

## Small Near-Earth Objects in the Taurid Resonant Swarm

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### Abstract

The Taurid Resonant Swarm (TRS) within the Taurid Complex hosts dynamically-concentrated debris in a 7:2 mean-motion resonance with Jupiter. The existence of TRS has been confirmed by episodic enhancements in the density of meteoric debris along specific orbital corridors, but it remains unclear if TRS could also host a significant amount of larger debris at sizes of asteroids that could pose impact risks to Earth. We reanalyze the data obtained by the Zwicky Transient Facility (ZTF) during the 2022 TRS encounter. We find that the TRS may host up to  $\sim 10^2$  Tunguska-sized objects and up to  $\sim 10^3$  Chelyabinsk-sized objects, translating to an impact frequency of Chelyabinsk-sized TRS objects of once every 4 million years. However, we caution that simplification and assumptions made in the model may undermine this conclusion. TRS encounters in the next couple of years, coinciding with the operation of next-generation near-Earth object surveys such as the Legacy Survey of Space and Time, offering opportunities to refine or refute this finding.

*Keywords:* near-Earth objects, Taurid Resonant Swarm, impact risk

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### 1. Introduction

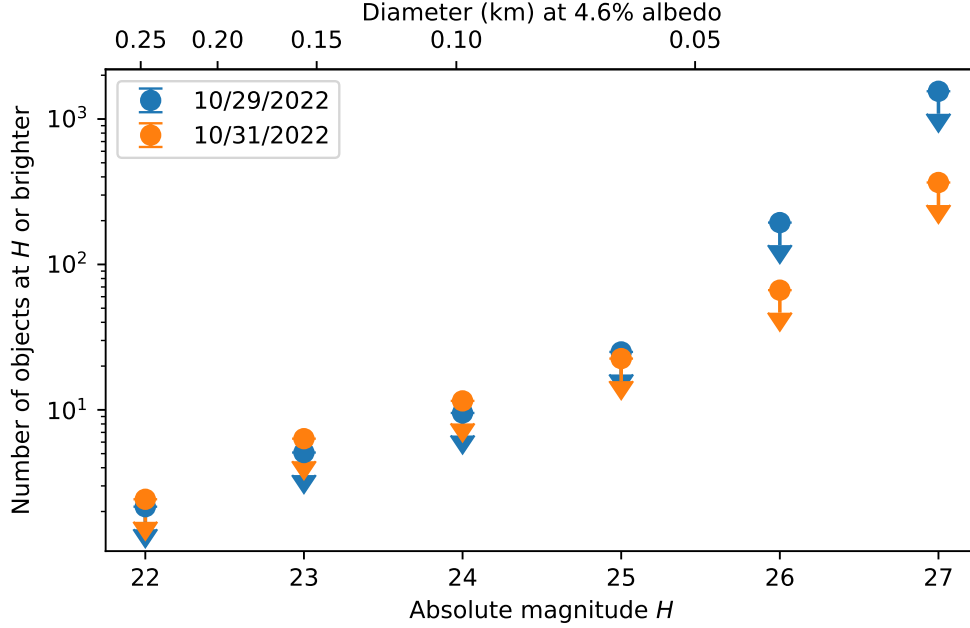
The Taurid Resonant Swarm (TRS) is a dynamically coherent substructure within the broader Taurid Complex, a stream of debris associated with comet 2P/Encke and possibly a number of asteroids. Materials in the TRS are dynamically trapped in a 7:2 mean-motion resonance with Jupiter [1, 2], resulting in episodic enhancements in the density of meteoroids and possibly larger near-Earth objects (NEOs) along specific orbital corridors. Earth periodically encounters the TRS, during which enhanced meteor activities have been observed [3, 4]. Increased close encounters with larger asteroidal counterparts in TRS have also been predicted [2], but have not been unambiguously detected.

Recent observational campaigns using wide-field telescopes, such as the 2022 Zwicky Transient Facility (ZTF) campaign [5], have sought to constrain the population of macroscopic TRS objects. The ZTF campaign placed an upper limit of no more than 9–14 objects brighter than  $H = 24$  in TRS (equivalent to a diameter of  $\gtrsim 100$  m), suggesting a reduced impact hazard of hectometer-scale TRS bodies relative to earlier theoretical speculations. However, as shown by the Tunguska and Chelyabinsk events, smaller, decameter-scale NEOs can still cause regional devastation, yet they are small enough to evade current NEO surveys. Thus, it is important to quantify or at least constrain the abundance of these smaller NEOs in the TRS.

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**Figure 1: Upper limits of TRS objects at an  $H$  range of 22–27 based on ZTF campaign data obtained on the two campaign dates, 2022 October 29 and 31.**

## 2. Small NEOs in the TRS and Their Impact Risk

The 2022 ZTF campaign searched an area of  $\sim 1600 \text{ deg}^2$  with an effective limiting magnitude of  $V \sim 20$ , covering 99% of  $H = 24$  TRS objects visible at the time of the campaign. The data was searched for moving objects using two approaches developed for detecting trailed fast-moving objects and slower objects, with no candidates found.

To understand the population of small NEOs in the TRS, we reanalyze the results obtained in the 2022 ZTF campaign. We modify the synthetic population originally used to guide the ZTF campaign to cover TRS objects with  $H = 22$  to 27, covering diameters between  $\sim 250 \text{ m}$  to 10 m, assuming 2P/Encke’s albedo of 0.046 [6]. We then use the non-detection result as well as the detection efficiency established in [5] to calculate the upper limit of the number of objects at each  $H$  bin.

Figure 1 shows the upper limits of the number of TRS objects at  $H$  range of 22–27. The profile bottoms out at  $N = 1$  near  $H \sim 20 - 21$ , which coincides with the largest NEO that is likely to be directly associated with the TRS, 2005 TF<sub>50</sub> ( $H = 20.3$ ) [7]. At the smaller end, the 2022 October 31 data appears to provide a better constraint compared to the 2022 October 29 data, possibly because Earth was closer to the center of TRS on October 31. We determined that the TRS may host up to  $\sim 10^2$  Tunguska-sized objects and up to  $\sim 10^3$  Chelyabinsk-sized objects.

The impact flux of the simulated TRS population can then be estimated by

$$F = n\sigma v_g \quad (1)$$

where  $n$  is the number density which is constrained by the upper limits derived above,  $\sigma = \pi R_\oplus^2 \left(1 + \frac{2GM_\oplus}{R_\oplus v_g^2}\right)$  is the collision cross-section (with  $G$ ,  $R_\oplus$ ,  $M_\oplus$  as the gravitational constant as well as the radius and mass of Earth),  $v_g \approx 30 \text{ km/s}$  the geocentric speed of the TRS objects. This is straightforward to estimate as the simulated TRS population nominally intersects Earth’s orbit, since it was derived from Taurid fireball orbits.

Taking  $N \lesssim 10^3$  from the upper limit of Chelyabinsk-sized objects in the TRS, we obtain  $F \lesssim 2 \times 10^{-7} \text{ yr}^{-1}$ , or less than once every 4 million years. This is two orders of magnitude longer than the dynamical age of TRS, suggesting that an impact from a TRS object of Chelyabinsk-scale or larger is statistically unlikely. However, we caution that this is based on a number of assumptions and simplification in the simulation, such as that the orbital distribution of macroscopic TRS objects are identical to the fireball-sized TRS objects, and that higher-order dynamical effects such as Yarkovsky drift were

not considered. Fragments larger than fireball-sized objects are less prone to dynamical dispersion and may have more concentrated orbits, which can lead to higher impact risks. As this requires a more detailed model to investigate, we defer this to future works.

### 3. Future TRS Campaigns

Data obtained in future TRS encounters could substantially improve the statistical constraints or even detecting members of the population. Earth will pass near the TRS again in 2025, 2026 and 2029, followed by two highly favorable, near-centric encounters in 2032 and 2036 [1], which coincide with the commissioning and operation of the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) and offer the possibility of deeper searches along the TRS orbital domain.

The search of TRS objects is somewhat different in scope compared to conventional NEO searches, since the parameter space is constrained. To compare the capability to search for TRS objects between different facilities and observing modes, we start with the Figure of Merit (FoM) appropriate for streaked objects, derived by [8]:

$$\text{FoM} \propto \left( \frac{\Omega_{\text{eff}} 10^{0.6m_{\text{lim}}}}{t_{\text{obs}}} \right) \left( \frac{\theta_{\text{PSF}}}{\theta_{\text{streak}}} \right) \quad (2)$$

where  $\Omega_{\text{eff}}$  is the effective field of view to be accounted for the spatial size of the search corridor,  $m_{\text{lim}}$  is the limiting magnitude,  $t_{\text{obs}}$  is the total observation time including overheads,  $\theta_{\text{PSF}}$  is the pixel size of the point-source function (PSF), and  $\theta_{\text{streak}}$  is the angular length of a streak at the  $m_{\text{lim}}$  for a PSF source. The value of  $\theta_{\text{streak}}$  varies depending on the size, distance, and therefore detectability, of the targeted population; for ease of discussion, we use the median value of 6''/min from the simulated TRS population for our comparison.

The model-guided search corridor of the TRS asteroids is a narrow arc that is over 270° long and ~ 2° wide (Figure 2). Therefore, we have

$$\Omega_{\text{eff}} = \begin{cases} \Omega, & (\Omega \leq 4 \text{ deg}^2) \\ 2\sqrt{\Omega}, & (\Omega > 4 \text{ deg}^2) \end{cases}$$

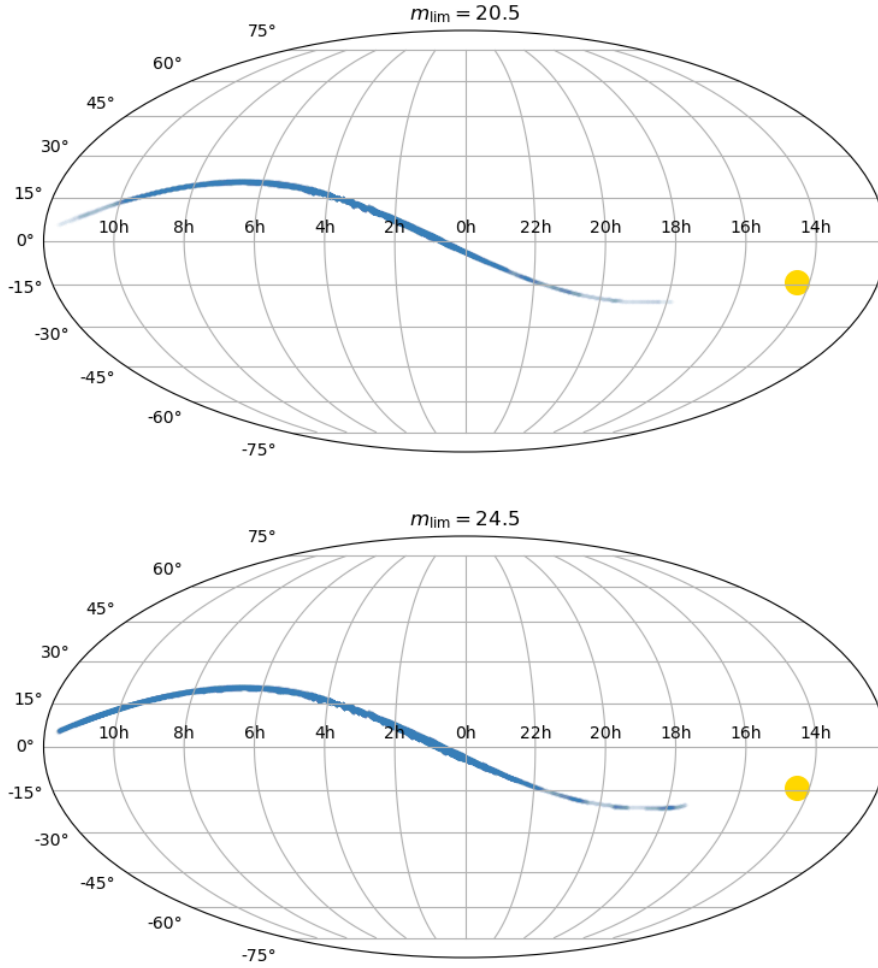
where  $\Omega$  is the original field of view of the telescope.

We calculate the FoM for a handful of wide-field telescopes, tabulated in Table 1. The advantage of LSST is significant: by this measure, LSST will be 28 times more efficient than ZTF for a TRS campaign. Telescopes with field-of-view significantly larger than 2°, such as ZTF, are actually in disadvantage since the TRS search corridor is only ~ 2° in width.

Telescope	$m_{\text{lim}}$	$t_{\text{obs}}$ (s)	$\Omega_{\text{eff}}$ (deg <sup>2</sup> )	$\frac{\theta_{\text{PSF}}}{\theta_{\text{streak}}}$	FoM (rel. ZTF)
ZTF	20.6	(30 + 10) × 3	$2\sqrt{47.0} \approx 13.7$	0.33	1
LSST	24.5	(30 + 2) × 3	$2\sqrt{9.6} \approx 6.2$	0.13	28
Subaru/HSC	24.4	(30 + 40) × 3	1.8	0.06	2.4
DECam	23.3	(30 + 20) × 3	3.0	0.06	1.9
CFHT/MegaCam	23.6	(30 + 12) × 3	1.0	0.06	0.8
Pan-STARRS	22.7	(30 + 10) × 3	$2\sqrt{7.0} \approx 5.3$	0.09	1.8

**Table 1: Comparison of the FoM of several wide-field telescopes. Listed are single-visit limiting magnitude  $m_{\text{lim}}$ , overhead-included observation time  $t_{\text{obs}}$  for 3 visits, effective field of view  $\Omega_{\text{eff}}$ , and the streak-reduction factor  $\theta_{\text{PSF}}/\theta_{\text{streak}}$ , with FoM normalized to  $\text{FoM}_{\text{ZTF}} = 1$ . We assume the exposure time of single visit to be 30-s for all telescopes.**

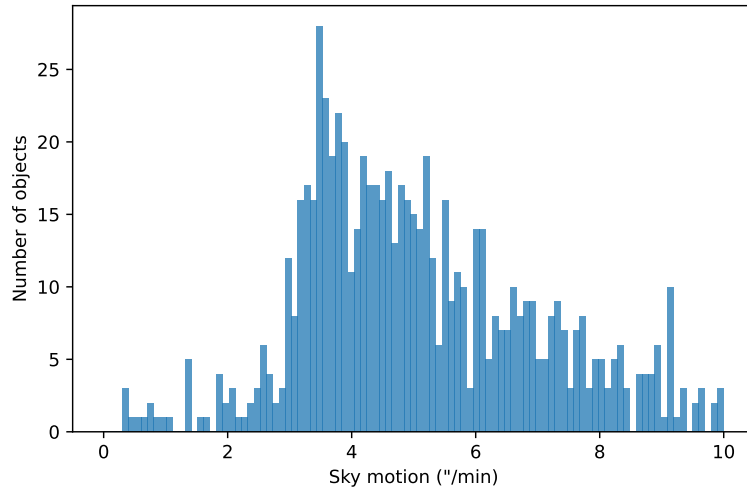
One challenge for future TRS campaigns is the high sky motion of TRS objects during their close encounter to Earth. Taking the 2022 encounter for example, most TRS objects are moving at a few arcsec/min or faster, fast enough to streak on most professional facilities. Facilities with larger pixel size, such as ZTF and LSST to a lesser extent, are less susceptible to the “trailing loss” caused by smeared objects. Thus, detection algorithms specialized in identifying streaked objects will be critical in finding TRS objects in survey images.



**Figure 2: On-sky footprints of simulated TRS particles on 2022 October 31 at ZTF ( $m_{\text{lim}} \sim 20.5$ ) and LSST depth ( $m_{\text{lim}} \sim 24.5$ ).**

#### 4. Conclusion

We reanalyzed the 2022 ZTF campaign for TRS asteroids, and found that the TRS may host up to  $\sim 10^2$  Tunguska-sized objects and up to  $\sim 10^3$  Chelyabinsk-sized objects. The larger end of object size (near  $H \sim 20 - 21$ ) in our constraint appears to agree with the observed population. Our constraint translates to an impact frequency of Chelyabinsk-sized TRS objects of once every 4 million years. While this number is well below the impact frequency of  $\sim 10^2$  years of similarly-sized objects from the general NEO population, we caution that it is dependent to the choice of model parameters. The effect of higher-order dynamical processes such as Yarkovsky drift remains to be explored. Future TRS encounters in the late 2020s to early 2030s coincides with the commissioning and operation of a number of next-generation NEO surveys such as LSST, offering opportunities to deepen our understanding of this intriguing population.



**Figure 3: On-sky motions of TRS objects on 2022 October 31.**

## Acknowledgments

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