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A Limit on the Mass of the Taurid Resonant Swarm at Sub-100 m Sizes

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Abstract

We report on a pencil-beam survey of the Taurid resonant swarm (TS), a possible concentration of bodies in the Taurid meteoroid stream associated with the 7:2 mean motion resonance with Jupiter. Canada–France–Hawaii Telescope MegaCam observations reaching apparent magnitudes of 24.5 in the *gri* filter were taken over 3 nights. Rates of motion on the sky allowed for the quick elimination of main-belt objects from the over 1000 moving sources seen. Eight candidates with on-sky rates of motion consistent with Taurids were detected, but seven were subsequently shown to be non-Taurids (Hungarias, Mars crossers, etc.). One object might be a 60 m class Taurid, but not enough data were collected and its orbit remains ambiguous. Our results are consistent with no Taurid swarm members observed, and an upper limit of fewer than 3×10^3–3×10^4 objects down to $H = 25.6 \pm 0.3$ (diameter of 47^{+29}_{-13} m assuming a 2P/Encke-like albedo) at the 95% confidence level. While meteor observations have confirmed the TS's existence at meter and smaller sizes, our results indicate that the current mass budget of the swarm at 100 m sizes does not require an outsize parent to explain it.

Unified Astronomy Thesaurus concepts: Small Solar System bodies (1469); Asteroids (72); Comets (280); Near-Earth objects (1092)

1. Introduction

The Taurid meteor shower is an unusual one. It has a very long duration (approximately 6 months) and contains above-average-sized particles, some up to 1 m in size (P. Spurný et al. 2017). The main Taurid meteor showers—the North and South Taurids—are dynamically connected to a larger complex of weaker showers (J. Stohl & V. Porubcan 1990), the whole seemingly connected to the unusual comet 2P/Encke (F. L. Whipple 1967). These features, together with the substantial total mass of the stream (10^{13} kg; Q. Ye & P. Jenniskens 2024), led to it being proposed as the remnant of a giant comet breakup by S. V. M. Clube & W. M. Napier (1984).

This hypothesis suggests that a particularly large (hundred kilometer scale) comet was delivered to and broke apart in the inner solar system 10–20 thousand years ago, and that the Taurids and 2P/Encke are the principal remnants. D. Asher & S. Clube (1993) further proposed that many of the fragments were captured into and dynamically protected by the 7:2 mean motion resonance (MMR) with Jupiter, forming what they called the Taurid resonant swarm (TS). It was also proposed that there could be an increase in Taurid meteor activity, particularly at larger (1 m possibly up to 100 m sizes) impacting Earth at the times when our planet happens to pass through the TS (D. Asher 1991; D. Asher & S. Clube 1993; D. J. Asher et al. 1994).

An extended version of this hypothesis, known as "coherent catastrophism," posits that the Taurid complex is the dominant source of Earth impactors at tens to hundreds of meters sizes (D. J. Asher et al. 1994). This proposal is not universally accepted. G. B. Valsecchi et al. (1995) pointed out the possibility of coincidental orbital similarities between the Taurids and unrelated near Earth asteroids. The past orbital history of the Taurid complex was investigated in detail by A. Egal et al. (2021), who found that some asteroids on Taurid-like orbits might be dynamically linked but that spectral observations would likely be needed to resolve whether or not they are from the same parent. In fact, many asteroids previously thought linked to the Taurids on the basis of orbital similarity (D. J. Asher et al. 1993; D. I. Steel & D. J. Asher 1996) have subsequently been found to have spectra that differ from each other and/or from 2P/Encke (M. Popescu et al. 2014; C. Tubiana et al. 2015), which argues against a genetic relationship.

However, there is also some evidence in support of the existence of the TS. Increased rates of seismically detected lunar impacts were reported in 1975 during a time of Earth's passage near the TS (J. Oberst & Y. Nakamura 1987). Increased meteor activity has also occurred during TS passages (D. J. Asher & K. Izumi 1998; M. Beech et al. 2004; A. Egal et al. 2022). In particular, a 2015 Taurid outburst occurred, resulting in more than 100 bright Taurid fireballs (decimeter-sized up to 1 m) being observed by the European Meteor Network (P. Spurný et al. 2017). The resulting data showed that most of the fireballs were indeed strongly associated with the 7:2 MMR with Jupiter.

Observational searches for TS members in space have so far been unsuccessful. A 2019 opportunity (D. L. Clark et al. 2019) went untapped when protests at Maunakea prevented telescope operations at the Canada–France–Hawaii Telescope (CFHT) during the observing window. Here we report on the results of a 2022 observing campaign also attempted at CFHT, in this case where imaging was successfully obtained. Another

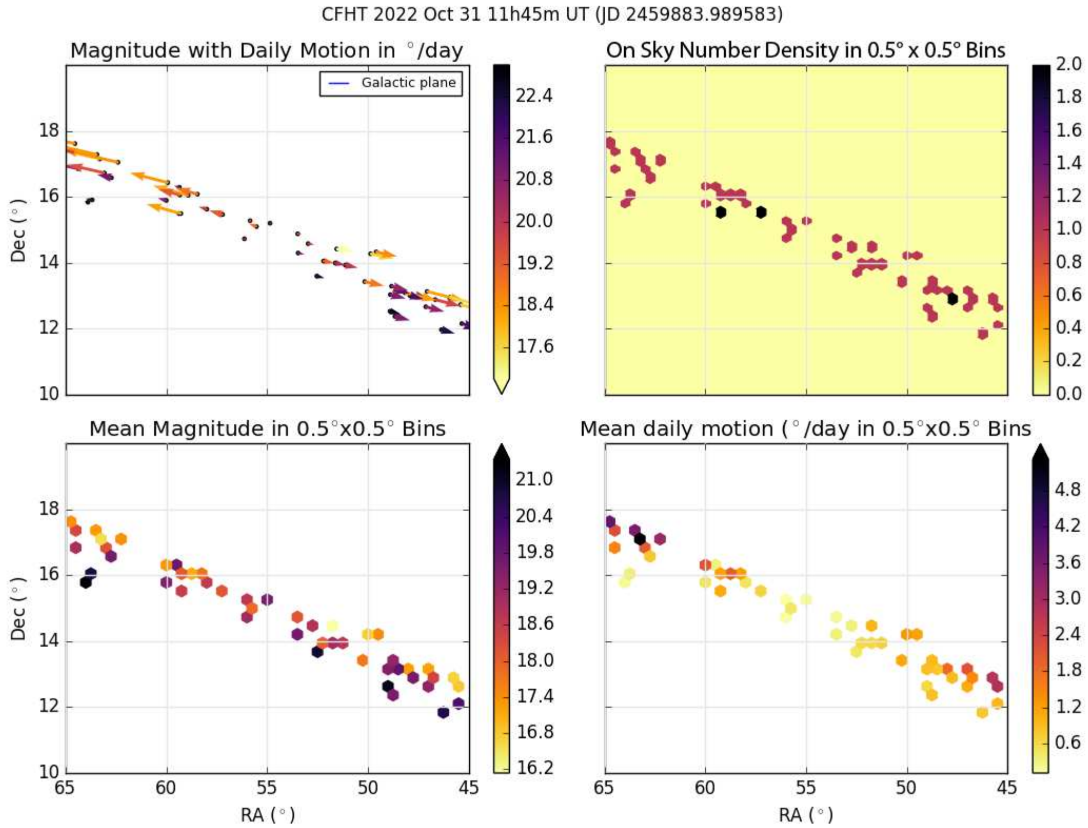

Figure 1. An example of modeled on-sky locations and motions of the TS used to plan observations. Each panel shows a portion of the sky, and the Taurid radiant is located near the center of the plot. Observations were chosen to cover a portion of the sky extending from the center to the lower right. The upper-left panel shows the location of simulated Taurids colored by their apparent magnitude along with an arrow indicating their direction of motion. The lower-left panel shows the mean apparent magnitude per bin; the upper-right panel shows the on-sky number density; and the lower-right panel indicates the mean binned on-sky motion. See the text for further details.

search for TS members during the 2022 apparition by the Zwicky Transit Facility reported no detections (J. Li et al. 2025).

2. Methods

2.1. Observations

Images were obtained from the CFHT with the MegaCam imager on 3 nights (2022 October 29–31) through the *gri* filter. Four separate pointings were arranged along the expected direction of motion of the Taurids, with the hope of doing self-follow-up of any Taurids imaged, as they were expected to be too faint to follow up easily with other telescopes. For each pointing, three dithered 260 s sidereally tracked exposures were taken before moving to the next pointing. With MegaCam's 40 s image download time, this resulted in each pointing acquiring three images over the course of 15 minutes, before the telescope proceeded to the next pointing. All four pointings could be completed in an hour with the sequence restarted if conditions allowed, for a total of 2 hr of observation. Only the first night saw the full 2 hr sequence completed, but substantial numbers of images were taken on subsequent nights, which allowed for significant additional coverage.

Observations were directed toward the point where the on-sky motion of the Taurids would be minimized, essentially near the radiant of the Taurid meteor shower near R.A. and decl. of (55°, 15°). Modeled Taurids were distributed as in D. L. Clark et al. (2019). Figure 1 shows the modeled on-sky motion of the TS used to plan observations. The upper-left panel shows the location of simulated Taurids colored by their apparent magnitude, along with an arrow indicating their direction of on-sky motion. Objects on the left-hand side of the plot are moving to the left and vice versa. The rates of motion typically increase the farther one goes from the center, which is also illustrated in the lower-right panel, which shows the mean daily motion in discrete bins. These two panels indicate that observing regions close to the center of the figure should capture objects with the lowest on-sky rates of motion, and that was the strategy we adopted. Observations were chosen to cover a portion of the sky extending from the center to the lower right of this portion of sky. The lower-left panel shows the mean apparent magnitude per bin, and the upper-right panel shows the magnitude-weighted on-sky density. These are relatively uniform and indicate that object brightness does not vary much across the region in question. Although the Taurids would be brighter in other parts of the sky, our limited angular coverage led us to concentrate on where the Taurids should be most densely concentrated, at some loss of apparent magnitude.

2.2. Moving-object Detection

The moving-object detection pipeline (which is described in A. M. Gilbert & P. A. Wiegert 2009, 2010) flagged triplets of sources moving in any direction at on-sky rates of up to 150″

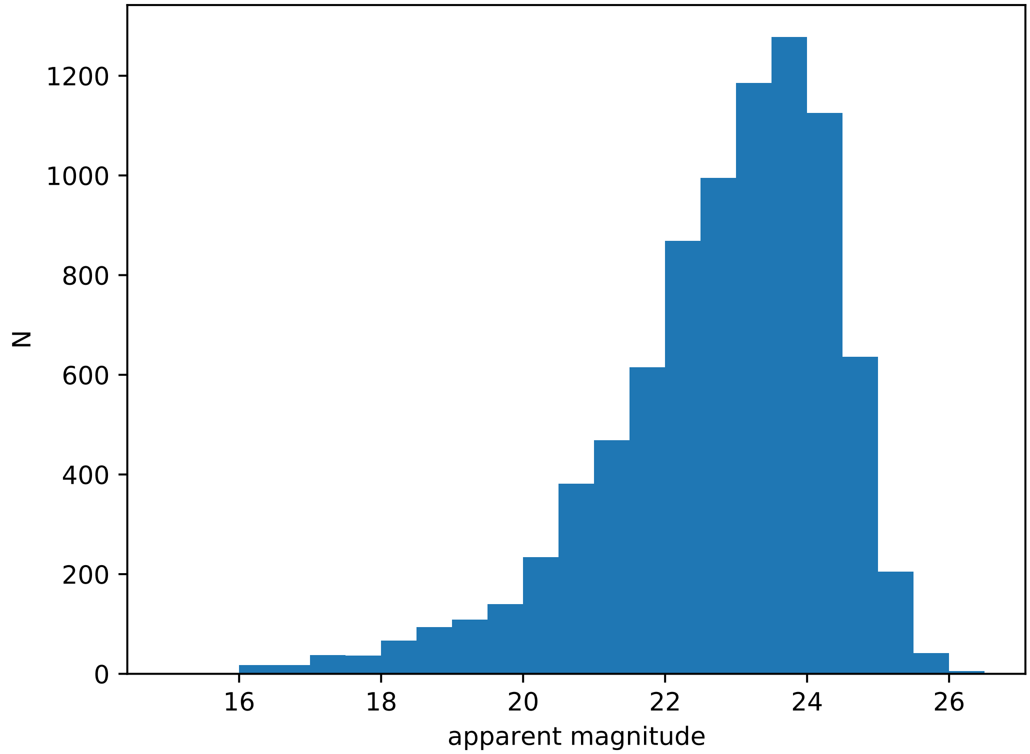

Figure 2. The distribution of apparent magnitudes of detected moving objects.

per hour. Each detection was verified by a human operator. Based on past experience with searches for moving objects at similar rates we expect a detection efficiency of 80%. The detection code requires the source to be detected in all three frames, and so the 20% of lost objects typically occurs due to sources moving into chip gaps or onto stars.

A total of 8739 individual moving sources were detected in the images, which were ultimately associated with 1433 unique minor planets, both known and unknown. Eight candidate Taurids were flagged for further analysis (discussed further in Section 3.1).

A histogram of the apparent magnitudes of the individual moving-object detections is presented in Figure 2. The overall 50% detection limiting magnitude is 24.5. From our simulations (see Section 3.2) we find that any Taurids within our CFHT images would be at distances $\Delta = 0.33 \pm 0.04$ au from Earth at low phase (10–20°). Assuming a photometric $G = 0.15$, a Taurid with a given absolute magnitude H would have an apparent magnitude simply offset so that $m = H - 1.1 \pm 0.3$. Therefore our limiting apparent magnitude of $m < 24.5$ translates roughly to an absolute magnitude limit of $H < 25.6 \pm 0.3$. Assuming an Encke-like albedo (0.046 ± 0.023; H. Campins & Y. Fernández 2002) and the use of the standard HG photometric approach (E. Bowell et al. 1989), our observational limiting magnitude corresponds to a limiting diameter of 47^{+29}_{-13} m.

2.3. Detections of Interest

Many non-Taurid objects, in particular main-belt asteroids, are present in our images. By design, the observing circumstances allow the majority of main-belt objects to be excluded from further analysis based simply on their on-sky rates of motion. To illustrate this, we present in Figure 3 the on-sky expected rates of motion for asteroids in the main belt as well as Taurids at the time our images were obtained.

The rates of motion were determined from a numerical integration of hypothetical particles distributed to approximate the main belt and the Taurid stream, and then selected based on the observing geometry applicable to the images taken. Main-belt asteroids were simply distributed on random orbits with semimajor axes a between 2 and 4 au, eccentricities e between 0 and 0.5, and inclinations i between 0° and 60°. This is not intended to provide an accurate description of the main belt but rather to provide a very broad sample for comparison. Taurid on-sky motions were derived from the model described in Section 2.1.

Figure 3 demonstrates that most main-belt objects can be quickly filtered out on the basis of their on-sky motion. There is only a small region of overlap where Taurids and main-belt objects have similar rates of motion at large negative rates in decl.. This allows us to rapidly reduce our list to those events most likely to be Taurids. We examine more carefully all the candidates that fall below the dashed line in Figure 3. Only eight of our >1000 moving objects are consistent with Taurids: they are discussed in the next section.

3. Results

Eight moving objects were detected with on-sky motions within the region where the Taurid and main-belt rates overlap. There are also three outliers that appear on the right-hand side of Figure 3.

3.1. Candidates and Outliers

The eight moving sources discussed below had rates of motion on the sky consistent with Taurids, but careful analysis

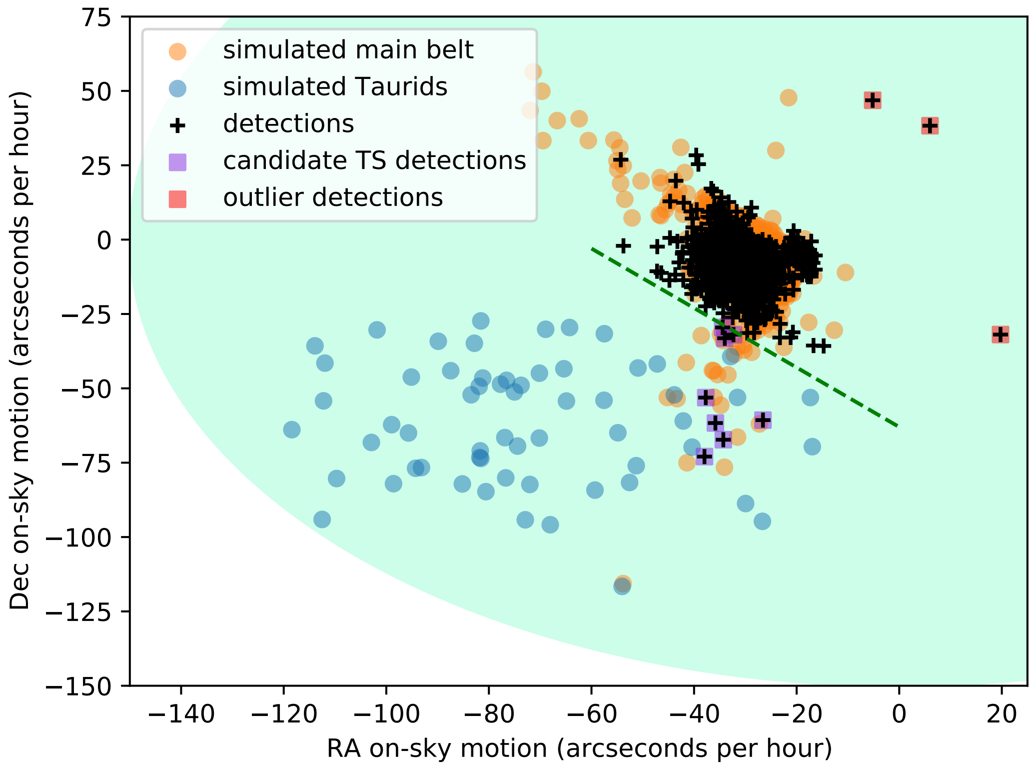

Figure 3. The expected on-sky motion of simulated main-belt asteroids and Taurid stream members within the images taken. The on-sky motions of all detected moving objects are superimposed. The rates of on-sky motion that pass our moving-object detection filter (that is, on-sky rates of motion less than 150″ per hour) are indicated by the green circular area. The moving objects falling below the dashed line are our Taurid candidates (indicated in purple). These eight, which include three near the boundary together with five with larger negative rates of motion in decl., are discussed in Section 3.1.

was able to eliminate seven of them. Their locations and on-sky motion are shown in Figure 4. Details are below.

1. The three candidates near the dashed boundary line in Figure 3 are ALA35F (m_{gri} = 22.3), ALA36W (m_{gri} = 20.6), and ALA3WE (m_{gri} = 21.5). These are asteroids 2017 GV35, (549797) 2011 SH284, and (566030) 2017 KA33, respectively, which are in the main belt.
2. Candidate ALA3D3 (m_{gri} = 22.3) was seen in two triplets of images on a single night (2022 October 29) by our survey. It was subsequently linked with Pan-STARRS1 and Pan-STARRS2 data. Now designated 2022 US$_{160}$, it has a main-belt orbit and is not a Taurid.
3. Candidate ALA3e1 (m_{gri} = 22.6) was seen by our survey only in a single triplet of images on a single night (2022 October 31). It is not a Taurid but rather a Hungaria, now designated 2022 UV$_{123}$, that was first observed by Pan-STARRS2.
4. Candidate ALA3dh (m_{gri} = 21.7) was seen in our survey in a single triplet on 2022 October 31. It is also a Hungaria, now designated 2022 UT$_{123}$ and provisionally discovered by the Catalina Sky Survey (G96).
5. ALA3MC was observed in two image triplets over 2 nights (2022 October 30 and 31) in our survey. With an apparent magnitude of m_{gri} = 23.3, it was not found in a search of Pan-STARRS images. Its Digest2 (S. Keys et al. 2019) scores are 10 and 20 on each night and its nominal orbit indicates a probable Mars crosser or a near-Mars crosser. It is not a Taurid.
6. Candidate ALA3gK was seen in only one triplet on 2022 October 31. A search for it in Pan-STARRS data was unsuccessful, and it was so faint that observations by other stations are unlikely (m_{gri} = 23.9 ± 0.5). Its orbit based on the short observational arc is ambiguous, though its rates of motion (see Figure 3) are consistent with it being a Taurid. Though we conclude it is unlikely to be a TS member, if it was a Taurid, using a typical distance to the TS during the observations and assuming an Encke-like albedo, it would be H = 25.0 and have a nominal diameter of 60 m.

The few outliers in rates of motion on Figure 3 are less common objects but are not Taurids.

1. Candidate ALA3h7 (m_{gri} = 21) was seen in two triplets on 2 nights (2022 October 30 and 31) and is a Mars crosser now designated 2022 WL$_1$.
2. Candidate ALA3Jy (m_{gri} = 24.5) was seen in two triplets on a single night (2022 October 30). Too faint to find in Pan-STARRS archival data, its Digest2 score (S. Keys et al. 2019) of 78 suggests it might be a near-Earth object (NEO). Its rates of motion are not compatible with it being a Taurid.
3. Candidate ALA3To (m_{gri} = 23.1) was seen in three triplets on 3 separate nights (2022 October 29, 30, and 31). It is not a Taurid but rather a Mars crosser now designated 2022 UT$_{160}$.

3.2. Upper Limit on Population of Taurid Resonant Swarm

This survey was deliberately timed to occur when the Earth was passing close to the middle of the Taurid stream. Figure 5 illustrates the relative geometry during the survey. At this

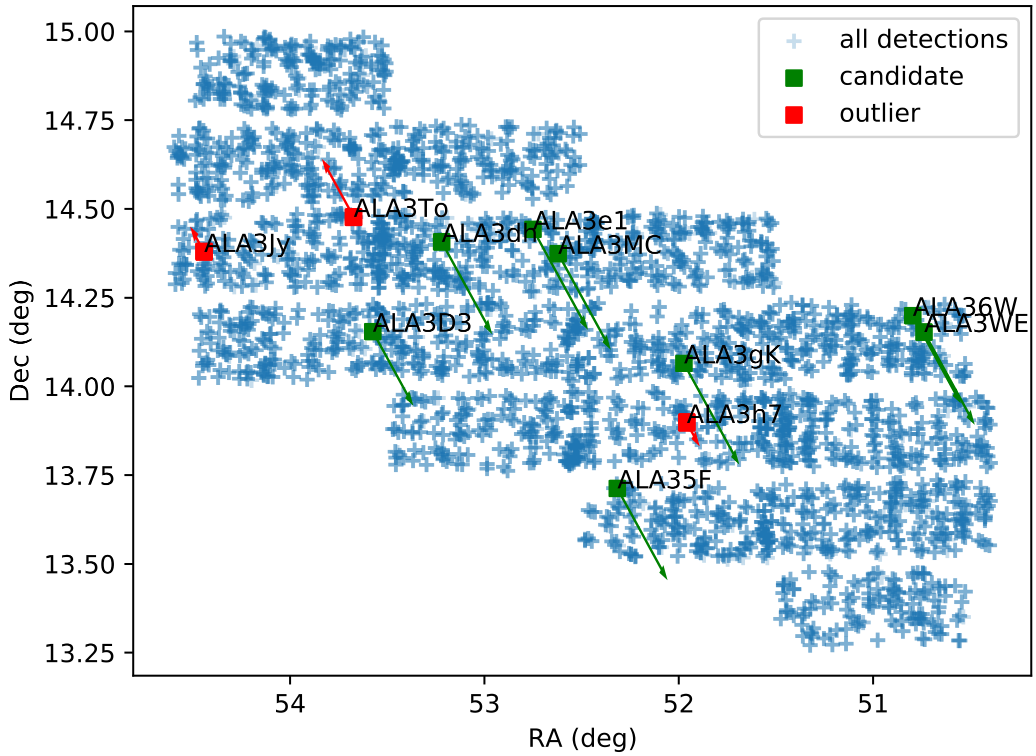

Figure 4. The locations of all object detections on the sky. Our four slightly overlapping CFHT MegaCam fields are aligned along the expected direction of motion of Taurids. The eight candidate TS objects discussed in Section 3.1 are superimposed, as are the three additional outliers in on-sky motion. Arrows are directed along the directions of motion. The gaps between detections correspond to the gaps between the chips of the MegaCam detector.

time, the relatively small area of our survey is compensated for by the relative concentration of Taurids on the sky as seen from the Earth's vantage point. However, we still only sample a small fraction of the TS cloud. But how much? The number of TS members detectable by our survey is a complicated function of their orbital distribution, sizes, and the observing circumstances. Nonetheless, we can set some limits on the population of the TS by considering some simple limiting cases. Here we will examine two hypothetical TS populations, designed to bracket the real one to the extent possible.

The first case (which we will call the "broad" scenario) is where the TS population is assumed to be distributed over the entire orbital phase space that is in 7:2 resonance with Jupiter. This spreads the TS mass over the largest volume. The scenario is modeled via a set of hypothetical TS particles generated in the work of D. L. Clark et al. (2019) without any restriction to the "core" of the swarm. The second case ("narrow" scenario) we will consider is where the TS population is confined in the portion of the 7:2 resonant phase space, which is known to be populated by fireball-producing material. This scenario is modeled via a set of hypothetical TS particles distributed within the range of orbital elements observed during the 2015 outburst, when 144 Taurid fireballs were observed by the European Fireball Network (P. Spurný et al. 2017). The narrow TS is populated only by particles within $\pm 35^\circ$ of the swarm center, representing the predicted extent of the TS (D. Asher & S. Clube 1993; see later in this section for more on the predicted extent of the TS in mean anomaly). By simulating the positions and motions of these two hypothetical TS populations on the dates of observation, we can determine what fraction of the TS would have been observed from CFHT in each case.

In the "broad" case, we find that only 1 in 8000 TS members would have been within our observing volume, while in the "narrow" case, that number increases by an order of magnitude, because our telescopic search area is concentrated on this notional center of the TS. Given that the Poisson 95% confidence range for zero detections is [0, 3.69] (W. Q. Meeker et al. 2017), we can therefore set an upper limit of fewer than 3×10^3–3×10^4 TS members at 50 m diameters, these numbers corresponding to the narrow and broad TS models, respectively. If all the TS mass is at these sizes, then this corresponds to an equivalent progenitor body of only $50\ \mathrm{m} \times (N)^{1/3} = 700$–$1500$ m diameter, far short of the 50–100 km size body proposed in the past (S. V. M. Clube & W. M. Napier 1984).

How much TS mass could be hiding at larger sizes? From recent estimates of the completeness of NEO catalogs by T. Grav et al. (2023), it is thought that the catalog is 88% complete at kilometer sizes and 38% at 140 m. Thus it is unlikely (though not impossible) that a kilometer-class TS member remains undetected, while undetected 100 m class members remain a distinct possibility. If for argument's sake we assume that all the mass in the TS is in 140 m class objects, our nondetection here only requires of the total size of the progenitor body a size of $0.14\ \mathrm{km} \times (N)^{1/3} = 2$–$4.5$ km diameter.

There are other possibilities that could result in our calculations above underestimating the mass of the TS. The first is that the mass could be highly localized within the swarm, and our observations examined a region with little or no mass. However, fireball outbursts have been reported for each of the November TS returns predicted since 1988, namely 1988, 1998, 2005, and 2015 (A. Egal et al. 2022), as well as 2018 and 2022 (P. Spurny & J. Borovicka 2023). During these returns the Earth passed within 5, −13, 11, −7, −48, and 17 degrees of mean anomaly, respectively, from the predicted TS

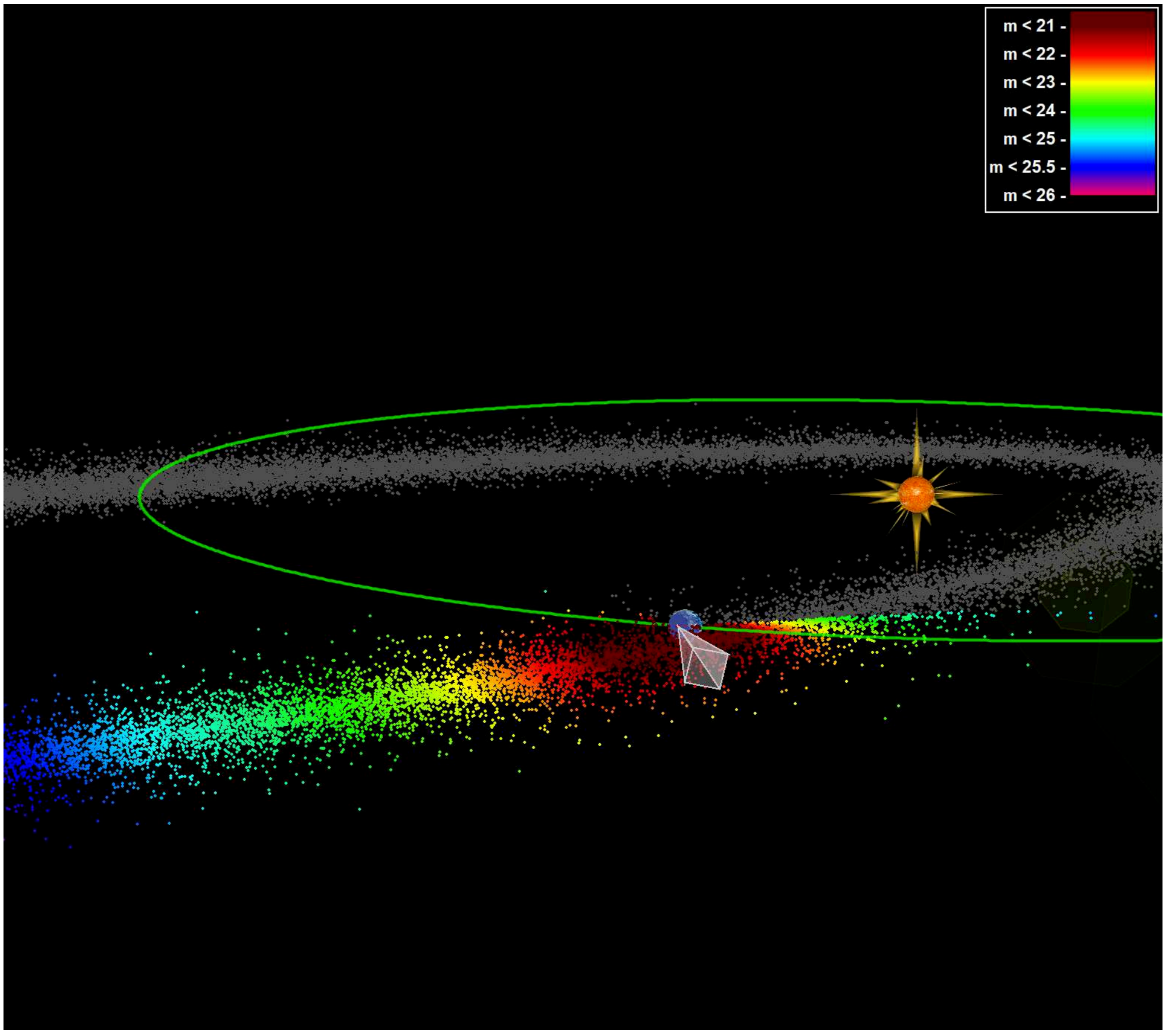

Figure 5. The geometry of the Earth relative to the Taurid stream at one instant during the survey. The white frustum indicates schematically the volume of space sampled by the observations. The color of the Taurid particles indicates their apparent magnitude as seen from Earth.

center. A positive value indicates that the center of the swarm is past the Earth at the time in question and vice versa for negative values.[6] These outburst observations suggest that the fireballs are distributed more or less evenly across at least a 30° stretch of mean anomaly, with 2018 being the only exception, when the mean anomaly offset was as high as −48°. The observations reported here were taken when the Earth was at 17° of mean anomaly from the TS center. During this 2022 apparition over 150 Taurid fireballs—the "vast majority" associated with the 7:2 resonance—were recorded by the European Fireball Network (P. Spurny & J. Borovicka 2023). Thus it seems clear that Earth was within the TS during the time when our observations were collected. However, we were also looking toward the outer edge of the swarm (of necessity, as the TS center was in the daytime sky; see Figure 5), which much reduces the volume of the TS we sampled.

Another possibility is that the TS contained larger objects in the past, and that these have decayed through the loss of volatiles or other processes into smaller ones. Comets are known to split: H. Boenhardt (2004) report that 10 of the 160 short-period comets known at the time had been observed to fragment at some level. The relatively low perihelion distance $q \approx 0.3$ au of the Taurid stream would also promote loss of volatiles, even without macroscopic fragmentation. The observed Jupiter-family comet distribution in general shows fewer members at sizes below ∼1 km than would be expected from a simple power-law extrapolation from larger sizes (C. Snodgrass et al. 2011 and references therein). This could be due to observational biases, but others have argued it is not entirely due to such effects (K. J. Meech et al. 2004). It is possible therefore that the TS contained more mass in the past, though observations do not show a need for much hidden mass at the current time.

Thus we conclude that while fireball observations do confirm the existence of a TS at small sizes (meter-sized and smaller), negative observations at telescopic sizes suggest that there is no need for the breakup of a particularly large parent body, but that the TS total mass is largely constrained to be no more than that of a more or less typical comet.

4. Conclusions

We conducted a deep, narrow survey of the Taurid resonant swarm during its 2022 apparition. No definite members were

[6] https://www.cantab.net/users/davidasher/taurid/swarmyears.html (retrieved 2024 October 13). See D. Asher & S. Clube (1993) for more details.

detected. One possible TS candidate was seen, but its orbit was ambiguous from the observational arc obtained, and a search for follow-up observations reported by Pan-STARRS and other stations was unsuccessful. Our results are consistent with no Taurids detected down to our apparent limiting magnitude of 24.5, which sets our overall upper limit on the population of the TS at fewer than 3×10^3–3×10^4 objects (95% confidence) down to diameters of 47^{+29}_{-13} m assuming an Encke-like albedo. Our results suggest that while fireball observations confirm the TS's existence, the mass in the swarm at 50–100 m sizes is limited to total values below those of a typical comet or asteroid. Though a larger body such as has been proposed in the past could be the parent of the TS, the current mass budget of the swarm does not require an outsize parent to explain it.

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Facilities: CFHT (MegaCam), PS1.

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