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CCD PHOTOMETRY OF THE URANIAN SATELLITES[1]

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ABSTRACT

Broadband V and R CCD observations of the Uranian satellite system have been obtained over the full range of solar phase angles observable from Earth. These first visual observations of the phase curves of Miranda, Ariel, and Umbriel show that Ariel and Miranda exhibit the large opposition surges previously seen on the two outer Uranian satellites. Umbriel, however, lacks an appreciable opposition surge; its surface is either extremely compact or consists of small particles which lack a backscattered component. The tenuous structure of the other satellites is most likely due to the effects of eons of meteoritic gardening.

1. INTRODUCTION

Observations of the near opposition phase curve of airless planets or satellites provide important information on the surface properties of these bodies. It is well known that most planetary surfaces exhibit a nonlinear surge in brightness as they become fully illuminated to an observer. This so-called "opposition effect" has been attributed to two primary causes: (1) the rapid disappearance of mutual shadows cast among loosely packed particles comprising the optically active portion of the regolith (Irvine 1966; Hapke 1986; Buratti 1991); and (2) highly backscattering single particle phase functions of the particles, which in turn can be attributed to their intrinsic properties including size, shape, and indices of refraction (Buratti, 1991). A third possible mechanism that has recently been suggested is coherent backscatter of aggregates of particles (Hapke 1990; Hapke & Blewett 1991). Accurate telescopic or spacecraft measurements of opposition phase curves can be compared to theoretical models and laboratory measurements to place important constraints on the current morphology and geologic evolution of the observed body. Ground-based observations of the satellites in the outer solar system continue to be particularly significant because constraints placed on the viewing geometries of these bodies by the Voyager spacecraft precluded the observation of opposition phase curves in most cases. The existence of large opposition effects for at least three of the Uranian satellites was first discovered from the ground in the near-IR region of the spectrum (Brown & Cruikshank 1983), and later for the outer two satellites in the V-filter (Goguen *et al.* 1989). From Voyager 2, only Titania was observed near opposition, with a minimum phase angle of 0.8 degrees. In contrast, we obtained data at phase angles less than one degree on 14 nights, and at phase angles less than 0.1 deg on 5 nights (see Table 1). Our minimum phase angle was 0.01 deg. Of course, spacecraft observations include many at large solar phase angles which are not attainable from Earth, so that the two data sets are highly complementary (Buratti *et al.* 1990).

Reliable photometric observations of these satellites in the visual region of the spectrum have been difficult to obtain with traditional astronomical instrumentation such as photomultiplier tubes because of scattered light from the primary bodies. Difficult strategems involving occulting disks and pseudoapertures placed on adjacent regions of the sky adjacent to individual satellites were devised. Typically errors of at least $\sim 10\%$ remained, and only observations of the outer two satellites—Titania and Oberon—could be obtained (Goguen *et al.* 1989). The advent of CCD detectors has enabled after-the-fact mathematical modeling of scattered light and a pixel-by-pixel subtraction of it. The Uranian satellite system is particularly amenable to the use of a CCD camera because the entire satellite system, which encompassed no more than 1.2 minutes of arc throughout the entire period of our observations, can easily be imaged within the CCD's field of view ($\sim 12 \times 12$ arcmin). Differences among the five satellites can thus be accurately obtained by computing direct ratios between the satellites themselves with no intermediate comparison to standard stars [of course, scattered light, which remains our largest source of error ($\sim 5\%$), must still be subtracted]. Finally, accurate relative photometric measurements can be obtained on contiguous nights through the use of several on-chip comparison stars. Absolute photometric measurements can be made on the night with the best observing conditions, or on a subsequent photometric night by imaging the same star field along with standard stars.

This paper describes V and R observations of the Uranian satellite system obtained with a CCD camera and the 60-inch telescope at Palomar Mountain Observatory. V and R phase curves spanning the full excursion in solar phase angle and opposition magnitudes are derived for the outer four satellites: these are the first visual phase curves of Ariel and Umbriel. Photometric observations were obtained for Miranda in the R filter on three nights to produce the first rudimentary phase curve of this satellite.

[1]Observations were made at the 60-inch telescope at Palomar Mountain which is jointly owned by the California Institute of Technology and the Carnegie Institute of Washington.

TABLE 1. Summary of observations of the Uranian satellites.

Date (UT)	Filter	Phase angle	#Images
8 June 1985	V	0.09	2
	R		1
5 April 1986	V	1.82	2
8 June	V	0.17	2
9 June	V	0.12	2
	R		2
11 June	V	0.01	2
	R		2
12 June	V	0.03–0.04	9
13 June	V	0.09	7
	R		2
27 June	V	0.82	3
28 June	V	0.97	3
24 July 1987	V	1.85	2
	R		3
14 March 1988	V	2.73	2
	R		2
28 June	V	0.43	4
	R		4
29 June	V	0.48	2
	R		1
30 June	V	0.53	1
	R		4
1 July	V	0.58	1
	R		5
June 19 1990	V	0.85	6
	R		3

2. OBSERVATIONS AND DATA REDUCTION

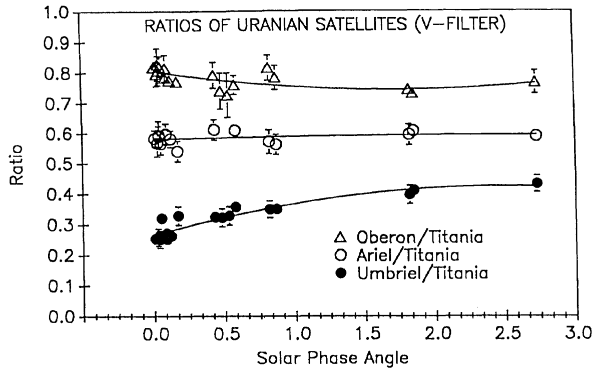
We have obtained 79 broadband (V and R, with effective wavelengths of 0.55 and 0.65 μm, respectively) CCD images of the Uranian satellite system over a six year period (Table 1). These observations were designed to acquire photometrically accurate measurements of the five major satellites over the full range of solar phase angles visible from Earth. All observations were obtained with a CCD camera mounted at the Cassegrain focus of the 60-inch reflecting telescope on Palomar Mountain. From 1985–1987, a 320$\times$512 array detector was used; in 1988 the camera was upgraded with a TI model 365 800$\times$800 detector. The field of view of the detector was enlarged by means of reimaging optics to approximately 12 arcmin square. The exposure times ranged from 1–20 s. We found that the shorter exposures gave better results for Ariel and the few observations we have of Miranda. Standard star measurements were obtained for 3–5 standards from Pergathofer (1969) or Landoldt (1983). However, on the nights of 1986 9, 12, 13, and 27 June, and 1988 29, and 30 June, and 1 July, we used 2–5 field stars similar in brightness and color to the satellites. These stars also appeared in the field of view of contiguous nights for which absolute standard measurements were obtained; all relative measurements were tied in to the absolute standards. In general, we obtained the absolute measurements on the night of an observing run with the best photometric conditions. In a few cases standard measurements were obtained on subsequent nights by imaging standard stars and the star field at the same airmass.

Each CCD image was processed in the standard fashion: unshuttered exposures were subtracted from the images, which were then corrected for field variations in sensitivity. (The flatfield frames created for these corrections were produced at the beginning and end of each night by flooding the top of the exposed telescope dome with an incandescent light and exposing the CCD camera until it reached approximately the center of its linear range). A square aperture of $\sim$5–7 arscec (depending on the seeing) was centered on each satellite and the signal from all the pixels within the box were summed. The scattered light (plus sky background) was accurately modeled with an eighth-order polynomial with the following method: For each image, a line scan was extracted radially from Uranus, saturated pixels were eliminated, and a polynomial regression fit was obtained. The value of the function was evaluated for each pixel of an imaginary aperture equal in size and at the same radial distance from Uranus as each satellite's aperture. The resulting values were summed for each aperture and subtracted from the sums computed for the apertures containing each satellite. If more than one image was obtained with a particular filter, the results were averaged (although in most cases we used the longer exposures only for the outer two satellites). Boxes of an equivalent size were used to compute the signal from the standard stars. Background was computed for each standard star by placing four boxes also $\sim$5 arcsec square outside each corner of the aperture, computing the average background per pixel, and subtracting the appropriate amount from the total signal. For several of our relative (on chip) standard stars, background stars appeared in one of these four sky apertures; in these cases only three boxes were used. We are confident that field stars down to at least 19th magnitude did not appear in any of our apertures or line scans for computing scattered light.

We estimate our typical error as 5%–6% for both filters. The actual error bars were computed for each point by root sum squaring the two major sources of error: scattered light subtraction and computation of absolute brightness from the standard stars. These individual errors were estimated from the scatter resulting from computations using individual images (in the case of scattered light), or individual standard stars. For the nights where only one image in a filter or appropriate exposure was obtained, we adopted a nominal value for the error due to scattered light subtraction.

3. RESULTS

Ratios of both the R and V integrated brightness of Ariel, Umbriel, and Oberon with respect to Titania are shown in Fig. 1. Titania was selected as the comparison object because it is the brightest of the five satellites and has the best signal-to-noise ratio. This simple figure shows clearly that these four outer satellites of Uranus exhibit important differences in their surface properties. To obtain actual phase curves of the satellites, the integrated bright-



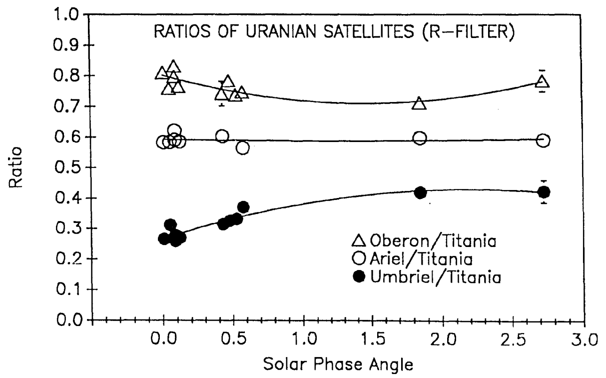


FIG. 1. The ratios of the integrated brightness as a function of solar phase angle for Oberon, Ariel, and Umbriel with respect to Titania in both the V filter (top) and R filter (bottom). These ratios are possible because the entire satellite system appears on each CCD image. Sky background and scattered light from Uranus have been subtracted for each measurement. Umbriel clearly has a different phase curve than the other three satellites. The phase curve of Oberon is possibly more sharply peaked than those of Titania and Ariel. The lines are the best-fit, second-order polynomials.

nesses for each satellite on each night were converted to a magnitude scale through the standard star measurements, and the observations were then converted to a physical scale (geometric albedo times a solar phase function) with the following equation:

$$p\cdot f(\alpha)=\frac{D^2d^2}{R^2}\,10^{m_s-m_{\rm Sun}/2.5},$$

where $f(\alpha)$ is the solar phase function, D is the heliocentric distance of Uranus on the day of the observation, d is the corresponding geocentric distance of Uranus, R is the radius of the satellite (Smith *et al.* 1986), m_s is the magnitude of the satellite, and $m_{\rm Sun}$ is the magnitude of the Sun (Allen 1976). The geometric albedos are listed in Table 2, with past results for comparison. These geometric albedos were computed by fitting a second-order polynomial to the phase measurements obtained at less than 0.1 deg (in the case of Miranda, all the observations were used for the fit). Both the V and R phase curves are shown in Fig. 2; to facilitate comparisons among the objects, the data are shown normalized. Absolute scales can be recovered with the geometric albedos listed in Table 2.

TABLE 2. Uranian satellites, geometric albedos.

Satellite	p_R	p_v	Voyager[1]	Anderson (p_v) (1974)[2]	Goguen (p_v) (1989)
Miranda	0.33±0.03	---	0.32±0.05	---	---
Ariel	0.30±0.02	0.29±0.02	0.31±0.05	---	---
Umbriel	0.13±0.01	0.13±0.01	0.20±0.05	---	---
Titania	0.26±0.02	0.27±0.02	0.28±0.04	0.22	0.32
Oberon	0.23±0.02	0.23±0.02	0.23±0.05	0.18	0.28

Notes to TABLE 2

[1]Buratti *et al.* (1990); Green filter (0.55 μm).
[2]Voyager radii assumed.

Photometric R observations were obtained for Miranda on three nights to produce the first opposition phase curve of this satellite (Fig. 3). Although the phase curve does not cover the full excursion in phase angles possible from Earth, the data are sufficient to show that Miranda has a sharp opposition surge similar to that observed for Ariel, Titania, and Oberon.

4. DISCUSSION AND SUMMARY

In the cases where our observations can be compared with previous results, we generally find consistency. Brown & Cruikshank (1983) observed large opposition surges for Ariel, Titania, and Oberon, and possibly a lack of one for Umbriel (even the Voyager observations, although not obtained at opposition, suggest Umbriel's phase curve is unusual; see Helfenstein *et al.* 1988). Goguen *et al.* confirmed the opposition surges in the V filter for the outer two Uranian satellites. The first measurements of Miranda's phase curve suggest this satellite also has a large opposition surge. Further observations of Miranda should be obtained in filters for which scattered light from Uranus is not as significant, such as in methane absorption bands. We find no evidence for a wavelength dependence to the phase curve. Given the relatively flat spectrum of the satellites in the spectral region over which we observed, this result was expected.

Our one important disagreement with previous results is the geometric albedo of Umbriel (see Table 2). Because of this satellite's lack of any significant opposition surge, we find that Umbriel is significantly darker under full illumination than the other Uranian satellites. This fact, coupled with its unusual phase curve, means its surface textural properties, as well as its composition, are unusual. Both facts point to a surface enriched in carbonaceous chondritic material, which has the required low albedo (Tedesco *et al.* 1989), and has been observed in some cases to lack an opposition surge (French 1987). Laboratory experiments suggest that the carbonaceous material may consist of small particles: measurements of the phase curves of dark particulate materials show that the opposition effect disappears as the particle sizes constituting the sample decrease from 500 μm to less than 63 μm (Buratti & Bur-

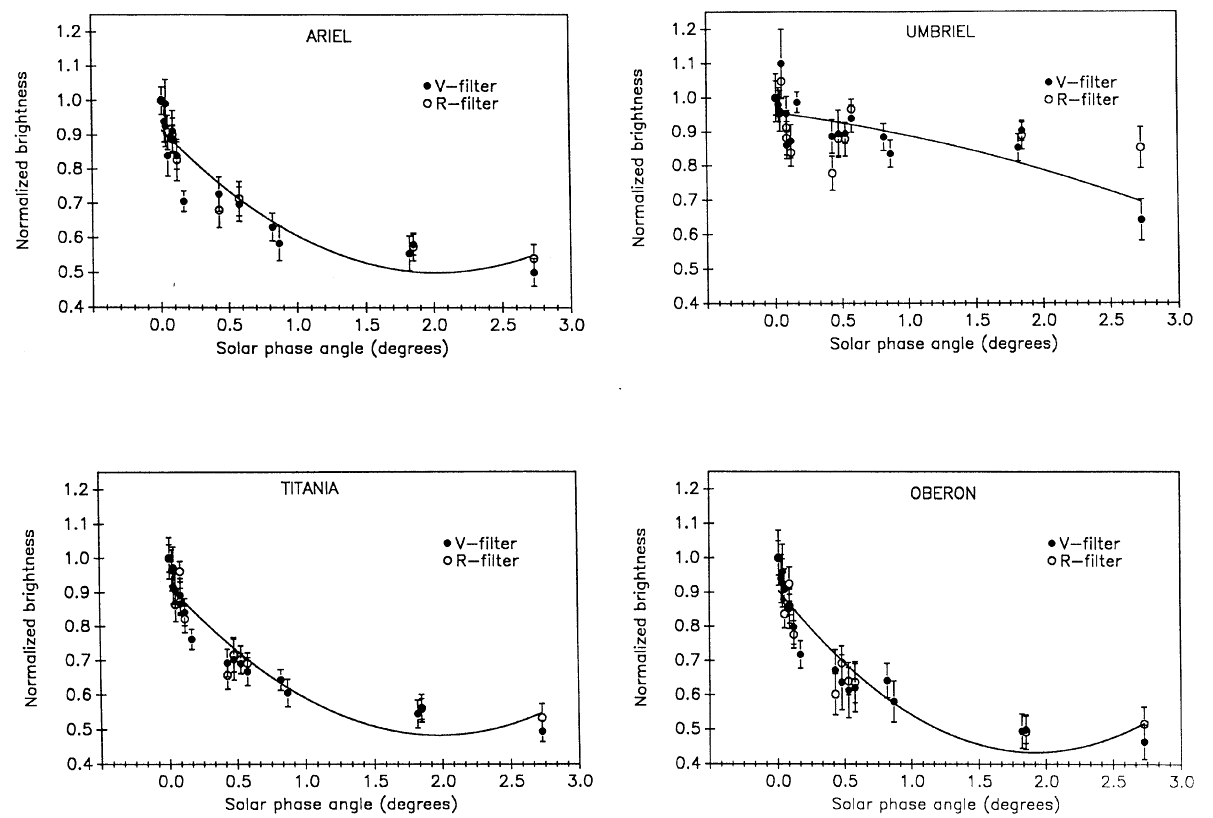


FIG. 2. The phase curves of the four outer satellites (see the text for an explanation of the procedures for normalization and conversion of the data from astronomical magnitudes to physical units). To facilitate comparisons between the satellite, the data have been normalized; the actual geometric albedos of the satellites are listed in Table 2. The lines are best-fit, second-order polynomials. Besides Umbriel, the only other satellite which has been observed to have a "concave" phase curve is Enceladus (Buratti & Veverka 1984); and that was measured between 8 and 43 deg.

rows, in preparation). These small particles may, in fact, be sufficiently transparent to allow photons to continue in the forward scattering direction. Another curious observable of Umbriel's surface is that it lacks the large albedo variegations seen on the other Uranian satellites, yet its optical color variations are at least as large (Buratti & Mosher 1991). Buratti *et al.* (1991) claim that all these unusual photometric properties of Umbriel are evidence for an optically thin coating of exogenous, dusty material, such as might be supplied by the impact of a comet. A large, low albedo region on Umbriel, which is located near the apex of motion of the satellite (Buratti & Mosher 1991), might be a large crater resulting from the impact of a dark comet or asteroid [Helfenstein *et al.* (1988) attribute the feature to an early endogenous resurfacing event].

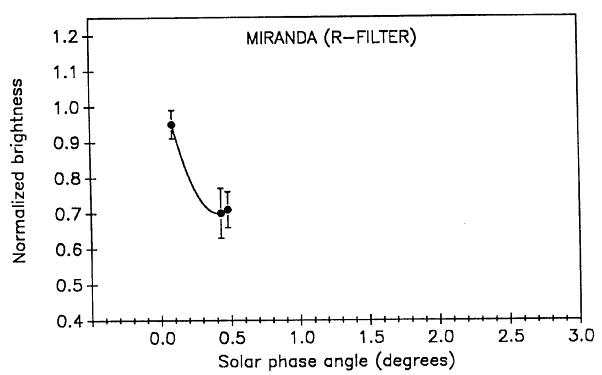


FIG. 3. Eight photometric images of Miranda were reduced to produce the first phase curve of this satellite. The few available data points suggest that this body has a large opposition surge similar to Ariel, Titania, and Oberon.

The large opposition surges of the Uranian satellites and other bodies with similar phase curves such as Io and the leading side of Callisto have traditionally been attributed to the existence of extremely fluffy surfaces (Irvine 1966; Hapke 1986; Helfenstein *et al.* 1988; Simonelli & Veverka 1986; Buratti *et al.* 1988; Buratti 1991). Io's surface morphology is controlled by volcanic activity and thus has little relevance to the Uranian satellites. The texture of Callisto's surface, which is primordial, has been attributed to micrometeoritic bombardment (Buratti 1991). Although the Uranian satellites underwent early geologic activity (Smith *et al.* 1986; Croft *et al.* 1991; Helfenstein *et al.* 1989), calculations by Gault *et al.* (1974) show that meteoritic gardening processes reach a saturation point in less than one million years, and could thus produce a gardened surface on the Uranian satellites similar to that of Callisto.

Another controlling factor, particularly at the very small phase angles (<0.5 deg) may be a strongly backscattering single particle phase function of individual particles, caused by an optical phenomenon such as diffracted glories or halos (Born & Wolf 1964). A third recently discussed phenomenon is coherent backscatter, in which multiply scattered photons traversing the same distance in different directions recombine coherently in the direction of retroreflectance (Hapke 1990; Hapke & Blewett 1991; Domingue *et al.* 1991). This explanation is somewhat problematic because multiple scattering is not significant for low albedo surfaces such as those of the Uranian satellites (Buratti 1984); it is however true that it is the lowest albedo satellite that lacks a surge. The inflection observed at ~0.3 deg does suggest that two phenomena may be responsible for the observed phase curve; similar inflections have been seen for the Galilean satellites (Buratti *et al.* 1988).

The current orientation of the spin axis of the Uranian satellite system precludes ground-based observations of geographical differences in surficial composition or texture. Analyzing Voyager imaging data, Buratti & Mosher (1991) found that the leading sides of the outer four satellites were redder than their trailing sides and that this effect increased with distance from Uranus (no corresp|onding albedo dichotomy was found). They suggested that accretion of reddish, possibly primordial dust offered the best explanation for this asymmetry (for an alternate explanation—at least for Oberon—involving emplacement of geologic units, see Helfenstein *et al.* 1991). This material is distinct in character from that found exclusively on Umbriel, which may have resulted from a catastrophic event such as a cometary impact and subsequent reaccretion of material. We note that there is some suggestion that Oberon's phase curve is even more sharply peaked than the other Uranian satellites (see Fig. 1). This result suggests that the material accreted on the leading sides of the Uranian satellites is very strongly backscattering.

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