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Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **466,** 3594–3599 (2017) doi:10.1093/mnras/stw3272
Advance Access publication 2016 December 15

The very homogeneous surface of the dwarf planet Makemake

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Accepted 2016 December 13. Received 2016 December 8; in original form 2016 October 14

ABSTRACT

The dwarf planet (136472) Makemake is one of the largest trans-Neptunian objects discovered to date. Noteworthy, the size and surface temperature of this celestial body put it in a transition region where nitrogen is preferentially lost, while the less volatile methane is retained. Indeed, literature spectra clearly show that the surface of Makemake is dominated by methane ice, though the presence of nitrogen and of irradiation products of methane has been inferred by several authors and a debate is still open about the eventual rotational variability of the surface composition. In this work, we present new visible and near-infrared spectra of Makemake obtained with the TNG telescope (La Palma, Spain) in the time span 2006–2013. Our data sample different rotational phases, covering about 80 per cent of the surface. All of the obtained spectra look very similar, suggesting an overall homogeneous composition. No secular variations appear when comparing our data to literature results (as expected, considering the quite short orbital arc travelled by Makemake since its discovery in 2005). The presence of methane diluted in nitrogen is evidenced by the shift of the observed absorption bands with respect to those of pure methane, with a dilution state looking homogeneous over the surface. We modelled a complete visible and near-infrared spectrum of Makemake using the Shkuratov formalism, and found that adding irradiation products of methane like ethane and ethylene seems indeed improving the fit of the synthetic spectrum to our data. We found no hints of a localized/temporary atmosphere.

Key words: techniques: spectroscopic – Kuiper belt objects: individual: (136472) Makemake.

1 INTRODUCTION

With a size of about 1450 km (Ortiz et al. 2012; Brown 2013), the dwarf planet (136472) Makemake is the third largest trans-Neptunian object (TNO), after (134340) Pluto and (136199) Eris.

Like the visible and near-infrared (NIR) spectra of Pluto and Eris, Makemake's spectrum is dominated by the absorption bands of methane (e.g., Licandro et al. 2006a; Brown et al. 2007; Tegler et al. 2007, 2008; Brown, Schaller & Blake 2015; Lorenzi, Pinilla-Alonso & Licandro 2015). However, on Pluto, nitrogen is the dominant species and most of the methane is diluted in N_2 (e.g. Douté et al. 1999; Grundy & Buie 2001; Olkin et al. 2007; Tegler et al. 2010, 2012; Merlin 2015). The same is possibly true also for Eris (e.g. Licandro et al. 2006b; Dumas et al. 2007; Merlin et al. 2009, Tegler et al. 2010, 2012; Alvarez-Candal et al. 2011). Conversely, the surface of Makemake seems to be dominated by methane: the mass and temperature of this TNO lie just in the transition region where nitrogen is lost, while the less volatile methane is retained (Schaller & Brown 2007). None the less, several authors (see Lorenzi et al. 2015 and references therein) have found that methane absorption bands in Makemake's spectra are slightly shifted to shorter wavelengths with respect to pure methane bands, suggesting that at least part of the methane on the surface is in solid solution with nitrogen.

The dominance of methane on Makemake should favour the formation of very large grains on its surface (Eluszkiewicz et al. 2007) and indeed all previous modelling works suggest the presence of centimetre-sized grains. However, polarimetric observations also suggest the presence of a thin fluffy layer of hoarfrost masking the ordinary surface structure (Belskaya et al. 2012), and a bimodal particle size distribution (namely, 6 cm–1 mm) has been proposed to match the observed spectrum of Makemake (Tegler et al. 2007, 2008).

The dominance of methane on Makemake also makes this dwarf planet a privileged target in the search for irradiation products. Ethane, one of the first irradiation products of methane, has been detected by Brown et al. (2007), while Brown et al. (2015) have detected ethylene (formed from the continued irradiation of ethane)

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Table 1. Observational circumstances (literature spectra are also reported).

Spec. ID	Instrument/ disperser/slit	Date	UT	*T*exp (s)	Airmass range	Solar analogue (airmass)	Slope (0.55-0.65 μm)	Rot. phase
1S2006	DOLORES/LRR/2 arcsec	2006 April 19	21:32–21:59	1620	1.08–1.14	HD 89010 (1.12)	16.1%/1000 Å ± 4%	–
2S2006	DOLORES/LRR/2 arcsec	2006 April 20	01:39–02:06	1620	1.11–1.17	HD 159222 (1.22)	20.5%/1000 Å ± 4%	–
1S2011	NICS/Amici/1.5 arcsec	2011 March 28	23:06–23:53	20 × 120	1.07–1.16	HIP 59932 (1.062)	–	0
2S2011	NICS/Amici/1.5 arcsec	2011 March 29	04:21–05:17	24 × 120	1.28–1.57	Land 107–998 (1.18)	–	0.69
3S2011	DOLORES/LRR/2 arcsec	2011 March 29	22:58–23:18	1200	1.12–1.17	Land 107–998 (1.23)	10.4%/1000 Å ± 3%	0.04
4S2011	DOLORES/LRR/2 arcsec	2011 March 30	00:04–00:54	3000	1.01–1.05	Hip 59932 (1.05)	6.9%/1000 Å ± 3%	0.22
5S2011	DOLORES/LRR/2 arcsec	2011 March 30	02:09–02:54	2700	1.02–1.07	Hip 59932 (1.05)	8.7%/1000 Å ± 3%	0.48
6S2011	DOLORES/LRR/2 arcsec	2011 March 30	04:18–05:13	3300	1.28–1.57	Land 107–998 (1.23)	11.2%/1000 Å ± 3%	0.77
7S2011	DOLORES/LRR/2 arcsec	2011 March 31	00:10–00:45	2100	1.01–1.03	Hip 59932 (1.05)	6.1%/1000 Å ± 3%	0.30
8S2011	DOLORES/LRR/2 arcsec	2011 March 31	03:54–04:19	1500	1.21–1.30	Land 107–998 (1.23)	7.6%/1000 Å ± 3%	0.77
9S2011	DOLORES/LRR/1.5 arcsec	2011 March 31	23:05–23:45	2400	1.06–1.14	Hip 59932 (1.05)	7.1%/1000 Å ± 3%	0.26
10S2011	DOLORES/LRR/1.5 arcsec	2011 April 01	02:29–03:09	2400	1.04–1.11	Land 107–998 (1.23)	7.8%/1000 Å ± 3%	0.69
1S2013	DOLORES/VHRI/2 arcsec	2013 January 19	03:07–03:27	1200	1.29–1.22	Land 102–1081 (1.28)	–	–
2S2013	DOLORES/VHRI/2 arcsec	2013 January 19	05:18–05:48	1800	1.02–1.01	Hyades 64 (1.09)	–	-
Licandro et al. (2006a)		2005 August 01					∼13%/1000 Å	
Tegler et al. (2007)		2006 March 05					∼10%/1000 Å	

and found evidence for acetylene (an irradiation product of ethylene) and other higher mass alkanes.

Intriguingly, thermal observations of Makemake could be modelled only with a two-terrain fit, suggesting the presence of a limited, low-albedo terrain and an extensive, high-albedo terrain (Stansberry et al. 2008; Lim et al. 2010). Analysing a stellar occultation by Makemake, Ortiz et al. (2012) suggested the possible presence of a localized atmosphere, which could also result in noticeable colour changes. Noteworthy, Lorenzi et al. (2015) obtained the first rotationally resolved spectroscopy of Makemake, without noticing major differences between the three visible spectra analysed. However, some variation in the spectral slope was detected by these authors, pointing to the possibility of a variation in the surface content or the particle size of the solid organic compound. The recent discovery of a satellite (designated S/2015 (136472) 1) in orbit about Makemake (Parker et al. 2016) makes plausible the hypothesis that the dark material does not reside on the overall bright surface of Makemake (with visible albedo 0.77 according to Ortiz et al. 2012), but rather covers the surface of the satellite. The discovery of S/2015 (136472) 1 also reduces the preference for a pole-on orientation of Makemake's spin axis, which was invoked to conciliate the presence of distinct terrains on its surface with its very small light-curve amplitude (Ortiz et al. 2012). Indeed, if the spin pole of Makemake and the orbit plane of its satellite are aligned, we are viewing Makemake nearly equator-on (Parker et al. 2016).

The presence of the satellite cannot however explain the eventual rotational variability. To investigate further the surface composition of Makemake and any potential variation with its rotational phase, we present here new visible and NIR observations obtained in 2006–2013 at the 3.6-m Telescopio Nazionale Galileo (TNG). In Section 2, we describe the observational circumstances and the data reduction. In Section 3, we present the spectral analysis and modelling. In Section 4, we present our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

The data were obtained in 2006–2013 during three observing runs (2006 April, 2011 March and 2013 January). All observations were carried out at the 3.6-m TNG telescope (La Palma, Spain), using the DOLORES (Device Optimized for the LOw RESolution)[1] instrument for visible observations (with the LRR and VHRI grisms, yielding a resolving power of ∼700 and ∼3000, respectively) and the NICS (Near Infrared Camera Spectrometer)[2] instrument (coupled with the Amici prism, yielding a resolving power of ∼50) for NIR observations. All observations were performed orienting the slit along the parallactic angle in order to minimize the effects of atmospheric differential refraction. The nodding technique of moving the object along the slit between two different positions was used for NIR observations, as is necessary at these wavelengths for a proper background subtraction. The observational circumstances are given in Table 1.

Data reduction (bias and background subtraction, flat-field correction, one-dimensional spectra extraction, atmospheric extinction correction – see Perna et al. 2015 for more details) was performed using standard procedures with the IRAF software package. For wavelength calibration of visible spectra, Ar, Ne + Hg and Kr lamps were used. Wavelength calibration of NICS data was obtained using a look-up table, available on the instrument website, which is based on the theoretical dispersion predicted by ray-tracing and adjusted to best fit the observed spectra of calibration sources.

The final reflectance spectra of Makemake (presented in Figs 1 and 2) were then obtained by dividing its visible and NIR spectra by those of solar analogues observed close in time and airmass to the scientific frames (cf. Table 1). The red end of visible spectra was cut at different wavelengths to remove regions affected by a poor sky subtraction longward.

3 DATA ANALYSIS AND RESULTS

A total of 12 visible and 2 NIR spectra of Makemake were obtained in 2006–2013, all showing strong methane absorption bands. All the spectra look very similar within the limits of noise, with the exception of the two visible spectra acquired in 2006 (see further

[1] http://www.tng.iac.es/instruments/lrs/
[2] http://www.tng.iac.es/instruments/nics/

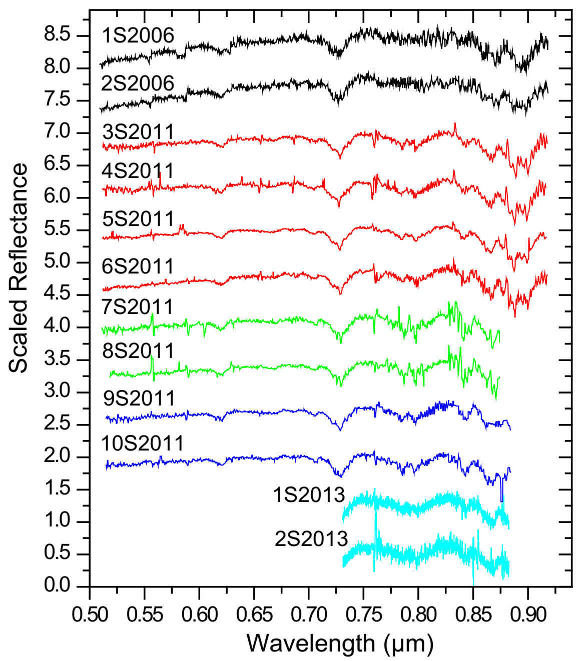

Figure 1. Visible reflectance spectra of Makemake obtained in 2006–2013. The colour code reflects the different observing nights. Spectra are normalized at 0.65 μm and scaled in reflectance for clarity.

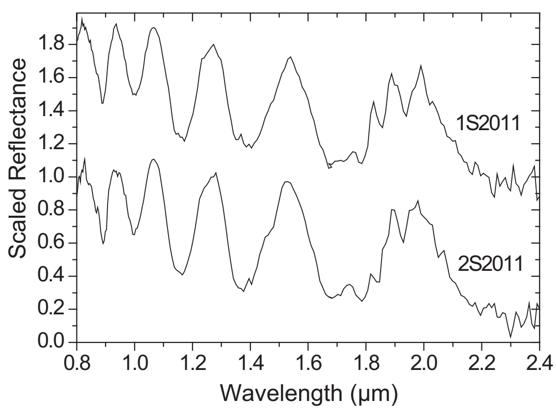

Figure 2. NIR reflectance spectra obtained on 2011 March 28/29. Spectra are normalized at 1.27 μm and scaled in reflectance for clarity.

discussion in Section 3.1). To extract information from our data, we used different methods: spectral slope calculation, analysis of the methane absorption bands (shifts and areas) and spectral modelling. The results of such analyses are presented in the following sections.

3.1 Spectral slope

To compare our results with those published by Licandro et al. (2006a) and Tegler et al. (2007), our visible spectra from 2006 and 2011 were normalized at 0.65 μm, and spectral slopes calculated for the 0.55–0.65 μm region by fitting the spectral continuum with a linear function. The values obtained for the slope are shown in Table 1, together with literature values. The reported errors take into account both the error in the fit and the uncertainty introduced by dividing Makemake's spectra by the spectra of different solar analogues, with the latter component dominating the final error.

For data obtained in 2011 March, we calculated the rotational phase corresponding to the mid-exposure of each spectrum (P_{rot} = 7.771 ± 0.003 h; Heinze & de Lahunta 2009), arbitrarily assigning a value of zero to the rotational phase of the first obtained spectrum (cf. Table 1). Eight visible spectra were acquired during this run, covering about 80 per cent of the surface of Makemake and hence providing an optimal benchmark to look for any spectral variation on the surface. However, the calculated values of the slope present only minor variations, and all look compatible within the associated errors, suggesting that the surface of Makemake is very homogeneous. Our measurements are also consistent with the slope values of spectra obtained in 2005 August and 2006 March by Licandro et al. (2006a) and Tegler et al. (2007), respectively. Of course we should keep in mind that if we are observing Makemake near a polar aspect, the claim of a surface homogeneity will be less strong; however, as discussed in the Introduction, a nearly edge-on configuration seems now preferred (Parker et al. 2016).

On the other hand, the visible data we obtained in 2006 April look slightly redder than both literature and 2011 spectra, at the wavelengths under consideration. To exclude systematic errors, data reduction has been performed twice for both 2006 and 2011 data sets, by different coauthors of this paper using different procedures, but we did not find any incongruity at this step. Moreover, the sky conditions were good during both the observing runs. Hence there is no apparent reason to discard the data we obtained in 2006. It is, however, difficult to explain the discrepancy they present with the rest of our and literature data. Noteworthy, during the ∼5 yr between the 2006 and 2011 observations (over an orbital period of about 309 yr), Makemake moved away from the Sun by only 0.273 AU, with a consequent drop of the surface equilibrium temperature of less than 0.1 K (according to the Stefan–Boltzmann law). Such minor temperature change could hardly justify volatiles condensation episodes with a consequent global change in surface colour. Moreover, it has to be stressed that the data by Tegler et al. (2007) have been obtained just 1.5 months earlier than our 2006 data: none the less, they are perfectly consistent with our 2011 rather than the 2006 data, suggesting that no seasonal variations have occurred on the surface of Makemake during this time span. In summary, while we keep our 2006 data for further analysis, at this stage, we cannot easily interpret their spectral slope difference and we invite the reader to bear in mind that they may be suffering from some unidentified issues.

3.2 Band shifts analysis

As said above, Makemake's spectrum is dominated by strong methane ice absorption bands, and the eventual presence of nitrogen on the surface can be determined only by detecting a shift of the centre of observed bands with respect to those of pure methane ice (indeed, N_2 ice cannot be directly detected in our spectra by means of its absorption at ∼2.15 μm, as such, the band is about a thousand times fainter than the nearby CH_4 band at 2.2 μm, and the spectral resolution of our data is too low to detect any possible N_2 thin feature). In particular, we concentrated our analysis on the strongest methane bands (e.g., Grundy, Schmitt & Quirico 2002) that are present in all our visible spectra, namely those at 7296, 7862, 7993, 8442 and 8691 Å. The spectral resolution of our NIR spectra is too low to perform this kind of analysis. To determine the shifts of the bands, we ran a cross-correlation analysis (e.g. Becker, Sargent & Rauch 2004) between our spectra and the spectral model of pure methane: we varied the wavelength axis of the model and

Table 2. Value of methane band shifts (in Å).

	7296 Å	7862 Å	7993 Å	8442 Å	8691 Å
1S2006	-5 ± 4	–	–	–	-9 ± 6
2S2006	-7 ± 6	–	–	–	–
3S2011	-4 ± 4	-5 ± 4	-9 ± 4	-4 ± 4	-3 ± 4
4S2011	-4 ± 4	-3 ± 6	-7 ± 5	-8 ± 6	-5 ± 5
5S2011	-6 ± 4	-6 ± 4	-5 ± 4	-9 ± 4	-3 ± 4
6S2011	-6 ± 5	-2 ± 3	-3 ± 5	-8 ± 5	-5 ± 6
7S2011	-6 ± 4	-5 ± 4	–	-6 ± 4	–
8S2011	-7 ± 5	-5 ± 5	–	-4 ± 4	–
9S2011	-6 ± 4	-6 ± 4	-5 ± 4	-8 ± 4	–
10S2011	-7 ± 5	-7 ± 6	-7 ± 5	-8 ± 5	–
1S2013	–	-7 ± 3	-8 ± 4	-8 ± 4	-7 ± 4
2S2013	–	-8 ± 4	-8 ± 4	-9 ± 5	-7 ± 3
Band Average (σ)	−5.9 (1.0)	−5.4 (1.7)	−6.5 (1.9)	−7.2 (1.8)	−5.7 (2.3)

the maximum of cross-correlation function indicated the value of shift.

The average value (and standard deviation) of the band shifts among all our data is -6.2 ± 1.9 Å, in good agreement with the previously reported blueshift of ~ -4 Å for the same absorptions of methane ice in the visible spectra of Makemake (Licandro et al. 2006a; Tegler et al. 2007, 2008; Lorenzi et al. 2015). The measured shifts of the absorption bands of each visible spectrum, with respect to the theoretical value, are reported in Table 2. Some values are missing due to the fact that we were not able to obtain a reliable measurement of the center of the band, e.g. because of poor signal-to-noise ratio (S/N) or the presence of observational artefacts. As for the spectral slope, we did not find significant differences between one spectrum and the other, suggesting a homogeneous CH_4/N_2 dilution over the Makemake's surface. Hence, our data do not seem to support the hypothesis by Ortiz et al. (2012) of localized sublimation and condensation processes.

We stress that the depth of absorption bands we observe is somehow correlated with the path-length travelled by light (though one should recall that multiple scattering can account for long path-lengths without the need to traverse great physical distances). This means that different bands can inform about the CH_4/N_2 dilution state at different depths below the surface (the weaker the band, the deepest the sampled layer). For example, by a similar analysis on band shifts, Licandro et al. (2006b) claimed the presence of a vertical compositional gradient on the dwarf planet Eris. The authors suggested that while Eris moved towards its aphelion during the last 200 yr, the less volatile methane condensed first, while the surface composition became more nitrogen-rich as the most volatile nitrogen started to condense at a later stage (such result has been partly confirmed by Alvarez-Candal et al. 2011).

Like Eris, Makemake is approaching its aphelion. However, we have not found (in agreement with the literature) different values of the band shift for the different absorption bands, within the limits of error bars. We note that laboratory experiments (Quirico & Schmitt 1997) also show that for a given dilution state, the smaller the wavelength of a band, the smaller the shift: at the wavelengths of our interest, the difference in the shift of the different bands is of the order of $\sim$1 Å only, below the uncertainties of our measurements. What above suggests is that at least the upper layers of the subsurface (first few centimetres, cf. results about the grain size in Section 3.4) present no trends in the methane/nitrogen dilution, and is in agreement with the absence of a temporary atmosphere on Makemake.

3.3 Band area analysis

To further check the hypothesis of a homogeneous surface for Makemake, we analysed the area of the band at $\sim$0.73 μm. Such band is the wider and better defined in our data, thus the most suitable to be analysed in order to look for eventual secular or rotational variations that may be attributed to changes in the methane abundance on the surface. Areas and their relative errors were calculated for visible spectra acquired in 2006 and 2011 using a Monte Carlo simulation. The reflectance of each data point was changed 1000 times as $R\prime = R + (\Delta R \times X)$, where ΔR is the measurement uncertainty and X is a random number from a normal distribution with $\mu = 0$ and $\sigma = 1$. The area values were calculated as the mean of the 1000 simulations, and the error as the associated standard deviation. The obtained results suggest that the 0.73-μm band area does not vary in a significant way with the rotational phase, nor between 2006 and 2011 data, further implying that the methane state on the surface of Makemake did not change during this timeframe (Table 3, 1σ deviations are reported).

3.4 Spectral model

To better constrain the surface composition of Makemake, we applied spectral modelling to a complete visible and NIR spectrum obtained combining spectra 1S2011 and 5S2011, which have the higher S/N for their respective wavelength ranges (the combined spectrum was first normalized to the value of the visible albedo of Makemake, $p_V = 0.77$, at wavelength 0.55 μm). For modelling, we used the mathematical formalism developed by Shkuratov et al. (1999). This model allows us to determine the albedo of a medium from individual physical properties of the different chemical components with measured optical constants. We used the optical constants of methane ice (Grundy et al. 2002) and its irradiation products, including ethane, ethylene and acetylene (Quirico & Schmitt 1997), whose presence on the surface of Makemake was suggested by Brown et al. (2015). We also used optical constants of ice tholins (Khare et al. 1993) and crystalline/amorphous water ice (Grundy & Schmitt 1998) that have been used to model the spectra of several TNOs. It should be noted that optical laboratory spectra depend on conditions under which they were obtained, and on the temperature, in particular. Therefore, we used optical constants that were obtained at temperatures similar ($\sim$40 K) to those on Makemake's surface ($\sim$30 K). As previous spectroscopic (Tegler et al. 2007, 2008) and polarimetric (Belskaya et al. 2012) results suggest the presence of millimetre-sized or smaller particles on its surface, in our model, we consider a bimodal particle size for CH_4 that includes both large and small methane ice particles. We varied the grain size (by steps of 50 μm for grains between 10 μm and 1 cm, and by steps of 1 mm between 1 and 10 cm) and the relative abundances of each considered possible constituent (by steps of 1 per cent). The best-fitting spectral model, obtained by minimization of the root-mean-square deviation (RMSD), is presented in Fig. 3 and discussed in the following (we note that the spectral resolution of our model is about 10 times higher than that of the data).

The surface of Makemake seems dominated ($\sim$60 per cent) by centimetre-sized methane ice grains, while the presence of small CH_4 particles seems limited to a few per cent only. We stress that the existence of such large particles of methane ice is probably not realistic and our results (which however agree with the literature as discussed in the Introduction) could be just indicative of long path lengths: in practice, the derived size could be a measure of the

Table 3. Value of methane band (0.690–0.746 μm) area.

	1S2006	2S2006	3S2011	4S2011	5S2011	6S2011	7S2011	8S2011	9S2011	10S2011	Average
Area ($\times 10^{-3}$ μm)	5.10 ± 0.35	5.65 ± 0.38	5.74 ± 0.28	5.56 ± 0.30	5.75 ± 0.29	5.61 ± 0.29	5.67 ± 0.34	5.16 ± 0.32	5.52 ± 0.34	5.95 ± 0.36	5.57 ± 0.25

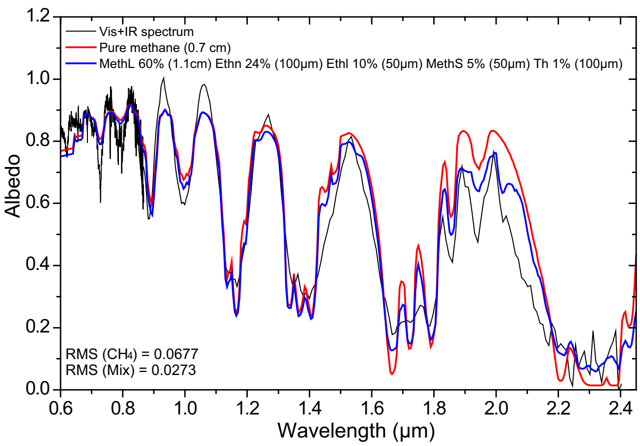

Figure 3. Spectrum of Makemake (black line), fitted by a model (blue line) of methane ice (large grains: 60 per cent; small grains: 5 per cent) plus ethane (24 per cent), ethylene (10 per cent) and ice tholins (1 per cent). The grain size is given in parentheses. A model of pure methane ice (red line) is shown for comparison. The RMSD of both the best-fitting model and pure methane model are reported.

spacing of voids in the solid methane rather than a measure of the actual grain size.

While the spectral resolution of our data is too low to directly detect the absorption bands of ethane and other irradiation products of methane, we stress that including them in our model clearly improves the fit, as demonstrated by the lowering of the RMSD with respect to a pure methane ice spectral model (cf. Fig. 3). The improvement of the fit is more evident in the NIR region, where most of the absorption features of methane irradiation products lie (see, e.g., Brown et al. 2015). The abundances we find for ethane and ethylene are more or less in agreement with those found by Brown et al. (2015), while acetylene is insignificant in our best-fitting model. This is not surprising if we consider that Brown et al. (2015) claimed for evidence of acetylene on Makemake based on a subtle extra absorption required to fit the 1.54-μm region: unfortunately, the S/N of our data is insufficient to identify such absorption by acetylene. More in general, we want to stress that while we can put some constraints on the properties of methane ice presenting numerous bands in our spectra, our analysis is limited for C_2H_X compounds whose spectral features are not visible at the given spectral resolution and S/N, preventing us to assess precise quantitative abundances of higher mass alkanes. Hence, here we do not claim our model to represent a unique solution (as combinations of different amounts of methane and other components can also reproduce relatively well the observed spectrum, with just slightly higher RMSD), but rather a hint of the presence of such irradiation products of methane.

Our best-fitting spectral model is completed by the introduction of ice tholins in small amounts, which helps to match the spectral continuum.

Finally, water ice is insignificant in our model, in agreement with the literature studies of Makemake. As water ice is expected to be abundant in the interior of TNOs, we can guess that it is confined in the subsurface and covered by more volatile compounds.

4 CONCLUSIONS

In this work, we present new visible and NIR spectral observations of the icy dwarf planet Makemake, whose mass and temperature just lie in a transition region between objects that can retain nitrogen and objects that are mostly nitrogen-depleted and are hence dominated by the less-volatile methane. In particular, we wanted to investigate further the hypothesized surface inhomogeneities and possible presence of a localized/temporary atmosphere, by means of data taken at different rotational phases and covering most part (∼80 per cent) of the surface.

In agreement with literature data, the spectra we obtained are dominated by methane ice absorption bands, whose central wavelengths are slightly blueshifted probably as a consequence of a (at least partial) dilution of methane in nitrogen. However, our data do not support the hypothesis of atmospheric freeze-out and escape episodes with consequent local colour changes, due to mixing of volatiles in different ratios over the surface. Indeed, the 12 visible and 2 NIR spectra of Makemake we obtained in 2006–2013 look very similar, in particular, in terms of spectral slopes and methane band shifts and areas. Such results seem to evidence a very homogeneous surface (noteworthy, the recent discovery of a Makemakean moon makes probable that we are looking at this dwarf planet quite close to an equator-on configuration).

Using the Shkuratov theory, we modelled a complete visible and NIR spectrum of Makemake and found that the surface is dominated by large centimetre-sized CH_4 ice grains (or, more realistically, by a consolidated slab), though the presence of smaller micrometre-to-millimetre particles (i.e. of a layer of hoarfrost covering the surface?) is also possible. While our reflectance spectra do not allow us to put firm constraints on the relative abundances of higher mass alkanes, the presence of C_2H_X compounds like ethane and ethylene (which are expected irradiation products of methane on the Makemakean surface) is suggested by the clear improvement of the modelling if such components are introduced in our synthetic spectrum.

Next-generation instruments will hopefully give us the possibility to study in higher detail the surface composition of this intriguing target, and to verify if any active process is actually ongoing over (and under) its icy surface.

ACKNOWLEDGEMENTS

This work is based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

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