Highlights of Spanish Astrophysics VIII, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society held on September 8–12, 2014, in Teruel, Spain. A. J. Cenarro, F. Figueras, C. Hernández-Monteagudo, J. Trujillo Bueno, and L. Valdivielso (eds.)

Characterization of trans-neptunian objects from thermal radiometry and stellar occultations

P. Santos-Sanz[1], E. Lellouch[2], J.L. Ortiz[1], B. Sicardy[2], R. Duffard[1], F. Roques[2], N. Morales[1], A. Doressoundiram[2], A. Thirouin[1] and S. Fornasier[2]

[1] Instituto de Astrofísica de Andalucía-CSIC, Granada, Spain
[2] Observatoire de Paris-Meudon, LESIA, France

Abstract

The Spanish-French project *'Characterization of trans-neptunian objects from thermal radiometry and stellar occultations'* is using the existing synergies between the radiometric technique and the stellar occultations technique to study one of the most primitive populations in our Solar System: the trans-neptunian objects (TNOs). These objects are the leftovers which survived the planetary formation until today, and they retain relevant physical information which provides unique clues about the origin and evolution of the Solar System and other planetary systems. This paper describes this research project and the two techniques used to get physical information on the TNOs. The strength of each technique and of the combination of both are discussed. The main results obtained from this project until now are presented.

1 Introduction to the project

Small bodies of the Solar System are considered the remnants of planetesimals that formed during the early phases of the planetary accretion. Trans-neptunian objects (TNOs), Centaurs, and cometary nuclei (at least when they remain in the Oort cloud) are the most distant and coldest of these small bodies which retain, mostly unaltered, physical, chemical and dynamical information on the primordial material(s) that formed the planets. The physical and dynamical study of these bodies constrains the processes that occurred over the Solar System history and its evolution.

With over 1700 known objects, the orbital characterization of the TNO population (a.k.a. the Kuiper Belt) is now relatively well established, showing several population families (classical, resonant, scattered/detached, centaurs, etc) of various dynamical origins ([18], [16]).

Although at a slower pace, physical characterization of TNOs has progressed significantly in the last ∼20 years after the discovery of the first TNO (apart of Pluto itself) in 1992.

Numerous results have been obtained on their surface colors from visible to near-IR photometry ([23]; [46]; [12]; [13]; [61]; [52] ;[24]; [47]), on their surface composition via spectroscopy ([1]; [3]), on their rotational state and shape from optical light-curves ([40]; [41]; [56]; [8]; [9]; [62]; [63]) and on their binarity/multiplicity by direct imaging or other techniques ([39]; [20]; [21]; [22]).

However, other relevant physical magnitudes are out of reach with these techniques: these are the size, the mass density, the albedo, and the thermo-physical properties (i.e. thermal inertia and emissivity). Knowing these quantities is needed not only for a complete characterization of each individual object, but also, if they can be measured on a sufficiently large sample, to evaluate possible correlations between physical and orbital characteristics, that could testify of physical processes that have been or are still at work within this population (e.g. collisions, surface irradiation, maintenance of volatile ices, existence of rings, satellites, etc).

The goal of this research project is to determine these difficult-to-measure physical properties of Kuiper Belt Objects (KBOs), using two complementary techniques: (i) thermal radiometry, and (ii) stellar occultations.

2 Thermal radiometry technique

The thermal radiometry technique allows to estimate simultaneously the equivalent size, geometric albedo and thermal regime of the object measuring its flux at several thermal wavelengths and combining those with its optical measurement ([30]). The thermal regimen of the object is determined from the shape of the Spectral Energy Distribution (SED), and provides information on the thermal inertia, either through thermo-physical modeling ([59]; [29]; [36]; [7]) or in a semi-empirical way through a thermal model ([25]) which use the so-called "beaming factor", a parameter that effectively describes the combined effect of thermal inertia and surface roughness.

In our project, we use thermal data of 130 TNOs/Centaurs acquired in the framework of a Key Programme of the Herschel Space Observatory entitled "TNOs are cool: a survey of the trans-neptunian region" ([37]). Most objects are observed with the Photodetector Array Camera and Spectrometer (PACS; [48]) onboard Herschel at 70, 100 and 160 μm, and a subset of 11 of them is also observed with the Spectral and Photometric Imaging Receiver (SPIRE; [19]) at 250, 350 and 500 μm. These data are combined, whenever possible, with similar data obtained by Spitzer-MIPS at 24 and 70 μm ([60]), which greatly improves the determination of the "beaming factor", the diameter and the albedo, and provides enhanced constraints on the thermal properties like the thermal inertia.

Typical accuracies obtained from this radiometry technique are of 10 % on the equivalent diameter and 20 % on the geometric albedo estimations ([54]; [33]). If the mass is known independently, which in general is the case of binary/multiple systems ([39]; [20]; [21]; [22]), the size measurements permits to determine the bulk density –though with reduced accuracy– ([54]; [64]; [35]), which is the most fundamental geophysical parameter, giving access to its bulk composition.

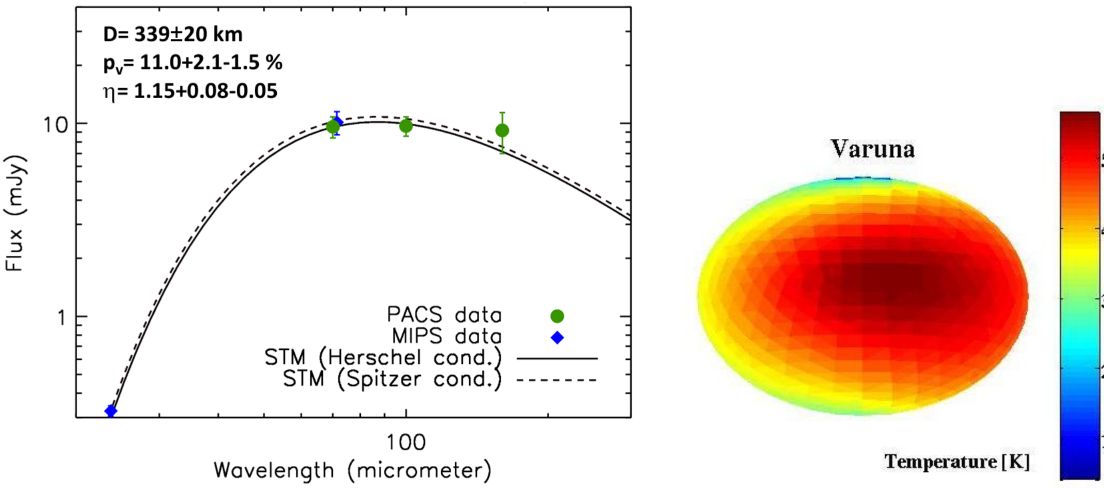

Figure 1: Left: Spectral Energy Distribution (SED) and thermal modeling applied for the TNO 1996 TL_{66}. This object was observed with Spitzer/MIPS (blue filled diamonds) and Herschel/PACS (green filled circles). The best fit is plotted for the Herschel conditions (solid line) and for the Spitzer conditions (dashed line). The results from the thermal modeling are the diameter (D), the geometric albedo at V-band (p_v), and the "beaming factor" (η). Right: Thermo-physical model applied to the TNO Varuna. (Figures adapted from [54] and [53]).

For objects observed at a large number of wavelengths, the precise SED shape may also provide information of the spectral emissivity ([17]). Finally the program has included the search for thermal light-curves for a few prominent and bright objects (see Figure 2), providing additional constraints on their thermal inertia and on surface properties such as porosity ([32]; [53]).

3 Stellar occultations technique

Stellar occultations provide an exquisitely simple method to determine the size and shape of airless bodies, by measuring the timing of disappearance/reappearance of a star behind an object limb and converting it into a chord length ([15]; [50]). When multiple chords of a single event can be obtained, they can be fit by a shape model.

The strength of the method is in its accuracy, with diameter/shape uncertainty at the kilometre level only ([58]; [42]). The main difficulty lies in the prediction of the events, which are rare due to the extremely small apparent size of the KBOs/Centaurs (typically 10 mas or even smaller) and the uncertainties in the orbit determination (due to the short arc of the orbit observed), although the situation has improved spectacularly over the last few years thanks to improved ephemerides and star catalogues. Anyway, only ∼17 occultations by 9 TNOs (see Table 1) have been recorded so far from ground-based telescopes what makes necessary an extra effort to involve other facilities.

The complementarity of the occultation method with the thermal radiometry technique

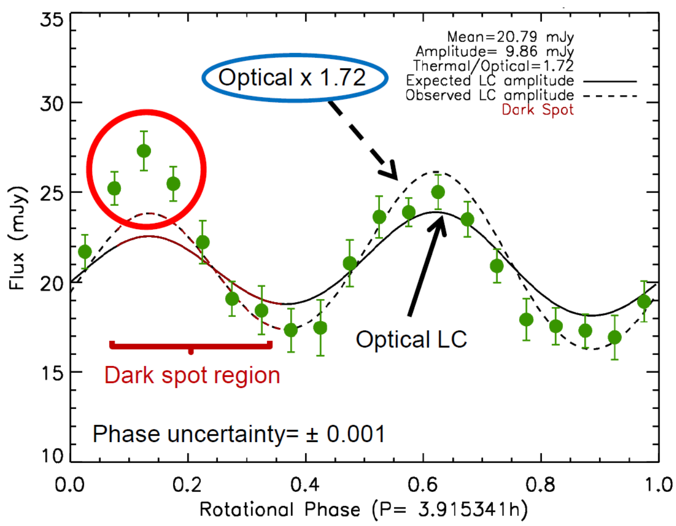

Figure 2: Haumea thermal light-curve at 100 μm. The green dots are the Herschel/PACS data. The solid line is the optical light-curve of Haumea and the dashed line is the same but plotted with the amplitude derived from the thermal light-curve. The amplitude of the thermal light-curve is 1.72 times the amplitude of the optical light-curve. The red parts in the plot mark the presence of a dark spot region in the Haumea's surface (Figure adapted from [55]).

is that (i) they provide a cross-check validation on the diameter results (ii) when accurate determinations are available from occultation, their use in modeling the thermal data provides greatly improved determination of the thermo-physical properties. Further, when the rotation period of an object is known, its measured shape (usually elongated) permits to investigate whether it is in an equilibrium state and to constrain its density. Finally, occultations permit to search/characterize tenuous atmospheres ([31]), with a sensitivity as low as the $\sim$10 nbar level. It will be also possible to detect and characterize satellites around the main body and to discover/characterize ring systems as the one recently detected around the Centaur Chariklo ([5]). Apart of the discovery, one can obtain information about astrometry, structure, and evolution of these satellites and rings. Our group has for a long time being exploiting the technique to study distant small bodies, being active at all steps from prediction to scientific exploitation ([58]; [42]; [5]).

3.1 Serendipitous stellar occultations

Besides these "predicted-occultations", we are attempting to detect random stellar occultations, i.e. trying to detect the diffraction shadow pattern in serendipitous stellar occultations by small numerous TNOs ([49]; [50]). These serendipitous occultations have no other competing methods, as the magnitudes of the corresponding objects, V $\sim$ 35 mag or fainter, are unreachable through classical ground-based –or even space-based– imaging.

Such occultations can reveal the vertical and radial distribution of the TNOs as far as

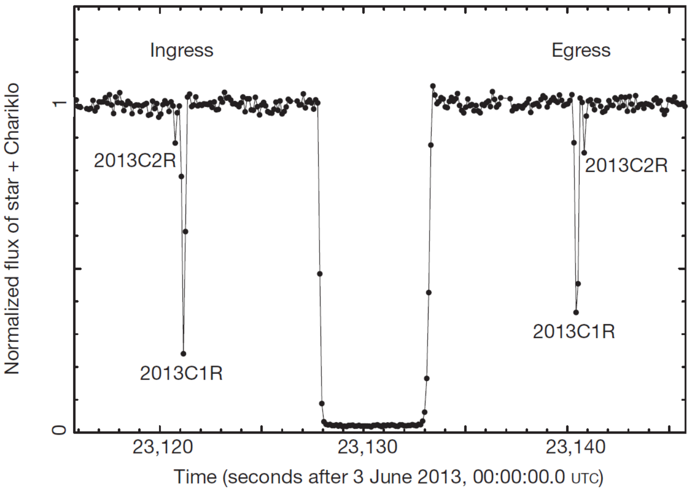

Figure 3: Light curve of the occultation by Chariklo observed with the Danish 1.54-m telescope (La Silla) on 3 June 2013. The fluxes has been normalized to unity outside the occultation. The central drop is caused by Chariklo and the two secondary symmetric events before and after the main drop (2013C1R and 2013C2R) are caused by the rings (Figure from [5]).

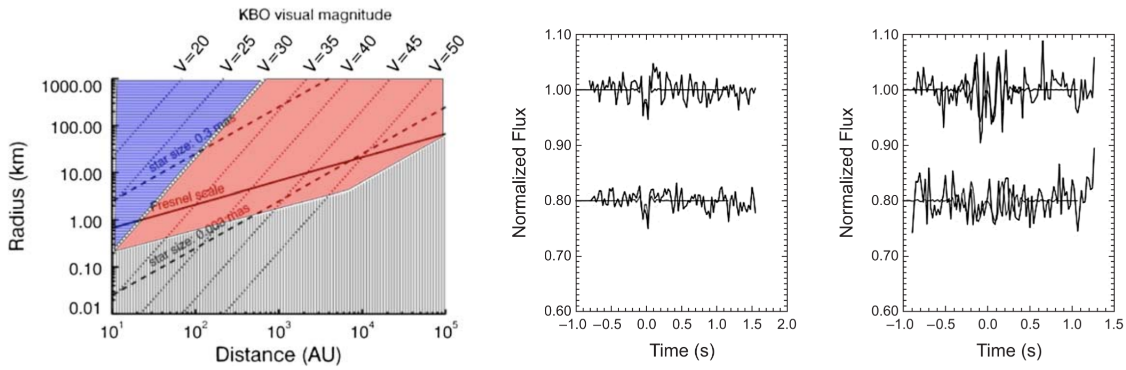

Figure 4: Left panel: The blue region indicates the objects detectable by direct observations and the pink region the ones detectable by occultations with a 4 m telescope and an integration time of 40 Hz. Two right panels: examples of serendipitous stellar occultation events (Figures adapted from [50] and [49]).

Table 1: Stellar occultations by TNOs observed so far. One-chord (single) or more that one-chord (multi) observation is indicated. Table updated and adapted from [43]

TNO	Date	Location
2002 TX_{300}	9-Oct-2009	Hawaii, multi
Varuna	19-Feb-2010	Brazil, single
Eris	6-Nov-2010	Chile, multi
2003 AZ_{84}	8-Jan-2011	Chile, single
Quaoar	11-Feb-2011	USA, single
Makemake	23-Apr-2011	Chile, Brazil
Quaoar	4-May-2011	Chile, Brazil
2003 AZ_{84}	3-Feb-2012	Israel, India
Quaoar	17-Feb-2012	France, single
2002 KX_{14}	26-Apr-2012	Spain, single
Quaoar	15-Oct-2012	Chile, single
Varuna	8-Jan-2013	Japan, multi
Sedna	13-Jan-2013	Australia, single
Quaoar	8-Jul-2013	Venezuela,single
2003 AZ_{84}	2-Dec-2013	Australia, single
2003 VS_2	12-Dec-2013	Reunion, single
Varuna	11-Feb-2014	Chile, multi
2003 VS_2	4-Mar-2014	Israel, single
Orcus' satellite	1-Mar-2014	Japan, single
Ixion	26-Jun-2014	Australia
2003 VS_2	7-Nov-2014	Argentina, multi
2007 UK_{126}	15-Nov-2014	USA, multi
2003 AZ_{84}	15-Nov-2014	Japan,China,Thai

50 AU and beyond (kilometre-sized objects could be detected at $\sim$ 500 AU, and even could be possible the detection of Oort cloud objects beyond 2000 AU, as is showed in the left panel of Figure 4). Also, they provide information on the size distribution down to hectometre-sized and smaller objects (left panel Figure 4), which is a key constraint to characterize the collisional history in the Kuiper Belt.

To reach this particular goal we have designed a specific instrument called MIOSOTYS (Multi-object Instrument for Occultations in the SOlar system and TransitorY Systems) ([6]; [57]). MIOSOTYS is a newly refurbished instrument designed at Observatoire de Paris (Meudon) which consists on a multi-fibre positioner coupled with a fast photometry camera. It has been mounted as a visitor instrument on the 193-cm telescope at Observatoire de Haute-Provence (France, [14]) and on the 123-cm telescope at Calar Alto Observatory (CAHA-Spain). Since 2015 it is mounted also as a visitor instrument on the 2.2-m telescope at CAHA (Spain). The installation of MIOSOTYS at Calar Alto Observatory is possible thanks to the collaboration between the Observatoire de Paris and the Instituto de Astrofísica de

Andalucía-CSIC. Last, but not least, this instrument is a prototype of a larger instrument called ULTRAPHOT (with more than 100 fibres) that could be used in one of the ESO-VLT units ([51]).

MIOSOTYS Science operations started since 2010, and we have acquired nearly 10000 star-hours. Preliminary data analysis has revealed one possible occultation event ([14]). Since our approach is based on statistics, more data are needed in order to derive strong and significant conclusions.

4 Results

Significant results have been already obtained on the first two aspects of the program. The TNOs are cool program (thermal radiometric technique, Section 2) has led already to about sixteen publications ([2]; [10]; [17]; [26]; [27]; [28]; [32]; [33]; [34]; [35]; [37]; [38]; [45]; [54]; [64]; [65]). The corresponding main results can be summarized as follows:

1 The measured TNOs/Centaurs present a diversity of diameters (150-2300 km) and albedos (3-100 %). Within the scattered disk/detached population, there are possible correlations between diameter and albedo, that could be interpreted from the ability of large objects to retain bright volatile ices ([54]).

2 From the thermal point of view, most TNOs/Centaurs appear to be rather close to a state of instantaneous equilibrium with insolation, which points to very low surface inertias and significant surface roughnesses and porosity ([33]).

3 The spectral emissivities of most objects decrease towards the longest wavelengths, indicative of a significant transparency of the surface, with long-wavelength radiation probing the colder subsurface ([17]).

4 The thermal light-curve of dwarf planet Haumea indicates combined effects due to shape and an albedo marking on the surface. There are also indications that this may also be happening in the TNO Varuna from the analysis of its thermal light-curve ([32]; [55]).

5 The albedos/diameters of Centaurs are not correlated with their orbital parameters. There is also no correlation between diameters and albedos. Most of the Centaurs observed are dark (albedos < 7 %) and small ($D < 120$ km). Color bimodality is only present in small Centaurs, which can be red or grey. All the large Centaurs are grey ([10]).

6 The surfaces of most TNOs can be classified in two types: dark neutral (albedos $\sim$ 0.05; spectral slopes $\sim$ 10 %) and bright red (albedos $\sim$ 0.15; spectral slopes $S \sim 35$ %). This color-albedo separation is evidence for a compositional discontinuity in the primitive solar system: bright red TNOs have presumably formed further from the Sun than the dark neutral ones ([28]).

The "targeted-occultation" program (Section 3) has led to the successful observations by about ten objects in the last ∼5 years (see Table 1), including prominent objects like Quaoar ([4]), Varuna, Eris, Makemake and Sedna. Several papers have been published recently ([58]; [42]; [5]).

Among the most remarkable results is the evidence that Eris' size is indistinguishable from Pluto's (unlike previous belief that Eris was larger), but that its albedo is even higher (96 %). This is best interpreted by the fact that Eris, currently near aphelion at 96 AU could be currently entirely covered by a fresh and ultra-bright layer of N2/CH4 ice resulting from the condensation of an atmosphere that develops near perihelion and collapses as Eris recedes from the Sun ([58]). Another result is the accurate size and shape of the dwarf-planet Makemake obtained from a stellar occultation observed from eight telescopes ([42]). Accurate sizes and improved densities of Eris, Makemake and Quaoar have become available thanks to this program. One of the last recent result, published in Nature, is the surprising and unexpected detection of a ring system around the centaur Chariklo ([5]), the first ring ever detected around a minor body. We also have characterized these Chariklo's rings ([11]) and we have proposed the possible existence of another ring system around the centaur Chiron ([44]). This open the exciting possibility to detect these very thin ring systems from the stellar occultation technique around other (perhaps not only centaurs) Solar System minor bodies.

Finally, as mentioned in Section 3.1, the "Serendipitous stellar occultations" program is recording evidence for a few positive events but more statistics, that will be obtained for sure from the 123-cm and 2.2-m Calar Alto Observatory telescopes, are needed.

The Spanish-French project described here has been awarded with the First *Sociedad Española de Astronomía (SEA)- Société Française d'Astronomie et d'Astrophysique (SF2A)* prize 2013 for outstanding achievements in a scientific research cooperation.

Acknowledgments

P. Santos-Sanz would like to acknowledge financial support by the Spanish grants AYA2008-06202-C03-01, AYA2011-30106-C02-01, 2007-FQM2998 and 2012-FQM1776 and by the Centre National de la Recherche Scientifique (CNRS-France). R. Duffard acknowledges financial support from the MINECO (contract Ramon y Cajal).

References

[1] Barucci, M. A., Brown, M. E., Emery, J. P.,& Merlin, F. 2008, The Solar System Beyond Neptune, 143

[2] Barucci, M. A., Merlin, F., Perna, D., et al. 2012, A&A, 539, AA152

[3] Barucci, M. A., Alvarez-Candal, A., Merlin, F., et al. 2011, Icarus, 214, 297

[4] Braga-Ribas, F., Sicardy, B., Ortiz, J. L., et al. 2013, ApJ, 773, 26

[5] Braga-Ribas, F., Sicardy, B., Ortiz, J. L., et al. 2014, Nature, 508, 72

[6] Boissel, Y., Shih, I. C., Chang, H. K., et al. 2010, Proceedings of High Time Resolution Astrophysics - The Era of Extremely Large Telescopes (HTRA-IV). May 5 - 7, 2010. Agios Nikolaos, Crete Greece. Published online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=108, id.44, 44

[7] Davidsson, B. J. R., Gutiérrez, P. J., & Rickman, H. 2009, Icarus, 201, 335

[8] Duffard, R., Ortiz, J. L., Santos Sanz, P., et al. 2008, A&A, 479, 877

[9] Duffard, R., Ortiz, J. L., Thirouin, A., Santos-Sanz, P., & Morales, N. 2009, A&A, 505, 1283

[10] Duffard, R., Pinilla-Alonso, N., Santos-Sanz, P., et al. 2014, A&A, 564, AA92

[11] Duffard, R., Pinilla-Alonso, N., Ortiz, J. L., et al. 2014, A&A, 568, AA79

[12] Doressoundiram, A., Peixinho, N., Moullet, A., et al. 2007, AJ, 134, 2186

[13] Doressoundiram, A., Boehnhardt, H., Tegler, S. C., & Trujillo, C. 2008, The Solar System Beyond Neptune, 91

[14] Doressoundiram, A., Roques, F., Liu, C.-Y., & Maquet, L. 2014, AAS/Division for Planetary Sciences Meeting Abstracts, 46, #421.05

[15] Elliot, J. L. 1979, Annual review of Astronomy and Astrophysics, 17, 445

[16] Elliot, J. L., Kern, S. D., Clancy, K. B., et al. 2005, AJ, 129, 1117

[17] Fornasier, S., Lellouch, E., Müller, T., et al. 2013, A&A, 555, AA15

[18] Gladman, B., Marsden, B. G., & Vanlaerhoven, C. 2008, The Solar System Beyond Neptune, 43

[19] Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, A&A, 518, LL3

[20] Grundy, W. M., Noll, K. S., Buie, M. W., et al. 2009, Icarus, 200, 627

[21] Grundy, W. M., Noll, K. S., Nimmo, F., et al. 2011, Icarus, 213, 678

[22] Grundy, W. M., Benecchi, S. D., Porter, S. B., & Noll, K. S. 2014, Icarus, 237, 1

[23] Hainaut, O. R., & Delsanti, A. C. 2002, A&A, 389, 641

[24] Hainaut, O. R., Boehnhardt, H., & Protopapa, S. 2012, A&A, 546, AA115

[25] Harris, A. W. 1998, Icarus, 131, 291

[26] Kiss, C., Szabó, G., Horner, J., et al. 2013, A&A, 555, AA3

[27] Kiss, C., Müller, T. G., Vilenius, E., et al. 2014, Experimental Astronomy, 37, 161

[28] Lacerda, P., Fornasier, S., Lellouch, E., et al. 2014, ApJL, 793, LL2

[29] Lagerros, J. S. V. 1996, A&A, 310, 1011

[30] Lebofsky, L. A., & Spencer, J. R. 1989, Asteroids II, 128

[31] Lellouch, E., Sicardy, B., de Bergh, C., et al. 2009, A&A, 495, L17

[32] Lellouch, E., Kiss, C., Santos-Sanz, P., et al. 2010, A&A, 518, LL147

[33] Lellouch, E., Santos-Sanz, P., Lacerda, P., et al. 2013, A&A, 557, A60

[34] Lim, T. L., Stansberry, J., Müller, T. G., et al. 2010, A&A, 518, LL148

[35] Mommert, M., Harris, A. W., Kiss, C., et al. 2012, A&A, 541, A93

[36] Müller, T. G., & Lagerros, J. S. V. 2002, A&A, 381, 324

[37] Müller, T. G., Lellouch, E., Böhnhardt, H., et al. 2009, Earth Moon and Planets, 105, 209

[38] Müller, T. G., Lellouch, E., Stansberry, J., et al. 2010, A&A, 518, LL146

[39] Noll, K. S., Grundy, W. M., Chiang, E. I., Margot, J.-L., & Kern, S. D. 2008, The Solar System Beyond Neptune, 345

[40] Ortiz, J. L., Gutiérrez, P. J., Santos-Sanz, P., Casanova, V., & Sota, A. 2006, A&A, 447, 1131

[41] Ortiz, J. L., Santos Sanz, P., Gutiérrez, P. J., Duffard, R., & Aceituno, F. J. 2007, A&A, 468, L13

[42] Ortiz, J. L., Sicardy, B., Braga-Ribas, F., et al., 2012, Nature, 491, 566

[43] Ortiz et al. 2014, European Planetary Science Congress 2014, EPSC2014

[44] Ortiz, J.L., Duffard, R., Pinilla-Alonso, N., et al. 2015, A&A in press. (arXiv:1501.05911)

[45] Pál, A., Kiss, C., Müller, T. G., et al. 2012, A&A, 541, LL6

[46] Peixinho, N., Boehnhardt, H., Belskaya, I., et al. 2004, Icarus, 170, 153

[47] Peixinho, N., Delsanti, A., Guilbert-Lepoutre, et al. 2012, A&A, 546, AA86

[48] Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, A&A, 518, LL2

[49] Roques, F., Georgevits, G., & Doressoundiram, A. 2008, The Solar System Beyond Neptune, 545

[50] Roques, F., Boissel, Y., Doressoundiram, A., Sicardy, B., & Widemann, T. 2009, Earth Moon and Planets, 105, 201

[51] Roques, F., Guinouard, I., Buey, J.-T., et al. 2009, Science with the VLT in the ELT Era, 429

[52] Santos-Sanz, P., Ortiz, J. L., Barrera, L., & Boehnhardt, H. 2009, A&A, 494, 693

[53] Santos-Sanz, P., Kiss, C., Lellouch, E., et al. 2011, EPSC-DPS Joint Meeting 2011, 1099

[54] Santos-Sanz, P., Lellouch, E., Fornasier, S., et al. 2012, A&A, 541, A92

[55] Santos-Sanz, Lellouch, E., Ortiz, J.L., et al. 2014, EPSC Meeting 2014,

[56] Sheppard, S. S., Lacerda, P., & Ortiz, J. L. 2008, The Solar System Beyond Neptune, 129

[57] Shih, I. C., Doressoundiram, A., Boissel, Y., et al. 2010, Proceedings of the SPIE, 7735, 773546

[58] Sicardy, B., Ortiz, J. L., Assafin, M., et al. 2011, Nature, 478, 493

[59] Spencer, J. R. 1990, Icarus, 83, 27

[60] Stansberry, J., Grundy, W., Brown, M., Cruikshank, D., Spencer, J., Trilling, D., & Margot, J.-L. 2008, The Solar System Beyond Neptune, 161

[61] Tegler, S. C., Bauer, J. M., Romanishin, W., & Peixinho, N. 2008, The Solar System Beyond Neptune, 105

[62] Thirouin, A., Ortiz, J. L., Duffard, R., et al. 2010, A&A, 522, AA93

[63] Thirouin, A., Noll, K. S., Ortiz, J. L., & Morales, N. 2014, A&A, 569, AA3

[64] Vilenius, E., Kiss, C., Mommert, M., et al. 2012, A&A, 541, AA94

[65] Vilenius, E., Kiss, C., Müller, T., et al. 2014, A&A, 564, AA35