Search for sub-kilometre trans-Neptunian objects using CoRoT asteroseismology data

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ABSTRACT

We present the search for sub-kilometre trans-Neptunian objects (TNOs) by re-examining the CoRoT (Convection Rotation and Planetary Transits) asteroseismology observations. The total observation time employed in this work is about 144 000 star hours with signal-to-noise ratio larger than 1000 computed on 30-s intervals. 13 Possible Occultation Events (POEs) were found from the deviation method. These detections gives a density in the ecliptic sky plane of TNOs larger than 400-m radius of \( N(R > 400 \text{ m}) = 1.4^{+4.2}_{-0.7} \times 10^7 \text{ deg}^{-2} \). The fit of the density of TNOs with the believed break \( R_{\text{break}} = 45 \text{ km} \) provides a power-law size distribution index \( q \) larger than 3.5. This value is consistent with the detection of two potential events from Hubble Space Telescope (HST)/Fine Guidance Sensor (FGS) observations that found \( q = 3.8 \pm 0.2 \). However, fitting the 13 POEs with the HST/FGS result alone gives a power-law size distribution index of \( q = 4.5 \pm 0.2 \) in the size range of \( 0.2--2.0 \text{ km} \). This value is then compared with evolution models of the Kuiper belt.

Key words: occultations – Kuiper belt: general – minor planets, asteroids: general – planets and satellites: formation.

1 INTRODUCTION

Trans-Neptunian objects (TNOs) are the witnesses of the formation of the planets during the dynamical and collisional period of our Solar system. The population characteristics of sub-kilometre TNOs may carry some important messages which can reveal the mystery of the origin. However, the knowledge of them is far from enough, particularly for those sub-kilometre ones, due to very few detections. Nowadays, only TNOs larger than \( \sim 25 \text{ km} \) can be directly observed (Chiang & Brown 1999; Gladman et al. 2001; Allen, Bernstein & Malhotra 2002; Bernstein et al. 2004; Petit et al. 2006; Fraser et al. 2008; Fuentes & Holman 2008; Fraser & Kavelaars 2009; Fuentes, George & Holman 2009; Fuentes et al. 2010; Fuentes, Trilling & Holman 2011). For the small-size TNOs, searching for serendipitous stellar occultation events is a possible way. Several serendipitous searches were proceed (Roques et al. 2006; Bickerton, Kavelaars & Welch 2008; Bianco et al. 2009; Wang et al. 2010; Chang, Liu & Chen 2011, 2013), but so far there is only two possible detections from archival data of Hubble Space Telescope (HST) by Schlichting et al. (2009, 2012).

In this paper, we report the result we have obtained from analysing the Convection Rotation and Planetary Transits (CoRoT) asteroseismology data taken within 2007 January to 2010 March, which in total is about 144 kilo-star hours, by following the similar method of the search in X-ray band (Liu et al. 2008; Chang et al. 2011, 2013) optimized to CoRoT observational parameters.

2 CoRoT LIGHTCURVES

2.1 CoRoT

CoRoT was developed and operated by the Centre National dEtudes Spatiales (CNES). It was launched in 2006 December and just completed its service in 2012 November. CoRoT had two major scientific objectives: to probe the stellar seismology phenomena and to detect the extrasolar planets. By the original mission design, CoRoT had on average four observation runs per year: two long-term and two short-term runs. For the long-term runs, it observed a particular field continuously for \( \sim 150 \text{ d} \) and for \( 20--30 \text{ d} \) during its short-term runs. CoRoT had a polar inertial circular orbit with 90-deg inclination at an altitude of 896 km. The orbital period is 6184 s.

The two scientific objectives of CoRoT, asteroseismology and exoplanets detection, used two fields with different observation modes. The asteroseismology programme monitored a tens of stars with extremely high photometric precision and 1-s integration time while the exoplanets programme observed thousands of stars with...
Search for small TNOs using CoRoT AN1 data

Table 1. CoRoT asteroseismology Level-1 data employed.

<table>
<thead>
<tr>
<th>Segment</th>
<th>RunCode</th>
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<th>Run stop date (MM/DD/YYYY hh:mm:ss)</th>
<th>Exposure time (starhours)</th>
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<td>04/02/2007 07:12:15</td>
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<td>03/03/2008 09:49:35</td>
<td>28 665.71</td>
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<td>03/31/2008 07:43:58</td>
<td>5422.20</td>
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<tr>
<td>6</td>
<td>SRa02</td>
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<td>11/12/2008 08:29:29</td>
<td>7450.72</td>
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<td>8</td>
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<td>04/03/2009 20:49:11</td>
<td>07/02/2009 03:53:58</td>
<td>9813.25</td>
</tr>
<tr>
<td>9</td>
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<td>10/01/2009 20:57:34</td>
<td>03/01/2010 08:37:24</td>
<td>16 203.11</td>
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Total exposure time (star hours): 144 408.34

Figure 1. Four histograms of CoRoT data sets.

spectral information and 32-s integration time. Ofek & Nakar (2010) show that CoRoT exoplanets data set is unlikely to detect TNOs or Oort Cloud objects, because the 32-s time resolution is too coarse for the search of sub-kilometre TNOs. In this work, we used the asteroseismology data sets for which CoRoT simultaneously monitored 10 stars selected from CoRoTSky (a data base generated from previous ground-based observations between 1998 and 2005; Charpinet et al. 2006) with a time resolution of 1 s. The nine observation runs we have analysed contain 165 seismological light curves from 79 different stars (see Table 1). The visible magnitudes of these stars are from 4.8 to 9.5, and their ecliptic latitudes are spread from −28° to −12° and from 16° to 26° (see Fig. 1d). For a complete overview of the mission, see the CoRoT book (Fridlund et al. 2006).

2.2 Data reduction

For the data reduction procedure, in order to keep as much as possible the original information from the data, we only filtered the data with one of the values of its flags, OVER, which represents the status of the satellite during the observation. OVER = 0 means the data bin is within a good time interval (Fridlund et al. 2006).
Let us consider the duration of the events we are searching with respect to the CoRoT integration time of the 1 s. In the frame of optical geometry, the duration of potential occultation of a given star can be estimated by dividing the star diameter by the Earth velocity projected on the sky plane towards this star:

\[ V_{\text{rel}}(i) = V_E - (V_E \cdot U) \cdot U, \]

(1)

where \( V_E \) is the orbital speed vector of the Earth, \( U \) is the unit vector from the Earth to the target star. For each bin \( i \), \( V_{\text{rel}}(i) \) and the potential occultation duration are computed. \( V_{\text{rel}}(i) \) is between 10 and 30 km s\(^{-1}\) and the duration is smaller than 1 s (Fig. 1c). The duration can be longer in case of diffracting occultation (Roques & Moncuquet 2000; Nihei et al. 2007) but as shown in Fig. 1(b), the CoRoT stars have large angular size which limits the role of diffraction. Most of the expected events last less than 1 s (Fig. 1c). Because of the 1-s integration time, the research of TNO occultation profiles is focused on the detection of one-bin events significantly outliers in the CoRoT light curves.

The poor temporal resolution will preclude from getting information on the distance of the potential occulting objects. Therefore, the search was done with the hypothesis that the objects are at 43 au from the Sun.

After removing suspicious bins with OVER different from 0, we have had 519 869 933 data bins corresponding to 144.4 kilo-star hours. The longest light curve is about 131.5 d, and the shortest one is only 411 s.

The selection of one-bin outliers needs to measure carefully the stability of data points in the stars light curves. For defining this stability, signal-to-noise ratio (SNR) is computed as mean value \( \mu \), divided by standard deviation value \( \sigma \). SNR of a 54-d light curve of a star of 7 apparent magnitude is around 360. This dispersion of the stellar flux due to the fact that this star, as most of the CoRoT asteroseismology field targets, is variable on time-scales of hours or days. The SNR values are much larger when it is computed on intervals smaller than the typical seismology time-scales. SNR computed on 30-s intervals (see Fig. 1a) are between 1000 and 6000. This extremely high photometric precision makes these data a unique data set for the exploration of the Kuiper belt by serendipitous occultation method, with events lasting less than 1 s.

3 SEARCH FOR OCCULTATIONS PROFILES

3.1 Search for outliers

The Possible Occultation Events (POEs) were searched in the data with three steps. The first step was the research of one-bin outliers. The second step was checking that there is no other reason than an occultation event to explain these outliers. The third step was to check that the events are compatible with occultation by comparing the event with synthetic profiles. This step also provided information about the size of the occultor. Because of the poor temporal resolution, it is not possible to search the diffracting fringes, which are the strong signature of occultation by a TNO (Roques & Moncuquet 2000; Nihei et al. 2007), that is why we speak about Possible Occultation Events.

We tested all the bins by comparing their depths to the neighbour bins. For this, we needed to compute mean \( \mu(n) \) and standard deviation \( \sigma(n) \) of neighbour bins. As stellar activity time-scale is much larger than 1 s, the search of outliers would need to define the bins’ properties on a window large enough but smaller than the stellar activity time-scales. For a given bin \( r(i) \), a window centred on the bin was used for setting statistical score on this bin. The length of this window is a sensitive parameter. We used lengths of windows from \( 2 \times 10 \) to \( 2 \times 90 \) s. A \( 2^\text{n}-\text{s} \) running window means to calculate \( \mu(n) \) and \( \sigma(n) \) values of the star intensity during \( n \)-s ahead and \( n \)-s behind the data bin, the data bin itself is excluded. Then, we represented the star intensity in the unit of the standard deviation. This new statistical value is known as the standard score (SS\(_n\)), or Z-Score, SS\(_n\)(i) = \((f(i) - \mu(n))/\sigma(n)\).

The histogram of \( SS_n \) for the 5.2 × 10\(^3\) data bins shows a distribution not far from a Gaussian distribution for \( SS_n \) between −5.8 and +5.8 (Fig. 2), whatever is the \( n \) value. But the distribution is not Gaussian for large values, in particular for positive values (right-end of the distribution on Fig. 2).

For the right-hand side part, the distribution curve displays a large deviation from the Gaussian curve. This corresponds to bright pixels leading to positive-\( SS_n \) increase-bins in the light curve. Most (\( >80\% \)) of these positive bins are due to the transit, in the field of view, of a satellite or space debris (time-scale \( >0.1 \) s). The remaining of these positive bins are caused by cosmic rays (CR) impact on the detector which typical impact rate is 0.01 particle cm\(^{-2}\) s\(^{-1}\) (Bugaev et al. 1998). The expected number of positive bins computed from this CR impact rate is similar with the number of positive \( SS_n \) values observed. Note that bins crossing the South Atlantic Anomaly have been discarded, because the OVER values are different from 0.

The distribution of negative values of \( SS_n \) is regular and shows some outliers. The potential occultation profiles are among these outliers. The slope of the negative \( SS_n \) distribution depends on the value of \( n \). This distribution cannot be fitted by a Gaussian curve but, considering the huge number of bins, we can make a simple model of the distribution to select the outliers. If \( N(SS_n) \) is the number of bins which \( SS_n \) is between \( SS_\text{min} \pm 0.05 \), we perform an exponential fitting of \( N(SS_n) \) for the negative values of the \( SS_n \) and for \( 3 \leq N(SS_n) \leq 1000 \) (see Fig. 2). The correlation is very good for all values of \( n \) (correlation coefficient larger than 0.98). This fitting allows us to define an SS threshold \( T(n) \) beyond the number of bins that is less than one. The outliers are the bins that \( SS_n \) are smaller than \( T(n) \). \( T(n) \) has values between −6.2 and −9.3 for window size decreasing from 180 to 20. Note that there are 519 869 933 1-s data bins employed in this work. The flux of each
Table 2. 13 POEs and 7 IEEs.

<table>
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<th>RunCode</th>
<th>WinSize† (s)</th>
<th>MID (d)</th>
<th>Depth (σ)</th>
<th>FluxDrop (per cent)</th>
<th>StarID</th>
<th>Vmag</th>
<th>β* (deg)</th>
<th>α* (deg)</th>
<th>R1‡ (km)</th>
<th>Vrel (km s⁻¹)</th>
<th>SNR</th>
<th>R0geom* (km)</th>
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<td>54208.482227</td>
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<td>13.94</td>
<td>2613</td>
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† The running-window sizes applied to the search for the events.
‡ The radii projected at 43 au of the background stars.
♯ The smallest detectable radii projected at 43 au of the occultators.
∗ Ecliptic latitude and opposition angle, respectively.

Table 3. 15 Running window sizes.

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<th>RW25ₜ</th>
<th>RW30ₜ</th>
<th>RW35ₜ</th>
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<th>RW55ₜ</th>
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<td>IEE06</td>
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<td>IEE07</td>
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1-s data bin is normalized by a running window with a certain length, and interpreted in the unit of SS rounded off to one decimal place. Thus, to know the possibility of SS(−6.2), one can use the Gaussian Probability Density Function (GPDF) to calculate GPDF(−6.15)–GPDF(−6.25) ≈ 1.82188 × 10⁻¹⁰, and times the total number of data bins. Then, SS(−6.2) corresponds to 0.0947142 ‘bin’ which would be found being outside of an equivalent Gaussian distribution between SS(−5.8) and SS(5.8).

This selection method was applied to 15 SS distributions computed with window sizes from 20 to 180 bins. This search has led to 20 outliers (see Tables 2 and 3).

To validate the reality of these events, we examined the raw data, i.e. the images, with the assistance from CoRoT team members. Seven outliers were excluded because they corresponded to defocusing processes or cross-talk interactions between seismology and exoplanetary CCDs. They are called IEE01–IEE07, i.e.
Instrumental Effect Events. The other 13 outliers were identified as Possible Occultation Events, the so-called POEs (Fig. 3). Among these 13 POEs, 2 were detected with four windows sizes and 11 were detected with only one window size.

Most of the POEs (10 on 13) were detected with window smaller than 35 bins. Actually we did use window sizes larger than 180 s, but all the outliers detected with windows equal or larger than 180 s were identified as instrumental artefacts, so Table 3 only shows the results until 180 s. Table 2 shows the properties of the 13 POEs and the 7 IEEs.

In conclusion, during the 144 400 star hours, there are some outliers that cannot be explained by other fact than occultation of the target stars. The exact number is uncertain because the event profiles do not have specific signature of occultation, and some of them can be artefacts. We conclude that there are between 2 and 13 POEs during 144 400 star hours and that two of them are more probable.

3.2 Estimation of stellar angular radius

The depth of a serendipitous occultation event is highly dependent on the angular size of the background star (Roques & Moncuquet 2000; Nihei et al. 2007; Bianco et al. 2010). To determine the stellar angular radius of our 79 background targets, we followed the work done by Bianco et al. (2010). The concept of this method is to derive the surface brightness $F_{k0}$ of one star by applying a fitting result of the $J$ and $K$ colour (van Belle 1999; Nordgren et al. 2002, equation 1), and then we can obtain the angular radius $\theta$ by the Barnes–Evans relation (equation 2):

$$ F_{k0} = 3.942 \pm 0.006 - (0.095 \pm 0.007)(J_0 - K_0). $$

$$ F_{k0} = 4.2207 - 0.1K_0 - 0.5\text{log}(2 \times \theta). $$

There are already some measuring results of CoRoT astroseismology observations (Mosser et al. 2013). The uncertainty of these results is about 15 per cent. We compared those results with their estimations with the equations above.

### Table 4. Comparison of angular radius results.

<table>
<thead>
<tr>
<th>Star name</th>
<th>Radius ($R_\odot$)</th>
<th>Parallax (mas)</th>
<th>$\theta_{\text{CoRoT}}$ (mas)</th>
<th>$\theta_{\text{Mosser}}$ (mas)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD46375</td>
<td>0.74</td>
<td>28.72</td>
<td>0.098 293</td>
<td>0.138 634</td>
<td>Mosser et al. (2013)</td>
</tr>
<tr>
<td>HD49385</td>
<td>1.92</td>
<td>13.91</td>
<td>0.124 311</td>
<td>0.130 695</td>
<td>Mosser et al. (2013)</td>
</tr>
<tr>
<td>HD49933</td>
<td>1.55</td>
<td>33.69</td>
<td>0.243 060</td>
<td>0.232 071</td>
<td>Mosser et al. (2013)</td>
</tr>
<tr>
<td>HD52265</td>
<td>1.34</td>
<td>34.53</td>
<td>0.215 368</td>
<td>0.209 255</td>
<td>Mosser et al. (2013)</td>
</tr>
<tr>
<td>HD175272</td>
<td>1.63</td>
<td>11.30</td>
<td>0.085 733</td>
<td>0.097 920</td>
<td>Ozel et al. (2013)</td>
</tr>
<tr>
<td>HD175272</td>
<td>1.01</td>
<td>37.73</td>
<td>0.177 373</td>
<td>0.179 885</td>
<td>Bruntt (2009)</td>
</tr>
<tr>
<td>HD181420</td>
<td>1.60</td>
<td>21.05</td>
<td>0.156 766</td>
<td>0.157 914</td>
<td>Ozel et al. (2013)</td>
</tr>
<tr>
<td>HD181906</td>
<td>1.39</td>
<td>14.72</td>
<td>0.095 236</td>
<td>0.103 657</td>
<td>Bruntt (2009)</td>
</tr>
</tbody>
</table>

From the Table 4, we found the results of these two independent measurements to be consistent. So we only use the Barnes–Evans relation for estimating the stellar angular radius in this work. After applying this method on our 79 target stars, the angular radius projected at 43 au are ranging from 0.7 to 46 km (Fig. 1b).

### 3.3 Size of TNOs

The very small depth of the POEs (from 0.16 to 1.01 per cent, Table 2) implies that the size of the potential occulting objects are a small fraction of the star size projected at 43 au. The stars involved in the POEs have radii between 1.1 and 15.6 km (Table 2). These potential occultors have size of the same order of the Fresnel scale, $F_i = \sqrt{\lambda D}$ where $\lambda$ is the wavelength and $D$ is the distance of the occultor. At 43 au, $F_i = 1.3$ km for $\lambda = 0.55$ $\mu$m, then diffraction plays a role in the occultation. However, the diffraction fringes are smoothed on star disc which are larger than the Fresnel scale. As most of the occultations last less than 1 s (Fig. 1c), the event is also smoothed on the integration time. Let us see how we can, nevertheless, obtain information on the potential occultor, and in particular the minimum size for TNOs responsible of the POEs.

For this, we compared the POEs with synthetic profiles and searched the minimal and maximal sizes for TNOs that occultation profiles fit the POEs. The code simulating the diffraction profiles is described in Roques, Moncuquet & Sicardy (1987). The code parameters are, in addition to the TNO radius, the TNO distance from the Earth, the star radius, the impact parameter i.e. the minimum distance between the star centre and the occultor centre in the sky plane, the wavelength range, the time of the occultation and the relative velocity of the star with respect to the object. Some parameters are known: the star’s radius (Table 2), the integration time (1 s), and wavelength ($\lambda = 0.37-0.95$ $\mu$m) range.

The relative velocity of the star with respect to the potential occultor was computed for the 4th POE as $V_{rel}(t) \pm \Delta V$. $V_{rel}(t)$ depends on the event date and on the occulted star. $\Delta V = 9.1$ km s$^{-1}$ corresponds to the rapidly varying velocity of CoRoT around the Earth (the orbital velocity of CoRoT is 4.6 km s$^{-1}$) and the unknown velocity of the TNO in the sky plane (the velocity of a TNO on a circular orbit at 43 au is 4.5 km s$^{-1}$).

On the three remaining parameters, the occultation time and the impact parameters were fixed, to get a minimal value for the occultor size, and the comparison of the POE and the synthetic profile was done with only the TNO size as free parameter. (see Fig. 4)

1. The occultation time is centred in the middle of the integration time to insure that the profile is not overlapping two bins.

2. The impact parameter is set to zero except for POE04. The impact parameter of POE04 is set to 0.6 $R_\odot$. Indeed, as considering the relative velocity of a TNO and the flux-drop percentage observed...
from its light curve, if we take an impact parameter equal to 0, the simulated profile will be on three points. But in fact, the decrease of a POE is just on one point, this is why we especially take an impact parameter of $0.6R_s$ for POE04.

The occultors’ minimal radii ($R_{\text{diff}}$) deduced from the comparisons with synthetic diffracting profiles are listed in Table 5. The maximum radius is not constrained. Synthetic profiles of occultation by TNO of several kilometres can fit the POEs. For example, the POE01 is well fitted by a 6 km radius object with a 5.5 km impact parameter.

In conclusion, we have had information on the minimal size of the TNOs responsible of the 13 POEs, and we have no constraint on their maximum size, keeping in mind the hypothesis that the occultors have circular orbit at 43 au from the Sun.
It is interesting to compare the radii computed by diffracting model with values estimated in the framework of optical geometry. When the occultor is smaller than the projected star and if the occultor (radius \( R_o \)) passes completely in front of the star (radius \( R_s \)), the normalized depth of a geometric occultation dip, depth, is the ratio of the occultor surface on the star surface projected at the occultor distance, i.e. \( R_o/R_s \). Then \( R_{geom} = \sqrt{\text{depth}} \times R_o \). When the occultor is smaller than the star and partial occultations, \( \sqrt{\text{depth}} \times R_o \) gives a minimal value of the occultor radius.

When the occultation duration is smaller than the integration time, the equation above is changed to:

\[
R_{geom} \geq \sqrt{\text{depth} \times R_o \times V_{ej}(i)}/2. \tag{4}
\]

The diffracting synthetic profile always gives TNO size smaller than the geometrical synthetic profile. This is due to diffraction (Cuzzi 1985).

### 3.4 TNOs density in the sky plane

On the detection of the [2–13] POEs, we have deduced information on the density of TNO in the sky plane. For a given POE, the radius of the occulting TNO, \( R_o \), is computed in the above section. Among the sky surface scanned by the CoRoT data, one compute \( S(R_o) \), the sky surface where a \( R_o \) TNO is detectable. The sky surface scanned during each 1-s interval is the elementary rectangle whose width is \( 2 \times R_o \) and whose length is \( V_{ej}(i) \times 1 \text{ s} \).

Then, one POE corresponds to the detection of one TNO with radius larger than \( R_o \) on \( S(R_o) \), and \( 1/S(R_o) \) is the density of TNO (\( > R_o \)) in the sky surface scanned by CoRoT. This density, which was computed at the ecliptic latitude of the CoRoT targets, can be translated into a density of TNO larger than \( R_o \) in the ecliptic plane.

To compute \( S(R_o) \), one has to estimate for each bin, if the occultation by an \( R_o \)-radius TNO is detectable. Following the detection method described in Section 3.1, the \( R_o \) TNO is detectable if it exists at least one value of \( n \) for which \( \text{drop}_{R_o,n} \geq T(n) \times \sigma(i, n)/\mu(i, n) \), where \( \text{drop}_{R_o,n} \) is the normalized flux decrease if an \( R_o \) occults the star at the bin \( i \), \( \mu(i, n) \) is the mean at bin \( i \) for window size \( n \), \( \sigma(i, n) \) is the standard deviation at bin \( i \) for window size \( n \). drop \( R_o,n \) was computed to an approximation: \( \text{drop}_{R_o,n} \approx (R_{geom}/R_o)^2 \times (R_{geom} + R_o)/V_{ej}(i) \).

\( S(R_o) \) was obtained by adding all the elementary rectangles of bins where an \( R_o \)-radius object is detectable.

To translate this density into a density of TNOs, we have referred to the result of Elliot et al. (2005). Since our target stars are between ecliptic latitude of \( \pm (10–30)° \), we computed that the density in the ecliptic plane is four times the density in the CoRoT fields. We then computed the density in the ecliptic plane from the [2–13] POEs and compared with the results from other surveys.

### 4 RESULTS ON SIZE DISTRIBUTION OF THE SUB-KILOMETRE TNOS

The TNO cumulative size distribution is described by \( N(r > r) \propto r^{-q} \), where \( N(r > r) \) is the number of TNOs larger than \( r \), and \( q \) is the power-law index.

We have detected 13 TNOs in Section 3.1. While analysing these results, we took two approaches. The first way was to merge our results in one single point, and the second was to consider the 13 detections individually. In both approaches, we consider POE04 and POE07 more robust than the other 11 POEs (see Section 3.1). We then gave those 11 points a weight of 1, while for the 2 robust points as well as the \( HST \) point we gave a weight of 4.

In Fig. 3, we collapsed our 13 detections in one single result with a weighted average value for the minimum radius of 400 m. The value of density in the sky plane of TNOs with radius larger than 400 m in the ecliptic plane is \( N(r > 400 \text{ m}) = 1.4^{+4.2}_{-2.7} \times 10^7 \text{ deg}^{-2} \). This density is compatible with the density of \( N(r > 250 \text{ m}) = 1.1^{+1.5}_{-0.7} \times 10^7 \text{ deg}^{-2} \) estimated from the events detected by the \( HST \) (Schlichting et al. 2012).

The fitting of the density of TNOs with radius larger than 400 m and the believed break \( r_{\text{break}} = 45 \text{ km} \) (Fuentes & Holman 2008) gives a power-law index \( q \) larger than 3.5. This value is consistent with the detection of two potential events from \( HST \) observations that found \( q = 3.8 \pm 0.2 \) (Schlichting et al. 2009, 2012).

Our results were then directly compared to the surveys achieved so far to detect possible occultations events (Fig. 3). All of them, except the Schlichting’s ones, are upper limits. The most size sensitive one is the survey performed by Chang et al. 2013, which can probe objects as small as 30 m, thanks to the X-Rays data of \( RXTE \) space observer. Our results are notably more potent because we are probing a larger surface on the sky plane. All those results are in good agreement and provide us reliable information on sub-kilometre objects of the Kuiper belt.

The second approach used to analyse our results was to consider the 13 POEs and the \( HST \) result as a whole and try to deduce some properties of the TNOs population between 180- and 710-m radius. This approach is more challenging since 11 out of 13 detections were less robust.

Moreover, the values of Table 5 correspond to minimum values for the occulting objects. Let us make the hypothesis that the actual values of the occultors are equal to the values of Table 5. This assessment is reasonable since smaller objects are more probable than larger ones. A slope of \( q = 4.5 \pm 0.2 \) was computed taking into account the weighted 14 points. (see Fig. 5). Let us compare this value with evolution models of the Kuiper belt.

Surveys indicate a slope approximately 4.5–4.8 for differential size distribution of large TNOs and a possible break at \( R \) magnitude = 25–26 (Fraser et al. 2008; Fraser & Kavelaars 2009). This
The 13 POEs (black) and the 2 combined Schlichting events approximately ±0.2 slope we found is much steeper than the one computed by Schlichting et al. (2011). The differential size distribution power law of collisional population was estimated to have a slope of 3.5 by Dohnanyi (1969) or as large as 4 according to Schlichting & Sari (2011).

Recently, Schlichting, Fuentes & Trilling (2013) used a coagulation and collisional model to investigate the evolution of TNO size distribution over 4.5 Gyr. They found indeed the size distribution below $r_1 \approx 30$ km has been affected by collisions and can be fitted rather by several slopes in the size range between 0.01 and 30 km, before reaching the Dohnanyi equilibrium value. In fact, compared to a single power-law distribution below the 30-km break, Schlichting et al. (2013) found in general a strong deficit of bodies around 10 km and a strong excess of bodies around 2 km in radius, which they attributed to the planetesimal size distribution left over from the runaway growth phase, which leaves most of the initial mass in small bodies.

Noticeably, the $q = 4.5 \pm 0.2$ slope we found is much steeper than the one computed by Schlichting et al. (2013) in the range $0.1 \leq r \leq 1$ km. We also noted here that Belton (2014) derived a differential power-law index of $q = 4.5 \pm 0.5$ (cumulative 4.24) in the range $r \geq 10$ km from the fitting of the scattered size--frequency distribution estimated from 161 observed Jupiter Family Comets to small TNO surveys of Fuentes et al. (2010), Schlichting et al. (2012), and Zhang et al. (2013). That is, the second break around $r \approx 1$–3 km predicted by evolution models may not exist.

Moreover we also reached the limits of detection. Dedicated observations from ground facilities will allow us to obtain better results, that is to say diffraction profiles with better time resolution.

Schlichting et al. (2013) studied theoretically the evolution of TNO size distribution over 4.5 Gyr. They found that the size distribution of small TNOs (e.g. $r < 30$ km) have different slopes. Indeed, this signature is not erased after 4.5 Gyr of collisional evolution. Therefore, probing sub-kilometre TNOs by stellar occultation is crucial to test all these evolution models of the TNO population.

5 SUMMARY AND CONCLUSION

We studied the size distribution of small TNOs by using the archival data of the CoRoT spacecraft. We used the serendipitous stellar occultation method to detect the shadow of small TNOs passing in front of the stellar discs. While the 1-s time resolution does not permit modelling the diffraction pattern, owing to the huge number of star-hours, we have detected 13 POEs. We obtained minimum radii for these possible small occulting TNOs ranging between 0.2 and 0.7 km. In that size range, we derived a $q = 4.5 \pm 0.2$ slope. Our results are notably more potent than the other surveys because we are probing a larger surface on the sky plane.

Moreover we also reached the limits of detection. Dedicated observations from ground facilities will allow us to obtain better results, that is to say diffraction profiles with better time resolution.

Schlichting et al. (2013) studied theoretically the evolution of TNO size distribution over 4.5 Gyr. They found that the size distribution of small TNOs (e.g. $r < 30$ km) have different slopes. Indeed, this signature is not erased after 4.5 Gyr of collisional evolution. Therefore, probing sub-kilometre TNOs by stellar occultation is crucial to test all these evolution models of the TNO population.

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