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INTEGRATED STUDY OF THE PHYSICAL CHARACTERISTICS OF PRIMITIVE SOLAR SYSTEM BODIES

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RESUMEN

Cometas, Centauros, objetos con órbita más lejana que la de Neptuno, etc., son los cuerpos menos procesados del Sistema Solar desde la formación del mismo. Su composición y estructura alberga las pistas del origen de los planetas solares y extrasolares, así como de la evolución de los discos protoplanetarios. Las características del Gran Telescopio Canarias (GTC), así como su instrumentación nos darán la oportunidad única de llevar a cabo un estudio integrado de las propiedades físicas de estos pequeños y remotos cuerpos.

ABSTRACT

Primitive bodies (comets, Centaurs, trans-Neptunian objects, etc.) are the best-preserved remnants of the Solar Nebula. Their composition and structure harbor clues to the origin of solar and exosolar planets and the evolution of protoplanetary disks. The capabilities of the Gran Telescopio Canarias (GTC) and its instrumentation provide us a unique opportunity to accomplish an integrated study of the physical properties of these remote small bodies.

Key Words: **INFRARED : SOLAR SYSTEM — PLANETARY SYSTEMS : FORMATION — PLANETARY SYSTEMS : PROTOPLANETARY DISKS — SOLAR SYSTEM**

1. INTRODUCTION

The past decade of planetary astronomy has been marked by an important event: the discovery of the Kuiper Belt objects (KBOs), numerous small bodies with the orbits located beyond 30 AU (this is why they are often called trans-Neptunian objects). Investigation of these objects has been recognized as one of the main scientific priorities by the planetary science community.[1]

The discovery of KBOs has significantly extended the family of primitive bodies in the Solar System, i.e., bodies that have experienced the least changes since the Solar System was formed and retain the pristine material of the protoplanetary disk (the Solar Nebula). According to the modern scenario of Solar System formation, the inwardly perturbed material of the Solar Nebula formed planets and asteroids. The planetesimals perturbed outward formed the Oort Cloud, the source of long-period comets. The majority of Kuiper Belt objects remained in the region of the Solar System where they have remained from the very beginning. They can be divided into dynamical classes such as:

- Classical KBOs, which have circular orbits at 42–48 AU;
- Scattered KBOs, which have elliptical orbits with perihelia close to the orbit of Neptune; and
- Plutinos, including Pluto–Charon, the bodies in or near the 3:2 mean motion resonance with Neptune. They have perihelia at 30 AU and aphelia at 50 AU.

Because of collisions and close encounters, some of these bodies changed their orbits becoming short-

[1] See http://www.aas.org/ dps/decadal/.

period comets, irregular satellites of Saturn, Uranus, and Neptune, and Centaurs (objects whose whole orbits are between Jupiter and Neptune, approximately 7–30 AU).

The study of KBOs and other primitive bodies is of crucial significance to understanding the origin and evolution of the Solar System, protoplanetary disks, and extrasolar planets. For this purpose, it is especially important to reveal composition, structure, and other physical properties of these objects. However, their observation is extremely demanding because of their remoteness and small size, and the low albedo of the majority of primitive bodies. In the following sections, we shall demonstrate the capabilities of the GTC and its instrumentation for the observation of KBOs, comets, and other primitive bodies. We shall review the observational means and theoretical methods we plan to use to obtain the composition and structure of these bodies. Finally, we outline the expected results of our study.

2. OBSERVATIONAL CAPABILITIES OF THE GTC FOR THE INTEGRATED STUDY OF THE PRIMITIVE BODIES

With its limiting magnitude at $\lambda = 0.55$ μm, equal to $m = 27.05$ with a 15 min exposure (Álvarez Martín et al. 1997), the GTC has the unique capability of detecting small, distant small Solar System bodies. Whereas at a heliocentric distance of 50 AU the New Technology Telescope (NTT, ESO, La Silla) can detect KBOs larger than 100 km in diameter and the Keck 10 m telescopes can see 80 km bodies, the GTC's limiting magnitude allows it to detect bodies 65k m in diameter. This makes a significant difference in the number of objects that can be detected. Estimates based on Gladman et al. (2001) indicate that the GTC will be able to detect 2.5 times more KBOs than the Keck telescopes and 50 times more objects than the NTT. This makes the GTC the best telescope for providing not systematic, instead of sporadic, studies of KBOs and other primitive bodies to achieve statistically representative results.

3. TRADITIONAL AND NEW METHODS OF STUDYING THE PHYSICAL CHARACTERISTICS OF PRIMITIVE BODIES

The specifics of observing primitive bodies are similar to those of other small Solar system bodies. Thus, the methods previously used for asteroids and planetary satellites can be used for KBOs. We shall call such methods "traditional". The GTC and its instrumentation can be used to study the following characteristics of the bodies using the traditional methods:

- Body size based on i) its brightness (magnitude) and supposing some albedo, ii) thermal-infrared observations supposing some models of the interiors, and iii) occultations;
- Albedo from simultaneous observations of scattered (optical) and emitted (thermal) radiation;
- Rotational period from light-curves, which also allow us to see surface inhomogeneities.

Also, the composition can be revealed: i) from the colors in the visual and near-infrared because of spectral variations of the refractive index; ii) from the spectral features in the near-infrared (for example, water has spectral bands at 1.5 and 2.03 μ, and organic bonds manifest themselves at 3.4 μm [C–H], and 1.7 and 2.25 μm [C–N]; iii) from mid-infrared spectral features such as those of silicate features at 10 and 20 μm.

Some results of applying traditional methods to KBOs (Brown, Blake, & Kessler 2000; Luu & Jewitt 1996) and bare cometary nuclei (Tegler et al. 1999) have been already reported. These reveal a great variety of such bodies and show some regularity between their compositional and dynamical characteristics (e.g., Trujillo & Brown 2002). With the GTC, such observations should be continued and extended to smaller, more distant, and darker objects in order to determine statistical regularities in the orbital characteristics, size, albedo, rotational period, and compositional features of these bodies, and, finally, to provide their taxonomy.

We also propose some new techniques for obtaining the physical characteristics of primitive bodies. The first is based on observations of the coherent backscattering effect (CBE) for KBOs and distant comets. This effect manifests itself as a sharp increase in body's brightness at very small phase angles, $\alpha < 3°$ (Hapke, Nelson, & Smythe 1993). The brightness surge is accompanied by a deep polarization minimum (Mishchenko 1993). These phenomena are results of the constructive interference of light that has experienced multiple scattering on a rough or particulate surface. The CBE theory is well developed, which makes it possible to use the brightness and polarization at small phase angles to discover the properties of regolith/dust particles. For example, half of the phase angle at which half of the maximum of the brightness surge is observed, $\alpha_{\rm HWHM}$, can be determined using the simple formula $\alpha_{\rm HWHM} = 0.067\lambda Q_{\rm sca} f/R$ (Mishchenko 1993), where λ is the wavelength, R is the radius of particles, f is the packing factor of the particles, defined as the ratio of the volume occupied by the particles to the total observed volume, and $Q_{\rm sca}$ is the particle scattering efficiency. Our estimates of the phase angle range where the coherent backscattering effect manifests itself show that these angles can be reached at the following heliocentric distances: 17.5 AU in case of a surface covered by silicate grains, 7.5 AU for organic grains, and 42 AU for icy grains (these estimates were made for the visual wavelengths and grains of size 0.1 μm with a packing factor $f = 50\%$). Thus, distant objects such as KBOs are perfect targets for determining surface composition and structure using the CBE. As soon as the angles and amplitudes of the CBE are measured, well developed theoretical tools (e.g., Mishchenko 1996; Hapke 2000; Tyshkovets 2002) can be used to obtain the sizes, packing factors, and refractive indices of regolith/dust grains. The obtained characteristics are important not only per se. They can also be used to improve the interpretation of near- and mid-infrared spectra since spectral feature shape depends on the size of the particles that cover the surface and on their packing factor (Hapke 1993; Shkuratov 1999).

One more new technique we plan to use in our study is to obtain cometary nucleus composition and structure based on the characteristics of cometary dust. The high resolution maps of cometary comae show that their color and polarization experience dramatic changes in the near-nucleus region (e.g., Jockers 1997). This leads to the conclusion that the cometary dust observed far from the nucleus represents not the original cometary material but the material changed by interaction with solar radiation. The most likely change in cometary dust is sublimation/destruction of its volatiles, ice, and organics. By studying the changes that appear in the near-nucleus coma, we can extrapolate the properties of cometary dust to the nucleus and obtain its characteristics. The higher the spatial resolution of such observations is, the more accurately can the characteristics of the nucleus material be obtained. Methods that can be used for such extrapolations have already been developed. These include methods based on spectrophotometric long-slit observations of comae (Kolokolova et al. 2001b), simultaneous polarimetric and colorimetric imaging of comae (Kolokolova et al. 2001a), and on the study of the evolution of the near-infrared organic and mid-infrared silicate features (e.g., Hayward, Hanner, & Sekanina 2000). The great advantage of the GTC is that its standard instrumentation has been designed to be able to carry out these types of studies. Table 1 shows the opportunities that the standard GTC instrumentation can provide for a detailed study of cometary dust.

4. CONCLUSIONS

The previous sections show that the GTC and its instrumentation will have remarkable capabilities to provide the integrated study of primitive bodies. Even though polarimetry is underrepresented at the GTC, the existing standard instrumentation allows not only the accomplishment of valid observations applying traditional methods of studying physical properties of small bodies but also the starting of new kinds of observations, such as the systematic study of coherent backscattering phenomena and the evolution of cometary dust. An advantage of our international team is that it includes experienced observers and theorists working on light scattering by dust and surfaces. One more advantage of our team is that its participants from the University of Florida have unique laboratory facilities to simulate the brightness and polarization of light scattered by irregular particles or surfaces of complex structure (Gustafson 2000). This makes our study really integrated in the sense that not only will all types of primitive bodies be studied and not only will a variety of observational techniques be applied, but also a broad range of theoretical and laboratory means is available for the data interpretation.

As results of the suggested study, we expect to achieve statistically representative data concerning the physical properties of primitive bodies, including their composition. This will allow us to suggest a taxonomy of these bodies by combining their dynamical and compositional characteristics. The recovered relationship between the dynamical and compositional classes will provide clues to the origin and evolution not only of these bodies but also of the Solar System and other planetary and protoplanetary systems. Owing to expected abundance of organics in the composition of the primitive bodies, the study will also provide us with a better understanding of prebiotic chemistry.

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TABLE 1

CAPABILITIES OF THE GTC INSTRUMENTATION TO STUDY EVOLUTION OF COMETARY DUST

Instrument	Spectral range, [μm]	FOV at 1 AU [km]	Spatial resolution at 1 AU [km]	Additional capabilities
OSIRIS	0.365–1.0	372000	90	Tunable filters
EMIR	0.9–2.5	262000	125	Z, J, H, K bands
CanariCam	8–24	18600	138	polarimetry

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