

CCD PHOTOMETRY AND SPECTROSCOPY OF THE OUTER *JOVIAN SATELLITES*<sup>1</sup>JANE LUU<sup>2</sup>

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## ABSTRACT

We present new charge-coupled device (CCD) photometry and spectroscopy of the eight outer *Jovian satellites* obtained from November 1987 to February 1989. The photometry consists of light curves for J7–J12, plus *BVRI* colors for J6, J8–J13. Spectroscopic data include reflectance spectra for J6, J8–J11. The satellites are spectrally diverse, with reflectivity gradients ranging from neutral ( $0.4\% \pm 0.1\%/10^3 \text{ \AA}$ ) to red ( $12\% \pm 1\%/10^3 \text{ \AA}$ ). The satellites thus resemble a mixture of C- and D-type asteroids. Similarities between the satellites and Trojan asteroids (diverse colors, low albedos) are consistent with the hypothesis that these two groups of objects share a common origin [Kuiper, *Vistas in Astronomy*, 2, 1631 (1956)]. However, the satellites seem to have less extreme shapes than the Trojans, perhaps due to the longer amount of time they spent in the proto-Jupiter nebula. Physical properties of the satellites are generally consistent with, but do not prove, the capture origin theory [Pollack *et al.*, *Icarus*, 37, 587 (1979)].

## 1. INTRODUCTION

The small outer *Jovian satellites* are little known compared to their brighter, more illustrious cousins, the *Galilean satellites*. There are eight known outer *Jovian satellites* clustered in two dynamically distinct groups, each containing four satellites. The inner group (J6 Himalia, J7 Elara, J10 Lysithea, and J13 Leda) travels in prograde orbits with a mean semimajor axis  $a = 1.151 \times 10^7$  km. In contrast, the orbits of the satellites in the outer group (J8 Pasiphae, J9 Sinope, J11 Carme, and J12 Ananke) are characterized by a retrograde direction, and are located twice as far away from Jupiter as the inner group (mean semimajor axis  $a = 2.275 \times 10^7$  km). The distinct orbital characteristics of the two groups led Kuiper (1951, 1956) to suggest that they were formed by the capture and break up of two separate bodies upon entry into the atmosphere of proto-Jupiter. Colombo & Franklin (1971) advocated the fragmentation hypothesis for the satellites, but suggested that they resulted from the collision of a larger outer *Jovian satellite* with an asteroid. The fragments of the original satellite would form the prograde group, while the retrograde group would consist of fragments of the asteroid. Pollack *et al.* (1979) performed a quantitative analysis of the hypothesis where the satellites are fragments of two planetesimals that were lost and recaptured by Jupiter, and found the hypothesis to be consistent with the then-known properties of the outer satellites. Tholen & Zellner (1984, hereafter referred to as TZ84) studied spectra of six of these satellites and concluded that at least five were of spectral class C. Hartmann (1987), noting that C types are concentrated among the outer satellites and not among Trojans, suggested that C-type asteroids were scattered around the solar system by Jupiter resonances near

the close of planet formation, some of which were then captured by the extended proto-atmosphere and became the outer satellites.

The small sizes of the outer *Jovian satellites* ( $\sim 10$ – $90$  km in radius) have discouraged rigorous studies of these objects, and most of the available information is restricted to the brightest members of the two groups, namely J6 and J7. Besides the small sizes of the satellites, strong scattered light from Jupiter often hinders single channel (e.g., photomultiplier) observations, making accurate photometry a difficult task. At present, *UBVRI* photometry has been published for J6, J7 and J8 (Degewij *et al.* 1980a, hereafter referred to as DAZ80), and multicolor photometry is available for all satellites except J12 and J13 (Tholen & Zellner 1984). Cruikshank (1977) obtained thermal infrared measurements for J6 and J7, reporting a geometric albedo of 0.02–0.03 for both satellites. Degewij *et al.* (1980b) confirmed the low albedo of J6 via *JHK* and polarization measurements, and also obtained a lightcurve of amplitude  $\sim 0.15$  mag and a period of 9.2–9.8 hr. The scant information on the outer *Jovian satellites* as a group prevents strong constraints on their origin and composition. However, from their multicolor data, TZ84 deduced that the satellites (in particular J6, J7, J8, and J10) resemble C-type asteroids, not the D types that dominate the outer belt and the Trojan population (Gradie & Tedesco 1982).

In this paper, we present the results of an independent study of the outer *Jovian satellites* and the first to be undertaken using modern, two-dimensional detectors. Our use of CCDs allowed accurate subtraction of the background scattered light from Jupiter, minimizing photometric errors due to scattered light and field star contamination. The new data include: (1) CCD light curves of J7, J8, J9, J10, J11, and J12; (2) *VRI* colors of J6, J8, J9, J10, J11, J12, and J13; and (3) CCD spectra of J6, J8, J9, J10, and J11. The different types of data for each satellite are summarized in Table 1. Our present goal is to improve the constraints on the origin of the satellites by adding new rotational and spectroscopic data to the existing database. Groundbased observations are currently the only means to study these objects, as there is no plan to observe the satellites with the spacecraft Galileo.

<sup>1</sup> Observations taken at the Michigan–Dartmouth–MIT Observatory, Kitt Peak, which is operated by a three-university consortium consisting of University of Michigan, Dartmouth College, and MIT.

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TABLE 1. The new Jovian satellite data.

	J6	J7	J8	J9	J10	J11	J12	J13
Lighcurve	—	✓	✓	✓	✓	✓	✓	—
VRI Photometry	✓	—	✓	✓	✓	✓	✓	✓
CCD Spectrum	✓	—	✓	✓	✓	✓	—	—

## 2. OBSERVATIONS

## 2.1 CCD Photometry

CCD photometry of the satellites was obtained in three observing runs in November–December 1987 and December 1988. All data were taken with broadband Mould filters on the Michigan–Dartmouth–MIT (MDM) 1.3 m, except for the December 1987 data, which were taken on the MDM 2.4 m. Both telescopes had a focal ratio  $f/7.5$ , and both were operated with CCD cameras at their Cassegrainian foci. In November 1987, the detector was the  $390 \times 594$  pixel MASCOT CCD, while the  $398 \times 598$  pixel BRICC CCD (Lupino 1989) was used from December 1987 onward. The MASCOT had  $22 \mu\text{m}$  pixels and a readout noise of 10 electrons per pixel; similarly, the BRICC was a TI 4849 chip with  $22 \mu\text{m}$  pixels, and also a 10 electron readout noise. The Mould filters  $V$ ,  $R$ , and  $I$  were used for all images. A summary of the instruments used for CCD photometry and their pixel scales can be found in Table 2.

All CCD images were calibrated by subtracting the bias (zero exposure) frames and dividing by “flatfield” frames. These flatfield frames were either created by averaging short exposures of the morning twilight sky or by computing the median of the images taken during the night. “Flattening” the images has the effect of removing the pixel-to-pixel sensi-

TABLE 2. Instrument log.

CCD Photometry									
Observing Run	Telescope	$f/l$ Ratio	Instrument	CCD Size [pixels]	Read Noise [ $e^-$ /pix]	Pixel Scale [arcsec]	Program		
Nov 1987	MDM 1.3 m	7.5	MASCOT	390 x 584	10	2.10	lightcurves: J7, J8		
Dec 1987	MDM 2.4 m	7.5	BRICC	398 x 598	10	0.26	lightcurve: J9		
Dec 1988	MDM 1.3 m	7.5	BRICC	398 x 598	10	0.48	lightcurves: J10, J11, J12 VRI colors: J6, J8, J9, J10, J11, J12, J13		
CCD Spectroscopy									
Telescope	$f/l$ Ratio	Instrument	CCD Size [pixels]	$\Delta\lambda$ FWHM [Å]	$\lambda$ Range [Å]	Read Noise [ $e^-$ /pix]	Spatial Scale [arcsec/pixel]	Slit Size [arcsec]	Dispersion [Å/pixel]
2.1 m	7.7	GoldCam	800 x 800	20	3600–7200	9	0.79	2.8 x 150	4.9

tivity variations in the CCD. Both methods of flattening were found to work equally well; the corrected images were found to be very flat, with less than 0.5% variations across the chip. This error is a negligible fraction of the photometric uncertainty, which mostly stems from sky-subtraction uncertainty and zero-point errors. The images were flux calibrated with standard stars from Landolt (1983). Nightly extinction coefficients were determined by photometry of field stars and of the same Landolt stars observed at different airmasses. Most light-curve observations were made with the  $R$  filter to exploit the maximum efficiency of the CCD; when this was not possible, the  $V$  filter was used. In general, the photometry was accurate to  $\pm 2\%$ – $3\%$ .

We present in Table 3 the dates of observations and the corresponding viewing geometry for each satellite. In Table 4, we list the photometric results, and where possible, the rotation periods determined from the photometry. The rotation periods were determined with the aid of the phase dispersion minimization method, assuming a double-peaked light curve expected of a nonspherical atmosphereless body. The observations are discussed in more detail in the following sections.

## 2.1.1 J6 Himalia

Our observations of the satellite J6 are restricted to  $VRI$  photometry measured on 13 December 1988 at the MDM 1.3 m. The absolute magnitudes  $m(1,1,0)$  were derived from the equation

TABLE 3. Observing geometry.

Satellite	Dynamical Group	UT Date	R [AU]	$\Delta$ [AU]	$\alpha$ [deg]
J6	Prograde	13 Dec 1988	5.09	4.17	4.4
J7	Prograde	19 Nov 1987	4.90	4.07	6.8
		20 Nov 1987	4.90	4.08	7.0
J8	Retrograde	15 Nov 1987	4.89	4.04	6.5
		16 Nov 1987	4.89	4.05	6.5
		11 Nov 1987	4.84	4.32	10.2
		13 Nov 1988	5.08	4.18	4.9
J9	Retrograde	10 Dec 1987	5.01	4.39	9.3
		11 Dec 1987	5.02	4.41	9.5
		12 Dec 1987	5.02	4.42	9.6
		13 Dec 1988	4.89	3.97	4.6
J10	Prograde	8 Dec 1988	4.98	4.03	3.3
		13 Dec 1988	4.98	4.05	4.4
J11	Retrograde	11 Dec 1987	4.81	4.25	10.3
		10 Dec 1988	5.11	4.18	4.1
		11 Dec 1988	5.11	4.19	4.3
		13 Dec 1988	5.11	4.20	4.7
J12	Retrograde	11 Dec 1987	5.10	4.51	9.5
		12 Dec 1987	5.10	4.53	9.6
		10 Jan 1988	5.10	4.98	11.1
		12 Dec 1988	5.05	4.11	3.9
		13 Dec 1988	5.05	4.12	4.1
J13	Prograde	13 Dec 1988	5.09	4.17	4.4

TABLE 4. Photometry of outer *Jovian satellites*.

Satellite	UT Date	$m_V$	$m_V - m_R$	$m_V - m_I$	$m_V(1,1,0)$	$m_R(1,1,0)$	Period [hr]	$\Delta m$ [mag]
J6	13 Dec 1988	$14.77 \pm 0.03$	$0.36 \pm 0.03$	$0.66 \pm 0.03$	$7.96 \pm 0.03$	$7.60 \pm 0.03$	9.5 <sup>1</sup>	
J7	19 Nov 1987	---	---	---	---	$9.45 \pm 0.02$	---	$\approx 0.1$
	20 Nov 1987	---	---	---	---	$9.44 \pm 0.02$	---	$\approx 0.1$
J8	15 Nov 1987	---	---	---	---	$10.09 \pm 0.03$	---	$\approx 0.1$
	16 Nov 1987	---	---	---	---	$10.12 \pm 0.03$	---	$\approx 0.1$
	11 Dec 1987	---	---	---	---	$10.16 \pm 0.03$	---	$\approx 0.1$
	13 Dec 1988	$17.26 \pm 0.03$	$0.42 \pm 0.05$	$0.81 \pm 0.03$	$10.43 \pm 0.03$	$10.01 \pm 0.04$	---	$\approx 0.1$
J9	10 Dec 1987	---	---	---	---	$11.08 \pm 0.04$	$13.16 \pm 0.1$	$\approx 0.2$
	11 Dec 1987	---	---	---	---	$11.08 \pm 0.04$	$13.16 \pm 0.1$	$\approx 0.2$
	12 Dec 1987	---	---	---	---	$11.08 \pm 0.04$	$13.16 \pm 0.1$	$\approx 0.2$
	13 Dec 1988	$18.25 \pm 0.02$	$0.46 \pm 0.07$	$0.85 \pm 0.09$	$11.63 \pm 0.03$	$11.17 \pm 0.07$	$13.16 \pm 0.1$	$\approx 0.2$
J10	8 Dec 1988	---	---	---	$11.42 \pm 0.02$	---	$12.78 \pm 0.1$	$\approx 0.27$
	13 Dec 1988	$18.05 \pm 0.14$	$0.28 \pm 0.14$	$0.54 \pm 0.14$	$11.36 \pm 0.14$	$11.08 \pm 0.03$	$12.78 \pm 0.1$	$\approx 0.27$
J11	11 Dec 1987	---	---	---	---	$10.66 \pm 0.03$	---	---
	10 Dec 1988	---	---	---	$10.99 \pm 0.03$	---	$10.40 \pm 0.05$	$\approx 0.22$
	11 Dec 1988	---	---	---	$10.99 \pm 0.03$	---	$10.40 \pm 0.05$	$\approx 0.22$
	13 Dec 1988	$17.80 \pm 0.03$	$0.31 \pm 0.04$	$0.89 \pm 0.04$	$10.96 \pm 0.03$	$10.65 \pm 0.03$	---	---
J12	11 Dec 1987	---	---	---	---	$11.66 \pm 0.06$	---	---
	12 Dec 1987	---	---	---	---	$11.75 \pm 0.10$	---	---
	10 Jan 1988	---	---	---	---	$11.77 \pm 0.03$	---	---
	12 Dec 1988	---	---	---	$12.21 \pm 0.04$	---	$8.3 \pm 0.1$	$\approx 0.26$
	13 Dec 1988	$18.85 \pm 0.06$	$0.40 \pm 0.06$	$0.76 \pm 0.06$	$12.13 \pm 0.06$	$11.73 \pm 0.02$	---	---
J13	13 Dec 1988	$19.66 \pm 0.20$	$0.29 \pm 0.22$	$0.33 \pm 0.36$	$12.85 \pm 0.20$	$12.56 \pm 0.10$	---	---

<sup>1</sup> Taken from Degewij *et al.* (1980)

$$m(1,1,0) = m - 5 \log(R\Delta) - \beta\alpha, \quad (1)$$

where  $m$  is the apparent magnitude,  $R$  is the heliocentric distance,  $\Delta$  is the geocentric distance,  $\beta$  is the phase coefficient, and  $\alpha$  is the phase angle. This use of a linear phase coefficient is the traditional method for treating phase darkening in asteroids. There now exists a new two-parameter magnitude system advocated by the IAU, where phase darkening is described by a slope parameter and phase functions (Bowell *et al.* 1989). We chose the traditional method mainly for direct comparison with previous results by DAZ80 and TZ84, who also used a linear phase coefficient for their reduced absolute magnitudes. To be consistent with DAZ80

and TZ84, we adopt the phase coefficient  $\beta = 0.039$  mag/deg for all satellites. Then the absolute  $V$  magnitude of J6 in December 1988 is calculated to be

$$m_V(1,1,0) = 7.96 \pm 0.03,$$

to be compared with other existing photometry,

$$m_V(1,1,0) = 8.33 \pm 0.02 \text{ (TZ84)},$$

and

$$m_V(1,1,0) = 8.14 \pm 0.11 \text{ (see Table III of DAZ80)}.$$

Our  $V$  absolute magnitude is brighter than that observed by TZ84, but is consistent with that of DAZ80. We also note

that DAZ80 reported a peak-to-peak amplitude  $\Delta m$  as large as  $\Delta m = 0.23$  mag for J6, which may explain the large dispersion in the absolute magnitudes. The TZ84 observations may also have found J6 at different aspect angles from ours. If J6 is a triaxial ellipsoid, then in general, it will not show the same cross section when viewed from different angles, i.e., there may be no discrepancy between our measurement and that of TZ84. Another possible explanation for the difference between the two measurements is contamination by scattered light from Jupiter when TZ84 observed J6. At the time of their observation, the separation between J6 and Jupiter was only  $37'$  (see Table III of TZ84), and since TZ84 used a spot photomultiplier, it is possible that imperfect background sky subtraction introduced errors into their (single) measurement of J6. Our measured  $m_V - m_R$  and  $m_V - m_I$  colors ( $0.36 \pm 0.03$  and  $0.66 \pm 0.03$ , respectively; see Table 4) are consistent with the observations of DAZ80, who measured  $m_V - m_R = 0.33$  and  $0.69 \leq m_V - m_I \leq 0.97$ .

### 2.1.2 J7 Elara

J7 was monitored over two photometric nights with the MDM 1.3 m, on 19–20 November 1987. The photometry from each night is plotted in Fig. 1. The figure shows that on both nights, during the entire monitoring periods ( $\sim 6$  hr on each night), the apparent brightness of the satellite did not deviate more than  $\Delta m \sim 0.1$  mag from the mean apparent  $R$  magnitude  $m_R = 16.18 \pm 0.03$ . Slight variations in the light curve do not appear to be periodic, and could be caused by

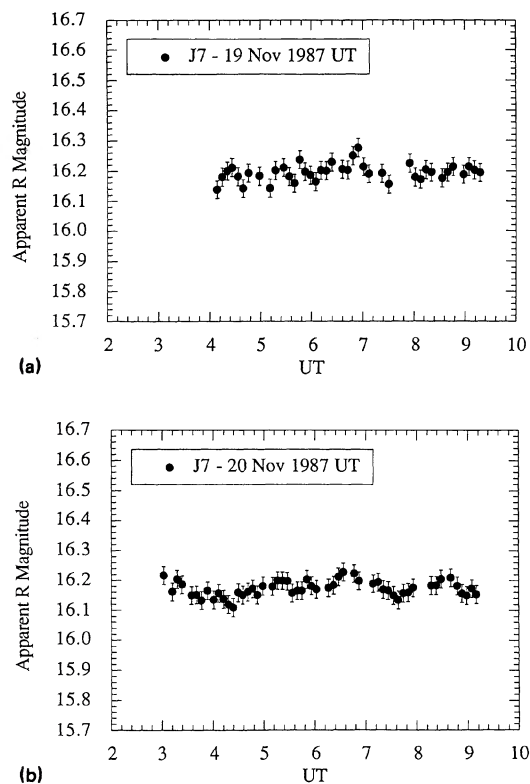


FIG. 1. CCD photometry of J7 obtained at the MDM 1.3 m on (a) 19 November 1987 UT and (b) 20 November 1987 UT. Neither light curve shows unambiguous periodicities.

albedo variations on the surface. We attempted to find periodicities using the phase dispersion minimization method, but no convincing period could be found. The apparent nonperiodicity in the data can be explained by any combination of the following three hypotheses: (1) J7 is very nearly spherical, hence it is not possible to measure its rotation period within the accuracy of the data; (2) the pole of J7 was aligned nearly parallel with the line of sight; and (3) J7 possesses a very long rotation period ( $> 24$  hr).

Using Eq. (1), the absolute magnitude of J7 in November 1987 is

$$m_R(1,1,0) = 9.40 \pm 0.03,$$

consistent with the DAZ80 observations [ $m_R(1,1,0) = 9.67 \pm 0.19$ ]. However, we see no evidence for the 0.51 mag variation reported by DAZ80 and advocated by TZ84. As the pole direction of J7 is not known, it is possible that the discrepancy between the current  $\Delta m$  and that of 1975 is simply due to a change in aspect angle. Since the orbital period of Jupiter is 12 yr, a satellite with an obliquity near  $90^\circ$  and viewed “equator on” from the Earth (pole direction perpendicular to the line of sight) can be viewed “pole on” (pole direction parallel to the line of sight) in just 3 yr, after the satellite has traversed  $90^\circ$  of its orbit around the Sun.

### 2.1.3 J8 Pasiphae

As with J7, the light curve of J8 was measured on 2 photometric nights (15–16 November 1987), with the MDM 1.3 m and the  $R$  filter. The photometry from both nights is plotted in Fig. 2, showing that the light curve of J8 is remarkably flat, with variations in the range  $\Delta m \leq 0.1$  mag, about a mean apparent magnitude  $m_R = 16.85 \pm 0.03$ . This is in marked contrast to various inferences (TZ84; Degewij & van Houten 1979) that J8 might have a light-curve amplitude as large as 1 mag. However, again, since the pole direction of J8 is not known, we cannot rule out the possibility of a 1 mag change in amplitude in the time period 1983–1987. No convincing period could be found from the data. We appeal to the three hypotheses offered in the case of J7 to explain the absence of periodicity in our J8 data.

Photometry of J8 over 1987 and 1988 yields the following absolute magnitudes:

$$m_R(1,1,0) = 10.12 \pm 0.03 \quad (15\text{--}16 \text{ November } 1987),$$

$$m_R(1,1,0) = 10.16 \pm 0.03 \quad (11 \text{ December } 1987),$$

$$m_R(1,1,0) = 10.01 \pm 0.04 \quad (13 \text{ December } 1988).$$

The 1988 measurements are significantly different (at the  $3\sigma$  level) from the 1987 measurements. It is not clear what is the cause of the discrepancy; the likeliest possibilities are different aspect angles or different rotational phases viewed at the two epochs. Comparing our  $V$  absolute magnitude with other photometry,

$$m_V(1,1,0) = 10.43 \pm 0.03 \quad (\text{this work, } 1988),$$

$$m_V(1,1,0) = 10.33 \pm 0.01 \quad (\text{DAZ80}),$$

$$m_V(1,1,0) = 10.18 \pm 0.03 \quad (\text{TZ84}),$$

we see that there is no statistical difference between our  $V$  absolute magnitude and that of DAZ80, but our  $V$  absolute magnitude is, however, significantly fainter than the TZ84 measurement.

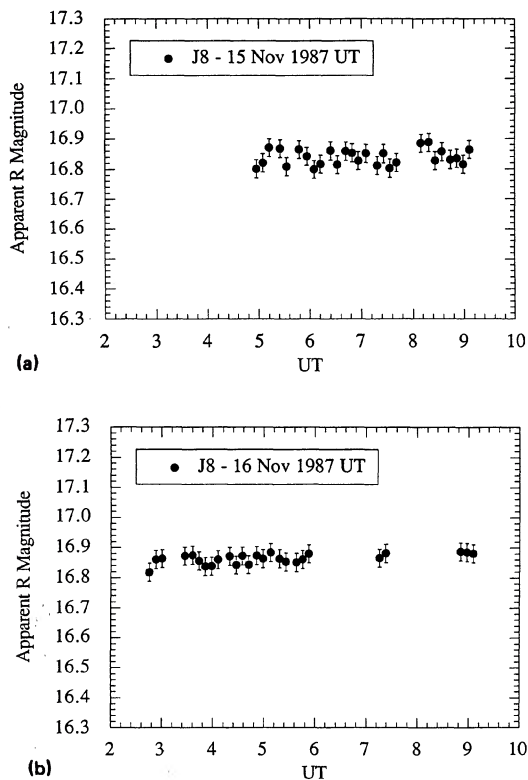


FIG. 2. CCD photometry of J8 obtained at the MDM 1.3 m on (a) 15 November 1987 UT and (b) 16 November 1987 UT. The light curves of J8 on both nights were remarkably flat and no periodicities were found.

#### 2.1.4 J9 Sinope

The light curve of J9 was obtained with the MDM 2.4 m in December 1987 with the  $R$  filter, and spanned three consecutive nights (10–12 December 1987). The phase dispersion minimization method applied to the data yields a rotation period  $P = 13.16 \pm 0.1$  hr, although periods which are multiples of  $P$  are not excluded. The phase curve for the 13.16 hr period is shown in Fig. 3. In this figure, J9 exhibits sinusoidal brightness variations about a mean apparent magnitude  $m_R = 18.17 \pm 0.04$ , corresponding to the mean absolute magnitude

$$m_R(1,1,0) = 11.08 \pm 0.04,$$

with brightness variations in the range  $\Delta m \approx 0.2$  mag. Observations on 13 December 1988 gave

$$m_R(1,1,0) = 11.17 \pm 0.07,$$

and

$$m_V(1,1,0) = 11.63 \pm 0.03.$$

The two  $R$  magnitudes are in agreement, while the  $V$  measurement is compatible with the  $V$  absolute magnitude  $11.34 \pm 0.20$  previously reported by TZ84. We note with interest that J9 was also recently observed at the Kiso Observatory and was reported to have a period of 18 hr and a 1.5 mag amplitude (Nakamura 1989). These measurements are at odds with our own observations, as is obvious from Fig. 3.

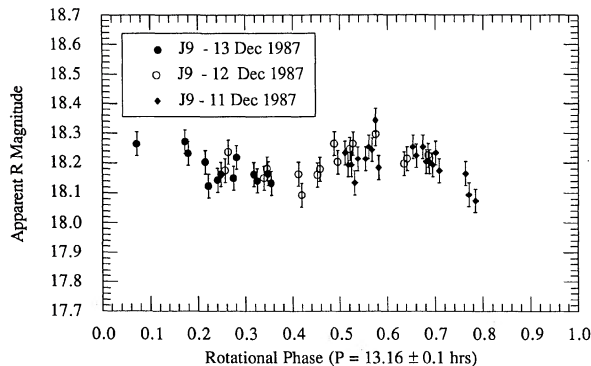


FIG. 3. Rotational phase curve for J9, using the best-fit period  $P = 13.16$  hr. The photometry was obtained 11–13 December 1987 UT at the MDM 2.4 m.

As a possible explanation for the large difference in amplitude, we considered the possibility that Nakamura (1989) observed the equatorial view of J9 while we had the polar view (with the spin axis parallel to the line of sight). However, the Kiso observations were made only 2 yr after our own, not sufficiently long for the maximum change in aspect angle (3 yr for a *Jovian satellite*, see discussion for *J7 Elara* above). A Hyperion-like chaotic orbit may be able to explain the two different rotation periods, but most likely not the different amplitudes. A future detailed comparison of the two sets of data and/or additional observations of J9 may explain the discrepancy.

#### 2.1.5 J10 Lysithea

J10 was monitored on 8 December 1988 with the MDM 1.3 m and the  $V$  filter. The phase curve for the best-fit period  $P = 12.78 \pm 0.1$  hr is shown in Fig. 4. The figure shows that

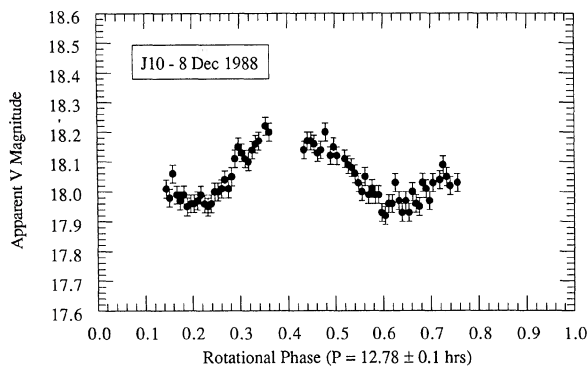


FIG. 4. Rotational phase curve for J10, using the best-fit period  $P = 12.78$  hr.  $P$  is uncertain in the sense that light-curve data on another night is needed to verify the period. The photometry was taken on 8 December 1988 UT with the MDM 1.3 m.

the light curve had a mean apparent magnitude  $m_V = 18.07 \pm 0.03$ , corresponding to

$$m_V(1,1,0) = 11.42 \pm 0.03,$$

and a photometric range  $\Delta m \approx 0.28$  mag. Measurements taken five days later gave  $m_V(1,1,0) = 11.36 \pm 0.14$ . Within the uncertainties, our measurements are compatible with those of TZ84 [ $m_V(1,1,0) = 11.52 \pm 0.08$ ]. We caution that, since we only measured the light curve of J10 on one night, the rotation period presented here is uncertain in the sense that additional light-curve data are desirable for the purpose of confirmation.

### 2.1.6 J11 Carme

Our most extensive coverage of J11 extended over two nights (10–11 December 1988), using the MDM 1.3 m and the  $V$  filter. The satellite showed systematic brightness variations about the mean apparent magnitude  $m_V = 17.12 \pm 0.03$ , corresponding to

$$m_V(1,1,0) = 10.99 \pm 0.03,$$

with the range  $\Delta m \approx 0.2$  mag. The best-fitting period is  $P = 10.40 \pm 0.05$  hr; the corresponding phase curve is shown in Fig. 5.  $VRI$  photometry taken on 13 December 1988 gave

$$m_V(1,1,0) = 10.96 \pm 0.03$$

and

$$m_R(1,1,0) = 10.65 \pm 0.03.$$

This  $V$  absolute magnitude is consistent with that obtained in 1987; it may be compared with that reported by TZ84 [ $m_V(1,1,0) = 11.20 \pm 0.07$ ].

### 2.1.7 J12 Ananke

J12 was observed over five different nights in 1987–1988 (see Table 3), but only on one night (12 December 1988) was the coverage extensive enough to estimate the rotation period. Observing with the  $V$  filter, we found that the best-fitting rotation period for J12 is  $P = 8.31 \pm 0.15$  hr. Since we do not have rotational data from another night, this period is uncertain, pending confirmation by additional data. Figure 6 shows the entire photometry used in calculating the period.

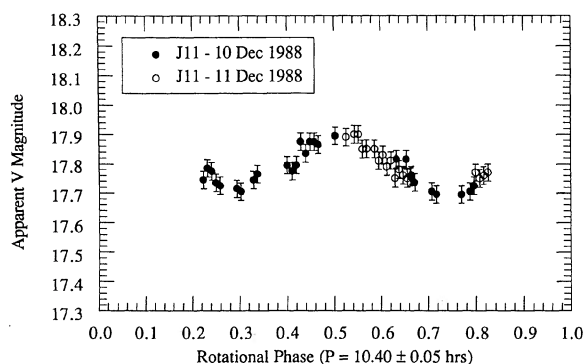


FIG. 5. Rotational phase curve for J11, using the best-fit period  $P = 13.42$  hr. The photometry was taken on 10–11 December 1988 UT with the MDM 1.3 m.

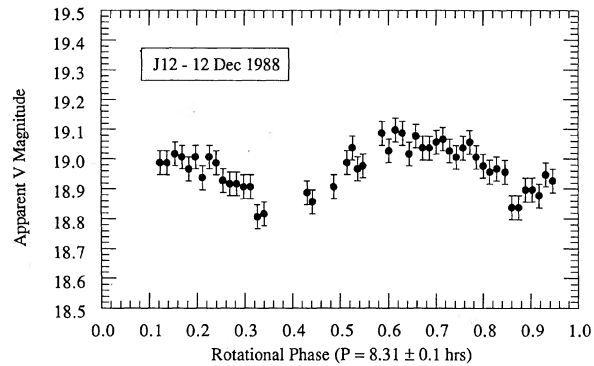


FIG. 6. Rotational phase curve for J12, using the best-fit period  $P = 8.31$  hr.  $P$  is uncertain in the sense that light-curve data on another night is needed to verify the period. The photometry was taken on 12 December 1988 UT with the MDM 1.3 m.

The light curve had a mean apparent magnitude  $m_V = 18.97 \pm 0.04$ , corresponding to an absolute magnitude

$$m_V(1,1,0) = 12.21 \pm 0.04,$$

with a photometric range  $\Delta m \approx 0.25$  mag. Observations the following night gave  $m_V(1,1,0) = 12.13 \pm 0.06$ . All  $R$  and  $V$  broadband magnitudes obtained in 1987–1988 were consistent with each other (see Table 3). We know of no other photometry of J12 with which to compare our measurements.

### 2.1.8 J13 Leda

Our observations of J13 are restricted to  $VRI$  magnitudes on 13 December 1988, obtained with the MDM 1.3 m. At the time, the satellite had the apparent magnitude  $m_V = 19.66 \pm 0.20$ , corresponding to an absolute magnitude

$$m_V(1,1,0) = 12.85 \pm 0.20,$$

making it the faintest of the eight outer *Jovian satellites*. The *Astronomical Almanac* (1991) lists J13 as having  $m_V(1,1,0) = 13.5$ , with no listed uncertainties. We know of no other J13 data.

## 2.2 CCD Spectroscopy

CCD spectra of satellites J6, J8, J9, J10, and J11 were obtained in October 1988 and February 1989, using the KPNO 2.1 m. The spectra were taken in conjunction with our spectroscopic programs on near-Earth and 3:1 resonance asteroids (Luu & Jewitt 1990), and Trojan asteroids (Jewitt & Luu 1990, hereafter referred to as JL90), thus the instrumentation used for the satellite spectra is identical to that used in these programs. We briefly summarize below the details of the instrument setup.

We used the “GoldCam” spectrograph attached to the  $f/7.7$  Cassegrain focus of the KPNO 2.1 m. The detector was an  $800 \times 800$  TI CCD, with a readout noise of nine electrons. The slit had projected dimensions  $2.8'' \times 150''$ , was oriented east–west in October 1988 and north–south in February 1989. The spectrograph had the spatial resolution of  $0.79''/\text{pixel}$ , and a dispersion of  $4.9 \text{ \AA}/\text{pixel}$ . The dispersion

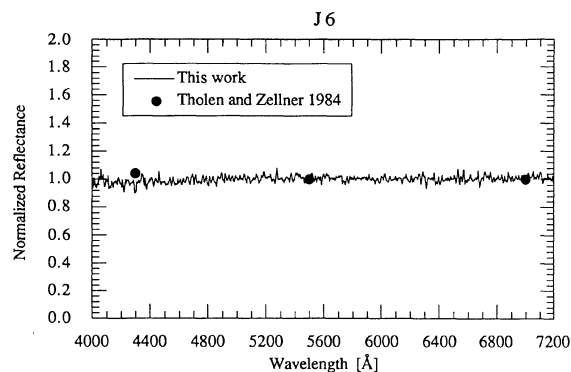


FIG. 7. Normalized reflectance spectrum of J6 compared with narrow-band filter data from TZ84. All plotted data have been normalized at 5500 Å. The formal error bars of the TZ84 data are smaller than the size of the plotted points.

was achieved with a 150 lines/mm grating used in the first order. The spectral coverage was  $3600 \leq \lambda \leq 7400$  Å, but for the subsequent data analysis, we only used the wavelength range  $4000 \leq \lambda \leq 7200$  Å to exploit the maximum efficiency of the instrument. A summary of the “GoldCam” and the 2.1 m configuration is available in Table 2. The relatively wide (2.8”) slit limited the effective resolution to 20 Å full width at half maximum (FWHM). To keep the object centered in the slit, we watched a reflection of the slit in the TV guider and added guiding corrections as necessary. We estimated the guiding errors to be  $\leq 1''$  (small compared to the width of the slit). At least two individual spectra were obtained for each satellite, and were later combined to form higher quality composite spectra.

Many spectra of helium-neon-argon lamps were taken throughout each night for wavelength calibration purposes. Similarly, flux standard stars [selected from IIDS (Oke 1974) and IRS (Stone 1977)] were observed frequently each night. Special efforts were made to record standard star spectra at airmasses similar to those of the satellites. All spectra were taken at small air mass ( $\leq 1.4$ ) to minimize

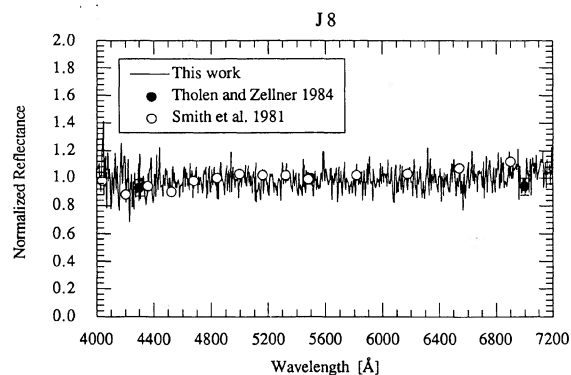


FIG. 8. Normalized reflectance spectrum of J8 compared with narrow-band filter data from TZ84 and with multichannel data from Smith *et al.* (1981). All plotted data have been normalized at 5500 Å. The formal error bars in the multichannel data are on the order  $\pm 0.03$ –0.05 in the blue.

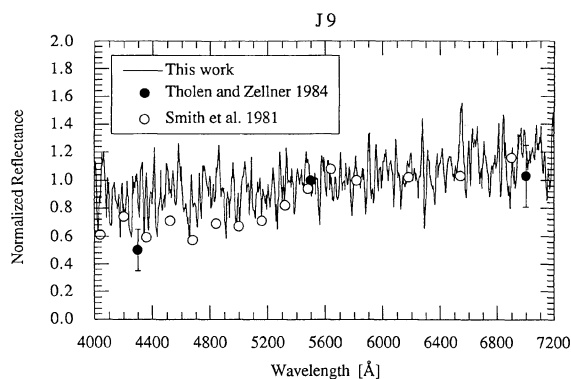


FIG. 9. Normalized reflectance spectrum of J9 compared with narrow-band filter data from TZ84 and with multichannel data from Smith *et al.* (1981). All plotted data have been normalized at 5500 Å. The formal error bars in the multichannel data are on the order  $\pm 0.03$ –0.05 in the blue.

errors introduced by differential refraction. Spectral reflectivities were computed by dividing the composite spectra by the spectrum of a solar analog. In October 1988, the solar analog available was 16 Cyg B (Hardorp 1978, 1980), while the solar analog used during the February 1989 run was Hyades 64 (Hyades 1978, 1980). The spectra were flattened with the average of  $\sim 50$ –100 flatfields taken with a quartz lamp. The reader interested in a more detailed description of the spectral reduction techniques is referred to Luu & Jewitt (1990) or Luu (1990).

The reflectivity spectra of the satellites are shown in Figs. 7–11. The viewing geometry for each satellite at the time of observation is presented in Table 5. To measure the reflectivity gradient  $dS/d\lambda$ , we performed linear least-squares fits to the slopes of the satellite reflectivities and normalized the slope at the central wavelength  $\lambda = 5500$  Å. Hence, we define the normalized reflectivity gradient  $S'$  (i.e., color) as

$$S'(\lambda_1, \lambda_2) = (dS/d\lambda)/S_{5500}. \quad (2)$$

Since our wavelength range roughly spans the  $V$  filter and the  $R$  filter bandpasses,  $S'$  most closely resembles the  $m_V - m_R$  color index. The approximate relation between  $S'$  and  $m_V - m_R$  is

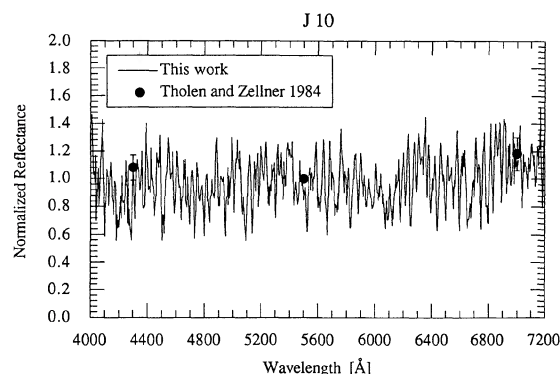


FIG. 10. Normalized reflectance spectrum of J10 compared with narrow-band filter data from TZ84. All plotted data have been normalized at 5500 Å.

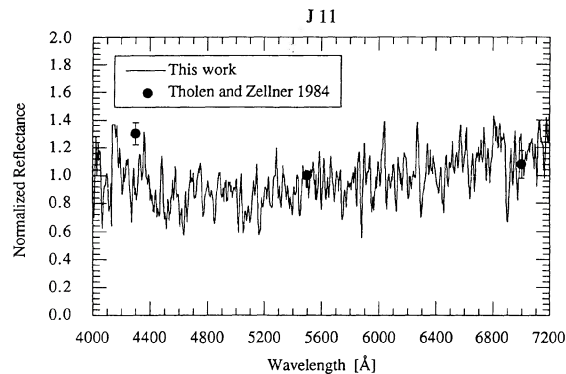


FIG. 11. Normalized reflectance spectrum of J11 compared with narrowband filter data from TZ84. All plotted data have been normalized at 5500 Å.

$$m_V - m_R = 2.5 \log[(2 + S' \Delta \lambda)/(2 - S' \Delta \lambda)], \quad (3)$$

where  $S'$  is in  $\%/10^3 \text{ \AA}$ ,  $\Delta \lambda = \lambda_2 - \lambda_1$  is the difference in the effective wavelength in ( $10^3 \text{ \AA}$ ) between the  $V$  and  $R$  bandpasses, and  $m_V - m_R$  is the object color index minus the solar color index (in mag.). All spectra were taken at relatively small phase angles ( $\alpha \leq 8.5^\circ$ ), hence we ignore the phase-reddening effect (e.g., Bowell & Lumme 1979) in the spectra. The value of  $S'$  measured for each spectrum and its equivalent  $m_V - m_R$  [computed from Eq. (3)] are listed in Table 5. For comparison, the color index  $m_V - m_R$  from broadband photometry is also indicated in Table 5. As is obvious from the table, the consistency between the colors obtained via spectroscopy and those obtained via broadband photometry (within the uncertainties) attests to the accuracy of our results.

From Figs. 7–11, the satellite reflectivity spectra appear featureless and linear, generally exhibiting a positive slope. A positive slope indicates a red color with respect to the Sun, the magnitude of the slope being an analog of the color. Of the five observed satellites, J6 exhibits the most neutral reflectivity ( $0.4 \pm 0.2 \%/10^3 \text{ \AA}$ ), while J9 is the reddest ( $12.1 \pm 1.0 \%/10^3 \text{ \AA}$ ). J8 and J9 were independently observed by Smith *et al.* (1981), while TZ84 independently observed J6, J7, J8, J10, and J11. The instrument used by Smith *et al.* (1981) was a 30-channel multichannel spectrometer, while TZ84 made use of narrowband filters. All independent spectra for J6 and J8 are consistent (Figs. 7 and 8), and show a neutral, featureless continuum. The agreement between independent spectra is not as good for J9 (Fig. 9), however, in the short wavelength range ( $\lambda < 5500 \text{ \AA}$ ). At first glance, the TZ84 spectrum looks particularly red, but within the uncertainties, there is no significant discrepancy between the two spectra shown. There is also general agreement between the TZ84 spectra and ours for J10 (Fig. 10). TZ84 claimed a UV upturn (thus a highly blue color) for J11, possibly caused by cometary CN emission at 3871 Å or Rayleigh scattering. Our spectral coverage does not extend to the 3800 Å range, but in the 4000–7200 Å range, we see no evidence for a blue upturn (Fig. 11).

In general, the slight differences between the independent sets of spectra may be explained by systematic errors, or possibly by color variations at different rotational phases of the satellites. The accuracy and reproducibility of our ob-

TABLE 5. CCD spectroscopy of outer *Jovian satellites*.

Satellite	UT Date	R [AU]	$\Delta$ [AU]	$\alpha$ [deg]	$S'$ [%/10 <sup>3</sup> Å]	$m_V - m_R^1$ [mag]	$m_V - m_R^2$ [mag]
J6	07 Feb 1989	5.04	4.80	0.2	$0.3 \pm 0.2$	$0.36 \pm 0.01$	$0.36 \pm 0.01$
	08 Feb 1989	5.04	4.81	0.2	$0.4 \pm 0.2$	$0.36 \pm 0.01$	...
J8	10 Oct 1988	5.11	4.36	8.0	$2.6 \pm 1.0$	$0.39 \pm 0.01$	$0.42 \pm 0.05$
	08 Feb 1989	5.04	4.87	0.2	$5.5 \pm 1.0$	$0.42 \pm 0.01$	...
J9	10 Oct 1988	4.91	4.17	8.5	$12.1 \pm 1.0$	$0.49 \pm 0.01$	$0.46 \pm 0.07$
J10	10 Oct 1988	5.06	4.33	8.4	$6.0 \pm 1.0$	$0.43 \pm 0.01$	$0.28 \pm 0.14$
J11	09 Oct 1988	5.14	4.40	8.1	$8.7 \pm 2.0$	$0.45 \pm 0.02$	$0.31 \pm 0.05$

<sup>1</sup> Calculated from Equation (3)

<sup>2</sup> From independent broadband photometry

servicing and analysis techniques have been demonstrated elsewhere, notably in the results presented in Luu & Jewitt (1990) and JL90.

### 3. DISCUSSION

A summary of the properties of the satellites is provided in Table 6. Where more than one measurement was made, the various values were weighted by their uncertainties and the weighted averages are listed.

It is believed that the satellites are fragments of two asteroidal bodies captured by the envelope of gas and dust around the proto-Jupiter (Pollack *et al.* 1979). The capture theory was first proposed by Kuiper (1951, 1956), who suggested that the outer *Jovian satellites* derived from planetesimals that condensed in the nebula, were lost, then were recaptured by Jupiter. Pollack *et al.* proposed a similar scenario and, based on a quantitative analysis, were able to compare their model predictions with the physical and dynamical properties of the satellites. In the Pollack *et al.* scenario, the two captured bodies were then fractured due to pressure forces and stresses encountered in their passage through the nebula. Gravitational attraction between the fragments exceeded the relative drag force, hence the fragments stayed together until a subsequent collision with a stray planetesimal caused them to disperse into the present configuration.

TABLE 6. Summary of physical properties of outer *Jovian satellites*.

Satellite	$m_R(1,1,0)$ [mag]	$m_V - m_R$ [mag]	$m_V - m_I$ [mag]	$S'$ [%/10 <sup>3</sup> Å]	Radius <sup>1</sup> [km]	Period [hr]	$\Delta m$ [mag]
J6	$7.60 \pm 0.03$	$0.36 \pm 0.03$	$0.66 \pm 0.03$	$0.4 \pm 0.1$	92	$9.5^2$	$0.12^2$
J7	$9.45 \pm 0.01$	...	...	...	39	...	= 0.1
J8	$10.11 \pm 0.02$	$0.42 \pm 0.05$	$0.81 \pm 0.03$	$4.1 \pm 0.7$	29	...	= 0.1
J9	$11.09 \pm 0.02$	$0.46 \pm 0.07$	$0.85 \pm 0.09$	$12.1 \pm 1.0$	19	$13.16 \pm 0.1$	0.2
J10	$11.08 \pm 0.03$	$0.28 \pm 0.14$	$0.54 \pm 0.14$	$6.0 \pm 1.0$	19	$12.78 \pm 0.1$	0.27
J11	$10.66 \pm 0.01$	$0.31 \pm 0.04$	$0.89 \pm 0.04$	$8.7 \pm 1.5$	23	$10.40 \pm 0.05$	0.22
J12	$11.73 \pm 0.02$	$0.40 \pm 0.06$	$0.76 \pm 0.06$	...	14	$8.3 \pm 0.1$	0.26
J13	$12.56 \pm 0.10$	$0.29 \pm 0.22$	$0.33 \pm 0.36$	...	9	...	...

<sup>1</sup> The radius was computed from  $m_R(1,1,0)$ , assuming a geometric albedo  $p = 0.03$ .

<sup>2</sup> From DAZ80.

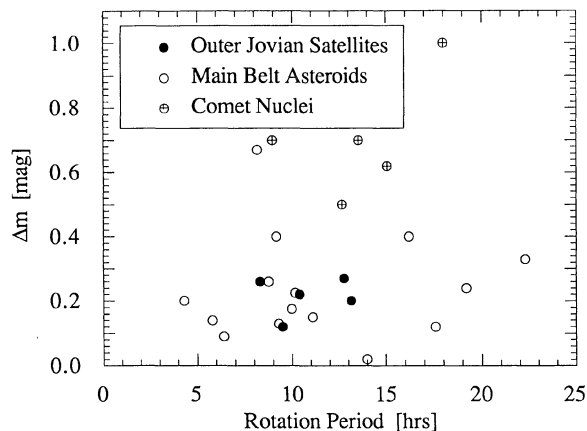


FIG. 12. Rotation period vs light-curve amplitude  $\Delta m$  for outer *Jovian satellites*, main belt asteroids, and comet nuclei. The nucleus data are taken from Table 1 of Jewitt (1991). The plot shows that all three groups of objects have similar rotation periods, but the comet nuclei have higher  $\Delta m$ 's than both the outer *Jovian satellites* and the main belt asteroids.

Pollack *et al.* pointed out that his model predictions agree fairly well with the orbital characteristics and the fragment size distribution of the satellites (see Table IV of Pollack *et al.*). However, our current observations point out that the Pollack *et al.* prediction (that the small  $\Delta m$ 's of the satellites are due to smoothing by gas drag) is not unique. Figure 12 showed that the  $\Delta m$ 's of the observed satellites are consistent with those of main belt asteroids, which are collision fragments with randomized spin vectors. The pole directions of the satellites need to be determined before a definite statement can be made about the shapes of the satellites.

Are there differences between the prograde and retrograde group? We calculate the mean properties of each group and list them in Table 7. From the Table, we find no statistical difference between the two groups: within the dis-

TABLE 7. Prograde vs. retrograde.<sup>1,2</sup>

	Prograde	Retrograde
Mean rotation period [hrs]	$11.1 \pm 2.3$ <sup>3</sup> (J6, J10)	$10.6 \pm 2.4$ (J9, J11, J12)
Mean $\Delta m$ [mag]	$0.20 \pm 0.10$ <sup>3</sup> (J6, J10)	$0.23 \pm 0.03$ (J9, J11, J12)
Mean $m_V - m_R$ [mag]	$0.31 \pm 0.04$ (J6, J12, J13)	$0.40 \pm 0.06$ (J8, J9, J11, J12)
Mean $m_V - m_I$ [mag]	$0.51 \pm 0.17$ (J6, J10, J13)	$0.83 \pm 0.06$ (J8, J9, J11, J12)
Mean $S^*$ [%/10 <sup>3</sup> Å]	$3.2 \pm 4.0$ (J6, J10)	$8.3 \pm 4.0$ (J8, J9, J11)

<sup>1</sup> This table lists the mean properties of the outer satellites, grouped by their sense of orbital rotation (prograde and retrograde). Not all measurements are available for all satellites. The available satellites used in computing the means are listed next to each mean value.

<sup>2</sup> The uncertainties listed here indicate the dispersion in the available measurements.

<sup>3</sup> The rotation period and  $\Delta m$  of J6 are from Degewij *et al.* (1980).

persion, the mean properties of the two groups are the same. The similarities that exist between the two distinct satellite clouds suggest that the two captured bodies either resembled each other in nature, or underwent a similar path of evolution after being captured. In this respect, the resemblance is consistent with the theory of a common capture origin for both dynamical groups.

### 3.1 Comparison with Main Belt Asteroids

In seeking the origin of the satellites, it is appropriate to ask how the satellites compare with main belt asteroids of similar sizes. Figure 12 compares the rotational properties of the outer satellites with those of main belt asteroids in the same size range. [These asteroids were randomly chosen from main belt asteroids of the same size for which light-curve amplitudes and rotation periods are tabulated in Lagerkvist *et al.* (1989).] In Fig. 12, the amplitudes  $\Delta m$  of the satellites and of 15 main belt asteroids are plotted against their respective rotation periods. It is clear from the figure that the measured satellites as a group do not differ from the main belt asteroids in terms of rotational properties. Table 8 further emphasizes this point, as it summarizes the mean properties of the satellites as compared to the mean properties of other small body populations.

It has been shown that the light-curve amplitudes of the main belt asteroids are consistent with a collision fragment origin (Catullo *et al.* 1984; Capaccioni *et al.* 1984). However, it is not clear whether the same explanation can be applied to the satellites: Pollack *et al.* (1979) attributed the relatively small  $\Delta m$ 's of the satellites to smoothing by ablation during capture (see Sec. 3.3 below). Our observations do not favor one explanation over the other; we can only note that, according to Fig. 12, the collision fragment origin is compatible with the evidence.

### 3.2 Comparison with Comet Nuclei

In Fig. 12, we also included the  $\Delta m$ 's and rotation periods of known comet nuclei (see Table 1 of Jewitt 1991) for comparison with the outer *Jovian satellites*. It has already been pointed out that the known comet nuclei share many common properties such as albedos, colors and shapes with the

TABLE 8. Comparison of physical parameters.<sup>1</sup>

Parameter	Outer Jovian satellites	Main belt asteroids	Comet nuclei	Trojans
$\Delta m$ [mag]	$0.21 \pm 0.06$ (5)	$0.30 \pm 0.03$ (270) <sup>2</sup>	$0.7 \pm 0.2$ (5) <sup>3</sup>	$0.4 \pm 0.2$ (19) <sup>4</sup>
Rotation period [hrs]	$10.8 \pm 2.1$ (5)	$12 \pm 14$ (270) <sup>5</sup>	$12.6 \pm 2.6$ (4) <sup>6</sup>	---
$S^*$ [%/1000 Å]	$6.3 \pm 4.4$ (5)	$5.2 \pm 6.0$ (23) <sup>7</sup>	$14 \pm 5$ (5) <sup>8</sup>	$10 \pm 4$ (32) <sup>9</sup>

<sup>1</sup> Number of objects in each sample is enclosed in parentheses.

<sup>2</sup> Estimated from Fig. 7 of Binzel *et al.* (1989).

<sup>3</sup> From Table 1 of Jewitt (1991).

<sup>4</sup> From Table 1 of Hartmann *et al.* (1988).

<sup>5</sup> Estimated from Fig. 5 and Table 1 of Binzel *et al.* (1989).

<sup>6</sup> From Table 1 of Jewitt (1991).

<sup>7</sup> From the 3:1 resonance asteroid sample (Table 5) of Luu and Jewitt (1990).

<sup>8</sup> From Table 1 of Jewitt (1991).

<sup>9</sup> From JL90.

Trojan asteroids, nearby neighbors of the satellites (see JL90 and references therein). How then do comet nuclei compare with the satellites? From Table 8, we see that the mean rotation periods of nuclei and of the satellites are very similar. However, the nuclei seem to be redder and have larger  $\Delta m$ 's than the satellites. The similarities and differences between the nuclei and the satellites are confirmed by Fig. 12, where the nuclei and the satellites are well mixed along the horizontal axis (rotation period) but are distinctly separated along the vertical axis ( $\Delta m$ ). It can thus be concluded that the shapes of the satellites are, in general, less extreme than those of the nuclei, possibly suggesting a different origin and evolutionary histories. However, it must be kept in mind that our current information on comet nuclei is based on a very small statistical sample (5) and firm conclusions on the relationship of nuclei with other primitive solar system bodies should wait until statistical properties of the nuclei are better established.

### 3.3 Comparison with Trojan Asteroids

Broadband colors of the satellites are diverse. We measured broadband colors for all satellites except J7 and J8, and found that the  $V - R$  colors for the six observed satellites all fall within the 0.3–0.4 mag range, while the  $V - I$  colors exhibit more dispersion, extending from 0.3 to 0.9 mag. The broadband colors are in agreement with the spectral colors, verifying that the satellites possess neutral to reddish colors, not unlike many of the known asteroids. In particular, the obvious group of asteroids with which to compare the outer Jovian satellites is the Trojan asteroids at the stable Lagrangian points of Jupiter. The proximity of the two groups of objects has naturally led to conjectures of a common origin (Kuiper 1956). The Trojans have been reported to be composed mostly of D-type asteroids (Gradie & Tedesco 1982; Tholen 1984), and a large sample of Trojan optical spectra are presented in JL90. JL90 showed the Trojan spectra to have neutral to reddish colors, with a broad range of  $S'$  (3–25  $\%/10^3 \text{ \AA}$ )—encompassing, in fact, the range of  $S'$  observed in the satellites (see also Table 8). A direct visual comparison can be made from Fig. 13, where  $S'$  histograms of the satellites and of the Trojans are plotted (the Trojan histogram is a reproduction of Fig. 4 from JL90). Figure 13 hints that the satellites as a group are slightly less red than the average Trojan (leading TZ84 to suggest that all satellites were like C-type asteroids), but this may be due to the small number of satellites compared to the large Trojan sample. This result contradicts that previously reached by TZ84, who found no reddish spectra among the six satellites which they observed, and thus concluded that the satellites resembled C-type asteroids instead of the nearby Trojans. In contrast, the overlapping of the two histograms in Fig. 13 shows that the satellites and the Trojans share a common range of colors.

To which asteroidal taxonomic class might each individual satellite belong? Since the albedo is not available for most satellites, we can only attempt a nonrigorous classification based on colors (as was also done by TZ84). We see that J6, with its low albedo of 0.03 (Cruikshank 1977) and a neutral reflectivity ( $S'_{J6} = 0.4 \%/10^3 \text{ \AA}$ ), is probably a C type. We do not have the albedos for the other satellites. However, if we follow the same criterion used by Luu & Jewitt (1990) to roughly identify the C types (C types:  $S' < 5 \%/10^3 \text{ \AA}$ ), two of the satellites (J6 and J8) fall into the C category, due to

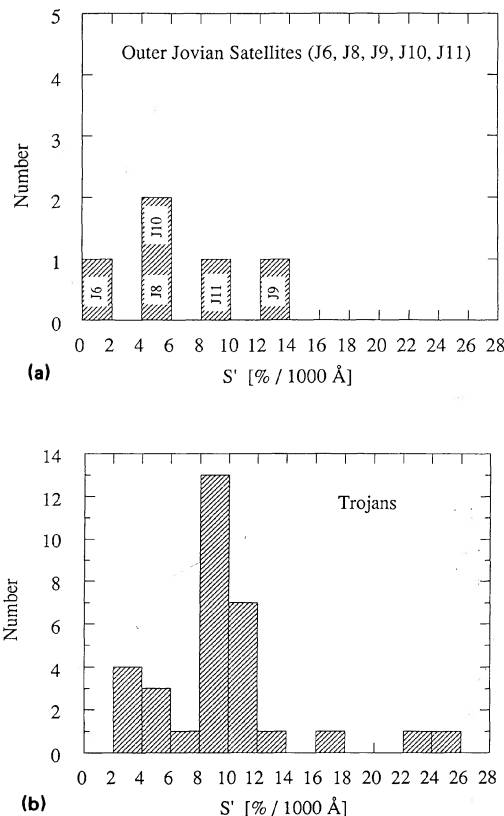


FIG. 13.  $S'$  histograms for (a) outer Jovian satellites and (b) Trojan asteroids. The values of  $S'$  for the satellites fall generally within the range of  $S'$  for the Trojans.

their relatively flat spectra. J9, J10, and J11 are red ( $S' = 12.1 \%/10^3 \text{ \AA}$ ,  $S' = 6.0 \%/10^3 \text{ \AA}$ , and  $S' = 8.7 \%/10^3 \text{ \AA}$ , respectively), so we would classify them as D's, assuming that their albedos are as low as those of J6 and J7 (Cruikshank 1977). From our results, it therefore appears that the outer Jovian satellites resemble both C- and D-type asteroids, i.e., like the Trojan asteroids, the satellites are spectrally diverse. To illustrate the diversity of the satellites and their resemblance to C- and D-type asteroids, Fig. 14 plots the satellite reflectance spectra with those of typical C and D asteroids. The slopes in the satellite spectra clearly range from flat (C-type) to distinctly positive (D-type). One possible explanation for the diverse colors is simple random statistics, since C types also exist among the Trojan population (Gradie *et al.* 1989). Another possible explanation is that the parent bodies were differentiated, with the core and the mantle having different compositions (and hence, colors). Different satellites originating from distinct parts of a single parent body could then have different colors.

As an additional comparison of the Trojans and the satellites, Fig. 15 plots the normalized reflectivities  $S'$  versus the light curve amplitudes  $\Delta m$  of both groups. The 13 Trojans represented in Fig. 15 are those for which  $S'$  and  $\Delta m$  are readily available from the samples of Hartmann *et al.* (1988) and JL90. The figure reemphasizes the similarities between the satellites and the Trojans: their ranges of  $S'$  and  $\Delta m$  overlap completely. However, the satellites have a smaller range

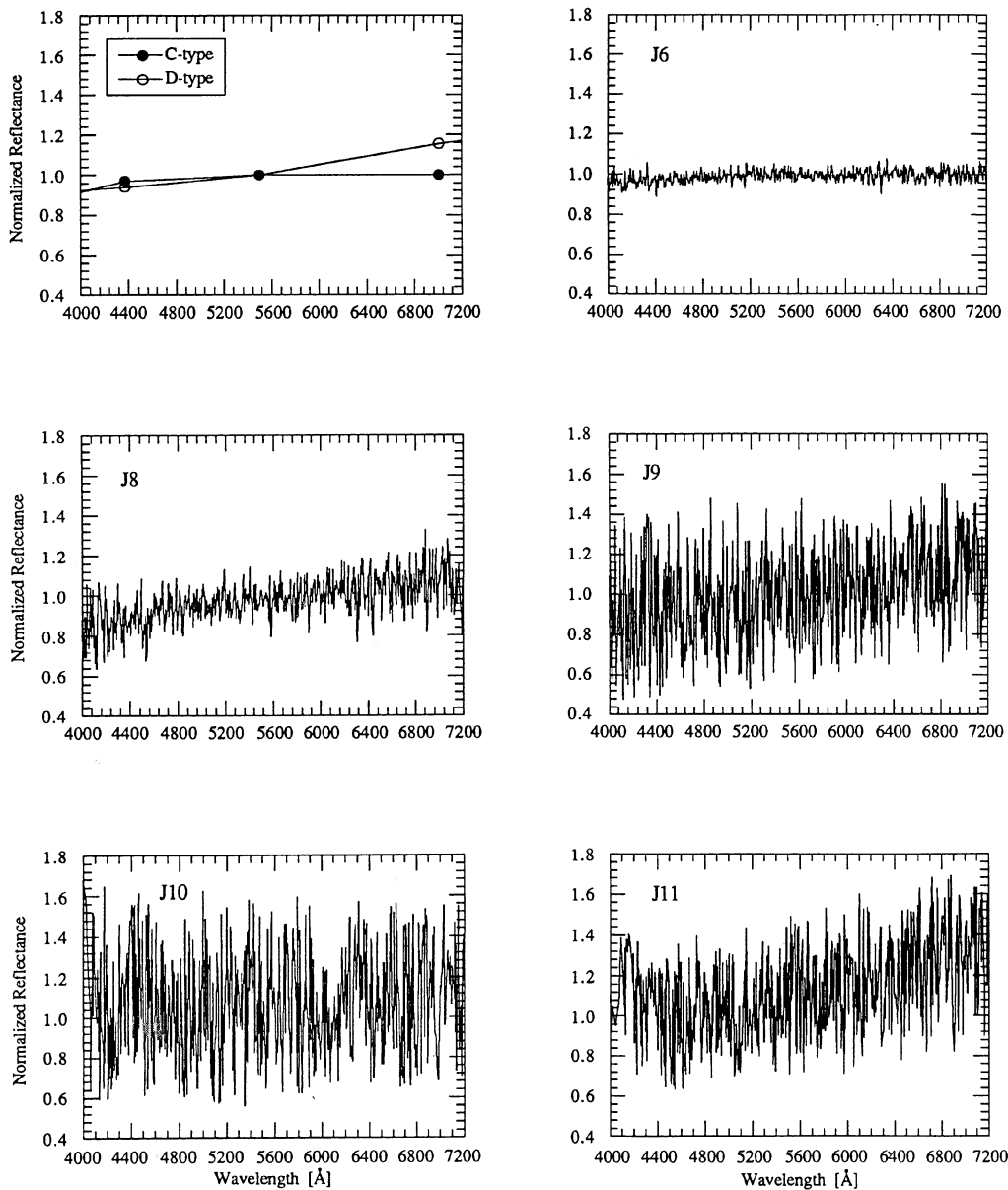


FIG. 14. Comparison of satellite spectra with typical spectra of C and D asteroids. The asteroid spectra were taken from Tholen (1984). The satellites exhibit both neutral (C-type) and red (D-type) spectra.

of  $\Delta m$  ( $\leq 0.27$  mag) than the Trojans as a group, suggesting that the satellites are more “rounded” than the Trojans in general. In fact, if we gather the statistical information collected thus far on the satellites, Trojans and nuclei (Figs. 12–15, and summarized in Table 8), we notice that in both  $\Delta m$  and  $S'$ , the satellites and the nuclei lie at opposing ends, while the Trojans take the middle ground. This can be best seen in Table 8: the satellites have the smallest mean  $\Delta m$  and  $S'$  (0.2 mag and  $6.3 \text{ \%}/10^3 \text{ \AA}$ , respectively), while the nuclei exhibit the largest  $\Delta m$  (0.7 mag) and the reddest color ( $14 \text{ \%}/10^3 \text{ \AA}$ ). The Trojans have the median values in both parameters

(0.4 mag and  $10 \text{ \%}/10^3 \text{ \AA}$ ) and thus can be considered to share common characteristics with both nuclei and satellites, although there is no strong resemblance between the two latter groups. It is not clear what implication this trend may have on the connection between the three groups, if any. To form a more definite picture will require more observations of the optically fainter (and thus less observed) groups, the satellites and comet nuclei.

It is interesting to note that Kuiper (1956) also extended his theory of the origin of the *Jovian satellites* to the Trojan asteroids. He argued that, whereas proto-planets can shed

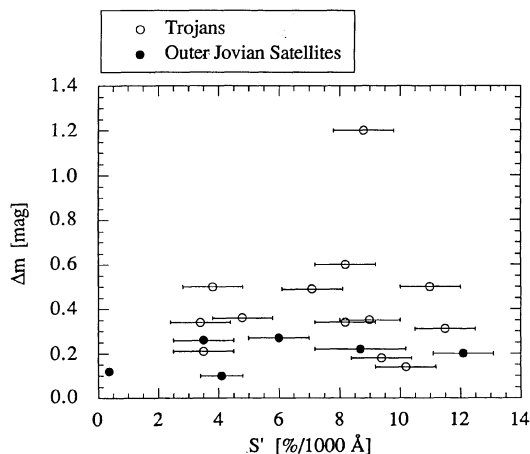


FIG. 15.  $S'$  vs light-curve amplitude  $\Delta m$  for outer *Jovian satellites* and Trojan asteroids. The satellites are statistically indistinguishable from the Trojans in both  $S'$  and  $\Delta m$ .

and recapture satellites to form irregular satellites, those satellites that were shed and *not* recaptured may turn into asteroids. In the case of Jupiter, these “ex-satellites” become Trojan asteroids. If this is true, we would expect some similarities between the Trojans and the satellites. From Fig. 15, we know that the Trojans and the satellites have similar colors, but the Trojans seem to have more irregular shapes than the satellites. One plausible hypothesis would be that the Trojans and the satellites shared a common origin in the Jovian nebula, as Kuiper (1956) suggested, but since then had evolved separately due to their different fates. After the fragmentation of the parent bodies, the satellites spent more time in the Jovian nebula and may have had any rough edges broken off by gas drag, while the Trojans were never recaptured by Jupiter and thus retained more primitive shapes.

We conclude that the evidence available so far is consistent with, but do not provide unique proof for, a common origin between the Trojans and the satellites. The similarities between the two groups ( $S'$ , low albedos) support a common origin, but the small satellite  $\Delta m$ 's compared to the Trojan  $\Delta m$ 's may hint at a different evolutionary path. To complete our big picture of the satellites, the missing “pieces” such as the spectra of J7, J12, and J13, and the albedos of all the satellites except J6 and J7 should be measured. Additional light curves taken at different epochs would also help to verify the light curves presented here and to calculate the pole directions of the satellites. Based on the findings of this pa-

per, it is likely that we will find more similarities, rather than differences, between the two groups.

#### 4. CONCLUSIONS

General conclusions that may be drawn about the outer *Jovian satellites* are as follows:

(1) The mean rotation periods and the light-curve amplitudes for the prograde and retrograde groups are 11.1 hr and 0.20 mag, and 10.6 hr and 0.24 mag, respectively (see Table 7). These means are consistent with each other and with the mean amplitude and rotation period for main belt asteroids. By analogy with the main belt asteroids, this suggests, but does not prove, a collisional origin for the shapes and rotations of the satellites.

(2) The satellites are spectrally diverse, with mean  $S'$  (colors) of five of the satellites range from neutral to red ( $0.4\% / 10^3 \text{ \AA}$  to  $12\% / 10^3 \text{ \AA}$ ). The reflectance spectra of the observed satellites are linear as a function of wavelength in the range 4000–7200  $\text{\AA}$ , with no obvious absorption or emission features.

(3) The wide range of colors, plus the assumed low albedo for most of the satellites, indicate that the satellites resemble a mixture of both C- and D-type asteroids. This result is a revision of the conclusion reached by Tholen & Zellner (1984), who claimed that most, if not all, of the satellites were C-types.

(4) The neutral to red colors of the satellites are reminiscent of the Trojan colors. The light-curve amplitudes  $\Delta m$  of the satellites also fall within the range of  $\Delta m$ 's observed among Trojan asteroids, but the satellite  $\Delta m$ 's are restricted to smaller values ( $\leq 0.27$  mag) than the Trojan  $\Delta m$ 's.

(5) The similarities between the satellites and the Trojan asteroids are consistent with the hypothesis suggested by Kuiper (1956) that these two groups of objects share a common origin (i.e., they both formed in the proto-Jupiter nebula, but the satellites were lost and recaptured, whereas the Trojans were lost and never recaptured). A common origin would explain the similar colors, whereas the longer amount of time spent by the satellites in the proto-Jupiter nebula might explain the difference in light-curve amplitudes (shapes).

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