The Astrophysical Journal, 599:L49–L52, 2003 December 10

COLOR PATTERNS IN THE KUIPER BELT: A POSSIBLE PRIMORDIAL ORIGIN

S. C. Tegler[1]
Department of Physics and Astronomy, Northern Arizona University, Box 6010, Flagstaff, AZ 86011; stephen.tegler@nau.edu
W. Romanishin[1]
Department of Physics and Astronomy, University of Oklahoma, Room 131 Nielsen Hall, Norman, OK 73019; wjr@nhn.ou.edu
and
G. J. Consolmagno, S.J.
Vatican Observatory, Specola Vaticana, V-00120, Vatican City State; gjc@specola.va
Received 2003 July 8; accepted 2003 October 30; published 2003 November 19

ABSTRACT

As a result of our continuing photometric survey, we report here optical colors for 36 Kuiper Belt objects, increasing our sample size to 91 objects. We find that certain dynamical classes of objects exhibit distinctive colors—21 out of 21 objects on small-inclination and small-eccentricity orbits with perihelion distances larger than 40 AU exhibit red surface colors ($B-R>1.5$), while 17 out of 20 objects on large-inclination and large-eccentricity orbits with aphelion distances larger than 70 AU exhibit gray surface colors ($B-R<1.5$). Our observations are consistent with a primordial origin for Kuiper Belt surface colors, if we assume that gray objects formed closer to the Sun than red objects, and as Neptune migrated outward it scattered gray objects onto dynamically hot orbits. By this model, the contrasting dynamically cold and red objects beyond 40 AU remained far enough away from Neptune that they were never perturbed by the planet.

Subject headings: Kuiper Belt — solar system: formation — techniques: photometric

1. INTRODUCTION

It is possible to divide the majority of the ~800 known Kuiper Belt objects (KBOs) into three broad dynamical classes: (1) classical objects with semimajor axes, *a*, greater than 42 AU, perihelia, *q*, greater than 35 AU, and eccentricities, *e*, and inclination angles, *i*, with small to moderate values; (2) resonant objects with moderate to large values of *e* and *i* as well as orbital periods about the Sun that are integer ratios of Neptune's orbital period (e.g., objects in the 2 : 3 resonance at $a\sim 39.4$ AU are known as Plutinos, like the prototype, Pluto); and (3) scattered disk objects (SDOs) with 50 AU $<a<$ 200 AU, large values for *e* and *i*, and aphelion distances, *Q*, that reach out to many hundreds of AU. In addition to these three dynamical classes, there is a related class of outer solar system objects known as Centaurs. These objects are under the gravitational control of the gas giants and have perihelion distances between the orbits of Jupiter and Neptune. They are likely escapees from some part of the Kuiper Belt.

KBOs provide us with an opportunity to study an interrupted case of planet formation in the outer solar system; therefore, a survey of their physical properties is likely to result in a better understanding of the formation and evolution of the outer solar system. Because of their faintness, broadband optical photometry is the only technique capable of surveying physical properties of the entire population of known objects. Since KBOs are thought to have formed at about the same time and at about the same place in the outer solar system, an early expectation was that essentially all KBOs should exhibit the same surface color. After a decade of observational study, it is surprising to find KBOs actually exhibit a wide range of colors rather than a single color.

Research groups using 2–10 m class telescopes all agree that KBOs and Centaurs exhibit, at the very least, a wide range of colors from gray to very red, i.e., $1.0<B-R<2.0$. For reference, the Sun has $B-R=1.03$. Every group, except our group, finds the entire KBO population and the individual dynamical classes exhibit a relatively uniform distribution of colors, i.e., a continuum of colors (Luu & Jewitt 1996; Jewitt & Luu 1998, 2001; Barucci et al. 1999, 2000; Boehnhardt et al. 2001; Delsanti et al. 2001; Doressoundiram et al. 2001, 2002; Hainaut & Delsanti 2002; Trujillo & Brown 2002). An explanation put forth to explain the continuum of colors is that solar ultraviolet photons and solar wind particles steadily redden KBO surfaces while occasional impacts by kilometer-sized KBOs puncture the red crusts and expose interior gray icy material in the form of craters and ejecta blankets (Luu & Jewitt 1996; Stern 2002). Such an evolutionary scenario predicts individual objects should exhibit large color variations as they rotate—an impact would excavate interior gray material on one hemisphere and leave the other hemisphere red. A major problem with the evolutionary scenario is that individual KBOs appear to exhibit uniform surface colors (Jewitt & Luu 2001; Tegler & Romanishin 2003).

We argue elsewhere (Tegler & Romanishin 1998, 2000, 2003) that within the range of KBO colors from gray to red, there is a significant paucity of objects with intermediate colors, contrary to the prediction of the surface evolution model described above. Furthermore, we find that with a proper sorting of orbital elements certain dynamical classes exhibit distinctive colors. We find that classical KBOs on small-*e* and small-*i* orbits with $q>40$ AU exhibit red surface colors (Tegler & Romanishin 2000, 2003). Here we report distinctive colors of additional dynamical classes. We use these patterns to suggest KBO colors are the result of their primordial composition.

2. OBSERVATIONS

A description of the telescopes and CCD cameras as well as our observational and data analysis techniques are in the literature (Tegler & Romanishin 1997, 1998, 2000, 2003; Romanishin et al. 2001). In Table 1, we present our new magnitude and color measurements. In Figure 1*a*, we present a histogram

[1] Visiting Astronomer, W. M. Keck Observatory, Steward Observatory, and the Vatican Observatory.

TABLE 1
KECK, STEWARD, AND VATICAN COLORS OF KBOs AND CENTAURS

Object	Number/Name	Class	V	$\sigma/\sqrt{n}$	$B-V$	$\sigma/\sqrt{n}$	$V-R$	$\sigma/\sqrt{n}$	$B-R$	$\sigma/\sqrt{n}$	UT
52975[a]	Cyllarus	Centaur	22.13	0.05	0.97	0.10	0.75	0.06	1.72	0.12	2002 Oct 30
1999 CF119		$Q > 70$	23.53	0.04	0.85	0.03	0.61	0.02	1.46	0.04	2002 Apr 10, 11
1999 DE9[a]	26375	$Q > 70$	20.73	0.01	1.03	0.02	0.58	0.03	1.60	0.03	2003 Jan 01
1999 HB12	38084	$Q > 70$	22.44	0.01	0.82	0.02	0.57	0.02	1.39	0.03	2002 Apr 10, 11
1999 TC36[a]	47171	Plutino	20.31	0.02	1.05	0.02	0.69	0.01	1.74	0.02	2001 Sep 18
2000 CF105(A)		Classical	…	…	…	…	…	…	1.70	0.07	2002 Apr 11
		Classical	…	…	…	…	…	…	1.79	0.09	2003 Mar 03
2000 CF105(B)		Classical	…	…	…	…	…	…	1.85	0.15	2002 Apr 11
		Classical	…	…	…	…	…	…	1.67	0.15	2003 Mar 03
2000 CM114	60458	$Q > 70$	23.77	0.02	0.73	0.02	0.50	0.02	1.24	0.04	2003 Mar 03
2000 CQ105		$Q > 70$	23.43	0.01	0.67	0.01	0.44	0.01	1.10	0.01	2002 Apr 11
2000 CR105		$Q > 70$	24.03	0.02	0.76	0.05	0.52	0.02	1.28	0.05	2002 Apr 10
2000 EE173	60608	$Q > 70$	22.09	0.01	0.66	0.01	0.49	0.01	1.16	0.01	2003 Mar 02
2000 FE8	60621	$Q > 70$	22.48	0.01	0.75	0.01	0.48	0.01	1.23	0.01	2003 Mar 02
2000 FZ53		Centaur	24.17	0.03	0.61	0.03	0.56	0.04	1.17	0.05	2002 Apr 10
2000 OO67[a]		$Q > 70$	23.17	0.12	1.08	0.20	0.72	0.13	1.80	0.24	2001 Sep 19
2000 QC243[a]	54598	Centaur	20.59	0.01	0.65	0.08	0.50	0.01	1.15	0.08	2001 Sep 18
2000 YW134[b]		$Q > 70$	21.26	0.03	0.92	0.02	0.55	0.03	1.46	0.04	2002 Oct 09, 10
2001 BL41[a]	63252	Centaur	21.25	0.01	0.70	0.01	0.51	0.03	1.21	0.03	2002 Dec 31
2001 FM194		$Q > 70$	23.61	0.01	0.76	0.03	0.44	0.03	1.19	0.04	2003 Mar 03
2001 FP185		$Q > 70$	21.79	0.01	0.78	0.02	0.58	0.01	1.37	0.02	2003 Mar 03
2001 FZ173		$Q > 70$	21.48	0.01	0.86	0.01	0.55	0.01	1.41	0.01	2003 Mar 02
2001 KF77		Centaur	24.13	0.01	1.08	0.04	0.73	0.01	1.81	0.04	2003 Mar 03
2001 KC77		$Q > 70$	22.83	0.02	0.91	0.01	0.56	0.01	1.47	0.01	2002 Apr 11
2001 KG77		$Q > 70$	24.15	0.06	0.81	0.04	0.44	0.06	1.24	0.07	2002 Apr 11
32532[a]	Thereus	Centaur	18.90	0.01	0.71	0.01	0.47	0.01	1.18	0.01	2001 Sep 18
2001 QX322[b]		$Q > 70$	22.69	0.07	0.93	0.11	0.60	0.09	1.54	0.14	2002 Oct 09
2001 SQ73[b]		Centaur	21.17	0.02	0.67	0.02	0.46	0.01	1.13	0.02	2002 Oct 11
2001 XZ255		Centaur	23.53	0.01	1.17	0.02	0.75	0.07	1.91	0.07	2003 Mar 03
2002 CR46[a]	42355	Centaur	20.29	0.01	0.74	0.02	0.52	0.01	1.26	0.02	2002 Dec 31
2002 GO9		Centaur	20.89	0.01	1.10	0.02	0.76	0.01	1.86	0.02	2003 Mar 02
2002 GZ32[a]		Centaur	20.73	0.02	0.61	0.01	0.42	0.04	1.03	0.04	2002 Dec 31
2002 LM60[b]	Quaoar	Classical	19.19	0.01	0.94	0.01	0.64	0.01	1.58	0.01	2003 May 05
2002 PN34		Centaur	20.25	0.01	0.76	0.01	0.52	0.02	1.28	0.02	2002 Oct 10
2002 TX300[a]	55636	Classical	19.66	0.01	0.66	0.01	0.36	0.01	1.03	0.02	2002 Oct 30
2002 VQ94[a]		$Q > 70$	19.66	0.02	0.92	0.04	0.47	0.02	1.39	0.05	2002 Dec 31
2003 CO1[b]		Centaur	20.34	0.02	0.74	0.03	0.49	0.02	1.24	0.04	2003 May 05
2003 FX128[b]	65489	$Q > 70$	20.70	0.03	0.86	0.03	0.56	0.03	1.42	0.04	2003 May 05

NOTE.—σ is the standard deviation of n measurements.
[a] Steward Observatory 2.3 m telescope.
[b] Vatican Observatory 1.8 m telescope.

of the 22 Centaurs in our survey. Measurements for 13 of the Centaurs are reported in Table 1 for the first time. We see that 14 objects fall into gray bins, $B-R < 1.5$, and eight objects fall into red bins, $B-R > 1.5$. The color gap between the two populations is much larger than the uncertainties of the individual points. The Centaurs appear to have a strong bimodal color distribution, not a continuum of colors.

In Figure 1*b*, we present a histogram of the 21 classical objects in our survey with small-*i* and small-*e* orbits and $q > 40$ AU. Measurements for three objects, Quaoar and the primary and secondary of the binary 2000 CF105 (Romanishin, Tegler, & Noll 2003), are reported here for the first time. The other 18 measurements come from our previous work (Tegler & Romanishin 2000, 2003). If we assume an albedo of 0.04, the diameters of the 21 objects range from 84 to 950 km, yet their surfaces exhibit only red colors, $B-R > 1.5$.

We present a histogram of the 20 objects in our survey on large-*i* and large-*e* orbits and $Q > 70$ AU in Figure 1*c*. Individual surveys in the literature each only have colors for two or three objects with $Q > 70$ AU (Barucci et al. 1999, 2000; Boehnhardt et al. 2001; Delsanti et al. 2001; Doressoundiram et al. 2001, 2002; Jewitt & Luu 2001; Trujillo & Brown 2002). We find excellent agreement between our $B-R$ colors and those in the literature (~0.05 mag difference) for the $Q > 70$ AU objects 15874, 1999 CF119, 26375, 38084, 29981, 2000 CQ105, and 2000 FE8. In our survey and as we show in Figure 1*c*, 17 of 20 objects with $Q > 70$ AU exhibit gray surface colors, $B-R < 1.5$. It appears the two very different dynamical populations in Figures 1*b* and 1*c* correlate with two different color populations.

2.1. *Statistical Significance*

Is it possible that KBOs and Centaurs actually exhibit a continuum of colors and that either insufficient sampling or chance are responsible for the noncontinuum distributions we think we see in Figure 1? Application of the binomial probability distribution (Taylor 1982) to the Centaurs in Figure 1*a* (three equal-width bins extending over the range $1.0 < B-R < 2.0$) indicates the probability of our observations occurring for an actual continuum of colors is 1/7500. Because the result of the binomial test is sensitive to the choice of bins, we apply the dip test (Hartigan 1985) to the Centaurs as well. The dip test tries to explain the data distribution with the best-fitting unimodal (continuum) distribution and requires no bin choices. We calculate a dip statistic of 0.156 for the 22 Centaurs, and hence the probability of our observations occurring for an actual continuum distribution is less than 1/1000. Both the binomial and dip tests

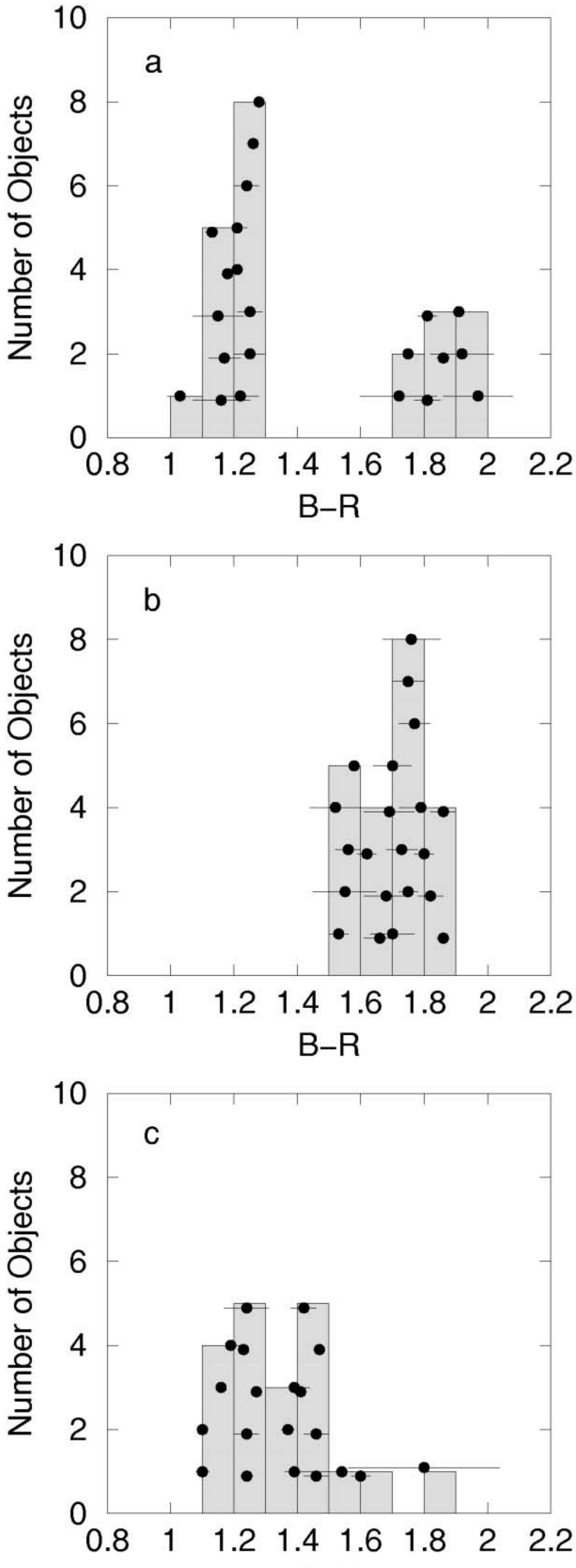

FIG. 1.—$B-R$ histograms. (*a*) Centaurs have bimodal colors. (*b*) Dynamically cold objects with small-i, small-e, and $q > 40$ AU are red, $B-R > 1.5$. (*c*) Dynamically hot objects with large-i, large-e, and $Q > 70$ AU are gray, $B-R < 1.5$.

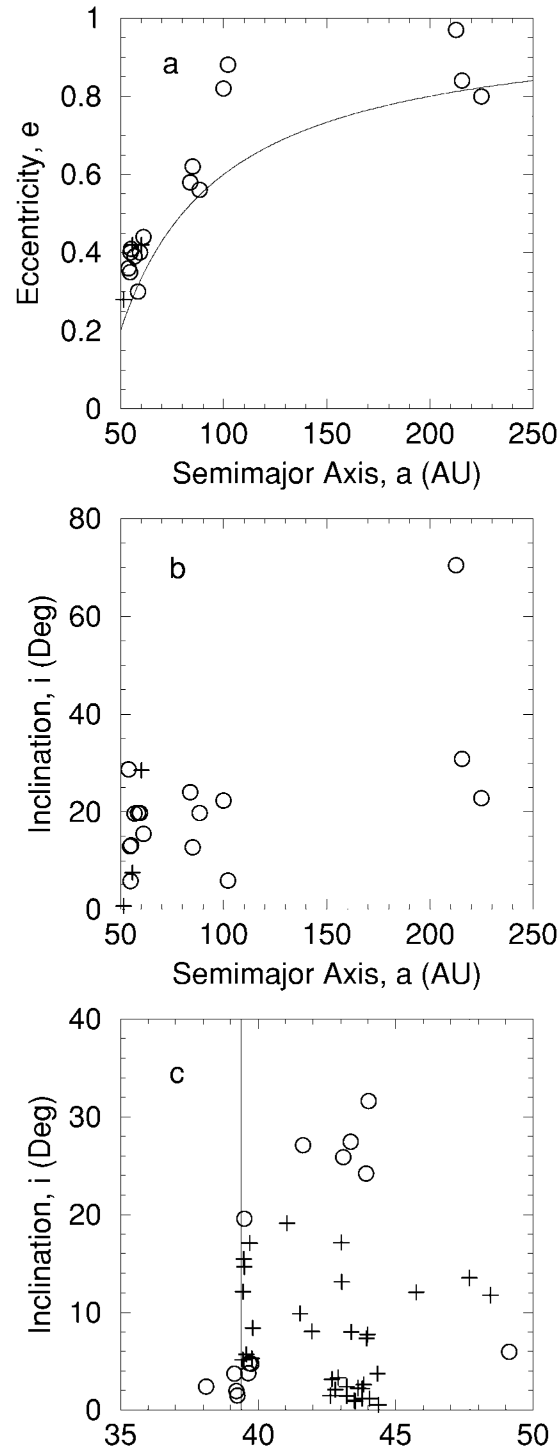

FIG. 2.—Dynamical properties and colors. (*a*) Eccentricity vs. semimajor axis for objects in our survey with $a > 50$ AU. Objects above the curve have $q < 40$ AU. (*b*) Inclination vs. semimajor axis for objects in our survey with $a > 50$ AU. Circles represent objects with gray surfaces ($B-R < 1.5$) and plus signs represent objects with red surfaces ($B-R > 1.5$). Objects with $a > 50$ AU are dominated by gray surfaces. (*c*) Inclination vs. semimajor axis for classical KBOs ($a \sim 43$ AU) and Plutinos ($a \sim 39.4$ AU). The vertical lines at 39.4 and 47.6 AU represent the 2 : 3 and 1 : 2 resonances. The classical KBOs with the five largest inclination angles are gray.

indicate our Centaur observations are inconsistent with a continuum of colors. Centaurs appear to exhibit two distinct color populations.

Application of the binomial test (two equal-width bins) to the dynamically cold population in Figure 1*b* and the dynamically hot population in Figure 1*c* indicates the probability of our observations occurring for an actual continuum of colors is 1/2,000,000 and 1/775. Application of Student's *T*-test to the objects in Figures 1*b* and 1*c* indicates there is less than one chance in 10,000 that the two color groups in Figures 1*b* and 1*c* actually come from a single population with a continuum of colors.

3. INTERPRETATION

A dynamical simulation (Gomes 2003) and some thoughts on methane chemistry in the outer solar system may provide a new way of interpreting the color patterns in Figure 1. The simulation predicts that as Neptune migrated outward it scattered objects originally 25 AU from the Sun onto the orbits of the present-day SDOs, high-*i* classical KBOs, and high-*i* Plutinos. In contrast, classical KBOs on low-*e* and low-*i* orbits remained far enough away from Neptune that they were never perturbed by the planet. Perhaps somewhere inside 40 AU, methane went from condensing in a water-ice–rich clathrate to condensing as pure methane (Lewis 1972). Whereas the loss of methane from a clathrate surface would result in a lag made up of colorless water-ice crust, a pure methane ice crust would provide much material for alteration into red organic compounds, even if there were a substantial amount of methane sublimation. If the dynamical simulation and our idea on methane surface chemistry are correct, we would expect SDOs, high-*i* classical KBOs, and high-*i* Plutinos to exhibit gray surface colors and low-*i* classical KBOs to exhibit red surface colors.

Do we observe such correlations between dynamical classes and surface colors? Figures 1*b* and 1*c* are consistent with such an interpretation; the dynamically cold objects are red, and the dynamically hot objects ($a > 50$ AU and $Q > 70$ AU) are gray. In Figures2*a* and 2*b*, we present another view of the dynamically hot objects in our survey—*e* versus *a* and *i* versus *a* plots for objects with $a > 50$ AU. The circles represent objects with $B-R < 1.5$, and the plus signs represent objects with $B-R > 1.5$. Gray colors dominate the surfaces of objects with $a > 50$ AU and moderate to large values of *e* and *i*. In Figure 2*c*, we see classical KBOs ($a \sim 43$ AU) on low-*i* orbits exhibit red surface colors. In addition, we find the five classical KBOs with the largest inclination angles, $i > 20°$, exhibit gray surface colors. As we pointed out 3 years ago (Tegler & Romanishin 2000), we believe that the high-*i* classical KBOs are not "true" classical KBOs. Rather, we believe the five gray objects are members of a different dynamical group, one we now suspect formed closer to the Sun and was scattered outward during Neptune's outward migration. Also, we see that the Plutino ($a \sim 39.4$ AU) with the largest value for *i* (~19°) in Figure 2*c* is gray. We count about a dozen known Plutinos with $19° < i < 28°$, and neither we nor the literature have optical colors for any of them. A valuable test of our hypothesis would be to secure colors for the 12 objects and see if they are dominated by gray colors.

Why do the Centaurs mostly exhibit gray objects but have a significant number of red objects? Perhaps the answer is related to the orbital stability of the SDOs ($a > 50$ AU) and Centaurs. If the gray objects formed closer to the Sun, then Neptune presumably scattered many more gray objects than red objects over the lifetime of the solar system, and hence the SDOs ($a > 50$ AU) are mostly gray. The Centaurs, on the other hand, have short orbital lifetimes, and their color distribution is dominated by recent KBO scattering by Neptune. Perhaps Neptune is far enough from the Sun now that it scatters some red KBOs but mostly gray objects.

So far, the color patterns we observe are consistent with a primordial origin for KBO colors. In addition, we suggest observing additional large-*i* classical KBOs and large-*i* Plutinos to test the primordial hypothesis. Clearly, additional telescope observations, dynamical simulations, and laboratory work is necessary to sort out a primordial or evolutionary origin for KBO colors.

We thank the NASA Planetary Astronomy Program for support of this research (NAG5-12694) and the NASA Keck Observatory, Steward Observatory, and Vatican Observatory Time Allocation Committees for consistent allocation of telescope time.

REFERENCES

Barucci, M. A., Doressoundiram, A., Tholen, D., Fulchignoni, M., & Lazzarin, M. 1999, Icarus, 142, 476
Barucci, M. A., Romon, J., Doressoundiram, A., & Tholen, D. J. 2000, AJ, 120, 496
Boehnhardt, H., et al. 2001, A&A, 378, 653
Delsanti, A. C., et al. 2001, A&A, 380, 347
Doressoundiram, A., Barucci, M. A., Romon, J., & Veillet, C. 2001, Icarus, 154, 277
Doressoundiram, A., et al. 2002, AJ, 124, 2279
Gomes, R. S. 2003, Icarus, 161, 404
Hainaut, O. R., & Delsanti, A. C. 2002, A&A, 389, 641
Hartigan, P. M. 1985, J. Appl. Statistics, 34, 320
Jewitt, D., & Luu, J. 1998, AJ, 115, 1667
———. 2001, AJ, 122, 2099
Lewis, J. S. 1972, Icarus, 16, 241
Luu, J., & Jewitt, D. 1996, AJ, 112, 2310
Romanishin, W., Tegler, S. C., & Noll, K. 2003, AJ, submitted
Romanishin, W., Tegler, S. C., Rettig, T. W., Consolmagno, G., & Botthof, B. 2001, Proc. Natl. Acad. Sci., 98, 11863
Stern, S. A. 2002, AJ, 124, 2297
Taylor, J. R. 1982, An Introduction to Error Analysis (Mill Valley: University Science Books)
Tegler, S. C., & Romanishin, W. 1997, Icarus, 126, 212
———. 1998, Nature, 392, 49
———. 2000, Nature, 407, 979
———. 2003, Icarus, 161, 181
Trujillo, C. A., & Brown, M. E. 2002, ApJ, 566, L125