The Outer Frontiers of the Solar System: Trans-Neptunian Objects and Centaurs

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The icy bodies in orbit beyond Neptune and known as Trans-Neptunian objects (TNOs), or Kuiper Belt objects, are the most distant objects of the Solar System accessible to direct investigation from the ground. The study of these objects, containing the least processed material of the Solar System, can help in understanding the still-puzzling accretion/evolution processes that governed planetary formation in our Solar System as well as in other dusty star discs. An ESO large programme has been devoted to obtaining simultaneous high quality visible and near-infrared spectroscopy and photometry of about forty objects with various dynamical properties. A few selected objects have also been observed with polarimetry to define their surface characteristics better and with detailed photometry to determine their rotational properties. The results provide a unique insight into the physical and surface properties of these remote objects.

Trans-Neptunian objects represent a newly identified population of pristine material in our Solar System. Discovered less than twenty years ago, these icy bodies revolutionised our understanding of the Solar System and most ideas on the evolution of the protoplanetary nebula. Located at the furthest frontiers of our planetary system observable with ground-based telescopes, these small bodies are considered to be the fossils of the protoplanetary disc and can provide unique information on the processes that dominated the evolution of the early solar nebula as well as of other planetary systems around young stars.

TNO science has rapidly evolved in recent years, linking together different populations of small bodies in our planetary system. The attempt to determine the physical properties of this population is at present one of the most active research fields in planetary science. More than 1400 Trans-Neptunian objects, with different sizes, orbits and surface characteristics, have been discovered up to now. But many more must be present. A few of them belong to the newly defined population of dwarf planets.

The TNO population is classified into several dynamical groups (see Figure 1), depending on their distance from the Sun and their orbital characteristics: i) classical objects; ii) resonant objects; iii) scattering(ed) disc objects; and iv) detached objects. The first two groups are also known as the Kuiper Belt, containing objects with an average distance from the Sun of between 30 and 55 astronomical units (AU) and with low eccentricity orbits. The resonant objects are trapped in mean-motion resonances with Neptune in more than 20 resonances, with the 3:2 mean-motion resonance (hosting Pluto) being the most densely populated. The scattering disc objects or scattered objects are considered to be those that have orbits with large eccentricities, and perihelion distances near the location of Neptune, while the detached objects are those with orbits at large eccentricities, and with perihelion distances out of Neptune's influence. The best example of this last category is (90377) Sedna, which has perihelion and aphelion distances of 76 and 927 AU, respectively. Another group of objects, the Centaurs (shown in orange in Figure 1), with unstable orbits between those of Jupiter and Neptune, can also be associated with the TNO population. Planetary perturbations and mutual collisions in the Kuiper Belt are probably responsible for the ejection of objects into Centaur orbits.

In order to investigate the surface properties of these remote and faint Solar System objects, a large programme has been carried out with the ESO Very Large Telescope (VLT) using, nearly simultaneously, the Unit Telescopes UT1, UT2 and UT4. The aim of this large programme was to obtain high signal-to-noise ratio (S/N), simultaneous visible and near-infrared (NIR) spectra for almost all objects that can be observed with the VLT. Forty objects have been studied, allowing a

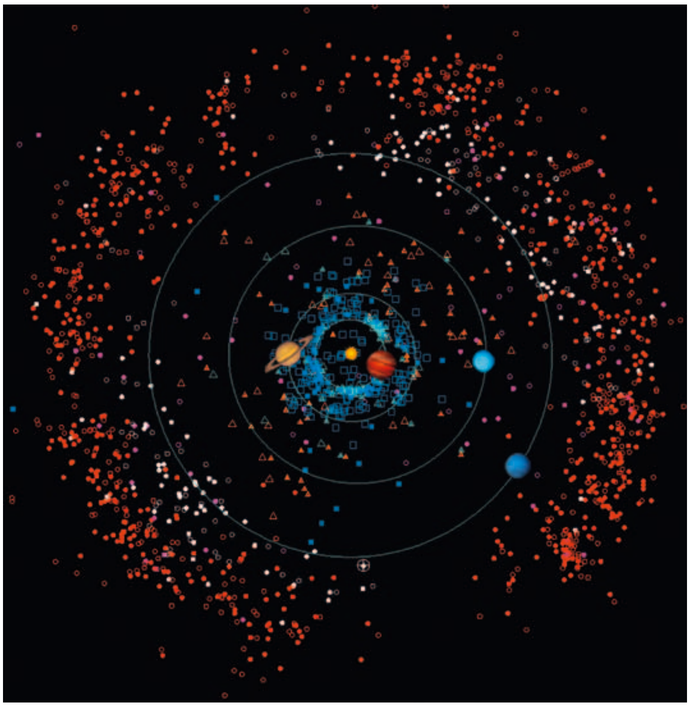

Figure 1. The location of TNOs (on 12 February 2010) are reported in different colours for different dynamical classes of objects. Unusual objects (high-ellipticity) are shown as cyan triangles, Centaurs as orange triangles, objects in 2:3 resonance with Neptune as white circles (Pluto is shown with the crossed white symbol), scattered-disc objects as magenta circles, while the classical objects are shown as red circles. Periodic comets are shown in blue squares. Objects observed at only one opposition are denoted by open symbols, while those with multiple opposition orbits are denoted by filled symbols. The orbits of the planets are shown in light blue with their respective images. (Adapted from a plot by the Minor Planet Center).

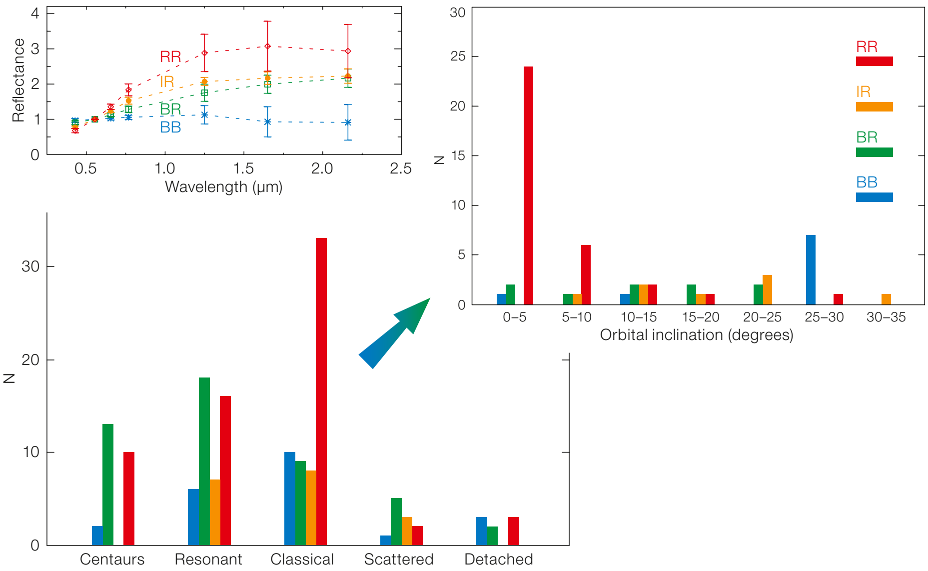

Figure 2. The lower left panel shows the distribution of the four TNO taxonomic groups (whose average photometric colours are represented in the upper left panel as reflectance values normalised to the Sun in the *V*-band) within each dynamical class. The right panel shows the distribution of the taxonomical groups, with respect to the orbital inclination relative to the ecliptic plane, for the "classical" TNOs.

broad characterisation of the brightest TNOs. All the targets have also been observed by *V, R, I, J, H* and *K* photometry to determine their taxonomic classes.

Surface colours, taxonomy and rotation

Visible and NIR photometry of forty objects have been carried out with FORS and ISAAC. Based on the computed colour indices, we derived the taxonomic classification of 38 bodies (DeMeo et al., 2009; Perna et al., 2010), by applying the G-mode statistical method according to the Barucci et al. (2005) system. This scheme identifies four classes that reasonably indicate different compositions and/or evolutional history, with increasingly red colours from BB (blue), BR (intermediate blue–red), IR (moderately red) to the RR (red) class. The observations performed in the framework of our ESO large programme were combined with the whole data sample presently available in the literature. We thus analysed a total of 151 taxonomically classified objects and performed a statistical analysis of the relationships between taxonomical and dynamical classification. The main results we obtained are (see Figure 2):

i) the enlarged sample of analysed Centaurs confirms the colour bimodality suggested previously;
ii) bodies belonging to the IR taxonomic class seem to be concentrated among the classical and resonant populations;
iii) within the classical objects, the most spectrally red bodies (RR class) dominate the population at low orbital inclination, while blue objects (BB class) are more abundant at high orbital inclinations. These results confirm the previously suggested relationship between spectral behaviour and dynamical evolution, the red and blue colours being associated with the dynamically cold and hot populations, respectively.

In the framework of this large programme we also investigated the spin rates of twelve bodies. Assuming ellipsoidal shapes with axes $a > b > c$, we derived a lower limit to the axis ratio a/b from the obtained light-curve amplitudes, under the hypothesis that the light curves are only affected by the shape elongation and that major albedo variations are not present on the surface of the observed bodies. From the rotational periods and light-curve amplitudes we also derived a range of variation of the density of the observed bodies, by applying the Chandrasekar theory for rotationally stable Jacobi ellipsoids under the simplified assumption of cohesionless and strengthless bodies (namely fluid objects). The obtained density values seem to confirm the existence of a magnitude/density trend with larger (brighter) TNOs being denser than smaller (fainter) ones, as had been suggested. However, this trend is strongly influenced by a single object (136 108 Haumea). The limited sample of densities currently available in the literature, together with the still unresolved ambiguity between brightness and size (due to the small number of reliable albedo measurements), prevent us from definitively assessing any relationship between TNO density and size.

Composition

Detailed information on the composition of TNOs can only be acquired from spectroscopic observations, especially covering the wavelength range between 0.4 and 2.4 µm. This spectral window provides the most sensitive technique to characterise from the ground the major mineral phases and ices present on Trans-Neptunian objects. Nearly simultaneous observations of FORS visible spectroscopy, ISAAC *J*-band and SINFONI *H*- and *K*-band spectroscopy been performed for forty objects selected among different dynamical groups. The exposure time required is generally long, and as the objects rotate around their principal axis, the resulting spectra often contain information coming from different parts of the object. The *V*-, *R*-, *I*-, *J*- and *H*-band photometry has been used to tie the different spectral ranges together.

The visible spectra are mostly featureless, showing, however, very large variations of their spectral slope, with colours from neutral to very red. The ultra-red slopes probably indicate the presence of complex organic material on the surface. A few big objects, like Eris and Pluto, show signatures of CH_4 in their spectra. We identify in a few other objects (10 199 Chariklo, 42 355 Typhon, and 2003 AZ84) new faint and broad absorption features that are, in general, associated with aqueous altered silicates on the surfaces of these bodies, by analogy with features present in the spectra of some main belt dark asteroids. Hydrous silicates are also known to be present in interplanetary dust particles (IDPs). The NIR 1–2.4 µm window provides powerful diagnostics for the study of astrophysical ices.

Radiative transfer models have been used to investigate TNO surface composition, and to interpret features and spectral behaviour using intimate or geographical mixtures of organics, silicate minerals, carbonaceous assemblages, ices, and/or light hydrocarbons. The red spectral slopes are typically well-reproduced by assuming the presence of organic compounds on the surface, such as kerogens (complex dark organic compounds) and tholins (Titan and Triton materials — substances formed in the laboratory by irradiation of gaseous mixtures of methane and nitrogen in different proportions) or ice tholins (formed by irradiating mixtures of essentially water and hydrocarbon ices). Other physical properties such as porosity and rugosity (the numerical measure of roughness) can, in principle, be derived from these models, but the observation of unresolved sources and the small phase angle coverage, due to the large heliocentric distance of these bodies, limit considerably confidence in the results. These models utilise numerical algorithms that fit the object spectra by reduced chi-squared minimisation. This minimisation provides the best set of parameters among the input free parameters (such as concentration and particle size). The models can provide insights into the chemical composition and the dilution state of the various compounds, or constraints on the way they are mixed (intimate mixtures, areal mixtures, combinations of both, etc.). They also provide information on the stratification state of the subsurface layers providing strong evidence of volatile transport or on limits on the irradiation level, depending on the depth.

The main results obtained during the ESO large programme on the forty objects observed spectroscopically, and the models of their surface by radiative transfer models, can be summarised by subdividing the targets into three main groups according to their composition:

1) Water ice group
More than 50 % of the targets show the presence of water ice on their surface. The best-fit compositional models of these objects include water ice in the crystalline state as well as in the amorphous state. The majority of spectra with high S/N ratios show the presence of a feature at 1.65 μm due to crystalline water ice. It is still a matter of debate whether water ice was amorphous or crystalline in the protosolar nebula. The presence of crystalline water ice implies that the ice has been heated above 100–110 K. This heating could have resulted from impacts, or the ices might have formed in the warmer deep interiors and were then exposed on the surface. The quality of the observations of fainter objects is not sufficient to distinguish between amorphous or crystalline water ice. Nonetheless, when trying to model the spectra the best-fit model is usually obtained when using a combination of the two water ice states.

2) Other ices group
Methane ice is present on the largest TNOs such as Eris, Pluto, Sedna and Quaoar. The spectra of some objects, such as Pluto and probably Eris, show that some of the methane ice must be dissolved in nitrogen. Methane is present at the surface of these large objects because their gravity is high enough to retain such a volatile component, but it may also be present in lower quantities on smaller objects. A small amount of ethane (a by-product of methane ice irradiation) has also been detected on Quaoar. Some objects, such as Pholus and (55638) 2002 VE95, show spectra with methanol features. In addition, many objects show spectra with a decreasing slope beyond 2.2 μm, implying the possible presence of methanol or similar molecules, even if these faint objects have spectra with a low S/N, especially in the *K*-band. The presence of ammonia or ammonia hydrate in the spectra of a few objects (Charon, Orcus) has been suggested. A firm detection of ammonia would have important implications on the composition of the primitive solar nebula in low density regions far from the Sun.

3) Featureless spectra group
Many objects have featureless spectra in the NIR, with a wide range of colours. These objects could be mantled by a surface rich in organics or carbon. As all these objects are supposed to be at least partly made of ices, irradiation processes have to be responsible for these properties. C-bearing molecules progressively lose their hydrogen atoms, which results in a polymerisation of the surface layer, and the formation of a crust.

The largest objects

The largest TNOs, many of which are also labelled as dwarf planets, have distinctly different surface compositions compared with the rest of the population. Specifically, they have strong signatures of methane or crystalline water ice in their spectra (see Figure 3). During this ESO large programme we managed to observe several of the largest TNOs: Pluto, Eris, Sedna, Quaoar, Charon and Orcus.

On Pluto we detect volatile species such as methane, nitrogen, and carbon monoxide. From our investigation, we confirm that the level of dilution of methane in nitrogen is different on different parts of the heterogeneous surface of Pluto. On Eris, the largest dwarf planet, we indirectly detect nitrogen on the surface based on the wavelength position of some of the bands of methane (Merlin et al., 2009). The data indicate that the dilution of methane ice in nitrogen changes as a function of depth below the surface. This suggests the formation of a temporary atmosphere around Eris when close to perihelion, as is observed for Pluto. Modelling of the data also suggests a large quantity of irradiated material and evolved chemistry on the surface, as well as the presence of a small amount of ethane that could be formed either in the atmosphere or on the surface.

Orcus has large amounts of crystalline water ice on its surface. Barucci et al. (2008) detected a signature attributed to hydrated ammonia, similar to the case of Charon, the satellite of Pluto, on which large amounts of water ice also exist in crystalline form. These observations suggest processes that are able to renew the surface with fresh and non-irradiated icy materials. For the largest objects evolutionary models indicate that cryovolcanism is possible (if enough radiogenic sources were present in their interiors). Non-disruptive collisions could also play a role in renewing the surface, as well as catastrophic collisions such as that at the origin of the Haumea family, which could explain the presence of fresh crystalline water ice even on small members of the family.

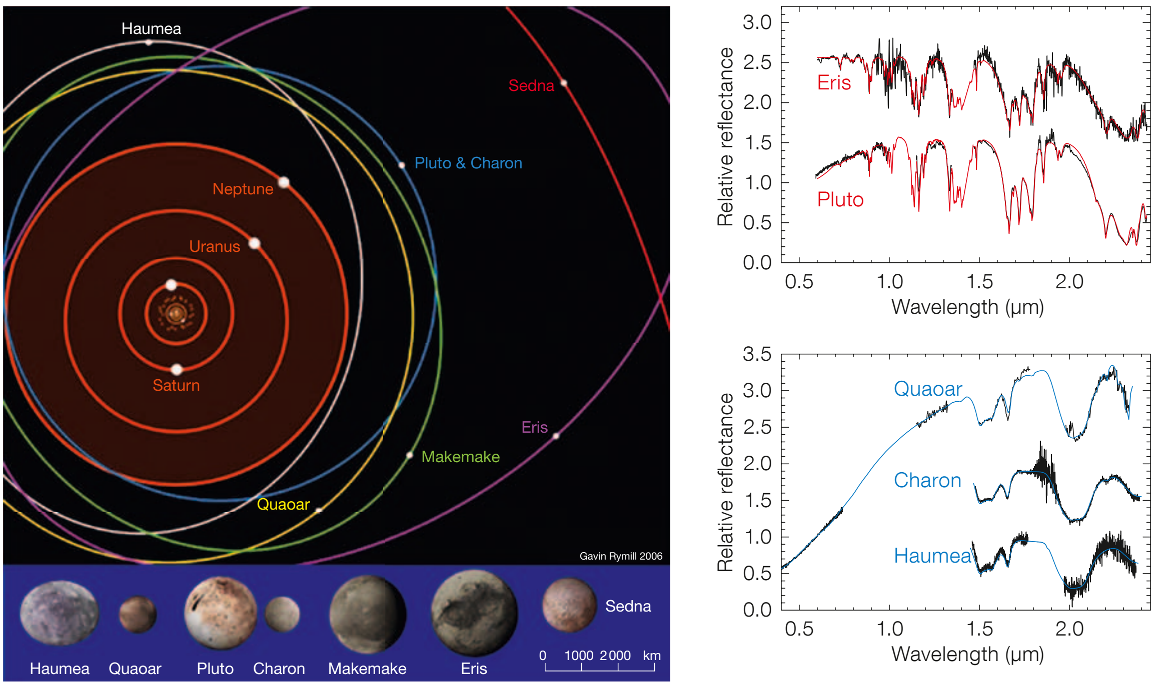

Figure 3. The image on the left (adapted from Gavin Rymill, 2006) shows the circular orbits of the eight planets versus the eccentric orbits of the biggest TNOs (Pluto, Eris, Quaoar, Sedna, ...) On the right are shown the two groups of TNO spectra: Eris and Pluto with methane ice dominated spectra and Quaoar, Haumea and Charon with water ice dominated spectra.

Although Quaoar's spectrum displays clear water ice features in the crystalline form, there is a strong red slope in the visible and other weak features in the NIR that suggest a small amount of methane on the surface and small grains of irradiated material. Dalle Ore et al. (2009) model a spectrum from the visible to the NIR, including the additional constraints of Spitzer data, and find a best-fit model consisting of crystalline and amorphous water ice, methane, nitrogen and ethane ices with, in addition, Triton and Titan tholins. Sedna, which is significantly further from the Sun (~ 90 AU) than most known TNOs (30–50 AU), also exhibits one of the reddest visible spectra, and weak features in the near-infrared that suggest a surface covered by water ice, methane and nitrogen ice, as well as small grains of irradiated material mainly formed via impacts of cosmic rays and interstellar medium particles (Sedna's orbit often takes it beyond the heliopause).

Surface properties

To investigate the surface characteristics of TNOs better we carried out polarimetric observations of eight objects belonging to different dynamical groups. These include dwarf planets Eris and Haumea, the classical object (20000) Varuna, the resonant object (38628) Huya, the scattered disc object (26375) 1999 DE9, and Centaurs (2060) Chiron, (5145) Pholus and (10199) Chariklo. The polarimetric characteristics of the scattered radiation contain much more accurate and specific information concerning the microscopic properties of the surface. We found that all observed bodies revealed negative polarisation, where the polarisation plane of linearly polarised light coincides with the scattering plane. It is a characteristic feature for surfaces with a complex structure, as observed for the majority of planetary surfaces. However, the measured polarisation phase angle behaviour of TNOs and Centaurs was found to be unique among other Solar System bodies observed so far. Objects with a diameter smaller than 1000 km exhibit a negative polarisation that rapidly increases (in absolute value) with the phase angle and reaches about –1 % at phase angles as small as 1°. The largest TNOs exhibit a small fraction of negative linear polarisation that does not noticeably change in the observed phase angle range. It has been suggested that the different types of polarimetric behaviour are related to different albedos and different capabilities for retaining volatiles for large and small TNOs (Bagnulo et al., 2008). The modelling of the polarimetric behaviour of the largest objects suggests that their topmost surface layer consists of large (compared to the observation wavelength) inhomogeneous particles (Belskaya et al., 2008). Smaller size TNOs, characterised by a pronounced branch of negative polarisation, revealed a similar polarisation behaviour regardless of the fact that they have different surface albedos and belong to different dynamical groups. The presence of a thin frost layer of submicron ice crystals on a dark surface is considered as one of the possible ways to explain the particular polarisation properties of these distant objects.

The overall picture

These results provide unique insights into the global population of these faint and distant objects. Important advances in elucidating the surface composition of TNOs have been achieved. Observations performed with SINFONI in the *H* and *K* regions have allowed us to detect spectral signatures, revealing the presence of surface deposits of ices such as H_2O, CH_4, CH_3OH, C_2H_6, NH_3 and N_2. We find that most of the largest objects have ices on their surface (water ice or ices of more volatile species), whatever their dynamical class (see Figure 4) and whatever their colours, although objects with neutral colours tend to be covered by water ice. The colours are very variable, from slightly blue

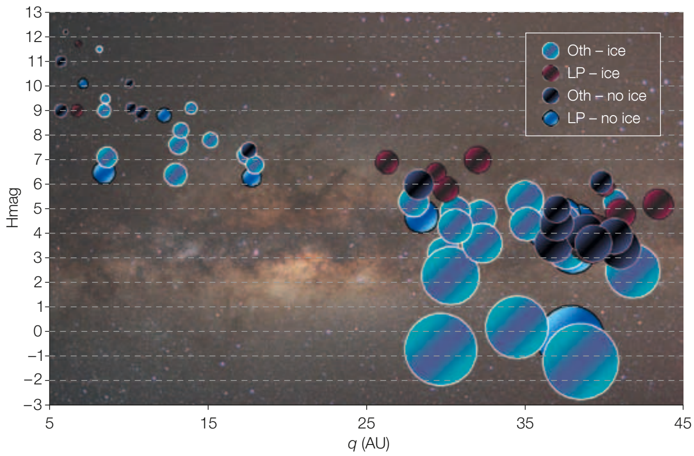

Figure 4. The absolute magnitude (in *H*-band) of the TNOs and Centaurs (with and without ice detected on their surface) is plotted as a function of the perihelion distance (*q*, in astronomical units). The dimension of the symbol is related to the diameter of the object (for clarity the scale used is not linear). The smallest size of the Centaurs is 20 km, while the biggest TNO has a diameter close to 2500 km.

to very red (Fornasier et al., 2009). The wide difference in surface composition and colour within the TNO population could be connected to different original compositions and/or the different processes they have experienced, as well as to their size. Even if TNOs are considered as the most pristine objects in the Solar System, over the 4.5 Gy of the Solar System's life they have experienced various modifying processes.

It is clear that the surface of these objects has been affected by bombardment by cosmic ray and solar wind ions and/or micrometeorites (space weathering), with the consequence that the molecular complexes are structurally changed and the molecular compositions of ice and minerals are altered over time. Laboratory experiments on plausible materials for TNOs show the formation of an irradiation mantle (forming a crust), breaking bonds in ice molecules, allowing the formation of radicals, escape of hydrogen and formation of a carbon-rich layer of low albedo. This can easily mask the presence of volatiles and the crust thus formed would hide the real composition of these icy bodies. The statistics do not, however, show any strong correlation between the surface properties and dynamical classes or orbital properties of TNOs. Many objects from the reddest class (RR), which are the reddest objects in the Solar System, have probably been heavily irradiated. The slopes of the spectra of these objects, which have typically low albedos, have been modelled with complex organic compounds such as Titan, Triton or ice tholins, or terrestrial-type kerogens, but the real nature of the organics present on these objects is still a matter of debate. The red class (RR) objects are present in all dynamical populations, with a higher concentration in the classical group. They are found amongst the Centaur population as well as in the detached population, as for example Sedna, which is considered as part of the inner Oort Cloud.

Other processes must be at work that could affect some objects more than others. Models of the interiors of TNOs indicate that cryovolcanism, which is considered to be the most probable form of geological activity on some satellites of the outer planets, may be possible on the larger Trans-Neptunian objects (diameter > 800 km). This could explain, for instance, the surface composition of Orcus which includes both water ice in the crystalline state, which is not supposed to exist at such low temperatures (around 30 K), and ammonia, which is easily destroyed by irradiation. Furthermore, the water ice in the crystalline state should be quickly amorphised by irradiation, as indicated by various laboratory studies.

Collisions must have also played an important role in the evolution of this population, inducing heating and chemical changes. The consequence of collisions is not only the alteration of the surface properties, but also the modification of the internal structure of the targets. Collisions are important both for small and large objects. A typical example is Charon, a moon of Pluto, but completely different in composition (see Figure 3), which is supposed (according to numerical models) to have formed from a disc of debris ejected during the collision of Pluto with a body of almost equal size.

In addition, the high albedos and the detection of volatiles on the surfaces on some TNOs indicate the possible presence of an atmosphere, even if only as a transient phenomenon. The only Trans-Neptunian object observed thus far with a seasonal atmosphere is Pluto, but other large objects like Eris or Sedna may have one as well. A cometary-type activity (outburst) has also been suggested for the Centaur Chariklo to explain differences in spectra obtained at different times (Guilbert et al., 2009).

Our understanding of the population of these faint and distant objects is, however, still limited. The observations that have been made so far lead to a lot of questions. If major differences in composition between the very large objects and the others can be attributed to a size effect, it is very hard to explain differences among smaller objects. The next generation of more powerful instruments on 10-metre-class telescopes will start giving us some answers, but most of the answers will probably come with the next generation of telescopes, the ELTs, which will open the study of smaller objects. These smaller objects are those that carry most of the information about the dynamical/collisional evolution of the Solar System. The definitive evidence for atmospheres can come only from occultations or direct spectroscopic detection with spacecraft. A major step in the study of this population is the New Horizons–NASA mission that will fly by Pluto in 2015 and will enable the detailed study of Pluto and its three satellites, Charon, Nix and Hydra. The New Horizons spacecraft will continue on into the Trans-Neptunian population to fly by one or more TNOs.

References

Bagnulo, S. et al. 2008, A&A, 491, L33
Barucci, M. A. et al. 2005, AJ, 130, 1291
Barucci, M. A. et al. 2008, A&A, 479, L13
Belskaya, I. et al. 2008, A&A, 479, 265
Dalle Ore, C. M. et al. 2009, A&A, 501, 349
DeMeo, F. et al. 2009, A&A, 493, 283
Guilbert, A. et al. 2009, A&A, 501, 777
Fornasier, S. et al. 2009, A&A, 508, 457
Merlin, F. et al. 2009, AJ, 137, 315
Perna, D. et al. 2010, A&A, 508, 457