THE COLORS OF EXTREME OUTER SOLAR SYSTEM OBJECTS

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ABSTRACT

Extreme outer solar system objects have possible origins beyond the Kuiper Belt edge, high inclinations, very large semimajor axes, or large perihelion distances. Thirty-three such objects were observed in this work to determine their optical colors. All three objects that have been dynamically linked to the inner Oort Cloud by several authors ((90377) Sedna, 2006 SQ_{372}, and (87269) 2000 OQ_{67}) were found to have ultra-red surface material (spectral gradient, $S \sim 25$). Ultra-red material is generally associated with rich organics and the low inclination “cold” classical Kuiper Belt objects (KBOs). The observations detailed here show that very red material may be a more general feature for objects kept far from the Sun. The recently discovered retrograde outer solar system objects (2008 KV_{42} and 2008 YB_{3}) and the high inclination object (127546) 2002 UX_{93} show only moderately red surfaces ($S \sim 9$) very similar to known comets, suspected dead comets, Jupiter and Neptune Trojans, irregular satellites, D-type asteroids, and damocloids. The extended or detached disk objects, which have large perihelion distances and are thus considered to be detached from the influence of the giant planets but yet have large eccentricities, are found to have mostly moderately red colors ($10 \leq S \leq 18$). The colors of the detached disk objects, including the dynamically unusual 2004 XR_{109} and (148209) 2000 CR_{105}, are similar to the scattered disk and Plutino populations. Thus the detached disk, scattered disk, Plutino, and high inclination “hot” classical objects likely have a similar mix of objects from the same source regions. Outer classical KBOs, including (48639) 1995 TL_{6}, were found to have very red surfaces ($18 \leq S \leq 30$). The low inclination “cold” classical KBOs, outer classical KBOs and possibly the inner Oort Cloud objects are likely to have different mix of objects as the other outer solar system reservoirs such as the scattered disk, detached disk, and Trojan populations. A possible trend was found for the detached disk and outer classical Kuiper Belt in objects with smaller eccentricities having redder surfaces irrespective of inclinations or perihelion distances. There is also a clear trend that objects more distant appear redder.

Key words: comets; general – Kuiper Belt; general – minor planets, asteroids; general – Oort Cloud – planets and satellites: formation

Online-only material: color figures

1. INTRODUCTION

The dynamical and physical properties of small bodies in our solar system offer one of the few constraints on the formation, evolution, and migration of the planets. The Kuiper Belt has been found to be dynamically structured with several observed dynamical classes (Trujillo et al. 2001; Kavelaars et al. 2008, 2009); see Figure 1. Classical Kuiper Belt objects (KBOs) have semimajor axes $42 \lesssim a \lesssim 48$ AU with moderate eccentricities ($e \sim 0.1$) and inclinations. These objects may be regarded as the population originally predicted for the Kuiper Belt, but their relatively large eccentricities and inclinations were unexpected. The dynamics of the classical KBOs have shown that the outer solar system has been highly modified through the evolution of the solar system (Duncan & Levison 1997; Petit et al. 1999; Ida et al. 2000; Morbidelli & Levison 2004; Gomes et al. 2005). Resonant KBOs are in mean motion resonances with Neptune and generally have higher eccentricities and inclinations than classical KBOs. These objects, which include Pluto and the Plutinos in the 3:2 resonance, were likely captured into these resonances from the outward migration of Neptune (Malhotra 1995; Hahn & Malhotra 2005; Levison et al. 2008). Scattered disk objects have large eccentricities with perihelia near the orbit of Neptune ($q \sim 25$–35 AU). The scattered disk objects are likely to have been scattered into their current orbits through interactions with Neptune (Duncan & Levison 1997; Duncan 2008a; Gomes et al. 2008).

A new class of outer solar system object, called the extended or detached disk (Figure 1), has only recently been recognized (Gladman et al. 2002; Emel’yanenko et al. 2003; Morbidelli & Levison 2004; Allen et al. 2006). To date only a few detached disk objects are known. The detached disk objects have large eccentricities, but unlike the scattered disk objects the detached disk objects have perihelia $q \gtrsim 38$ AU, which do not appear to be directly caused by Neptune interactions alone (Gladman & Collin 2006; Levison et al. 2008). Though unexpected, the discovery of these detached disk objects have given us a new understanding of our solar system’s chaotic history.

A few objects have been found that have very large semimajor axes and eccentricities (Sedna, 2006 SQ_{372}, and 2000 OQ_{67}). Through dynamical simulations these objects are best described as coming from the inner Oort Cloud (Brown et al. 2004; Kenyon & Bromley 2004; Morbidelli & Levison 2004; Kaib et al. 2009). Two objects have also been found to have retrograde orbits in the outer solar system (2008 KV_{42} and 2008 YB_{3}). These two retrograde objects along with the very high inclination object 2002 UX_{93} ($i \sim 78^\circ$) could be from the outer Oort Cloud or a possibly yet to be discovered high inclination source region (Gladman et al. 2009).

Some trans-Neptunian objects (TNOs) have likely not experienced significant thermal evolution since their formation. The amount of thermal evolution depends on how close the object formed to the Sun and how close it has approached the Sun during its lifetime (Meech et al. 2009). The objects in the Kuiper
Belt dynamical classes had varied histories with some experiencing very little thermal evolution, making them some of the most primitive bodies in the solar system. Optical observations of TNOs and Centaurs have shown some of these objects have the reddest material known in the solar system (Figure 2; Jewitt et al. 2001; Peixinho et al. 2004; Doressoundiram et al. 2008; Tegler et al. 2008). This ultra-red material is currently thought to be rich in organic material (Gradie & Veverka 1980; Vilas & Smith 1985; Cruikshank et al. 2005; de Bergh et al. 2008). The ultra-red color may be from Triton tholins and ice tholins, which can be produced by bombarding simple organic ice mixtures with ionizing radiation (Doressoundiram et al. 2003; Barucci et al. 2005a; Emery et al. 2007; Barucci et al. 2008).

Interestingly, short-period comets that are believed to have originated from the Kuiper Belt do not show this ultra-red material (Figure 2; Jewitt 2002). The reason is because comet surfaces have been highly processed from their relatively close passages to the Sun (Jewitt 2002; Grundy 2009). This demonstrates that the surfaces of comets are not reliable for understanding the original compositions of the comets. Some Centaurs, which are the precursors to the short-period comets, do show these ultra-red colors probably because they have not yet been near the Sun for a long enough time to have their surfaces highly modified from thermal, sublimation, or evaporation processes. No long-period comets from the Oort Cloud have been sufficiently observed before any significant heating would have taken place on their surfaces. Thus we do not have a good knowledge of what color an Oort Cloud comet may have been before it started to thermally evolve (Meech et al. 2009).

There have been one or possibly two subsets of TNOs that appear to be dominated by the ultra-red material (Figure 2). First are the low inclination “cold” classical KBOs that also have large perihelions (Tegler & Romanishin 2000; Trujillo & Brown 2002; Doressoundiram et al. 2005; Gulbis et al. 2006; Fulchignoni et al. 2008; Peixinho et al. 2008). These objects likely formed in the more distant solar system unlike the higher inclination KBOs, which may have formed closer to the Sun and were transported to and captured in the Kuiper Belt during the planet migration process (Levison & Morbidelli 2003; Gomes 2003; Levison et al. 2008). Sedna, an object well beyond the Kuiper Belt edge at 50 AU (Jewitt et al. 1998; Allen et al. 2001), also has an ultra-red color and could be a new class of object, possibly from the inner Oort Cloud (Brown et al. 2004; Morbidelli & Levison 2004; Kenyon & Bromley 2004; Brassier et al. 2006; Barucci et al. 2005b). Some previous works (Tegler & Romanishin 2000; Trujillo & Brown 2002; Doressoundiram et al. 2005) have noted that objects with larger perihelion distances tend to have redder surfaces, but most of the ultra-red objects observed were in the main classical Kuiper Belt. No systematic survey of the colors of the large perihelion detached disk population has been performed to date.

In this work, the optical colors were observed for most of the known detached disk objects, possible inner Oort Cloud objects, and other outer solar system objects that exhibit extreme orbits in terms of their inclination, semimajor axis, or perihelion distance. Understanding any color trends or correlations, in particular the ultra-red material, will constrain where these extreme objects may have formed in the solar system and thus how they may have ended up on their current orbits. This in turn will allow...
us to determine how the planets may have migrated and what amount of this ultra-red organic-rich material may have been incorporated into the planets.

2. OBSERVATIONS AND ANALYSIS

Observations of the outer solar system objects presented in this work were obtained with the twin Magellan Baade and Clay 6.5 m telescopes at Las Campanas, Chile and the 8.2 m Subaru telescope atop Mauna Kea in Hawaii. Table 1 shows the various observational circumstances for the 33 objects observed. The LDSS3 camera on the Clay telescope was used on the nights of 2005 November 2 and 3, 2008 May 7 and 8, 2009 January 28, 2009 May 23 and 24, and 2009 August 25 and 26. LDSS3 is a CCD imager with one STA0500A 4064 × 4064 CCD and 15 μm pixels. The field of view is about 8.3 arcmin in diameter with a scale of 0.189 arcsec per pixel. The IMACS camera on the Baade telescope was used on the nights of 2008 October 19 and 2008 December 3. IMACS is a wide-field CCD imager that has eight 2048 × 4096 pixel CCDs with a pixel scale of 0.20 arcsec per pixel. The eight CCDs are arranged in a box pattern with four above and four below and about 12 arcsec gaps between chips. Only chip 2, which is just north and west of the camera center, was used in the IMACS color analysis. The Suprime-Cam imager on the Subaru telescope was used on the night of 2009 October 15. Suprime-Cam is a wide-field CCD imager that has ten 2048 × 4096 pixel CCDs with a pixel scale of 0.20 arcsec per pixel (Miyazaki et al. 2002). The 10 CCDs are arranged in a 5 × 2 box pattern similar to the IMACS imager. Only chip 5, which is just west of the camera center, was used in the Suprime-Cam color analysis.

Dithered twilight flat fields and biases were used to reduce each image. Images were acquired through either the Sloan $g'$, $r'$, or $i'$ filter while the telescope was auto-guiding at sidereal rates using nearby bright stars. Exposure times were between 300 s and 450 s. Southern Sloan standard stars were used to photometrically calibrate the data (Smith et al. 2005). In order to more directly compare our results with previous works, the Sloan colors were converted to the Johnson–Morgan–Cousins $BVRI$ color system using transfer equations from Smith et al. (2002). To verify the color transformation, the known ultra-red (44594) 1999 OX3 and gray (19308) 1996 TO66 TNOs were observed (Tegler & Romanishin 1998, 2000; Jewitt & Luu 2001; Barucci et al. 2005a). The $BVRI$ photometric results are shown in Table 2 (Figures 2 and 3) and the Sloan results in Table 3 (Figure 4).

Photometry was performed by optimizing the signal-to-noise ratio of the faint small outer solar system objects. Aperture correction photometry was done by using a small aperture on the TNOs ($0.57–0.95$ in radius) and both the same small aperture and a large aperture ($2.46–3.40$ in radius) on several nearby unsaturated bright field stars with similar point-spread functions (PSFs). The magnitude within the small aperture used for the TNOs was corrected by determining the correction from the small to the large aperture using the PSF of the field stars (cf. Tegler & Romanishin 2000; Jewitt & Luu 2001). For a few of the brighter objects (Sedna, 2003 FY128, 2007 JI13, 2008 YB3), both small apertures and the full large apertures were used on the TNOs to confirm both techniques obtained similar results.

3. RESULTS

The orbital parameters of the 33 outer solar system objects observed in this work are shown in Table 4. There were three main classes of objects in the observation sample: (1) objects dynamically linked to the inner Oort Cloud, (2) outer solar system retrograde and high inclination objects, and (3) extended or detached disk and outer classical belt objects. Each class is discussed in the subsections below. In addition, the well-measured gray object (19308) 1996 TO66 that is part of the Haumea KBO collisional family and ultra-red object (44594) 1999 OX3 were observed to confirm the photometry is consistent with previous works.

As seen in Figure 2, all objects observed appear to have correlated broadband optical colors. In other words, the objects appear to follow a nearly linear red slope in the optical. This has also been confirmed through spectroscopy and correlation analysis on other TNOs (Doressoundiram et al. 2008). Because of the near linearity in the optical colors, we can obtain the spectral gradient, $S$, of the objects using two unique optical broadband filters. The spectral gradient is basically a very low resolution spectrum of an object and is usually expressed in percent of reddening per 100 nm in wavelength. We follow

![Figure 3](http://example.com/figure3.png)

**Figure 3.** Same as Figure 2 except for $B-I$ and $V-R$ colors. Colors with $B-I \gtrsim 2.2$, $V-R \gtrsim 0.6$, or $R-I \gtrsim 0.6$ mag indicate ultra-red colors (based on including the reddest 90% of the low inclination classical KBOs).

(A color version of this figure is available in the online journal.)

![Figure 4](http://example.com/figure4.png)

**Figure 4.** Same as Figure 2 except for Sloan colors $g' - i'$ and $g' - r'$. Colors with $g' - i' \gtrsim 1.2$, $g' - r' \gtrsim 0.8$, or $r' - i' \gtrsim 0.4$ mag indicate ultra-red colors (based on including the reddest 90% of the low inclination classical KBOs).

(A color version of this figure is available in the online journal.)
### Table 1

| Name          | UT Date           | R (AU) | Δ (AU) | α (deg) |
|---------------|-------------------|--------|--------|---------|
| (90377) Sedna | 2008 Dec 3.267–291| 87.95  | 87.05  | 0.25    |
| (48639) 1995 TL8 | 2009 Aug 25.289–347| 43.86  | 43.52  | 1.25    |
| (19308) 1996 TO66 | 2005 Nov 2.017–028 | 46.47  | 45.64  | 0.67    |
| (181874) 1999 HW11 | 2008 May 7.234–299 | 42.99  | 42.00  | 0.26    |
| (87269) 2000 OO67 | 2008 Oct 19.043–065 | 21.30  | 20.38  | 1.01    |
| (148209) 2000 CR105 | 2009 Aug 25.201–260 | 42.30  | 41.36  | 0.50    |
| (118702) 2000 OM67 | 2008 Oct 15.596–635 | 21.02  | 20.84  | 2.68    |
| (2002 PE30) | 2008 Oct 19.043–065 | 21.30  | 20.38  | 1.01    |
| (82075) 2000 YW134 | 2008 May 7.390–404 | 38.31  | 38.33  | 1.51    |
| (2001 QW297) | 2008 May 7.963–972 | 43.86  | 43.06  | 1.29    |
| (2003 HB57) | 2008 May 7.315–365 | 39.63  | 39.69  | 1.46    |
| (2003 QK69) | 2008 May 8.339–357 | 39.63  | 39.68  | 1.46    |
| (2003 UY291) | 2008 Dec 3.154–228 | 43.29  | 43.22  | 0.19    |
| (2004 OJ14) | 2009 Aug 25.142–200 | 45.39  | 44.54  | 0.69    |
| (2004 VN112) | 2009 Aug 26.144–178 | 45.40  | 45.55  | 0.70    |
| (2004 XR190) | 2008 Oct 19.087–105 | 47.33  | 46.37  | 0.35    |
| (2005 EQ297) | 2008 Dec 3.052–083 | 47.33  | 46.56  | 0.75    |
| (2005 PU21) | 2009 Aug 25.354–383 | 41.75  | 41.53  | 1.36    |
| (2005 SD278) | 2009 Aug 26.373–390 | 41.75  | 41.51  | 1.35    |
| (145480) 2005 TB190 | 2008 May 7.405–417 | 46.47  | 46.91  | 1.11    |
| (2006 SQ372) | 2008 Dec 3.238–267 | 58.08  | 57.10  | 0.05    |
| (2007 JJ43) | 2008 May 7.070–104 | 41.71  | 41.47  | 1.35    |
| (2007 TG422) | 2008 Dec 3.292–238 | 35.71  | 34.85  | 0.79    |
| (2007 VJ305) | 2009 Aug 25.261–288 | 35.36  | 34.59  | 1.07    |
| (2008 KV42) | 2009 Aug 26.232–270 | 35.36  | 34.58  | 1.05    |
| (2008 OQ19) | 2009 Aug 25.083–142 | 36.84  | 37.86  | 0.87    |
| (2008 YB3) | 2009 Aug 26.085–101 | 38.68  | 37.87  | 0.89    |

**Notes.** Quantities are the heliocentric distance (R), geocentric distance (Δ), and phase angle (α). UT date shows the year, month, day, and time span of the observations.

Doressoundiram et al. (2008) and express the spectral gradient as \( S(λ_2 > λ_1) = (F_{2,V} - F_{1,V})/(λ_2 - λ_1) \), where \( λ_1 \) and \( λ_2 \) are the central wavelengths of the two filters used for the calculation and \( F_{1,V} \) and \( F_{2,V} \) are the fluxes of the object in the two filters normalized to the V-band filter. \( S \) is the measure of the reddening of an object’s surface determined between two
wavelength measurements (two different filters). We determined the spectral gradient of the observed objects using the $g'$ and $i'$ filters, which have well-separated central wavelengths of 481.3 and 773.2 nm, respectively. The spectral gradient results for the observed objects are shown in Table 3, and the spectral gradient determined for known small body populations in the solar system are shown in Table 5. Ultra-red color is here defined as including the reddest 90% of the measured low inclination classical KBOs (ultra-red: $\alpha \geq 25$, $B-R \geq 1.6$, $V-I \geq 1.2$, $B-I \geq 2.2$, $V-R \geq 0.6$, $R-I \geq 0.6$, and using Sloan colors $g'-r' \geq 1.2$, $g'-i' \geq 0.8$, and $r'-i' \geq 0.4$ mag).

### 3.1. Inner Oort Cloud Objects

The Oort Cloud is believed to have formed from the scattering of planetesimals from the giant planet region during early planet formation and is usually separated into two parts (Oort 1950; Stern 2003; Leto et al. 2008; Brasser 2008). The inner Oort Cloud is within a few thousands to ten thousand AU and is fairly stable to Galactic tides and passing star perturbations unlike the outer Oort Cloud at several tens of thousands of AU. While the short-period comets are all likely from the Kuiper Belt region's scattered disk population (Duncan et al. 2004; Levison et al. 2006), the long-period comets are believed to be from the Oort Cloud (Kaib & Quinn 2009). All the known long-period comets have perihelia within about 10 AU of the Sun. The surfaces of the long-period comets have already been highly altered before they are first observed because of the thermal and sublimation processes that occur as they approach the Sun (Meech et al. 2009).

Sedna was the first object suggested to be part of the inner Oort Cloud (Brown et al. 2004). Recently, Kaib et al. (2009)
have suggested through dynamical simulations that the relatively large perihelia and semimajor axes of 2006 SQ372 and (87269) 2000 OO67 also make them likely objects from the inner Oort Cloud. The three inner Oort Cloud objects Sedna, 2006 SQ372, and 2000 OO67 could be the first objects from the inner Oort Cloud region that we have observed with thermally unaltered surfaces. These inner Oort Cloud objects are likely to have formed in a different location than many of the KBOs.

The observations obtained of these three possible inner Oort Cloud objects in this work show all to be among the reddest objects observed in this sample. Their surfaces are of ultra-red material ($S \gtrsim 25$). Though all three having ultra-red material are a promising trend, more inner Oort Cloud type objects are needed to be discovered (see Schwamb et al. 2009) in order to confirm a strong significant (3σ) color correlation for inner Oort Cloud objects and ultra-red material. The spectral gradients of the possible inner Oort Cloud objects are very similar to the red lobe of the Centaur distribution, the low inclination classical KBOs, and outer classical belt KBOs (Table 5). As discussed in the introduction, ultra-red material is likely rich in organic material (Barucci et al. 2008).

3.2. Retrograde and High Inclination Objects

Until recently all known retrograde objects had perihelia within the inner solar system. In the last year, two objects have been discovered with retrograde orbits and perihelia in the giant planet region. Neither shows any current evidence of cometary activity. 2008 YB$_3$ has a perihelion around 6.5 AU and thus is likely to have undergone surface sublimation and interior recrystallization during its lifetime (Meech et al. 2009). 2008 KV$_{42}$ has a perihelion of about 21 AU and thus the amount of surface alteration of this object could be significantly less than other retrograde objects and comet-type objects. Gladman et al. (2009) simulated the orbit of 2008 KV$_{42}$ and found its perihelion distance likely has not been interior to Saturn over the age of the solar system. It is unknown where 2008 KV$_{42}$ came from but its orbit is similar to Halley’s comet, and thus it could have come from the Oort Cloud or another yet to be discovered high inclination reservoir.

The observations obtained of these two outer solar system retrograde objects and the similar high inclination object (127546) 2002 XU$_{93}$ show all to have only moderately red surfaces.
### Table 4

Orbital Information for Observed Objects

| Name          | Type   | $q$ (AU) | $a$ (AU) | $e$ | $i$ (deg) |
|---------------|--------|----------|----------|-----|-----------|
| (90377) Sedna | Oort(3), Det(1,9) | 76.3 | 501 | 0.85 | 11.9 |
| (48639) 1995 TL8 | Det(9), Obelt(1) | 40.0 | 52.6 | 0.24 | 24.2 |
| (19308) 1996 TO66 | Fam(4) | 38.3 | 43.4 | 0.12 | 27.4 |
| (181874) 1999 HW11 | Det(1,2) | 39.2 | 52.7 | 0.26 | 17.2 |
| (44594) 1999 OX3 | Sca(1) | 17.6 | 32.5 | 0.46 | 2.6 |
| (148209) 2000 CR105 | Det(1,2,9) | 44.1 | 218 | 0.80 | 22.8 |
| (118702) 2000 OM67 | Det(1) | 39.2 | 100.0 | 0.61 | 23.3 |
| (87269) 2000 OO67 | Oort(5), Sca(1) | 20.8 | 639 | 0.97 | 20.1 |
| 2002 PE310 | Det(1) | 35.8 | 54.9 | 0.35 | 18.4 |
| (82075) 2000 YW134 | Det(9), Res(1) | 41.1 | 57.6 | 0.29 | 19.9 |
| (182397) 2001 QW297 | Det(2), Obelt(1) | 39.7 | 52.0 | 0.24 | 17.0 |

Notes. Quantities are the perihelion distance ($q$), semimajor axis ($a$), eccentricity ($e$), and inclination ($i$). Data taken from the Minor Planet Center.

| Notes | Type | $q$ (AU) | $a$ (AU) | $e$ | $i$ (deg) |
|-------|------|----------|----------|-----|-----------|
| Det: detached disk; Fam: (136108) Haumea (2003 EL 61) collisional family | 76.3 | 501 | 0.85 | 11.9 |
| Detached disk | 40.0 | 52.6 | 0.24 | 24.2 |
| Fam: (136108) Haumea (2003 EL 61) collisional family | 38.3 | 43.4 | 0.12 | 27.4 |
| Det(1,2): detached disk | 39.2 | 52.7 | 0.26 | 17.2 |
| Sca(1): scattered disk | 17.6 | 32.5 | 0.46 | 2.6 |
| Det(1,2,9): detached disk | 44.1 | 218 | 0.80 | 22.8 |
| Det(1): detached disk | 39.2 | 100.0 | 0.61 | 23.3 |
| Oort(5), Sca(1): Oort cloud | 20.8 | 639 | 0.97 | 20.1 |
| Det(1): detached disk | 35.8 | 54.9 | 0.35 | 18.4 |
| Det(9), Res(1): resonance object | 41.1 | 57.6 | 0.29 | 19.9 |
| Det(2), Obelt(1): detached disk | 39.7 | 52.0 | 0.24 | 17.0 |

### Table 5

Spectral Gradients of Small Solar System Objects

| Name          | Type   | $S^a$ | Reference |
|---------------|--------|-------|-----------|
| Haumea KBO family | 0.7 ± 2 | 1.9,13 |
| C-type asteroids | 2.0 ± 2 | 20 |
| Moderate red color | 0.7 ± 2 | -- |
| Dead comets | 7.2 ± 5 | 2 |
| Jupiter Trojans | 7.6 ± 3 | 6,18,19,20 |
| Irregular satellites | 7.8 ± 5 | 7,10,11 |
| Neutral Centaur lobe | 8.2 ± 5 | 8,15,17,21 |
| Outer retrograde | 8.7 ± 2 | 1 |
| D-type asteroids | 8.9 ± 3 | 5,20 |
| Neptune Trojans | 9.1 ± 3 | 4 |
| Comets | 10.0 ± 3 | 2,14,22 |

Notes. $^a$ Spectral gradient as defined in the text using known $B$- or $g'$- and $I$- or $i'$-band photometry normalized to the $V$ band. The ± on the spectral gradient is not an error but displays the general range the type of objects span.

### References.

1. (1) Gladman et al. 2008; 2. (2) Elliot et al. 2005; 3. (3) Brown et al. 2004; 4. (4) Ragozzine & Brown 2007; 5. (5) Kalb et al. 2009; 6. (6) Gladman et al. 2009; 7. (7) Becker et al. 2008; 8. (8) Allen et al. 2006; 9. (9) Lykawka & Mukai 2007a.

3.3. Extended/Detached Disk and Outer Classical Belt Objects

Objects with large semimajor axes and perihelion distances have only recently been discovered (Gladman et al. 2002). Knowledge of the physical properties of these dynamically interesting objects is important to constrain their origins and evolution. Detached disk objects are considered to have moderate to large eccentricities ($e > 0.2$–0.25), large perihelion distances ($q \gtrsim 38$ AU), and large semimajor axes ($50 < a < 500$ AU; Elliot et al. 2005; Lykawka & Mukai 2007a; Gladman et al. 2008). Detached disk objects are somewhat decoupled from the giant planet region yet have been considerably influenced dynamically to obtain their relatively large eccentricities. The objects in the detached disk can thus be considered intermediate between the Kuiper Belt and the inner Oort Cloud. Objects with dynamics closely related to the detached disk are the outer classical belt population. The outer classical belt objects have $a > 48.4$ AU, $e < 0.25$ and are nonresonant (Gladman et al. 2008). Objects with $39.4 < a < 48.4$ AU and $e < 0.25$ are considered main classical belt objects or cubewanos. The 2:1 Neptune resonance separates the main classical belt from the outer classical belt.

In this work, most of the known detached disk and outer classical belt objects were observed to determine their optical colors for the first time in order to compare them to other solar system small body reservoirs. In particular, determining if these populations are dominated by ultra-red material allows important constraints to be placed on the origin and evolution of these populations.
3.3.1. Detached Disk

Though the detached disk has been defined differently by various authors, this work takes a very strict definition. A detached disk object must have $q > 38$ AU, $e > 0.25$, and $50 < a < 500$ AU. Thus 13 objects that were observed in this work qualify as detached disk objects under this definition (2008 OG$_{19}$, 2005 SD$_{278}$, (145480) 2005 TB$_{190}$, 2004 OJ$_{14}$, 2004 VN$_{112}$, 2003 QK$_{91}$, 2005 EO$_{297}$, 2003 FZ$_{29}$, (84522) 2002 TC$_{302}$, (148209) 2000 CR$_{305}$, (82075) 2000 YW$_{134}$, (118702) 2000 OM$_{27}$, (181874) 1999 HW$_{11}$).

The colors of the detached disk objects do not appear to be extraordinary (Figure 2). Except for one ultra-red detached disk object, the rest show only moderately red colors ($10 \leq S \leq 18$). Their spectral gradient average ($S = 14.5 \pm 5$) is very similar to the scattered disk KBOs. Plutinos, high inclination classical KBOs as well as the damocloids and comets (Table 5). The detached disk objects are thus not likely from the same source region as the ultra-low inclination classical KBO population or the inner Oort Cloud though if they are from the same source region than the detached disk objects had significantly different surface altering histories. Inclination is not important in the color of detached disk objects with even the few very low inclination objects observed in the detached disk (2003 FZ$_{129}$ and 2003 QK$_{91}$) showing only moderately red colors. The discovery of more low inclination detached disk objects is needed to further confirm that this population is not rich in ultra-red material. More low inclination objects are not dominated by ultra-red material. More outer classical belt objects need to be discovered to confirm this population is dominated by very red objects ($S \geq 20$).

3.3.2. Outer Classical Belt Objects

The outer classical belt objects have $a > 48.4$ AU, $e < 0.25$, $i < 40^\circ$ and are nonresonant. Outer classical belt objects are separated from the main classical belt by the 2:1 resonance and have slightly smaller eccentricities than the detached disk objects. The observed sample has five bona fide outer classical belt objects (2007 JJ$_{43}$, (120132) 2003 FY$_{128}$, 2003 UY$_{291}$, (182397) 2001 QW$_{297}$, and (48639) 1995 TL$_{38}$).

The only other possible outer disk object in our sample would be 2004 XR$_{190}$. This is a very dynamically unusual object since it has a relatively low eccentricity, large semimajor axis, and large inclination (Table 4). It is to date a dynamically unique object but has been classified as an outer disk object by Gladman et al. (2008) and a detached disk object by Allen et al. (2006) and Lykawka & Mukai (2007a). Gomes et al. (2008) believe that 2004 XR$_{190}$ is a fossil-detached object. 2004 XR$_{190}$ was likely scattered by a close planetary encounter into the 3:8 mean motion resonance with Neptune. 2004 XR$_{190}$ then escaped from the 3:8 mean motion resonance while Neptune was still migrating outward during the very early evolution of the solar system. Scattering and escaping the mean motion resonance would help explain the rather large inclination, large perihelion distance, and large size of 2004 XR$_{190}$. In addition, the Gomes (2003) model found outer classical belt objects are not expected to obtain such high inclinations as 2004 XR$_{190}$. 2004 XR$_{190}$ has only a moderately red color of $S = 10.3 \pm 3$ like the higher eccentricity detached objects (further discussion of 2004 XR$_{190}$ is in Section 4).

Excluding the dynamically unique 2004 XR$_{190}$, the outer classical belt objects are significantly redder ($18 \leq S \leq 30$) than the average detached disk objects ($10 \leq S \leq 18$). The average outer classical belt objects spectral gradient ($S = 22.8 \pm 5$ or $S = 21.0 \pm 5$ if including 2004 XR$_{190}$) is similar to the ultra-red material seen in the low inclination classical Kuiper Belt and inner Oort Cloud objects (Table 5). The sample of outer classical belt objects are all very red even though they cover a wide range of inclinations with both 2003 UY$_{291}$ and 1995 TL$_{38}$ having very low inclinations ($i < 4^\circ$) and 2001 QW$_{297}$, 2003 FY$_{128}$, and 2007 JJ$_{43}$ having moderate inclinations ($i \sim 12^\circ$–$17^\circ$). This is unlike the main classical belt were the low inclination objects are dominated by ultra-red objects ($S \geq 25$) while the higher inclination objects are not dominated by ultra-red material. More outer classical belt objects need to be discovered to confirm this population is dominated by very red objects ($S \geq 20$).

4. DISCUSSION

4.1. Detached and Scattered Disk

The scattered disk is probably made up of two main source populations. Some scattered disk objects are likely the surviving members of a relic population of objects that were scattered during Neptune’s migration in the very early solar system (Gomes et al. 2008). A second source for the scattered disk is from recently dislodged objects from the Kuiper Belt through various slow dynamical processes (resonances) or collisions (Duncan et al. 1995; Levison & Duncan 1997; Duncan & Levison 1997; Nesvorny & Roig 2001; Gomes et al. 2008).

How the detached disk may have formed is still an open question (Gomes et al. 2008; Morbidelli et al. 2008; Kenyon et al. 2008; Duncan et al. 2008b; Gladman et al. 2008). For high inclination objects ($i > 50^\circ$) the Kozai resonance can allow scattered objects to obtain large perihelion distances (Thomas & Morbidelli 1996; Gallardo 2006). For objects with moderate inclinations, the Kozai mechanism only works in increasing the perihelion distance of a scattered object if the object is also in a mean motion resonance with Neptune (Gomes 2003). Using Neptune mean motion resonances and the Kozai mechanism, Gomes et al. (2008) believe the high perihelia and relatively large semimajor axes of some moderate inclination detached objects can be explained through the above mechanism, specifically 2000 YW$_{134}$, 2005 EO$_{297}$, and 2005 TB$_{190}$ as well as the high inclination object 2004 XR$_{190}$, since they are all in or near Neptune mean motion resonances. These objects were likely at some point scattered disk objects that simply had their perihelia raised through Neptune mean motion resonances and the Kozai effect.

Based on the similar average spectral gradients of the two populations, the origin of the objects in the detached disk could be similar as the scattered disk (Table 5). The scattered disk spectral gradient ($S = 10.1 \pm 5$) shown in Table 5 uses the strict definition similar to Gladman et al. (2008) which eliminates objects thought to be in any resonance with Neptune from being called a scattered disk object (called here the strict scattered disk: objects not in an obvious high-order resonance with Neptune, perihelia less than 35 AU, and semimajor axis between 30 and 100 AU). If objects in high-order resonances with Neptune are allowed in the definition used for what is a scattered disk object, the spectral gradient increases slightly and is almost the same as the detached disk average spectral gradient ($14.5 \pm 5$). It is interesting to note that very red ($S \geq 20$) objects are absent in the strict definition of the scattered disk but are not when
including the higher order resonance objects. This may hint that many high-order resonance scattered disk objects are coming from the ultra-red low inclination classical belt or outer classical belt objects. It may be that the only efficient way to dislodge these fairly dynamically stable ultra-red objects is through some resonance interactions.

To further compare the scattered disk to the detached disk population, the Student’s t-test and the Kolmogorov–Smirnov (K–S) test were performed on the spectral gradients of the two populations (Figure 5). The differences in the two population distributions were not statistically significant ($< 3\sigma$) in either test and thus are consistent with both populations coming from the same parent population (Table 6). This is true no matter if the high-order outer resonance objects are considered scattered disk objects or not (Figure 6). The similarity of spectral gradients may hint that Neptune mean motion and Kozai resonances allowed scattered disk objects to become detached over time from significant Neptune influence and that the detached disk is a simple extension of the scattered disk (Gallardo 2006; Lykawka & Mukai 2007b; Emel’yanenko & Kiseleva 2008; Gladman et al. 2008; Gomes et al. 2008). Based on the spectral gradients and dynamics of the objects in the detached and scattered disk, it appears that they likely contain many objects from the same source region.

### 4.2. Ultra-red Colors and the Outer Classical Belt

The outer classical belt objects have lower eccentricities and usually lower semimajor axes than the detached disk objects. They are separated from the main classical belt by the Neptune 2:1 mean motion resonance. The dynamical origin of the outer classical belt objects is not easy to explain through simple Neptune mean motion resonances and the Kozai effect, and may have a different origin than the detached disk objects (Gomes 2003; Gomes et al. 2008; Morbidelli et al. 2008). Simulations by Gomes (2003) of Neptune’s migration and the formation of the Kuiper Belt show that the objects coming from the outer most portion of the disk that Neptune migrates through would have preferentially low inclinations ($i < 10^\circ$) and low eccentricities ($e \lesssim 0.1$) when dispersed to near 40 AU. This is likely the source of the “cold” classical disk (see Gomes 2003; Figure 2). The inclination distribution for these objects is found in the simulations to increase slightly at larger semimajor axes.

More importantly, the Gomes simulations show that these same objects further out in semimajor axis around 50 AU would have significantly larger eccentricities ($e \sim 0.2$). Using these ideas, Gomes et al. (2008) suggest that objects with orbits like the outer classical belt are not fossilized detached disk objects and more likely share a similar origin as the low inclination “cold” classical population (Gomes 2003; Morbidelli et al. 2008). The very red colors ($S \gtrsim 20$) found in this work for these outer classical belt objects support this hypothesis.

The spectral gradient of the outer classical belt objects averages $S = 22.8 \pm 5$ which is similar to that found for the low inclination “cold” classical main belt objects ($27.4 \pm 5$; see Table 5).
To compare the spectral gradients of outer classical belt objects with the low inclination "cold" classical belt objects the Student's t-test and the K–S test were performed on the two populations (Figure 5). The two distributions do not appear to be significantly different (< 2σ) and thus could come from the same parent population (Table 6). This is unlike the detached and strict scattered disks which have > 3σ confidence in the differences of their spectral gradient distributions when compared to the low inclination "cold" classical belt objects (Table 6). Thus the detached disk and strict scattered disk objects are unlikely to have come from the same parent population as the low inclination "cold" classical belt objects.

Table 6 shows that the K–S test hints at a possible trend with there being significant differences between the outer classical belt spectral gradient distribution and the strict scattered and detached disk objects but with only five known outer classical belt objects the test is unreliable. About twice as many outer classical belt objects need to be discovered and have their spectral gradients determined in order to confirm or reject them as having significantly different spectral gradients from the various dynamical populations in the outer solar system. It is apparent that the outer classical belt objects are very red objects and they are redder than both the detached disk and strict scattered disk, and less red than the low inclination "cold" classical KBOs.

As shown in Figure 5, the colors of the scattered disk objects not in resonances are the least red. The detached disk objects are slightly redder while the outer classical belt objects are even redder and finally the low inclination "cold" classical KBOs are the reddest objects. The high-order resonance objects appear to span most of the spectral gradient range of the various populations (Figure 6). The significant differences in spectral gradients for some of the populations are likely because the objects come from different source regions. It is also possible that the differences in the spectral gradients of the various populations come from significantly different surface weathering processes on the objects over the age of the solar system, such as different collisional or sublimation histories. It is apparent that the objects more distant from the Sun are on average redder.

4.3. Spectral Gradients Versus Orbital Dynamics

To further explore the origins of the detached disk and outer classical belt objects, their eccentricities versus spectral gradient were plotted (Figure 7). There is an apparent trend that the lower the eccentricity the redder the object. The Pearson correlation coefficient is −0.49 using the 18 known spectral gradients of the detached disk and outer classical belt objects. The correlation with eccentricity is only significant at about the 97% level and additional low eccentricity outer classical belt objects need to be found to confirm or reject this possible trend (Table 7). Including the strict scattered disk objects increases the significance of the correlation with eccentricity to 99%. If the low inclination "cold" main classical KBOs are also included, the trend is even stronger with a Pearson correlation coefficient of −0.80 and a significance at the 99.99% confidence limit (Figure 8). There is no trend of spectral gradient with the inclination or perihelion distances of the detached disk and outer classical belt objects (Table 7). Including the strict scattered disk also finds no trend with spectral gradient and inclination or perihelion distance.

5. SUMMARY

Thirty-three extreme outer solar system objects were observed to determine their optical colors.

1. The three possible inner Oort Cloud objects (Sedna, 2006 SQ₃₇₂, and 2000 Oₐ₆₇) all have ultra-red surfaces (spectral gradient S ∼ 25). These ultra-red surfaces are abundant in the low inclination "cold" classical KBO population and is believed to be associated with organic-rich material. Because the ultra-red material is only seen in the very outer parts of the observable solar system, it is likely that this material has not been significantly thermally altered. The red lobe of the Centaur distribution could thus either be from the low inclination classical KBO population or from the inner Oort Cloud population.

2. For the first time, a systematic color determination of extended or detached disk objects was obtained. Most
detached disk objects have only moderately red surfaces ($10 \lesssim S \lesssim 18$). Though slightly redder on average than the scattered disk, the detached disk colors are consistent with being from the same source region as the scattered disk objects. The only ultra-red objects observed with scattered disk-like orbits appear to be objects in high-order resonances with Neptune.

3. The outer classical KBOs, which have semimajor axes beyond the 2:1 resonance with Neptune and low eccentricities, were found to be very red ($S \gtrsim 20$) and are on average redder than the detached disk objects. Unlike the scattered disk and detached disk, the outer classical belt objects have spectral gradients similar to the ultra-red low inclination “cold” classical KBOs though they appear to be less red on average.

4. The two retrograde objects with perihelia in the outer solar system (2008 KV$_{12}$ and 2008 YB$_{19}$) and the extremely high inclination object (127546) 2002 XU$_{93}$ show only moderately red colors ($S \approx 9$). These colors are very similar to the known comets, dead comets, damocloids, Jupiter Trojans, Neptune Trojans, irregular satellites, D-type main belt asteroids, scattered disk objects, and the neutral lobe of the Centaurs. 2008 YB$_{19}$ perihelion is near Jupiter; thus this object has had its surface thermally altered over the age of the solar system as is probably true for all the above moderately red populations. 2008 KV$_{12}$ has a rather large perihelion at 21 AU and it is unknown if it has ever approached closer to the Sun. The moderately red surface color suggests its surface has likely been thermally altered.

5. The detached disk and outer classical KBOs show a trend that the lower the eccentricity the redder the object. This trend is currently not statistically significant since only a few of these objects are known. The trend is strengthened when adding the strict scattered disk and low inclination “cold” classical KBOs. The trend must be confirmed through discovering and measuring the colors of more outer classical belt objects.

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THE COLORS OF EXTREME OUTER SOLAR SYSTEM OBJECTS
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