VRI PHOTOMETRY OF KUIPER BELT OBJECTS AND CENTAURS. A. G. Ekholm[1], M. Dahlgren, C.-I. Lagerkvist, J. Lagerros, M. Lundström, P. Magnusson, and J. Warell, all at Astronomiska observatoriet, Box 515, 751 20 Uppsala, Sweden, [1]now at Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, aekholm@lpl.arizona.edu.

INTRODUCTION: In 1992, David Jewitt and Jane Luu discovered 1992 QB_1, the first member of the growing group of trans-Neptunian objects commonly known as the Kuiper belt. At the time of writing, there are 89 known Kuiper-belt objects (KBOs) — see http://cfa-www.harvard.edu/iau/lists/TNOs.html for an updated list. The Centaurs are a dynamically separate group of objects with semimajor axes between those of Jupiter and Neptune. They are believed to originate in the Kuiper belt, and are thought to represent future short-period comets. There are presently 9 known Centaurs.

A few of the brightest KBOs have had their spectra taken (e.g. 1993 SC [1,2] and 1996 TL_{66} [3]), but only for 22 have broadband colors been published. Here we present V, R, and I-band observations of seven KBOs (for three of which there are no previously published colors) and three Centaurs. The observations were obtained August 15–17 1996 and January 5–10 1997 with the 2.6-meter Nordic Optical Telescope on La Palma.

METHODS: A novel technique called growth-curve fitting was applied in reducing the observations. Because of the extreme faintness of KBOs, the random background fluctuations significantly affect the integrated flux. Therefore, simply measuring the flux within a specific aperture seemed very crude; within the suitable radius range, the measured flux easily varied with 10% (~0.1 magnitudes), sometimes even 20% (~0.2 magnitudes), as the aperture radius was changed one pixel. So we decided to use a technique introduced by Howell [4]: growth curve flux correction. The idea is to define a standard growth curve for each frame by measuring the flux of one or a few bright stars on the frame within a series of increasingly larger apertures centered on the star. If the sky-subtraction is done right, the curve should rise steeply at first and then level off to reach a total flux. The flux of the faint source of interest can then be measured using an optimum aperture radius for which the S/N is as high as possible, without concern for whether or not all light is included. The standard growth curve is then used to "correct" this value to what it would be for a larger aperture that includes all the light from the source.

The corrections were carried out by doing a weighted least-squares fit of the standard curve to the object curve (using a flux scale factor and offset). What range of aperture radii to use in the fit was determined individually for each frame through trial and error to see which interval gave the best overall match; most intervals lay between aperture radii of 2–10 pixels (0.4–2''). Unfortunately, the growth curve approach did not improve the accuracy as much as we had hoped; the choice of points used in the fit significantly affected the corrected flux, often 0.1 magnitudes for reasonable selections.

The errors were estimated empirically from the data — all KBO observations were combined to yield an average error, while the Centaur observations were treated separately.

RESULTS: A summary of the measurements is given in Table 1. The V–R and R–I colors are plotted in Figure 1. No distinction between the Centaurs and the KBOs can be seen, and there is no apparent color color relation. The failure to find the two groups repor-

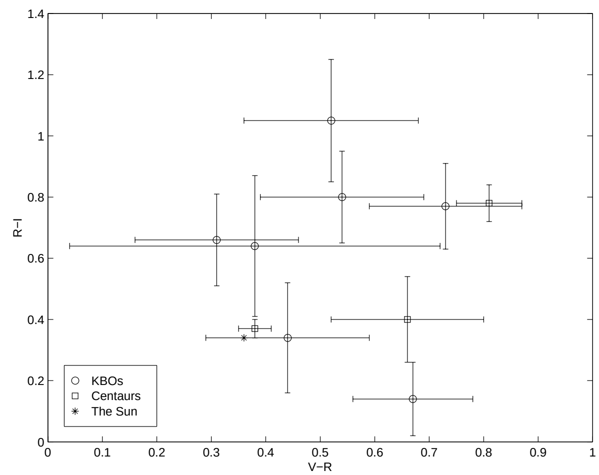

Figure 1. R–I color plotted against V–R color for KBOs (circles) and Centaurs (squares). The Sun is included for reference.

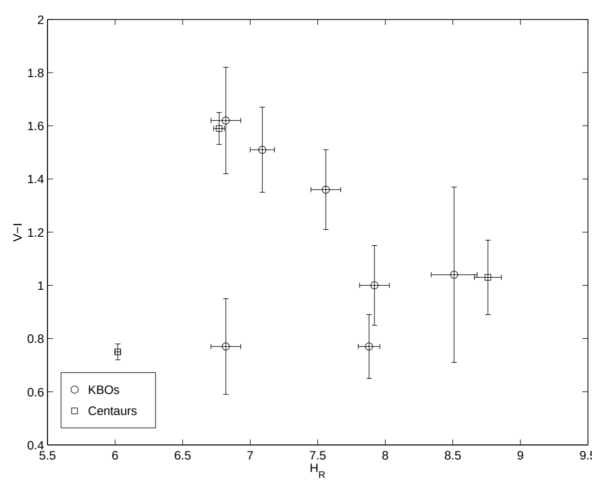

Figure 2. V–I color plotted against absolute R magnitude H_R.

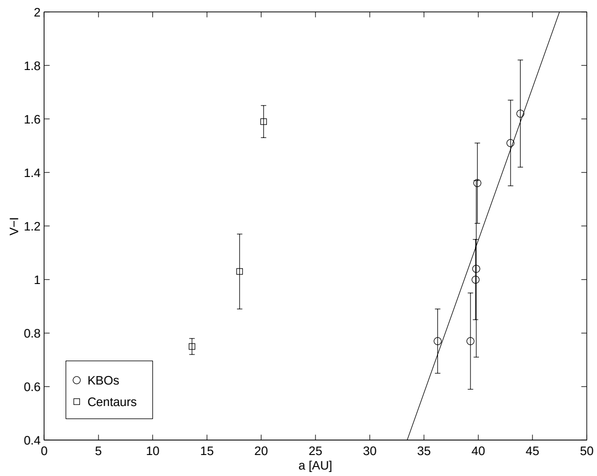

Figure 3. V–I color plotted against semimajor axis.

ted by Tegler and Romanishin [5] is not surprising (and shared with all other studies), as the number of objects in this study is fewer and the uncertainties much larger.

In Figure 2, V–I is plotted against the absolute R magnitude H_R (all absolute magnitudes were calculated using the standard value of G for low-albedo bodies, 0.05). Jewitt and Luu [6] report finding a V–J color-absolute magnitude relation (with slope ~0.6) significant at the 3σ (99.7%) confidence level, indicating that the surface composition is related to the diameter of the object, possibly due to preferential retention of surface frosts by large objects. Our data show a tendency in the opposite direction — disregarding the brightest KBO, there is a correlation significant at the 95% confidence level among the KBOs. However, there is no valid reason to exclude that data point, and it must therefore be concluded that our data show no significant correlation.

Finally, Figure 3 shows V–R plotted against the semimajor axis. There is an obvious trend, with the KBOs becoming redder the farther from the Sun they orbit; the solid line shows a weighted least-squares fit to the KBO data. The observed correlation is significant at the 99% confidence level. No relationship of this kind has been reported elsewhere, and it is up to future, larger and more accurate, studies to verify or disprove this result.

SUMMARY: Our data confirms the presence of a wide range of colors among Kuiper-belt objects. We find no color-color or color-absolute magnitude correlations, but our data do show redder KBO colors with increasing semimajor axis, at a confidence level of 99%.

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Table 1. Photometry summary.

Object	V–R	R–I	V–I	H_R	a [AU]
KBOs					
1993 SB	0.31±0.15	0.66±0.15	1.00±0.15	7.92±0.11	39.746
1994 JR_1	0.44±0.15	0.34±0.18	0.77±0.18	6.82±0.11	39.285
1994 TB	0.54±0.15	0.80±0.15	1.36±0.15	7.56±0.11	39.919
1994 VK_8	0.73±0.14	0.77±0.14	1.51±0.16	7.09±0.09	42.979
1995 DA_2	0.67±0.11	0.14±0.12	0.77±0.12	7.88±0.08	36.257
1995 DC_2	0.52±0.16	1.05±0.20	1.62±0.20	6.82±0.11	43.879
1995 QZ_9	0.38±0.34	0.64±0.23	1.04±0.33	8.51±0.17	39.818
Centaurs					
2060 Chiron	0.38±0.03	0.37±0.03	0.75±0.03	6.02±0.02	13.620
5145 Pholus	0.81±0.06	0.78±0.06	1.59±0.06	6.77±0.04	20.217
8405	0.66±0.14	0.40±0.14	1.03±0.14	8.76±0.10	18.012