# Visible spectra of (474640) 2004 VN$_{112}$–2013 RF$_{98}$ with OSIRIS at the 10.4 m GTC: evidence for binary dissociation near aphelion among the extreme trans-Neptunian objects

## J. de León,[1,2]★ C. de la Fuente Marcos[3] and R. de la Fuente Marcos[3]

[1]*Instituto de Astrofísica de Canarias, C/ Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain*
[2]*Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain*
[3]*Universidad Complutense de Madrid, Ciudad Universitaria, E-28040 Madrid, Spain*

## ABSTRACT

The existence of significant anisotropies in the distributions of the directions of perihelia and orbital poles of the known extreme trans-Neptunian objects (ETNOs) has been used to claim that trans-Plutonian planets may exist. Among the known ETNOs, the pair (474640) 2004 VN$_{112}$–2013 RF$_{98}$ stands out. Their orbital poles and the directions of their perihelia and their velocities at perihelion/aphelion are separated by a few degrees, but orbital similarity does not necessarily imply common physical origin. In an attempt to unravel their physical nature, visible spectroscopy of both targets was obtained using the OSIRIS camera-spectrograph at the 10.4 m Gran Telescopio Canarias (GTC). From the spectral analysis, we find that 474640–2013 RF$_{98}$ have similar spectral slopes (12 versus 15 per cent/0.1 μm), very different from Sedna's but compatible with those of (148209) 2000 CR$_{105}$ and 2012 VP$_{113}$. These five ETNOs belong to the group of seven linked to the Planet Nine hypothesis. A dynamical pathway consistent with these findings is dissociation of a binary asteroid during a close encounter with a planet and we confirm its plausibility using *N*-body simulations. We thus conclude that both the dynamical and spectroscopic properties of 474640–2013 RF$_{98}$ favour a genetic link and their current orbits suggest that the pair was kicked by a perturber near aphelion.

**Key words:** techniques: photometric – techniques: spectroscopic – astrometry – celestial mechanics – minor planets, asteroids: individual: (474640) 2004 VN$_{112}$ – minor planets, asteroids: individual: 2013 RF$_{98}$.

## 1 INTRODUCTION

The dynamical and physical properties of the extreme trans-Neptunian objects or ETNOs (semimajor axis, $a$, greater than 150 au and perihelion distance, $q$, greater than 30 au; Trujillo & Sheppard 2014) are intriguing in many ways. Their study can help probe the orbital distribution of putative planets going around the Sun between the orbit of Pluto and the Oort Cloud as well as understand the formation and evolution of the Solar system as a whole. The first ETNO, (148209) 2000 CR$_{105}$, was found in 2000 and its discovery was soon recognized as a turning point in the study of the outer Solar system (e.g. Gladman et al. 2002; Morbidelli & Levison 2004). The current tally stands at 21 ETNOs.

Trujillo & Sheppard (2014) were first in suggesting that the dynamical properties of the ETNOs could be better explained if a yet to be discovered planet of several Earth masses is orbiting the Sun at hundreds of astronomical units. This interpretation was further

supported by de la Fuente Marcos & de la Fuente Marcos (2014) with a Monte Carlo-based study confirming that the observed patterns in ETNO orbital parameter space cannot result from selection effects and suggesting that one or more trans-Plutonian planets may exist. A plausible multiplanet dynamical scenario was explored by de la Fuente Marcos, de la Fuente Marcos & Aarseth (2015). Based on observational data, and analytical and numerical work, Batygin & Brown (2016) presented their Planet Nine hypothesis that was further developed by Brown & Batygin (2016), but questioned by Shankman et al. (2017). The orbits of seven ETNOs–Sedna, 148209, (474640) 2004 VN$_{112}$, 2007 TG$_{422}$, 2010 GB$_{174}$, 2012 VP$_{113}$ and 2013 RF$_{98}$ – were used by Brown & Batygin (2016) to predict the existence of the so-called Planet Nine, most probably a trans-Plutonian super-Earth in the sub-Neptunian mass range. Out of the 21 known ETNOs, only Sedna has been observed spectroscopically (see Fornasier et al. 2009).

Among the known ETNOs, the pair 474640–2013 RF$_{98}$ clearly stands out (de la Fuente Marcos & de la Fuente Marcos 2016). The directions of their perihelia (those of the vector from the Sun to the respective perihelion point) are very close (angular separation

★ E-mail: jmlc@iac.es

of 9°8), their orbital poles are even closer (4°1), and consistently, the directions of their velocities at perihelion/aphelion are also very near to each other (9°5), although improved values are given in Section 3.3; in addition, they have similar aphelion distances, $Q$ (589 au versus 577 au). Assuming that the angular orbital elements of the ETNOs follow uniform distributions (i.e. they are unperturbed asteroids moving in Keplerian orbits around the Sun), the probability of finding by chance two objects with such a small angular separation between their directions of perihelia and, what is more important, also between their orbital poles is less than 0.0001, which suggests a common dynamical origin. However, a probable common dynamical origin does not imply a common physical origin. In an attempt to unravel their physical nature, visible spectroscopy of the two targets was obtained on 2016 September using the OSIRIS camera-spectrograph at the 10.4 m Gran Telescopio Canarias (GTC) telescope, located in La Palma (Canary Islands, Spain). Here, we present and discuss the results of these observations. This Letter is organized as follows. Section 2 reviews the state of the art for this pair of ETNOs. The new observations – including spectroscopy, photometry and astrometry – and their results are presented in Section 3. The possible origin of this pair is explored in Section 4, making use of the new observational results and *N*-body simulations. Conclusions are summarized in Section 5.

## 2 STATE OF THE ART OF 474640–2013 RF$_{98}$

Asteroid (474640) 2004 VN$_{112}$ was discovered on 2004 November 6 by the ESSENCE supernova survey observing with the 4 m Blanco Telescope from Cerro Tololo Inter-American Observatory (CTIO) at an apparent magnitude $R$ of 22.7 (Becker et al. 2007). Its absolute magnitude, $H = 6.4$ (assuming a slope parameter, $G = 0.15$), suggests a diameter in the range 130–300 km for an assumed albedo in the range 0.25–0.05. The orbital solution (2016 August) for this object is based on 31 observations spanning a data-arc of 5113 d or 14 yr, from 2000 September 26 to 2014 September 26; its residual rms amounts to 0.19 arcsec.[1] Such an object would have been visible to ESSENCE for only about 2 per cent of its orbit, suggesting that the size of the population of minor bodies moving in orbits similar to that of 474640 could be very significant (Becker et al. 2008). Sheppard (2010) gives a normalized spectral gradient of 11±4 per cent/0.1 μm for this object based on Sloan $g'$, $r'$ and $i'$ optical photometry acquired in 2008. Some additional photometry was obtained with the Hubble Wide Field Camera 3 (Fraser & Brown 2012). Its optical colours are relatively neutral and this was interpreted by Brown (2012) as a sign that it is not dominated by methane irradiation products.

Asteroid 2013 RF$_{98}$ was discovered on 2013 September 12 by the Dark Energy Camera ( Flaugher et al. 2015) observing from CTIO for the Dark Energy Survey (Abbott et al. 2005) at an apparent magnitude $z$ of 23.5 (Abbott et al. 2016). Its absolute magnitude, $H = 8.7$, suggests a diameter in the range 50–120 km. The orbital solution (2016 August) for this ETNO is rather poor as it is based on 38 observations spanning a data-arc of just 56 d, from 2013 September 12 to November 7; its residual rms amounts to 0.12 arcsec.[2] No other

data, besides these 38 observations, its $H$ value and its orbital solutions, are known about this ETNO.

Asteroid 474640 has been classified as an extreme detached object by Sheppard & Trujillo (2016) and their integrations show that it is a stable ETNO within the standard eight planets-only Solar system paradigm; this result is consistent with that in Brown & Batygin (2016). In Sheppard & Trujillo (2016), 2013 RF$_{98}$ is classified as an extreme scattered object and found to be unstable within the standard paradigm over 10 Myr time-scales due to Neptune perturbations. Both ETNOs are rather unstable within some incarnations of the Planet Nine hypothesis (de la Fuente Marcos, de la Fuente Marcos & Aarseth 2016). The heliocentric orbits available in 2016 August (see footnotes 1 and 2) have been used to compute the values of the angular separations quoted in the previous section. In spite of the limitations of the orbital solution of 2013 RF$_{98}$, the uncertainties mainly affect orbital elements other than inclination, $i$, longitude of the ascending node, $\Omega$, and argument of the perihelion, $\omega$. These three orbital parameters are the only ones involved in the calculation of the directions of perihelia, location of orbital poles and directions of velocities at perihelion (de la Fuente Marcos & de la Fuente Marcos 2016). In sharp contrast, the value of $Q$ of 2013 RF$_{98}$ is affected by a significant uncertainty (12 per cent).

## 3 OBSERVATIONS

### 3.1 Spectroscopy

Visible spectra of the two targets were obtained using OSIRIS (Cepa et al. 2000) at 10.4 m GTC. The apparent visual magnitude, $V$, at the time of observation was 23.3 for (474640) 2004 VN$_{112}$ (heliocentric distance of 47.7 au and phase of 1°1) and 24.4 for 2013 RF$_{98}$ (36.6 au, 1°3). For each target, acquisition images in the Sloan $r'$ filter were obtained in separate nights in order to identify reliably the object in the field of view. This procedure ended up being the most efficient to detect these dim, slow-moving (apparent proper motion < 2 arcsec h$^{-1}$) targets. Visible spectra were acquired using the low-resolution R300R grism (resolution of 348 measured at a central wavelength of 6635 Å for a 0.6 arcsec slit width) that covers the wavelength range from 0.49 to 0.92 μm, and a 2 arcsec slit width. Two widely accepted solar analogue stars from Landolt (1992) – SA93−101 and SA115−271 – were observed using the same spectral configuration at an airmass identical to that of the targets to obtain the reflectance spectra of the ETNOs. For a given ETNO, the spectrum was then divided by the corresponding spectrum of the solar analogue. Additional data reduction details are described by de León et al. (2016) and Morate et al. (2016). For 474640, we acquired two spectra of 1800 s each, while for 2013 RF$_{98}$, we acquired four individual spectra of 1800 s each. Observational details are shown in Table 1. The resulting individual reflectance spectra, normalized to unity at 0.55 μm and offset vertically for clarity, are shown in Fig. 1.

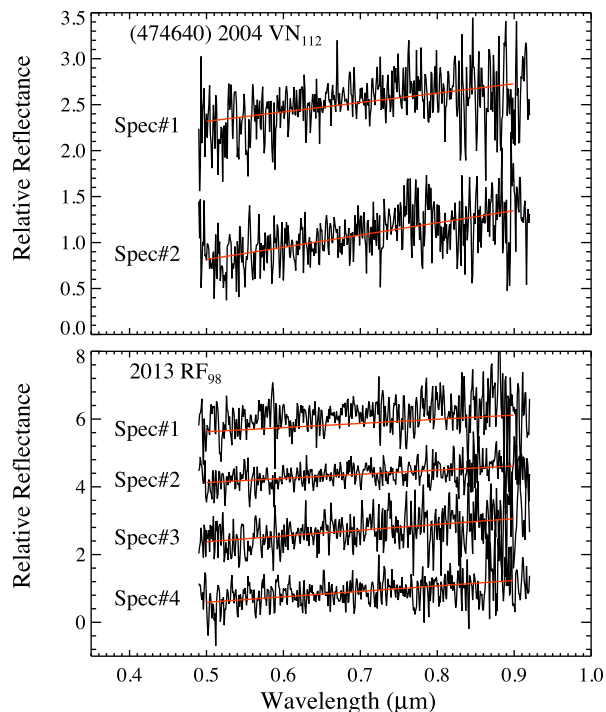In Table 1, the spectral slope (in units of per cent/0.1 μm) has been computed from a linear fitting to the spectrum in the wavelength range 0.5–0.9 μm. We used an iterative process – removing a total of 50 points randomly distributed in the spectrum and performing a linear fitting – and obtained a value of the slope for each iteration. The resulting slope value is the mean of a total of 100 iterations and the associated error is the standard deviation of this mean. The process of dividing by the spectra of the solar analogue stars introduces an error of 0.3 per cent/0.1 μm. The error value shown in the last column of Table 1 is sum of these two contributions. For each target, we averaged individual spectra to obtain the average

---

[1] Orbit available from JPL's Small-Body Database and HORIZONS On-Line Ephemeris System: $a = 318 \pm 1$ au, $e = 0.8513 \pm 0.0005$, $i = 25°5748 \pm 0°0004$, $\Omega = 65°9990 \pm 0°0007$ and $\omega = 327°121 \pm 0°010$, referred to the epoch 2457600.5 JD TDB.

[2] Orbit available from HORIZONS: $a = 307 \pm 37$ au, $e = 0.882 \pm 0.015$, $i = 29°62 \pm 0°08$, $\Omega = 67°51 \pm 0°13$ and $\omega = 316° \pm 6°$, referred to the epoch 2457600.5 JD TDB.

**Table 1.** Observational details of the visible spectra (1800 s each) obtained for (474640) 2004 VN$_{112}$ and 2013 RF$_{98}$ (see the text for further details).
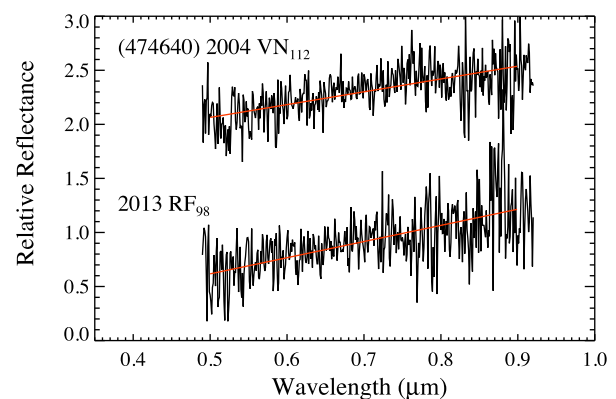
| Target | Spec # | Date | UT start | Airmass | Slope (per cent/0.1 μm) |
|--------|--------|------|----------|---------|--------------------------|
| 474640 | 1 | 16-03-09 | 04:37 | 1.085 | 10.2±0.6 |
|  | 2 | 16-03-09 | 05:07 | 1.072 | 13.3±0.6 |
|  |  |  |  | **Mean** | **12±2** |
| 2013 RF$_{98}$ | 1 | 16-08-09 | 03:07 | 1.234 | 14.9±0.8 |
|  | 2 | 16-08-09 | 03:37 | 1.181 | 12.3±0.8 |
|  | 3 | 16-08-09 | 04:07 | 1.151 | 17.1±0.8 |
|  | 4 | 16-08-09 | 04:38 | 1.142 | 16.1±0.8 |
|  |  |  |  | **Mean** | **15±2** |



**Figure 2.** Final visible spectra of the pair of ETNOs (see the text for details).



**Figure 3.** Comparison between the spectra of (474640) 2004 VN$_{112}$ and 2013 RF$_{98}$ smoothed by a Savitzky–Golay filter (see the text) and scaled to match at 0.60 μm. The most prominent absorption band of pure methane ice at 0.73 μm is not seen on either spectra.
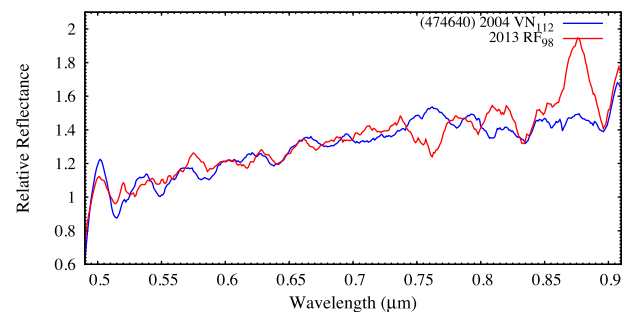


**Figure 1.** Individual visible spectra of (474640) 2004 VN$_{112}$ (top panel) and 2013 RF$_{98}$ (bottom panel) normalized to unity at 0.55 μm and offset vertically for clarity. Red lines correspond to the linear fitting in the range 0.5–0.9 μm to compute the spectral slope.

visible spectra for 474640 and 2013 RF$_{98}$ shown in Fig. 2; the mean spectral slopes in Table 1 are the means of the individual spectra and their errors, the associated standard deviations. The value of the spectral slope of 474640 is consistent with the one obtained by Sheppard (2010). The values in Table 1 are similar to those of scattered disc TNOs, Plutinos, high-inclination classical TNOs as well as the Damocloids and comets (see e.g. table 5 in Sheppard 2010).

The spectra in Fig. 2 show an obvious resemblance, but the low S/N makes the identification of absorption features difficult. In order to make a better comparison and assuming that the relative reflectance is both slowly varying and corrupted by random noise, we applied a Savitzky–Golay filter (Savitzky & Golay 1964) to both data sets. Such filters provide smoothing without loss of resolution, approximating the underlying function by a polynomial as described by e.g. Press et al. (1992). Fig. 3 shows the smoothed spectra after applying a 65-point Savitzky–Golay filter of the or-

der of 6 to the data in Fig. 2. The smoothed spectra, in particular that of 474640 (blue), show some weak features that might be tentatively identified as pure methane ice absorption bands (Grundy, Schmitt & Quirico 2002). However, the most prominent methane band at 0.73 μm is observed neither in the spectrum of 474640 nor in that of 2013 RF$_{98}$ (red). The S/N is insufficient to identify reliably any absorption band, but the spectral slopes in the visible of both objects provide some compositional information. Objects with visible spectral slopes in the range 0–10 per cent/0.1 μm can have pure ices on their surfaces (like Eris, Pluto, Makemake and Haumea), as well as highly processed carbon. Slightly red slopes (5–15 per cent/0.1 μm) indicate the possible presence of amorphous silicates as in the case of Trojans (Emery & Brown 2004) or Thereus (Licandro & Pinilla-Alonso 2005). In any case, the objects will not have a surface dominated by complex organics (tholins). Differences between the spectra of 474640 and 2013 RF$_{98}$ might be the result of their present-day heliocentric distance. Mechanisms that are more efficient in altering the icy surfaces of these objects at smaller perihelion distances include sublimation of volatiles and micrometeoroid bombardment (Santos-Sanz et al. 2009).

### 3.2 Photometry

We obtained a total of 3 and 11 acquisition images to identify (474640) 2004 VN$_{112}$ and 2013 RF$_{98}$, respectively. Images were taken using the Sloan $r'$ filter and calibrated using the zero-point values computed for the corresponding nights. The resulting $r'$ magnitudes and their uncertainties are shown in Table S1.

### 3.3 Astrometry

We used the acquisition images to compute the celestial coordinates of each target and improve its orbit. This was particularly relevant for 2013 RF$_{98}$ that, prior to our observations, had a rather uncertain orbital determination. (see footnote 2) We found (474640) 2004 VN$_{112}$ within 1 arcsec of the predicted ephemerides, but 2013 RF$_{98}$ was found nearly 1.2 arcmin away. Both ETNOs were in Cetus. Astrometric calibration of the CCD frames was performed using the algorithms of the Astrometry.net system (Lang et al. 2010). The quality of high-precision astrometry with OSIRIS at GTC matches that of data acquired with FORS2/VLT (Sahlmann et al. 2016). The collected astrometry is shown in Tables S2 and S3. The new orbital solution for 2013 RF$_{98}$ available from HORIZONS (as of 2016 December 18 18:51:59 UT) is based on 51 observations spanning a data-arc of 1092 d, its residual rms amounts to 0.12 arcsec: $a = 349 \pm 11$ au, $e = 0.897 \pm 0.003$, $i = 29°572 \pm 0°003$, $\Omega = 67°596 \pm 0°005$ and $\omega = 311°8 \pm 0°6$, referred to the epoch 2457800.5 JD TDB; the time of perihelion passage is 2455125$\pm$95 JED (2009 October 20.7289 UT). The time of perihelion passage for 474640 is 2009 August 25.8290 UT. Using the new orbit, the directions of the perihelia of this pair are separated by 14°2$\pm$0°6, their orbital poles by 4°056$\pm$0°003 and the directions of their velocities at perihelion/aphelion by 14°1$\pm$0°6.

## 4 ORIGIN OF THE PAIR 474640–2013 RF$_{98}$

From the spectral analysis discussed above, we have found that the members of the pair (474640) 2004 VN$_{112}$–2013 RF$_{98}$ show similar spectral slopes, very different from that of Sedna that has ultrared surface material (spectral gradient of about 26 per cent/0.1 μm according to Sheppard 2010, and 42 per cent/0.1 μm according to Fornasier et al. 2009) but compatible with those of (148209) 2000 CR$_{105}$ (spectral gradient of about 14 per cent/0.1 μm, Sheppard 2010) and 2012 VP$_{113}$ (spectral gradient of about 13 per cent/0.1 μm, Trujillo & Sheppard 2014). These five objects have been included in the group of seven singled out as relevant to the Planet Nine hypothesis (Brown & Batygin 2016). Such spectral differences suggest that the region of origin of the pair 474640–2013 RF$_{98}$ may coincide with that of 148209 and 2012 VP$_{113}$ but not with Sedna's, which is thought to come from the inner Oort Cloud (Sheppard 2010). Other ETNOs with values of their spectral gradient in Sheppard (2010) are 2002 GB$_{32}$ (∼17 per cent/0.1 μm) and 2003 HB$_{57}$ (∼13 per cent/0.1 μm).

Objects with both similar directions of the orbital poles and perihelia could be part of a group of common physical origin (Öpik 1971). This particular pair of ETNOs is very unusual and a model analogous to the one used by de la Fuente Marcos & de la Fuente Marcos (2014) to study the overall visibility of the ETNO population predicts that the probability of finding such a pair by chance is less than 0.0002. This model uses the new orbital solutions and assumes an unperturbed asteroid population moving in heliocentric orbits. Following Öpik (1971), there are two independent scenarios that could explain this level of coincidence: (1) a large object broke up relatively recently at perihelion and these two ETNOs are fragments, or (2) both ETNOs were kicked by an unseen perturber at aphelion. Sekanina (2001) has shown that minor bodies resulting from a fragmentation episode at perihelion must have very different times of perihelion passage. Fragmentation at perihelion can thus be readily discarded as the difference in time of perihelion passage for this pair is less than a year.
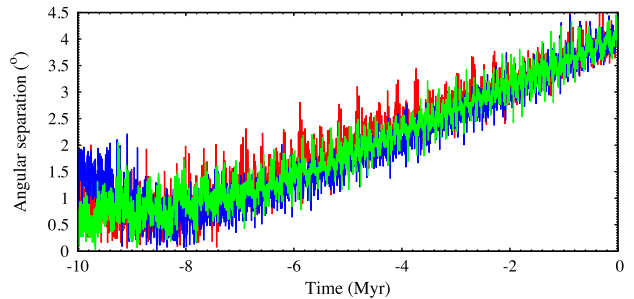


**Figure 4.** Evolution of the angular separation between the orbital poles of the pair (474640) 2004 VN$_{112}$–2013 RF$_{98}$ for three representative test calculations with different perturbers. Red: $a = 549$ au, $e = 0.21$, $i = 47°$ and $m = 16$ M$_\oplus$. Blue: $a = 448$ au, $e = 0.16$, $i = 33°$ and $m = 12$ M$_\oplus$. Green: $a = 421$ au, $e = 0.10$, $i = 33°$ and $m = 12$ M$_\oplus$.

The second scenario pointed out above implies the presence of an unseen massive perturber, i.e. a trans-Plutonian planet. Close encounters between minor bodies and planets can induce fragmentation directly via tidal forces (e.g. Sharma, Jenkins & Burns 2006) or indirectly by exciting rapid rotation (e.g. Scheeres et al. 2000; Ortiz et al. 2012). Alternatively, wide binary asteroids can be easily disrupted during close encounters with planets. The existence of wide binaries among the populations of minor bodies orbiting beyond Neptune is well documented (e.g. Parker et al. 2011). Wide binary asteroids have very low binding energies and can be easily dissociated during close encounters with planets (e.g. Agnor & Hamilton 2006; Parker & Kavelaars 2010). Binary asteroid dissociation may be able to explain the properties of this pair of ETNOs, but only if there is a massive perturber well beyond Pluto.

In order to test the viability of this hypothesis, we have performed thousands of numerical experiments following the prescriptions discussed by de la Fuente Marcos et al. (2016) and aimed at finding the most probable orbital properties of a putative perturber able to tilt the orbital plane of the pair 474640–2013 RF$_{98}$ from an initial angular separation close to zero at dissociation to the current value of nearly 4°. These simulations involve *N*-body integrations backwards in time under the influence of an unseen perturber with varying orbital and physical parameters (per numerical experiment). Our preliminary results indicate that a planet with mass, *m*, in the range 10–20 M$_\oplus$ moving in an eccentric (0.1–0.4) and inclined (20°–50°) orbit with semimajor axis of 300–600 au, may be able to induce the observed tilt on a time-scale of 5–10 Myr. Perturbers with $m < 10$ M$_\oplus$ or $a > 600$ au are unable to produce the desired effect. Fig. 4 illustrates the typical outcome of these calculations. A detailed account of these numerical experiments will be presented in an accompanying paper (de la Fuente Marcos, de la Fuente Marcos & Aarseth, in preparation). The orbital parameters of this putative planet are somewhat consistent with those of the object discussed by Holman & Payne (2016). Super-Earths may form at 125–750 au from the Sun (Kenyon & Bromley 2015, 2016). Our analysis favours a scenario in which 474640–2013 RF$_{98}$ were once a binary asteroid that became unbound after a relatively recent gravitational encounter with a trans-Plutonian planet at hundreds of astronomical units from the Sun. An alternative explanation involving an asteroid break-up near aphelion, also after a close encounter with a planet, is possible but less probable because it requires an approach at closer range, i.e. 20 planetary radii versus 0.8 au, for binary dissociation.

# 5 CONCLUSIONS

In this Letter, we provide for the first time direct indication of the surface composition of (474640) 2004 VN$_{112}$ and 2013 RF$_{98}$. Both objects are too faint for infrared spectroscopy, but our results show that they are viable targets for visible spectroscopy. The analysis of our results gives further support to the trans-Plutonian planets paradigm that predicts the presence of one or more planetary bodies well beyond Pluto. Summarizing as follows:

(i) Our estimate of the spectral slope for 474640 is 12$\pm$2 per cent/0.1 µm and for 2013 RF$_{98}$ is 15$\pm$2 per cent/0.1 µm. These values suggest that the surfaces of these ETNOs can have pure methane ices (like Pluto) and highly processed carbons, including some amorphous silicates.

(ii) Although the spectra of the pair 474640–2013 RF$_{98}$ are not perfect matches, the resemblance is significant and the disparities observed might be the result of their different present-day heliocentric distance.

(iii) By improving the orbital solution of 2013 RF$_{98}$, we confirm that the pair 474640–2013 RF$_{98}$ has unusual relative dynamical properties. The directions of their perihelia are separated by 14$^\circ$2 and their orbital poles are 4$^\circ$1 apart.

(iv) Our numerical analysis favours a scenario in which 474640–2013 RF$_{98}$ were once a binary asteroid that became unbound after an encounter with a trans-Plutonian planet at very large heliocentric distance.

## REFERENCES

Abbott T. et al., 2005, The Dark Energy Survey, preprint (astro-ph/0510346)
Abbott T. et al., 2016, MNRAS, 460, 1270
Agnor C. B., Hamilton D. P., 2006, Nature, 441, 192
Batygin K., Brown M. E., 2016, AJ, 151, 22
Becker A. C., Arraki K. S., Rest A., Wood-Vasey W. M., Marsden B. G., 2007, MPEC Circ., MPEC 2007-S29
Becker A. C. et al., 2008, ApJ, 682, L53
Brown M. E., 2012, Annu. Rev. Earth Planet. Sci., 40, 467
Brown M. E., Batygin K., 2016, ApJ, 824, L23
Cepa J. et al., 2000, in Iye M., Moorwood A. F. M., eds, Proc. SPIE Conf. Ser. Vol. 4008, Optical and IR Telescope Instrumentation and Detectors. SPIE, Bellingham, p. 623
de la Fuente Marcos C., de la Fuente Marcos R., 2014, MNRAS, 443, L59
de la Fuente Marcos C., de la Fuente Marcos R., 2016, MNRAS, 462, 1972
de la Fuente Marcos C., de la Fuente Marcos R., Aarseth S. J., 2015, MNRAS, 446, 1867
de la Fuente Marcos C., de la Fuente Marcos R., Aarseth S. J., 2016, MNRAS, 460, L123
de León J. et al., 2016, Icarus, 266, 57
de León J., de la Fuente Marcos C., de la Fuente Marcos R., 2016, MPEC Circ., MPEC 2016-U18
Emery J. P., Brown R. H., 2004, Icarus, 170, 131
Flaugher B. et al., 2015, AJ, 150, 150
Fornasier S. et al., 2009, A&A, 508, 457
Fraser W. C., Brown M. E., 2012, ApJ, 749, 33
Gladman B., Holman M., Grav T., Kavelaars J., Nicholson P., Aksnes K., Petit J.-M., 2002, Icarus, 157, 269
Grundy W., Schmitt B., Quirico E., 2002, Icarus, 144, 486
Holman M. J., Payne M. J., 2016, AJ, 152, 80
Kenyon S. J., Bromley B. C., 2015, ApJ, 806, 42
Kenyon S. J., Bromley B. C., 2016, ApJ, 825, 33
Landolt A. U., 1992, AJ, 104, 340
Lang D., Hogg D. W., Mierle K., Blanton M., Roweis S., 2010, AJ, 139, 1782
Licandro J., Pinilla-Alonso N., 2005, ApJ, 630, L93
Morate D., de León J., De Prá M., Licandro J., Cabrera-Lavers A., Campins H., Pinilla-Alonso N., Alí-Lagoa V., 2016, A&A, 586, A129
Morbidelli A., Levison H. F., 2004, AJ, 128, 2564
Öpik E. J., 1971, Ir. Astron. J., 10, 35
Ortiz J. L. et al., 2012, MNRAS, 419, 2315
Parker A. H., Kavelaars J. J., 2010, ApJ, 722, L204
Parker A. H., Kavelaars J. J., Petit J.-M., Jones L., Gladman B., Parker J., 2011, ApJ, 743, 1
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical Recipes in FORTRAN. Cambridge Univ. Press, Cambridge, p. 644
Sahlmann J., Lazorenko P. F., Bouy H., Martín E. L., Queloz D., Ségransan D., Zapatero Osorio M. R., 2016, MNRAS, 455, 357
Santos-Sanz P., Ortiz J. L., Barrera L., Boehnhardt H., 2009, A&A, 494, 693
Savitzky A., Golay M. J. E., 1964, Anal. Chem., 36, 1627
Scheeres D. J., Ostro S. J., Werner R. A., Asphaug E., Hudson R. S., 2000, Icarus, 147, 106
Sekanina Z., 2001, Publications of the Astronomical Institute of the Academy of Sciences of the Czech Republic, 89, 78
Shankman C., Kavelaars J. J., Lawler S. M., Gladman B. J., Bannister M. T., 2017, AJ, 153, 63
Sharma I., Jenkins J. T., Burns J. A., 2006, Icarus, 183, 312
Sheppard S. S., 2010, AJ, 139, 1394
Sheppard S. S., Trujillo C. A., 2016, AJ, 152, 221
Trujillo C. A., Sheppard S. S., 2014, Nature, 507, 471

## SUPPORTING INFORMATION

Supplementary data are available at *MNRASL* online.

**ETNOpairGTC_appendix.pdf**

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the Letter.