

THE SURFACE COMPOSITION OF LARGE KUIPER BELT OBJECT 2007 OR10

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ABSTRACT

We present photometry and spectra of the large Kuiper belt object 2007 OR10. The data show significant near-infrared absorption features due to water ice. While most objects in the Kuiper belt with water ice absorption this prominent have the optically neutral colors of water ice, 2007 OR10 is among the reddest Kuiper belt objects known. One other large Kuiper belt object—Quaoar—has similar red coloring and water ice absorption, and it is hypothesized that the red coloration of this object is due to irradiation of the small amounts of methane able to be retained on Quaoar. 2007 OR10, though warmer than Quaoar, is in a similar volatile retention regime because it is sufficiently larger that its stronger gravity can still retain methane. We propose, therefore, that the red coloration on 2007 OR10 is also caused by the retention of small amounts of methane. Positive detection of methane on 2007 OR10 will require spectra with higher signal to noise. Models for volatile retention on Kuiper belt objects appear to continue to do an excellent job reproducing all of the available observations.

Key words: Kuiper belt: general – Kuiper belt objects: individual (2007 OR10) – molecular processes – planets and satellites: atmospheres

Online-only material: color figures

1. INTRODUCTION

The large majority of Kuiper belt objects (KBOs) contain no detectable volatile ices on their surfaces, but a small number of the largest objects have been found to have signatures of CH₄, CO, or N₂, all ices with high vapor pressures at Kuiper belt temperatures. After the discovery of volatiles on the surfaces of Eris (Brown et al. 2005), Makemake (Brown et al. 2007a), and Sedna (Barucci et al. 2005), Schaller & Brown (2007b) proposed a simple method for assessing the possibility of volatile retention on KBOs. For each relevant ice, they compared the volatile loss due to Jeans escape—the slowest of many possible escape mechanisms—to the total volatile inventory of the object and divided the Kuiper belt into objects which could and could not have retained that ice over the age of the solar system. Only a handful of objects are massive enough or cold enough to be able to retain volatiles. Their model provided a compelling explanation of the low abundance of N₂ on Makemake (Brown et al. 2007a; Tegler et al. 2008), which is smaller than Pluto and Eris, and was also used to successfully predict the presence of methane on Quaoar (Schaller & Brown 2007a). To date, the volatile retention model has been completely successful predicting which objects will and which will not have detectable surface volatiles, with the unique exception being the large KBO Haumea, which is the parent body of the only collisional family known in the Kuiper belt (Brown et al. 2007b) and clearly had an unusual history.

We provide an update to the Schaller & Brown (2007b) calculations in Figure 1. We have used new vapor pressure data from Fray & Schmitt (2009) and, where possible, have used measured sizes and masses of the largest KBOs. For Quaoar, the current measured diameter is 890 ± 70 km implying a density of 4.2 ± 1.3 g cm⁻³ (Fraser & Brown 2010), but we assume the upper limit of size as the smaller sizes lead to physically implausible densities. (Note that even for the smaller size and

higher density, however, Quaoar is still expected to retain surface methane.) The size of 2007 OR10 is unmeasured, so, as will be justified below, we assume that it has an albedo identical to the 0.18 albedo of Quaoar that gives the size that we assume above, though we allow albedo uncertainties of 50% in either direction. As in Schaller & Brown (2007b), we calculate an “equivalent temperature” for each object by integrating the volatile loss through the object’s entire orbit and determining the temperature that an object in a circular orbit would have to have, to lose the volatile at that rate.

For our assumed albedo range, 2007 OR10 is somewhere between the fourth and seventh largest object known in the Kuiper belt. Its potential size spans the range between the small volatile-poor objects and the handful of volatile-rich objects. 2007 OR10 is thus an excellent test object for our understanding of volatile retention in the outer solar system. We explore the surface composition of this object below using a combination of near-IR spectroscopy and multi-wavelength photometry.

2. OBSERVATIONS

The low-resolution, near-infrared spectrum of 2007 OR10 was obtained on 2010 September 20 (UT) using the Folded-port Infrared Echelle (FIRE) spectrograph on the 6.5 m Magellan Baade Telescope (Simcoe et al. 2008, 2010). FIRE’s prism-dispersed mode provides continuous coverage of the 0.85–2.45 μ m band with a variable resolution of $\lambda/\Delta\lambda = 250$ –350. 2007 OR10 was acquired and its motion confirmed using FIRE’s *J*-band imaging channel. The source was maintained on the 0.6 slit by manual corrections to sidereal tracking. Two series of ABBA dither exposure sequences were obtained with integrations of 120 s at an average airmass of 1.04. These were followed by a single ABBA sequence of the G2 V star HD 211544 ($V = 10.9$) at a similar airmass. Exposures of a quartz flat-field lamp (set at 1.2 V and 2.2 V) and arc lamps (NeAr) were obtained for pixel response and wavelength calibration. Data were reduced using the methods described in

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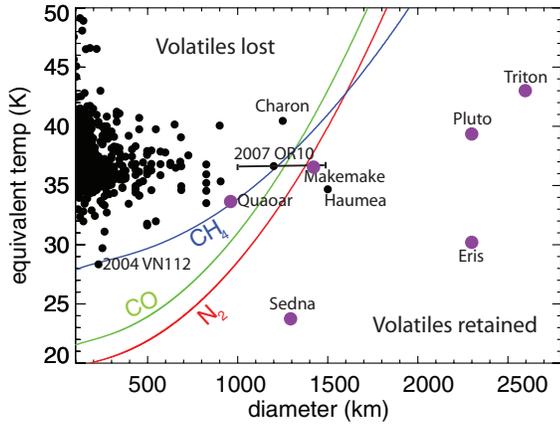


Figure 1. Plot of volatile retention and loss in the Kuiper belt, updated from Schaller & Brown (2007b). Objects to the left of the CH_4 , CO , and N_2 lines are too small and too hot to retain any of those surface volatiles over the age of the solar system, while objects to the right can retain those volatiles. All objects shown in purple have had CH_4 measured on their surfaces. Some have additionally had N_2 or CO detected. No objects to the left of the lines have had any of these volatiles detected.

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

Brown et al. (2007a). The spectrum was converted into relative reflectance as well as corrected for telluric absorption and instrument response by dividing the raw spectrum of 2007 OR10 by the spectrum of the solar type star HD 211544.

Photometry were obtained with the Wide-Field Camera 3 (WFC3) on the *Hubble Space Telescope* during cycles 17 (GO Program 11644) and 18 (GO Program 12234). In cycle 17, two 130 s exposures were taken in the F606W and F814W filters, and two 453 s exposures were taken in the F139M and F153M filters. During the cycle 18 observations, two exposures were acquired in each of the F606W, F775W, F098M, and F110W with exposure times of 128 s, 114 s, 115 s, and 207 s, respectively. As well, four exposures of 275 s were acquired in the F127M filter. For both the cycles 17 and 18 observations, 3'' dithers were applied between image pairs to reduce the effects of cosmic rays and pixel defects, with the exception of the F127M observations, in which two images were taken at each dither position. All observations in a cycle were acquired within a single orbit, minimizing the effect of any light curve 2007 OR10 may have. All data were processed through CalWFC3 version 2.3, the standard WFC3 image processing pipeline (Rajan et al. 2010). Circular apertures were used to measure the photometry. *Tiny Tim* version 7.1 point-spread functions (Krist 1993) were used to generate infinite aperture corrections as well as interpolate over any bad pixels flagged during the image reductions.

Fluxes were converted to relative reflectance by comparing to fluxes computed using the *calphot* routine for a model solar spectrum (Kurucz 1979) provided as part of the *iraf* package *stdas.synphot*. Approximate absolute reflectances were then obtained by scaling the F606W relative reflectance to a value of 0.18, our assumed albedo of 2007 OR10. All are shown in Table 1. Before calculating relative reflectances, the cycle 18 magnitudes were adjusted upward by 0.03 to account for the difference in the F606W magnitudes between the two epochs. The small magnitude difference is an expected consequence of object rotation.

3. RESULTS

Figure 2 shows the FIRE reflectance spectrum with the WFC3 photometric points overlaid. We scale all points to an albedo of

Table 1
Photometry of 2007 OR10

Filter	2007 OR10 (mag)	Sun (mag)	Reflectance
Cycle 17			
F606W	21.68 ± 0.02	-27.00	0.18
F814W	21.39 ± 0.01	-26.54	0.37
F139M	22.06 ± 0.01	-25.34	0.59
F153M	22.47 ± 0.02	-25.09	0.51
Cycle 18			
F606W	21.65 ± 0.02	-27.00	0.18
F775W	21.32 ± 0.02	-26.64	0.34
F098M	21.37 ± 0.01	-26.13	0.52
F110W	21.62 ± 0.02	-25.78	0.58
F127M	21.84 ± 0.01	-25.54	0.58

0.18 in the F606W filter, though we note that the true value of the albedo has not been measured. To increase the signal to noise in the FIRE spectrum, we also plot the median of every 32 spectral channels, oversampled by a factor of two, to simulate how the spectrum would appear to a lower resolution spectrograph. Uncertainties on these data points are obtained by calculating the median absolute deviation of each 32-channel sample, which we multiply by 1.48 to obtain what would be the standard deviation in a normally distributed sample, and then divide by the square root of the number of spectral channels, approximating the standard deviation.

The FIRE spectrum and the WFC3 photometry are in broad agreement in the area of overlap, though the match is imperfect. We suspect that the differences are due to differential refraction in the FIRE data, which, for these early attempts at tracking a moving object, were not obtained with the slit aligned along the parallactic angle. Both data sets show, in particular, a very red optical slope and a distinct absorption around $1.5 \mu\text{m}$. The FIRE spectrum shows an additional broad absorption feature near $2.0 \mu\text{m}$ and, potentially, additional features redward. Absorptions at 1.5 and $2.0 \mu\text{m}$ are the characteristic features of water ice, which is frequently found on the largest KBOs (Barkume et al. 2008).

Figure 3 compares the spectrum of 2007 OR10 to a modeled spectrum of a surface consisting of a mixture of water ice and a neutral material. We place no special significance on the precise water ice surface model, as many different types of specific parameters yield similar modeled spectra, but, for concreteness we use the water ice absorption coefficients of Grundy & Schmitt (1998) and construct a simple Hapke model (Hapke 1993) with $50 \mu\text{m}$ grains at 50 K spatially mixed with equal amounts of a neutral material with an albedo of 80%. The model spectrum is sampled at the same resolution as the smoothed spectrum of the object. Even at the low signal-to-noise ratio of the data, the water ice model provides an excellent match to the spectrum redward of $1.4 \mu\text{m}$. At shorter wavelengths, however, 2007 OR10 is significantly redder than water ice.

Most of the KBOs with significant water ice absorption, such as Orcus, Haumea, and the Haumea family members, have nearly neutral optical colors (Barkume et al. 2008). The most notable exception to this trend is Quaoar, which has water ice absorptions nearly identical in depth to those of 2007 OR10 and is almost as red. A spectrum of Quaoar (Jewitt & Luu 2004) over the same wavelength range is shown, for comparison, in Figure 3. The coloring of Quaoar was suggested by Schaller & Brown (2007a) to be due to the effects of methane, which turns red with irradiation (Brunetto et al. 2006). Quaoar, as seen in

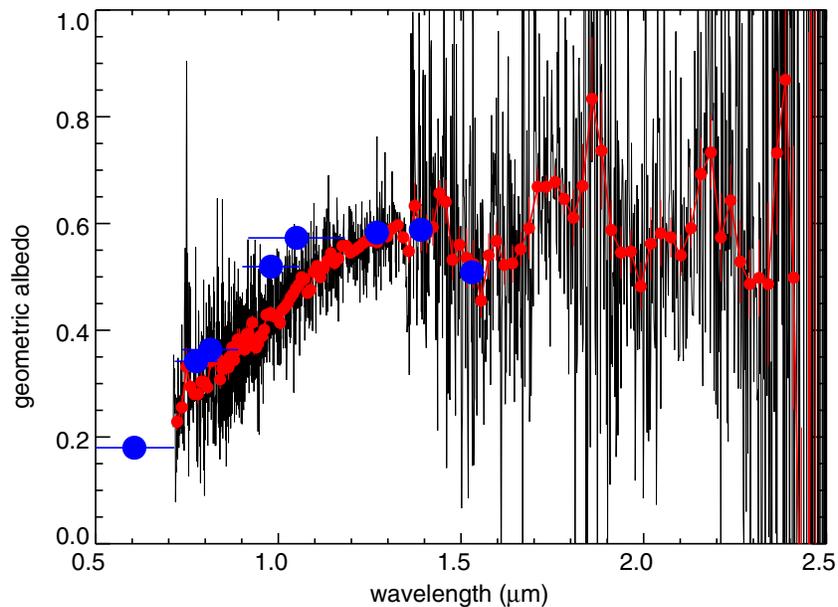


Figure 2. Absolute reflectance spectrum of 2007 OR10. The gray lines show the full resolution FIRE spectrum of 2007 OR10. Regions of poor atmospheric transmission are easily identified by the substantial increase in noise. To increase the signal to noise, we show a 32-channel median filtered version of the spectrum in red, with error bars derived from the scatter in the 32 channels. The large blue points show the WFC3 photometry, with the horizontal error bars representing the width of each of the filters used. The uncertainties in the WFC3 photometry are smaller than the size of the data points. As the albedo of 2007 OR10 is not known, both data sets are arbitrary normalized. The FIRE and WFC3 data both clearly show a $\sim 1.5 \mu\text{m}$ absorption feature, while the FIRE spectrum also shows an absorption around $2.0 \mu\text{m}$. These absorption features are characteristic of water ice on the surface.

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

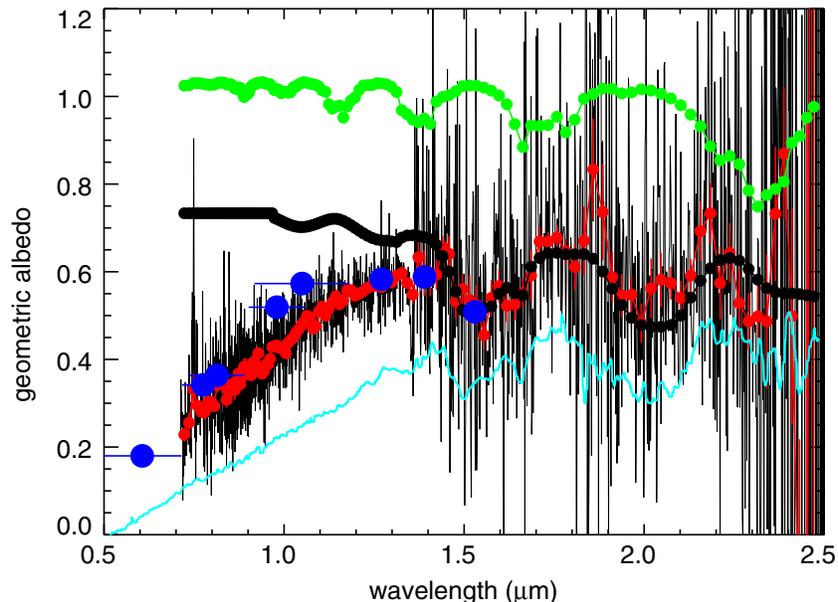


Figure 3. Spectrum of 2007 OR10 compared to simple surface models. The black points show a modeled spectrum with a mixture of water ice and a neutral material. This model clearly reproduces the prominent absorption features at 1.5 and $2.0 \mu\text{m}$, but cannot account for the very red color of the object. Such a coloration on the equally water-ice-rich object Quaoar is hypothesized to be due to irradiation of remnant methane, which is detected on Quaoar. The spectrum of Quaoar (Jewitt & Luu 2004) is shown for comparison in light blue, offset downward by 0.15 units for clarity. The green points show a modeled spectrum with a mixture of methane ice and a neutral material, shifted upward by 0.3 units for clarity. While the signal to noise of the 2007 OR10 spectrum is insufficient to positively detect any methane features, the large deviation from the water ice model at $2.3 \mu\text{m}$ occurs near the largest absorption expected from methane.

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Figure 1, is barely large enough or cold enough to retain methane on its surface and the amount left is small and detectable only at high signal to noise.

2007 OR10, depending on its precise size, could be in a similar regime of volatile retention as Quaoar. If true, the Quaoar-like optical color of 2007 OR10 could be a signature

of the retention and irradiation of methane on the KBO. Indeed, if 2007 OR10 is assumed to have the same albedo as Quaoar—as the close match in visible and near-infrared spectra might suggest—2007 OR10 sits in almost precisely the same volatile loss regime as Quaoar. While the perihelion distance of 2007 OR10 of only 33.6 AU (compared to Quaoar’s of 41.6 AU)

makes it significantly hotter than Quaoar, the significantly larger size of 2007 OR10 allows its larger gravitational pull to nonetheless potentially retain methane.

If the hypothesis that the extreme red coloration on 2007 OR10 is—like that of Quaoar—caused by the irradiation of a small amount of remaining surface methane is correct, we predict that methane absorption should be visible on 2007 OR10 as it is on Quaoar. Figure 3 also shows a simple model of a surface including solid methane and a neutral component. The model is simply the water model from above but with the absorption coefficients of methane (Grundy et al. 2002) replacing those of water. The spectrum is shifted upward by 0.3 units for clarity. The strongest absorption feature of methane, at $2.3\ \mu\text{m}$, does indeed correspond with a large variation from the water ice model. We conclude that while these data do not have sufficient signal to noise, particularly in the K band, to positively detect methane on 2007 OR10, the existence of this volatile is plausible, and would provide a pleasing explanation for the extreme red coloration of the KBO.

The large KBO 2007 OR10 provides an excellent test of our understanding of volatile loss and retention on the surfaces of objects in the outer solar system. While the size of 2007 OR10 has yet to be measured, the simple assumption that it has an identical albedo to Quaoar—the object whose spectrum most resembles its spectrum—places 2007 OR10 into a regime where it would be expected to retain trace amounts of methane on its surface. Such an object would be expected to have red optical coloration from methane irradiation, which both Quaoar and 2007 OR10 do have. In addition, such an object should have detectable signatures of methane if observed at sufficient signal to noise. Such methane signatures have been detected on Quaoar, but require higher signal to noise to be positively identified on

2007 OR10. While additional measurements of the size and spectrum of 2007 OR10 are clearly required, we conclude that volatile retention models (Schaller & Brown 2007b) appear to continue to flawlessly predict both the presence and absence of volatiles on all objects in the Kuiper belt which have been observed to date.

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