

SCHOOL OF PHYSICAL AND CHEMICAL
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ASTR480

Asteroids in TESS

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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 corrseponding Figure

Brayden Leicester

ABSTRACT

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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 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

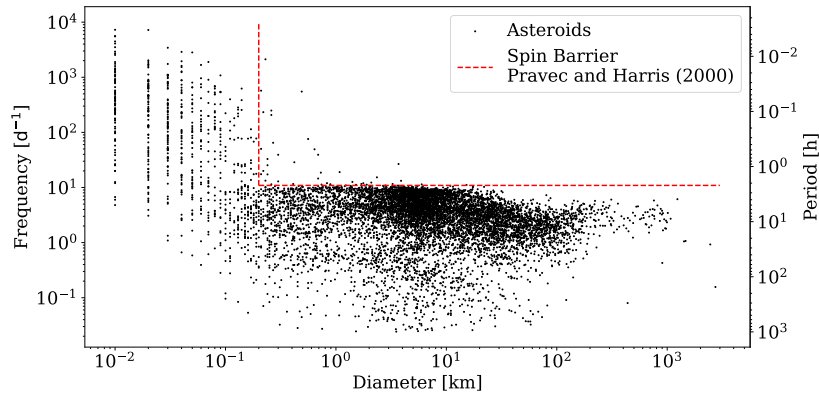


Figure 1: Rotation rate of asteroids by their size, recreated from the October 1st, 2023 LCDB after Warner et al. (2009).

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 diameter presented in the LCDB here calculated from the absolute magnitude H of the bodies, assuming an albedo. Warner et al. acknowledge that there are direct measurements of diameter for more asteroids in the present day, but continue to present the H derived diameters for consistency. 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 ± 0.34 h (Belton et al., 2018) and seemed to be tumbling (e.g. Drahus et al., 2018, Fraser et al., 2018). Combining 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.

1.2 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 2s 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.

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. The search was limited to only asteroids with an average visual magnitude $V \geq 20$ mag. As TESS sectors are 27d long, so querying every 12h is both computationally feasible and allows for a good understanding of a bodies motion. 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 used to query JPL Horizons was used to obtain the orbital elements of each asteroid, a , e , and i , as well as an absolute magnitude H , which is a good proxy for size (as discussed above).

2.2 Interpolation

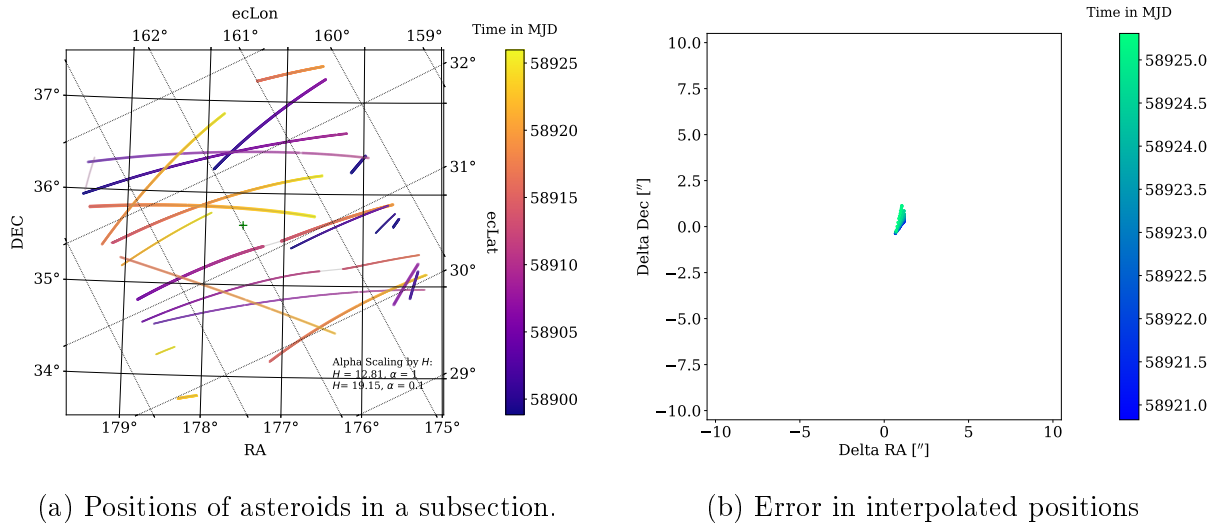


Figure 2: (a) The interpolated positions of asteroids in one subsection of a TESS sector. The colours of the lines are time sequenced, as shown in the colour bar. The alpha of the colours are scaled by the absolute magnitude H of the asteroid, queried from JPL Horizons. Both celestial (RA and Dec) and ecliptic (ecLon and ecLat) coordinates axes are shown. The green + is the centre of the subsection. This subsection 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).

With TESS data coming 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 subsection of sector 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.

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.

The integer coordinates of the asteroids seemed to be leading the object in any given

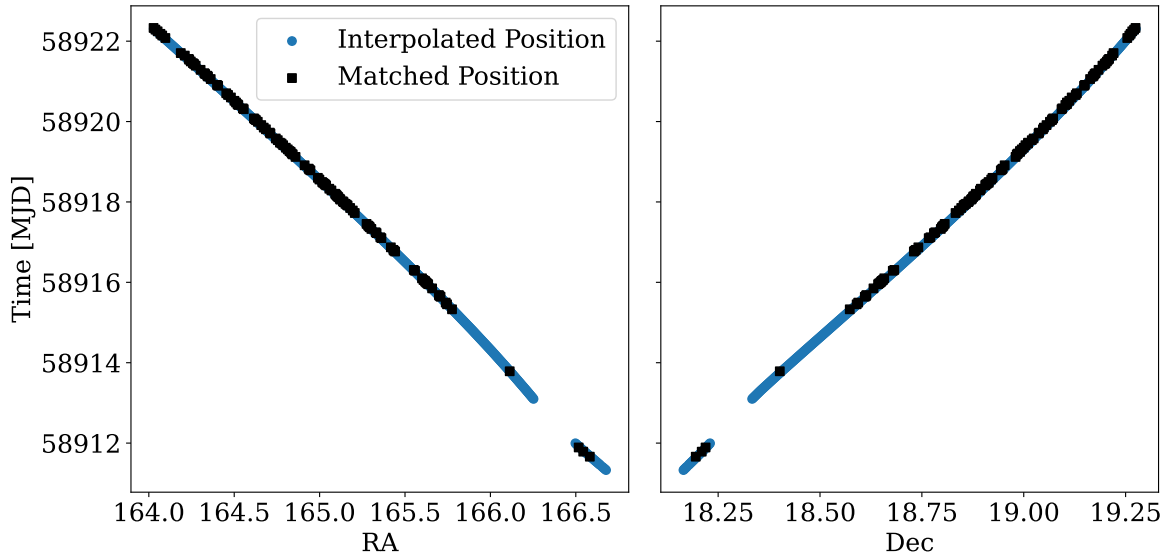


Figure 3: The RA (right plot) and Dec (left plot) against the time of observation of the interpolated points (blue dots) or the matches to **TESSELLATE** detections (black squares).

The gap at low times is from the TESS downtime in the sector, when it was passing close to earth.

frame of TESS. This was decreasing the total flux of the asteroid, as the box used for aperture was hitting mostly background. 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. Both of these issues can be fixed by calculation of the centre of mass (COM), the average brightness in xy space on a 5×5 px box of the image centred on the interpolated position. I did not 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 centred on the COM with the same radius of 1.5 px sorted some of the discrepancies in the lightcurve, with a far smoother transition from maximum to minimum, as expected from rotating asteroids. Hereafter, unless otherwise specified, “flux” refers to this COM flux measurement of the asteroid.

A few steps need to be taken to clean these COM lightcurves. 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 moves through of is too great. The subsections made by **TESSELLATE** have a small overlap. If an object moves between these, there will be a few frames where it is found in multiple of these subsections. This makes the lightcurve have two simultaneous observations of the asteroid, which clearly is not possible. At the very edge of the subsections, the asteroid can have a COM position that would have the aperture be summing over pixels that are outside the field, and thus the asteroid would have a lower flux value on the edge. The overlap is great enough that the decrease in flux should only be happening on one of the edges at a time. So, sorting by flux on a per asteroid basis, then removing the duplicate observation times, keeping only those with the highest flux, will clean the lightcurve.

A comparison between the three light curves is interesting, as one might expect only

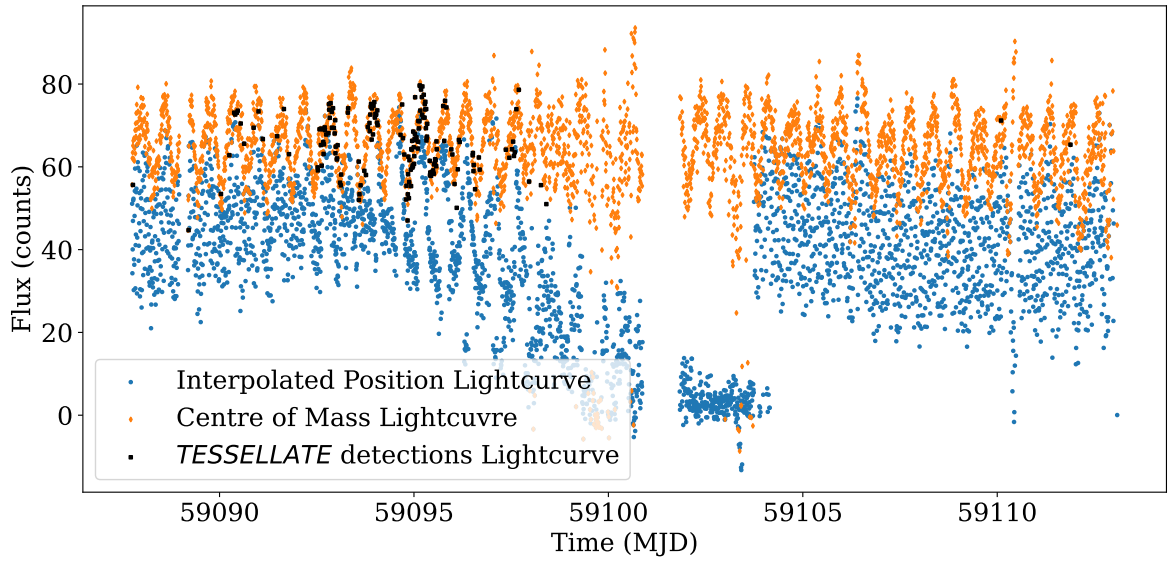


Figure 4: The light curves of the asteroid (5254) Ulysses throughout its entire journey across sector 29, with the flux of the interpolated positions in blue circles and the flux from the COM in orange diamonds, and the *TESSELLATE* flux for any matched points in the black squares. The Flux axis is measured in counts, as calculated by *TESSreduce*, and the times are in modified Julian date (MJD).

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 positions 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. Lightcurves with an average flux < 10 counts are lost in the random noise floor, so a minimum mean flux limit needs to be applied to ensure quality and reliability of any periods calculated.

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 (1976), Scargle (1982), but see VanderPlas, 2018, for a review). This method can efficiently take discrete time-series 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 periodogram reduces to both a fast Fourier transform or a direct least squares fit in appropriate limits, but outperforms them markedly in unevenly sampled data.

There are a few different implementations of a Lomb-Scargle periodogram available in world of astronomy python packages. I first tried using the **Lightcurve** (Lightcurve Collaboration et al., 2018) package built for period analysis of TESS (and Kepler) data of variable stars. **Lightcurve** was easy to use but did not 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. **Lightcurve** 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 non-uniform 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 the subsection I was trialling my code on.

The minimum period returned by the periodograms will be set by the Nyquist limit of the data. For the 10 min FFIs (the cadence analysed here), the Nyquist period is 20 min = $\frac{1}{3}$ h, a threefold increase in time sensitivity for fast rotating asteroids. Based on their experimentation with the 30 min cadence FFIs, McNeill et al. (2023) use a 17 d maximum period for their periodogram analysis. While a lack of signal in the rotation curve causes the calculated period to find this low frequency limit, such cases can be filtered out by keeping only periods less than 90% of this maximum. They recommended that periods less than 3h be interpreted with caution, due to lack of reliability in recovering injected sources. Because of the increase in FFI rate, this time will be dropped to 1h for the minimum reliable period, as the lightcurve sampling on these timescales is equivalent.

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. The matches are often having fewer observations and are much sparser in time that the forced photometry measurements (see the black squares in Figure 4), so would give worse periodograms. While the rotation period and other properties of the lightcurve will be calculated from the forced photometry on the COM positions, the matching is still beneficial to the **TESSELLATE** pipeline as a whole. Taking previously unidentified detections and assigning them to an asteroid category, the remaining unknown transients can be more efficiently searched for other interesting astrophysical phenomena.

An example of such a periodogram and the corresponding fit to the lightcurve is given in Figure 5. The periodogram calculated that this object had a frequency double that listed in the LCDB, as seen with the vertical dotted lines. This is expected due to the double peaked nature of most asteroid lightcurves (McNeill et al., 2023). The stared peak

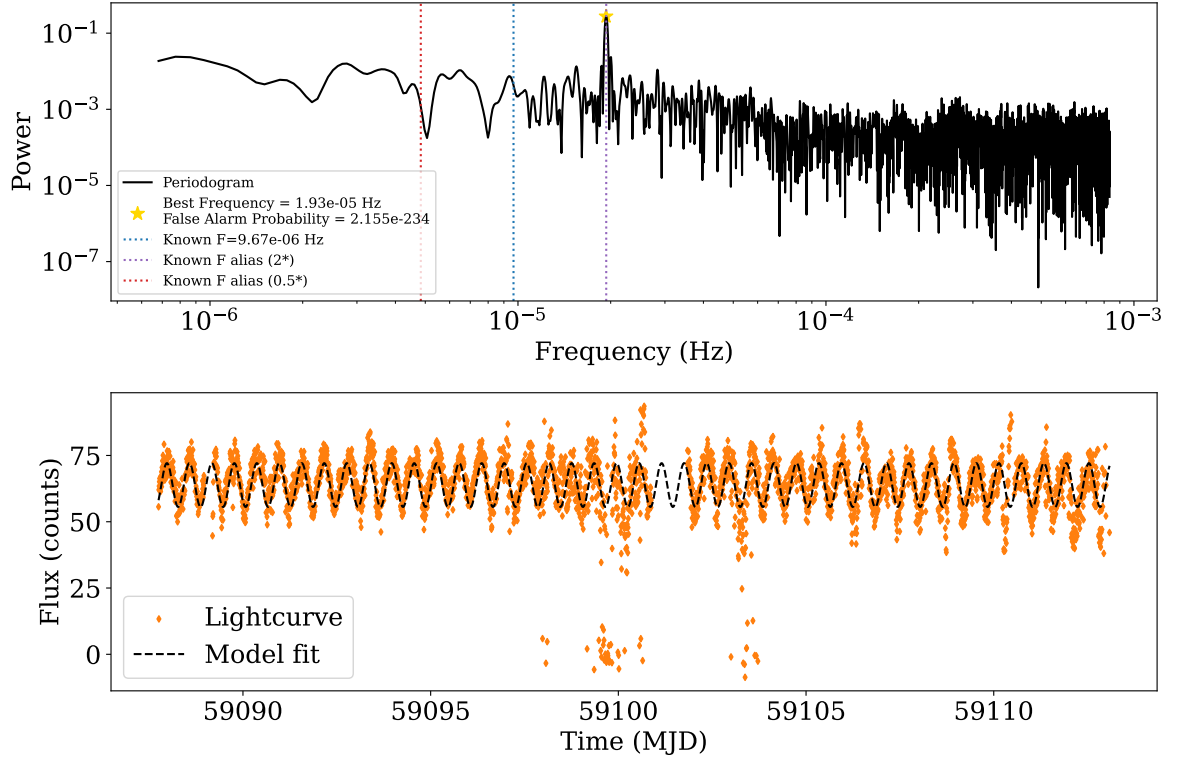


Figure 5: *Upper Panel:* The Periodogram of the COM flux of an asteroid, with the power of each frequency displayed, both axes are in log scale. The maximum power of the periodogram is highlighted with the gold star. This maximum is the calculated rotation frequency. The known frequency, from the LCDB (Warner et al., 2009), is shown in the blue dotted lines, and a factor of 2 alias each way is shown in the purple dotted lines (2*) and red dotted lines (0.5*). *Lower Panel:* The COM flux lightcurve and the returned model (dashed black curve) of the lightcurve from the periodogram analysis. The frequency of this model is the same as the gold starred point in the upper panel.

is by far the most prominent peak in the periodogram, as it is in log scale. Not all the asteroids have such well-defined maximums, and the peak power of the periodogram is an important factor in its quality. A peak power less than 0.1 means there is little to no signal observed and it will be almost indistinguishable from the noise. The lower panel of Figure 5 shows the model given in Equation 1 fit to the COM flux lightcurve by *Astropy*. This looks to be a good fit, with the peaks and troughs lining up. The amplitude of the sinusoid appears to be slightly lower than the variation of the data, but it is consistent with the scatter. This model is successfully fit over a break in the lightcurve, and ignores the observations with a lower flux that did not quite get sigma clipped. This asteroid was chosen as an alias of the known frequency is recovered by this analysis, which is promising for those asteroids where no known frequency exists. The double alias is expected here due to the double peaked nature of the lightcurve (McNeill et al., 2023).

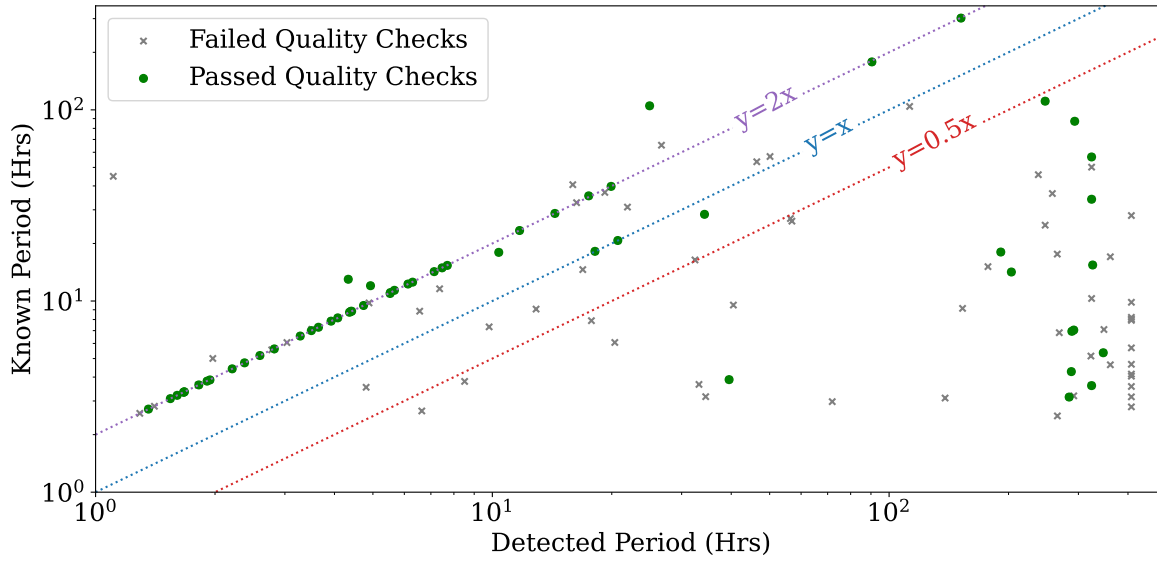


Figure 6: A comparison of the calculated periods of the objects in the Sector to their known periods in the LCDB. Dotted lines of a constant relationship are plotted, coloured the same as Figure 5. Both axes are in log scale.

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 subsection of one camera of one CCD of one TESS sector, the same code was 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.

For accurate statistics, accurate data is needed. So there must be checks on the quality of the values calculated. These have mostly been discussed already, but for completeness I list them here. A lightcurve must have a mean flux of at least 10 counts to be reliable. For an accurate periodogram, it is required that the lightcurve also contain more than 200 observations, which is very easy for TESS and its 10 min cadence. The periodogram itself must have a peak power of at least 0.1, and the calculated period must be $1 \text{ h} \leq P \leq 367.2 \text{ h}$, where the upper bound is 90 % of the 17 d window suggested by McNeill et al. (2023). While some of the checks were chosen to agree with the past work of others, some were chosen to make sure the derived periods were in agreement with the known ones from the LCDB. A comparison between objects in both the sector and the LCDB is seen in Figure 6. The $y = 2x$ line is of interest here, the known periods being twice the detected period. This line corresponds to the calculated frequency being at the double alias of the known frequency, as frequency and period are inverses of each other. As seen in Figure 5 and expected from McNeill et al. (2023), this line is what the periodogram should return. Most of the asteroids the pass the cut line along or near this key relation. Few asteroids on the line fail the checks, which is also reassuring that the checks do what they are supposed to and filter out incorrect periods. The vertical line of grey points on the right-hand side of Figure 6 is on that maximum of the window of searched periods at 408 h, and

demonstrates why the 90% upper bound is necessary. Many asteroids, across an order of magnitude of known periods, have detected periods at the edge of the window which shows that the periodogram will return this value when no signal is present. There are about a dozen asteroids that pass the checks with large detected periods when compared to their known period. These green points in the lower right of Figure 6 speak to the checks not being perfect. Some experimentation was done on the limiting values, and the ones presented here achieved the highest recovery of asteroid periods, while minimising the number that were incorrectly recovered. The idea of doubling the detected period of all the asteroids and calling that number the rotation period has had some doubt cast on it, as there are a couple of points recovered nicely on the $y = x$ line, indicating that the true period is found. Either the LCDB has not accounted for the alias, which is unlikely as I only took the periods with high quality codes as they suggest (Warner et al., 2009), or the rotation signal sometimes returns the true period. The latter implies the lightcurve is not double peaked, as is normally expected.

3 Results

This is the results for TESS sector 29. This sector was chosen because it is early in the 10min 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.

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 7. Looking at the data as a whole, all objects in the field of the instrument during the sector, with $V \leq 20$ mag, are plotted. The exception being comets and centaurs, which have an a (really q , the perihelion distance) too large to see the detail of the majority of the objects. The distinction between the resonances in the main belt can be seen. There are vertical strips 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. A some Mars crossers and near earth asteroids (NEAs) at progressively smaller a and a few more objects that are scattered with high e and/or i complete the distribution. Many objects have failed the quality checks on their lightcurve and periodogram, but the ones that pass have a similar distribution in orbital parameters to the sample as a whole. In total, 309 objects passed all the quality checks, out of a total sample of 5664 small bodies in the sector.

The number of asteroids belonging to each class of objects is highlighted in Figure 8. As expected from the orbital elements in Figure 7, the majority of the minor planets fall in the three regions of the main belt. There are some objects that are not asteroids, 20 comets were in the field and 1 centaur. While they have a V mag less than 20, these objects are often not bright enough to have lightcurves with high enough mean fluxes to be detected well by TESS, as seen by the green bars. Around 5% of any class have lightcurves and periodograms that pass the quality checks. The highest fraction is the $\frac{2}{9}$

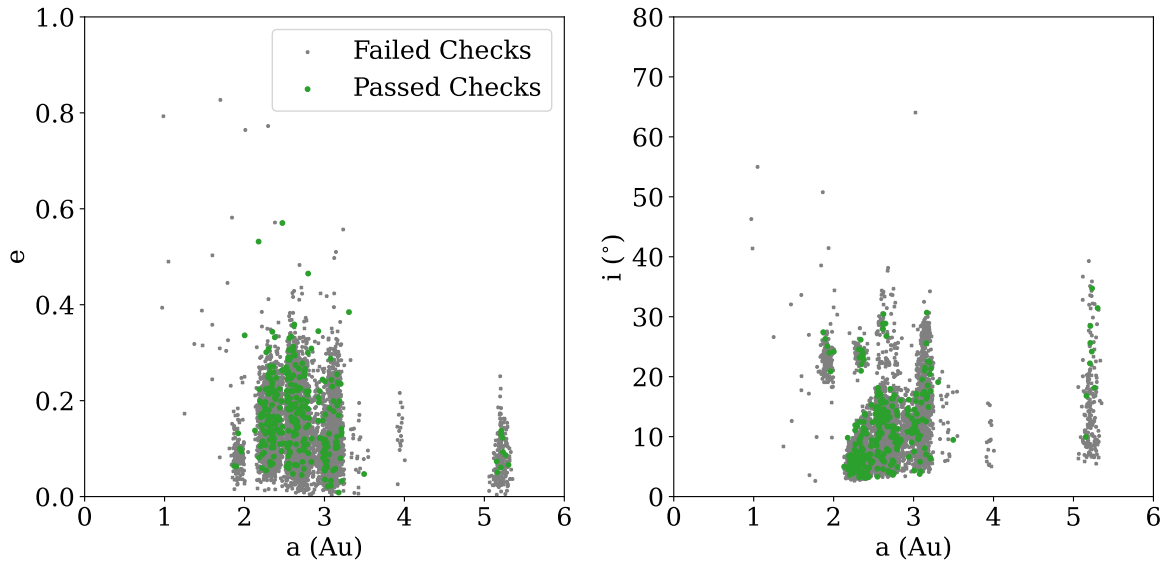


Figure 7: The a against both e and i of all the objects that SkyBot found in Sector 29 with $V < 20$ mag (Other than the comets and centaurs with poorly defined a values). The grey crosses are those objects that did not pass the quality checks on the lightcurve and periodogram, while the green is those that did. The values of these proper elements were queried from JPL Horizons on 30/09/24.

of the Amor family of NEAs, however with only 9 total objects the sample is too small to be representative of the detectability of this class as a whole.

3.2 Detectability

The number of forced photometry observations in a lightcurve is more evenly distributed than the number of matches, as shown in Figure 9. The quality cut of 200 observations in a lightcurve only cuts out ~ 200 asteroids. Most asteroids are well sampled, with the mode of the distribution in the 2900 to 3000 observation bin, which means the asteroids are in a large fraction of the about 3500 frames in a sector.

The matches have a very different distribution to the observations. While both plots are limited to 600 asteroids on the y-axis, the matches histogram far exceeds this in the first bin, ≤ 100 matches, as indicated by the text and arrow. Yet the y-limit is too large for detail to be seen in any higher bin. There are only 102 asteroids matched more than 100 times in the TESSELLATE detections.

The fits of to the fraction recovered in Figure 10 take the form

$$y = 0.5 - \frac{1}{\pi} \arctan(\alpha \cdot (m - m_{1/2})) \quad (2)$$

where y is the recovered fraction, α is how the steep the transition from 1 down to 0 is, m the magnitude and $m_{1/2}$ is the shift along the magnitude axis. The constant of 0.5 in Equation 2 raises the point of inflection to be at $\frac{1}{2}$, and the $\frac{-1}{\pi}$ makes the function take the expected maximum at bright magnitudes at 100% recovered, down to no dim asteroids

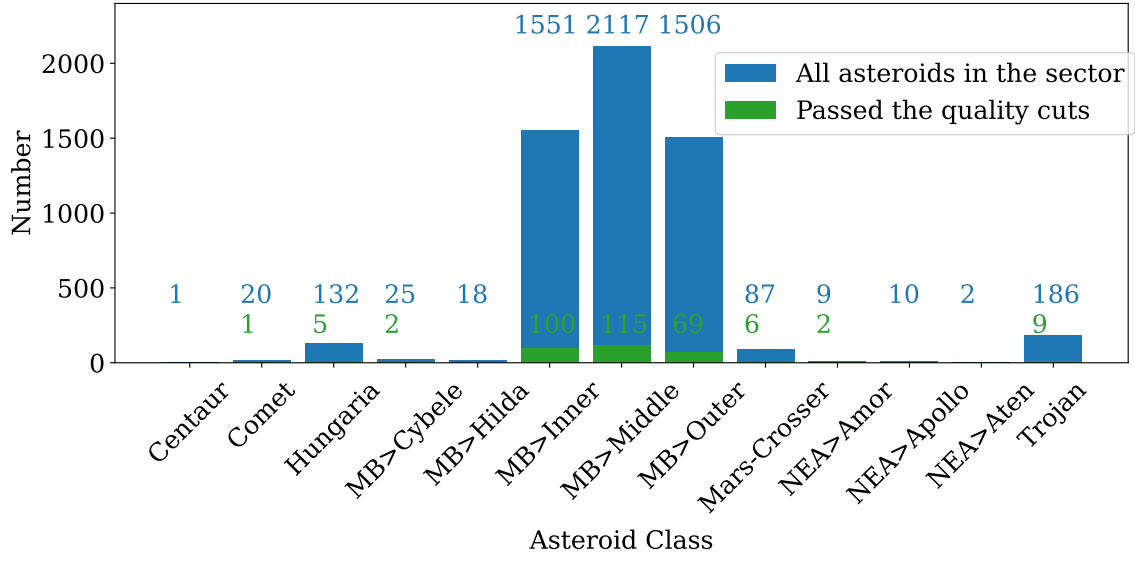


Figure 8: A bar chart distribution of the total number of objects per class that SkyBot found in the Sector (blue) and the same distribution of those that passed all the quality checks (green). The numbers above each class (coloured the same) correspond to the height of the bar, as some classes have too few objects to be seen. As with Figure 7, this is for all objects brighter than 20th mag. For the class labels, MB is “main belt” and “NEA” is near earth asteroid.

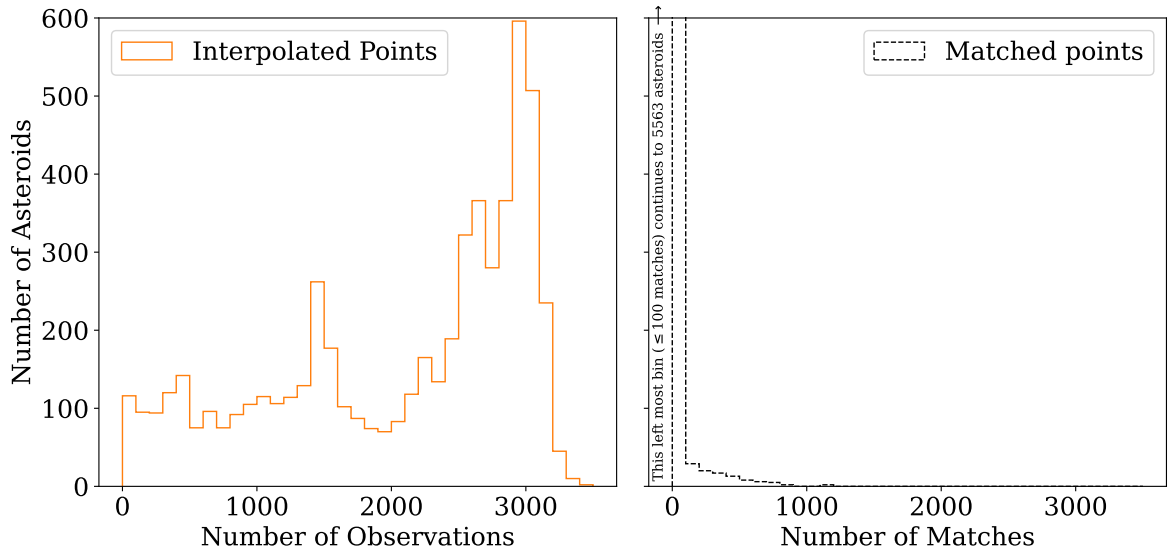


Figure 9: *Left*: A histogram of the number of observations in the lightcurve of each asteroid (orange solid line) in 100 observation bins. *Right*: The number of matches each asteroid gets in the TESSELLATE detections (black dashed).

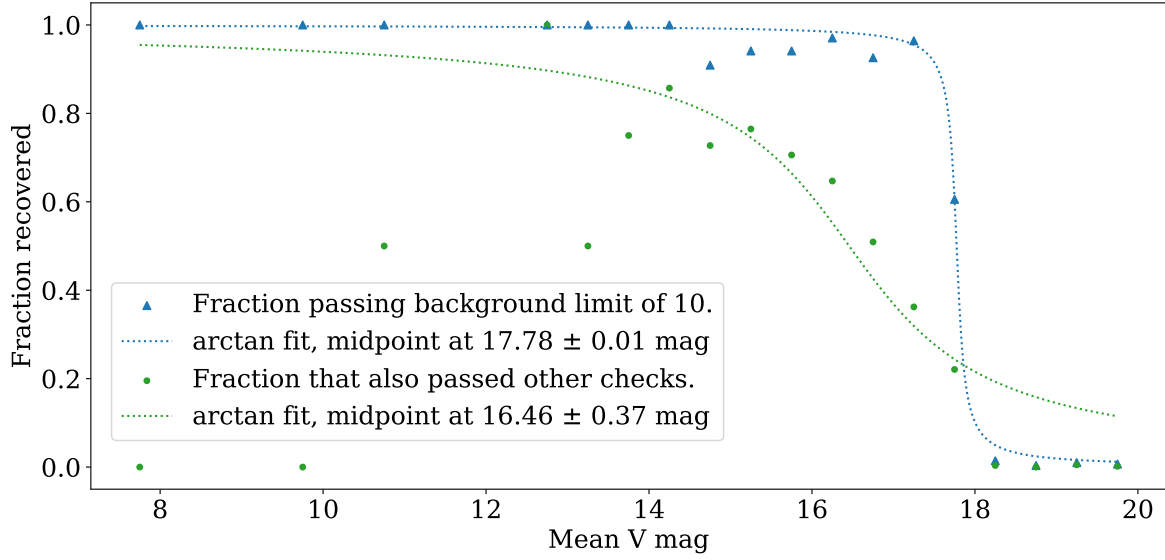


Figure 10: The recovery fraction against the known visual magnitude of each object against the whether the object exceeds only the average flux requirement of the quality checks (blue triangles) or passes all of the quality checks on the lightcurve and periodogram (green dots). A fit of an arctan function is provided in dotted lines of the same colour.

being detected. The $m_{1/2}$ parameter dictates the limiting magnitude, as dimmer than this value less than half of the asteroids are recovered. The fit is preformed on all bins (of 0.5 mag) dimmer than the first bin with more than one asteroid in it, to stop extremely bright asteroids from having too much influence.

Only taking the minimum average flux of 10 counts requirement, blue in Figure 10, the limiting magnitude is 17.78 ± 0.01 mag. When all the quality checks are imposed, this gets over a mag brighter, to 16.46 ± 0.37 mag. It is expected that a higher threshold for quality will make the limiting magnitude brighter, but is value is so uncertain because of the scatter in the recovery fraction at brighter magnitudes, and the shallower decrease in efficiency.

3.3 Period Analysis Results

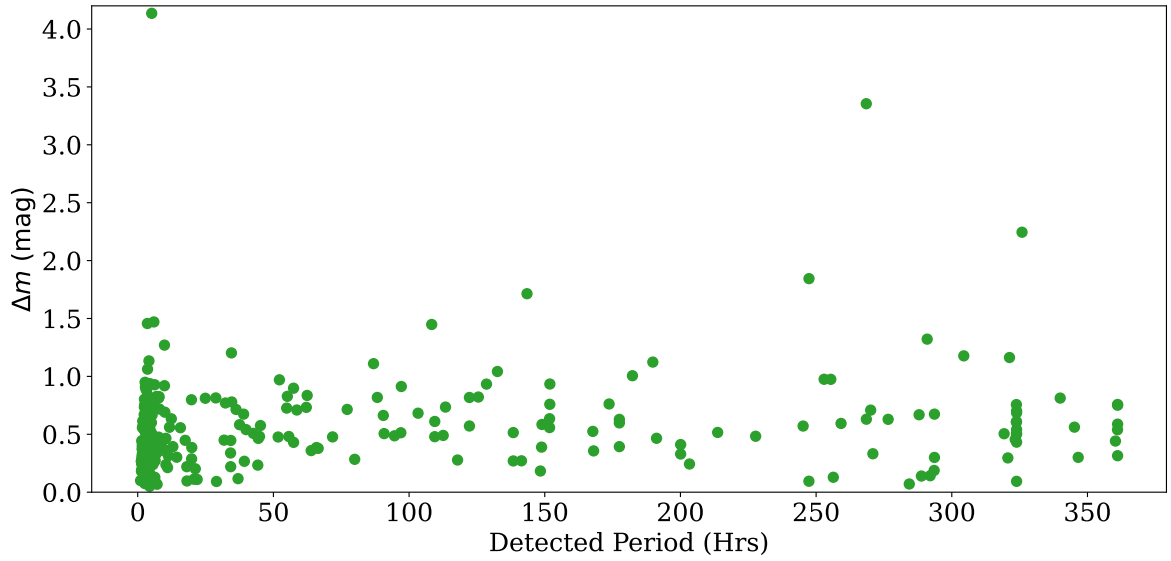


Figure 11: The amplitude of variation in the model from the period analysis against the calculated rotation period. This is for all 309 objects that pass the quality checks.

4 Discussion

4.1 Comparison to other work

The limiting magnitude of the recovery fraction demonstrated in Figure 10 agrees well with other tests of TESSELLATE. Concurrent work by another Honours student (Montilla et al., In Prep.) achieves a similar recovery fraction detection efficiency of $\sim 17^{\text{th}}$ mag. She has been performing injection/recovery tests across many sectors, and finding the limiting magnitude is consistent across sectors and cadence of the FFIs. This is promising, as it means that asteroids will be detected to a similar depth as they are here for any further sectors processed, something I could not check myself.

4.2 Future work

It is clear from the outliers in Figure 11 and the clearly incorrect periods of known objects in Figure 6 that the quality checks have room for improvement. Some of these checks were taken to agree with the how others analyse similar data, like the maximum period from McNeill et al. (2023). Others were more empirically derived, such as the minimum average flux value. There is a delicate balance between detecting as many known periods as possible and maintaining strict enough cuts to keep out the junk.

The periodogram noise at the low frequency end is quite strong throughout the range of rotation periods. Currently it is responsible for a lot of undetected rotation rates, due to the 90% of the 17d window check, and this noise region having a larger power than any signal. Modelling this excess to try and remove the noise and boost the signal from the rotation could be done to improve the maximum power of the periodogram. There are a few asteroids with known longer rotation periods than this check allows for, but one TESS sector will not be enough to determine those accurately.

Linking lightcurves of asteroids between sectors was not considered here, as only one sector has been analysed. Any one asteroid will be in multiple sectors, as TESS has surveyed that whole sky more than once. The different FFI cadence, as well as the large temporal gap between these observations makes it non-trivial to recover the rotation periods. The different depths that the shortest cadence FFIs have (Montilla et al., In Prep.)

5 Conclusion

It works ok
but could be better
summerise findings

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

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