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Implied Evolutionary Differences of the Jovian Irregular Satellites from a BVR Color Survey

Terrence W. Rettig
Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46556
E-mail: trettig@nd.edu

Kevin Walsh
Department of Astronomy, University of Maryland, College Park, Maryland 20742

and

Guy Consolmagno
Steward Observatory, Vatican Observatory Research Group, University of Arizona, Tucson, Arizona 85721

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We present BVR colors and magnitudes for four jovian irregular prograde satellites (Himalia J6, Elara J7, Lysithea J10, and Leda J13) and four irregular retrograde satellites (Pasiphae J8, Sinope J9, Carme J11, and Ananke J12). All eight have generally 'solar' colors but the retrograde group has slightly redder and more diverse colors. The strikingly similar colors of the four prograde satellites suggest the parent planetesimal was likely very homogeneous. The four retrograde satellites show a diversity in color that suggests a heterogeneous progenitor and thus variations in precapture formation history. The absolute magnitudes and revised diameters are presented. We also report new colors and diameters for two uranian irregular satellites (Caliban (S/1997 U1) and Sycorax (S/1997 U2) that are slightly redder than any of these jovian satellites.

Key Words: **jovian; satellites; irregular; BVR colors.**

INTRODUCTION

All of the giant planets have both regular and irregular satellites. Regular satellites have prograde orbits with low eccentricities and low orbital inclinations which are generally thought to have formation histories tied to the giant planets. The regular Galilean satellites mimic the Solar System density progression and suggest the satellites were formed from a similar condensation sequence in which less dense moons are formed further from the parent planet (Pollack and Fanale 1982). In contrast, most of the irregular satellites were probably captured prior to regular satellite formation when an extended protoplanetary nebula was still effective in capturing objects with close approach paths (Kuiper 1956, Pollack *et al*. 1979). Satellite resonances between the largest moon and smaller moons, and tidal interactions, which facilitate the transfer of angular momentum from planets to satellites, make tracing their orbital history, and thus reconstructing their evolutionary history, difficult (Hagihara 1972, Saha and Tremaine 1993). There are now a minimum of 28 Solar System irregular satellites: 20 in orbit around Jupiter with 11 being recent discoveries (Sheppard *et al*. 2000, 2001), 4 around Uranus (including U1, U2), 1 around Saturn (Phoebe S9), 1 around Neptune (Nereid N2), and 2 around Mars. The 20 still in orbit around Jupiter represent only a small fraction of the number captured during the early history of its protoplanetary nebula. Gas drag from the nebula as well as tidal interactions have been suggested to be effective in removing many captured satellites by spiraling them toward the parent planet or by providing an escape mechanism (see Burns 1973, Ward and Reid 1973, Harris 1978, Pollack *et al*. 1979, Jarvis *et al*. 2000).

The two distinct groups of jovian irregular satellites discussed in this paper consist of four satellites in prograde orbits and four satellites in retrograde orbits. The irregular prograde group consists of Himalia J6, Elara J7, Lysithea J10, and Leda J13, with an average inclination of ∼27 degrees, orbital periods of about 250 days, and a mean distance of ∼150 Jupiter radii. The irregular retrograde group of Pasiphae J8, Sinope J9, Carme J11, and Ananke J12 have a mean inclination of 150 degrees, periods of about 700 days, and a mean distance of ∼320 jovian radii—see Table I for general characteristics. The high eccentricities and inclinations suggest these two groups of irregular satellites resulted from two independent interplanetary bodies captured into two very different orbits around protoJupiter (Kuiper 1956, 1957, Pollack *et al*. 1979). Kuiper (1956) suggested a common origin with the Trojan asteroids at the stable Lagrangian points of

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TABLE I[a]

	Semimajor (10^6 km)	Rev. Period (∼days)	Inclination (degrees)	Eccentricity	Diameter (km)
Prograde					
J13 Leda	11.1	240	26.7	0.146	15–16 km
J6 Himalia	11.4	251	27.6	0.158	185–190 km
J10 Lysithea	11.7	260	29.0	0.120	35–40 km
J7 Elara	11.7	260	24.8	0.207	∼75–80 km
Retrograde					
J12 Ananke	20.7	617	147	0.169	30 km
J11 Carme	22.3	692	163	0.207	40–44 km
J8 Pasiphae	22.3	735	147	0.400	∼50–70 km
J9 Sinope	22.7	758	156	0.275	∼35–40 km

[a] General satellite data from Binzel *et al*. (1989) and Burns (1986). The ranges of diameters are from Cruikshank *et al*. (1982) and Burns (1986).

Jupiter. Hartmann (1987, 1990) suggested the jovian irregulars resulted from Jupiter resonances that likely scattered a high flux of C-class objects out of the asteroid belt at the close of planet accretion; this effect was an important phase of Solar System history, influencing the nature of moons, meteorites, and perhaps even atmospheres.

Capture of the two irregular parents likely resulted from aerobraking in the extended protojovian atmosphere (Kuiper 1957). The nonnegligible gas drag would have caused the vast majority of satellites to spiral into the protoplanet but, given the proper conditions, the atmospheric drag could have resulted in stable orbits (Pollack *et al*. 1979). The gas density had to be relatively low for these moons to survive for any length of time, or the capture events must have occurred just before the jovian nebula experienced hydrodynamic collapse.

Kuiper (1957) suggested fragmentation of the parent satellites occurred during capture because the gas dynamical pressure in the jovian atmosphere exceeded the parent body tensile strength. Similarly, Pollack *et al*. (1979) suggested the fracture might have occurred at the time of capture but that breakup of the two parent satellites occurred as a result of later collisions (see also Colombo and Franklin 1971). Dynamical studies by Whipple and Shelus (1993) and Saha and Tremaine (1993) noted that weak gas drag may have influenced two of the retrograde satellites (J8, 9) as they are now locked into a secular resonance that acts to protect them from solar perturbations. In addition to constraining theories of satellite formation, it suggested that slow orbital evolution, possibly due to Jupiter mass changes or to dissipation due to weak gas drag, may have played a major role in the determination of the current orbits. Jarvis *et al*. (2000) theorized that the prograde group, with no indication of secular resonances, separated sometime after capture. A more recent satellite capture and fragmentation event revealed itself with the discovery of Comet Shoemaker–Levy 9 (1993e) (Shoemaker *et al*. 1993). Dynamical results indicate that the original satellite capture likely occurred in the 1930's, but the subsequent Jupiter–satellite encounter near the Roche limit in 1991 fragmented the parent body into approximately 20 subnuclei which became temporary irregular satellites until collision with Jupiter.

Numerous observations of colors and low-resolution spectra have provided informative, and sometimes contradictory, data for the jovian irregular satellites. Degewij *et al*. (1980a) used aperture photometry to produce UBVRI colors for J6, J7, and J8 that suggested similarities with C-type asteroids. VJHK measurements of J6 Himalia (Degewij *et al*. 1980b) showed carbonaceous chondritic type colors in the 0.5- to 2.2-micrometer region. Smith *et al*. (1981), using narrow band photometry, showed that the normalized spectral reflectance of J8 and J9 rises steadily toward longer wavelengths that suggested they are too bright in the near infrared (IR) to be C-type asteroids. Cruikshank *et al*. (1982) suggested the irregular prograde satellites are similar to C-type asteroids and the retrograde appear more like D-type, similar to Trojans. Gradie and Veverka (1980) hypothesized that the reflectance and albedo characteristics of the D-type may be due to aromatic kerogen-like compounds with spectral reddening between 0.4 and 1.1 micrometers. Tholen and Zellner (1984) used eight-color asteroid survey photometry of J6–11 that indicated a similarity to C-class asteroids, except for J11, which showed a remarkable brightness in the ultraviolet. They noted the absence of D-class spectra implied the irregulars were not derived from the same population as the outer-belt and Trojan asteroid populations. Luu (1991), using low resolution spectra, noted J9, J10, and J11 could be D-type though they are slightly less red. The spectra appeared generally featureless with reflectivity gradients ranging from neutral to somewhat red. Results from a CCD V, R, I photometric study (Luu 1991) suggested the range of satellite colors and spectra resemble a mixture of C- and D-class asteroids, similar to the Trojan asteroids, and that, in contrast to this paper, there were no statistically significant differences in the mean properties between the prograde and retrograde groups.

Using IJKH data, Dumas *et al*. (1998) extended the observation of Himalia (J6) to 2.4 micrometers. The results confirmed the absence of water ice and the relatively neutral, flat spectrum typical of the C-class. They noted that the irregular satellites, and many asteroids, could be interpreted in terms of comet-like objects that have undergone various degrees of aging (see also Thompson *et al*. 1987). Vilas (1994) found Himalia tested positively for water of hydration; the iron oxide absorption feature at 0.7 micrometers supports the hypothesis that these may be captured C-class asteroids from postaccretional dispersion. Brown (2000), using low-resolution spectra in the near IR, showed Himalia, Elara, and Pasiphae are featureless with no evidence of water ice; the spectra do hint at a slight redward slope which is consistent with asteroidal origins. Jarvis *et al*. (2000) used visible and near-IR narrow band reflectance spectra to support the C-type classification for Himalia and confirmed the presence of a weak absorption feature attributed to oxidized iron. They suggested the prograde parent body may have originated as an F-class (subclass of C) object near the 2.5 AU Kirkwood gap. From the Two Micron All Sky Survey, using the JHK band passes, Sykes *et al*. (2000) produced colors for five of the jovian irregular satellites. They found prograde satellite colors are consistent with fragments of a captured C-type asteroid, and the retrograde satellites show considerable diversity. They suggested that the prograde jovian satellites are fragments of a captured parent body more homogeneous than the retrograde parent (see also Luu 1991). None of the observation sets for these eight satellites are complete, and the comparisons are difficult, but in general the observations suggest the retrograde satellites are distinct from the prograde irregulars. The colors are not adequate to infer more detailed classification of the parent bodies, and it is not clear whether the satellites have an origin similar to the Trojans or are a random sampling of planetesimals from the early Solar System.

OBSERVATIONS

All of the jovian irregular satellite observations were made on a total of seven nights at the Vatican Advanced Technology Telescope (VATT) Observatory on Mt. Graham. The nights of observation were 23, 24 September 1998 UT and 15–19 November 1999 UT. The VATT 1.8-m telescope was equipped with a 2048 × 2048 15-μm pixel Loral 3-edge buttable CCD. Binning was set at 2 × 2 mode which produced a 1024 × 1024 pixel image with 0.4 arcsec/pixel covering a total of ~7.1 square arcmin of the sky. The CCD has a quantum efficiency (QE) of 80–90% in all of the Harris B, V, R filters.

Standard bias subtraction and flatfielding removed gradients, dust spots, and hot columns. Two different methods were used to flatfield the images. For the two nights in September (1998) and the first two nights in November (1999), a series of twilight images were median averaged and then divided out of the images. This removed most of the systematic irregularities typically present in all CCDs. For the last three nights during the November observations, BVR flatfields were produced from a median averaging of the data frames throughout the night. Each of the 300-s images were taken with small movements of the telescope between each exposure. The exposures were normalized and median combined to produce a very accurate flatfield for each filter. With ~35 images in each filter, this flatfielding procedure produced very uniform images with errors less than 1% across the CCD. This allowed for very accurate subtraction of the background scattered light from Jupiter, subtraction of nearby faint galaxies, etc.

Since the measurement errors of the smallest/faintest satellites were dominated by sky noise, the stellar photometric technique of aperture correction (Howell 1989) was used. Typically a small aperture was used to measure the raw counts for each satellite image. The small aperture captures most of the image as defined by the point spread function (psf), but the outer tail of the psf is often lost in the noise. To correct for this effect, a field star, 4 or 5 mag brighter than the satellite, common to the images of the objects for each night, was chosen for a comparison star. This star was measured using both a small and large aperture. Typically we used a 10-arcsec aperture to determine the amount of signal in a larger area defined by the point spread function. The magnitude difference between the two apertures provided a magnitude correction to account for the tail of the point spread function that was beneath sky level. To account for variations in atmospheric seeing, each of four smaller apertures—1.2, 1.6, 2.0, and 2.4 arcsec diameter—were corrected to the 10-arcsec aperture. The four resulting magnitudes were averaged to produce an instrumental magnitude and an error estimate for each satellite.

The images were flux calibrated using numerous Landolt (1983) field stars. We determined extinction coefficients and transformation equations for each night of observation. The instrumental transformation equations were consistent (to within 2%) from year to year, suggesting a very stable telescope and detector. In November 1999, the conditions were extremely uniform during the five nights and the resulting colors matched the standard system to 2% or less. The satellites and standards were observed with multiple 300-s exposures in each filter. Since the satellites have an apparent motion, the exposure times were kept short to minimize smearing to 2–3 pixels, usually within the seeing disk 0.8 to 1.8 arcsec. Cosmic rays were easy to identify and were rarely a problem, thus few images were actually discarded due to cosmic ray hits near the actual object.

RESULTS

The results are summarized in Tables II and III. In Table II, the B–V and V–R colors, apparent magnitude, and number of observations (N) are presented for the dates of observation. The errors have been calculated using $\sigma/\sqrt{N}$ for each color and adding to account for the summation in errors. All B, V, R magnitudes and resulting B–V and V–R colors were obtained from multiple observations on each night. The colors remain quite consistent to within a few hundredths of a magnitude, and the variations in the night-to-night magnitudes can mostly be attributed to differences in phase angle, distance, and light curve effects. The colors of the uranian irregular satellites Caliban (S/1997 U1) and Sycorax (S/1997 U2) have been included for comparison; see notes below. All the colors and magnitudes for the jovian satellites as well as Sycorax (S/1997 U2) were obtained from the VATT; the KPNO 4-m telescope was used for Caliban (S/1997 U1).

Table III lists the r (heliocentric distance), Δ (geocentric distance), α (phase angle), D (satellite diameter in kilometers), and H (the absolute magnitude at unit heliocentric and geocentric distance and the phase angle of zero degrees). The magnitudes from various observation dates are compared using the formalism of Bowell *et al.* (1989) to correct the photometry for phase angle and distance variations. The relationship between the apparent magnitude V of an asteroid, or satellite in this case, and the absolute magnitude, H, is given by

$$V = H + 5\log(r\Delta) + f(\alpha),$$

TABLE II

Object	Dates (UT)	Magnitudes B–V	 V–R	 V	N
J6 Himalia	1998 Sept 23	0.62 ± .02	0.40 ± .02	14.61 ± .01	6
	1998 Sept 24	0.66 ± .03	0.35 ± .02	14.63 ± .02	11
J7 Elara	1999 Nov 12	0.65 ± .02	0.35 ± .02	16.30 ± .02	6
	1999 Nov 13	0.66 ± .02	0.36 ± .02	16.30 ± .02	6
	1999 Nov 14	0.67 ± .02	0.36 ± .02	16.35 ± .02	6
J8 Pasiphae	1998 Sept 23	0.69 ± .02	0.41 ± .02	16.85 ± .02	8
	1998 Sept 24	0.68 ± .02	0.41 ± .02	16.90 ± .02	8
	1999 Nov 13	0.68 ± .02	0.40 ± .02	17.04 ± .02	6
	1999 Nov 14	0.67 ± .02	0.42 ± .02	17.18 ± .02	6
J9 Sinope	1998 Sept 23	0.77 ± .03	0.50 ± .03	18.02 ± .02	5
	1998 Sept 24	0.76 ± .04	0.47 ± .03	18.07 ± .02	8
	1999 Nov 13	0.71 ± .03	0.47 ± .02	18.05 ± .02	6
	1999 Nov 14	0.78 ± .04	0.49 ± .03	18.05 ± .02	6
	1999 Nov 15	0.74 ± .04	0.49 ± .03	18.07 ± .02	6
J10 Lysithea	1998 Sept 23	0.67 ± .02		17.79 ± .02	2
	1999 Nov 13	0.67 ± .03	0.38 ± .03	18.26 ± .03	11
	1999 Nov 14	0.71 ± .04	0.36 ± .04	18.31 ± .03	6
	1999 Nov 15	0.60 ± .06	0.41 ± .06	18.25 ± .04	6
J11 Carme	1998 Sept 24	0.73 ± .02	0.44 ± .02	17.59 ± .02	10
	1999 Nov 12	0.71 ± .02	0.45 ± .02	17.49 ± .02	24
J12 Ananke	1998 Sept 24	0.77 ± .03	0.41 ± .03	18.64 ± .02	22
	1999 Nov 13	0.75 ± .03	0.44 ± .03	18.75 ± .02	10
	1999 Nov 14	0.75 ± .04	0.44 ± .04	18.83 ± .02	6
J13 Leda	1999 Nov 13	0.64 ± .04	0.34 ± .04	19.53 ± .03	19
	1999 Nov 14	0.64 ± .03	0.36 ± .03	19.69 ± .03	51
	1999 Nov 15	0.65 ± .03	0.34 ± .03	19.50 ± .03	42
Caliban (S/1997 U1)	1998 June 19	0.83 ± .06	0.52 ± .06	22.32 ± .05	18
Sycorax (S/1997 U2)	1999 May 16, 19	0.87 ± .05	0.44 ± .04	21.04 ± .06	24

where

$$f(\alpha) = -2.5 \log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$$

and

$$\Phi_i = \exp[-A_i(\tan \alpha/2)^{B_i}],$$

where $G = 0.15$ (see Bowell *et al*. 1989), $i = 1, 2$, $A1 = 3.33$, $B1 = 0.63$, $A2 = 1.87$, and $B2 = 1.22$. The satellite diameters (D) were obtained from the equation (Jewitt and Luu 1993)

$$p\Phi(\alpha)D^2 = 9 \times 10^{16} r^2 \Delta^2 10^{0.4(m\odot - v)},$$

where $\Phi(\alpha)$ is the phase function from Bowell *et al*. (1989), p is the albedo, r and Δ are in AU, m (sun) is the apparent solar magnitude (−26.74), and V is the apparent magnitude of the object. All satellites are assumed to be relatively low-albedo objects. We used a 4% albedo, the nominally used albedo for outer Solar

TABLE III

Object	Date (UT)	m_v	r (AU)	Δ (AU)	α (degrees)	Diameter (km)	H m_v (1,1,0)
J6 Himalia	1998 Sept 23	14.61 ± .01	4.89	3.89	1.54	169 (194)	8.00
	1998 Sept 24	14.63 ± .02	4.89	3.89	1.77	168 (193)	8.01
J7 Elara	1999 Nov 12	16.30 ± .01	4.94	4.00	4.04	86 (100)	9.45
	1999 Nov 13	16.30 ± .01	4.94	4.01	4.25	87 (101)	9.43
	1999 Nov 14	16.35 ± .01	4.94	4.01	4.46	85 (99)	9.47
J8 Pasiphae	1998 Sept 23	16.85 ± .01	5.00	4.00	1.29	62 (72)	10.16
	1998 Sept 24	16.90 ± .01	5.00	4.00	1.50	61 (61)	10.20
	1999 Nov 13	17.04 ± .01	4.92	4.01	4.92	62 (72)	10.15
	1999 Nov 14	17.18 ± .01	4.92	4.01	5.12	59 (68)	10.28

TABLE III—*Contiuned*

Object	Date (UT)	m_v	r (AU)	Δ (AU)	α (degrees)	Diameter (km)	H m_v (1,1,0)
J9 Sinope	1998 Sept 23	18.02 ± .01	5.06	4.06	1.31	37 (43)	11.27
	1998 Sept 24	18.07 ± .01	5.06	4.06	1.51	36 (42)	11.31
	1999 Nov 13	18.05 ± .01	4.85	3.91	4.14	37 (43)	11.29
	1999 Nov 14	18.05 ± .02	4.85	3.92	4.35	37 (43)	11.27
	1999 Nov 15	18.07 ± .02	4.85	3.92	4.55	37 (43)	11.28
J10 Lysithea	1998 Sept 23	17.79 ± .02	4.93	3.93	1.38	39 (45)	11.17
	1999 Nov 13	18.26 ± .03	4.96	4.04	4.63	36 (42)	11.35
	1999 Nov 14	18.31 ± .03	4.96	4.05	4.83	35 (42)	11.38
	1999 Nov 15	18.25 ± .04	4.96	4.06	5.02	36 (43)	11.31
J11 Carme	1998 Sept 24	17.59 ± .01	4.97	3.97	1.45	44 (51)	10.92
	1999 Nov 12	17.49 ± .01	4.82	3.89	4.73	48 (56)	10.72
J12 Ananke	1998 Sept 24	18.64 ± .03	5.03	4.03	1.88	28 (33)	11.88
	1999 Nov 13	18.75 ± .03	5.07	4.13	4.03	30 (34)	11.78
	1999 Nov 14	18.83 ± .03	5.07	4.14	4.24	29 (33)	11.84
J13 Leda	1999 Nov 13	19.53 ± .03	4.94	4.02	4.65	20 (23)	12.64
	1999 Nov 14	19.69 ± .03	4.94	4.03	4.85	19 (21)	12.78
	1999 Nov 15	19.50 ± .03	4.94	4.04	5.05	21 (24)	12.58
Caliban (S/1997 U1)	1998 June 19	22.32 ± .05	19.82	19.09	2.09	97	9.18
Sycorax (S/1997 U2)	1999 May 16,19	21.04 ± .06	19.88	19.68	2.88	190	7.78

Note.

- Most, but not all, of the color and magnitude variations can be attributed to lightcurve and viewing-aspect effects and are briefly detailed below. The estimated diameters have typical errors of ± 1–2 km. Previous diameter estimates are provided in Table I; note comparison to the 4% albedo diameters.
- The eight irregular satellite absolute magnitudes can be compared using m(v)(1,1,0) from a V, R, I survey of the irregular satellites (Luu 1991)—J6 (7.96 ± .03), J7 (9.76 ± .03), J8(10.43 ± .03), J9(11.63 ± .03), J10(11.42 ± .03), J11(10.96 ± .03), J12(12.21 ± .04), and J13(12.85 ± .20).

J6 Himalia—The lightcurve for J6 was reported to have a best fit period of 9.5 h and an amplitude as great as 0.23 mag (Degewij *et al.* 1980a). The absolute V magnitude is very similar to that reported by Degewij *et al.* (1980a) and Luu (1991).

J7 Elara—Since only the R magnitude was presented for J7 (Luu 1991), it was converted to V using this work and is ∼0.3 mag fainter than what we report. Degewij *et al.* (1980a) report a 0.5 mag variation for J7. The possibility of aspect effects are noted for J7, J8, and J9 (see Luu 1991).

J8 Pasiphae—Our absolute V magnitude is brighter (∼0.20 mag) than the Luu (1991) measurements which show somewhat random variations of less than 0.1 mag. Our results show a similar variation and are most consistent with photometry from Degewij *et al.* (1980a) and Tholen and Zellner (1984). They also suggest the possibility that J8 may have a large amplitude lightcurve.

J9 Sinope—Results indicate an absolute V magnitude ∼0.35 brighter than that reported by Luu (1991) where a 13.16 h period with an amplitude of ∼0.20 was noted. The appreciably larger diameter reported in this work suggests the possibility that the satellite is rather elongated and has presented different aspects between the reported observation dates.

J10 Lysithea—In general the absolute V magnitude is only slightly brighter than that reported by Luu (1991) who reported a period of 12.78 ± 0.1 with a 0.27 mag variation. The variation seen in the September and November magnitudes is likely a result of lightcurve effects. We note that the consistency across the three consecutive nights in November might be due to observations made at similar positions on the lightcurve as expected with a 12 h period. On September 23, 1998, scattered light made the R images unusable.

J11 Carme—The B–V has not been previously reported. Our absolute V magnitude is similar to that reported by Luu (1991) within the reported lightcurve magnitude variation.

J12 Ananke—Our results show the absolute magnitude to be nearly 0.4 mag brighter than the value reported by Luu (1991) where the reported lightcurve amplitude was ∼0.26 mag, with a period of 8.3 ± 0.1 h.

J13 Leda—Colors for J13 have not been reported previously. J13 was the most thoroughly observed of all the jovian satellites and was found to be ∼0.2 mag brighter than reported previously. It does not have a published lightcurve and thus was observed extensively on two nights. The observations exhibited no apparent pattern. The possibility of a ∼24-h period is noted, as the V magnitudes from 13, 14, and 15 November 1999 differed by ∼0.15 mag.

Caliban (S/1997 U1) and Sycorax (S/1997 U2)—The R magnitudes from this work are 21.8 and 20.6 for U1 and U2, respectively, similar to those of M Nicholson *et al.* (1998) and Gladman (1998). They determined the R magnitudes for the retrograde satellites U1, U2 to be R = 21.9 and 20.4; the B–R and R–I colors are ∼1.6 and ∼0.6, respectively. Gladman (1998) used a 7% albedo to determine diameters of 60 km (U1) and 120 km (U2).

System objects, to determine the relative diameters of each object. From radiometric measurements, Cruikshank (1977) found the albedos of J6 and J7 to be 3%; resulting diameters are presented in parentheses.

In Tables I and II obvious differences can be seen in the sizes (D) and thus the mass distributions within the prograde and retrograde groups. The total inferred mass of the jovian prograde irregular satellites (assuming similar densities and albedos) is larger than that of the irregular retrograde satellites. The prograde group is dominated by Himalia (J6). The other prograde satellites each decrease proportionally by approximately a factor of 2 in diameter. It is not known whether this size structure is inherent to the accretion process prior to fragmentation, but the distribution of fragment sizes is typical of rocks colliding in nature (Hartmann 1969). The four retrograde satellites are not dominated by one large object and have roughly similar radii within a factor of 2. The mass/size distributions of these groups cannot rule out collisional, tidal, or gas drag fragmentation as recent numerical simulations have shown that tidal disruption can lead to differing, size distributions depending on the bulk density, encounter speed, and spin of the progenitor (Leinhardt *et al.* 2000, D. Richardson personal communication, 2001). The B–V and V–R colors, absolute magnitudes, and revised diameters provide a solid basis for further studies of the dynamical properties of these irregular satellites.

The colors from Table II are plotted on a V–R vs B–V color–color plot (Fig. 1) similar to that of Tegler and Romanishin (1998, 2000) who used the B–V and V–R colors to identify the bimodal distribution of Kuiper Belt objects and Centaurs. The prograde jovian satellites are plotted as squares and the retrograde satellites are plotted as open circles. Both the jovian prograde and the irregular satellite groups are in what is often referred to as the grey (neutral) area, with the prograde being tightly constrained to nearly solar colors. The irregular retrograde group appears redder and more diverse in both B–V and V–R. The B–V color difference between the two groups of jovian irregular satellites is ~0.10, and the V–R color difference is ~0.08; the color errors are typically ±0.03. The two irregular uranian satellites Caliban (S/1997 U1) and Sycorax (S/1997 U2) are plotted as a triangle and a diamond and tend to be redder than any of the jovian satellites. The uranian satellites are separated from the prograde jovian satellites by ~0.20 in both B–V and V–R. Interestingly, the colors of the uranian satellites, which are very similar to the Centaur 1995 GO, are located at the very 'red edge' of the grey group (see Tegler and Romanishin 1998), but they are definitely not among what they classify as the 'red' group.

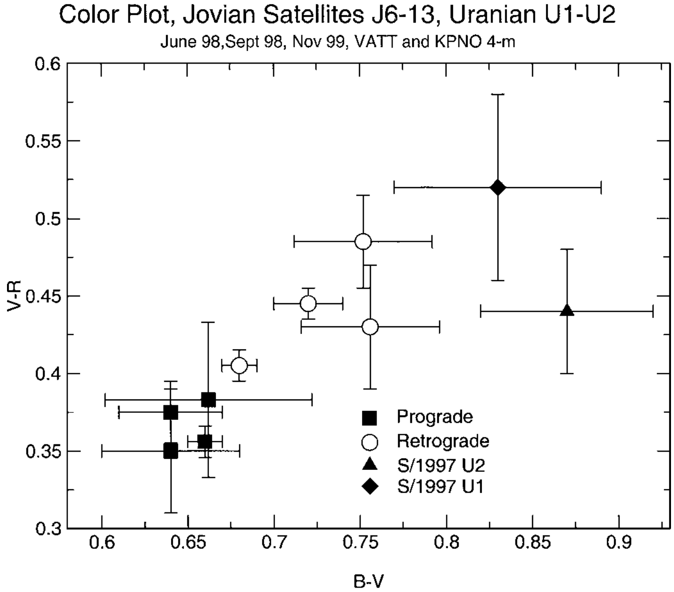

FIG. 1. V–R vs B–V color–color plot of the eight jovian satellites and two uranian satellites. The jovian prograde satellites are plotted as squares and the retrograde satellites are plotted as open circles. The two irregular uranian satellites Caliban (S/1997 U1) and Sycorax (S/1997 U2) are plotted as a triangle and a diamond, respectively.

DISCUSSION

The observations presented in this paper provide a uniform BVR magnitude and color survey of eight jovian irregular satellites as well as the uranian irregular satellites U1 and U2. Revised diameters are presented in Table III. Absolute magnitude comparison to other observations points out the possibility that the satellites may be rather elongated objects that may have been observed at different aspects. More importantly, the differing colors of the two jovian groupings support the hypothesis that these irregular satellites likely resulted from the capture of two rather different parent planetesimals that had formation histories tied to different regions in the solar nebula. The tightly clustered colors of the four prograde satellites strongly suggest a very homogeneous progenitor. The redder and more diverse B–V and V–R colors seen in the four retrograde satellites suggest that inherent inhomogeneities in the retrograde group existed prior to fragmentation. The even redder colors for the two uranian satellites hint they may be captured trans-neptunian objects (TNOs) or Centaurs (see Fig. 1) and suggest a different precapture formation history.

A large range in color has been noted for Centaurs and TNOs (Luu and Jewitt 1996, Tegler and Romanishin 1998). To explain the color variations, Luu and Jewitt (1996) suggested a possible combination of steady reddening due to cosmic ray bombardment in combination with stochastic collisional resurfacing. The global resurfacing of the roughly hundred-kilometer-sized TNOs has likely occurred during the past few eons as the TNOs collided with numerous kilometer-sized objects. The collisions provide a mechanism to reveal the 'grey' solar-colored material preserved below the surface. Due to numerous objects and particles trapped by the jovian gravitational field, the jovian irregular satellites experienced some degree of collisional resurfacing throughout their history but it was likely similar for each satellite. Thus, color differences noted between the four prograde and the four retrograde satellites, as well as within the retrograde group itself, imply compositional and dynamical differences prior to capture.

The tendency toward a gradient in Fig. 1 suggests the redder satellites had primordial compositions enriched with organic material. UV and X-ray irradiation early in the protoplanetary phase of formation, and cosmic ray bombardment throughout their remaining history, may have produced a higher abundance of complex organic molecules with a redder reflectance. Gradie and Ververka (1980) proposed that the low-albedo and reddening of the Trojan asteroids can be explained by very opaque, very red, polymer-type organic compounds similar to kerogen, presumably resulting from Fischer–Tropsch-type reactions in the early solar nebula. They suggested that the nonsoluble carbonaceous residue may have required lower temperatures for formation and preservation than carbonaceous materials in the C-type asteroids and thus explain the absence of D-type objects closer than 4 AU from the sun. Gradie and Tedesco (1982) and Gradie *et al.* (1989) noted that asteroid color differences, including those of Centaurs and Trojans, can be interpreted as due to a combination of solar irradiation, original water content, and thermal and cosmic ray processing which is a function of primordial orbital history and distance. Perhaps the solar-colored 'grey' satellites were formed in a warmer region of the solar nebula and thus had primordial compositions depleted in ice components such as CH4 and thus did not age to the 'redder' color. The irregular jovian prograde parent might have evolved in a way similar to the abundant C-type asteroids typically found in the outer asteroid belt. The retrograde parent might have originated from a slightly redder group of D- or P-type Trojan asteroids with a slightly higher content of organic molecules.

The results suggest that the progenitor parent bodies for these groups had fundamental compositional differences that provide clues to the formation conditions of the preplanetary accretion disk 4 billion years ago. Not only do the retrograde satellites suggest a composition enriched in organics but also, the results, though unexplained, suggest that the amount of enrichment may have been slightly different for each of these four satellites. Improved understanding of the mass distributions, colors (composition), and color gradients of these and the newly discovered irregulars may aid future studies of the dynamics and physical parameters of the early Solar System.

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