made with Uranus near quadrature and thus at maximum phase.

The B-V colors are 0.70 for Titania and 0.68 for Oberon. The first is rather uncertain, while Oberon's color is well determined (mean error of the mean $0^{m}_{.}01$). The U-B colors are 0.27 and 0.20, rather uncertain for both satellites, but in reasonable agreement with Harris' values (0.25 and 0.24). Harris gives bluer B-V values for both satellites (0.62 and 0.65) than the new photometry does, but since he quotes no uncertainties the difference may not be significant.

Steavenson (1964) discussed his visual intercomparisons of Uranus satellites during various periods since 1921, and claimed that the magnitude difference between Titania and Oberon was definitely variable by a few tenths, even when the orbits were seen nearly pole-on. For a period in early 1950 he gives a detailed record of comparisons of Titania and Oberon with each other and with field stars. Steavenson's comparison stars were measured photoelectrically in V and B on 1972 Jan 18; each star was measured only once and the magnitudes are therefore not of the highest accuracy but should be adequate for this discussion. The stars are listed in Table XLII; the new photometry is also included in the Appendix (stars identified by "6" in the "Remarks" column). The observations of Titania and Oberon reduced with the new comparison star data are listed in Table XLIII. It is clear that the magnitudes used by Steavenson are partly responsible for the apparent variation of the satellites noted by him. There is also a strong correlation between Titania's and Oberon's magnitudes (in other words, their magnitude difference is practically constant), suggesting that a systematic error affects both satellites equally, likely connected with the distance of the comparison star from the planet at the time of observation. It is concluded that Steavenson's observations in 1950 do not indicate any light variations for Titania or Oberon. The resulting mean magnitudes, however, are probably fairly reliable.

The photometry of Titania and Oberon is summarized in Table XLIV. If the quoted errors are realistic one may draw some conclusions about the albedo distribution with latitude on the two satellites, since Steavenson's and Harris' observations were made when the northern

Table XLII

Comparison stars used by Steavenson in 1950.

Star	m_v (Steavenson)	V (Appendix)	B-V	$V-m_v$
A	14.43[a]	14.40	0.68	-0.03
B	14.46	14.60	0.75	+ .14
C	14.22	14.35	0.72	.13
D	14.17	14.27	0.43	.10
E	14.08	14.27	0.70	.19
F	14.39	14.60	0.69	.21
G	14.14	14.56	0.05	.42
H	14.00	14.27	1.31	.27
J	14.41	14.52	0.42	.11

[a]erroneously given as 14.00 in Steavenson's star list

Table XLIII

Observations of Titania and Oberon
by Steavenson

Date 1950	V_o-V	V_o Titania	V_o Oberon
Mar 6	-0.02	14.03	14.23
Mar 7	- .02	14.08	14.23
Mar 9	- .01	14.20	14.29
Mar 17	+ .01	14.28	14.38
Mar 19	+ .02	14.32	14.42
Mar 20	+ .02	14.20	14.28
Mar 21	+ .03	14.29	14.39
Mar 24	+ .04	14.01	14.11
Mar 25	+ .04	14.01	14.16
Apr 7	+ .08	-	14.30
	Mean	14.16	14.28
	m.e. of mean	0.04	0.03

Range of solar phase angle: 2°88 to 3°02

Table XLIV

Titania and Oberon photometry summary.

Year of obs.	Titania V_o	Titania B-V	Titania U-B	Titania n	Oberon V_o	Oberon B-V	Oberon U-B	Oberon n	$\langle\alpha\rangle$	$\phi_\oplus$	Ref.
1950	14.16 ±04	-	-	9	14.28 ±03	-	-	10	2°97	+74°	1
a	14.01	0.62	0.25	3	14.20	0.65	0.24	3	-	b	2
1972-73	14.01 ±06	0.71 ±08	0.30 ±12	6	14.27 ±01	0.68 ±02	0.20 ±05	12	3.02	-31 ± 5	3

[a]during 1950-56; exact year unknown

[b]$+45° < \phi_\oplus < +75°$

n number of nights of V observation

$\langle\alpha\rangle$ mean solar phase angle for observations

$\phi_\oplus$ planetographic (Uranus) latitude of sub-earth point

References: 1 Steavenson (1964) and this work
2 Harris (1961)
3 this work

Errors are m.e. of the mean

Colors in 1972-73 calculated from V_o, B_o, and U_o in Tables XXXIX and XL.

The means of the observed colors are:

	B-V	U-B
Titania	0.70 ± .04	0.28 ± .03
Oberon	0.68 .01	0.20 .03

hemisphere was visible, while the new photometry measures mainly the southern hemisphere. (North and South are here, as always in this work, taken in the I.A.U. sense, so that the northern hemisphere includes the pole pointing North of the invariable plane of the solar system.) The two hemispheres are equally bright on Oberon, but Titania's southern hemisphere appears to have a higher albedo than its northern. Because Harris supplies no error estimates, it is uncertain whether the difference between his and Steavenson's magnitudes is significant. The difference is in the expected sense considering that the latter's observations include the time of quadrature so that Harris must have observed at a smaller phase angle than did Steavenson.

L. Triton.

The only photoelectric data on Triton available in the literature is due to Harris (1961). New PE observations were made on four nights in 1972. The first observation, on Jan 21, was too poor for inclusion here; the others are given in Table XLV. The Jun 20 observation was made at the f/45 Cassegrain focus of the Catalina 61-inch telescope with small diaphragms (4", 5", 9" diameter). While the internal consistency of the integrations is good, no other satellite was ever measured by the author as close to its primary as Triton was on this occasion (8" from Neptune), and the magnitude derived is rather dependent on the model adopted for the sky brightness profile.

Table XLV

New Triton photometry.

UT date	V_o	B_o	U_o	est.m.e. V B U	α	Θ'
1972 Jun 15.22	13.49	14.23	14.54	6 6 10	0°.69	76°
Jun 15.37	13.52	-	-	7 - -	0.69	85
Jun 16.30	13.43	14.22	-	8 6 -	0.72	142
Jun 20.19[a]	13.28	14.07	14.27	10 12 15	0.84	20

All measurements made by the concentric diaphragm method

Mean opposition distance: a = 30.06 AU, Δ = 29.06 AU.

[a]Observation obtained with the assistance of R. B. Minton.

The Triton photometry is tied to the star BD-19°4326, for which the following UBV data were assumed: V = 9.41, B-V = 1.16, U-B = 1.07. The magnitude and colors of this star are poorly determined and could be wrong by as much as $0^m\!.05$.

The mean V_o from the table is 13.43, but in view of the probable rotational variation mentioned by Harris and the uncertainty of the photometry at least the second decimal place is not significant. Harris states that the leading side may be ~ $0^m\!.25$ brighter than the trailing side. The new photometry does not cover the eastern elongation (trailing side) but it does suggest that Triton is fainter at WE (leading side) than at both conjunctions. At the time of Harris' observations the orbit was seen nearly edge-on so he must have measured Triton close to the elongations. Perhaps the light curve has two minima (at the elongations). Wirtz' visual estimates (1905) make Triton brighter at EE than at WE. Since Harris gives no exact dates for his observations it is also conceivable that the variation noted by him was due to changes of solar phase angle; the observable range is $0<\alpha<2°$, and if an opposition effect is present this could easily account for a $0^m\!.25$ range of magnitudes.

The B-V color is 0.77, in perfect agreement with Harris. My two U-B measurements are quite uncertain, and whether the difference from Harris' value (0.40) is significant is unclear.

The existing photometry of Triton is summarized in Table XLVI. The exact dates of Baade's (1934) observations are not given, so the

Table XLVI

Triton photometry summary.

Year of obs.	V_o	B-V	U-B	n	$<\alpha>$	ϕ	Ref.
1933	13.41	-	-	3?	-	+26° ± 2°	Baade (1934)
1950, 51, 53, 56	13.55	0.77	0.40	5	-	0 ± 6	Harris (1961)
1972	13.43	0.77	0.3	3	$0^{\circ}\!.74$	-26 ± 1	this work

n number of nights

$<\alpha>$ mean solar phase angle for observations

ϕ planetographic (Triton) latitude of sub-earth point phase angle is unknown. Baade's m_{pg} were converted to V using $B = m_{pg} + 0.11$ (Allen 1963) and B-V = 0.77.

Attention is called to the striking similarity between Triton and Pluto (cf. also Baade). The B-V colors are nearly the same, and while Triton's U-B is very uncertain, it does not differ much from Pluto's. Comparing their absolute magnitudes (at $\alpha=1°$) one finds that the observed range for Pluto is about -0.7 to -1.2 (see ch. VI), while for Triton the range (partly due to observational uncertainties) is -1.0 to -1.4. It will be interesting to see whether, for instance, polarimetric data for Triton will suggest a comparable albedo for both.

VIII. SUMMARY AND CONCLUSIONS

The principal photometric data for the objects studied in this thesis are listed in Table XLVII. Note that the data apply to the period 1970-72 only; for objects of large obliquity the properties may be significantly different at other times when the angle between the axis of rotation and the line of sight is different (as in the case for Pluto). For error estimates and other comments on individual objects, see the appropriate sections of ch. VI and VII.

The B-V and U-B colors are plotted in Fig. 34 for practically all solar system bodies for which such data are available and which are known or presumed to lack photometrically significant atmospheres. Two satellites (Io and Titan) are very red and fall far outside the diagram; they are not further considered in this paragraph. The satellites occupy roughly the same region as the asteroids; in particular, the satellites of Saturn and Uranus are similar in color to the group of about a dozen measured asteroids (e.g., 2 Pallas) with $B-V < 0.80$ and $U-B < 0.35$. The Moon and, to a lesser extent, three of the Galilean satellites, are similar to the main grouping of asteroids centered near $B-V = 0.85$ and $U-B = 0.45$. Finally, Jupiter VI has colors not unlike those of the small group at $B-V = 0.70$ and $U-B = 0.40$, which includes 1 Ceres. Zellner et al. (1974) suggest that the first group of asteroids has the composition

Table XLVII

Satellites and Pluto: photometry summary.

Object	V(1,α)	dV/dα (mag/deg)	ΔV	B-V	dB/dα (mag/deg)	Δ(B-V)	U-B	α
Jupiter VI	8.12	0.05	-	0.68	-	-	0.46	2°5
Enceladus	2.0	-	-	.70	-	-	.28	2.0
Tethys	0.62	.03	-	.73	0.03	-	.30	4.0
Dione	0.89	.05	-0.40	.71	.04	-0.06	.31	4.0
Rhea	0.16	.02:	- .15	.78	.02:	- .05:	.38	4.0
Titan	-1.265	.004	.00	1.28	.006	.00	.75	4.0
Hyperion	4.68	.02	.1	0.78	.03	-	.33	4.0
Iapetus	1.66[a]	b	+1.85	.72	b	+ .06	.30	4.0
Phoebe	6.82	.10:	0.2	.66	-	-	.33	2.0
Titania	1.3	-	-	.70	-	-	.28	3.0
Oberon	1.55	-	+ .1	.68	-	-	.20	3.0
Triton	-1.3	-	-	.77	-	-	.3	0.7
Pluto	-0.79	.05[c]	.22	.81	-	-	.31	1.6

[a] mean of minimum and maximum magnitudes

[b] dV/dα and dB/dα vary with rotational phase from about $0^m.02$ to $0^m.06$/deg

[c] at α = 1°2

ΔV and Δ(B-V) are amplitudes of rotational variations. The last column gives the phase angle α at which the other quantities are evaluated; it is usually near the mean α for the observations.

In the ΔV column, a plus sign indicates that the satellite is brightest at WE, a minus sign that it is brightest at EE. In the Δ(B-V) column, the signs indicate where the satellite is bluest (+ WE, - EE).

of carbonaceous chondrites, and that the second group consists of silicate bodies. If so, the similarity in color between the Saturn satellites and the first group is coincidental, since Rhea, Dione, Tethys, and Enceladus are known to have high albedos ($p_V \gtrsim 0.5$; Morrison and Cruikshank 1974). A chondritic surface would be expected to have a low albedo, and $p_V \approx 0.08$ has been measured for Pallas (Zellner et al. 1974). Note that Iapetus, with colors similar to those of the inner Saturn satellites, has a very low albedo ($p_V \approx 0.04$) on its leading side (Murphy et al. 1972).

From the data available it appears that Iapetus, Hyperion, and Rhea exhibit an opposition effect: the magnitude at $\alpha<1°$ is at least $0^{m}\!.05$ brighter than suggested by a linear extrapolation from the interval $2°<\alpha<6°$. It must be stressed that because only phase angles $\lesssim 6°$ are accessible for the satellites of Saturn, there is no assurance that the linear part of the phase function has been reached even at $\alpha=6°$. For this reason the phase coefficients in Table XLVII are labeled $dV/d\alpha$ and $dB/d\alpha$ rather than β_V and β_B. Confirmation of a strongly curved shape of the phase function at $\alpha<6°$ for a high-albedo object (Rhea, Dione, or Tethys) would be of great interest, since most theoretical phase functions with an opposition effect neglect multiple scattering in the surface layer, and thus implicitly assume a low albedo. The implications for models of the rings of Saturn are discussed by Franklin and Cook (1974).

The synchronous rotations of Iapetus, Rhea, and Dione are verified. The case of Hyperion remains undecided, but the data are

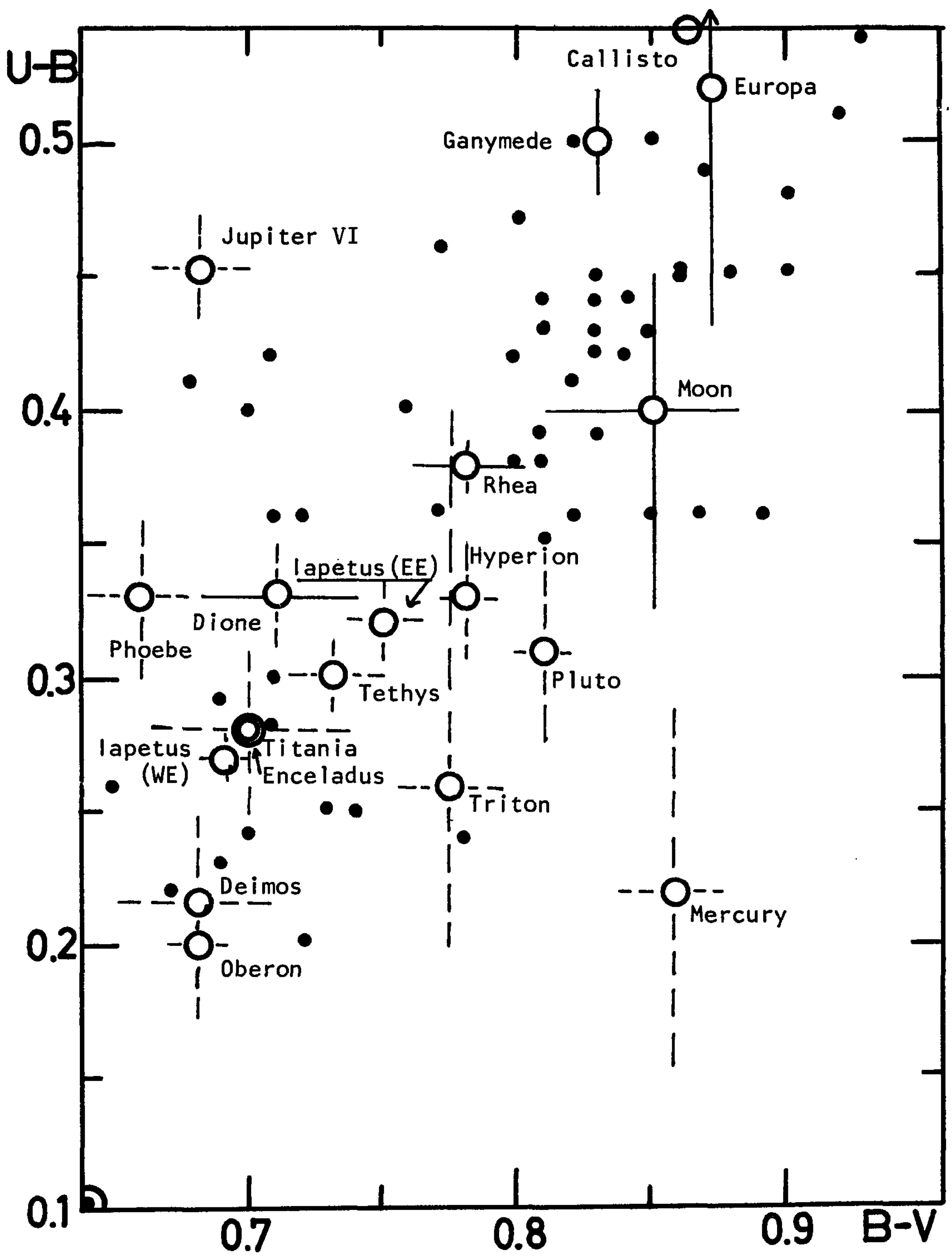


Figure 34. UBV colors of satellites, asteroids, Pluto, and Mercury, reduced to α=5°. Sources: Galilean satellites, Harris 1961; Deimos, Zellner and Capen 1974; Moon, Table XI in Gehrels et al. 1964; other satellites and Pluto, this thesis; asteroids (small dots), see Fig. 6. The colors of Mercury are extrapolated from data in Irvine et al. 1968. Solid bars through symbols indicate actual range of variation; dashed bars are error bars.

consistent with synchronous rotation. It is well-known that the outermost major satellites of Jupiter and Saturn are brightest on their trailing side, while the inner satellites are brightest on the leading side. This may apply to Uranus too, since Oberon has been found to be in synchronous rotation with maximum brightness on the trailing side, as reported in this work. Unfortunately, the data presented in this thesis do not confirm or deny the possible nonsynchronous rotation of Tethys or the light curve maximum at $\Theta' = 90°$ for Enceladus, as reported by Franz and Millis (1973). According to my data, Rhea and Dione are bluest at light maximum; that this is the case for Iapetus is well known, and it generally holds true also for the Galilean satellites (Harris 1961, Morrison et al. 1974b). Any theory attempting to explain the abovementioned regularities in the phase of maximum light must also consider the similar regularities in the color variation. Mendis and Axford (1974) suggest some possible mechanisms for the light curve regularities, involving the magnetospheres of the respective planets.

Finally, the slow light variations of Titan, which are described in detail for the first time here, add another facet to this complex body, whose dense atmosphere (Hunten 1974) makes it one of the most interesting objects in the outer solar system.

APPENDIX:

PHOTOMETRY OF ZODIACAL STARS

The following list contains photometric results for 131 stars observed in the course of the work on this thesis. It includes stars adopted as standards for the photometry of Pluto and satellites; stars used as comparison stars by earlier observers; and a few miscellaneous objects. With about ten exceptions, the stars lie within a few degrees of the ecliptic. The photometric system used and the method of reduction are discussed in ch. V. Further comments on individual stars can be found in the appropriate sections of chapters VI and VII.

Column 1 gives a name or designation for the star (other than HR, BD, and HD numbers). For faint stars the key to the designation is generally found in the reference given in the remarks. The stars are listed in order of increasing R.A.

Col. 2 gives the HR number, if available, otherwise the BD number.

Col. 3 gives the HD number of the star.

Col. 4, 5, and 6 give the V magnitude and the B-V and U-B colors, respectively, as determined in this investigation. Reference to published values is given in the remarks. While a U-B color has been measured for most stars listed, it is not given for many stars for which the U-B value obtained was of low accuracy and not needed in this work.

Col. 7 gives estimated external mean errors of the listed V, B-V, and U-B, in units of 0.01 mag. The error estimates take into account the agreement between different nights and the formal m.e. of the photometric solution for the individual nights. For the faintest stars observed once only, the estimates are based on the scatter of the individual deflections (for stars measured by pulse counting, the usual $\sqrt{N}$ estimate has been employed). For brighter stars observed on one night, the error estimate is the formal m.e. of the night's photometric solution.

Col. 8 gives the number of nights on which V and B-V were determined. U-B was in many cases not determined on all of these nights.

Col. 9 contains remarks, identified below. In most cases reference is given to either the work where the star was used as a comparison star or else to other photometry. The name of a planet in this column indicates a standard star adopted in this thesis for photometry of the planet indicated or its satellites.

Remarks: P The star is listed in the "Photoelectric Catalogue" (Blanco et al. 1968)

1 Blanco and Catalano (1971). Revised values from the same authors (private communication 1974) are:

	V	B-V	U-B
+3°180	9.71	0.66	0.23
+4 213	9.18	0.52	0.03
+9 304	9.78	0.88	0.55
+9 305	8.20	1.16	1.17

The agreement of the revised values with my data is good.

2 Payne (1971 a,b)

3 =LP 414-120. Luyten (1971). The star is apparently a white dwarf member of the Hyades.

4 $\alpha = 4^h11^m25^s$, $\delta = +18°55'.4$ (1950.0)

5 V is 0.04 mag brighter than published value. Range of my observations 7.39 to 7.47.

6 Steavenson (1964). The single standard star used when measuring these stars is M35-2 (Hoag et al. 1961)

7 Graff (1930). The m_v given by Graff for stars a, b, and c, respectively, are 13.49, 13.83, and 14.26.

8 Walker and Hardie (1955)

9 Widorn (1950)

10 R. Hardie, private communication, 1973.

11 Graff (1939). In col. 1 the stars are numbered in order of listing in Graff's table I.

12 Jerzykiewicz and Serkowski (1967)

13 Wendell (1913)

14 CD numbers given instead of BD numbers

15 Poor agreement in V. Possible variable.

16 Häggkvist and Oja (1973)

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
-	+40° 167	4685	7.05	1.02	0.84	2 2 3	1	
-	+ 4 213	7436	9.15	0.53	-0.01	2 2 2	2	1
-	+ 3 180	-	9.73	0.67	0.19	2 2 2	2	1
-	+ 7 258	-	9.36	0.82	-	2 2 -	2	2
-	+ 9 304	-	9.79	0.88	0.54	3 2 2	2	1
-	+ 9° 305	14513	8.22	1.16	1.17	3 2 2	2	1
-	+13 494	18972	7.835	1.05	0.79	1 1 1	4	Saturn
-	1036	21335	6.54	0.165	0.07	2 1 2	6	P,Saturn
-	1110	22695	6.15	0.965	0.74	2 1 1	6	P,Saturn
LB 228	-	-	16.32	0.02	-0.76	4 4 5	2	3
-	-	-	11.655	0.855	0.50	1 1 2	7	4,Saturn
vB 23	+17° 703	27149	7.515	0.685	0.225	1 1 1	11	P,Saturn
vB 31	+18 623	27406	7.43	0.56	0.065	2 1 1	8	P,5,Saturn
-	+20 863	32127	7.97	0.74	0.25	2 1 2	3	Saturn
104 Tau	1656	32923	4.92	0.66	0.14	2 2 2	2	P
A	-	-	14.40	0.68	-	4 5 -	1	6
B	-	-	14.60	0.75	-	4 5 -	1	6
C	-	-	14.35	0.72	-	4 5 -	1	6
D	-	-	14.27	0.43	-	4 5 -	1	6
E	-	-	14.27	0.70	-	4 5 -	1	6

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
F	-	-	14.60	0.69	-	4 5 -	1	6
G	-	-	14.56	0.05	-	4 5 -	1	6
H	-	-	14.27	1.31	-	4 5 -	1	6
J	-	-	14.52	0.42	-	4 5 -	1	6
a	-	-	13.75	0.42	-	5 2 -	3	7
b	-	-	13.85	0.42	-	4 2 -	3	7
c	-	-	14.22	0.52	-	6 6 -	1	7
A	-	-	13.15	0.80	-	4 3 -	2	8
B	-	-	12.11	0.58	-	3 2 -	2	8
C	-	-	12.79	0.65	-	3 3 -	2	8
D	-	-	12.43	0.94	-	3 2 -	2	8
-	+13°2231	-	10.76	0.66	0.14	2 2 3	2	9
-	+13 2235	-	10.51	0.51	0.12	2 2 5	2	9
-	+12 2195	-	9.60	1.04	1.0:	2 2 -	2	9
-	+13 2255	-	10.01	0.52	0.02	2 2 3	2	9
-	+12°2212	-	10.33	0.97	0.75	2 3 5	2	9
-	+12 2215	90700	7.80	0.96	0.70	2 2 3	2	9
-	+11 2238	-	9.60	0.52	0.10	2 2 4	2	9
-	+11 2239	91150	8.28	0.16	0.10	3 2 3	2	9
-	+20 2578	-	10.60	1.12	-	4 1 -	2	10

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
-	+20°2580	-	9.71	0.34	-	4 1 -	2	10
10 Vir	4626	105639	5.96	1.12	-	2 2 -	1	P,11
Grf 21	-	-	12.10	0.38	-	2 2 -	1	11
" 22	-	-	12.76	0.57	-	2 2 -	1	11
" 13	+ 2 2520	-	10.94	0.29	-	2 3 -	2	11
" 10	+ 1°2669	-	10.02	0.64	-	3 6 -	2	11
" 9	+ 1 2675	-	10.12	0.56	-	2 2 -	1	11
" 12	+ 1 2677	-	10.25	0.35	-	2 2 -	1	11
" 18	-	-	11.45	0.35	-	2 2 -	1	11
" 11	+ 1 2683	-	10.18	1.16	-	2 2 -	1	11
Grf 8	+ 1°2684	-	9.94	1.46	-	2 2 -	2	11
-	+16 2362	107415	6.49	1.02	0.82	2 2 3	1	P,16,Pluto
-	+16 2363	-	10.32	0.61	0.06	2 2 3	1	
-	+16 2364	107496	9.41	0.55	0.14	2 2 3	1	
Grf 16	-	-	11.38	0.61	-	2 2 -	1	11
" 14	-	-	11.05	0.82	-	2 2 -	1	11
" 4	+ 1°2689	107842	8.68	0.50	-	5 2 -	2	11
" 7	+ 1 2690	-	9.72	0.60	-	2 2 -	1	11
" 6	+ 1 2691	107954	9.49	0.49	-	5 3 -	2	11
" 15	-	-	11.26	0.56	-	2 2 -	1	11

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
Grf 20	-	-	11.93	0.4:	-	3 - -	2	11
" 3	+ 1°2696	108263	8.31	1.06	-	2 2 -	1	11
" 5	+ 0 2945	108360	8.92	0.85	-	4 2 -	2	11
" 19	-	-	11.48	0.89	-	2 3 -	6	11
" 24	-	-	12.91	0.51	-	2 2 -	1	11
" 23	-	-	12.33	0.55	-	2 2 -	1	11
-	+14°2523	109942	7.22	1.18	1.27	2 1 3	3	Pluto,16
" 2	- 0 2595	109969	7.22	0.02	-	2 2 -	1	11
-	+14 2428	109997	9.23	0.25	0.13	2 1 3	3	Pluto,16
38 Vir	4891	111998	6.125	0.48	0.03	1 1 1	5	P,12,Uranus
-	4896	112048	6.45	1.08	1.02	2 1 2	5	P,12,Uranus
-	- 2°3597	112283	7.66	0.47	-0.07	2 2 3	1	
-	- 4 3377	112302	9.25	0.74	0.22	2 2 3	5	Uranus
-	- 5 3636	114046	9.22	0.585	0.06	2 1 3	4	Uranus
-	- 6 3742	114095	8.37	0.96	0.59	3 1 3	4	P,Uranus
-	+47°2066	117815	7.07	0.21	0.07	2 2 2	2	
-	-11 3671	123523	6.86	0.10	0.02	2 2 4	1	
-	5360	125349	6.23	0.03	0.04	2 2 2	1	
μ Lib	5523	130559	5.32	0.08	-0.01	2 2 3	5	P,13
-	-12 4141	130708	8.00	0.41	-	2 2 -	4	13

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
-	-13°3994	130953	7.69	1.40	-	3 2 -	3	13
-	-13 4003	131221	9.37	0.64	-	2 3 -	4	13
-	-13 4022	131898	8.82	0.33	-	2 2 -	3	13
-	-14 4085	132568	9.05	0.35	-	4 4 -	3	13
-	-14 4095	133034	8.87	1.18	-	2 3 -	3	13
-	-14°4118	-	9.82	0.93	-	2 2 -	3	13
-	-16 4116	138887	8.86	0.93	-	4 2 -	2	13
-	-16 4120	139061	7.77	0.46	-	2 3 -	2	13
-	-16 4122	139157	9.48	0.48	-	2 5 -	2	13
-	-17 4388	139409	7.15	1.05	-	3 5 -	2	13
-	-16°4129	139485	9.55	0.78	-	3 3 -	2	13
-	-17 4395	139709	9.50	1.00	-	4 6 -	3	13
-	-16 4138	139819	9.68	0.38	-	3 3 -	2	13
-	-16 4144	140053	9.27	1.09	-	4 3 -	2	13
-	-17 4413	140559	9.68	0.99	-	2 3 -	2	13
-	-19°4326	-	9.41	1.16	1.07	3 4 5	3	Neptune
-	-19 4327	145275	9.13	0.60	0.04	3 2 3	4	
-	-19 4362	147195	8.73	0.72	-	2 2 -	2	13
ψ Oph	6104	147700	4.50	1.03	0.82	2 2 2	1	P
-	-19 4368	147931	9.02	0.54	-	2 2 -	2	13

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
-	-19°4374	-	10.92	1.82	-	2 8 -	3	13
-	-19 4375	148970	9.66	0.85	-	3 5 -	3	13
-	-19 4381	149330	8.88	1.66	-	2 3 -	1	13
-	-19 4399	-	10.75	1.45	-	2 2 -	2	13
-	-21 4539	155251	8.91	1.19	-	2 2 -	2	13
-	-21°4540	155269	9.04	0.52	-	3 3 -	2	13
-	-21 4554	155866	8.99	1.3:	-	6 - -	2	13,15
-	-21 4557	155993	9.70	0.88	-	3 5 -	2	
-	-21 4564	-	9.86	1.54	-	4 4 -	3	13
ξ Oph	6445	156897	4.37	0.41	-0.02	2 2 2	1	P
-	-21°4594	157351	8.2:	0.52	-	- 2 -	3	13,15
-	-21 4605	-	9.88	2.08	-	4 6 -	3	13
-	-21 4641	159012	9.62	0.43	-	3 3 -	2	13
-	-21 4648	159211	9.84	0.68	-	4 3 -	2	13
-	-22 4479	163919	8.96	1.42	-	2 2 -	1	
-	-22°4480	163936	9.07	1.21	-	2 2 -	2	13
4 Sgr	6700	163955	4.75	-0.02	-0.06	2 2 2	1	P
-	-22 4511	164534	9.22	0.17	-	2 5 -	2	13
-	-22 4555	165223	9.02	0.04	-	2 3 -	2	13
-	-22 4581	165812	7.96	0.03	-	2 2 -	1	13

1	2	3	4	5	6	7	8	9
	HR/BD	HD	V	B-V	U-B	m.e.	n	Remarks
-	-22°4597	166263	7.75	1.26	-	2 2 -	2	13
-	-22 4613	166742	9.00	0.10	-	3 5 -	2	13
-	-22 4619	166852	8.50	0.30	-	3 2 -	2	13
14 Sgr	6816	167036	5.49	1.53	-	2 2 -	1	P
-	-22 4648	167663	8.14	1.63	-	2 2 -	1	13
-	-22°4655	167842	7.71	1.10	-	2 2 -	1	13
-	-22 4702	168900	9.32	0.09	-	2 3 -	1	13
-	-23 14320	169039	9.33	1.28	1.10	2 2 3	2	14,Jupiter
-	-22 4722	169635	9.16	1.84	-	2 2 -	2	13
-	-23 14580	172052	6.73	0.64	-	3 2 -	2	14,Jupiter
ν^1 Sgr	7116	174974	4.85	1.41	-	2 2 -	1	P

LIST OF SYMBOLS AND ABBREVIATIONS

This list is not complete. Many symbols, used only once or twice and explicitly identified in context, have been omitted. Page numbers refer to definition or first mention.

Å	Ångström unit (10^{-8} cm)
a	semimajor axis
AE	"American Ephemeris and Nautical Almanac", annual publication by the U.S. Government Printing Office; identical in contents to the British "Astronomical Ephemeris"
AU	Astronomical Unit (1.495×10^{8} km)
B	saturnicentric latitude of Earth referred to the plane of the rings; similarly, B': latitude of Sun
B	blue magnitude on the UBV system; B_o: reduced to mean opposition distance (p. 7)
B-V	color on the UBV system
BD	Bonner Durchmusterung star catalog
cd	concentric diaphragms method (p. 64)
CD	Cordoba Durchmusterung star catalog
deg	degree (of angle)
EE	eastern elongation
est.m.e.	estimated mean error (p. 93)
$F(\alpha)$	phase function (p. 7)
HD	Henry Draper star catalog
HR	Harvard Revised Photometry star catalog
J VI	Jupiter VI; similarly J VII etc.
K_0	coefficient in Fourier expansion of light curve (ch. V: D); similarly, K_1 and K_2

k_2	potential Love number of order 2 (p. 26)
KPNO	Kitt Peak National Observatory
L	mean orbital longitude (p. 19)
LPL	Lunar and Planetary Laboratory, University of Arizona
m	magnitude (in general); for m_o, $\overline{M}_o$, m(1,α), see p. 7
m_{pg}	photographic magnitude
m_v	visual magnitude
mag.	magnitude
McD	McDonald Observatory, Universities of Texas and Chicago
m.e.	mean error
ms	multiple skies method (p. 93)
p	geometric albedo (p. 11)
PE	photoelectric
Q	reciprocal of specific dissipation factor (p. 28)
r	distance from Sun; in ch. V:C, distance from central image
SA	Selected Area
SC	superior conjunction
s.e.	standard error
ss	symmetrical skies method (p. 64)
U	geocentric longitude of Saturn, referred to the plane of the rings (p. 19)
U	ultraviolet magnitude on the UBV system; U_o: reduced to mean opposition distance (p. 7)
U-B	color on the UBV system
UBV	the photometric system of Johnson and Morgan (1953)
V	yellow (visual) magnitude on the UBV system; for V_o, $\overline{V}_o$, V(1,α), see p. 7
vB	van Bueren's numbering of stars in the Hyades, employed by Johnson and Knuckles (1955)
WE	western elongation
α	solar phase angle (p. 6)
β	phase coefficient (p. 9); in ch. V:D, latitude
Θ	orbital phase (p. 14); in ch. V:D, angle between spin axis and line of sight

Θ'	rotational phase (p. 17)
λ	wavelength
λ	celestial longitude (usually heliocentric)
μ	micron (10^{-4} cm)
μ	rigidity (ratio of shear stress to shear strain)
σ	standard deviation
ϕ	scale factor for opposition effect (p. 11)
ϕ	planetographic latitude of subsolar (subscript $_\odot$) or sub-earth (subscript $_\oplus$) point (p. 20)
< >	average value of quantity enclosed in brackets
:	(following numerical value in table) data of greater than average uncertainty; symbol doubled for extreme cases

Star designations of the type +17°703 are BD numbers unless otherwise indicated.

The I.A.U.-approved three-letter abbreviations for the names of the constellations are used.

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VITA

Name: Leif Erland Andersson

Born: November 4, 1943, in Falkenberg, Sweden

Citizenship: Swedish

Spouse: Gloria Lee née Ptacek, of East Chicago, Indiana

Education: Fil.kand. 1966, University of Lund, Sweden

A.M. (Astronomy) 1970, Indiana University

Experience: Institute of High Tension Research (University of Uppsala, Sweden)
technical assistant, 1962, 1963

Swedish Astrophysical Station, Anacapri, Italy
solar patrol observer, 1965

Warner and Swasey Observatory, Case Western Reserve University
research assistant, 1968

Astronomy Department, Indiana University
associate instructor, 1969-70, 1971-73
research assistant, 1970-71

Societies: Svenska Astronomiska Sällskapet

American Astronomical Society

Division of Planetary Sciences (A.A.S.)

Publications: "Observations of the satellite Jupiter VI"
Astron.J. 75, 743 (1970) /with M.S. Burkhead/

"The eclipsing binary BD+16°516"
Inf.Bull.Variable Stars 657 (1972) /with M.A. Seeds/

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