

SCHOOL OF PHYSICAL AND CHEMICAL
SCIENCES

ASTR480

Asteroids in TESS

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October 3, 2024

DECLARATION

I certify that content of this report was mostly my own work.

My supervisors helped by proofreading the report and offering feedback. As well as providing useful insight into problems when I was stuck.

Graduate students, X and Y, helped me understand ...

The derivation in section 3 was taken from ...

Figure 1 has been constructed from data from the Light Curve Database (LCDB) Warner et al. (2009), as cited in text. That data has being built suplimented with my own work in the corseponding Figure

Brayden Leicester

ABSTRACT

This is where the abstract goes.

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1 Introduction

This project aims to find and characterise the light curves of all the asteroids seen by the Transiting Exoplanet Survey Satellite (TESS). Combining knowledge of these asteroid's positions with the high cadence imaging of TESS should allow for the determination of rotation periods of these small bodies.

1.1 TESS

TESS is a large area, high cadence imaging, space telescope (Ricker et al., 2014). TESS is tasked with observing one piece of sky for 27 d at a time (a sector), delivering $96^\circ \times 24^\circ$ full frame images (FFIs) at regular intervals. These FFIs are built from stacked 2 s exposures, leveraging the short readout times of the 16 CCD cameras on-board. With the initial cadence for these full frame images set to 30 min, the time resolution of TESS is unparalleled. The highest frequency (shortest period) that can be found from time series data like this is at the Nyquist limit, twice the minimum time between images. Due to the short cadence, the Nyquist frequency of TESS is quite high, 1 h^{-1} . This is well sampled enough to characterise most variable stars, as well as find the orbital periods of exoplanets to a high precision. As the mission was extended, after TESS had already mapped the entire sky, the length of the FFIs has decreased to 10 min and then later to 200 s. This decreased in the FFI exposure time comes with a complementary increase in the Nyquist frequency. This high time resolution and observation area does come at the cost of spatial resolution, as the pixels are each $21''$ square. Of interest here is what such a high sampling rate can do for statistic on the asteroid population. For bright asteroids the rotation periods should be able to be easily determined from this vast dataset. The shortest FFIs will be able to accurately determine the rotation periods of all but the fastest rotating asteroids, most of which will be too dim to see in the TESS data.

There have been attempts to find and classify the asteroids in TESS data before. Pál et al. (2018) proposes that TESS will be a good instrument for solar system object study, and simulate some detections down to 20^{th} visual magnitude, but that good photometry should only be expected to $V \lesssim 19$. The sentiment of using TESS in this way is shared by Wong (2019). The first data release in Pál et al. (2020) catalogues nearly 10,000 asteroid light curves from the first year of TESS operation, and they report that they triple the number of asteroids with accurate rotation periods. McNeill et al. (2023) also analyse TESS cycle 1, and detect almost 38,000 objects. They determine reliable rotation periods for about 3,500 asteroids in this sample and show a lack of reliability for objects with periods less than 3 h. In the overlap from the data from Pál et al. (2020), McNeill et al. find good agreement between the two sets of periods and amplitudes. The Minor Planet Center (MPC) gets regular updates from TESS thanks to the work of Woods et al. (2021) and their LINEAR-TESS program, which creates tracklets of objects over a day, and then stitches these together to form a track of each asteroid through an FFI. Gowanlock et al. (2024) uses TESS photometry as well as observations by the Zwicky Transient Facility (ZTF, Bellm et al., 2018) to get a longer baseline on mutually observed objects while combining ground and space based observations. There were not very many objects in both samples with known periods for comparison, with only 222 objects analysed, however they demonstrate that the technique is effective. Fainter and unknown solar

system objects can be found by shift and stacking (Holman et al., 2019, Payne et al., 2019, Rice and Laughlin, 2020) or taking a fast X-ray transform (Nguyen et al., 2024) of the FFI data.

This work aims to extend these studies to more sectors, hence characterising more asteroids. The aim is to get a volume complete set of asteroid lightcurves and periods, by analysis of the whole sky as seen by TESS using data from more than just the first year of TESS’s operation. I also employ a different data reduction method, reducing the data with the `TESSreduce` package (Ridden-Harper et al., 2021) should increase the accuracy of the photometry due to the improved background subtraction process. Because of the survey properties, TESS provides a self-consistent way to measure the properties of asteroids over the full sky. By using the higher cadence FFIs of later TESS sectors, the $P \leq 3$ h limit on the accurate periods (as found by McNeill et al., 2023) should be lowered. Another beneficial part of this work is that as part of a full sky transient survey using TESS, `TESSELLATE` (Roxburgh and Ridden-Harper, In Prep.). Asteroids can spike the brightness of a pixel for only a few frames while it is passing by. This can confuse pipelines looking for transients such as flare stars and supernova, as they can look very similar, having the brightness change in one pixel for a short time. The goal of finding all the asteroids will allow for the removal of these spikes from the transient pipeline, as well as to understand the asteroid population better. By filtering the asteroid detections out, while also self consistently determining rotation properties of a large sample of the population, more science can be done with the one action.

1.2 Asteroids

Asteroids are a key class of solar system objects. The orbits of asteroids can be well characterised by only a few values. The semi-major axis, a , is the largest distance from the sun that the asteroid achieves on its elliptical orbit. Main belt asteroids have typical a s of 2 AU to 3.3 AU DeMeo et al. (2015). The bounds between the inner, middle and outer main belt at 2.5 AU and 2.82 AU, these separations are due to resonances with Jupiter (the 3:1 and 5:2 mean motion resonances mark the edges of middle main belt) and Saturn (the ν_6 secular resonance cuts off the lowest a edge of the inner belt) carving swathes where asteroids cannot be in stable orbits. The eccentricity, e , of this orbit is the next parameter of interest. $e = 0$ implies a perfectly circular orbit, $0 < e < 1$ are ellipses, $e = 1$ give a parabolic orbit, and $e > 1$ are unbound, hyperbolic orbits. Main belt asteroids have small e , in the range of 0 to 0.35 (DeMeo et al., 2015) Comets have larger e , with some long period comets having $e \approx 1$, but the typical range is 0.2 to 0.7 (Lewis, 2012). Interstellar objects (ISOs) have $e > 1$ as they are on unbound hyperbolic trajectories. The inclination, i , of asteroids is also a key orbital element, it is the angle relative to the ecliptic plane and in principle asteroids can span the whole range. Main belt asteroids have typical inclinations of 0° to 30° (DeMeo et al., 2015), so the TESS cameras closer to the ecliptic plane are expected to have the most asteroids in their fields.

Asteroids can be grouped into families based on clustering of the proper orbital elements and similarities in their colour or spectra (Nesvorný et al., 2015). These families are named for their largest member. Families are thought to all originate from the same body that was destroyed by a collision earlier in the solar system’s history.

Asteroids can have their rotation properties changed with time, collisions can do this,

but so can light from the sun. The YORP effect (named for the discoverers Yarkovsky, O’Keefe, Radzievskii, and Paddack) is the process of torquing asteroids of an asymmetric shape by both bombardment of photons and thermal (re-)emission (Rubincam, 2000).

Understanding the rotation properties of asteroids has long been of interest to astronomers (e.g. Weidenschilling, 1981, Harris, 1994, for early work into the limits of rotation period and the tumbling nature of some small bodies). This is still at the forefront of research, with more lightcurves being published year-on-year (Harris, 2015). This will only increase with more large survey telescopes coming online soon, such as the Legacy Survey of Space and Time (LSST Ivezić et al., 2019), the number of new asteroids that are well characterised will increase by more than 2 orders of magnitude on the Sloan Digital Sky Survey (SDSS York et al., 2000) which had ~ 88000 objects Parker et al. (2008). LSST needs a dedicated pipeline for asteroid classification, the Solar System Notification Alert Processing System (SNAPS Trilling et al., 2023) has been developed using ZTF data and is can scale up handle volume of data coming from LSST. Work is being done to understand the biases of how asymmetric shape high amplitude variations can lead to selection effects of such large sample of asteroids Levine and Jedicke (2023). For the smallest objects ingenious observation techniques are employed to measure rotation periods such as intentionally streaking the asteroid down a column of pixel on a detector, and making the lightcurve from the streak, as done by Bolin et al. (2023).

Because of such a rich history of study, many asteroids have a known rotation period. These are catalogued by Warner et al. (2009) in the Light Curve Database (LCDB). In the October 1st, 2023 release, the LCDB has nearly 9000 objects with periods determined to a quality code $U \geq 2-$, which is the minimum reliability recommended by Warner et al. for statistical analysis. This includes other TESS data from Pál et al. (2020) and Woods et al. (2021). The frequencies against diameter plot of these asteroids in Figure 1 shows the collection of all the asteroids in the LCDB. The spin barrier (Pravec and Harris, 2000) is seen in the red dashed lines as there are very few asteroids larger than 0.15 km rotating faster than $\sim 10 \text{ d}^{-1}$. It is thought that the YORP effect spins up asteroids so fast that they pass above this barrier and then no longer have the internal strength necessary to hold themselves together, implying that all asteroids made to spin faster have torn themselves apart and that they have no tensile strength, i.e they are rubble piles instead of monoliths (Harris, 1996). This idea of the cohesive strength of small bodies is still explored today (e.g. Oszkiewicz et al., 2020, for V-type asteroids). Comparing the periods I find of asteroids that are already in the LCDB is key to making sure my methods are reliable, and that the periods for asteroids for which no data exists can be trusted.

Interstellar Objects

High amplitude variation has come to the forefront of questions about asteroid properties because of the first interstellar object, 1I/‘Oumuamua (see Bannister et al., 2019, for a review). ‘Oumuamua was determined to be spectroscopically red (Fitzsimmons et al., 2017, Meech et al., 2017), and having a photometric colour in the neutral end of the solar system range (Bannister et al., 2017). 1I was classed as asteroid due to lack of a coma, and no noticeable activity. This contrasts the second ISO, 2I/Borisov, which had many cometary characteristics (see Dorofeeva et al., 2023, for a review). ‘Oumuamua was measured to have a rotation period of $8.67 \pm 0.34 \text{ h}$ (Belton et al., 2018) and seemed

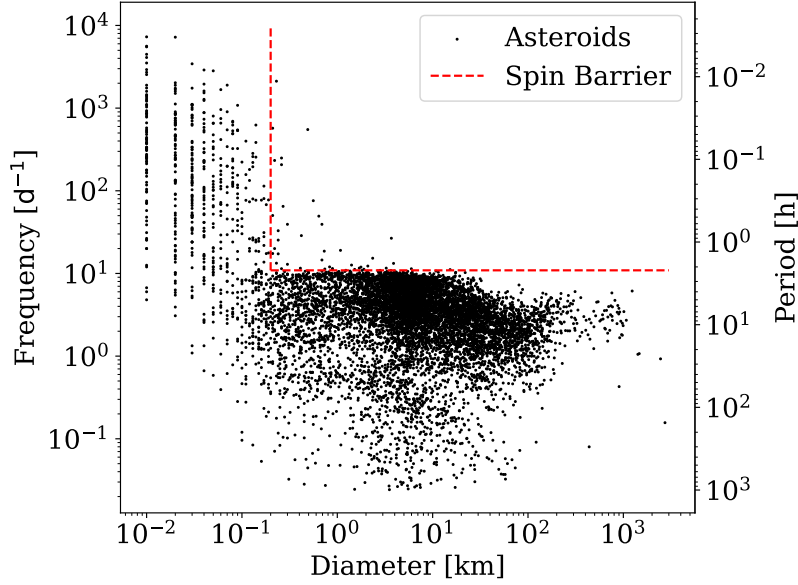


Figure 1: The $U \geq 2$ — rotation frequencies in d^{-1} and the inverse as a period in h againsts the diameter of the body in the October 1st, 2023 LCDB Warner et al. (2009). This is using the diameter of the asteroids from the LCDB H to diameter conversion. The spin barrier of Pravec and Harris (2000) is shown in red dashed lines

to be tumbling (e.g. Drahus et al., 2018, Fraser et al., 2018). Combing the tumbling with an elongation ratio of up to $6 \pm 1:1$ (McNeill et al., 2018), 1I is said to have a cigar shape (Belton et al., 2018). The peak to peak amplitude variation of this ISO was 2.5 mag (Meech et al., 2017) over its double peaked light curve. This is quite interesting, as it varies more than most asteroids. With the full sky survey of bright asteroids, we hope to find many asteroids with such a large amplitude variation, and to see just how rare ‘Oumuamua is.

2 Methods

2.1 Querying Databases

To check for asteroids in the TESS data, the positions of the asteroids with time are required. For most asteroids, their orbital elements are well known, so it is a matter of looking them up and cross-matching with transients in the TESS data. Python was used to make API calls to Skybot (Berthier et al., 2006) to get positions of asteroids in a cone search box in right ascension (RA) and declination (Dec) space. As TESS sectors are 27 d long, querying every 12 h is manageable. These positions are still very sparsely spaced in time compared to the TESS data, so an interpolation is needed to bridge the gap.

Knowing where the asteroids are is helpful for finding them in the archival TESS data, but knowing more about the individual asteroids is also useful for population statistics. The **astroquery** (Ginsburg et al., 2019) package was use to query JPL Horizons was used to obtain the orbital elements of each asteroid, a , e , and i , as well as an absolute magnitude

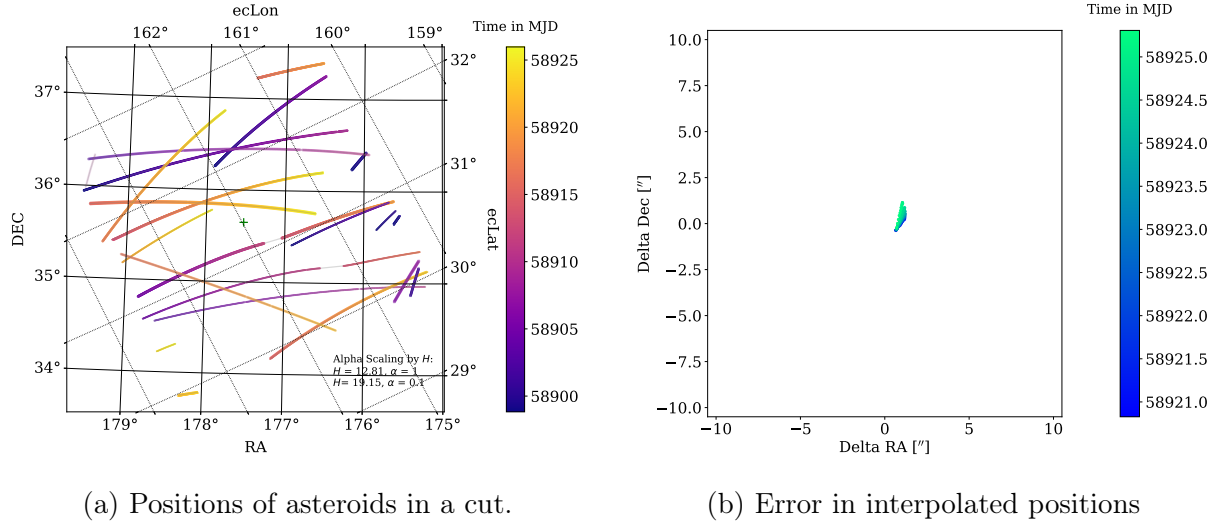


Figure 2: (a) The interpolated positions of asteroids in one cut of a TESS sector. The colours of the lines are time sequenced, as shown in the colour bar. The alpha of the colours are scaled by the absolute magnitude H of the asteroid, queried from JPL Horizons. Both celestial (RA and Dec) and ecliptic (ecLon and ecLat) coordinates axes are shown. The green + is the centre of the cut. This cut was chosen because of how many asteroids there were, enough to see the shape of the box, but not so much that the lines are overwhelming to the eye.

(b) The difference in the interpolated position of an asteroid from bulk queries to JPL Horizons, with interpolated coordinate being subtracted from the coordinate returned by Horizons. The colour bar is a different colour map to (a) as the range of time is shorter. The extent of the box is one TESS pixel, $21''$. This is of asteroid “1989 BC1”, but all others checked are similarly accurate (It is very expensive to check them all by brute force queries of Horizons).

H , which is a good proxy for size (as discussed above).

2.2 Interpolation

With TESS data coming in in $\frac{1}{2}$ h chunks, 24 interpolated points are needed between each API call. These interpolated positions can be seen in Figure 2.a for a cut from TESSELLATE. There are a few interesting features, such as the asteroids are moving in the same direction, indicated by the colouring, they come in from low RA and Dec and tend to increase both coordinates as the month of the sector progresses. There is also a large size range in this slice of sky, ranging over 5 mag in absolute magnitude, which can be seen in the alpha (or transparency) of the tracks in Figure 2.a. Because of a small change in position between each frame, (~ 1 px per frame Pál et al., 2018), this interpolation should be accurate. The Checking against a higher frequency query to the JPL Horizons ephemeris confirmed this accuracy on a few asteroids, as shown in Figure 2.b. This is not a feasible way of getting all the positions, as the queries are per name and time, not per area and time like the cone search in Skybot. They are also rate limited, so while a few asteroids can be checked, filling the gaps between the Skybot half day queries for all the asteroids would take far too long. For the faster TESS FFIs, more interpolated points are needed, but a

smaller the change in position between each point will be. Forcing the interpolations to be at the same time as the TESS frames, which are known thanks to **TESSELLATE** saving them out, simplifies the matching to detections and forced photometry of these points.

2.3 Detection Matching

Matching these interpolated positions to **TESSELLATE** detections is important to lower the unknown transient outputs of this pipeline. Having interpolated their positions, the asteroids have a well sampled set of RA, Dec and time values of where they should be in the TESS data. They should show up in a pixel for a small number of frames, of order ~ 1 . This is the same as a lot of other transient events, a sharp rise in brightness and then disappearing quickly again. The number of frames do change, type Ia supernova will brighten is a matter of a few hours and then dim for days, while stellar flares are of similar profile by a smaller max brightness and a correspondingly shorter decay time. Asteroids are very short spikes, however these detection pipelines are robust. These pipelines have already found the aforementioned supernova, stellar flares and variable stars, by matching to catalogues of those types of objects (Gaia, ZTF etc.). The job of this work is to catch all the asteroids in the set of all the transients that are returned from the pipeline. To do this, catalogue matching is in order.

Using the **KDTree** algorithm (Maneewongvatana and Mount, 1999) as implemented in **SciPy** (Virtanen et al., 2020), the RA and Dec coordinates of the interpolated points and the detections can be compared and matched together. Filtering this **KDTree** output by restricting the time between spatially coincident matches to less than 0.1 d stops any accidental matches in position from non-asteroid detections. A cut is then made by smallest distance, in coordinate space, and any distance must be smaller than 0.01° ($36''$), which is within 2 TESS pixels. Then, if multiple detection match to the same interpolated point, the detection with the smallest distance will be taken. An example of the matches found using this **KDTree** is shown in Figure 3. It is clear that **TESSELLATE** is not detecting every frame that an asteroid is in. Detections in **TESSELLATE** are done on a per pixel basis, and asteroids only cross each pixel for a short number of frames. Not every interpolated point gets a match, due to a variety of reasons, which culminate in there being not an extreme enough of a difference between frames at that pixel location. Instead there are bunches of frequently matched points, and then patches where there are few matches detected at all.

2.4 Lightcurves

There are two sets of points to take light curves from. The matches from the detections, which already have a flux calculated, and the interpolated points themselves, which are more numerous but require forcing the photometry. There were some challenges getting the flux of the interpolated points, even when **TESSELLATE** has already reduced all the FFIs of interest.

Using the **SkyCoord** module of **Astropy**, the world coordinates, in RA and Dec, can be transformed into pixel coordinates, x and y , using a world coordinates system (WCS) from **TESSELLATE**. **Photutils** (Bradley et al., 2024) was then used to do aperture photometry with a 1.5 px radius to account for the spread in the TESS PRF.

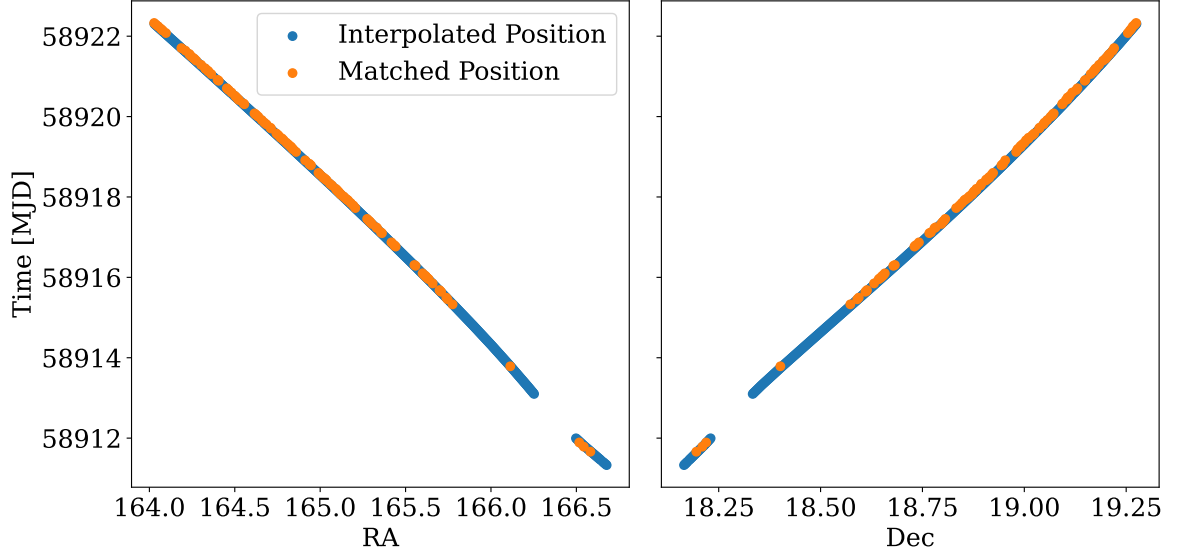


Figure 3: The RA (right plot) and Dec (left plot) of the interpolated points (blue) and the matched TESSELLATE sources(orange) against the time. The gap is from the TESS downtime in the sector, when it was passing close to earth.

The integer coordinates of the asteroids seemed to be leading the object in any given frame of TESS. This was decreasing the total flux of the asteroid, as the box used for summation of the fluxes was hitting mostly sky. This also caused a “sawtooth” effect, where the lightcurve would jump from a minimum to a maximum when the integer coordinate snapped from being a pixel out to back on the asteroid. This both of these issues can be fixed by calculation of the centre of mass (COM) flux, the average brightness in xy space on a 5×5 cut of the image centred on the interpolated position. I didn’t take the highest pixel value in this box because there could be a rouge star in the field that it snaps to, instead of the asteroid. A `Photutils` aperture photometry call to this COM with a radius of 1.5 px was enough to get fluxes of the same order, but with a far more smooth transition from maximum to minimum, as expected from rotating asteroids.

Following McNeill et al. (2023), any fluxes more than 3σ from the mean value are sigma-clipped from the forced photometry lightcurves. This does introduce gaps into an otherwise regularly sampled lightcurve, but the contamination from background stars the object is passing in front of is too great.

A comparison between the three light curves is interesting, as one might expect only the brightest parts of the lightcurve will be matched. Figure 4 shows these three light curves for a single body. The COM flux seems much more stable than the interpolated flux on its own, and at a higher average flux count. This should result in more accurate periodograms as there is less overall curve to the data. The matched points are comparatively sparse for this object, which is not the case for all. Many have no matches, and some have almost fully matched, this will be discussed more later.

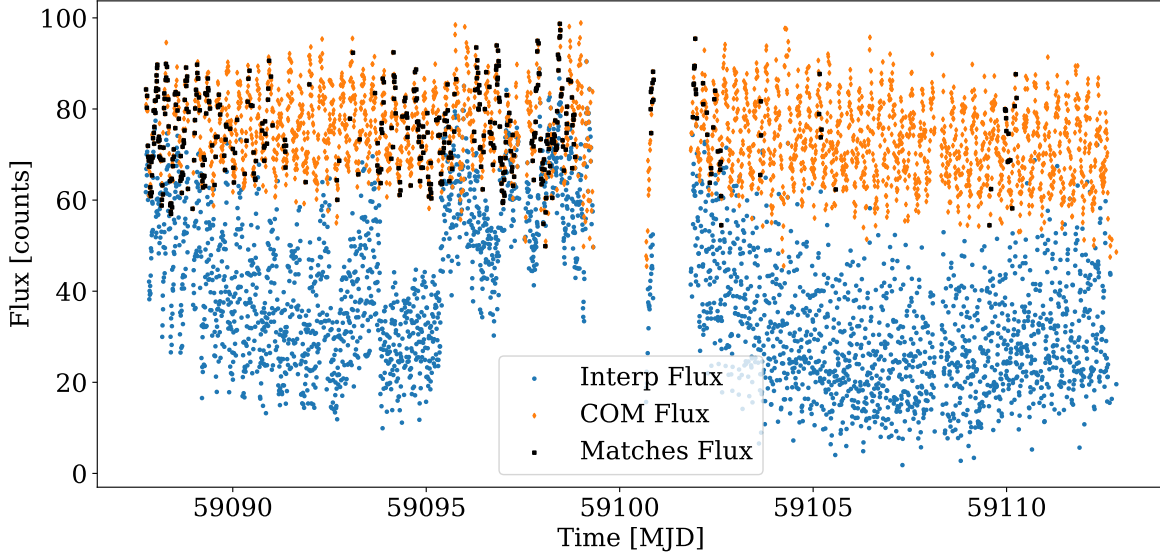


Figure 4: The light curves of the asteroid 1991 VT throughout its entrie journey across sector 29, with the flux of the interpolated positions in blue circles and the flux from the COM in orange diamonds, and the `TESSellate` flux for any matched points in the black squares. The Flux axis is measured in counts, as calculated by `TESSreduce`, and the times are in modified Julian date (MJD).

2.5 Period detection

The next part of my analysis has to do with determining the periods and amplitudes of each asteroid’s light curve.

A widely used technique in determining the periods of astronomical data is the Lomb-Scargle periodogram (Lomb et al. (1976), Scargle et al. (1982), but see VanderPlas, 2018, for a review). This method can efficiently take discrete timeseries data of which the observations are unevenly spaced and calculate the frequencies present in the sample. TESS should have rather evenly spaced data, as the FFIs are produced on a set cadence, but sometimes data will be missing. For example, it may have been sigma clipped due to a spike in brightness that is unphysical for an asteroid, or TESS sees the same asteroid in the same sector on either side of the day long mid-sector break it takes for data transfer. The Lomb-Scargle periodogram deals with this uneven sampling much better than either a fast Fourier transform or a direct least squares fit.

There are a few different implementations of a Lomb-Scargle periodogram available in world of astronomy python packages. I first tried using the `Lightkurve` (Lightkurve Collaboration et al., 2018) package built for period analysis of TESS (and Kepler) data of variable stars. `Lightkurve` was easy to use but didn’t allow for fine-tuning of the periodogram, or give any model of the curve it produced. The next option was peeling back a layer of abstraction and using the Lomb-Scargle periodogram as implemented by `Astropy` (Astropy Collaboration et al. (2022) but see VanderPlas et al., 2012, VanderPlas and Ivezić, 2015, for the implementation). There were interesting similarities and differences between the packages. `Lightkurve` is based on the `Astropy` methods, but does not give all the functionality, instead opting to simplify the process. `Astropy` gives a statistic

on how confident it is in the detected frequency is, the false alarm probability. It also returns a model, in the form of

$$F(t; f, \vec{\theta}) = \theta_0 + \theta_1 \cdot \sin 2\pi ft + \theta_2 \cdot \cos 2\pi ft \quad (1)$$

where the flux, F , is given in terms of time, t , the calculated frequency, f , and the model parameter $\vec{\theta} = [\theta_0, \theta_1, \theta_2]$. These parameters are useful in reconstructing the sinusoid without rerunning the periodogram. The method used for the periodogram fits is the new **nifty-ls** package (Garrison et al., 2024) that has can be implemented on its own, or by interfacing with **Astropy**. I use the later implementation as the speed up from the nonuniform fast Fourier transform is helpful on the large dataset from **TESSELLATE**, but the **astropy** interface is how I had everything set up to run on just one cut.

I am using a frequency window of for the periodogram between the the inverse of twice the time the asteroid spends in the sector and the Nyquist frequency ($1/\text{TESS cadance}$).

There will be differences in the period between the matched points and the interpolated points, not just because of the difference in average flux, but also from the larger number of points. This difference needs to be carefully thought through to understand what is the more likely period.

2.6 Asteroid Statistics

The **TESSELLATE** pipeline has been running on the OzSTAR supercomputing facilities. After I was confident that all the parts of the asteroid detection and subsequent light curve analysis worked as required on one cut of one camera of one ccd of one TESS sector, the same code was be refactored slightly to work on OzSTAR and a large-scale analysis of all the processed TESS sectors can be run.

I will be looking for completeness of detections of asteroids, as well as accuracy of periods and amplitude variation by comparison to the LCDB.

The completeness of the asteroid population in TESS as a function of their apparent magnitude can be determined. The apparent magnitude is one of the properties returned from the queries, and is in the V band. By taking a limit on the if an asteroid is detected ... Breaking the average V mag of these objects into 0.5 mag bins for both the sample returned from a query and the sample detected, a ratio of completeness can be calculated per bin. (Note: If there are no asteroids in a bin, none have a chance of being recovered, so the all did get recovered. I.e. $\frac{0}{0} = 1$, this is only an issue at the brightest magnitude where the fewest asteroids exist.)

3 Results

This is the results for TESS sector 29. This sector was chosen because it is early in the 10 min cadence of TESS FFIs, and had been fully run through **TESSELLATE**. Similar results can be found in any of the sectors, the computation time was a limiting factor in getting more sectors processed.

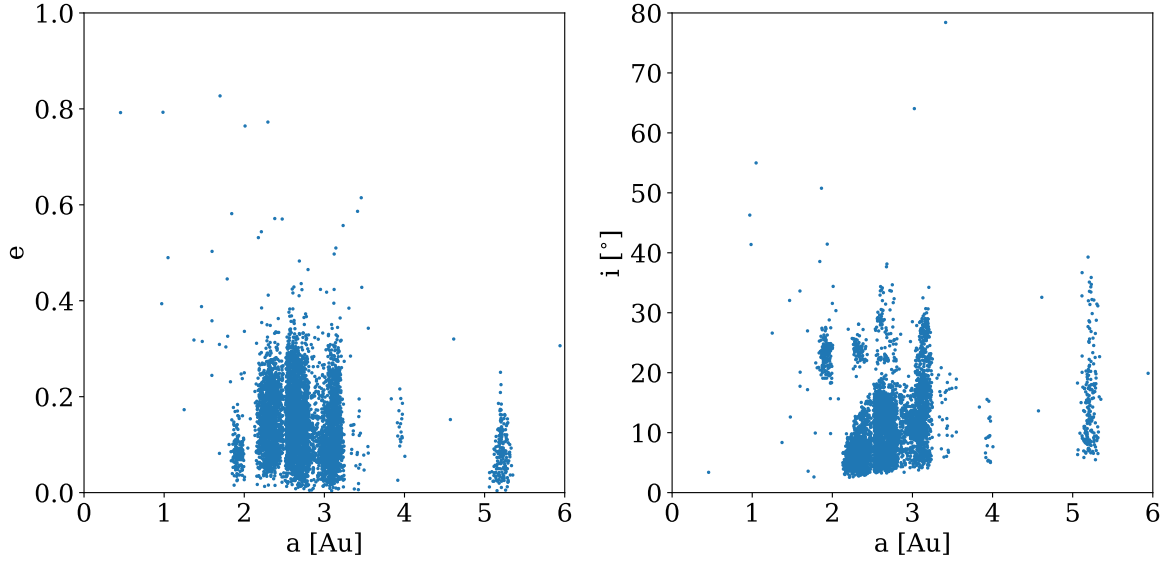


Figure 5: The a against both e and i of all the objects that SkyBot found in Sector 29 with $V < 20$ mag. (Other than the comets and centaurs with poorly defined a values)
The values of these proper elements were queried from JPL Horizons on 30/09/24.

3.1 Asteroid Properties

The orbital element properties of the asteroids were returned by JPL Horizons queries. A plot of the semi-major axis against the other orbital elements, eccentricity and inclination, is shown in Figure 5. The distinction between the resonances in the main belt are clearly seen. There are lines separating the middle belt from the inner and outer belt. The Jupiter Trojans are well-defined, at just past 5 AU, with a small range of eccentricity but a large spread in the inclination. In between the outer belt and the Jupiter Trojans, sit some Mars crossers. A some near earth objects (NEOs) at smaller a and a few more objects that are scattered with high e and or i complete the distribution. These are all objects in the field of the instrument during the sector. Many of them will not be detected, as they will not be bright enough, this is seen below.

The number of asteroids belong to each class of objects is highlighted in Figure 6. As expected from the orbital elements in Figure 5, the majority of the minor planets fall in the three regions of the main belt. ...

3.2 Detectability

3.3 Period Analysis Results

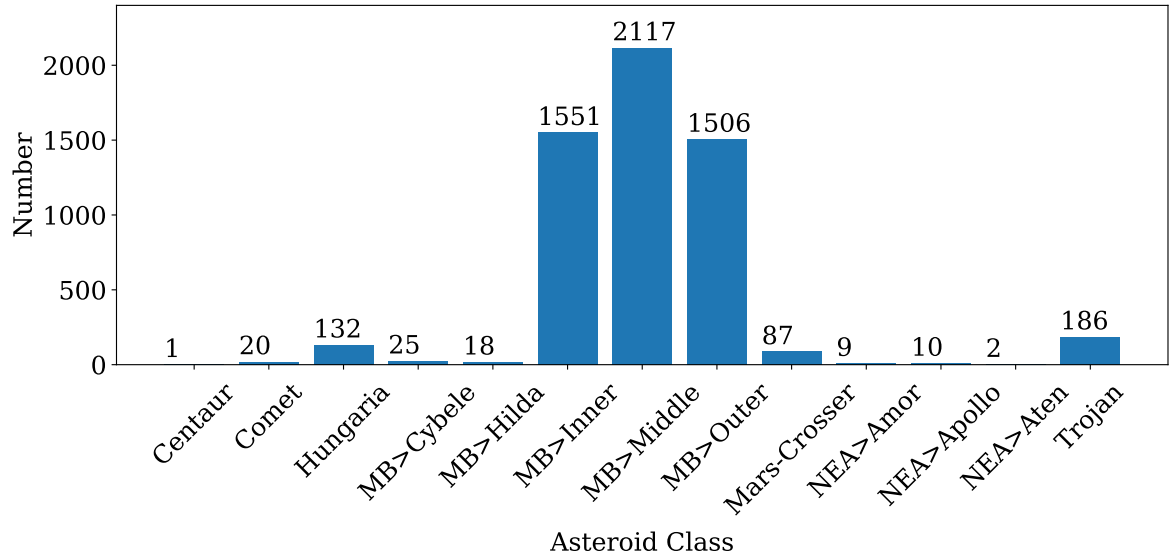


Figure 6: A distribution of the number of asteroids per class that SkyBot found in the Sector. As with Figure 5, this is for all objects brighter than 20th mag. For the class labels, MB is “main belt” and “NEA” is near earth asteroid.

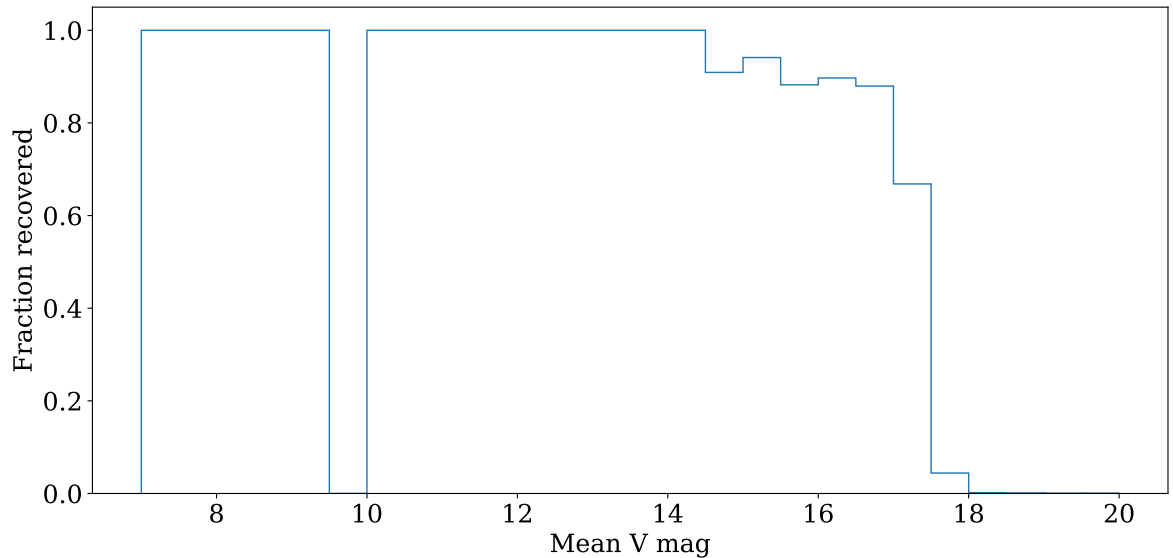


Figure 7: A histogram of known average visual magnitude of each object against the whether the object has a lightcurve with an average flux value above 10 counts for its COM flux.

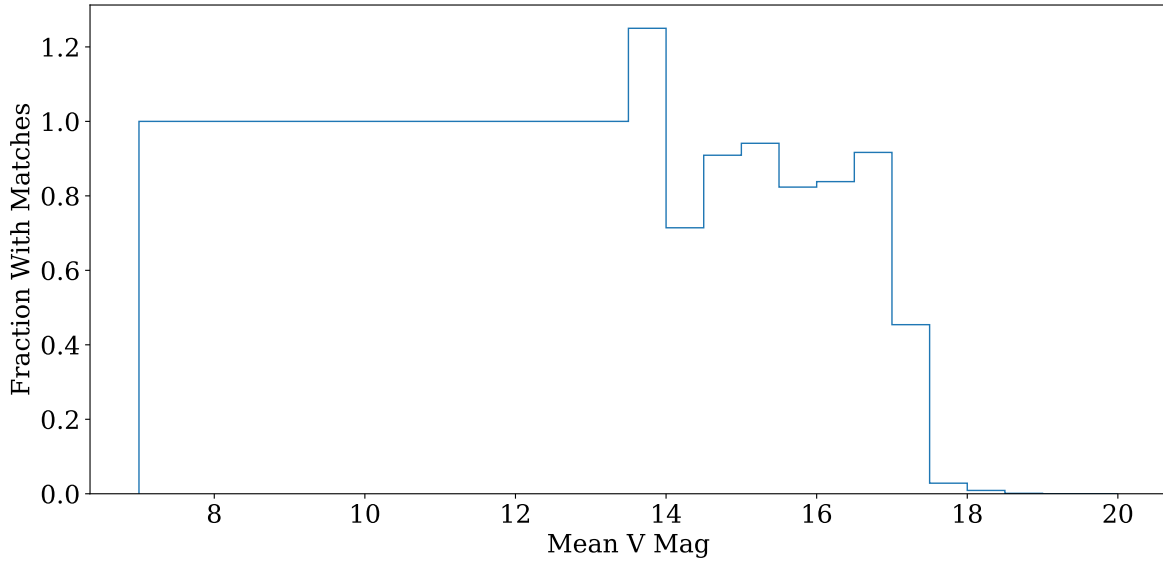


Figure 8: The visual magnitude of the asteroid against the fraction of asteroids in this bin with more than 3 matches.

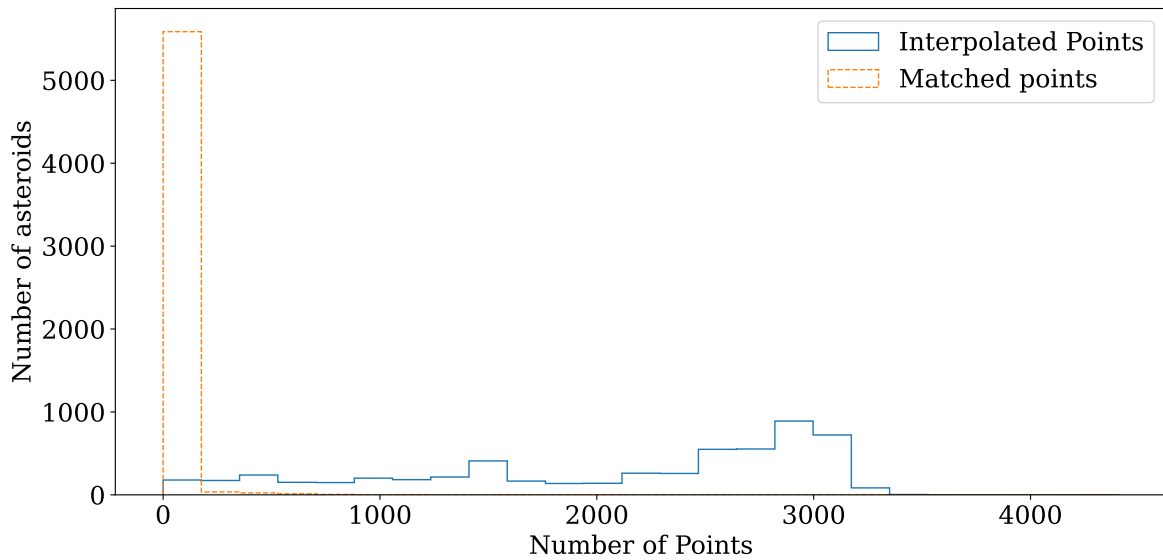


Figure 9: A histogram of the number of observations in the lightcurve of each asteroid (blue) against the number of matches each asteroid gets in the TESSELLATE detections(orange dashed).

4 Discussion

5 Conclusion

Acknowledgements

This work was performed on the OzSTAR national facility at Swinburne University of Technology. The OzSTAR program receives funding in part from the Astronomy National Collaborative Research Infrastructure Strategy (NCRIS) allocation provided by the Australian Government, and from the Victorian Higher Education State Investment Fund (VHESIF) provided by the Victorian Government.

This research has made use of data and/or services provided by the International Astronomical Union’s Minor Planet Center.

This work has used data and/or services provided by NASA’s Solar System Dynamics website, <https://ssd.jpl.nasa.gov/>. Specifically JPL Horizons: <https://ssd.jpl.nasa.gov/horizons/>.

This research made use of Photutils, an Astropy package for detection and photometry of astronomical sources (Bradley et al., 2024).

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