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A dynamical and observational study of an unstable TNO: 59358 ($1999CL_{158}$)⋆

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ABSTRACT

Context. The physical surface properties of a trans-Neptunian Object is believed to be mainly produced as a result of interplay between irradiation from different kinds of cosmic rays and collisions. Objects recently resurfaced by collisions are likely to have very different physical properties from those of the bulk population. In particular, pristine ices from the interior are expected to be present on the surface. A possible way to identify a trans-Neptunian object that has suffered a major collision is by investigating the lifetime of the orbit near its present location. If the lifetime is very short, a physical encounter is a possible way by which the TNO has evolved into such a short lived orbit.
Aims. The goal of this investigation is to search for tracers of a young surface on objects with very short orbital lifetimes in the trans-Neptunian Belt. We are looking for any evidence that indicates that they reached their current unstable orbits through collisions. In particular, we have studied the case of 59358 ($1999CL_{158}$), a trans-Neptunian object that currently has the most chaotic orbit in the Classical Belt.
Methods. By numerically integration its orbit, we estimate that 59358 ($1999CL_{158}$) has resided near its location for about 10 Myr. We have also obtained a near-infrared spectrum of 59358 ($1999CL_{158}$) in the region between 1.43–1.96 microns using the near infrared imager and spectrograph, NIRI, at Gemini North 8-m telescope. These NIR observations are of the faintest and smallest TNO so far observed.
Results. We present the results of the search of ice-bands, such as CH_4 and H_2O, having found evidence of the presence of the first mentioned molecule.
Conclusions. The detection of methane implies that it must be an abundant component of this object. Methane is also evidence of a young surface, therefore we conclude that it is likely that 59358 ($1999CL_{158}$) has experienced a recent collision or collisions.

Key words. Kuiper Belt – techniques: spectroscopic

1. Introduction

Since the discovery of the first trans-Neptunian object (TNO) in 1992 (Jewitt & Luu 1993), the number of known members has steadily increased with over 1000 currently cataloged. With this increase in the population, it has become evident that some regions are under-populated with respect to others. For instance, the so-called classical belt does not extend beyond the 2:1 mean-motion resonance with Neptune, probably due to cosmogonic reasons (Levison & Morbidelli 2003; Tsiganis et al. 2005; Melita et al. 2005; Kobayashi et al. 1991). Another under-dense region exists where objects have semi-major axes between 40 and 42 AU. This "gap" had been predicted by Knežević et al. (1991). At this location, the eccentricities of the orbits increase steadily due to the overlapping of secular resonances. This causes the perihelion distances to decrease, resulting in close-encounters with Neptune which ejects the TNOs out of the region. The location of this gap can be clearly seen in Fig. 1.

Not all orbits with semi-major axes between 40 and 42 AU exhibit a chaotic behavior. A small number can survive at small stability niches (see, for example, Duncan et al. 1995). Jones et al. (2005) found that with a plausible initial distribution of objects, the number surviving in their model was smaller than the number of real objects presently observed in the location. They also found that several of the real objects are on dynamical unstable orbits.

There are at least two scenarios by which a TNO can evolve into an unstable orbital regime. A substantial number of objects may survive in small stable niches for a long time until they enter the chaotic regime, or they could be inserted there by a collision. An attempt can be made to discern between these scenarios, since the observed spectral properties of a recently collisionally resurfaced object must be different than a pristine one. However, it is important to note that although small-scale collisions may not substantially change the orbit, they can still alter the surface.

The TNOs exhibit a wide range of colors, from bluish-neutral up to very red (Luu & Jewitt 1996; Hainaut & Delsanti 2002). It is known that the trans-Neptunian Belt is collisionally

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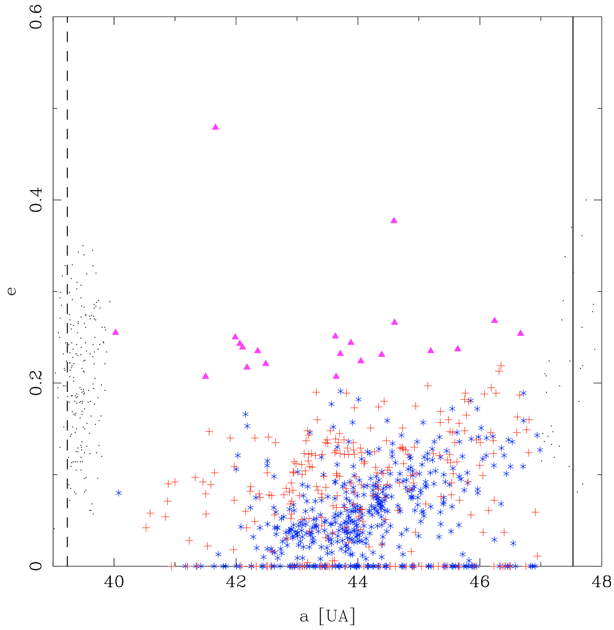

Fig. 1. A plot of eccentricity against semi-major axis for known trans-Neptunian objects in the range 39–48 AU. Different symbols/colors indicate different populations. Triangles: scattered objects, plus: hot classical objects, asterisks: cold classical objects, and dots: resonant objects. The vertical lines mark the position of the 3:2 and 2:1 resonances, dashed and continuous lines, respectively.

active (Durda & Stern 1999) and that collisional resurfacing is one of the possible mechanisms that can explain the TNO color distribution (Luu & Jewitt 1996; Gil-Hutton 2002; Thébault & Doressoundiram 2003). The present TNO surface properties are believed to be the result of a competition between different mechanisms, namely, space-weathering, collisions, cometary activity and cryo-vulcanism. Space-weathering is the surface bombardment of an atmosphere-less object by charged particles carried by the solar wind, cosmic rays, and UV radiation. This breaks the bonds of the ice molecules, leaving a carbon-rich dark-red material (Moore et al. 1983; Strazzulla & Johnson 1991). Collisions break through the surface layers thus allowing buried ices to be transported to the surface typically generating a bluish color. Cometary activity and cryo-vulcanism also bring fresh material to the surface and thus again generate a bluish colour (Thélbault & Doressoundiram 2003; Jewitt & Luu 2004).

The important parameter is the characteristic time-scale for each of the mechanisms to be effective. A layer of 0.01 μm can be formed by space weathering in a timescale of about 10^4 years, while thicker layers can take up to the Solar System age to be formed (Strazzulla et al. 2003). After a collision has re-surfaced the object, pristine ices will be present on the surface only until a layer of space-weathered material has grown.

With this in mind we initiated a study of the surfaces of classical TNOs that are on unstable orbits and so are more likely to have suffered a recent collision. We search for evidence of absorption bands associated with ices such as as CH_4 or H_2O that appear in the near infrared wavelengths (Brown & Cruikshank 1997).

We investigated the TNO 59358 ($1999CL_{158}$) whose dynamical evolution is described in the next section. The observation and data reduction of its spectrum are given in Sect. 3. In Sect. 4 we perform the analysis and discussion of the obtained results, while in the last section we present a short summary of the results.

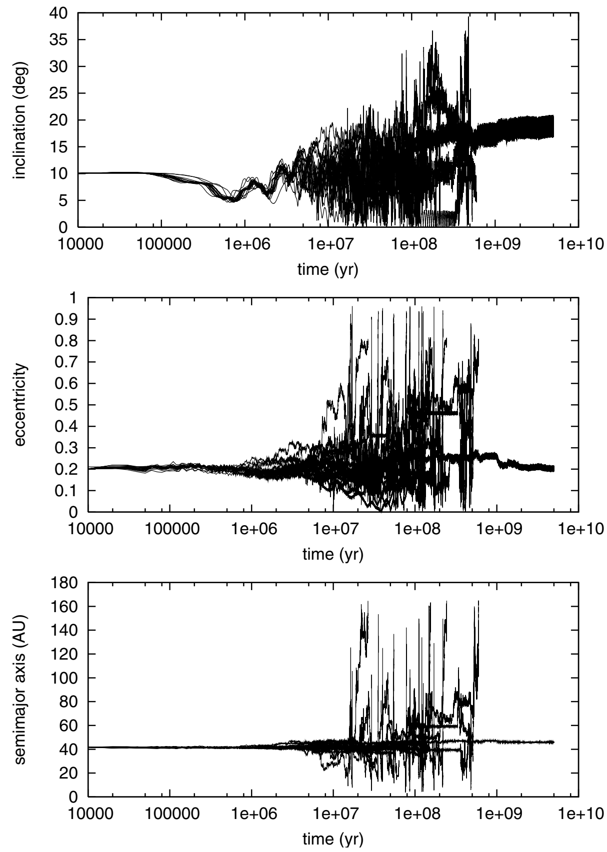

Fig. 2. A plot of semi-major axis, eccentricity and inclination evolution of 59358 ($1999CL_{158}$) and its 20 clones against time.

2. Dynamical evolution of 59358 ($1999CL_{158}$)

To investigate the stability of the region where the orbit of 59358 ($1999CL_{158}$) is located, we integrated the equations of motion of 59358 plus those of 20 clones for their whole lifetime within the region. The orbital elements and their standard deviations are: $a = (41.44 \pm 0.03)$ AU, $e = (0.2066 \pm 0.0006)$, and $I = (10.039 \pm 0.001)^{\circ}$, taken from the Asteroid Dynamics website[1]. The 20 clones were produced by generating orbital elements with values randomly generated within one standard deviation of the six Keplerian orbital elements of the real object. Thus we created a cloud of hypothetical objects with orbits near to the orbit of 59358 ($1999CL_{158}$). The epoch of the orbital elements used was 2 453 800.0, i.e. 12 h UT on 5th March 2006.

The equations of motion were integrated using the Mercury6 N-body integration program (Chambers 1999). This is a hybrid symplectic integrator that changes from the symplectic regime to a Burlish-Stoer step by step integrator for close encounters. Perturbations from the four giant planets were included in the simulation. The program was run for a maximum time of 5×10^9 yr unless the heliocentric distance of an object exceeded 300 AU at which point that body was considered to have permanently left the region of interest and the integration of its orbit was terminated.

In the simulation 59358 ($1999CL_{158}$) itself and all but one of the clones were lost from the region of interest within 600 Myrs. Their orbital evolution is shown in Fig. 2.

[1] http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo?objects:1999CL158

Table 1. Dynamical lifetimes of 59358 ($1999CL_{158}$) and its clones. τ_{gap} refers to the time span with orbits with semi-major axis, a, in the range $41 < a < 42$ AU, while τ refers to the time span in the Classical trans-Neptunian belt.

clone	τ_{gap} [Myr]	τ [Myr]
59358 ($1999CL_{158}$)	0.99	127.93
1	43.39	43.79
2	5.58	6.06
3	5.00	43.70
4	5.29	11.86
5	41.02	91.11
6	70.00	>4500
7	4.87	20.24
8	43.34	79.77
9	33.90	102.27
10	76.05	76.27
11	4.14	9.20
12	0.74	20.48
13	7.24	16.96
14	5.95	21.18
15	2.85	52.53
16	2.36	4.18
17	3.87	5.30
18	1.92	81.01
19	3.37	79.06
20	12.23	73.72

To estimate the order of magnitude of the orbital change of a TNO due to a collision, we use the following approximation, valid if the eccentricity is not too high, (see for example Davis et al. 2002):

$$\Delta a = 2\,a\,\frac{V_T}{V},$$

where a is the semi-major axis and Δa its change due to the collision, V_T is the tangent component of the relative impact velocity and V is the target's orbital velocity. If V_T/V is of the order 10^{-2}, then $\Delta a \approx 1$ AU. In Table 1 we give the times for which the orbits of 59358 ($1999CL_{158}$) and each of its clones remain in the Classical trans-Neptunian Belt, defined as $q > 30$ AU and $39 < a < 50$ AU, where q is the perihelion distance. We also give the times for which the semi-major axis of each orbit remains in a band of width $\approx$1 AU from its current position. The former is smaller than ~100 Myr in all but one case, while the latter is always smaller than ~76 Myr. If the origin of the present unstable orbit of 59358 ($1999CL_{158}$) is collisional, then the timescale in which this object has resided near its present location should be between the above two timescales.

In the $41 < a < 42$ AU region of the Classical trans-Neptunian Belt the orbital evolution is very complex and highly chaotic. Different mechanisms contribute to this behavior, such as secular resonances and mean-motion resonances with Neptune and Uranus (see for example Nesvorný & Roig 2001). However, the main cause for chaos in the region is the ν_8 secular resonance in which the angular argument $S = \varpi - \varpi_N$ librates about a constant value, where ϖ and ϖ_N are the longitudes of perihelion of the object and of Neptune respectively. Passages through this resonance occur in all cases studied, and, as a consequence, the eccentricity is pumped up to a value where the object becomes a Neptune crosser. After a close encounter with the planet the dynamics develop extremely chaotically. In Fig. 3 we illustrate the case of clone #16.

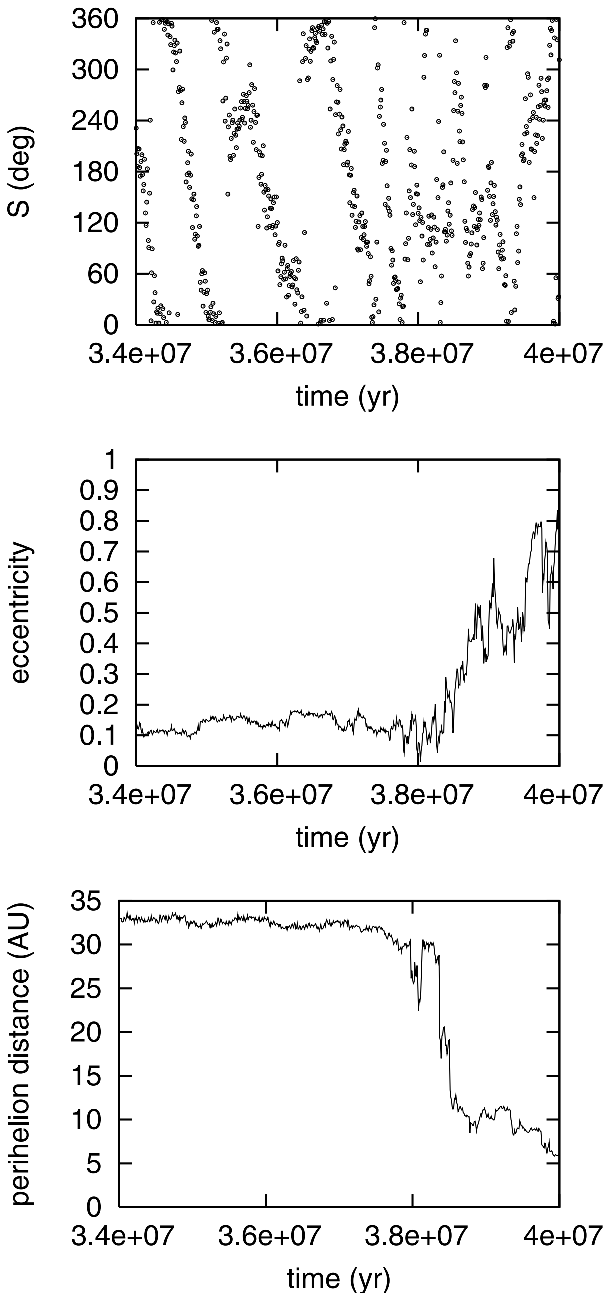

Fig. 3. A plot of three orbital elements against time, showing the dynamics of the passage through the ν_8 secular resonance of clone #16. This orbit enters the secular resonance after 3.8 Myr, as a consequence, the eccentricity increases and the perihelion distance is reduced. It becomes a Neptune-crosser and it is finally inserted into the inner Solar System.

3. Observations

The trans-Neptunian object 59358 ($1999CL_{158}$) was observed at the 8-m Gemini North telescope during the nights of 6, 15, 16 and 17 February of 2006. The observation was performed using the Near Infrared Imaging and Spectrograph, NIRI, using the f6 camera with the H-grism and a 6 pixels slit oriented in the direction of the apparent motion of the target. The spectral coverage with this instrumental configuration is 1.4–1.9 μm.

The total exposure time was divided into a number of 150 s exposures in order to avoid CCD saturation. The exposures were taken in blocks of 20 images, with the exception of the last block

Table 2. Ephemeris of 59358 ($1999CL_{158}$) during the observations.

RA	Dec	Δ [AU]	r [AU]	α [°]	V	Day	Number of exposures
09:18:52.5	+18:43:17	33.866	34.851	0.1	22.3	06	20
09:18:00.6	+18:47:38	33.883	34.855	0.3	22.3	15	20
09:17:54.9	+18:48:06	33.886	34.855	0.3	22.3	16	40
09:17:49.2	+18:48:34	33.890	34.856	0.3	22.3	17	34

with only 14, resulting in a grand total of 114 images being obtained. The images were taken following a dithering pattern of 10 different position on the slit in order to extract the sky contribution. The detail of the ephemeris and the number of images taken each day are given in Table 2, where Δ and r are the geocentric and heliocentric distances, respectively, and α is the phase angle.

Data reduction was performed using the external task `gemini` in the Image Reduction and Analysis Facilities, IRAF, package. The procedures were those usual for NIRI reduction. A median FLAT-FIELD was used to correct the non-uniform response of the detector while sky subtraction was done by subtracting consecutive images. As an example, given two consecutive images a and b, the FLAT-FIELDed and sky subtracted images are

$$a' = \frac{a-b}{\text{FLAT-FIELD}} \quad \text{and} \quad b' = \frac{b-a}{\text{FLAT-FIELD}}.$$

The corrected images were then added, with corresponding offsets. Note that it was not possible to use all the 114 images. Each first image of a session of 20 had to be discarded due to a ghost light. Several other images were also discarded due to diverse problems. Therefore, the total *observing* time on the target was 3h 47m 30s.

The combined spectrum was extracted and wavelength calibrated, using an He-Ar lamp. Finally the spectrum was divided by that of a solar analog in order to extract the signature of the Sun and obtain the object's reflectance. The solar analog used was SA 102–1081 (Landolt 1992). It was observed as part of the baseline calibrations of the program and reduced in similar fashion to 59358 ($1999CL_{158}$). The total exposure time of the solar analog was 9 s.

In order to improve the signal-to-noise ratio, the spectrum was then re-binned into bins with a width of about 82 Å. It is worth noting that, although the re-binning increases the signal-to-noise ratio, it also lowers the spectral resolution.

4. Results

Although the spectrum has a low signal-to-noise ratio some interesting features can be seen, especially in the range between 1.5–1.8 μm where the atmosphere is almost transparent (see McCord & Clark 1979). In that range some relevant ices like CO, H_2O, and CH_4 have vibrational bands. Carbon monoxide has a small band centered at 1.58 μm, water-ice has a broad band centered at 1.5 μm, while the methane-ice produces three bands at 1.65, 1.70 and 1.79 μm.

The spectrum of 59358 ($1999CL_{158}$) shows a suggestive feature at about 1.7 μm, corresponding to CH_4-ice (red vertical lines in Fig. 4 indicate each of the three bands mentioned above). On the other hand, there exists a decrease with respect to the continuum at 1.58 μm, corresponding to the second overtone of the fundamental transition of CO (blue line in Fig. 4). However, there is not a noticeable band in the region of the H_2O ice.

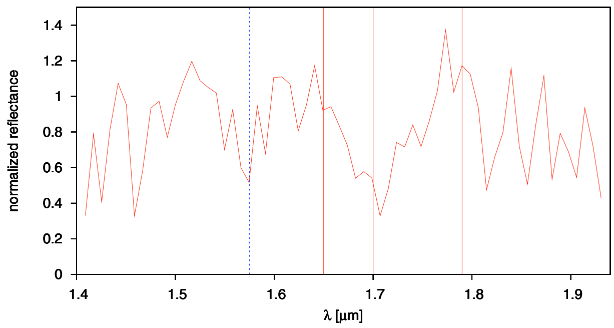

Fig. 4. Reflectance spectrum of 59358 ($1999CL_{158}$). The vertical lines indicate the position of the CO ice band (dashed line) and the CH_4 ice band (three continuous lines).

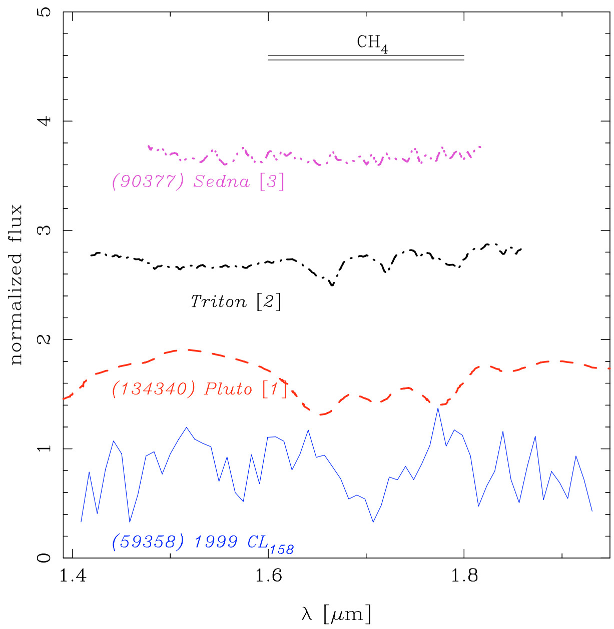

Fig. 5. Comparison between the spectrum of 59358 ($1999CL_{158}$) and other outer Solar System objects with known content of methane ice. References: [1] Dumas et al. (2001), [2] Cruikshank et al. (2000), [3] Barucci et al. (2005). All the spectra have the same vertical scale. An arbitrary offset of 0.9 in the flux has been applied for clarity.

Figure 5 compares the spectrum of 59358 ($1999CL_{158}$) and three objects with known methane ice in their surfaces. The resolution of our spectrum is not high enough as to detect the three bands separately, nevertheless, there is a decrease in the flux relative to the continuum at about 1.7 μm possibly indicating, therefore, the presence of CH_4 ice in the surface of 59358 ($1999CL_{158}$).

The detection of CH_4 on the surface of 59358 ($1999CL_{158}$) supports the hypothesis that it has suffered a recent collision that injected the body onto its present unstable orbits. Additional support should come from its visible colors available at the

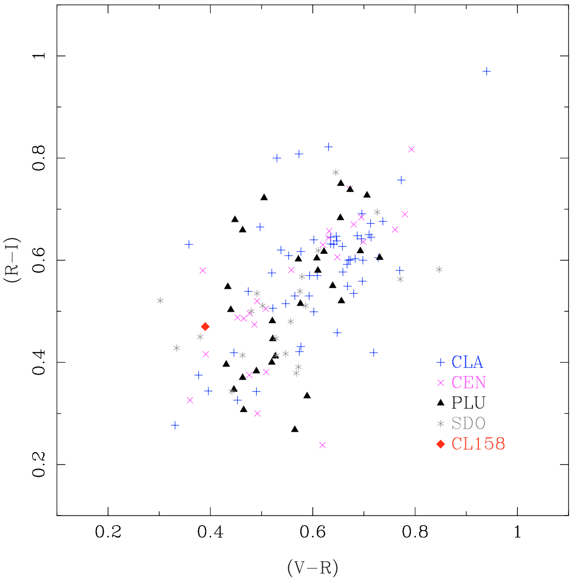

Fig. 6. Color–color diagram of the outer Solar System icy bodies. Plus symbols indicates classical objects while times, triangles, and asterisks indicates Centaurs, Plutinos and scattered disc objects. 59358 (1999CL$_{158}$) is plotted with a red polygon.

MBOSS[2] database (Hainaut & Delsanti 2002). According to the collisional resurfacing model, an object that has experienced a recent collision should have neutral-bluish colors due to fresh material on the surface.

In Fig. 6 we show the colors of the TNOs and Centaurs taken from the MBOSS database. In the figure the plus symbols are the classical belt objects, the times symbol are the Centaurs while the triangles and asterisks represent Plutinos and scattered disk objects, respectively. The red symbol shows 59358 (1999CL$_{158}$), whose colors are $(V-R) = 0.39 \pm 0.04$ and $(R-I) = 0.47 \pm 0.06$. From the figure it is apparent that this object has colors compatible with the neutral-bluish objects, further supporting the collisional hypothesis.

5. Discussion

Laboratory experiments show that major products of irradiation of H_2O-rich ices (such as H_2O+CO and H_2O+CH_4) are CH_3OH and H_2CO (Moore et al. 2003). In fact, recently the detection of CH_3OH on the surface of 55638 (2002VE$_{95}$) has been claimed by Barucci et al. (2006).

Continuous irradiation of CH_3OH can form CO (Moore et al. 2003), so that its presence on the surface of 59358 (1999CL$_{158}$) should not be ruled out, provided that a volatile-depleted irradiation crust has not yet built up. Nevertheless further observations of the target are needed in order to confirm whether or not CO exists.

The infra-red radiation coming from the ices below the radiation layer cannot be detected remotely if the cover is $\gtrsim 50\ \mu$m thick. Since we detected CH_4-ice and we estimate that the collision event that injected 59358 (1999CL$_{158}$) must have occurred during the last $\sim 10^7$ yr, the irradiation layer cannot have grown to a thickness much greater than that scale, so that the CH_4-ice should be detectable. These results indicate that 59358 (1999CL$_{158}$) very likely suffered a recent collision that renewed its surface by excavating fresh ices buried below the radiation crust.

More observations of this target should be performed in order to corroborate the finding of the methane ice and spectra in the visible can give further insight into the surface mineralogy of 59358 (1999CL$_{158}$). The confirmation of the existence of H_2O-ice would indicate that, together with CH_4, these two ices are typical inner constituents of the TNOs, and would give support to the scenario in which CH_3OH forms in the surface as a result of long-term irradiation.

It is interesting to note that, except for the cases of Charon and 136108 (2003EL$_{61}$), H_2O-ice has been detected in all TNOs observed in the NIR with absolute magnitudes $H \gtrsim 2$ and, with the exception of 59358 (1999CL$_{158}$), all TNOs with $H \lesssim 2$ exhibit a CH_4-ice band in the NIR. More observations of targets dynamically similar to 59358 (1999CL$_{158}$) will give statistical support to our results and may help to understand this apparent correlation and the overall dynamical, collisional and physical evolution in the trans-Neptunian region.

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