ICARUS **134,** 213–227 (1998)
ARTICLE NO. IS985931

Visible and Infrared Photometry of Six Centaurs

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Received October 27, 1997; revised March 18, 1998

We present infrared (*JHK*) and visible (*VRI*) observations of the Centaurs 2060 Chiron, 5145 Pholus, 7066 Nessus, 1995 DW$_2$, 1995 GO, and 1997 CU$_{26}$. These are combined whenever possible to derive relative reflectance spectra between 0.55 and 2.2 μm. The extreme visible to infrared color of Pholus found in 1992 is confirmed, as is the redness of 7066 Nessus. We refine the rotation period and lightcurve of 1995 GO and resolve ambiguous determinations of its *V–R* color. We find that 1997 CU$_{26}$ has *V–JHK* colors very similar to 1995 GO. Our data imply changes in the visible–IR color of 2060 Chiron with level of cometary activity and, aware of the difficulties of combining nonsimultaneous data, we comment on the likely reality of these. We find a wide range of reflectances within the Centaur population with no obvious correlations with heliocentric distance. © 1998 Academic Press

Key Words: **Centaurs; Kuiper Belt; photometry; infrared; visible.**

1. INTRODUCTION

The Centaurs are minor planets following unstable orbits with semi-major axes between those of Jupiter and Neptune. They are believed to be objects which have been perturbed from the inner edge of what has become known as the Kuiper Belt[3] by the gravitational influences of Neptune and Uranus. Their properties have been reviewed by Stern and Campins (1996) and in the introductions to recent observational papers such as that of Romanishin *et al.* (1997). Recently, Jedicke and Herron (1997) estimated that there must be fewer than ~2000 Centaurs of which only 3 would have diameters greater than about 200 km.

Photometric (e.g., Luu and Jewitt 1996, Davies *et al.* 1996, Romanishin *et al.* 1997) and spectroscopic (e.g., Davies *et al.* 1993, Luu *et al.* 1994) observations have shown that there is considerable diversity among the Centaurs, ranging from 2060 Chiron, which is active and has neutral colors, to 5145 Pholus, which is extremely red and has unique spectral features. Luu and Jewitt (1996) argued that the range of *BVRI* colors among the Centaurs is similar to that among the Kuiper Belt objects, but there is often significant disagreement between different workers on the colors of these objects. Examples are the *V–R* color of 1995 GO (see Section 4.2), of 1995 DW$_2$ (Section 4.5), and of the Kuiper Belt object 1993 SC (Tegler and Romanishin 1997, Davies *et al.* 1997, Luu and Jewitt 1996). We have

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[3] Note that Edgeworth–Kuiper Belt may be more appropriate since Edgeworth (1943) suggested the existence of "a very large number of comparitively small bodies beyond the orbits of the planets."

0019-1035/98 $25.00

been conducting a program to determine visible to infrared (*V–JHK*) colors of Centaurs and Kuiper Belt objects which, for the reasons set out in Section 3, require us to obtain *V* photometry. We have made repeated infrared observations of these objects over, in some cases, a period of 5 years in order to minimize the uncertainty in the visible–IR colors which we derive. In this paper we present the results of this program as applied to six of the seven known Centaurs and present our conclusions on the issue of the spectral diversity of this population.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Visible Observations*

Visible photometry was carried out on 1997 May 5–7 from the Observatorio del Roque de Los Muchachos, La Palma, using the 2.5-m Isaac Newton Telescope (INT) with a prime focus CCD camera fitted with a TEK3 1024 × 1024 thinned chip. Frames were taken through Kitt Peak *VRI* broadband filters (which in combination with the CCD approximate to the Johnson *V* and Kron–Cousins *RI* photometric system) at an image scale of 0.59 arcsec per pixel. Since autoguiding of the INT is possible only for celestially fixed sources, the telescope was tracked and guided at the sidereal rate resulting in image motion of typically <0.5 arcsec during the 300- to 500-s object exposures. Flat field frames were obtained using defocused images of the uniformly illuminated dome interior. The observations were bias corrected and flat fielded using the Starlink software package KAPPA (Currie 1992).

Photometric calibration was performed using equatorial standard fields PG1323 and PG1633 (Landolt 1992) providing Kron–Cousins standard magnitudes (N.B. star A in the field PG1323 is variable and so was not used). The nights of May 5 and 6 were not photometric due to cirrus clouds but the extinction curves deduced from numerous observations of the standard fields confirmed that the night of May 7 was photometric. Since the Centaurs move relatively slowly, it was possible to use the May 7 observations of stars common to all the images to calibrate the data from the other two nights. The seeing throughout the run was in the range 1 to 1.5 arcsec.

The photometry of both objects and standards was performed using the IRAF aperture photometry package IMEXAM with apertures of 10 pixels (6 arcsec) diameter. The aperture is automatically centroided around the object with the sky level being defined by using the median value within a concentric annulus. The sky annulus started 1 pixel beyond the object aperture, and had a width of 2 pixels, a radius chosen as a compromise between sampling an adequate area of sky while avoiding background objects in what were in some cases quite crowded fields. To verify that this annulus adequately sampled the background sky, tests were carried out using sky annuli of up to 8 pixels which resulted in a magnitude variation of <0.01 mag. The effect of doubling the size of the aperture containing the object while keeping a constant sky annulus was also investigated. As expected, the larger aperture contained additional flux (at the 0.02 mag level) but this was the same for both standard and object frames and so we do not expect the aperture size chosen to affect the photometry. However, as a precaution, we assign a minimum uncertainty of 0.02 mag to any single photometric point irrespective of the formal errors produced by the photometry package.

Relative photometry of the data obtained on 1997 May 5 and 6 was by means of six secondary reference stars on each frame which were generally brighter than the target object. These stars were individually checked to ensure that they were not saturated and were examined as a group to verify that there were no relative variations between each of the six stars from night to night.

The visible data are given in Table I. Times are mid-frame, not light–time corrected.

2.2. *Infrared Photometry*

Apart from two observations of Pholus made in 1992 (Davies *et al.* 1993, 1996) with the UKT9 single channel photometer, all the infrared photometry presented here was obtained between 1993 and mid-1997 with the infrared camera IRCAM on the 3.8-m UK Infrared Telescope, UKIRT. The camera, originally fitted with a 58 × 62 InSb array (0.62 arcsec pixels), was upgraded in 1994 to a 256 × 256 InSb array (0.286 arcsec pixels, field of view of 73.2 arcsec).

An IRCAM image for a given filter comprises a mosaic of several separate frames, each with exposure times set to be background limited (except for brighter objects where the exposures were shortened to reduce any risk of saturation). The mosaics comprised nine frames in the case of fainter objects and five for the brighter ones, each offset by 8 or 15 arcsec from each other to minimize the effect of bad pixels. After subtracting an appropriate dark, frames in each filter were median filtered to produce a flat field, divided by this flat field, and then mosaicked together. In the case of observations of 1995 DW_2, three nine-frame mosaics were then further co-added in the asteroid's reference frame to improve the signal to noise ratio in the final image.

Early observations were made by tracking the telescope at the predicted rate of the asteroid's motion but, with the installation of a tip-tilt fast guider at UKIRT in 1996, most recent observations have been made guiding at the sidereal rate to take advantage of the improved image quality when using tip-tilt. In this case, post facto image registration was used during the mosaicking process for objects which moved more than two to three pixels during an observation. Identification of targets was confirmed by noting

TABLE I
VRI Photometry from the INT 1997 May 5–7

UT date	*R*(AU)	Δ(AU)	*α*°	Exp (s)	Filter	Mag
5145 Pholus						
1997 May 6.15301	12.154	11.423	3.4	300	*V*	18.70 ± 0.02
1997 May 6.15720				300	*V*	18.72 ± 0.02
1997 May 6.16139				300	*V*	18.73 ± 0.02
1997 May 6.16568				300	*V*	18.73 ± 0.02
1997 May 6.98260	12.158	11.432	3.4	300	*V*	18.66 ± 0.02
1997 May 6.98742				300	*V*	18.70 ± 0.02
1997 May 7.06466				300	*V*	18.63 ± 0.02
1997 May 7.06883				300	*V*	18.65 ± 0.02
1997 May 7.15022				300	*V*	18.64 ± 0.02
1997 May 7.98156	12.160	11.445	3.5	300	*V*	18.68 ± 0.02
1997 May 7.98572				300	*V*	18.68 ± 0.02
1997 May 8.06324				300	*V*	18.74 ± 0.02
1997 May 8.06806				200	*R*	18.00 ± 0.02
1997 May 8.07138				150	*I*	17.16 ± 0.02
1997 May 8.14704				200	*R*	17.85 ± 0.02
1997 May 8.15014				150	*I*	17.02 ± 0.02
1997 May 8.15462				300	*V*	18.61 ± 0.02
1995 GO						
1997 May 5.95074	11.291	10.365	2.1	500	*R*	19.39 ± 0.03
1997 May 5.95725				500	*R*	19.35 ± 0.03
1997 May 6.00653				500	*R*	19.76 ± 0.03
1997 May 6.01403				500	*R*	19.65 ± 0.03
1997 May 6.05117				500	*R*	19.46 ± 0.03
1997 May 6.05787				500	*R*	19.44 ± 0.03
1997 May 6.06502				500	*V*	19.78 ± 0.03
1997 May 6.07209				500	*R*	19.36 ± 0.03
1997 May 6.07986				500	*V*	19.75 ± 0.03
1997 May 6.08760				500	*R*	19.25 ± 0.03
1997 May 6.09464				500	*V*	19.63 ± 0.03
1997 May 6.10253				500	*R*	19.28 ± 0.03
1997 May 6.12056				500	*R*	19.21 ± 0.03
1997 May 6.12741				500	*R*	19.20 ± 0.03
1997 May 6.99434	11.287	10.368	2.2	500	*R*	19.35 ± 0.03
1997 May 7.00137				500	*V*	19.74 ± 0.03
1997 May 7.01730				200	*R*	19.19 ± 0.03
1997 May 7.02353				400	*I*	18.64 ± 0.03
1997 May 7.03002				500	*V*	19.63 ± 0.03
1997 May 7.03698				500	*R*	19.19 ± 0.03
1997 May 7.04311				400	*I*	18.69 ± 0.03
1995 GO (cont.)						
1997 May 7.93674	11.284	10.372	2.3	500	*R*	19.36 ± 0.03
1997 May 7.94376				500	*V*	19.76 ± 0.03
1997 May 7.99260				500	*R*	19.26 ± 0.03
1997 May 8.00762				500	*V*	19.76 ± 0.03
1997 May 8.01484				500	*R*	19.28 ± 0.03
1997 May 8.10485				500	*R*	19.43 ± 0.03
1997 May 8.11297				500	*V*	19.73 ± 0.03
1997 May 8.11993				500	*R*	19.32 ± 0.03
1997 CU_{26}						
1997 May 5.93396	13.857	14.007	4.1	300	*V*	18.48 ± 0.02
1997 May 5.93860				300	*R*	18.03 ± 0.02
1997 May 5.94325				300	*I*	17.43 ± 0.02
1997 May 5.95284				300	*R*	18.00 ± 0.02
1997 May 5.96885				300	*R*	18.01 ± 0.02
1997 May 6.92266	13.857	14.023	4.1	300	*V*	18.46 ± 0.02
1997 May 6.92736				300	*R*	18.00 ± 0.02
1997 May 6.93138				200	*I*	17.49 ± 0.02
1997 May 6.93476				200	*I*	17.42 ± 0.02
1997 May 6.95758				300	*V*	18.46 ± 0.02
1997 May 7.88626	13.856	14.038	4.1	300	*R*	18.03 ± 0.02
1997 May 7.89002				200	*I*	17.47 ± 0.02
1997 May 7.89454				300	*V*	18.47 ± 0.02
1997 May 7.90006				250	*R*	18.01 ± 0.02
1997 May 7.90391				200	*I*	17.47 ± 0.02
1997 May 7.90803				300	*V*	18.46 ± 0.02
1997 May 7.95131				300	*R*	18.00 ± 0.02
1997 May 7.95521				200	*I*	17.45 ± 0.02
1997 May 7.95931				300	*V*	18.47 ± 0.02
2060 Chiron						
1997 May 8.05637	8.610	7.655	2.3	20	*R*	15.58 ± 0.02
1997 May 8.05782				20	*I*	15.18 ± 0.02
1997 May 8.05928				20	*V*	15.95 ± 0.02
1997 May 8.08808				20	*R*	15.54 ± 0.02
1997 May 8.08916				20	*I*	15.16 ± 0.02
1997 May 8.09085				35	*V*	15.91 ± 0.02
1997 May 8.09285				35	*R*	15.56 ± 0.02
1997 May 8.09414				40	*I*	15.16 ± 0.02
1997 May 8.09584				35	*V*	15.93 ± 0.02

movement relative to background stars either immediately in the UKIRT acquisition camera or subsequently in the reduced images. When necessary, observations were made at intervals to allow the object to move as an aid to identification.

Magnitudes were extracted via the IRCAM data reduction package IRCAMDR using 5 arcsec diameter software apertures on the images and were calibrated via images of UKIRT faint standard stars. The quoted errors for individual observations include statistical uncertainties in the images and uncertainties in the photometric calibration. Observational details and individual magnitudes are given in Table II. The times are for the start of the mosaic and are not corrected for light travel time.

3. OBSERVATION AND REDUCTION PHILOSOPHY

Ideally, to derive visible–IR colors, data over the whole range of wavelengths would be obtained simultaneously, or at least within a period of a few minutes, as was done for 2060 Chiron in 1988 (Hartmann *et al.* 1990). However in practice visible and infrared observations tend to be made at different times and most attempts to derive visible–IR colors (e.g., Davies *et al.* 1993, 1996, 1997, Weintraub *et al.* 1997, Jewitt and Luu 1998) have used assumed values of the phase curve slope parameter *G* and the object's absolute magnitude H_V to estimate a *V* magnitude at the time of the infrared observations. However, the published values of H_V are often rounded to the nearest 0.5 and so may be of relatively low photometric precision. In addition, the *G* parameter may not be known and, even if it is, it is often impossible to allow for lightcurve variations when estimating a *V* magnitude. In the case of the Pholus observations in 1992 it was possible to use the lightcurve of Buie and Bus (1992) to deduce the lightcurve amplitude at the time of the infrared observations and so refine the *V–JHK* colors originally published (see Davies *et al.* 1996) but in general, uncertainties in the rotation

TABLE II
Infrared Photometry from UKIRT

UT date	R(AU)	Δ(AU)	$\alpha°$	Filter	Mag	Notes
5145 Pholus						
1992 Mar 15.40	8.719	8.159	5.6	J	14.78 ± 0.02	UKT9 Photometer
1992 Mar 15.40				H	14.27 ± 0.02	
1992 Mar 15.40				K	14.32 ± 0.02	
1992 Mar 17.28	8.720	8.186	5.7	J	14.69 ± 0.02	
1992 Mar 17.28				H	14.31 ± 0.03	
1992 Mar 17.28				K	14.33 ± 0.02	
1996 Mar 09.48	11.086	10.180	2.2	J	15.47 ± 0.03	IRCAM
1996 Mar 09.48				H	15.16 ± 0.03	
1996 Mar 09.49				K	15.15 ± 0.03	
1996 Mar 09.51				J	15.49 ± 0.03	
1996 Mar 09.52				H	15.18 ± 0.03	
1996 Mar 09.52				K	15.16 ± 0.03	
1996 Mar 10.54	11.089	10.180	2.2	J	15.51 ± 0.03	
1996 Mar 10.55				H	15.19 ± 0.03	
1996 Mar 10.55				K	15.23 ± 0.03	
1997 Jan 15.53	11.870	11.622	4.6	J	16.25 ± 0.03	
1997 Jan 15.53				H	15.87 ± 0.03	
1997 Jan 15.54				K	15.94 ± 0.03	
1997 Jan 15.60				J	16.13 ± 0.03	
1997 Jan 15.60				H	15.73 ± 0.03	
1997 Jan 15.61				K	15.81 ± 0.03	
1997 Mar 20.45	12.034	11.139	2.2	J	15.91 ± 0.03	
1997 Mar 20.46				H	15.51 ± 0.03	
1997 Mar 20.46				K	15.55 ± 0.03	
1997 Mar 20.56				J	16.00 ± 0.03	
1997 Mar 20.57				H	15.66 ± 0.03	
1997 Mar 20.57				K	15.73 ± 0.03	
1997 Apr 10.48	12.089	11.195	2.2	J	15.91 ± 0.03	
1997 Apr 10.48				H	15.57 ± 0.03	
1997 Apr 10.49				K	15.58 ± 0.03	
1997 Apr 11.58	12.092	11.202	2.3	J	16.04 ± 0.03	
1997 Apr 11.58				H	15.59 ± 0.03	
1997 Apr 11.59				K	15.72 ± 0.03	
1995 GO						
1997 Mar 20.48	11.440	10.532	2.1	J	18.50 ± 0.05	
1997 Mar 20.48				H	18.21 ± 0.10	
1997 Mar 20.49				K	18.08 ± 0.25	
1997 Mar 20.58				J	18.03 ± 0.05	
1997 Mar 20.59				H	17.65 ± 0.10	
1997 Mar 20.60				K	17.58 ± 0.25	
1997 Mar 20.61				J	18.07 ± 0.05	
1997 Apr 10.35	11.373	10.377	0.6	J	18.15 ± 0.05	
1997 Apr 10.36				H	18.01 ± 0.10	
1997 Apr 10.36				K	17.84 ± 0.25	
1997 Apr 10.37				J	18.16 ± 0.05	
1997 Apr 10.45				J	17.91 ± 0.05	
1997 Apr 10.46				H	17.58 ± 0.10	
1997 Apr 10.47				K	17.42 ± 0.25	
1997 Apr 10.48				J	18.14 ± 0.05	
1997 Apr 10.54				J	17.98 ± 0.05	
1997 Apr 10.54				H	17.49 ± 0.10	
1997 Apr 10.55				K	17.43 ± 0.25	
1997 Apr 11.48	11.369	10.372	0.5	J	18.11 ± 0.05	
1997 Apr 11.48				H	17.61 ± 0.10	
1997 Apr 11.49				K	17.60 ± 0.25	
1997 Apr 11.56				J	17.87 ± 0.05	
1997 Apr 11.56				H	17.47 ± 0.10	
7066 Nessus						
1993 Jul 03.31	11.958	11.558	4.6	K	18.45 ± 0.3	
1993 Jul 03.33				J	18.43 ± 0.15	
1993 Jul 03.34				H	17.89 ± 0.25	
1993 Jul 04.48	11.959	11.577	4.6	J	18.33 ± 0.15	
1993 Jul 04.48				H	18.00 ± 0.25	
7066 Nessus (cont.)						
1993 Jul 04.49				K	17.88 ± 0.3	
1993 Jul 05.29	11.959	11.589	4.6	J	18.58 ± 0.15	
1993 Jul 05.30				H	18.39 ± 0.25	
1993 Jul 05.31				K	18.24 ± 0.3	
1994 Apr 27.08	12.170	11.178	0.8	J	18.05 ± 0.10	
1994 Apr 27.08				K	17.78 ± 0.3	
1994 Jul 14.33	12.240	11.838	4.4	J	18.39 ± 0.05	
1994 Jul 14.33				H	18.16 ± 0.25	
1994 Jul 14.33				K	18.35 ± 0.3	
1995 Mar 27.33	12.507	11.865	3.6	J	18.52 ± 0.05	Exp ends Mar 27.40
1996 Mar 10.61	12.956	12.697	4.3	J	18.55 ± 0.05	
1996 Mar 10.61				J	18.45 ± 0.05	
1996 Mar 10.62				K	18.18 ± 0.25	
1996 Mar 10.63				K	18.16 ± 0.25	
1996 Mar 10.64				J	18.54 ± 0.05	
1996 Mar 10.66				K	18.29 ± 0.25	
1996 Mar 11.61	12.957	12.683	4.3	K	18.87 ± 0.25	
1996 Mar 11.62				K	18.22 ± 0.25	
1996 Mar 11.63				J	18.90 ± 0.05	
1996 Mar 11.63				J	18.86 ± 0.05	
1996 Mar 11.64				J	18.79 ± 0.05	
1996 Mar 11.65				K	18.44 ± 0.25	
1997 CU$_{26}$						
1997 Apr 10.26	13.875	13.598	4.0	J	16.61 ± 0.03	
1997 Apr 10.27				H	16.18 ± 0.03	
1997 Apr 10.27				K	16.13 ± 0.03	
1997 Apr 10.32				J	16.66 ± 0.03	
1997 Apr 10.33				H	16.26 ± 0.03	
1997 Apr 10.33				K	16.15 ± 0.03	
1997 Apr 10.38				J	16.66 ± 0.03	
1997 Apr 10.39				H	16.32 ± 0.03	
1997 Apr 10.39				K	16.14 ± 0.03	
1997 Apr 22.30	13.867	13.789	4.2	J	16.84 ± 0.03	
1997 Apr 22.31				H	16.43 ± 0.03	
1997 Apr 22.31				K	16.39 ± 0.03	
1997 Apr 22.34				J	16.89 ± 0.03	
1997 Apr 22.35				H	16.43 ± 0.03	
1997 Apr 22.35				K	16.38 ± 0.03	
1995 DW$_2$						
1995 Mar 27.55	18.860	17.863	0.2	J	20.78 ± 0.2	Exp ends Mar 27.66
1997 Apr 10.41	18.928	17.933	0.4	J	20.85 ± 0.2	Sum of 3, 9 frame, J mosaics
1997 Apr 10.51				J	20.64 ± 0.2	Sum of 3, 9 frame, J mosaics
2060 Chiron						
1996 Mar 09.45	8.454	7.536	2.7	J	14.39 ± 0.03	
1996 Mar 09.45				H	14.09 ± 0.03	
1996 Mar 09.46				K	13.99 ± 0.03	
1996 Mar 09.46				J	14.37 ± 0.03	
1996 Mar 09.47				H	14.16 ± 0.03	
1996 Mar 09.47				K	14.15 ± 0.03	
1996 Mar 10.51	8.454	7.529	2.6	J	14.40 ± 0.03	
1996 Mar 10.51				H	14.10 ± 0.03	
1996 Mar 10.52				K	14.04 ± 0.03	
1996 Mar 11.45	8.454	7.523	2.5	J	14.43 ± 0.03	
1996 Mar 11.45				H	14.11 ± 0.03	
1996 Mar 11.46				K	14.07 ± 0.03	
1997 Apr 10.58	8.592	7.600	1.0	J	14.56 ± 0.03	
1997 Apr 10.59				H	14.25 ± 0.03	
1997 Apr 10.59				K	14.17 ± 0.03	

phase of a rapidly rotating object can render the lightcurve correction virtually useless unless the visible and infrared datasets are taken within a relatively short time of each other.

We have attempted to address these difficulties by independently deriving *V* magnitudes using our own photometric observations and by obtaining multiple datasets in the expectation that we will sample any lightcurve at a number of different rotational phases. In the case of 5145 Pholus, where the rotation period is known, we often made observations separated by approximately 0.25 of a period so that if we happened to make one observation at a peak in the lightcurve, the following observation would fall close to a minimum and the mean magnitudes would be representative of a typical value for the object (although we note that in general this may not be strictly true if the lightcurve is considerably asymmetric). In the case of objects for which we had no knowledge of the lightcurve, we made observations at random intervals in the expectation that uncertainties due to lightcurve effects will be minimized.

Quoted uncertainties in colors comprise the random photometric errors and the systematic uncertainties in the calibration. In the case of *V–JHK* colors of 5145 Pholus we assign an error in *V* of 0.5 times the lightcurve amplitude in the case of single observations for which we have no knowledge of the rotational phase. When no information on lightcurves is available, we do not include this uncertainty, but comment on the possible implications in the text. The estimated error introduced when correcting between phase angles typical of the observations reported here is ±0.02 with the worst case ±0.05 mag (assuming *G* in the range 0.05–0.25). In all cases this is small compared to the other uncertainties involved in the estimation of the visible–IR colors and so it has not been explicitly included in the error estimates.

Since some Centaurs have better defined amplitudes and periods, we describe observations of each separately to address issues specific to that object before attempting to draw conclusions from the data as a whole. We start by considering 5145 Pholus since this is fairly well understood and provides a test of our methodology.

4. RESULTS

4.1. 5145 Pholus

Discovered in 1992 by the Spacewatch team (Scotti 1992), 5145 Pholus was the second Centaur to be identified and was soon found to be extraordinarily red in the visible (Mueller *et al.* 1992, Binzel 1992, Fink *et al.* 1992). Nonsimultaneous *JHK* data suggested that this extreme color continued into the infrared *J* band (Davies and Sykes 1992, Davies *et al.* 1993) before leveling off. Infrared spectroscopy also revealed the presence of unique spectral features (Davies *et al.* 1993, Luu *et al.* 1994). Buie and Bus (1992) presented a lightcurve which demonstrated convincingly a 9.9825 ± 0.004-h rotation period of amplitude ~0.15 mag with no significant *V–R* variations with rotation.

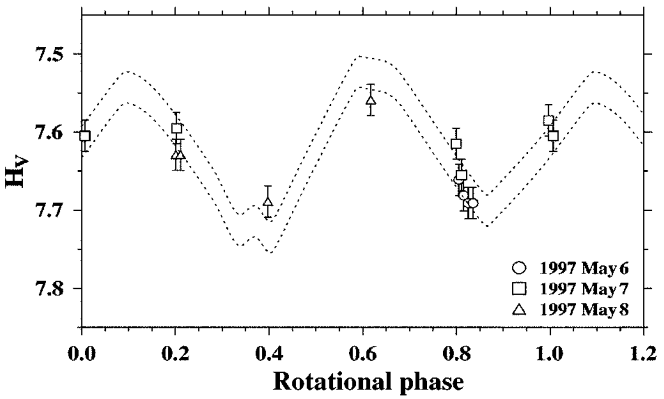

FIG. 1. The composite *V* lightcurve of 5145 Pholus obtained 1997 May, using the period determined by Buie and Bus (1992). The Buie and Bus (1992) lightcurve is shown as a range (dotted curves) indicating the spread in their original data.

4.1.1. Visible observations. During May 1997 we obtained 13 *V* magnitudes over three nights. Figure 1 shows our reduced *V* magnitudes, converted to $\alpha = 0°$ using $G = 0.16$ (Buie and Bus 1992) and plotted as a lightcurve using the period of 9.9825 h determined by Buie and Bus (1992). We determine an H_V of 7.63 ± 0.02. From the distribution in phase of our data it can be seen that our strategy of making observations separated by ~0.25 of a period during several nights did indeed adequately sample the rotation curve. The overall shape of the Buie and Bus lightcurve is overlaid in Fig. 1, with an arbitrary shift in phase (as the data sets are separated by 5 years). A vertical shift in the Buie and Bus lightcurve (for which $H_V = 7.645 \pm 0.011$) of only −0.015 mag is required to overlay our data adequately. We therefore adopted a weighted mean of $H_V = 7.64 \pm 0.01$ and $G = 0.16$.

Using *R* and *I* magnitudes determined on 1997 May 7, and taking account of the lightcurve shape as implied in Fig. 1, we deduce mean *V–R* and *V–I* colors of 0.75 ± 0.02 and 1.59 ± 0.02. Our *V–R* color is consistent with that obtained by Romanishin *et al.* (1997; 0.78 ± 0.04) but slightly lower than the mean value from Buie and Bus (1992; 0.810 ± 0.006). Our data are in close agreement with those of Mueller *et al.* (1992) on 1992 January 9 for which they quote *V–R* of 0.75 ± 0.03 and *V–I* of 1.51 ± 0.04 (using the errors quoted in IAUC 5434 which refers to the same data). The agreement with their colors of 1992 January 23 (*V–R* = 0.66, *R–I* = 1.34) is not as good,

TABLE III
Visible–Infrared Colors

UT date	V used	V–J	V–H	V–K	Notes
			5145 Pholus[a]		
1992 Mar 15.40		2.47 ± 0.02	2.98 ± 0.02	2.93 ± 0.02	See Davies *et al.* 1996
1992 Mar 17.28		2.59 ± 0.02	2.97 ± 0.03	2.96 ± 0.02	See Davies *et al.* 1996
1996 Mar 9.48	18.15	2.69 ± 0.09	2.99 ± 0.09	3.00 ± 0.09	
1996 Mar 9.52	18.15	2.66 ± 0.09	2.97 ± 0.09	2.99 ± 0.09	
1996 Mar 10.55	18.15	2.64 ± 0.09	2.96 ± 0.09	2.92 ± 0.09	
1997 Jan 15.53	18.73	2.48 ± 0.09	2.86 ± 0.09	2.79 ± 0.09	
1997 Jan 15.60	18.73	2.60 ± 0.09	3.00 ± 0.09	2.92 ± 0.09	
1997 Mar 20.46	18.53	2.62 ± 0.09	3.02 ± 0.09	2.98 ± 0.09	
1997 Mar 20.57	18.53	2.53 ± 0.09	2.87 ± 0.09	2.80 ± 0.09	
1997 Apr 10.48	18.55	2.64 ± 0.09	2.98 ± 0.09	2.97 ± 0.09	
1997 Apr 11.58	18.55	2.51 ± 0.09	2.96 ± 0.09	2.83 ± 0.09	
			1995 GO[b]		
1997 Mar 20.48	20.16	1.66 ± 0.05	—	—	
1997 Mar 20.48	20.12	—	1.91 ± 0.10	—	
1997 Mar 20.49	20.04	—	—	1.96 ± 0.25	
1997 Mar 20.58	19.72	1.69 ± 0.05	—	—	
1997 Mar 20.59	19.72	—	2.07 ± 0.10	—	
1997 Mar 20.60	19.71	—	—	2.13 ± 0.25	
1997 Mar 20.61	19.73	1.66 ± 0.05	—	—	
1997 Apr 10.35	19.79	1.64 ± 0.05	—	—	
1997 Apr 10.36	19.76	—	1.75 ± 0.10	—	
1997 Apr 10.36	19.76	—	—	1.92 ± 0.25	
1997 Apr 10.37	19.75	1.59 ± 0.05	—	—	
1997 Apr 10.45	19.54	1.63 ± 0.05	—	—	
1997 Apr 10.46	19.59	—	2.01 ± 0.10	—	
1997 Apr 10.47	19.68	—	—	2.26 ± 0.25	
1997 Apr 10.48	19.75	1.61 ± 0.05	—	—	
1997 Apr 10.54	19.74	1.76 ± 0.05	—	—	
1997 Apr 10.54	19.73	—	2.24 ± 0.10	—	
1997 Apr 10.55	19.70	—	—	2.27 ± 0.25	
1997 Apr 11.48	19.75	1.64 ± 0.05	—	—	
1997 Apr 11.48	19.75	—	2.14 ± 0.10	—	
1997 Apr 11.49	19.72	—	—	2.12 ± 0.25	
1997 Apr 11.56	19.53	1.66 ± 0.05	—	—	
1997 Apr 11.56	19.52	—	2.05 ± 0.10	—	

but no errors are quoted for this second dataset which is described as "preliminary."

4.1.2. Infrared observations. Using $H_V = 7.64 \pm 0.01$ deduced from our visible observations we estimated the V magnitude at the times of our infrared observations and from these deduced the visible–IR colors listed in Table III. These predicted V magnitudes do not include allowance for lightcurve effects due to the undefined rotational phase of the infrared data but we assume that the observations are well spread over rotational phase and therefore the lightcurve does not affect the mean colors derived. The colors deduced using IRCAM data agree within the errors with the 1992 values using the UKT9 photometer which validates both the IRCAM photometry and the general reduction philosophy. Accordingly, we combined all our data and the resulting average values (mean and standard error) are $V–J = 2.58 \pm 0.02$, $V–H = 2.96 \pm 0.02$ and $V–K = 2.92 \pm 0.02$. These agree with the recently published values of Weintraub *et al.* (1997) of $V–J = 2.67 \pm 0.2$, $V–H = 2.97 \pm 0.2$ and $V–K = 3.01 \pm 0.2$, which are based on a single set of JHK observations combined with a non-simultaneous V magnitude (N.B. these authors themselves remark that it is the uncertainty in the assumed V which dominates the uncertainty in their quoted V–J, V–H and V–K).

4.2. 1995 GO

1995 GO was discovered by the Spacewatch project (Scotti and Jedicke 1995) and visible–IR colors were given by Weintraub *et al.* (1997) using a small number of JHK

TABLE III—*Continued*

UT date	V used	$V–J$	$V–H$	$V–K$	Notes
			7066 Nessus[c]		
1993 Jul 3.33	20.65	2.22 ± 0.15	2.76 ± 0.25	2.20 ± 0.30	See Davies *et al.* (1996)
1993 Jul 4.38	20.66	2.33 ± 0.15	2.66 ± 0.25	2.78 ± 0.30	See Davies *et al.* (1996)
1993 Jul 5.30	20.66	2.08 ± 0.15	2.27 ± 0.25	2.42 ± 0.30	See Davies *et al.* (1996)
1994 Apr 27.08	20.35	2.30 ± 0.10	—	2.57 ± 0.30	See Davies *et al.* (1996)
1994 Jul 14.33	20.74	2.35 ± 0.10	2.58 ± 0.25	2.39 ± 0.30	See Davies *et al.* (1996)
1995 Mar 27.33	20.75	2.23 ± 0.05	—	—	
1996 Mar 10.61	21.01	2.46 ± 0.05	—	—	
1996 Mar 10.61	21.01	2.56 ± 0.05	—	—	
1996 Mar 10.62	21.01	—	—	2.83 ± 0.25	
1996 Mar 10.63	21.01	—	—	2.85 ± 0.25	
1996 Mar 10.64	21.01	2.47 ± 0.05	—	—	
1996 Mar 10.66	21.01	—	—	2.72 ± 0.25	
1996 Mar 11.61	21.01	—	—	2.14 ± 0.25	
1996 Mar 11.62	21.01	—	—	2.79 ± 0.25	
1996 Mar 11.63	21.01	2.11 ± 0.05	—	—	
1996 Mar 11.63	21.01	2.15 ± 0.05	—	—	
1996 Mar 11.64	21.01	2.22 ± 0.05	—	—	
1996 Mar 11.65	21.01	—	—	2.57 ± 0.25	
			1997 CU_{26}[c]		
1997 Apr 10.27	18.39	1.78 ± 0.04	2.21 ± 0.04	2.26 ± 0.04	
1997 Apr 10.33	18.39	1.73 ± 0.04	2.13 ± 0.04	2.24 ± 0.04	
1997 Apr 10.39	18.39	1.73 ± 0.04	2.07 ± 0.04	2.25 ± 0.04	
1997 Apr 22.31	18.43	1.59 ± 0.04	2.00 ± 0.04	2.04 ± 0.04	
1997 Apr 22.35	18.43	1.54 ± 0.04	2.00 ± 0.04	2.05 ± 0.04	
			1995 DW_2[c]		
1995 Mar 27.55	22.05	1.27 ± 0.20	—	—	
1997 Apr 10.41	22.10	1.25 ± 0.20	—	—	
1997 Apr 10.51	22.10	1.46 ± 0.20	—	—	
			2060 Chiron[d]		
1996 Mar 9.45	15.87	1.48 ± 0.05	1.78 ± 0.05	1.88 ± 0.05	
1996 Mar 9.47	15.87	1.50 ± 0.05	1.71 ± 0.05	1.72 ± 0.05	
1996 Mar 10.51	15.86	1.46 ± 0.05	1.76 ± 0.05	1.82 ± 0.05	
1996 Mar 11.45	15.85	1.42 ± 0.05	1.74 ± 0.05	1.78 ± 0.05	
1997 Apr 10.59	15.79	1.23 ± 0.05	1.54 ± 0.05	1.62 ± 0.05	

[a] Quoted errors dominated by unknown rotational phase of lightcurve with amplitude ±0.08.

[b] V used determined from lightcurve.

[c] No corrections for possible lightcurve included in V used.

[d] Quoted errors include unknown rotational phase of lightcurve of amplitude ±0.04.

data points and an assumed V magnitude. Brown and Luu (1997) presented an R band lightcurve from which a period of 8.87 ± 0.02 h and an amplitude of 0.34 mag was reported and they determined a $V–R$ color of 0.73 ± 0.04, significantly different from the value of 0.47 ± 0.04 obtained almost simultaneously by Romanishin *et al.* (1997).

4.2.1. The lightcurve of 1995 GO. Our visible observations of 1995 GO were taken at random intervals over three nights and were not intended to determine the lightcurve, but rather to gauge its likely amplitude to assess the possible effects on our visible–IR colors. However, the subsequent publication of the data of Brown and Luu (1997) and Romanishin *et al.* (1997) allowed us to combine these datasets into a consistent whole, indicating that our observations did cover the entire rotational phase of 1995 GO. We could then use our data to obtain a period independently and compare this directly with that found by Brown and Luu (1997).

Because 1995 GO was slow-moving, we obtained relative photometry using reference stars that were common to all frames over the three nights. This reduced any errors which might have been introduced by uncertainties in the absolute calibration from night to night (particularly due to uncertainties in the extinction curve for observations at high airmass) and maintained the accuracy of the lightcurve shape. Absolute calibration of the photometry was obtained on the third night.

The rotational period was found by fitting a fourier series in the manner described by Harris *et al.* (1989). We derived a period for 1995 GO of 8.93 ± 0.03 h from our INT data which is somewhat longer than the 8.87 ± 0.02 h reported by Brown and Luu (1997). Using the data in Table 2 of Brown and Luu (1997) to obtain light-time corrected, mid-frame times, we applied the same fourier fitting technique to their data. The fitting treats the three nights' data independently and allows the fitting program to shift the data sets "vertically" to produce the lowest residuals, so uncertainties in the absolute calibration of each night's data do not affect the period determination. When reduced in this way the Brown and Luu (1997) data produce a period for 1995 GO of 8.93 ± 0.02 h which is well constrained and consistent with the value derived using our data. Figure 2a shows our treatment of the Brown and Luu (1997) data for 1995 GO, plotted as reduced magnitudes (i.e., at $\Delta = R = 1$ AU and at the phase angle 1.2°), with magnitude shifts relative to night 1 of $+0.182$ and -0.089 mag applied to night 2 (April 18) and night 3 (April 19), respectively. Brown and Luu used the airmass coefficient determined on their first night to reduce both their second and third nights' data, but any errors in the zeropoints do not affect our period determination as the data are allowed to shift vertically. We note that treating the Brown and Luu three nights of data as a single data set produces a period of 8.89 ± 0.02 h, consistent with their value of 8.87 ± 0.02 h.

Romanishin *et al.* (1997) report 7 R magnitudes taken 4 days before the Brown and Luu (1997) data. Note that the caption for Fig. 1 of Romanishin *et al.* (1997) quotes the data as being from April 13 UT when it was in fact taken on April 14th as reported in the text and the times plotted are mid-frame values uncorrected for light travel time (Romanishin, pers. commun.). Combining the Brown and Luu and Romanishin *et al.* datasets (using light time corrected values) produces the lightcurve shown in Fig. 2b and a period of 8.92 ± 0.02 h. The Romanishin *et al.* data are plotted as reduced magnitudes (phase angle 0.8°), and the Brown and Luu data have been shifted vertically by the fitting program (as described above). The shift needed for the three nights of the Brown and Luu data are $+0.33$, $+0.16$, and $+0.25$ mag, respectively. If we assume a typical slope parameter of $G = 0.15$, then we would expect the required shift due to the different phase angles to be about -0.04 mag ($0.0 < G < 0.5$ gives a shift between -0.05 and -0.025). Hence there is an inconsistency between these two datasets at the level of ~0.3 mag which we are unable to explain and which is surprising since both groups estimate their absolute uncertainties to be of the order of 0.05 mag.

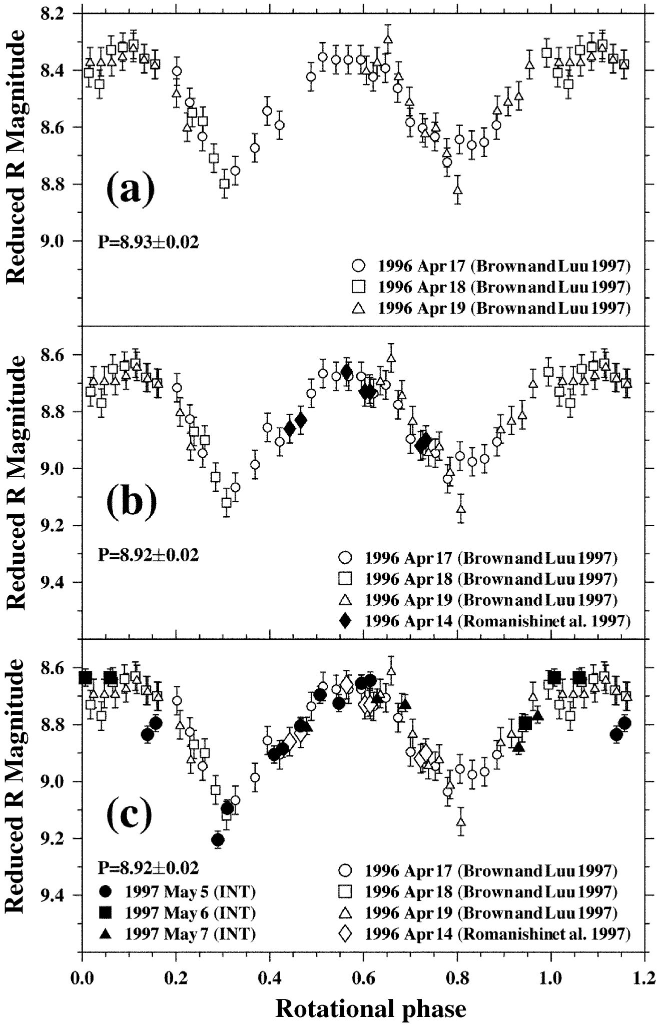

FIG. 2. (a) Composite lightcurve of 1995 GO deduced here using data from Brown and Luu (1997) taken on 1997 April 17–19 ($R = 12.51$ AU, $\Delta = 11.54$ AU, $\alpha = 1.2°$), plotted as reduced magnitudes $R(1, \alpha = 1.2°)$ with $T_0 = 2450190.5$ JD, and our best fit period of 8.93 ± 0.02 h. We take the data of 1997 Apr 17 as being the "nominal" dataset and the Fourier fitting allows arbitrary shifts in the level of the following two nights' data to overlay the 1st night. The relative shifts are $+0.182$ and -0.089 mag, respectively. (b) The lightcurve of 1995 GO using data from Romanishin *et al.* (1997) ($R = 12.53$ AU, $\Delta = 11.54$ AU, $\alpha = 0.8°$) plotted as reduced magnitudes $R(1, \alpha = 0.8°)$, combined with the Brown and Luu (1997) data. The period is determined as 8.92 ± 0.02 h. We have assigned errors of ±0.05 mag. The three nights of the Brown and Luu data have vertical shifts applied to them of $+0.33$, $+0.16$, and $+0.25$ mag, respectively. (c) As (b), but with our INT data ($R = 11.23$ AU, $\Delta = 10.37$ AU, $\alpha = 2.2°$) added using the same period of 8.92 h (see text). The vertical shift needed for the INT data is -0.21 mag, of which -0.14 is expected due to the change in phase angle (assuming $G = 0.15$).

Our INT data were taken 13 months later (i.e., over 1050 revolutions) so cannot be combined with that of Brown and Luu and Romanishin *et al.* to constrain the period. However, the period already established can be applied and the data compared. Between the 1996 April and 1997 May datasets, the aspect angle changed by ~6° and so we expect only relatively subtle changes in the lightcurve. The composite *R* lightcurve, obtained using a 10th order fit, is shown in Fig. 2c. This figure is again plotted relative to the Romanishin *et al.* data and the shift applied to the INT data (taken at phase angle 2.2°) is −0.21 mag. If we assumed a slope parameter of $G = 0.15$, then we would expect the required shift due to the different phase angles to be −0.14 mag. Considering the uncertainty of registration in both phase and reduced magnitude combined with observational errors and subtle changes due to the difference in aspect angle, we feel that the INT data are generally consistent with those of Romanishin *et al.* (1997) but are inconsistent with those of Brown and Luu.

Brown and Luu reported a lightcurve amplitude of 0.34 mag deduced from minimizing the χ^2 value of a sine fit. However, it is clear from Fig. 2 that this value is not representative of the absolute range of the lightcurve, which is in fact ~0.55 mag.

Our *JHK* data were taken on 1997 March 20, April 10, and April 11. This spread of observations, when combined with the 1996 April and 1997 May visible data further constrains the period of 1995 GO. Since there are only 10 infrared observation times (i.e., 10 *J* frames) in total, we did not allow the lightcurve fitting routine to shift the three separate nights, but converted the data to a single phase angle assuming $G = 0.15$ (G values between 0.05 and 0.25 would introduce a maximum additional uncertainty of only ±0.02 mag). Figure 3 presents the final composite lightcurve of 1995 GO, using the *J* data, plotted as before, at a phase angle of $\alpha = 0.8°$. The period, assuming no aspect changes, is constrained to 8.93510 ± 0.00005 h. However, because of the 6° aspect change over the range of observations, the true error may be as large as 0.0003 h. We thus determine the rotation period of 1995 GO as 8.9351 ± 0.0003 h.

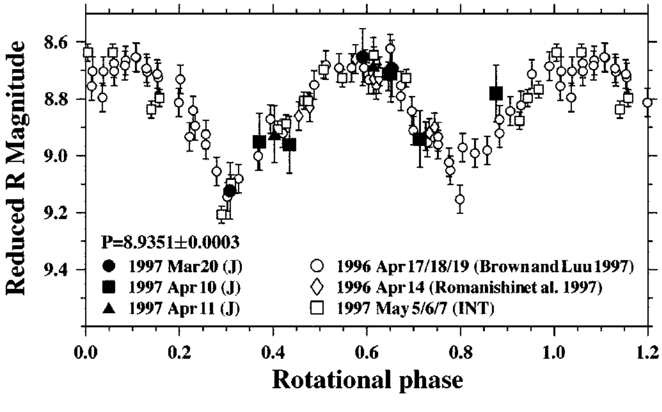

FIG. 3. The final composite lightcurve of 1995 GO, obtained by combining the Romanishin *et al.* (1997) data, the Brown and Luu (1997) data, our optical INT data, with the UKIRT *J* band data. The spread of observations is such that the period is well constrained to 8.9351 ± 0.0003 h. The lightcurve allows *V* magnitudes to be determined at the time of the *JHK* photometry, so producing *V–JHK* colors.

4.2.2. Visible colors of 1995 GO. Over the three nights we obtained eight values of *V–R* which show no significant change with rotational phase. The average *V–R* color is determined by the shift in the *V* data relative to the *R*, produced by the lightcurve fitting technique. From this we determine a *V–R* = 0.41 ± 0.02. Similarly, we find *V–I* = 0.96 ± 0.04 from two *I* frames. Our *V–R* is lower than the value of Romanishin *et al.* (1997) of 0.47 ± 0.04 although the values are consistent within the quoted errors. The Brown and Luu (1997) value of *V–R* = 0.73 ± 0.04 is not consistent with the Romanishin *et al.* or our value. However, the reduced *V* magnitude of Brown and Luu is consistent with our *V* magnitudes and therefore the difference seems to be dominated by an unexplained difference in the absolute value of *R*. The difference in *V–R* is ~0.3 mag, which is the same as the shift required to fit the Brown and Luu R lightcurve to the other data. Note that a *V–R* of 0.73 would imply that 1995 GO was as red as Pholus (which has *V–R* ~ 0.75) and so it might be expected that 1995 GO would also have a "Pholus-like" *V–I* of ~1.59. However, we find that 1995 GO has *V–I* of 0.96 ± 0.04, favoring values of *V–R* of ~0.45.

4.2.3. Infrared colors of 1995 GO. To derive *V–JHK* values, we must estimate the *V* magnitudes at the specific times of the infrared observations, making due allowance for phase angle and rotation. This was done using the fit shown in Fig. 3 and applying a phase angle correction assuming $G = 0.15$. Table III shows the individual values which result in mean colors of *V–J* = 1.65 ± 0.02, *V–H* = 2.02 ± 0.06, and *V–K* = 2.11 ± 0.05. These colors agree within the errors with those of Weintraub *et al.* (1997) (*V–J* = 1.72 ± 0.30, *V–H* = 2.15 ± 0.30, and *V–K* = 2.39 ± 0.31), which were obtained from a single set of IR observations.

4.3. 7066 Nessus (1993 HA$_2$)

7066 Nessus was the third Centaur to be discovered (on 1993 April 26 by the Spacewatch project; Rabinowitz 1993) and visible colors were presented by Luu and Jewitt (1996) and by Romanishin *et al.* (1997). Visible–IR colors were given in Davies *et al.* (1996) using data from 1993 and 1994 combined with a *V* derived using an H_V of 9.5. The observations presented here improve on the coverage of this object by adding infrared data from 1995 and 1996. Further observations were not possible in 1997 since at that time the object was not accessible from the INT and lay in a field close to the galactic center which, while observable from UKIRT, was so crowded with infrared sources as to make reliable photometry impossible.

There is no published lightcurve for this object and this complicates establishing its visible–IR colors. We adopted an H_V of 9.55 ± 0.05 based on three V observations from Luu and Jewitt (1996), one V from Romanishin *et al.* (1997), and an R magnitude from Green *et al.* (1997) with $V{-}R = 0.80 \pm 0.07$ from a combination of values in Luu and Jewitt (1996) and Romanishin *et al.* (1997). The data are sufficiently scattered to be fitted by any low value of G so we adopted $G = 0.15$. We also adopted $V{-}I = 1.49 \pm 0.1$ from Luu and Jewitt (1996). All the visible–IR colors were then recomputed with this new value of H_V and are presented in Table III. The expected error in a single J data point is no more than 0.1 mag for an object of this brightness observed in this way but we note that the actual range of the values of $V{-}J$ is greater, by factors of 2 or 3, than the standard deviation. This may be indicative of lightcurve variations with an amplitude of a few tenths of a magnitude which cannot be taken into account when deducing a V magnitude entirely from H_V. We urge visible observations to establish if this is indeed the case. The scatter in the V photometry used to derive the absolute magnitude and variations of up to 0.5 in magnitudes reported by Rabinowitz (1993) provide further evidence for a nonnegligible lightcurve. Averaging all of the data obtained, assuming any lightcurve is well sampled, generates colors of $V{-}J = 2.29 \pm 0.04$, $V{-}H = 2.57 \pm 0.11$, $V{-}K = 2.57 \pm 0.08$ and confirms 7066 Nessus as the second reddest Centaur so far observed.

4.4. 1997 CU_{26}

4.4.1. Visible observations. Discovered by the Spacewatch team (Scotti 1997), this is one of the brightest Centaurs and Binzel (1997) reported that it had a visible spectrum typical of a D type asteroid. Due to its relatively small elongation, 1997 CU_{26} was observable for only a short time each evening during the INT observing run and this prevented us from obtaining detailed coverage of its lightcurve. On each day single sets of *VRI* observations were made, although on May 7 three sets of *VRI* observations separated by a few minutes were possible. All the *VRI* data taken are very consistent (e.g., $V = 18.47 \pm 0.01$) and this suggests that either the object has almost no significant lightcurve, that its period must be close to an exact fraction of 24 h, or that its period is very long. The mean visible colors of 1997 CU_{26} (which do not rely on an assumption of G) are $V{-}R = 0.45 \pm 0.02$ (which is in agreement with the Tegler and Romanishin (1998) value of 0.48) and $V{-}I = 1.01 \pm 0.02$. Assuming $G = 0.15$ we derive $H_V = 6.65 \pm 0.01$.

4.4.2. Infrared observations. Infrared data for 1997 CU_{26} were taken earlier in 1997 when the observing constraints were not so severe and on these two nights either two or three sets of data were taken at roughly 2- to 3-h intervals. On each night these data are internally consistent at a level of ±0.03 mag which again points to a very small lightcurve amplitude. However, the visible–IR colors deduced using our value of H_V (see Table III) are not consistent within these errors. For example, on April 10 we derive $V{-}J = 1.75 \pm 0.02$ and on April 22 we derive $V{-}J = 1.57 \pm 0.03$; a difference of 0.18 mag which, although small, is outside the expected range of error. Since both the visible and the infrared data by themselves point to little variability on time scales of a few hours (infrared) or 24 h (visible) it is difficult to explain this inconsistency in the visible–IR colors with the present data. Neglecting some undiscovered error in one set of *JHK* photometry, obvious possibilities are a very slow rotation of moderate amplitude or some sort of outburst between the two sets of infrared observations. An error in the G value is unlikely to be the solution since both infrared datasets are taken at close to the same phase angle. In the absence of a suitable explanation, we average the two data sets and present the results in Table V.

4.5. 1995 DW_2

1995 DW_2 is one of the faintest Centaurs and we did not observe it in May 1997. Infrared observations were confined to three measurements, one in March 1995 and two on a single night in April 1997. With a J magnitude of approximately 21 it is a challenging observation and no further infrared observations were possible in the limited time available to us in 1997. To determine the visible–IR colors given in Table III we use two reported sets of $V{-}R$ colors (Luu and Jewitt 1996, Green *et al.* 1997) from which we adopt an H_V value of 9.35 ± 0.08 and $V{-}R = 0.41 \pm 0.05$ and $V{-}I = 0.87 \pm 0.15$, having noted that the two groups give significantly different values of $V{-}R$ which are not consistent within their quoted errors. There is no lightcurve information available for this object and so, since the derived $V{-}J$ colors were within the likely error of the J data alone, we averaged the $V{-}J$ values obtained (Table V). The resulting reflectivity curve is very flat in comparison to the objects described above.

4.6. 2060 Chiron

2060 Chiron was discovered in 1977 during a search for faint Solar System objects (Kowal and Gehrels 1977). It is the most widely studied Centaur although rarely are visible and infrared data taken simultaneously. Hartmann *et al.* (1981) presented the first *JHK* colorimetry of 2060 Chiron and subsequently repeated their observations in *VJHK* later in 1981 (Hartmann *et al.* 1982). Further visible observations are presented in Bus *et al.* (1988, 1989), the latter containing an R lightcurve with an amplitude of

TABLE IV
2060 Chiron Visible–Infrared Colors

Observation	$V–R$	$V–I$	$V–J$	$V–H$	$V–K$	Notes
1981 Feb[a]	—	—	0.90 ± 0.16	1.21 ± 0.20	1.38 ± 0.20	V based on B(1, 0)
1981 Sep[b]	—	—	0.88 ± 0.22	—	—	Simultaneous V
1988 Feb[c]	0.37 ± 0.02	0.68 ± 0.03	1.15 ± 0.04	1.43 ± 0.04	1.47 ± 0.05	Simultaneous V
1988 Sep[c]	—	—	1.11 ± 0.06	1.41 ± 0.03	1.53 ± 0.04	Simultaneous V
1996 Mar	—	—	1.47 ± 0.05	1.75 ± 0.05	1.80 ± 0.05	From V within ±2 weeks
1997 Apr	—	—	1.23 ± 0.05	1.54 ± 0.05	1.62 ± 0.05	From V 1 month later
1997 May	0.37 ± 0.03	0.76 ± 0.01	—	—	—	

Note. Chiron has semi-major axis of 13.75 AU and perihelion distance of 8.46 AU.

[a] Hartmann *et al.* 1981.

[b] Hartmann *et al.* 1982.

[c] Hartmann *et al.* 1988.

0.09 mag and period of 5.92 h. Five filter colorimetry and thermal infrared observations are presented in Lebofsky *et al.* (1984) and a full set of *VRIJHK* data in Hartmann *et al.* (1990), whose simultaneous (same night) visible and infrared data permitted a determination of the relative reflectance of 2060 Chiron between 0.55 and 2.2 μm.

The cometary activity of 2060 Chiron is well-known. Its outbursts were first observed in 1987 as an increase in absolute magnitude (Tholen *et al.* 1988), with detection of a coma in 1989 (Meech and Belton 1990). Subsequent monitoring of the absolute magnitude (e.g., Hartmann *et al.* 1990) indicated a peak of activity at a heliocentric distance of 12 AU in 1989 January about 1.1 mag brighter than in 1983–1986. There has been a decline in absolute magnitude in the early 1990s with little or no activity in 1995 (Lazzaro *et al.* 1996) and 1996 (Lazzaro *et al.* 1997). Meech and Belton (1990) produced a coma and nucleus model to describe the lightcurve amplitude variations (see also Luu and Jewitt 1990, Marcialis and Buratti 1993), which ranged from ~0.09 when least active to ~0.03 mag when a significant coma was present.

This activity greatly complicates the determination of visible–IR colors but, mindful of the difficulties, we have attempted to generate *V–JHK* colors for comparison with previous data.

4.6.1. Visible observations. Although the G value of Chiron is not well defined due to its "contaminating" coma, a value could be derived if sufficient observations with no significant coma were available. We have examined all published visible observations of Chiron and conclude that an envelope of reduced magnitudes, $H_V(1, \alpha)$, is consistent with $H_V = 6.56 \pm 0.02$ with $G = 0.15$ (Green *et al.*, in preparation) for the faintest magnitudes. We find the value of $G \sim 0.7$ inferred by Bus *et al.* (1989) and Lazzaro *et al.* (1996) over a small range of phase angles is not consistent with the full photometry dataset available.

We obtained *VRI* photometry in 1997 May which is consistent with the lower envelope of all previous data and conclude that Chiron was inactive at that time with mean colors $V–R = 0.37 \pm 0.03$ and $V–I = 0.76 \pm 0.02$.

4.6.2. Infrared observations. We obtained *JHK* photometry on 1996 March 9–11 and 1997 April 10. The mean infrared colors in 1996 March ($J–H = 0.28 \pm 0.02$ and $H–K = 0.05 \pm 0.02$) and in 1997 April ($J–H = 0.31 \pm 0.04$ and $H–K = 0.08 \pm 0.04$) are in agreement within quoted uncertainties with the colors in 1981 February (Hartmann *et al.* 1981, 1982) and 1988 February and September (Hartmann *et al.* 1990).

Since we have no simultaneous visible data we must estimate V magnitudes using other sources to determine the *V–JHK* colors. Lazzaro *et al.* (1997) observed 2060 Chiron on a number of occasions during the first half of 1996 and confirm its state of relative inactivity around this time. V magnitudes 2 weeks before and after our infrared data are consistent with the "bare nucleus" absolute magnitude $H_V = 6.56 \pm 0.02$ with $G = 0.15$ so we used these values to derive V magnitudes. We also assumed no activity in April 1997, 1 month before our visible data, to derive a V magnitude appropriate for the April infrared observations. The resultant *V–JHK* colors are listed in Table III (with errors generated including a contribution of ±0.04 for the unknown lightcurve phase).

Table IV lists all available visible–IR data for comparison. On 1981 February 5 Hartmann *et al.* (1981) obtained *JHK* data and used an old style absolute magnitude, $B(1, 0)$, an assumed linear phase function and $B–V$ color, to derive a V magnitude of 18.67 ± 0.14. We predict $V = 19.11 \pm 0.05$ for a bare nucleus on that date, implying a coma contribution of 0.44 mag if the Hartmann *et al.* V is reliable, although in 1981 the activity of Chiron was not identified so the assumptions they made to calculate V were unrealistic and the true V magnitude on that date is not well determined. On 1981 September 26, Hartmann *et al.* (1982) obtained $V = 18.64 \pm 0.10$ and $J = 17.76 \pm 0.2$.

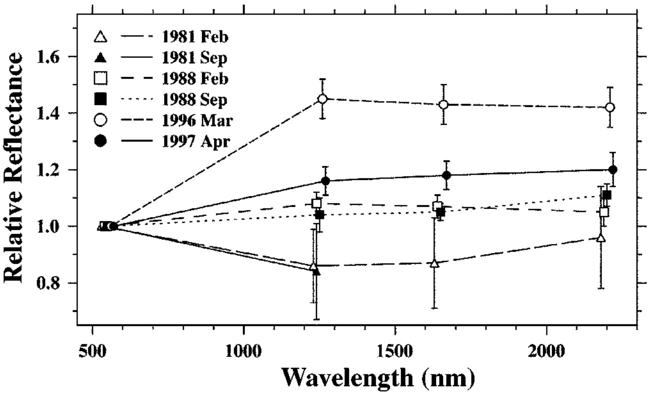

FIG. 4. Relative reflectance of Chiron (normalized to 1 at *V*) based on data from a number of different dates (see text for details). The symbols have been deliberately offset left–right slightly for clarity.

This *V* magnitude implies a coma contribution of 0.25 mag based on our bare nucleus absolute magnitude.

Relative reflectances calculated from the colors given in Table IV are plotted in Fig. 4. The 1988 February and September data obtained when Chiron was active (we estimate a coma contribution of 0.63 and 1.04 mag respectively) agree well. The February and September 1981 data appear somewhat bluer, although the error bars overlap with the 1988 data and the February 1981 colors were produced using an assumed *V* which could have a larger error than quoted. Our 1996 March data, obtained when Chiron was inactive, appear significantly redder. If these are the "true" colors of the bare nucleus, then we would expect to see similar behavior in the 1997 April data, when Chiron also appeared to be inactive. However, the 1997 April data are only slightly redder than the "active" colors in 1988.

We acknowledge that in the case of Chiron, which is known to outburst over various time scales and with a range of magnitudes, using estimated *V* magnitudes may introduce errors in the *V–JHK* color. An error of only ~0.1 mag in the *V* used in combination with our *JHK* is sufficient to bring our 1997 data into agreement with the data from 1988. Such variation was observed over time scales of 1 month, in 1996, by Lazzaro *et al.* (1997).

However, an error in the estimated *V* of 0.3 mag is required to bring the 1996 March data into agreement. Such a difference could have been caused by an outburst, but in this case to have escaped detection by the monitoring of Lazzaro *et al.* (1997) the outburst must have occurred not more than 1 week before our infrared observations and its effects must have almost vanished within about 2 weeks of them, since visible data taken in late February and late March 1996 show no sign of excursions of this magnitude. We find no variations greater than 0.15 mag in the data of Lazzaro *et al.* (1997) from 1996 Jan 27 to 1996 June 12. Note that Parker *et al.* (1997) report a "brightening" of Chiron of 60% in the UV between January and April 1996, which they attribute to "an unusually steep phase function and/or strong opposition surge" or activity. However, the brightening expected in the visible with the $G = 0.15$ phase function would be 52% simply due to the different viewing geometry.

Although we accept that the evidence for a significant change in the visible–IR color of Chiron in 1996–1997 is not overwhelming, we feel that it cannot be ruled out. If the change in reflectance spectrum is due to the contamination of the coma, we would expect to see a range of colors correlated with apparent activity, but this is not the case. Alternatively, if the apparent increase in redness is due to an intrinsic difference in the surface properties of Chiron between the early 1980s and the mid 1990s, which would imply that Chiron's activity in the intervening years may have significantly changed the body's surface properties, then we need to seek some additional explanation for the difference in colors between the 1996 and the 1997 data. Additional, simultaneous, observations are clearly required to resolve this question.

5. DISCUSSION

For ease of comparison we present our average *V–RIJHK* colors in Table V and have plotted the resulting reflectivity gradients in Fig. 5 (normalised to 1 at *V*). The *BVRI* and visible–IR colors, and the possible relationships between them, of various outer Solar System objects have been discussed extensively in several recent papers (e.g., Luu and Jewitt 1996, Weintraub *et al.* 1997, Davies *et al.* 1997) and for conciseness this discussion will not be repeated here. The two fundamental issues which can be addressed with the dataset presented here are as follows:

(i) Are the surface colors of the Centaur objects representative of objects in the Kuiper Belt?

(ii) Are there any trends in surface composition, as deduced from visible–IR colors, with heliocentric distance?

Luu and Jewitt (1996) argued on the basis of visible colors alone that the Kuiper Belt comprises objects with a range of surface properties and that the Centaurs have a range of colors which is essentially indistinguishable from them. A similar conclusion on the color diversity of these distant objects was reached by Green *et al.* (1997). However, Tegler and Romanishin (1998) argue on the basis of *BVR* colors that these distant objects form a bimodal population with one group of objects being only slightly redder than the Sun while the others are very red indeed and that the two groups are well separated in the *BVR* plane. Tegler and Romanishin state that they believe that their photometry, on which they base this conclusion, is

TABLE V
Visible–Infrared Colors of the Other Centaurs

Object	*a* (AU)	*q* (AU)	*V–R*	*V–I*	*V–J*	*V–H*	*V–K*	Notes
5145 Pholus	20.44	8.69	0.75 ± 0.02	1.59 ± 0.02	2.58 ± 0.02	2.96 ± 0.02	2.92 ± 0.02	Eight dates 1992–1997
1995 GO	18.07	6.85	0.41 ± 0.02	0.96 ± 0.03	1.65 ± 0.02	2.02 ± 0.06	2.11 ± 0.05	Three dates in 1997
(7060) Nessus	24.76	11.82	0.80 ± 0.07[a,b]	1.49 ± 0.10[a]	2.29 ± 0.04	2.57 ± 0.1	2.57 ± 0.1	Eight dates 1993–1996
1997 CU_{26}	15.82	12.91	0.46 ± 0.02	1.01 ± 0.02	1.67 ± 0.1	2.08 ± 0.1	2.17 ± 0.1	Two dates in 1997
1995 DW_2	25.03	18.86	0.41 ± 0.10[a,c]	0.87 ± 0.15[c]	1.33 ± 0.1	—	—	Two dates in 1995 and one in 1997

[a] Luu and Jewitt 1996.
[b] Romanishin *et al.* 1997.
[c] Green *et al.* (1997).

"significantly more accurate" and imply that the spectral diversity reported by other groups is due to the larger photometric uncertainties in the earlier data. That such differences in photometry can exist is clear when comparing the data of Tegler and Romanishin (1998) with that of Jewitt and Luu (1998). Both of these papers present *BVR* data, albeit using Harris (*BVR*) and Johnson, Kron–Cousins (*BVRI*) filter systems, respectively, and there are five Kuiper Belt objects common to these datasets. While in some cases the colors (particularly *V–R*) are in good agreement, in others both the *V–R* and, particularly, the *B–V*, are not consistent within the quoted photometric errors. These differences do not appear to be related to the redness of the objects and so are probably not explained by color correction effects due to the differences in filter passbands. Davies *et al.* (1997) emphasize the difficulties involved in photometry of faint moving objects and show, based on reduction of 33 frames of the Kuiper Belt object 1993 SC using different techniques, that the statistical uncertainties provide an underestimate of the true observational errors.

The new Centaur data presented here do not include any *B* data and so are only partly helpful in resolving the diversity issue. However, our *V–R* colors are consistent with those of Tegler and Romanishin (1998) and could be regarded as evidence of a bimodal distribution comprising 5145 Pholus and 7066 Nessus in the "red" group with the remaining four objects being in the "neutral" group.

Few visible–IR colors have been presented for Kuiper Belt objects other than those of 1993 SC (Davies *et al.* 1997) and Jewitt and Luu (1998) who observed 1993 SC plus four others. Jewitt and Luu (1998) remark that they "find extreme differences, especially in the measured *V–J* color indices, that indicate a wide range of surface compositions in the Kuiper Belt," but, while referring to some objects as spectral analogs of Chiron and others as more closely resembling 5145 Pholus, they do not argue specifically for a bimodal distribution. The new *V–J* colors of Centaurs presented here do not represent a bimodal distribution as, with the exception of 1995 GO and 1997 CU_{26}, the reflectivity curves in Fig. 5 do not overlap. Thus despite the fact that our *VRI* data are broadly supportive of bimodality, our *V–JHK* data are not. Jewitt and Luu (1998) also present a linear relationship between *V–J* and absolute red magnitude M_R for five Kuiper Belt objects which has a linear correlation coefficient at the 99.7% confidence level. If M_R is related directly to size, this implies that the smaller objects are systematically redder. However, no such trend of color with size is seen for the Centaurs since 2060 Chiron and 5145 Pholus, which are believed to be approximately the same size (Campins *et al.* 1994, Davies *et al.* 1996), represent extremes in the *V–J* color range. Even if 2060 Chiron is removed from consideration based on its activity, the remaining Centaurs do not show a linear relationship of *V–J* with H_V. However, the infrared data presented here confirm the wide range of colors of the Centaur objects and support the view of Luu and Jewitt

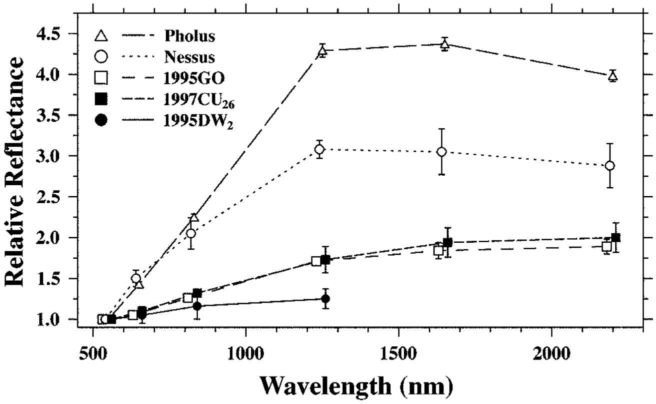

FIG. 5. Mean relative reflectance (normalized to 1 at *V*) of the five other Centaurs studied during this program. Chiron has been removed for clarity but all the data shown in Fig. 4 falls below the 1995 GO curve. The symbols have been deliberately offset left–right slightly for clarity. We assume solar colors of *V–R* = 0.36, *V–I* = 0.71 (Meech *et al.* 1995), *V–J* = 1.07, *V–H* = 1.36, and *V–K* = 1.42 (Degewij *et al.* 1980).

that they are indistinguishable on this basis from objects in the Kuiper Belt.

When presenting their data on 1995 GO, Weintraub *et al.* (1997) suggested that there might be a trend of decreased reddening with reducing semi-major axis. They attributed this to a likely relationship between semi-major axis and the time since an object escaped from the Kuiper Belt and began to move into the rest of the Solar System. An obvious physical explanation of this might be that objects covered by a red irradiation crust have this crust removed or covered over by cometary activity, which becomes more likely as the objects evolve into orbits with smaller perihelion distances. The activity of 2060 Chiron near aphelion and the CO driven activity of Comet Hale–Bopp at 7 AU (Jewitt *et al.* 1996, Biver *et al.* 1996) support this possibility. Since the individual orbits of the Centaurs are chaotic this is essentially a statistical argument, the resolution of which may require observations of a larger sample than is presently available. However, our confirmation that 1995 DW_2 is neutral in color, despite having the largest semi-major axis of all the well observed Centaurs, and the failure of Tegler and Romanishin (1998) to find any correlation of *BVR* color with a number of parameters including semi-major axis, inclination, or absolute magnitude, does not support this proposed relationship between reddening and semi-major axis.

6. CONCLUSIONS

The extreme visible–IR colors, absolute magnitude, lightcurve period and amplitude of Pholus reported in 1992 are confirmed.

The visible–IR colors of 7066 Nessus are not as extreme as 5145 Pholus but are redder than all the other Centaurs. Inconsistencies in the *V–J* colors deduced using an assumed value of H_V suggest that this object may have a lightcurve amplitude of a few tenths of a magnitude.

We have examined the apparent inconsistency in the reported *V–R* colors of 1995 GO and favor a lower value of $V{-}R \sim 0.45$. We derive an improved rotation period of 8.9351 ± 0.0003 with a peak to peak lightcurve amplitude of ~0.55 mag.

1995 GO and 1997CU_{26} are similar in color to each other, to D type asteroids, and to the cometary nucleus candidate 1996PW (Davies *et al.* 1998).

The colors of 1995 DW_2 are similar to the spectrally neutral object 2060 Chiron when it was quiescent.

The *V–JHK* colors of Chiron, measured in 1996 March when there was no apparent activity, appear to be significantly redder than in 1988 when there was a coma present. However, further simultaneous visible–IR colors are required to resolve the ambiguities in most of the current data.

The Centaurs have a wide range of *V–J* colors consistent with them being escapees from the Kuiper Belt but their *VRI* colors are less scattered and may indicate a bimodal distribution.

There is no convincing trend of increasing redness with semi-major axis among the Centaurs studied so far.

ACKNOWLEDGMENTS

The Isaac Newton telescope is operated by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias and UKIRT is operated by the Joint Astronomy Centre, on behalf of the UK Particle Physics and Astronomy Research Council (PPARC). Image processing and data reduction were performed using the STARLINK network and software. STARLINK is funded by PPARC. N. McBride acknowledges the financial support of PPARC. We thank David J. Tholen and Iwan P. Williams for constructive and positive comments on the original manuscript.

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