The Reflectance of Cold Classical Trans-Neptunian Objects in the Nearest Infrared

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Abstract
Recent photometric surveys of Trans-Neptunian Objects (TNOs) have revealed that the cold classical TNOs have distinct z-band color characteristics and occupy their own distinct surface class. This suggested the presence of an absorption band in the reflectance spectra of cold classicals at $\lambda > 0.8 \mu m$. Here we present reflectance spectra spanning 0.55–1.0 $\mu m$ for six TNOs occupying dynamically cold orbits at $a$ $\sim$ 44 $au$. Five of our spectra show a clear and broadly consistent reduction in spectral gradient above 0.8 $\mu m$ that diverges from their linear red optical continuum and agrees with their reported photometric color data. Despite predictions, we find no evidence that the spectral flattening is caused by an absorption band centered near 1.0 $\mu m$. We predict that the overall consistent shape of these five spectra is related to the presence of similar refractory organics on each of their surfaces, and/or their similar physical surface properties such as porosity or grain size distribution. The observed consistency of the reflectance spectra of these five targets aligns with predictions that the cold classicals share a common history in terms of formation and surface evolution. Our sixth target, which has been ambiguously classified as either a hot or cold classical at various points in the past, has a spectrum that remains nearly linear across the full range observed. This suggests that this TNO is a hot classical interloper in the cold classical dynamical range and supports the idea that other such interlopers may be identifiable by their linear reflectance spectra in the range 0.8–1.0 $\mu m$.

Unified Astronomy Thesaurus concepts: Classical Kuiper belt objects (250); Trans-Neptunian objects (1705); Spectroscopy (1558)

Supporting material: data behind figure

1. Introduction
The cold classical Trans-Neptunian Objects (TNOs) are minor planets on nonresonant, nonscattering, low-inclination ($i \lesssim 5^\circ$), and low-eccentricity ($e < 0.24$) heliocentric orbits with semimajor axes between 40 and 50 $au$ (Gladman et al. 2008; Petit et al. 2011; Bannister et al. 2018). The cold classicals are distinct from the dynamically excited (hot) TNOs in a number of ways, including their lack of dynamical excitation; their higher fraction of surviving, and in particular widely separated, binary pairs (Stephens & Noll 2006; Noll et al. 2008; Parker & Kavelaars 2010); their distinct size distribution and its lack of large objects (diameter $\gtrsim 400$ km; e.g., Fraser et al. 2014; Müller et al. 2020); and their unimodally (rather than bimodally) distributed colors and albedos, which on average sit at the very red and high ends of the color and albedo distributions of TNOs as a whole (Tegler et al. 2003; Brucker et al. 2009; Fraser & Brown 2012; Lacerda et al. 2014; Vilenius et al. 2014; Pike et al. 2017; Terai et al. 2018; Schwamb et al. 2019). Notably the cold classical TNOs are not typically as red as the very reddest TNOs, such as 225088 Gonggong (2007 OR10; Brown et al. 2011). Taken together, the distinct properties of the cold classicals support the prediction that they formed and evolved in situ, separately from the other TNO populations, and that they emerged mostly unscathed from the period of giant planet migration thought to have emplaced the dynamically hot TNOs into the modern trans-Neptunian Belt (Levison et al. 2008; Parker & Kavelaars 2010; Batygin et al. 2011; Wolff et al. 2012; Nesvorný 2015).

After setting aside any interlopers sharing their orbital parameter space (such as the blue binaries; Fraser et al. 2017), the cold classical TNOs constitute the best preserved samples of material derived from the outermost reaches of the solar protoplanetary disk at the time of planet formation. They have been spared significant surface evolution from most of the common sources that affect minor planets. The delivery of collisional and accretional heat to the cold classicals is limited by the relatively low frequency and velocities of the collisions they experience (Dell’Oro et al. 2012; Fraser et al. 2014; Greenstreet et al. 2019; Spencer et al. 2020). TNOs as small as most cold classicals ($D < 400$ km) tend to have low densities (e.g., Grundy et al. 2007; Momert et al. 2012; Santos-Sanz et al. 2012; Vilenius et al. 2012, 2014; Lellouch et al. 2013; Kovalenko et al. 2017), suggesting that they may have a low rock/ice ratio, and consequently a lower capacity for internal radiogenic heating (e.g., Coradini et al. 2008). At large heliocentric distances of 40–50 $au$, weak insolation does not drive significant thermal evolution of planetary surfaces (e.g., Guilbert-Lepoutre et al. 2011). By residing at these distances since their formation (Parker & Kavelaars 2010; Morbidelli & Nesvorný 2020), the cold classicals are also predicted to have received relatively low doses of photonic and ionic radiation from both the Sun and galactic sources (Cooper et al. 2003, 2006; Hudson et al. 2008).

Because the materials on their surfaces are relatively primitive, the cold classical TNOs are enticing targets for spectroscopic study and may provide one of the most direct observational routes to measurement of the chemical and...
thermal conditions that prevailed in the outer protoplanetary disk of the young Sun. Their faintness, however, also makes them challenging observational targets. To date, only four TNOs that have been solidly classified as cold classicals have been observed spectroscopically (see Table 1).

Within the signal-to-noise ratio (S/N) of the observational data and the wavelength ranges covered so far, the reflectance spectra of cold classicals are almost completely featureless. In the optical range they show only continuum with a strong positive gradient, while in the near-infrared (NIR) they appear neutrally reflective or very slightly blue (Grundy et al. 2005, 2020; Barkume et al. 2008). The only absorption bands confidently identified in the reflectance spectrum of a cold classical were observed at 2.271 and 2.338 μm in the NIR spectrum of Arrokoth by the NASA New Horizons probe; these bands were attributed to surface methanol ice (Grundy et al. 2020). The red optical color of the cold classicals is typically attributed to the presence of complex macromolecular organic residues on their surfaces (e.g., Dalle Ore et al. 2015). Such materials are predicted to be primarily comprised of a highly diverse agglomeration of complex hydrocarbon molecules, and are known to be produced through radiolytic and/or photolytic processing of the simple molecular ices from which the TNOs are thought to have formed (e.g., Khare et al. 1989; Cruikshank et al. 2005; Brunetto et al. 2006; Materese et al. 2014, 2015). The featureless nature of the optical and NIR reflectance spectra of TNOs has so far precluded robust quantitative chemical analysis of their surfaces, however.

Recently, the reflectance properties of the cold classicals were reported to be distinct from those of the dynamically hot TNOs based on photometric colors obtained by both the Colors of the Outer Solar System Origins Survey (Col-OSSOS; Pike et al. 2017) and an independent study conducted by Terai et al. (2018). From the colors measured by both teams, the dynamically hot TNOs were inferred to have average reflectance spectra with only a small decrease in gradient across the range 0.6–1.0 μm, if any at all. By contrast, cold classicals were found to occupy a unique space in $(g − r)/r − z$ color space, implying a reduced spectral gradient at $λ \approx 0.9 \mu m$ compared to that across the same wavelength region for the dynamically hot TNOs with similar optical color (Pike et al. 2017; Terai et al. 2018).

The distinct spectroscopic behavior of the cold classicals may set them apart from dynamically hot TNOs with similar optical redness in terms of composition; a distinction like this warrants spectroscopic investigation. With the broad aim of spectroscopically confirming and characterizing the distinct spectral behavior of the cold classical TNOs at $λ > 0.8 \mu m$, we set out to obtain a sample of their reflectance spectra.

### 2. Target Selection

Our original sample was comprised of nine targets. 505476 (2013 UL15) and 511552 (2014 UE225) were selected because they had published colors obtained by the Col-OSSOS survey and were predicted by Pike et al. (2017) to have a large divergence from linearity in their reflectance spectra at $λ > 0.8 \mu m$. The other seven TNOs were selected from the catalog of Peixinho et al. (2015) if they were dynamically classified as a cold classical, had a full set of $BVRI$ photometric colors, and were bright enough ($R < 22.5$) that spectroscopic observations would be obtainable, reducible, and useful for characterization and analysis. Of the nine initially selected targets, six were successfully observed.

### 3. Observations

Each spectrum presented here was observed during a visitor-mode observing run at the European Southern Observatory’s (ESO’s) Very Large Telescope (VLT) that took place during the three nights between 2019 August 28 and 31. Table 2 presents a log of our successful observations. At the VLT we used the FOcal Reducer/low dispersion Spectrograph 2 (FORS2; Appenzeller et al. 1998) mounted on the 8.2 m UT1 (Antu) unit telescope. FORS2 is a multipurpose optical spectrograph, imager, and polarimeter, which we used in longslit spectroscopy mode to observe our TNOs and solar calibrators. FORS2 was configured with the red-sensitive MIT CCD detector, the standard resolution collimator, and a longslit of width 1.6′. The nonstandard GRIS_2001+28 grism was installed in FORS2 for our observations, offering a resolving power of $λ/Δλ = 380$ at 0.745 μm and a wavelength coverage of 0.55–1.1 μm. The extremely low S/N of the spectra at the longest wavelengths would effectively limit the extent of our useful data to the range 0.55–1.0 μm, however. The GRIS_2001+28 grism has an OG550 order separation filter cemented to it, so no extra order blocking filter was required.

For all TNOs and solar calibrators we used a two-point repeating spatial dither pattern between spectroscopic exposures centered at $+1''$ and $−1''$ from the center of the spatial axis of the slit. To mitigate the effects of atmospheric differential refraction (Filippenko 1982), we aligned the slit to the parallactic angle before commencing spectroscopic observations of each target, and for each TNO the slit was realigned to the parallactic angle after every four exposures (approximately once every 45 minutes). All exposures were read out using the standard 100 kHz, $2 \times 2$, high-readout mode.

We ensured that the observations of each TNO were bracketed by observations of a solar calibrator obtained at a similar airmass and pointing. The spectra of these calibrators were used to cancel the solar spectrum from those of the TNOs and derive the TNO reflectance spectra; they also double as telluric standards. Only one bracketing calibrator spectrum was required, but observation of two provided redundancy in the event of unexpected changes in conditions. At least one solar calibrator for each TNO was selected from published catalogs of solar twins and analogs (Ramírez et al. 2009, 2014). If the second calibrator was not a solar twin or analog, it was a star with both a reported spectral type and $B − V$ color that were

| TNO                      | Wavelength Ranges Covered, μm | References                        |
|--------------------------|-------------------------------|-----------------------------------|
| 58534 Logos (1997 CQ20)  | 0.6–0.88                      | Boehnhardt et al. (2001)          |
| 66652 Borasini-Fab (1999 RZ235) | 1.4–2.4                     | Barkume et al. (2008)             |
| 79360 Sia-Nunam (1997 CS20) | 0.4–0.88; 1.4–2.5              | Boehnhardt et al. (2001); Grundy et al. (2005) |
| 486958 Arrokoth (2014 MU69)  | 1.2–2.5                      | Stern et al. (2019); Grundy et al. (2020) |
close to solar (Weng et al. 2000). Ultimately, we were able to calibrate each TNO spectrum with an associated solar twin or solar analog spectrum, and we therefore expect the gradients and shapes of the TNO reflectance spectra to be accurate. All our spectra were observed under clear (sky 90% cloudless at elevation > 30°, transmission variation < 10%) or photometric (sky cloudless, transmission variation < 2%) conditions as defined by ESO. We therefore expect any effects of cloud cover on the continuum color of our spectra to be minimal. Conditions also remained consistently dry throughout our run (precipitable water vapor; PWV < 1.5 mm).

4. Data Reduction

Standard spectroscopic data reduction steps including bias subtraction, flat-fielding, and wavelength calibration were conducted for all our raw spectra with the ESO FORS data reduction pipeline (v. 5.4.3\(^5\)) in the ESO Reflex data processing environment (v. 2.9.1; Freudling et al. 2013). The spectra were not corrected for instrument response, as the response of FORS2 is stable over a period of several days, and any response calibration applied to a TNO spectrum and a solar calibrator star spectrum would only be canceled out once the former was divided by the latter later on.

While not a problem for the 2D spectra of the bright solar calibrator stars, low-level fringing was identified at longer wavelengths in the 2D spectra of the TNOs, so a fringe frame was constructed for each TNO to remove them. First, for each 2D spectrum associated with a given TNO, a linear profile was fitted and subtracted from each pixel column parallel to the spatial axis to approximately cancel the illumination pattern of sky emission lines. Next, each spatial pixel column within each 2D spectrum was sigma-clipped at ± 2σ before all the sigma-clipped 2D spectra were mask-median combined to form a fringe frame that did not contain spectra of any sources. This fringe frame was then subtracted from each 2D spectrum of the TNO to cancel the fringes. A linear profile was then fitted to and subtracted from each pixel column parallel to the spatial axis again to remove the sky emission line illumination pattern. This procedure makes the simple assumption that the sky line illumination has a spatially linear profile, but tests making use of a second-order polynomial did not show significant improvement in the illumination pattern cancellation.

Sky subtraction, cosmic-ray removal, and extraction of the spectra were performed using a method similar to that used by Secull et al. (2018). Briefly, Moffat functions (Moffat 1969) were fitted to the spatial profile of the 2D wavelength-calibrated spectrum at many locations along the dispersion axis in order to track the wavelength-dependent center and width of the spectrum’s spatial profile. Sky region boundaries were defined at ±3 FWHM from each Moffat profile center with sky outside these boundaries. Fifteen iterations of sigma clipping at 5σ were separately conducted in the sky and target regions to remove cosmic rays. In each unbinned wavelength element, the median background was subtracted. While the TNO spectra had effectively been background subtracted during fringe removal, performing a simple median sky subtraction was useful in making small improvements to the quality of the background removal.

Another round of Moffat fitting was conducted for the sky-subtracted spectrum, and extraction limits were defined at ±2.5 FWHM from each of the Moffat profile centers. During this process, pixels that formerly contained cosmic rays had their values replaced using a process that is similar to that used in the

Table 2: Observation Log

| Target\(^6\) | UT Observation Date | Time | \(T_{\text{exp}}\) s | \(N_{\text{exp}}\) | Airmass | IQ, \(^7\) | \(\Delta, \text{au}\) | \(r, \text{au}\) | \(\alpha, \text{°}\) |
|-------------|---------------------|------|---------------------|---------------|----------|---------|--------------|--------------|--------------|
| HD 225194   | 2019-08-29          | 05:25:06–05:33:21 | 0.3              | 2             | 1.29     | 0.81–1.11 | 46.02        | 46.59        | 1.03         |
| 511552 (2014 UE\(_{225}\)) | 2019-08-29 | 05:33:39–09:16:49 | 500.0           | 16            | 1.28–1.54| 0.69–1.10 | 43.94        | 43.94        | 0.13         |
| HD 209562   | 2019-08-30          | 09:17:03–09:26:16 | 0.3              | 2             | 1.10     | 0.81–1.09 | 39.12        | 40.05        | 0.56         |
| 2001 HZ\(_{56}\) | 2019-08-30       | 05:40:27–05:48:51 | 0.7              | 2             | 1.11     | 0.80–0.83 | 43.89        | 43.75        | 1.31         |
| HD 218251   | 2019-08-30          | 05:19:07–05:30:20 | 0.4              | 2             | 1.02     | 0.85–0.96 | 1.10–1.16    |              |              |
| BD-00 4557  | 2019-08-30          | 05:49:04–08:24:16 | 500.0           | 12            | 1.09–1.32| 0.66–1.02 | 39.12        | 40.05        | 0.56         |
| 138537 (2000 OK\(_{57}\)) | 2019-08-30 | 05:49:04–08:31:55 | 0.4              | 2             | 1.13     | 0.72–1.01 | 39.12        | 40.05        | 0.56         |
| HD 224448   | 2019-08-30          | 08:24:42–08:31:55 | 0.3              | 2             | 1.13     | 0.72–1.01 | 39.12        | 40.05        | 0.56         |
| 66652 Borasisi-Pabu | 2019-08-31 | 01:59:50–04:18:28 | 500.0           | 12            | 1.16–1.78| 0.70–0.90 | 41.27        | 42.23        | 0.41         |
| HD 224448   | 2019-08-31          | 04:18:47–04:26:34 | 0.4              | 2             | 1.21     | 0.78–0.81 | 41.27        | 42.23        | 0.41         |
| HD 8291     | 2019-08-31          | 04:26:51–04:35:27 | 0.3              | 2             | 1.58     | 0.81–0.83 | 42.79        | 43.50        | 0.96         |
| 505476 (2013 UL\(_{13}\)) | 2019-08-31 | 04:35:38–09:43:25 | 500.0           | 24            | 1.18–1.5 | 0.46–0.93 | 42.79        | 43.50        | 0.96         |
| HD 2141     | 2019-08-31          | 09:43:30–09:49:51 | 0.4              | 2             | 1.47     | 0.56–0.67 | 42.79        | 43.50        | 0.96         |

Notes. For each target we present the UT observation date and time, the integration time per exposure \((T_{\text{exp}})\), the number of exposures \((N_{\text{exp}})\), and the airmass at which they were observed. The range of estimated image quality (IQ) values presented for each target is the range of full widths at half maximum (FWHM) measured from Moffat profiles (Moffat 1969) fitted to the set of spatial profiles produced by median collapsing each of a target’s reduced 2D spectroscopic exposures along the dispersion axis. For the TNOs we present their geocentric distances \((\Delta)\), heliocentric distances \((r)\), and phase angles \((\alpha)\) at the time of observation. The apparent magnitude of our targets lay in the range 21.5 ≤ \(r\) ≤ 23.

\(^6\) Stars presented in bold are those ultimately used to calibrate the spectra of their associated TNOs.

\(^7\) Values presented for each target is the range of full widths at half maximum (FWHM) measured from Moffat profiles (Moffat 1969) fitted to the set of spatial profiles produced by median collapsing each of a target’s reduced 2D spectroscopic exposures along the dispersion axis. For the TNOs we present their geocentric distances \((\Delta)\), heliocentric distances \((r)\), and phase angles \((\alpha)\) at the time of observation. The apparent magnitude of our targets lay in the range 21.5 ≤ \(r\) ≤ 23.
ESO X-Shooter pipeline for the same purpose (Modigliani et al. 2010); details are presented in the X-Shooter pipeline manual.\(^6\) Within the defined extraction limits, the flux was summed for each wavelength element to form the 1D spectrum.

The spectra were then all corrected for atmospheric extinction using \(f_c(\lambda) = f(\lambda)10^{-f_c(\lambda)}\), where \(f_c(\lambda)\) and \(f(\lambda)\) are the extinction-corrected and uncorrected spectra, respectively, \(a\) is the median airmass at which the spectrum was observed, and \(k(\lambda)\) is the FORS2 extinction coefficient (taken from the FORS2 data reduction pipeline) interpolated to the resolution of the spectra.

Once corrected for atmospheric extinction, the 1D spectra for each target were median stacked. For Borasisi-Pabu, 2000 OK\(_{67}\), 2001 QY\(_{297}\), and 2001 HZ\(_{58}\); however, one, three, three, and two spectra, respectively, were excluded from their final stacks due to their very low S/N or large sky emission line residuals. The stacked spectra of all other targets, including the solar calibrators, were produced using all of their available spectroscopic exposures. Solar calibration of the stacked TNO spectra was performed by dividing them by their associated stacked solar calibrator spectrum, resulting in the production of the reflectance spectrum of each TNO. The reflectance spectra were then binned using the bootstrapping method described by Secull et al. (2019) to estimate their uncertainties and boost their S/N at the expense of wavelength resolution. Binning factors for each spectrum are presented in Figure 2 in the Appendix.

5. Results and Analysis

Figure 1 presents the reflectance spectra of the six TNOs we observed. These are the first optical reflectance spectra reported for any of these targets, and five of them (excluding Borasisi-Pabu, which has a NIR spectrum; Barkume et al. 2008) are the very first to be reported for these objects at any wavelength. These TNOs have red and nearly linear spectra at 0.55–0.75 \(\mu\)m, and all with the exception of 2000 OK\(_{67}\) (see Section 6) have a clear transition in their reflectance spectra at \(\lambda > 0.75 \mu\)m where their spectral gradients decrease toward the NIR. It is worth noting that a moderately strong telluric water absorption band exists in the range 0.9–1.0 \(\mu\)m (see Smette et al. 2015). While differences between the strength of this telluric band in the raw spectra of the TNOs and their solar calibrator stars have the potential to affect the shape of the reflectance spectra at \(\lambda > 0.9 \mu\)m, the very stable dry conditions (PWV < 1.5 mm) under which our spectra were observed give us confidence that any curvature at these wavelengths is intrinsic to the TNOs themselves. We note that the 0.9–1.0 \(\mu\)m telluric band cannot account for any curvature in the spectra at \(\lambda < 0.9 \mu\)m. Our observation of this curvature spectroscopically supports inferences of the existence of such a flattening in the reflectance spectra of cold classicals from photometric color measurements (Delsanti et al. 2004; Doressoundiram et al. 2007; Fraser & Brown 2012; Pike et al. 2017; Terai et al. 2018; Schwamb et al. 2019).

Ancillary plots showing the appearance of our spectra at their native wavelength resolution (Figure 2), the consistent shape of the spectra of our solar calibrators (Figure 3), and the wavelength-dependent S/N of our binned spectra (Figure 4) can be found in the Appendix.

5.1. Comparison to Published Photometry

Since no optical reflectance spectra have yet been reported in the literature for any of our targets, we compared our data set to coarse reflectance spectra produced from published photometric colors using the methods described by Hainaut & Delsanti (2002). For Borasisi-Pabu, 2001 QY\(_{297}\), and 2001 HZ\(_{58}\), BVRI reflectance points were determined using optical colors reported by Peixinho et al. (2015). The simultaneous \(V – J\) color measurement of Borasisi-Pabu reported by McBride et al. (2003) was used to estimate its \(J\)-band reflectance. The BVRIJ reflectance points for 2000 OK\(_{67}\) were determined using simultaneously observed BVRIJ colors reported by Delsanti et al. (2004). grizJ reflectance points for 2013 UL\(_{15}\) and 2014 UE\(_{222}\) were derived from colors published by the Outer Solar System Origins Survey (Pike et al. 2017; Schwamb et al. 2019). We make use of updated values, however, which reflect post-publication improvements to the photometry pipelines developed by that group (see Figure 1; W. C. Fraser et al. 2021, in preparation). Solar BVRI, \(V – J\), \(r – J\), and griz photometric colors were taken from Ramirez et al. (2012), Casagrande et al. (2012), Schwamb et al. (2019), respectively, and from the web pages of the Sloan Digital Sky Survey.\(^7\) Overall, the photometrically derived reflectances of our targets are in good agreement with our reflectance spectra. We note that our reflectance spectra do not extend to wavelengths that are short enough to test for the presence of the nonlinearity suggested to be present in the reflectance spectrum of 2001 HZ\(_{58}\) by its \(V\)-band photometric point (Peixinho et al. 2015). In addition, some difference between our spectrum and the photometrically derived reflectance of 2000 OK\(_{67}\) may be expected, as this object has been reported to have variable optical colors (Doressoundiram et al. 2002).

5.2. Measurements and a Search for Trends

We measured the optical gradient of each reflectance spectrum across the wavelength range 0.55–0.75 \(\mu\)m relative to the reflectance at 0.65 \(\mu\)m using the bootstrapping method of Secull et al. (2019). Measured gradients are presented in Table 3 along with the average values of these measurements for this sample. The average optical gradient measured from our spectra (see Table 3) is consistent with the gradients previously determined from photometric color measurements of cold classical TNOs (e.g., Hainaut et al. 2012), and also with the gradients measured from the limited number of previously published optical reflectance spectra of cold classicals (see Boehnhardt et al. 2001). We did not attempt to constrain the surface composition of our targets via use of Hapke (2012) modeling on our reflectance spectra as they are featureless, and such analysis would therefore only return highly degenerate results.

To estimate the central wavelength of the transition in our spectra (\(\lambda_T\)) and constrain the gradient of the NIR continuum, we fit a dual sloped spectral model to each spectrum, including \(J\)-band spectral photometry where available. The precision of this method was ultimately limited by our lack of spectral coverage in \(J\) band, however, resulting in poor constraint of \(\lambda_T\) and the NIR continuum gradient, making them insufficient for use in further analysis. A crude estimate of the lower limit of \(\lambda_T\) was made for each spectrum by finding the lowest wavelength at which all redward data points

\(^6\) See the Standard Extraction algorithm; ftp://ftp.eso.org/pub/dfs/pipelines/instruments/xshooter/xshoo-pipeline-manual-3.3.5.pdf.

\(^7\) https://www.sdss.org/dr12/algorithms/ugrizvegasun/
We also present the dynamical properties of our targets in Table 3 alongside their absolute V-band magnitudes, $H_V$. $H_V$ values for Borasisi-Pabu, 2001 QY$_{297}$, and 2000 OK$_{67}$ were taken directly from the published database of the TNOs are Cool survey (Vilenius et al. 2012, 2014). $H_V$ for 2001 HZ$_{58}$ was calculated using the $H_R$ magnitude and $V - R$ color of this object from Peixinho et al. (2015). Because the $H_R$ values

| TNO            | $S'(0.65)$, %/(0.1 μm) | $\lambda_T$, μm | $a$, au | $e$  | $i$,° | $q$, au | $H_V$        |
|----------------|-------------------------|------------------|---------|------|-------|---------|--------------|
| 66652 Borasisi-Pabu$^{**}$ | 24.76 ± 0.08            | > 0.81           | 43.98   | 0.092| 0.563 | 39.95   | 6.12 ± 0.07  |
| 138537 (2000 OK$_{67}$)       | 19.76 ± 0.15            | > 0.87           | 46.77   | 0.143| 4.877 | 40.04   | 6.47 ± 0.13  |
| 275809 (2001 QY$_{297}$)$^{**}$ | 22.72 ± 0.31           | > 0.87           | 44.17   | 0.085| 1.547 | 40.42   | 5.86 ± 0.31  |
| 505476 (2013 UL$_{25}$)       | 22.28 ± 0.20            | > 0.80           | 45.90   | 0.101| 2.025 | 41.26   | 7.04 ± 0.07  |
| 511552 (2014 UE$_{225}$)      | 33.87 ± 0.27            | > 0.75           | 43.73   | 0.066| 4.504 | 40.84   | 6.54 ± 0.04  |
| 2001 HZ$_{58}$                | 29.12 ± 0.91            | > 0.86           | 42.94   | 0.032| 2.933 | 41.55   | 6.63$^{±0.08}$ |
| Average                      | 25.41 ± 2.12            | > 0.83           |        |      |       |        |              |
| Average w/o 2000 OK$_{67}$    | 26.55 ± 2.19            | > 0.82           |        |      |       |        |              |

Note. For each TNO that we observed, we present the properties that we compared in a search for evidence of any trends between their reflectance properties, their absolute V-band magnitudes ($H_V$), and their orbital semimajor axes, eccentricities, inclinations, and perihelia ($a$, $e$, $i$, and $q$, respectively). The gradients measured from our spectra across 0.55–0.75 μm ($S'(0.65)$) are shown alongside the minimum wavelength at which each spectrum diverges from a linear gradient ($\lambda_T$). Averages of these values and the standard errors of these averages are also presented for the full sample, and the full sample excluding the potential interloper 2000 OK$_{67}$. Methods used to estimate the $H_V$ values for our targets are described in Section 5.2. TNOs with marked with a double asterisk are known binaries.
published by Peixinho et al. (2015) are not corrected for phase
darkening, we must account for the possibility that our value of
$H_V$ is overestimated. $\beta_V = 0.157 \pm 0.017$ mag/° was adopted as
a nominal phase coefficient by averaging the values of $\beta_V$
reported by Rabinowitz et al. (2007) for TNOs with $H_V > 4$.
From its JPL Horizons ephemeris, we determined that
2001 HZ$_{58}$ has never been observed at a phase angle greater than
$\alpha = 17.35$ since discovery. Based on this maximum phase
angle and nominal phase coefficient, we predict that $H_V$ may be
overestimated by up to 0.21 magnitudes, hence the asymmetric
uncertainty of $H_V$ for 2001 HZ$_{58}$ reported in this work. To
estimate $H_V$ for our Col-OSSOS targets, 2013 UL$_{15}$ and
2014 UE$_{22a}$, we first used the $H_r$ and $g-r$ values from
Schwamb et al. (2019) to obtain $H_V$. We then followed the
example of Sheppard (2010, 2012) and used $V = g - 0.55$
$\pm 0.03$ from Smith et al. (2002) to determine $H_V$.
Finally, we corrected $H_V$ for phase darkening using our
nominal $\beta_V$ and the phase angles of these two targets at the time
they were observed by Col-OSSOS (Schwamb et al. 2019).

Thorough statistical analysis of the properties of such a small
table of TNOs would be a foolhardy effort, but we did compare
their measured reflectance properties to their dynamical properties
and $H_V$ values by eye to see if any potential trends in the data
might be glimpsed. No convincing trends were observed, however.
Neither do the binary TNOs, Borasisi-Pabu and 2001 QY$_{57}$,
refute any spectral behavior that differentiates them from the rest
of the objects in our sample, nor do we observe any discernible
relation between the reflectance properties of our targets and
dynamical residence within, or near to, the cold classical kernel
(Petit et al. 2011; Bannister et al. 2016).

6. Interlopers

Pike et al. (2017) put forward the possibility that observers
may be able to distinguish hot classical TNOs from cold
classical TNOs by the shape of their reflectance spectra at
$\lambda > 0.8$ μm. Here we present the first spectroscopic implement-
ation of this technique by reporting that 2000 OK$_{67}$ is very
likely to be a hot classical interloper in cold classical orbital
parameter space. 2000 OK$_{67}$ has been variably attributed
membership in both the hot and cold classical dynamical
classes (e.g., Peixinho et al. 2015; Müller et al. 2020),
depending on where researchers have chosen to divide the two
populations in terms of inclination. While our assignment of
2000 OK$_{67}$ to the hot classicals is partly based on the fact that
its reflectance spectrum does not level out toward the NIR
nearly as much as those of the other cold classical targets in our
sample, it is important to note that distinction of hot classical
TNOs from cold classical TNOs cannot be done by
characterization of their $z$-band reflectance properties alone.
Two of the cold classical TNOs observed by Col-OSSOS have
colors that suggest that their reflectance spectra may be close to
linear from 0.4–1.0 μm (Pike et al. 2017). Indeed, Arrokoth
also shares this trait, as its average optical spectral gradient
remains approximately constant at least as far to the red as
$\sim 1.0$ μm (Stern et al. 2019; Grundy et al. 2020). Our
classification of 2000 OK$_{67}$ is based upon the combination of
its near linear reflectance spectrum from 0.55–1.0 μm, its
relatively low optical redness in comparison to the average for
cold classical TNOs (see Table 3), and its already ambiguous
dynamical classification. Note that 2000 OK$_{67}$ would not look
out of place among the cold classics when compared in terms of
size and albedo ($D = 164^{+33}_{-45}$ km and $p_V = 0.169^{+0.159}_{-0.052}$
respectively; see Müller et al. 2020). We caution that multiple
properties of a classical TNO must be considered before it may be
assigned to either the hot or cold dynamical classes.

7. Discussion

7.1. Silicates

Based on their finding that the cold classicals occupy a
unique region of $g - r/r - z$ color space, Pike et al. (2017)
inferred that their reflectance spectra have distinct behavior at
$\lambda > 0.9$ μm that might possibly result from the presence of
surface material on cold classicals that has an absorption band
at those wavelengths, and is not present on the surfaces of the
dynamically hot TNOs. We find, however, that there is no
obvious absorption band present at $\lambda > 0.9$ μm in any of our
reflectance spectra. Inclusion of published $J$-band photometric
data for our targets (McBride et al. 2003; Delsanti et al. 2004;
Schwamb et al. 2019) further strengthens this nondetection.
Rather than the presence of an absorption band, all three cold
classical targets in our sample that have $J$-band photometric
measurements exhibit reflectance properties that are more
consistent with the existence of featureless linear continuum in
their spectra between $\sim 1.0$ μm and $\sim 1.2$ μm.

The nondetection of a silicate absorption band is disappoint-
ing, but given the low densities so far typically determined for
cold classical TNOs, it is not surprising (see Vilenius et al.
2014; Müller et al. 2020). If anhydrous mafic silicates are
present on the surfaces of the cold classicals, it is plausible that
their strong 1.0 μm absorption bands may be masked by any
opaque macromolecular organics they are mixed with (e.g., de
Bergh et al. 2008). Laboratory studies have shown that
masking of the 1.0 μm band may be achieved when irradiated
organics are present at only half the concentration of the mafic
silicate component within a porous refractory mantle (e.g.,
Poch et al. 2016). Because of this possible masking of the
1.0 μm silicate band, our reflectance spectra can neither rule out
nor confirm the presence of silicates on the surfaces of our
targets. IR observations of these cold classical TNOs at
$\lambda > 2.5$ μm may fare better in directly detecting the signatures of
mafic silicates on the surfaces of cold classical TNOs (e.g.,
Parker et al. 2016).

7.2. Carbonaceous Material

As in previous spectroscopic studies of cold classicals and
other extremely red TNOs, the reflectance properties of our
targets appear most consistent with those of irradiated residues
comprised of complex macromolecular organic compounds
(e.g., Cruikshank et al. 1998; Barucci et al. 2006; Brunetto
et al. 2006; Grundy et al. 2020). Like our targets, such
materials have optical reflectance spectra that broadly consist of
a linear continuum with a strong positive gradient that may
curve downward close to the boundary between the optical and
NIR ranges (e.g., de Bergh et al. 2008).

Delocalized $\pi$-bonded electrons within organic molecules
absorb light via $\pi-\pi^*$ and $n-\pi^*$ excitation; the energy structure of
these delocalized electrons is governed by the size and
clustering of the conjugated $\pi$-bond networks in which they
reside. In turn, these factors are influenced by the inter-
connected compositional and structural properties of the
organic molecules themselves, such as the $sp^2$/$sp^3$ bond ratio,
the extent of $sp^2$ bond clustering, the abundance ratios of
various constituent elements (e.g., C/N, C/H, and C/O), and

Seccull, Fraser, & Puza
the number of nitrogen- and oxygen-bearing heterocycles and auxochrome functional groups. In concert, all of these factors determine the albedo of an irradiated organic sample or residue, and the gradient and curvature of its reflectance spectrum from the near-UV to the nearest IR (e.g., McKay 1996; Imanaka et al. 2004; Cruikshank et al. 2005; Bernard et al. 2006; Brunetto et al. 2006; de Bergh et al. 2008).

Unfortunately, the mapping between the optical reflectance properties of an irradiated organic sample and the properties of its diverse constituent macromolecules is often intrinsically degenerate (Bernard et al. 2006). As a result, it is not possible to use our reflectance spectra to diagnostically characterize any carbonaceous material present on the surfaces of our targets. Sufficiently sensitive observations at \( \lambda > 1.0 \mu \text{m} \) stand a better chance of being useful in efforts to characterize any refractory organics on the surfaces of cold classical TNOs through detection and characterization of the vibrational molecular absorption bands that refractory organics often exhibit at IR wavelengths (e.g., Imanaka et al. 2004; de Bergh et al. 2008; Materese et al. 2014, 2015). Sufficiently sensitive observations of cold classical TNOs at near-UV wavelengths may also be informative about the carbonaceous materials on their surfaces, as carbon-rich phases exhibit multiple near-UV spectral behaviors that are diagnostic of both their composition and physical state (Hendrix et al. 2016; Applin et al. 2018).

### 7.3. The Cold Classical Surface Type

While optical reflectance spectra of organics cannot be used for precise characterization, it is possible to use them to tell different classes of carbonaceous material apart (e.g., de Bergh et al. 2008; Fraser & Brown 2012). Because organic compounds are predicted to dominate the optical and very-NIR reflectance properties of very red TNOs (e.g., Dalle Ore et al. 2015), the distinctly consistent overall shape of the reflectance spectra of all our 100 km scale cold classical targets suggests that the class of refractory organics on their surfaces is similar from object to object. If this homogeneity is a property shared by all larger members of the cold classical population, as suggested by their unimodal and relatively narrow color and albedo distributions (Pike et al. 2017; Schwamb et al. 2019; Müller et al. 2020), it supports the prediction that the cold classical TNOs are likely to have both formed under similar conditions and experienced a common history of surface processing. Laboratory studies support this idea by repeatedly showing that if refractory organics are formed from different initial ice mixtures, processed in different ways, or processed to different extents, they will typically exhibit reflectance spectra with large differences in shape, unlike those of the cold classicals (Imanaka et al. 2004; Cruikshank et al. 2005; Bernard et al. 2006; de Bergh et al. 2008; Materese et al. 2014, 2015; Poston et al. 2018).

While the composition and molecular structure of any refractory organics on the surfaces of our targets may define their reflectance properties, the role of the physical properties of their surfaces, such as grain size distribution or porosity, must not be ignored. The physical properties of the surface of a TNO may determine the properties of its reflectance spectrum independently of composition (e.g., Poch et al. 2016; Cloutis et al. 2018). The homogeneous shape of the reflectance spectra of cold classical TNOs may therefore indicate that their surfaces have similar physical properties, while the physical properties of the surfaces of the dynamically hot TNOs may be more diverse. Unfortunately, without high phase angle observations of TNOs, it is not currently possible to disentangle any effects that the physical properties and composition of their surfaces have on their reflectance spectra. High phase angle measurements from spacecraft will be required to examine the physical properties of TNO surfaces (see Porter et al. 2016).

It is worth noting that some of the reflectance spectra of dynamically hot TNOs (here we include the centaurs) also exhibit a flattening of their optical gradients toward the NIR (e.g., Alvarez-Candal et al. 2008; Fornasier et al. 2009; Merlin et al. 2010). In particular, the behavior appears more commonly in the reflectance spectra of TNOs with similar optical redness to the cold classicals. In contrast to that of the cold classicals, however, the flattening behavior observed for dynamically hot TNOs is diverse in both the shape and the wavelength at which it occurs. Reports show that the spectra of dynamically hot TNOs can begin to diverge from their linear continuum slopes anywhere within the range 0.65−1.4 \( \mu \text{m} \) (e.g., Cruikshank et al. 1998; Boehnhardt et al. 2004; Merlin et al. 2005, 2010, 2017; Barucci et al. 2006; Fornasier et al. 2004, 2009; Alvarez-Candal et al. 2008; Gourgeot et al. 2015; Schwamb et al. 2019). By comparison, all of our cold classical reflectance spectra flatten within the narrower range of 0.75−0.9 \( \mu \text{m} \). Therefore, while flattening behavior is not a unique quality of the reflectance spectra of cold classical TNOs, the shape of their reflectance spectra is remarkably consistent in comparison to those of the dynamically hot TNOs. Our cold classical reflectance spectra support the prediction of Pike et al. (2017) that the cold classical TNOs (at least those observable from current ground-based facilities) comprise a unique surface type among TNOs. Not only do the cold classicals have distinct distributions in terms of optical color and albedo, they also appear to have reflectance spectra with a consistent characteristic shape from optical wavelengths to the nearest IR.

### 7.4. Comparison to Arrokoth

Benecchi et al. (2019) noted that their photometric measurements of cold classical TNOs indicated the existence of an interesting but not statistically significant increase in the F606W − F814W color of cold classicals of decreasing size. The F814W filter used by Benecchi et al. (2019) has a bandpass covering 0.7−0.97 \( \mu \text{m} \) and includes the region in which our cold classical reflectance spectra flatten. An increase in F606W − F814W color for smaller cold classicals may therefore be interpreted as a shift toward longer wavelengths of the point at which a reduction in the spectral gradient occurs.

We note that not one of the five nearly randomly selected ~100 km scale cold classical TNOs in our sample has a reflectance spectrum like that of the ~10 km scale Arrokoth, which has linearly increasing reflectance at least as far to the red as ~1.0 \( \mu \text{m} \). The potential size-color trend hinted at by Benecchi et al. (2019) and the absence of linear spectral behavior in our sample at \( \lambda > 0.8 \mu \text{m} \) raises the question as to whether spectral flattening at \( \lambda > 0.8 \mu \text{m} \) is more common in the reflectance spectra of large cold classicals than it is in those of small ones.

Our spectra unfortunately do not have sufficient NIR wavelength coverage for us to precisely measure the central wavelength of their downward curvature at \( \lambda > 0.8 \mu \text{m} \). Nor is our sample large enough for statistically significant analysis. As a result, further speculation on this suggested trend without a stronger foundational data set would be reckless. We conclude
here by stating that the size-color trend for cold classical TNOs hinted at by Benecchi et al. (2019) appears, at least in broad qualitative terms, to be consistent with the absence of linear spectral behavior at $\lambda > 0.8 \mu m$ in the reflectance spectra of all our $\sim100$ km scale cold classical targets.

8. Conclusions

Following reports by Pike et al. (2017) and Terai et al. (2018) that the cold classical TNOs have distinct photometric color properties, and potentially even an absorption band in their reflectance spectra at $\lambda > 0.8 \mu m$, we observed the reflectance spectra of six TNOs currently residing in the cold classical dynamical range. Our reflectance spectra, which cover 0.55–1.0 $\mu m$, are the first to be observed in the optical range for any of our targets. We find that the reflectance spectra obtained are consistent with coarse reflectance spectra derived from previously published photometric colors for our targets.

Five of the six targets we observed, including Borasisi-Pabu, 2001 QY$_{297}$, 2001 HZ$_{58}$, 2013 UL$_{15}$, and 2014 UE$_{255}$, have reflectance spectra that are linear and red in the range 0.55 $\leq \lambda < 0.75 \mu m$, but show a broadly consistent flattening at $\lambda > 0.8 \mu m$. This result is consistent with the reported lower average $r-z$ color of cold classics in comparison to dynamically hot TNOs with similar $g-r$ color, and the suggestion that the cold classics occupy a distinct surface class (Pike et al. 2017). We find no evidence that the observed flattening in our spectra is associated with the presence of an absorption band at $\lambda \sim 1.0 \mu m$; anhydrous mafic silicates remain elusive on the surfaces of TNOs. We predict that the similar shape of the reflectance spectra of these five targets arises due to the presence of similar refractory organics on their surfaces and/or similarity between the physical properties of their surfaces. This apparent consistency between the reflectance properties of cold classics aligns well with their unimodal and relatively narrow color and albedo distributions, supporting predictions that the cold classical TNOs formed under similar conditions and have since experienced similar types and extents of surface evolution.

We assert that the sixth TNO in our sample, 2000 OK$_{67}$, is likely to be a hot classical TNO interloping in the cold classical dynamical range. While this part is because the reflectance spectrum of 2000 OK$_{67}$ is close to linear across the full 0.55–1.0 $\mu m$ range, we caution that the presence or absence of flattening at $\lambda > 0.8 \mu m$ in a TNO’s reflectance spectrum is insufficient on it own for the purposes of classification. Our assignment of 2000 OK$_{67}$ to the hot classicals is also based upon its sporadic assignment to the hot classicals in prior reports, and its relatively low optical spectral gradient in comparison to the average for cold classical TNOs.

Future sufficiently sensitive observations at near-UV and IR wavelengths will be crucial in making headway in determining whether refractory organics are responsible for the distinct reflectance properties of cold classical TNOs, as these wavelength regions have been shown to exhibit features that are diagnostic of both the chemical composition and molecular structure of complex carbonaceous materials (e.g., Materese et al. 2014, 2015; Hendrix et al. 2016; Applin et al. 2018). Observations of cold classical TNOs at high phase angles (which are only feasible from vantage points at large heliocentric distances; e.g., Porter et al. 2016) will also be required to explore any possible connection between the physical properties and the distinct reflectance properties of cold classical surfaces.

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Facility: ESO: VLT-UT1(FORS2).

Software: Astropy (Astropy Collaboration et al. 2013), ESO Reflex (Freudling et al. 2013), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020).

Appendix

Figures 2–4, respectively, show our TNO reflectance spectra at their native resolution, the consistency of the spectra of our solar calibrator stars, and the wavelength-dependent S/N of the binned TNO reflectance spectra.
Figure 2. Reflectance spectra presented in Figure 1, but prior to spectral binning, are plotted here in black. The associated binned spectra are plotted with yellow points. The binning factor (i.e., number of resolution elements per bin) used to produce the binned spectrum from the unbinned one is presented at the bottom of each panel.
Figure 3. Unbinned stacked spectra of the solar twins used to calibrate each of our TNO spectra. They are scaled to unity at 0.7 μm, but are not corrected for instrument response. The shapes of the star spectra are very consistent across our full wavelength coverage, with the only noteworthy variation between them occurring in bands of moderate telluric absorption at λ ≈ 0.77 μm and 0.93–0.95 μm. The consistency of our calibrator star spectra shows that any variation between the reflectance spectra of our TNO targets primarily results from differences between the intrinsic reflectance properties of the TNOs themselves.

Figure 4. Wavelength-dependent S/N of our reflectance spectra. From left to right along the top and then the bottom row, the panels present data for 2014 UE225, Borasisi-Pabu, 2013 UL15, 2001 HZ58, 2001 QY297, and 2000 OK67.

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10
