2004 EW\textsubscript{95}: A Phyllosilicate-bearing Carbonaceous Asteroid in the Kuiper Belt

Tom Seccull\textsuperscript{1}, Wesley C. Fraser\textsuperscript{1}, Thomas H. Puzia\textsuperscript{2}, Michael E. Brown\textsuperscript{3}, and Frederik Schönbeck\textsuperscript{4}

\textsuperscript{1}Astrophysics Research Centre, Queen’s University Belfast, Belfast BT7 1NN, UK; tseccull01@qub.ac.uk
\textsuperscript{2}Institute of Astrophysics, Pontificia Universidad Católica de Chile, Av. Víncula Mackenna 4860, 7820436, Santiago, Chile
\textsuperscript{3}Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
\textsuperscript{4}Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstraße 12-14, D-69120 Heidelberg, Germany

Received 2018 January 29; revised 2018 March 2; accepted 2018 March 3; published 2018 March 15

Abstract

Models of the Solar System’s dynamical evolution predict the dispersal of primitive planetesimals from their formative regions among the gas-giant planets due to the early phases of planetary migration. Consequently, carbonaceous objects were scattered both into the outer asteroid belt and out to the Kuiper Belt. These models predict that the Kuiper Belt should contain a small fraction of objects with carbonaceous surfaces, though to date, all reported visible reflectance spectra of small Kuiper Belt Objects (KBOs) are linear and featureless. We report the unusual reflectance spectrum of a small KBO, (120216) 2004 EW\textsubscript{95}, exhibiting a large drop in its near-UV reflectance and a broad shallow optical absorption feature centered at \(\sim 700\) nm, which is detected at greater than 4σ significance. These features, confirmed through multiple epochs of spectral photometry and spectroscopy, have respectively been associated with ferric oxides and phyllosilicates. The spectrum bears striking resemblance to those of some C-type asteroids, suggesting that 2004 EW\textsubscript{95} may share a common origin with those objects. 2004 EW\textsubscript{95} orbits the Sun in a stable mean motion resonance with Neptune, at relatively high eccentricity and inclination, suggesting it may have been emplaced there by some past dynamical instability. These results appear consistent with the aforementioned model predictions and are the first to show a reliably confirmed detection of silicate material on a small KBO.

Key words: Kuiper belt objects: individual (2004 EW95) – minor planets, asteroids: general – techniques: photometric – techniques: spectroscopic

1. Introduction

Current models of the Solar System’s dynamical evolution, such as the Nice model (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005; Levison et al. 2011), predict that the Kuiper Belt should largely be composed of objects that formed beyond the giant planet region. Concurrently, the Grand Tack model (Walsh et al. 2011, 2012) posits that the primitive carbonaceous asteroids formed among the giant planets and were injected into the outer asteroid belt due to the early migrations of Jupiter and Saturn. By the same mechanism the Grand Tack model also predicts that carbonaceous asteroids could have been scattered outward into the Kuiper Belt region, suggesting that a small number of objects beyond Neptune would possess primitive, dark, carbon-rich, asteroidal surfaces like those of C/D/P-type asteroids.

The optical (400 \(\leq\lambda\leq 900\) nm) reflectance spectra of small Kuiper Belt Objects (KBOs) typically exhibit a red, linear, featureless slope that reveals little about their surface composition (Fornasier et al. 2009). So far the only material commonly found on the surfaces of small KBOs is water ice, which characteristically absorbs in the near infrared (NIR) at \(\sim 1.5\) \(\mu\)m and \(\sim 2.0\) \(\mu\)m (Barucci et al. 2011; Brown et al. 2012). No diagnostic optical features have been confirmed.

(120216) 2004 EW\textsubscript{95} is a small 3:2 resonant KBO with absolute magnitude \(H_R = 6.31 \pm 0.05\) (Peixinho et al. 2015) and radiometric diameter \(r = 291.1_{-25.9}^{+20.3}\) km (Mommert et al. 2012). Its reflectance spectrum was initially revealed to be atypical of KBO spectra from optical and NIR spectral photometry gathered with the \textit{Hubble Space Telescope} (HST; Fraser et al. 2015). Of the eight small outer Solar System objects observed in \textit{HST} GO-Program 12234, 2004 EW\textsubscript{95} was unique in that instead of exhibiting a linear optical spectrum, it possessed an apparent upward curvature through the optical range. This peculiar property of the object, along with hints of a drop in its near-UV reflectance (Fraser et al. 2015), warranted subsequent spectroscopic observations.

2. Observations

We observed 2004 EW\textsubscript{95} twice at the European Southern Observatory’s (ESO’s) Very Large Telescope (VLT), during 2014 August 3 and 2017 April 22–23 using the X-Shooter (Vernet et al. 2011) and FORS2 (Appenzeller et al. 1998) spectrographs, respectively.

X-Shooter is a medium-resolution echelle spectrograph with three arms covering the near-UV/blue (UVB; 300–560 nm), visual (VIS; 550–1020 nm), and NIR (1024–2480 nm) spectral range. While 2004 EW\textsubscript{95} was observed in all three of X-Shooter’s arms simultaneously, the NIR observations had such a low signal-to-noise ratio (S/N) that they could not be properly reduced. Hence, from this point we only consider the UVB and VIS observations. The UVB and VIS detectors share a common pixel scale of 0\textdegree 16 and slit length of 11\textquoteleft. We set the UVB and VIS slits to widths of 1\textquoteleft 0 and 0\textquoteleft 9, each providing a respective resolving power of \(\sim 5100\) and \(\sim 8800\). All observations were performed with a UVB and VIS detector readout binning of 1 \times \times 2, except for observations of the solar calibrator HD 117286, when no binning was performed. The difference in binning between 2004 EW\textsubscript{95} and HD 117286 produces no observable change to the features we detect in the UVB and VIS reflectance spectrum when compared to those calibrated with the other stars.

The X-Shooter observations were performed in a three-point dither pattern to mitigate bad pixel artifacts and contamination.
by cosmic rays in the stacked spectrum. The slit was realigned
to the parallactic angle at the beginning of each observation
to reduce the effects of atmospheric differential refraction; this was
especially important in light of X-Shooter’s disabled Atmospheric
Dispersion Corrector (ADC) at the time of observing. Of
nine total observed exposures of 2004 EW95, seven were usable.
Two exposures where the object appeared to drift off the slit
were ignored during data reduction. Three solar calibrator stars,
HD 117286, Hip 075235, and Hip 077439, were similarly
observed adjacent in time to 2004 EW95 and at similar airmass.
Flux calibrators EG 274 and Feige 110 were observed as part of
the standard calibration program. Details of observing conditions
are reported in Table 1.

FORS2 is a multipurpose spectrograph and imager. We
obtained FORS2 spectra of 2004 EW95 over two nights in
Long Slit Spectroscopy mode with a two-point dither pattern,
using the blue sensitive E2V detector, the standard resolution
collimator, and the 600B+22 grism. At the beginning of each
image pair the slit was realigned to the parallactic angle. On
each night four exposures were obtained for 2004 EW95. In
addition, on each night two solar calibrators were observed just
before and just after 2004 EW95. These calibrators were: HD
106436, HD 106649, HD 136122, and HD 140854. Two
additional solar calibrators (BD-00 2514 and TYC-4949-897-
1) were observed two hours prior to 2004 EW95 on night one.
All of the solar calibrators were observed at similar airmass
to 2004 EW95. BD-00 2514, the star that produced the lowest
calibration residuals below 400 nm and at 517 nm, was used to
calibrate the science spectra presented in Section 4. Flux
standards were observed, but the images were later found to be
saturated and therefore useless. During the reduction process all
of the FORS2 spectra were corrected for airmass extinction
using the instrument extinction table. Over both nights the
cloud cover never warranted greater than a “Clear” designation
and does not appear to have affected the slope of the final
spectra. Further details on the FORS2 observations are reported
in Table 1.

3. Data Reduction

Standard reduction steps (including order rectification and
merging, and flux calibration in the case of X-Shooter) were
performed for all of the observed spectra with the ESO-
provided instrument pipelines (X-Shooter v.2.7.1; FORS2
v.5.3.2, Modigliani et al. 2017; Smoker et al. 2017) in the
ESO Reflex data processing environment (v. 2.8.4 and v. 2.8.5,
respectively; Freudling et al. 2013).

We applied two different methods for sky subtraction,
cosmic-ray removal, and extraction of the spectra. This was
done to test the consistency of the two methods and confirm
that any observed features were not simply reduction artifacts.

3.1. Method 1

Due to X-Shooter’s disabled ADC at the time we observed
2004 EW95, the spectra were found to have a wavelength-
dependent spatial position in the 2D rectified images, which was
most pronounced at the shortest wavelengths (see Figure 1). The point spread function (PSF) of the spectrum
was also wavelength dependent, due to a combination of
variations across X-Shooter’s echelle orders and wavelength-
dependent seeing. These factors made a simple straight
extraction of the 1D spectrum impossible without including
increased background noise in the extracted spectrum. A
Python script was created to track the wavelength-dependent
spectral width and center within each image to evaluate
wavelength-dependent extraction limits, thus preserving S/N
while avoiding wavelength-dependent extraction losses, espe-
cially in the near-UV. The script worked as follows.

Secull et al.

3.2. Method 2

The spectra were reduced using only the ESO Reflex instrument pipelines (Freudling et al. 2013) which performed the sky subtraction, cosmic-ray flagging, and spectrum extraction as described in the pipeline user manuals (Modigliani et al. 2017; Smoker et al. 2017). The FORS2 spectra were extracted with both optimal (Horne 1986) and aperture methods, while the X-Shooter spectra were extracted with only the aperture method. The widths of the straight extraction apertures for each spectrum were set at the greatest separation between the extraction limits calculated using method 1.

All methods tested produced spectra with consistent features for both FORS2 and X-Shooter observations. However, spectra extracted via method 1 showed increased S/N relative to those reduced via method 2. For this reason the spectra presented in Section 4 were extracted via method 1.

Following extraction, the individual spectra were normalized, median stacked, solar calibrated, and binned. Dithers with extremely low S/N were omitted from the final stack. Regions near ~456, ~560, and ~640 nm in the X-Shooter spectrum were rejected to avoid copious artifacts produced by bad pixels and the edges of the echelle orders.

Because the UVB arm and VIS arm of the X-Shooter spectrum were normalized at different wavelengths during stacking, the arms required rescaling relative to each other to produce a continuous spectrum. The scaling factor of UVB relative to VIS was calculated as the ratio between the relative flux of the KBO with respect to the solar calibrator measured at the wavelengths of normalization in each arm. The scaling was then adjusted to account for the spectral slope in the region where the UVB and VIS arms join.

In all spectra the shortest wavelength has been limited to ~400 nm due to large residuals produced by differences in metallicity and temperature between the solar calibrators used and the Sun (Hordorp 1980).

The FORS2 spectrum presented in Figures 2 and 3 comprises observations only from night 1, observed under photometric conditions.

To further display the integrity of our reduction methods we show the spectrum of the KBO 1999 OX₃ in Figure 3. The X-Shooter data of this target exhibit a very similar S/N as in the X-Shooter data of 2004 EW₉₅. Thus, any extraction issues of our pipeline that may be apparent in the spectra of 2004 EW₉₅ should be equally apparent in the spectra of 1999 OX₃. As can be seen in Figure 3, the spectra produced with extraction method 1 result in a typical KBO spectrum; that is linear, featureless, red, and exhibits no identifiable absorption features. Hence, we conclude that the features observed in the spectrum of 2004 EW₉₅ are not reduction artifacts and instead are inherent to the spectrum itself. Via linear regression, the optical slope of 1999 OX₃’s spectrum was measured to be 30.6 ± 1.5% per 100 nm, in accord with literature values (Peixinho et al. 2015).

4. Results and Discussion

We have detected two features in the reflectance spectrum of 3:2 resonant KBO 2004 EW₉₅: a large drop in reflectance at

![Figure 1. Diagram of the method 1 reduction process for the 2D flux calibrated, rectified, and merged UVB X-Shooter spectra of solar calibrator star HD 117286 (panels (A), (C)–(E)) and 2004 EW₉₅ (panels (B), (F)–(H)). The amount of flux gathered for HD 117286 in panel (A) is ~5 orders of magnitude greater than that gathered for 2004 EW₉₅ in panel (B). Panels (A) and (B) show lines tracing the Moffat profile centers for each extraction bin along the dispersion axis (solid black), and their associated extraction limits (solid white). Panels (C)–(H) show the median spatial profiles of example data bins taken from various wavelengths along the spectrum (black), fitted with their associated Moffat profiles (red).](image-url)
wavelengths below 550 nm, and a broad \( \sim 0.2 – 0.3 \mu m \) wide, shallow absorption feature centered at around 700 nm (see Figure 2). Previously, neither feature has ever been reliably detected in the spectrum of a KBO. Each of these two features has been independently observed by two separate instruments, and are present in the reported reflectance spectra regardless of which of our solar calibrator targets, or which of two separate spectral extraction techniques, were used in our data reduction. The FORS2 and X-Shooter spectra of 2004 EW95 fully agree above 430 nm (see Figure 3). At 415 nm the X-Shooter spectrum has a greater spectral slope and is discrepant from the FORS2 spectrum in that wavelength range by \( \sim 2 \sigma \). This difference corresponds to the known difference in \( B – V \) color between the solar calibrator stars used to calibrate each spectrum.

The UV-optical spectrum of 2004 EW95 bears a striking resemblance to those of primitive carbonaceous asteroids. Specifically, 2004 EW95 resembles a hydrated C-type asteroid (Bus & Binzel 2002b; DeMeo et al. 2009; Vernazza et al. 2016; we compare 2004 EW95 to the asteroid 38 Leda in Figure 2). The shallow optical absorption feature at \( \sim 700 \) nm defines the hydrated \( \text{Ch}/\text{Cgh} \) asteroid subclasses, being observed in \( \sim 30\% \) of C-types (Rivkin 2012), and has been associated with charge transfer in aqueously altered silicate material (Vilas & Gaffey 1989; Fornasier et al. 2014; Rivkin et al. 2015). To characterize the \( \sim 700 \) nm feature and test the significance of its detection, we first remove a linear continuum slope of 3.6% per 100 nm that was determined from a linear fit to the 530–580 nm and 850–900 nm wavelength ranges. A Gaussian profile was then fit to the continuum in a maximum likelihood sense, using the emcee Monte Carlo Markov Chain sampler (Foreman-Mackey et al. 2013). We adopt as a best fit the

![Figure 2. Reflectance spectra and photometry (Fraser et al. 2015) of 2004 EW95 compared to the combined optical and NIR reflectance spectrum of the hydrated C-type asteroid, 38 Leda from the SMASSII and SMASSir catalogs (Bus & Binzel 2002a, 2002b; DeMeo et al. 2009). 2004 EW95’s drop in reflectance toward the UV is clearly visible in both the X-Shooter and FORS2 spectra, matching well with 38 Leda. The presence of the broad feature centered near 700 nm is apparent in both the X-Shooter spectrum and the HST spectrophotometry. We attribute this feature to phyllosilicate absorption like that of the hydrated C-type asteroids. The NIR behavior observed for 2004 EW95 in the HST photometry closely resembles the NIR spectral behavior of C-type asteroids, presenting a featureless red slope, remaining roughly constant from \( \sim 1000 \) nm to \( \sim 1400 \) nm. 2004 EW95’s reflectance drops slightly at \( \sim 1500 \) nm, hinting at possible absorption due to surface water ice. Reflectances in all data sets are normalized at 589 nm. The FORS2 spectrum (in red) is offset by +0.4 for clarity. The apparent difference in overall slope between overlapping regions of the FORS2 and X-Shooter spectra are calibration artifacts resulting from the use of slightly different solar analog stars.](image1)

![Figure 3. Spectrum comparison plot. Here we compare the spectra of 2004 EW95 observed with X-Shooter and FORS2, along with the X-Shooter spectrum of a typical KBO, 1999 OX3. Both spectra of 2004 EW95 agree with each other very well at wavelengths greater than \( \sim 430 \) nm. Below \( \sim 430 \) nm there is a divergence in the slope of each spectrum caused by difference in color of the solar calibrators used. Both 2004 EW95 and 1999 OX3 were of similar brightness when observed. All spectra have been reduced using the method 1 extraction technique described in Section 3.](image2)
median sample point, uncertainty as the 1σ sampling range when marginalizing over the other parameters. The best-fit depth, center, and FWHM were $4_{-1}^{+1}$%, $734_{-43}^{+43}$ nm and $319_{-101}^{+101}$ nm, respectively. The 4σ lower limit on the feature depth is 1% demonstrating the veracity of the detection. Technically, our routine quoted a higher significance of detection; however, at this high a significance, the ability to determine the continuum is the ultimate limiting factor.

Indications for phyllosilicate features have previously been reported in the spectra of KBOs 2003 AZ$_{64}$ (Fornasier et al. 2004), 2000 EB$_{173}$ (38628 Huya) and 2000 GN$_{171}$ (Lazzarini et al. 2003; de Bergh et al. 2004). Follow-up spectra of sufficient quality to detect those reported features, however, have revealed featureless spectra on later occasions, with rotational spectral variability reported as a possible but unconfirmed explanation for the disappearance of the feature on these objects (Fornasier et al. 2004, 2009; Merlin et al. 2017). Repeat photometric observations of 2004 EW$_{95}$ with $HST$ reported by Fraser et al. (2015) have shown its spectrum to be invariable, which is supported by the consistency between that $HST$ spectrophotometry of 2004 EW$_{95}$ and the reflectance spectra reported in this work (see Figure 2). With multiple independent photometric and spectroscopic detections of the 700 nm feature in the spectrum of 2004 EW$_{95}$ over multiple epochs, we report the first confident detection of phyllosilicates on any KBO.

Like 2004 EW$_{95}$, some S-, V-, and C-type asteroids also exhibit a drop in near-UV reflectance, including the hydrated C-types to which this spectrum is most similar. On asteroids the UV drop has been attributed to the presence of ferric oxide material (Bus & Binzel 2002a). It should be noted that other materials such as complex aromatic organics can also produce a similar drop-off (Izawa et al. 2014; Hendrix et al. 2016), though organic-rich bodies such as the P- and D-type asteroids have not been observed to exhibit this UV drop in their reflectance spectra (Bus & Binzel 2002a, 2002b; DeMeo et al. 2009; Marsset et al. 2014). Moreover, other than 2004 EW$_{95}$ of the 41 published optical spectra of KBOs and centaurs with sufficient short wavelength coverage, only the centaur (32532) Thereus hints at the presence of a similar UV drop (Barucci et al. 2002), though the presence of this feature on Thereus has not yet been confirmed.

The longest wavelength at which 2004 EW$_{95}$ was observed was in the $HST$/WFC3 153M filter centered at 1532.2 nm (see Figure 2). Here the observed reflectance of the object appears to decrease relative to the NIR photometric points from 1000–1400 nm. The decrease is consistent with the presence of a small amount of water ice, which characteristically absorbs at these wavelengths (Brown et al. 2012; Fraser & Brown 2012). This feature is the only one to distinguish the spectrum of 2004 EW$_{95}$ from that of a C-type asteroid, and suggests that unlike the C-types in the outer asteroid belt, 2004 EW$_{95}$ has retained its primordial surface water content.

The Grand Tack model (Walsh et al. 2011, 2012) predicts that as a result of the early migrations of Jupiter and Saturn, the primitive small bodies that formed between the gas giants would be scattered and injected into the outer asteroid belt, making up the bulk of the organic-rich asteroids. Models of Jupiter’s and Saturn’s rapid gas accretion show that primitive interplanetary asteroids could also be scattered as the gas giants formed (Raymond & Izidoro 2017). By either mechanism (they are not mutually exclusive), a small fraction of those bodies would be scattered outward into the Trans-Neptunian belt, where they could later be captured in the mean motion resonances (MMRs) of Neptune (Levison et al. 2008). 2004 EW$_{95}$ orbits the Sun in Neptune’s 3:2 MMR, at relatively high orbital eccentricity and inclination ($a = 39.316$ au, $e = 0.3139$, $i = 29.3^\circ$, Peixinho et al. 2015). The presence of a phyllosilicate feature indicates that 2004 EW$_{95}$ has been subjected to significant heating, either radiogenic (McAdam et al. 2015), from a very large single collision or extensive collisional bombardment (Rubin 1995; McKinnon 2002), or via solar irradiation. The striking similarity between 2004 EW$_{95}$ and certain C-type asteroids points to the plausible idea that 2004 EW$_{95}$ shares a common origin with these objects. Taken together, the spectroscopic similarity to C-type asteroids and the orbital properties of 2004 EW$_{95}$ are consistent with the idea that this object may have formed near Jupiter among the primordial C-type asteroids (Walsh et al. 2011) and was subsequently emplaced into the Kuiper Belt by the migrating planets.

We thank Faith Vilas and Alan Fitzsimmons for their encouraging constructive discussion and comments. This work is based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programs 093.C-0259(A), 095.C-0521(A) and 099.C-0651(A). W.C.F. acknowledges support from STFC grant ST/P003094/1. T.H.P. acknowledges support through the FONDECYT Regular project No. 1161817 and the BASAL Center for Astrophysics and Associated Technologies (PB-06). M.E.B. acknowledges support from the NASA Planetary Astronomy Program through grant NNX09AB49G.

Facility: ESO VLT(X-Shooter and FORS2).


ORCID iDs
Tom Secull ORCID: https://orcid.org/0000-0001-5605-1702
Wesley C. Fraser ORCID: https://orcid.org/0000-0001-6680-6558
Thomas H. Puzia ORCID: https://orcid.org/0000-0003-0350-7061
Michael E. Brown ORCID: https://orcid.org/0000-0002-8255-0545

References
Appenzeller, I., Fricke, K., Fürtig, W., et al. 1998, Msngr, 94, 1
Bus, S. J., & Binzel, R. P. 2002a, Icar, 158, 106
Bus, S. J., & Binzel, R. P. 2002b, Icar, 158, 146
Foreman-Mackey, D., 2016, JOSS, 1, 24
Fornasier, S., Lanz, C., Barucci, M. A., & Lazzarini, M. 2014, Icar, 233, 163


Secull et al.