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Modeling of the spectral properties of the dwarf planet Makemake

T. A. Hromakina, L. V. Starukhina, I. N. Belskaya, V. V. Korokhin

Institute of Astronomy of V.N. Karazin Kharkiv National University

We present the results of spectral modeling for dwarf planet Makemake in the visible and near infrared ranges. The spectral modeling of surface properties suggests the presence of both large and small (~1 μm) grains of methane ice on the top surface, and possible presence of ethane ice and other long-chain hydrocarbons.

Keywords: small Solar system bodies, planetary surfaces, spectral modeling.

В работе представлены результаты моделирования спектра карликовой планеты Макемаке в видимой и ближней инфракрасной областях. Предложена наиболее вероятная модель поверхности Макемаке, которая предполагает наличие как крупных, так и мелких (~1 микрон) частиц метанового льда в поверхностном слое, а также возможное наличие льда этана и более сложных гидрокарбонатов в качестве примесей.

Ключевые слова: малые тела Солнечной системы, планетные поверхности, моделирование спектра.

У роботі наведені результати моделювання спектра карликової планети Макемаке у видимому та ближньому інфрачервоному діапазоні. Запропонована найбільш імовірна модель поверхні Макемаке, яка передбачає наявність як великих, так і малих за розмірами (~1 мікрон) часток метанового льоду на поверхні, а також можливу наявність льоду етану та більш складних гідрокарбонатів у якості домішок.

Ключові слова: малі тіла Сонячної системи, планетні поверхні, моделювання спектра.

Introduction

The dwarf planet (136472) Makemake is one of the largest and brightest trans-Neptunian objects (TNOs). The first hints of its surface composition were obtained shortly after the discovery in 2005; they were based on spectral observations in the 0.3-2.5 μm spectral region by Brown et al. [3] and Licandro et al. [13]. Spectral observations have revealed the presence of methane absorption bands. Moreover, Makemake's spectra show the strongest absorption bands of methane ice compared to other methane-rich Solar system objects, namely (134340) Pluto, (136199) Eris, and Neptune's satellite Triton [3, 13].

Later Makemake was repeatedly observed in the visible and near-IR spectral region in search for possible surface heterogeneity [5, 14, 17]. Available for ground-based observations, this spectral range is particularly useful because it contains absorptions bands of silicate minerals, ices and hydrocarbons [1]. All spectra of Makemake are compatible with each other. Some discrepancies between the continuum slope and the depth of absorption bands are due rather to the use of different solar analog stars than due to real changes over surface. However, as stated in [14], the color variation over the surface of Makemake is also not excluded.

Spectral modeling [3, 5, 13] suggests that the dominant substance on the surface of Makemake is methane and not nitrogen as it is for Pluto and Eris. No nitrogen absorption lines were detected. But close examination of the methane ice bands revealed that they are blue shifted by ~4 Å [14, 17]. The authors argue that such shift is related to the presence of a small (up to a few percents) amount of nitrogen on the surface. As for methane ice, spectral modeling performed by [3, 13, 17] in the visible and near-IR spectral ranges using Hapke model [9] implies the presence of large grains at least one centimeter in size. By applying both Hapke and so-called slab model, the authors [7] suggested that methane presented on Makemake's surface in the form of low-porosity ice slab formed by sintered micron-sized grains.

The red spectral slope in the visible range measured for Makemake is rather typical of outer Solar system bodies. This is usually explained by the presence of tholins that could be formed by solar irradiation of simple organic compounds such as methane or ethane [3]. The presence of ethane and more complex hydrocarbons as natural products of methane irradiation on the Makemake's surface was also suggested [3, 5].

The presence of very large particles or slab on the Makemake's surface looks rather unrealistic, since the typical estimate of the methane grain size on the other dwarf planets is about 100 μm or less (see., e. g, [19, 20]). Furthermore, according to recent polarimetric observations of Makemake [2], its surface should be covered by a thin fluffy layer of submicron grains. In this paper we use spectral modeling based on other approach to analyze possible texture of the Makemake's surface.

Spectral modeling

We have analyzed spectral data published by Brown et al. [3] and Licandro et al. [3 13], and kindly provided by the authors. The spectra were normalized at the wavelength λ = 0.55 μm to the value of the visible albedo $p_v = 0.8$ [4, 15]. Both spectra are rather similar with only minor differences in the absorption bands shape at 1.4 and 1.95 μm. For the modeling we used spectrum from [3] in the 1.0-2.5 μm wavelength range which has the higher signal-to-noise ratio.

In order to model the spectrum of Makemake we used the model of Shkuratov et al. [21, 23]. One of the advantages of this model is that it uses directly the optical constants of the surface material (real and imaginary parts of the complex refractive index). Another advantage is its invertibility, i.e. possibility to calculate both the albedo of the surface starting from its optical constants and the absorption coefficient of the surface material starting from the albedo, if the value of the real part of complex refractive index is preliminary estimated. The mathematical concept of the model is described in [21, 23].

In our modeling we used optical constants of methane, ethane, tholins, acetylene, and other hydrocarbons [6, 8, 10, 11, 12, 18]. It should be noted that optical laboratory spectra depend on conditions under which they were obtained, in particular, on the temperature. Therefore, we used optical constants that were obtained at the temperatures corresponding to those on Makemake surface (~40 K).

We also used modification of the model [21, 23] for submicron particles (~λ), because the presence of such small grains results in change of both absorption and refraction indices. The modification is also described in [21, 23].

The best agreement between the observed reflection spectrum and the model was achieved by minimizing the chi-square value:

$$\chi^2 = \sum_{i=1}^{n} \frac{(\mathrm{O}_i - M_i)^2}{M_i},$$

where O_i are the points of the measured spectrum, M_i are the points of model spectrum, n is the number of points. For fitting procedure we used the astronomical software “xIRIS Framework” developed by V. V. Korokhin, E. V. Shalygin., and Yu. I. Velikodsky (for more information see http://www.astron.kharkov.ua/dslpp/iris/xiris.html).

Assuming that the Makemake’s surface is covered mostly by methane ice [3, 13, 17], at the beginning we used only laboratory spectrum of methane obtained at 40 K [8]. Varying methane grain size from 10^{-5} to 1 cm we have found the best fit for the grain size of 0.3-0.4 mm though the coincidence is not perfect (Fig. 1).

Polarimetry results for Makemake [2] indicate presence of micron-size particles on its surface. Taking this into account, as the next step of our modeling we used a two-component surface model, that includes large (d > λ) and small (d ~ λ) methane ice particles.

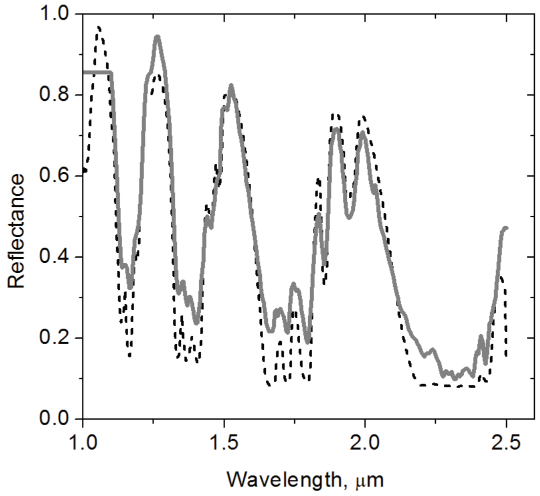

Fig. 1. Comparison between the measured spectrum of Makemake (dashed black line) and the spectral model that uses large (~0.35 mm) methane ice grains (solid gray line).

The assumption about the presence of small methane ice particles on the surface significantly improved the agreement between the model and the observed spectra. The minimum of χ^2 value was achieved at 70:30 mix of large (~ 0.3 cm) and small (~1 μm) methane ice grains, respectively (Fig. 2). Note that two free parameters of our modeling (the concentration and grain size) cannot be varied independently, so the determination of both free parameters is difficult. Very similar model spectra can be obtained either with very large grain size and high concentration of

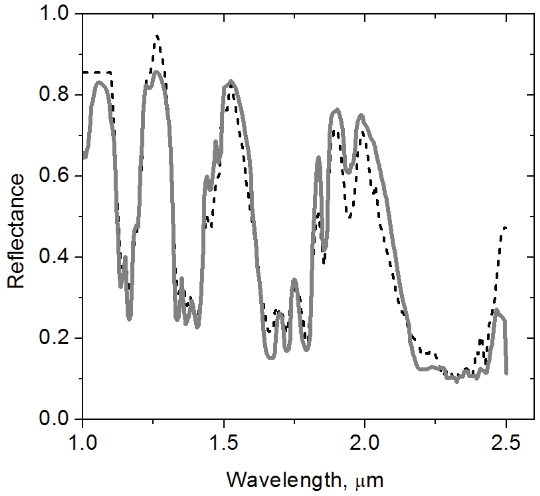

Fig. 2. Comparison between the measured spectrum of Makemake (dashed black line) and model that uses large (~0.3 mm) and small (~1 μm) methane ice in a 70:30 mix (solid gray line).

micron-sized component or with smaller grain size and low concentration of micron-sized component.

To improve the agreement between the measured and calculated spectra we used different admixtures found by spectral modeling on the surfaces of dwarf planets and methane-rich Solar system bodies, and theoretically possible on the surface of Makemake. We used reflectance spectra of tholins, ethane, acetylene, and other hydrocarbons. Spectral modeling of methane ice mixed with various inclusions has shown that an addition of ~30 μm ethane ice grains in concentration of about 20% reduces the difference between the observed and calculated spectra of Makemake at some wavelengths. It also reduces total residual in comparison with pure methane ice spectrum (Fig. 3). The presence of tholins is also not ruled out. The influence of other organic materials on the model is insignificant.

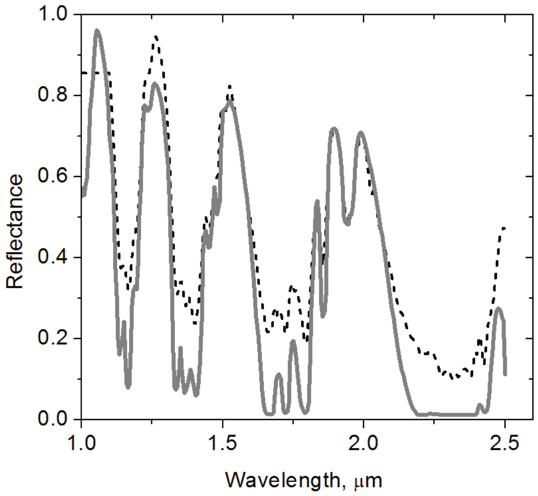

Fig. 3. Comparison between the measured spectrum of Makemake (dashed black line) and the model that uses large methane ice grains (~0.3 mm), small methane ice grains (~1 μm), and ethane ice (~30 μm) in a 60:20:20 mix (solid gray line).

Conclusion

We present the results of spectral modeling for dwarf planet Makemake. We used a slightly different approach as compared to other researchers in order to analyze surface properties of Makemake and to check the plausibility of very coarse methane ice grains on the surface of Makemake suggested before [3, 13, 17]. According to our results, the most likely model of the Makemake's surface suggests the presence of large methane ice particles of a size ~0.3 cm (~60%) coated with fine particles of a size ~1 μm (~20%), as well as the possible presence of ethane ice (~20%). The assumption about the presence of small particles covering large particles enables us to reconcile the results of spectral and polarimetric observational data.

1. M. A. Barucci. Composition and Surface Properties of Transneptunian Objects and Centaurs. The Solar System Beyond Neptune, University of Arizona Press (2008), p. 143.
2. I. N. Belskaya et al. A&A, 479, 265 (2008).
3. M. E. Brown et al. The Astronomical Journal, 133, 284 (2007).
4. M. E. Brown et al. The Astrophysical Journal Letters, 767, L7, (2013).
5. M. E. Brown et al. The Astronomical Journal, 149, 105 (2015).
6. R. N. Clark et al. Journal of Geophysical Research, 114, E03001 (2009).
7. J. Eluszkiewicz et al. Journal of Geophysical Research, 122, E06003 (2007).
8. W.M. Grundy et al. Icarus, 155, 486 (2001).
9. B. Hapke and E. Wells. Journal of Geophysical Research, 86, 3039 (1981).
10. R. L. Hudson et al. Icarus, 228, 276 (2014).
11. R. L. Hudson et al. Icarus, 243, 148 (2014).
12. B. N. Khare and K. Sagan. Icarus, 60, 127 (1984).
13. J. Licandro et al. A&A, 445, 35 (2006).
14. V. Lorenzi et al. A&A, 577, 86 (2015).
15. J. L. Ortiz et al. Nature, 491, 566 (2012).
16. F. Poulet et al. Icarus, 160, 313 (2002).
17. S.C Tegler et al. Icarus, 195, 844 (2008).
18. E. Quirico et al. Icarus, 127, 354 (1997).
19. D. L. Rabinowitz et al. The Astrophysical Journal, 639, 1238 (2006).
20. T. Sasaki et al. The Astrophysical Journal, 618, 57 (2005).
21. Yu. Shkuratov and L. Starukhina. Icarus, 137, 235 (1999).
22. B. Sicardy et al. Nature, 478, 493 (2011).
23. L.V. Starukhina, Yu. G. Shkuratov. Astron. Vestnik, 30, 4, 299 (1996).