CCD SPECTRA OF ASTEROIDS. II. THE TROJANS AS SPECTRAL ANALOGS OF COMETARY NUCLEI

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ABSTRACT

Recent measurements of the reflectance spectra of the nuclei of comets P/Tempel 2 and P/Encke highlight the need for similar spectra of possibly related bodies in the outer solar system. Foremost among these are the Trojan asteroids. Both cometary nuclei and Trojan asteroids have geometric albedos on the order of a few percent, and both groups of objects are known to be elongated relative to main-belt asteroids of comparable size (Jewitt and Meech 1988; Hartmann *et al.* 1988). We explore the nucleus–Trojan interrelation further by performing a systematic comparison between spectral reflectivities of cometary nuclei and Trojan asteroids. For this purpose, we have obtained high signal-to-noise ratio charge coupled device (CCD) spectra of 32 Trojan asteroids for comparison with the existing cometary nucleus spectra. The Trojan CCD spectra cover the wavelength range $4000 \leqslant \lambda \leqslant 7400$ Å at 20 Å resolution, with typical signal-to-noise ratios ~ 50 per pixel. We find that the reflectivity spectra of Trojan asteroids are characterized by a broad range of linear continuum gradients S' in the range $3 \leqslant S' \leqslant 25\%/10^3$ Å, with a mean near $S' \sim 10\%/10^3$ Å. The reflectivity gradients of the comet nuclei fall within the range defined by the Trojan asteroids. In this sense, the optical spectra of the cometary nuclei and of the Trojan asteroids are consistent, enhancing the resemblance between the two groups of objects. Existing photometric and spectral data therefore suggest a remarkable similarity between the Trojans and the nuclei—both are elongated objects, mantled with low albedo, reddish, probably carbon-rich material.

I. INTRODUCTION

Recent advances in the technology of astronomical detectors have permitted the direct study of several cometary nuclei using ground-based techniques. The ground-based observations consist mostly of broadband measurements of reflected and thermal radiation, but the most recent studies have also produced detailed reflection spectra of cometary nuclei in the optical wavelength range ($4000 \leqslant \lambda \leqslant 7000$ Å; Jewitt and Luu 1989; Luu and Jewitt 1990b). In their optical properties, the nuclei may be effectively summarized as low albedo and reddish. These properties are thought to be due to a nucleus-wide mantle of refractory matter, through which cometary volatiles escape either by diffusion or through discrete vents. High-resolution spacecraft images of the nucleus of P/Halley confirm that much of the surface is covered by a dark, refractory mantle, and that outgassing is concentrated in a handful of active vents (Keller *et al.* 1987). Measurements of small solid particles in the coma of P/Halley suggest a carbon-rich composition (Kissel *et al.* 1986) which may be indicative of the composition of the mantle. The low albedos and reddish reflection spectra of the nuclei would be naturally explained if polymerized organic compounds were abundant constituents of this mantle (e.g., Johnson *et al.* 1987).

The increasingly detailed portraits of cometary nuclei now appearing in the literature motivate comparative studies of possibly related bodies in the outer solar system. Of the known outer solar system population, the Trojan asteroids are among the most attractive candidates for a comparison with comet nuclei (Hartmann 1986). Selected physical properties of the brighter Trojans are known with reasonable confidence. These objects are redder and darker (e.g., Cruikshank 1977) on average than typical main-belt asteroids, with 60% or more falling into the taxonomic class D and the rest in classes C and P (Gradie and Tedesco 1982; c.f., Bell *et al.* 1989). The low albedo and red color are generally assumed to indicate a surface rich in organic compounds (Gradie and Veverka 1980; see also the discussion in Bell, Cruikshank, and Gaffey 1985). However, no compelling direct evidence for organic material in asteroids has yet been produced (c.f., Cruikshank 1987; Cloutis 1989). The rotational photometric variations in Trojan asteroids are large compared to those in main-belt asteroids (Hartmann *et al.* 1988), suggesting that the Trojans are elongated relative to main-belt asteroids. This might be a consequence of the different collisional environments of the main-belt and Trojan asteroids.

The visual colors, albedos, and elongated body shapes of the Trojan asteroids resemble the corresponding properties of cometary nuclei. If real, the apparent optical and physical similarities between the cometary nuclei and the Trojan asteroids might be products of the distinctive collisional and thermal environments in which these objects exist. The Trojans, for example, populate two dynamically distinct "clouds" associated with the L4 (preceding) and L5 (following) Lagrangian points of Jupiter. Temperatures in the

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protoplanetary cloud near the orbit of Jupiter are thought to have been sufficiently low that water and possibly other volatiles could be directly incorporated within objects accreted there (Prinn and Fegley 1989). Even now, water ice could be present in the interiors of Trojan asteroids in large abundance, if shielded from direct solar radiation by a mantle of nonvolatile material. A high surface abundance of organic compounds might also result from the low temperatures at accretion. The origin of the Trojans is not known. Suggested sources include *in situ* accretion, capture of Jovian satellites and capture of short-period comets (Rabe 1972; c.f., Yoder 1979). The number densities of the asteroids in the clouds are smaller than in the main belt, suggesting that the Trojans may be less evolved as a result of mutual collisions than are their main-belt asteroidal counterparts. High volatile abundances in cometary nuclei independently suggest origins in distant locations where the collision frequency is small, so that recent collisional evolution of their bulk physical properties is expected to have been minimal.

These observations are the natural outgrowth of an observational program of CCD spectroscopy of asteroids (Luu and Jewitt 1989a, hereafter referred to as Paper I). Our current knowledge of the physical properties of Trojans is based mostly on filter photometry having poor spectral resolution. In this study we seek to use a uniform set of *spectra* to provide answers to the following questions:

(1) What are the basic characteristics of the visual reflection spectra of the Trojan asteroids? It is known (mostly from the low-resolution filter data) that the Trojans are reddish objects. What is the range of colors present among the Trojans and what does this range imply for the compositional diversity of these bodies?

(2) Do absorption features exist in the visual spectra of Trojan asteroids? Discrete absorptions are known in the spectra of some near-Earth (Paper I) and main-belt asteroids (Vilas and McFadden 1987). No features have yet been reported in the spectra of Trojans, but is this due to the paucity of spectra (as opposed to filter data) that have been published?

(3) Are the statistical spectral properties of the Trojans in the preceding cloud consistent with those in the following cloud? Asteroids in the two clouds are dynamically isolated from one another. If they share a common source we would expect the two groups to have common color distributions. Is this observed?

(4) How do the spectral characteristics compare with spectra of the near-Earth and main-belt asteroids? The Trojan asteroids are dynamically isolated from the main-belt and near-Earth populations, and presumably have a different source. Chemical differences should be reflected in different color distributions for the various groups.

(5) How do the reflection spectra of Trojan asteroids compare with the reflection spectra of cometary nuclei? To what extent are the spectral properties comparable? As discussed above, the low albedos of both Trojan asteroids and cometary nuclei may be produced by polymerized carbon compounds. To what extent can the Trojan asteroids be used as spectral analogs of the cometary nuclei?

In addition to the Trojan observations which form the bulk of this paper, we also present the spectrum of asteroid 279 Thule. 279 Thule is unusual in that it is the only distant asteroid in the 4:3 resonance with Jupiter. We will show how 279 Thule compares spectroscopically with the Trojan asteroids.

II. OBSERVATIONS

The present observations were taken at the 2.1 m telescope of the Kitt Peak National Observatory in Arizona, concurrently with the observations presented in Paper I. The observational circumstances are described in detail in Paper I—here we present only a brief account. The "GoldCam" CCD spectrograph was used for all observations. This instrument houses a Texas Instruments 800×800 pixel CCD and uses a set of interchangeable grisms to provide dispersion. A 150 line/mm grating blazed at wavelength $\lambda = 5000$ Å was used for these spectra. The grating gives a dispersion 4.9 Å/pixel, and covers the spectral range from 3600 to 7400 Å, although only the wavelength range 4000–7000 Å is used in this analysis. All spectra were taken using a 2.8" wide spectrograph entrance slit, with an effective spectral resolution of 20 Å full width at half maximum (FWHM). The CCD was preflashed with a 50 electron equivalent signal in order to improve charge transfer efficiency at the lowest light levels. The image scale was 0.78" per pixel. The atmospheric seeing was near 1.5" FWHM on each night of observation.

Finding and guiding at the 2.1 m were accomplished using an intensified TV system. The finder TV was used to identify the asteroid via its motion with respect to the fixed stars, and the guider TV was used to position the asteroid in the spectrograph slit. The telescope was tracked at asteroidal rates. Since the pointing of the telescope was monitored at all times during the acquisition of the spectra, we were able to control the pointing to better than $\pm 0.5''$ (i.e., a small fraction of the slit width). Errors in guiding potentially cause variable light loss at the slit jaws. The accuracy of the guiding was demonstrated by a comparison of the flux recorded in independent spectra of the same asteroid (at least two independent spectra were taken for each asteroid). Generally, the measured absolute flux density at any wavelength was constant at the $\pm 20\%$ level. In a few cases, larger flux variations were detected, probably resulting from rotation of the asteroid between integrations and/or variable atmospheric seeing.

The effects of atmospheric dispersion were minimized in our data by observing at small airmasses and hour angles and by using a wide slit. The effective absence of atmospheric dispersion in our spectra was empirically confirmed by comparing spectra of a given object taken at a range of airmasses and hour angles (see Paper I). The spectral slopes were generally consistent to $\pm 1\%/10^3$ Å, independent of airmass or hour angle. Except for the faintest asteroids, the spectral slope uncertainty is determined by systematic effects, rather than by photon noise or other sources of noise. Therefore, all but the faintest asteroids have slope errors of $\pm 1\%/10^3$ Å.

Atmospheric emission lines and bands were removed from the asteroid spectra by using spectra from portions of the slit on either side of the asteroid to define and to subtract the spectrum of the night sky. The success of this operation can be judged from the removal of the strong night sky lines due to [O I] at 5577, 6300, and 6363 Å.

Atmospheric extinction was removed from the spectra by using standard stars at airmasses close to those of the asteroids. Typical airmass differences between asteroids and standard stars were $\Delta\chi\leqslant0.1$, leading to possible extinction cancellation errors $\leqslant$0.02 mag (extinction is approximately 0.1 mag/airmass in the red and 0.2 mag/airmass in the blue).

We define the reflectivity $S(\lambda)$ as the ratio of the asteroid flux density at wavelength λ to the flux density of the Sun at the same λ. For practical purposes we used the solar analog stars 16 Cyg B, Hyades 64, and Hyades 106 (Hardorp 1978, 1980) to define the spectrum of the Sun and to compute $S(\lambda)$. We also observed, but rejected, the Hardorp solar analog Hyades 142. Figure 1 shows that Hyades 142 is redder than the other solar analogs by $1.5\%/10^3$ Å causing us to doubt its usefulness as a solar analog. Oscillations near $\lambda \sim 6800$ Å in the ratios of standard stars plotted in Fig. 1 are an artifact caused by imperfect removal of interference fringes in the CCD data.

III. DISCUSSION

a) Spectral Properties of Trojan Asteroids

The reflectivity spectra of the 32 Trojan asteroids are shown in Figs. 2(a)–2(k), while that of 279 Thule is shown in Fig. 2(l). The Trojan spectra are plotted on a common scale to facilitate comparison; the lower, middle, and upper spectra within each panel of Fig. 2 have been displaced vertically by -0.5, 0, and 0.5 units of normalized reflectivity for clarity of presentation. Each spectrum has been cleaned (to remove cosmic rays missed during preprocessing), collapsed from two dimensions to one, and smoothed using a 3 pixel (15 Å) running mean. The spectra in Fig. 2 are presented in order of increasing redness, so as to emphasize the steady progression in the spectral reflectivities of the Trojans. The spectrum of a given Trojan can be quickly located in Fig. 2 by reference to column 8 of Table I.

Three of the Trojans in Fig. 2 were independently observed by Smith, Johnson, and Shorthill (1981) using a multichannel spectrometer. Figure 3 shows asteroids 884 Priamus, 1172 Aneas, and 1173 Anchises from Table II of Smith *et al.* renormalized to $\lambda = 6000$ Å and plotted with spectra from this work. Comparison of the spectra in Fig. 3 shows approximate agreement, although systematic differences in reflectivity as large as $\Delta S \sim 10\%$ occur at wavelengths $\lambda < 4500$ Å. These differences may be attributed to the use of a different solar analog (Smith *et al.* used HD28992, which is not one of the solar analogs championed by Hardorp 1978, 1980), to rotational spectral variations on the Trojans, to extinction errors in the multichannel data, or to some combination of all three. The systematic discrepancies shown in Fig. 3 highlight the importance of uniform spectral data when making comparisons among asteroids. Three Trojans from our current sample [asteroids 1583 Antilochus, 1867 Deiphobus and 2241 (1979WM)] were also independently observed by Vilas and Smith (1985). Unfortunately, the small scale of the figures in their paper prevents a quantitative comparison with the present data.

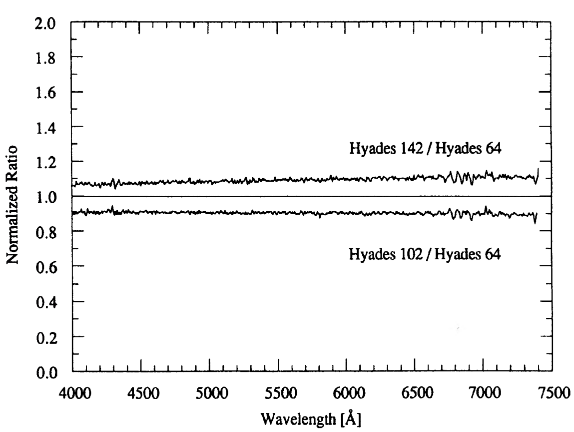

FIG. 1. Normalized ratios of solar analog spectra; both spectra were taken on the same night. The top ratio is the spectrum of Hyades 142 divided by that of Hyades 64, the bottom ratio is the spectrum of Hyades 106 divided by Hyades 64. Hyades 142 is reddened with respect to other solar analogs by $1.5\%/10^3$ Å (compare the top ratio with the bottom ratio).

Figure 2 shows that the reflectivities of a majority of the observed Trojan asteroids are linearly proportional to wavelength in the range $4000 \leqslant \lambda \leqslant 7400$ Å. Within the uncertainties of the data, there are only a few instances of clear departures from this linear reflectivity trend—these instances will be discussed below in Sec. IV. Given the overall linearity of the majority of the Trojan spectral reflectivities, we elect to employ the normalized reflectivity gradient,

$$S' = (dS/d\lambda)/S_{6000},$$

as a convenient parameter with which to characterize the spectra. Our parameter S' is the spectral counterpart of the color index and is most analogous to the $m_V - m_R$ color (see Paper I). The uncertainties in S' are estimated from repeated measurements of independent spectra. The 1σ uncertainty in S' is of order $\pm 1\%/10^3$ Å in the brighter asteroids (see column 7 of Table I) rising to approximately $\pm 2\%/10^3$ Å in the faintest asteroids. The values of S' in Table I have not been corrected for phase reddening. However, the maximum phase angle attainable by a Trojan asteroid is $\alpha \sim 12°$, hence any phase-reddening effect is likely to be small ($\leqslant 1\%/10^3$ Å). We therefore neglect the possible influence of phase reddening in our spectra (see Paper I for a fuller discussion of phase reddening in the near-Earth and main-belt asteroids).

A histogram of S' (Fig. 4) emphasizes that the Trojans are spectrally diverse, with a range of slopes from nearly neutral ($S' = 3 \pm 1\%/10^3$ Å) to very red ($S' = 25 \pm 1\%/10^3$ Å). The mean value of the reflectivity gradient of the Trojans is

$$\overline{S'} = 9.6 \pm 4.7\%/10^3 \text{ Å},$$

where the quoted uncertainty is the standard deviation on the mean of 32 asteroids. The distribution is not Gaussian, however. Two thirds of the asteroids have S' within $\pm 2\%/10^3$ Å of the mean. There are no blue asteroids ($S' < 0$) in our Trojan sample.

Examination of the slope-ordered spectra in Fig. 2 suggests that the redder Trojans are also the fainter ones in the present sample. This suspicion is confirmed by Fig. 5(a), in which we plot S' versus the apparent magnitude of each asteroid at the time of observation (since the Trojans are all at essentially same geocentric distance, the apparent magnitude distribution differs from the absolute magnitude distribution only by a constant). There is a clear trend towards increasing S' with increasing magnitude. The linear correlation coefficient computed from the data in Fig. 5(a) is $r_{\rm corr} = 0.51$ ($N = 32$). The chance that this correlation or a larger one could arise from random, uncorrelated data is $P(r \leqslant r_{\rm corr}) = 0.005$ (Bevington 1969), showing that the color–magnitude trend is statistically significant at this level. The slope of a linear least-squares fit to the data in Fig. 5(a) is $2.7 \pm 0.8\%/10^3$ Å/mag. To test the possibility that the color–magnitude trend might be an artifact of a few atypically red asteroids, we arbitrarily omitted the two reddest asteroids in Fig. 5(a) (1870 Glaukos and 1872 Helenos) and

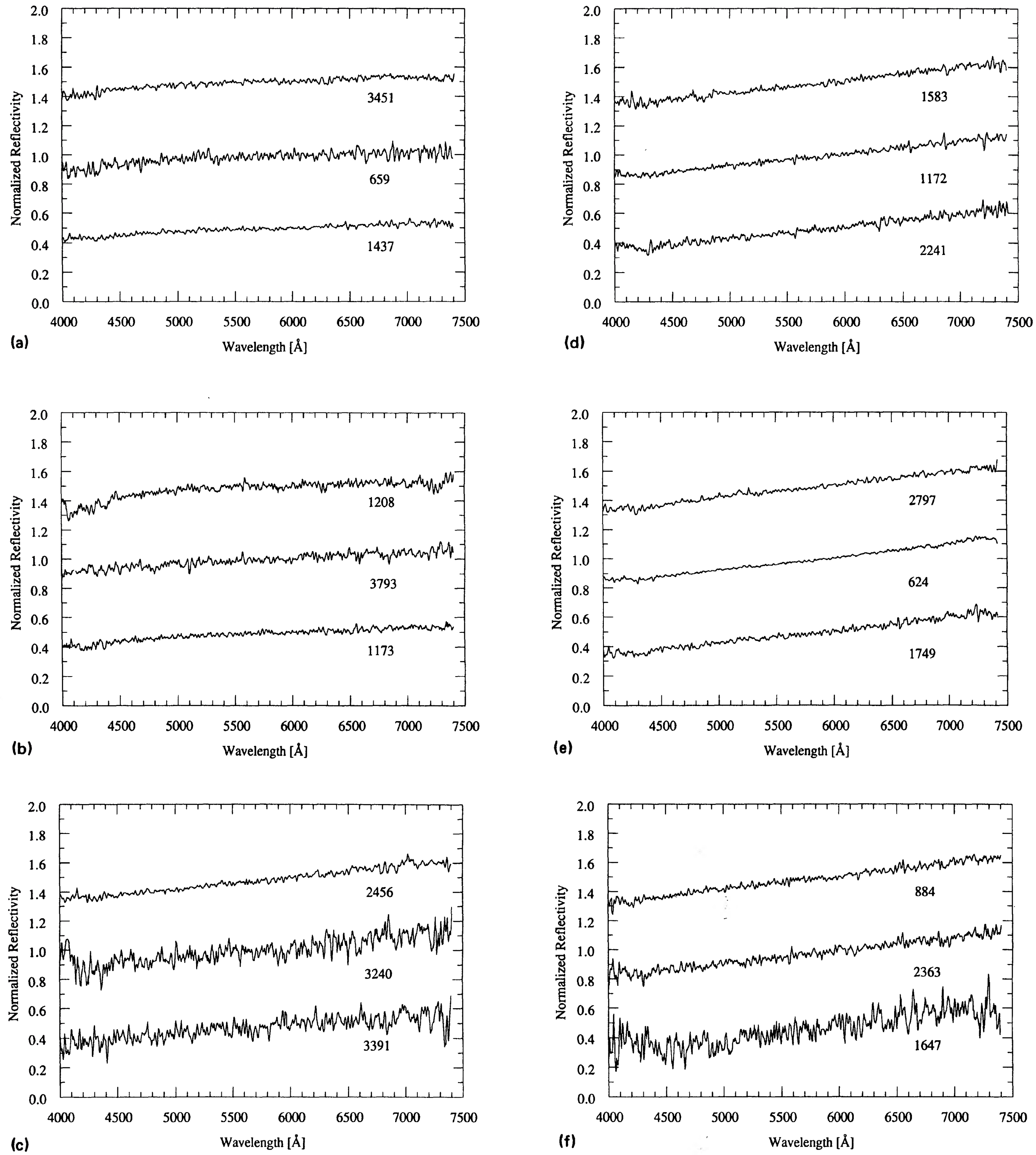

FIG. 2. Reflectivity spectra of 32 Trojan asteroids [(a)–(k)] and of 279 Thule (1). The asteroids are plotted on a common scale to facilitate easy comparison. Spectra of Trojan asteroids within each panel are displaced in normalized reflectivity by $\Delta S' = -0.5, 0.0$, and 0.5, respectively, for clarity of presentation. The Trojan spectra are presented in order of increasing reflectivity gradient S'.

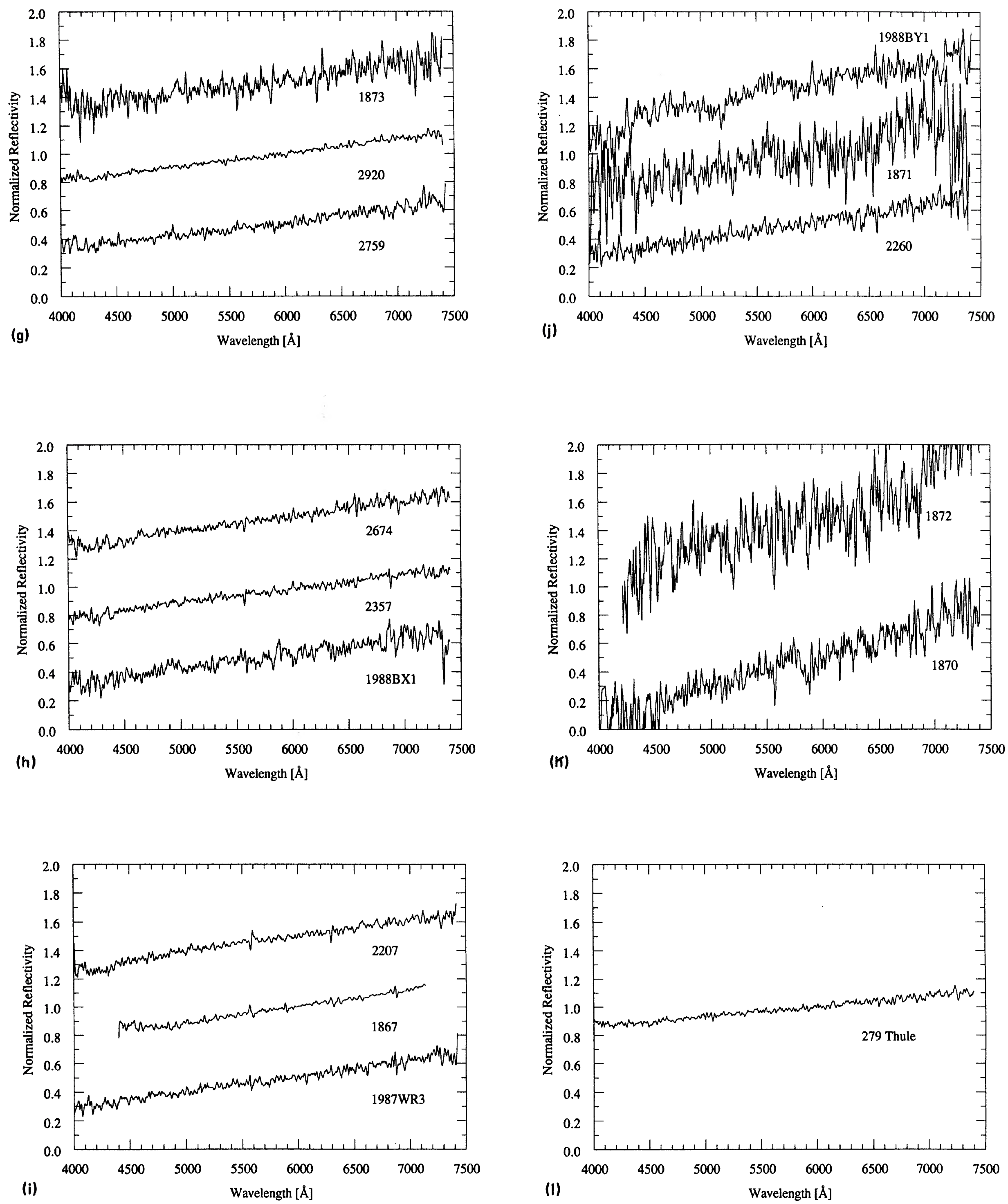

FIG. 2. (continued)

TABLE I. Observed asteroids.

N	Name	UT Date	Airmass	Integration [s]	V[a] [mag.]	S' [% / 1000 Å]	Fig.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
624	Hektor	1989 / Feb / 03	1.0600	1200	14.3	8.8 ± 1	2e
659	Nestor	1989 / Feb / 07	1.0100	1800	16.3	3.4 ± 1	2a
884	Priamus	1988 / Oct / 08	1.1800	1400	15.8	9.4 ± 1	2f
1172	Aneas	1988 / Oct / 09	1.2500	1200	15.1	8.2 ± 1	2d
1173	Anchises	1988 / Oct / 10	1.0500	1000	15.5	3.8 ± 1	2b
1208	Troilus	1988 / Oct / 10	1.5400	1400	15.7	4.8 ± 1	2b
1437	Diomedes	1989 / Feb / 04	1.1100	1300	15.1	3.1 ± 1	2a
1583	Antilochus	1989 / Feb / 04	1.4800	1600	15.8	8.6 ± 1	2d
1647	Menelaus	1989 / Feb / 07	1.0900	2400	17.2	9.0 ± 1	2f
1749	Telamon	1989 / Feb / 03	1.0800	1800	16.8	8.6 ± 1	2e
1867	Deiphobus	1988 / Sep / 09	1.1800	1600	15.6	11.2 ± 1	2i
1870	Glaukos	1988 / Oct / 09	1.3700	2300	17.8	23.1 ± 2	2k
1871	Astyanax	1988 / Oct / 08	1.4000	3000	18.4	13.6 ± 2	2j
1872	Helenos	1988 / Oct / 10	1.1800	2000	16.9	24.7 ± 1	2k
1873	Agenor	1988 / Oct / 09	1.1300	1200	18.1	10.0 ± 1	2g
2207	Antenor	1988 / Oct / 07	1.3500	1800	16.2	11.5 ± 1	2i
2241	1979WM	1988 / Oct / 07	1.0900	1800	16.3	8.2 ± 1	2d
2260	Neoptolemus	1989 / Feb / 08	1.0000	2100	16.0	11.7 ± 1	2j
2357	Phereclos	1988 / Oct / 08	1.4400	1800	16.1	10.2 ± 1	2h
2363	Cebriones	1988 / Oct / 09	1.0700	1400	15.8	9.0 ± 1	2f
2456	Palamedes	1989 / Feb / 04	1.0000	1800	16.5	8.1 ± 1	2c
2674	Pandarus	1988 / Oct / 08	1.3100	1900	16.4	11.0 ± 1	2h
2759	Idomeneus	1989 / Feb / 03	1.2200	2000	16.8	9.4 ± 1	2g
2797	Teucer	1989 / Feb / 03	1.0600	1800	15.4	8.9 ± 1	2e
2920	Automedon	1989 / Feb / 04	1.1400	1800	16.1	9.8 ± 1	2g
3240	Laocoon	1988 / Oct / 10	1.3500	2000	16.5	7.1 ± 1	2c
3391	Sinon	1989 / Feb / 04	1.0600	1800	17.2	5.8 ± 2	2c
3451	1984HA1	1988 / Oct / 07	1.2200	1350	14.9	3.5 ± 1	2a
3793	Leonteus	1989 / Feb / 07	1.3100	1800	15.5	4.4 ± 1	2b
1987WR3	1979HA2	1989 / Feb / 03	1.1600	1800	16.4	11.0 ± 1	2i
1988BX1	unnamed	1989 / Feb / 04	1.0700	1900	16.7	10.2 ± 1	2h
1988BY1	unnamed	1989 / Feb / 03	1.1200	2000	17.1	16.2 ± 2	2j
279	Thule	1989 / Feb / 07	1.0400	1400	14.5	7.1 ± 1	2l

[a] Estimated from V(1,1,0)

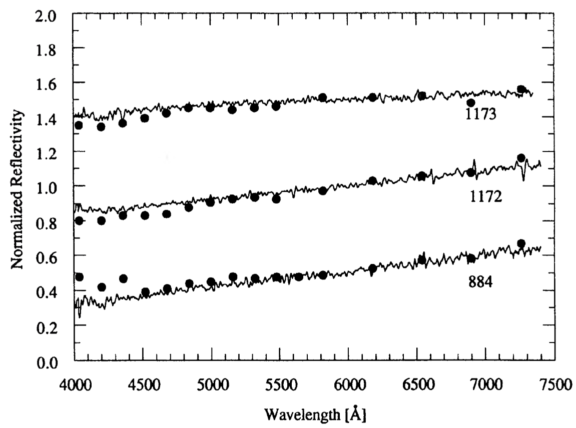

FIG. 3. Reflectivity spectra of Trojan asteroids 884 Priamus, 1172 Aneas, and 1173 Anchises compared with multichannel data from Smith *et al.* (1981). The multichannel data have been renormalized at $\lambda = 6000$ Å. Spectra of 884 Priamus and 1173 Anchises are displaced in normalized reflectivity by $\Delta S' = -0.5$ and 0.5, respectively, for clarity of presentation. Formal error bars in the multichannel data approach ± 0.03–0.05 in the blue.

recomputed $r_{\rm corr}$. The correlation coefficient decreased to $r_{\rm corr} = 0.46$, which is significant at the $P(r \leqslant r_{\rm corr}) = 0.01$ level (i.e., the correlation retains 1% significance).

What might be the cause of this unexpected color–magnitude trend? The obvious possibility that the trend is an artifact of an unknown but magnitude-dependent error in the data reduction is effectively eliminated by Fig. 5(b). The figure shows S' versus magnitude for main-belt and near-Earth asteroids (data taken from Paper I). The main-belt and near-Earth asteroid spectra were taken on the same dates as the Trojan spectra, using the same telescope and detector, and reduced and measured following the same procedures. These three datasets should thus suffer identically from any magnitude-dependent error which might be present. However, Fig. 5(b) gives no evidence for a color–magnitude trend in either the main-belt or the near-Earth asteroid data. We conclude that the color–magnitude trend is specific to the Trojans, and is not of instrumental or spectral-reduction origin.

The color–magnitude trend [Fig. 5(a)] may be plausibly interpreted as a color–diameter trend among the Trojans. The fainter Trojans in Table I have generally smaller diameters than the brighter Trojans, since the geometric albedos vary by only a factor of 2–3 while the apparent magnitudes differ by a factor of 40 ($\Delta m \sim 4$). This diameter–magnitude correlation may be seen directly from a comparison of the magnitudes (column 6 of Table I) and *IRAS* diameters (column 6 of Table II) of the Trojans. Therefore, the color–magnitude trend in Fig. 5(a) may be interpreted as a color–diameter trend, with the smaller Trojans being optically redder than their larger counterparts.

We postulate that, among the Trojans, the size distribution of the very red D asteroids is peaked towards smaller diameters than are the size distributions of the (less red) C and P asteroids. The size distributions of the main-belt asteroids are thought to be controlled (at least at diameters $\leqslant$100–200 km) by mutual collisions between asteroids (Davis *et al.* 1979; Dermott, Harris, and Murray 1984). Presumably, collisions are also important in controlling the size distribution of the Trojan asteroids. An overabundance of Trojan red D fragments at small sizes might be expected if the dark, red material is more prone to collisional fragmentation than its more neutral counterpart. This, in turn, would be qualitatively compatible with the expected low degree of metamorphism experienced by the Trojans (Bell *et al.* 1989). Some evidence exists for differences in the size distributions of main-belt asteroids belonging to different spectral classes (Chapman 1989).

b) Preceding Cloud Versus Following Cloud

In Fig. 6 we distinguish the Trojans of the preceding cloud from those of the following cloud (see column 4 of Table II). Our sample includes 16 asteroids from each cloud. The figure shows that the reflectivity gradients of the asteroids within the two clouds are similar, so that no evidence exists for a compositional difference between the two clouds. The mean gradient in the preceding cloud is $\bar{S}' = 8.6 \pm 3.2\%/10^3$ Å while that in the following cloud is $\bar{S}' = 10.6 \pm 5.7\%/10^3$ Å. Within the uncertainties, the difference between the two values is zero. Therefore, we conclude that the two Trojan clouds are spectrally indistinguishable.

c) Comparison with Other Asteroids

In Fig. 7 we plot the reflectivity gradient S' versus the semimajor axis a (AU) for near-Earth and main-belt asteroids (from Paper I) and Trojan asteroids (this work). Also plotted is S' for the asteroid 279 Thule ($a = 4.27$ AU). As noted earlier, the comparison of data from this paper with data from Paper I is completely legitimate, since all objects were observed and reduced under standardized conditions, and systematic errors are likely to be small. The figure shows that, from the main belt outward to the Trojans, the values of S' exhibit a clear trend towards increasing redness with increasing heliocentric distance. The significance of the linear correlation between S' and a is better than 0.001 (i.e., the correlation has high statistical significance). The figure also emphasizes that the Trojan population is distinguished from asteroids at smaller distances by the complete absence of blue asteroids. Specifically, 0 out of 32 Trojans have $S' \leqslant 0$ while 3 out of 19 NEAs and 5 out of 23 main-belt asteroids fall into this category. What is *not* clear from Fig. 7 is whether S' is a smooth function of semimajor axis, or whether the Trojans are simply redder as a group than all other asteroids. The former case has been advocated by Vilas and Smith (1985).

IV. SPECTRAL FEATURES

Although the reflectivity spectra of most Trojan asteroids are well fitted by a straight line, deviations from linearity exist and fall into two broad categories.

(1) Several spectra show a downturn in S' at short wavelengths $\lambda \leqslant 5000$ Å relative to a linear extrapolation from longer wavelengths. Good (but subtle) examples may be seen in asteroids 3451 (1984 HA1), 659 Nestor, 1437 Diomedes [all in Fig. 2(a)], 1208 Troilus [Fig. 2(b)] and 2207 Antenor [Fig. 2(i)]. This downturn is seen in the spectra of many main-belt asteroids (e.g., Zellner, Tholen, and Tesesco 1985; Paper I) where it is attributed to the presence of an ultraviolet charge transfer absorption in a transition metal silicate (Gaffey and McCord 1977). The downturn is strongest in those Trojan asteroids having relatively neutral reflectivities, suggesting that the surface abundance of the UV

TABLE II. Asteroid physical data.

N (1)	Name (2)	a [AU] (3)	p/f[a] (4)	Class[b] (5)	Diameter[c] [km] (6)	Geometric Albedo[d] (7)
624	Hektor	5.1788	p	U		
659	Nestor	5.2456	p	C	115	0.040
884	Priamus	5.1576	f	D		
1172	Aneas	5.1646	f	D	151	0.038
1173	Anchises	5.3128	f	P	135	0.026
1208	Troilus	5.2009	f	C	111	0.036
1437	Diomedes	5.1066	p		171	0.029
1583	Antilochus	5.1036	p	D	109	0.051
1647	Menelaus	5.2493	p		72	0.028
1749	Telamon	5.2230	p		115	0.012
1867	Deiphobus	5.1630	f	D	131	0.037
1870	Glaukos	5.2459	f			
1871	Astyanax	5.3346	f			
1872	Helenos	5.1937	f			
1873	Agenor	5.2671	f		65	0.024
2207	Antenor	5.1383	f	D	93	0.058
2241	1979WM	5.2432	f	D	123	0.040
2260	Neoptolemus	5.1905	p	D	85	0.064
2357	Phereclos	5.1781	f	D	103	0.042
2363	Cebriones	5.1323	f	D	92	0.066
2456	Palamedes	5.1871	p		103	0.035
2674	Pandarus	5.1786	f	D	102	0.041
2759	Idomeneus	5.1618	p		73	0.041
2797	Teucer	5.1665	p		123	0.046
2920	Automedon	5.1792	p		123	0.034
3240	Laocoon	5.2622	f			
3391	Sinon	5.2567	p			
3451	1984HA1	5.0936	f			
3793	Leonteus	5.1667	p			
1987WR3	1979HA2	5.2634	p			
1988BX1	unnamed	5.2637	p			
1988BY1	unnamed	5.2244	p			
279	Thule	4.2694	n/a	D	135	0.03

Notes to TABLE II

[a] p = preceeding Trojan cloud, f = following Trojan cloud.
[b] Spectral class, from Asteroids II database.
[c] *IRAS* diameter, from Asteroids II database.
[d] *IRAS* Albedo, from Asteroids II database.

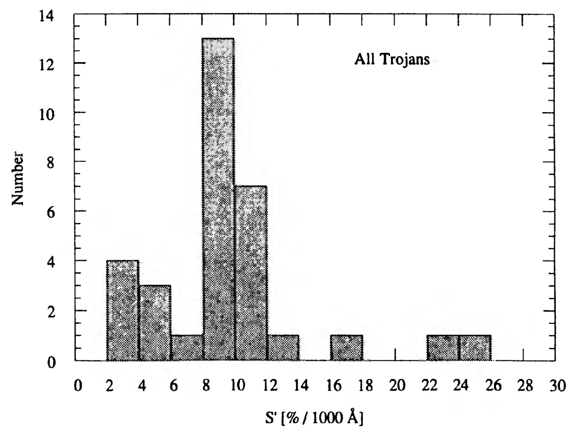

FIG. 4. The number of Trojans having S' in a specified range is plotted against the value of S'. The histogram emphasizes that the spectra of Trojan asteroids are diverse.

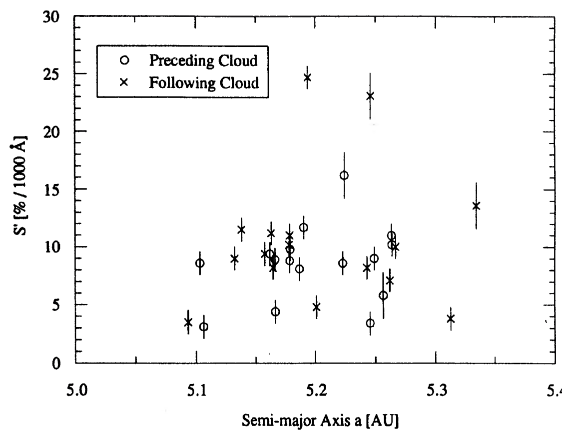

FIG. 6. Color vs semimajor axis for Trojan asteroids in the preceding and following clouds. The figure shows that the distribution of S' is similar in the two clouds.

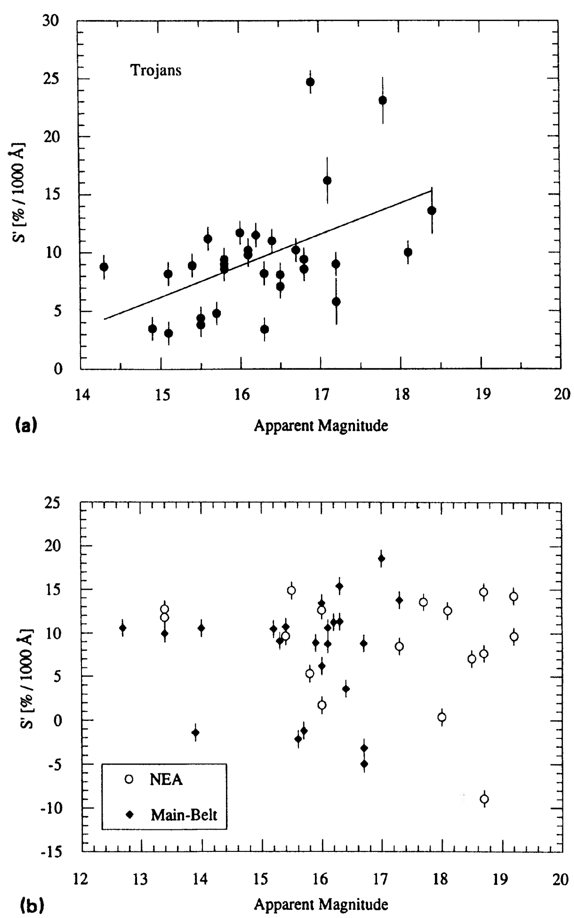

FIG. 5. (a) Color vs apparent magnitude for the Trojan asteroids. The trend towards redder colors is significant at the 0.005 level. The solid line is a least-squares fit to the data. The data are taken from Table I. (b) Color vs apparent magnitude for main-belt and near-Earth asteroids (data are from Paper I). No color–magnitude trend is apparent.

absorber is anticorrelated with the abundance of the dark red material. As noted above, the more neutral Trojans also tend to be the largest in our sample. Thus, the UV absorber is more prominent among the larger Trojans, providing an independent hint that the size distributions of the various spectral classes may differ from one another (see Sec. III*a*).

(2) Broad, shallow absorptions are apparent in the spectra of Trojans 1988BY1 [Fig. 2(j)] and 1870 Glaukos [Fig. 2(k)]. In 1988BY1 the most prominent absorption occurs at $\lambda \sim 5100$ Å, while a weaker feature at $\lambda \sim 5900$ Å is partially obscured by a noise spike in the data. In 1870 Glaukos only a feature near 5900 Å can be discerned. The estimated absorption bandwidths are 300–500 Å, with considerable uncertainty due to the continuum noise. The absorption depths are in both cases comparable to the continuum peak-to-peak

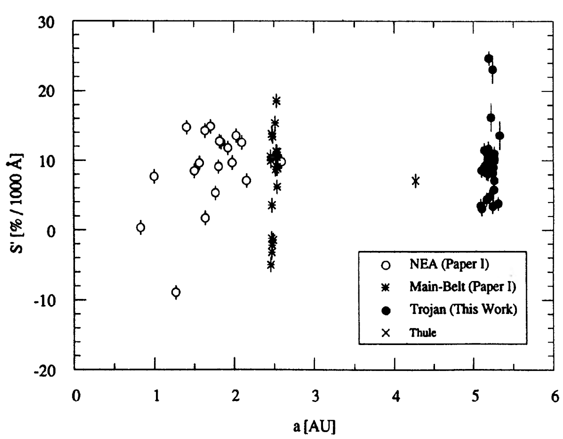

FIG. 7. Color vs semimajor axis for near-Earth and main-belt asteroids (from Paper I) and Trojan asteroids from this work. Asteroid 279 Thule is also plotted (denoted by the × symbol). The figure emphasizes the net color difference between the Trojans and other asteroids.

noise, so that we regard the reality of the features as tentative, and in need of independent confirmation. Evidence supporting their reality includes:

(a) They exist in each of the two independent CCD integrations which were added to form the 1988BY1 and 1870 Glaukos spectra in Fig. 2.

(b) Comparable features are absent from all other spectra, and they are specifically absent from the spectra of those asteroids observed immediately before and after 1988BY1 and 1870 Glaukos.

(c) The absorptions are not dependent on the standard star used to compute the spectral flux, and do not depend on the method of extinction correction employed. In any event, the terrestrial atmosphere possesses no remarkable spectral features, either in emission or absorption near the wavelengths of the observed bands.

An attempt to identify the asteroidal absorptions with features in the spectra of main-belt and near-Earth asteroids (Paper I) proved unsuccessful. However, the number of published reflectance spectra having resolution and signal-to-noise comparable to that of the present data is small, so that the failure to find other examples is perhaps not surprising. A similarity to the reflection spectra of porphyrins is noted (Holden and Gaffey 1987), but we will delay a detailed comparison until observational confirmation of the features is obtained. Significantly, porphyrins are carbon-rich compounds and, if present, would satisfy long-standing suspicions regarding the carbon abundance of the Trojan asteroids.

V. COMPARISON WITH COMETARY NUCLEI

As noted in the Introduction, a major motivation for this work was the desire to obtain a set of spectra of distant asteroids for comparison with existing and, especially, future spectra of cometary nuclei. Only a handful of cometary nuclei have been identified to date, so that any comparison must be regarded as preliminary in nature. In addition, the typical cometary nuclei are about one order of magnitude smaller than the typical Trojan asteroids studied, so that the possibility of size dependent selection effects must be considered. In fact, empirical evidence for a size versus S' relationship among the Trojans has already been described in Sec. III. Despite this potential complication, it is interesting to compare the available reflectance data on cometary nuclei with the new asteroid spectra reported in this paper.

Broadband visual colors are currently available for the nuclei of five comets [P/Arend-Rigaux, P/Neujmin 1, P/Encke, P/Halley and P/Tempel 2; see Table I in Jewitt (1990a) for the colors of individual nuclei]. CCD spectra of nuclei comparable in spectral resolution to the asteroid spectra reported and in Paper I are available only for P/Encke (Luu and Jewitt 1990b) and P/Tempel 2 (Jewitt and Luu 1989). The visual colors of the nuclei as a group are quite varied, ranging from P/Halley being only slightly reddened with respect to the Sun ($S'_{\rm Halley} = 6 \pm 3\%/10^3$ Å; Thomas and Keller 1989), to P/Tempel 2 being substantially redder than any of the near-Earth or main-belt asteroids sampled in Paper I ($S'_{\rm Tempel\,2} = 20 \pm 3\%/10^3$ Å; Jewitt and Luu 1989). To compare the nucleus color distribution with that of the Trojans, we present in Fig. 8 the color histograms of the two types of object. Evidently, the colors of the nuclei and of the Trojans are similar, within the very substantial uncertainties imposed by the small size of the nucleus sample.

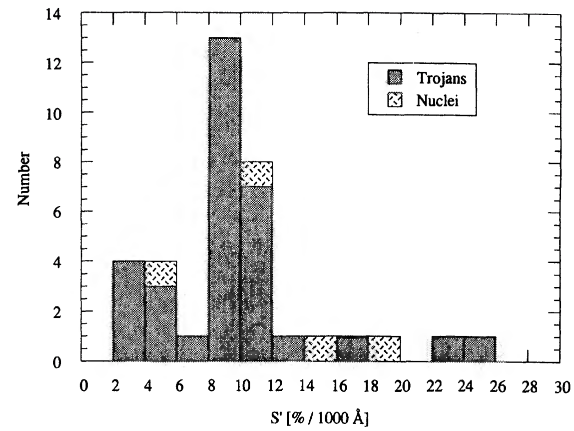

FIG. 8. The numbers of Trojans (shaded histogram) and cometary nuclei (white) having S' in a specified range are plotted against the value of S'.

A more detailed comparison of the spectrum of the nucleus of comet P/Tempel 2 (from Jewitt and Luu 1989) with that of the Trojan asteroid 1988BY1 is given in Fig. 9. Only wavelengths believed to be free of gaseous emission are plotted in the P/Tempel 2 spectrum. Figure 9 shows that the

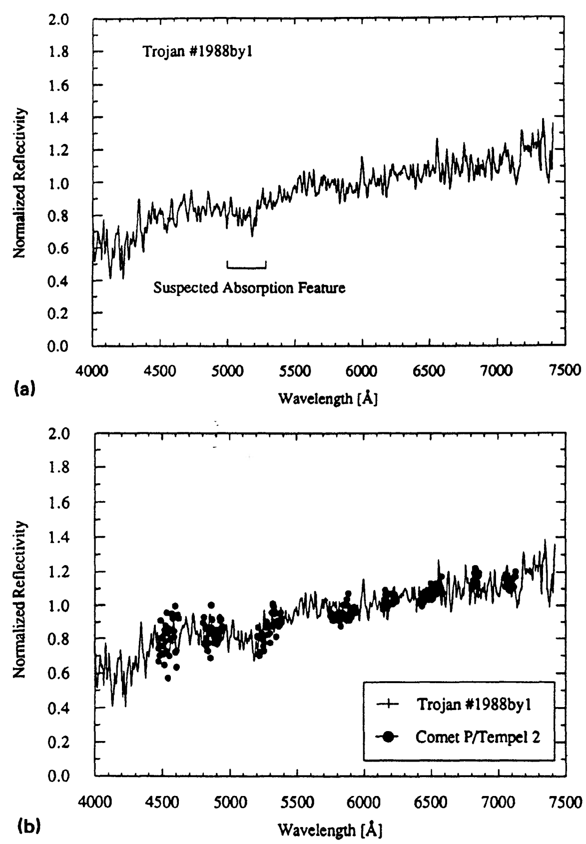

FIG. 9. Comparison of the reflection spectrum of Trojan asteroid 1988BY1 [Fig. 9(a)] with the spectrum of the nucleus of comet P/Tempel 2 [black dots in Fig. 9(b)]. The P/Tempel 2 spectrum is from Jewitt and Luu (1989). A close correspondence exists between the two spectra.

reflection spectrum of the nucleus of P/Tempel 2 is identical with that of 1988BY1, within the uncertainties of the measurements. This observation is consistent with, but does *not* prove, a compositional similarity between the refractory mantle covering the surface of P/Tempel 2 and the surface material on Trojan 1988BY1. The similarity between the spectra of the nucleus of P/Tempel 2 and 1988BY1 is compatible with the hypothesis that the comets and the Trojans are derived from a single-source population, although this hypothesis is clearly non-unique.

It is also noteworthy that the Trojans and the cometary nuclei share very low values of the geometric albedo. The average geometric albedo determined for the nuclei of comets P/Arend-Rigaux, P/Neujmin 1, P/Halley, and P/Tempel 2 is $p_V \sim 0.03 \pm 0.01$ (cf. Campins, A'Hearn, and McFadden 1987; Keller *et al.* 1987; Millis, A'Hearn, and Campins 1988; A'Hearn *et al.* 1989). Geometric albedos of well-studied Trojans are comparable, $p_V \sim 0.02$–0.05 (c.f., column 7 of Table II). One popular belief is that the Trojans are primitive bodies, formed near $R \sim 5$ AU, and having experienced little metamorphism in the near surface regions (Bell *et al.* 1989). The surface regions are thought to be high in carbon abundance, giving rise to the low albedos and generally reddish reflection spectra of these bodies. Formation scenarios for the comets are even less certain than those for the Trojans, but similarly high carbon abundances have been postulated for the mantles of comets (Johnson *et al.* 1987). The mantles may consist of complex organic molecules modified by exposure to cosmic rays (Andronico *et al.* 1987; Cruikshank 1987; Johnson *et al.* 1987).

The similarity between the optical properties of the comets and the Trojans is extended to the physical properties by a comparison of the gross shapes of these bodies. The shapes of the above-mentioned cometary nuclei are inferred to be highly elongated from observations of the rotational lightcurves (Jewitt and Meech 1988; Jewitt and Luu 1989; Luu and Jewitt 1990b). Evidence that the light curves are controlled by shape (rather than by azimuthal albedo variations) is provided by simultaneous thermal infrared-visual photometry of P/Arend-Rigaux, P/Neujmin 1, and P/Tempel 2 (cf: references cited above). Independently, Hartmann *et al.* (1988) found that the Trojans display large rotational light curves indicative of asphericity. Again, simultaneous thermal-visual photometry provides evidence that the lightcurve amplitude is indicative of shape rather than azimuthal albedo variations (Hartmann and Cruikshank 1980; Lebofsky *et al.* 1988). The physical significance of the aspherical shapes of the Trojans and the nuclei is obscure. Proffered explanations for the comets include the retention of primordial body shapes, the effect of anisotropic mass loss and a projection effect due to nonprincipal axis rotation induced by sublimation torques (see Jewitt and Meech 1988). If the Trojans possess high water abundances, it is possible that previous outgassing has modified the body shapes in just the same way as for the cometary nuclei. In addition, Hartmann *et al.* (1988) have remarked that spin axis alignment among the Trojans could be responsible for the large rotational amplitudes, although no obvious mechanism exists for producing such alignment. Unfortunately, we do not possess sufficient evidence to distinguish among these explanations. Table III summarizes the average physical properties of the cometary nuclei and the Trojan asteroids.

The similarities observed between the physical properties of the nuclei and those of the Trojan asteroids could potentially be explained by any of the capture hypotheses of the origin of the Trojans (cf., Rabe 1972; Yoder 1979). According to these authors, the Trojans may be cometary nuclei captured by Jupiter at the Lagrangian points with the aid of nongravitational forces due to sublimation. Temporary captures of comets at the Lagrangian points are known to have occurred in the recent past (e.g., comet P/Slaughter–Burnham; Rabe 1972), supporting the notion that Trojans might be captured comets. On the other hand, it is not clear that mass loss from comets at $R \sim 5$ AU can produce the dynamically significant nongravitational accelerations needed to effect permanent capture. For example, comet P/Schwassmann Wachmann-1 is continuously active at $R \sim 6$ AU (Jewitt 1990b) but it has never exhibited a measurable nongravitational acceleration (Marsden 1989, personal communication). A similar scenario, in which capture is effected by asteroid collisions rather than by outgassing forces, has been advanced by Shoemaker, Shoemaker, and Wolfe (1989). These data are unable to prove or disprove the capture hypothesis, but they are certainly compatible with a capture origin for the Trojan asteroids from any source beyond the main belt.

TABLE III. Comparison of physical parameters.[a]

Quantity	Comet nuclei[b]	Trojans[c]
Albedo	0.03 ± 0.01 (4)	0.04 ± 0.01 (20)
Δm_R [mag.]	0.7 ± 0.2 (5)	0.4 ± 0.2 (19)[d]
S'[%/10^3 Å]	14 ± 5 (5)	10 ± 4 (32)

Notes to TABLE III

[a] Number of objects in each sample is enclosed in parentheses.
[b] From Table I of Jewitt (1990a).
[c] From Tables I and II of this work.
[d] From Table I of Hartmann *et al.* (1988).

The individual similarities between the albedos, colors, and shapes of the Trojans and the cometary nuclei might not by themselves be particularly remarkable. Taken together, however, they suggest that an extraordinary overlap exists between the known physical properties of the Trojan asteroids and those of the cometary nuclei (see Table III). It will be of interest to see whether the similarities persist as the Trojans and nuclei are subject to closer scrutinization in future observations. In fact, whereas the initial observational challenge behind our work was to find the extent to which the Trojans and the nuclei are physically and optically *similar*, the new observational challenge is to determine whether any significant *differences* exist between the Trojans and the cometary nuclei. Our future work will be directed towards this end.

VI. SUMMARY

From a systematic study of the optical reflectances of 32 Trojan asteroids at 20 Å resolution we find the following:

(1) The Trojan asteroids are a spectrally diverse group of objects. The reflectance spectra of the majority of Trojans are linear functions of wavelength in the range $4000 \leqslant \lambda \leqslant 7400$ Å. The gradient of the reflectivity S' has minimum and maximum values $S' = 3$ and $25\%/10^3$ Å, respectively, with a mean $S' = 9.6 \pm 4.7\%/10^3$ Å.

(2) The mean gradient S' increases with apparent magnitude m_R in the range $14 \leqslant m_R \leqslant 18$. The correlation is significant at the 0.005 level, and may reflect a size dependence of

the dominant spectral class, with dark, red "D" asteroids dominant at small diameters.

(3) There is no significant difference between the distributions of S' in the preceding and following Trojan clouds (i.e., there is no evidence for a colorimetric or compositional difference between the two clouds).

(4) The Trojan asteroids are, on the average, redder than main-belt or near-Earth asteroids. Whether this results from a systematic variation of S' with heliocentric distance (as suggested by Vilas and Smith 1985) is not clear from the existing data.

(5) A number of Trojan reflectivity spectra exhibit a downturn in the blue, which probably marks the onset of an ultraviolet charge transfer absorption. This feature is more common in the brighter, more spectrally neutral Trojans, showing that the surface abundances of the UV absorber and the dark, red material are anticorrelated. The reflectance spectra of two Trojan asteroids show evidence for discrete spectral features in the 5000–6000 Å range, resembling features present in porphyrins. Especially noteworthy are two broad minima near 5100 and 5800 Å in 1988BY1 and one near 5900 Å in 1870 Glaukos. These features are regarded as tentative pending observational confirmation.

(6) The range of S' exhibited by the Trojan asteroids encompasses the range of S' measured in cometary nuclei to date. In this sense, the Trojan asteroids and the cometary nuclei are spectrally similar. An essentially exact match of the spectrum of the nucleus of P/Tempel 2 exists in the Trojan 1988BY1. The similarity is further enhanced by the large light-curve amplitudes seen in both sets of bodies, and by the very low geometric albedos which they both possess. Observational similarities between the Trojans and the cometary nuclei are so great that we regard the identification of significant differences between these objects as the next major observational challenge.

Note added in proof: An absorption feature near 5170 Å has been reported in the spectrum of 279 Thule by Lagerkvist, Williams, Fitzsimmons, and Dahlgren (IAU Circular No. 4992). No comparable feature is present in our spectrum of this object (see Fig. 21). If real, the feature must be either time-variable, or associated with the side of Thule not sampled in our spectrum, or both. Additional spectra of Thule might be of value.

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REFERENCES

A'Hearn, M. F., Campins, H., Schleicher, D. G., and Millis, R. L. (1989). Astrophys. J. **347**, 1155.
Andronico, G., Baratta, G. A., Spinella, F., and Strazzulla, G. (1987). Astron. Astrophys. **184**, 333.
Bell, J. F., Cruikshank, D. P., and Gaffey, M. J. (1985). Icarus **61**, 192.
Bell, J. F., Davis, D. R., Hartmann, W. K., and Gaffey, M. J. (1989). In *Asteroids II*, edited by R. P. Binzel, T. Gehrels, and M. Matthews (University of Arizona, Tucson).
Bevington, P. R. (1969). *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York).
Campins, H., A'Hearn, M. F., and McFadden, L. (1987). Astrophys. J. **316**, 847.
Chapman, C. R. (1989). In *Asteroids, Comets, Meteors III*, Uppsala Astronomical Observatory Report No. 48, (Uppsala University, Uppsala).
Cloutis, E. A. (1989). Science **245**, 165.
Cruikshank, D. (1977). Icarus **30**, 224.
Cruikshank, D. (1987). Adv. Space Res. **7**, 109.
Davis, D. R., Chapman, C. R., Greenberg, R., Weidenschilling, S. J., and Harris, A. W. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), pp. 528–557.
Dermott, S. F., Harris, A. W., and Murray, C. D. (1984). Icarus **57**, 14.
Gaffey, M. J., and McCord, T. B. (1977). In *Comets, Asteroids, Meteorites*, edited by A. H. Delsemme (University of Toledo, Toledo), pp. 199–218.
Gradie, J., and Tedesco, E. (1982). Science **216**, 1405.
Gradie, J., and Veverka, J. (1980). Nature **283**, 840.
Hardorp, J. (1978). Astron. Astrophys. **63**, 383.
Hardorp, J. (1980). Astron. Astrophys. **91**, 221.
Hartmann, W. K. (1986). In *Asteroids, Comets, Meteors II*, edited by C.-I. Lagerkvist, B. A. Lindblad, H. Lundstedt, and H. Rickman (Uppsala University Press, Uppsala), pp. 191–193.
Hartmann, W. K., and Cruikshank, D. P. (1980). Science **207**, 976.
Hartmann, W. K., Tholen, D. J., Goguen, J., Binzel, R. P., and Cruikshank, D. P. (1988). Icarus **73**, 487.
Holden, P. N., and Gaffey, M. J. (1987). Meteoritics **22**, 412.
Jewitt, D. C. (1990a). In *Comets in the Post-Halley Era*, edited by R. Newburn (Kluwer, Dordrecht).
Jewitt, D. C. (1990b). Astrophys. J. **351**, 277.
Jewitt, D. C., and Luu, J. X. (1989). Astron. J. **97**, 1766.
Jewitt, D. C., and Meech, K. J. (1988). Astrophys. J. **328**, 974.
Johnson, R. E., Cooper, J. F., Lanzerotti, L. J., and Strazzulla, G. (1987). Astron. Astrophys. **187**, 889.
Keller, H. U., Delamere, W. A., Huebner, W. F., Reitsema, H. J., Schmidt, H. U., Whipple, F. L., Wilhelm, K., Curdt, W., Kramm, R., Thomas, N., Arpigny, C., Barbieri, C., Bonnet, R. M., Cazes, S., Coradini, M., Cosmovici, C. B., Hughes, D. W., Jamar, C., Malaise, D., Schmidt, K., Schmidt, W. K. H., and Seige, P. (1987). Astron. Astrophys. **187**, 807.
Kissel, J., Sagdeev, R. Z., Bertaux, J. L., Angarov, V. N., Audouze, J., Blamont, J. E., Büchler, K., Evlanov, E. N., Fechtig, H., Fomenkova, M. N., von Hoerner, H., Inogamov, N. A., Khromov, V. N., Knabe, W., Krueger, F. R., Langevin, Y., Leonas, V. B., Levasseur-Regourd, A. C., Managadze, G. G., Podkolzin, S. N., Shapiro, V. D., Tabaldyev, S. R., and Zubkov, B. V. (1986). Nature **321**, 280.
Lebofsky, L. A., Greenberg, R., Tedesco, E. F., and Veeder, G. J. (1988). Icarus **75**, 518.
Luu, J. X., and Jewitt, D. C. (1990a). Astron. J. (in press) (Paper I).
Luu, J. X., and Jewitt, D. C. (1990b). Icarus (in press).
Millis, R. L., A'Hearn, M. F., and Campins, H. (1988). Astrophy. J. **324**, 1194.
Prinn, R. G., and Fegley, B., Jr. (1989). In *Origin and Evolution of Planetary and Satellite Atmospheres*, edited by S. K. Atreya, J. B. Pollack, and M. S. Matthews (University of Arizona, Tucson), pp. 78–136.
Rabe, E. (1972). In *The Motion, Evolution of Orbits, and Origin of Comets*, IAU Symposium No. 45, edited by G. A. Chebotarev, E. I. Kazimirchak-Polonskaya, and B. G. Marsden (Springer, New York), pp. 55–60.
Shoemaker, E. M., Shoemaker, C. S., and Wolfe, R. F. (1989). In *Asteroids II*, edited by R. P. Binzel, T. Gehrels, and M. S. Matthews (Univeristy of Arizona, Tucson), pp. 487–523.
Smith, D. W., Johnson, P. E., and Shorthill, R. W. (1981). Icarus **46**, 108.
Vilas, F., and Smith, B. A. (1985). Icarus **64**, 503.
Vilas, F., and McFadden, L. A. (1987). Bull. Am. Astron. Soc. **19**, 825.
Yoder, C. F. (1979). Icarus **40**, 341.
Zellner, B., Tholen, D. J., and Tedesco, E. F. (1985). Icarus **61**, 355.