FOSSIL. I. The Spin Rate Limit of Jupiter Trojans

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Abstract

Rotation periods of 53 small (diameters 2 km < D < 40 km) Jupiter Trojans (JTs) were derived using the high-cadence lightcurves obtained by the FOSSIL phase I survey, a Subaru/Hyper Suprime-Cam intensive program. These are the first reported periods measured for JTs with D < 10 km. We found a lower limit of the rotation period near 4 hr, instead of the previously published result of 5 hr for larger JTs. Assuming a rubble-pile structure for JTs, a bulk density of ~0.9 g cm~3 is required to withstand this spin rate limit, consistent with the value ~0.8–1.0 g cm~3 derived from the binary JT system, (617) Patroclus–Menoetius system.

Unified Astronomy Thesaurus concepts: Jupiter trojans (874); Asteroid rotation (2211); Time series analysis (1916); Time domain astronomy (2109)

Supporting material: machine-readable tables

1. Introduction

The Formation of the Outer Solar System: An Icy Legacy (FOSSIL) Survey is an intensive survey program using Subaru/Hyper Suprime-cam (HSC). The goal of the program is to measure the populations and characteristics of Jupiter Trojans (JTs) and the various dynamical subpopulations of the small bodies in the Trans-Neptunian region. The results of this survey program will provide important clues to our understanding of the formation and evolution of our solar system. A major scientific goal of the initial phase of the survey is to obtain high-cadence lightcurves of small JTs and measure their rotation periods.

JTs are a population of asteroids co-orbiting with Jupiter near its L4 and L5 Lagrangian points. Because the orbits of JTs are relatively stable, it is believed that their properties hold important information about the primitive solar system. JTs could have been formed at their present locations during the formation of Jupiter or formed somewhere else during the early stages of the solar system formation and were then captured into their current locations as Trojans during migration of the giant planets (Fernandez & Ip 1984; Malhotra 1995; Morbidelli et al. 2005; Lykawka & Horner 2010; Nesvorny et al. 2013). Comparative studies of the overall physical properties between JTs and other small body populations...
are crucial to our understanding of the origin of JTs and the formation of our solar system.

A significant amount of previous work has been completed in order to better understand the JT population. Two major spectral groups, i.e., red (D type) and less red (P type), have been identified within this population (Emery et al. 2011; Wong et al. 2014; Wong & Brown 2015) and only a very small fraction of C types were also found (DeMeo & Carry 2013). However, it is not clear how this color bimodality is related to other small body populations in the solar system that also have dichotomous colors. Although the size distribution of JTs is different from that of the Main Belt asteroids (MBAs; Yoshida & Terai 2017), this difference could be a result of either different primordial origins or different evolutionary histories. Finally, several measurements of the JT binary fraction have been reported (Mann et al. 2007; Sonnett et al. 2015; Ryan et al. 2017; Szabó et al. 2017; Nesvorny et al. 2020), but this value is very uncertain, with estimates in the range of 10%–30%.

The bulk densities and interior structures of JTs will also provide useful insight when compared with other small body populations. In addition to probing these properties for individual objects through space missions or binary searches, overall estimations can be made through their common spin-rate limit, which can be identified from a rotation-period survey. Thanks to the availability of wide-field cameras, this application has been extensively used on MBAs in the past few years. It is believed (Chapman 1978; Davis et al. 1985; Weissman 1986) that MBAs with diameters 1 km \( \lesssim D \lesssim 100 \) km are gravitational aggregates (rubble-pile structures). These asteroids can thus be destroyed if they spin too fast, and consequently have an upper limit for their spin rates. Harris (1996) first reported a 2 hr rotation-period lower limit for MBAs of diameters \( D > 150 \) m and suggested that these asteroids have rubble-pile structures with a lower limit on their bulk densities of \( \sim 3 \) g cm\(^{-3}\). This 2 hr rotation-period limit has consistently been seen in more recent data sets (Masiero et al. 2009; Chang et al. 2015, 2016, 2019). Interestingly, more than two dozen super fast rotators (SFRs), asteroids with \( D > 300 \) m and rotation periods \(< 2 \) hr, have been found (see Chang et al. 2019, and references therein). Unless these objects have extremely high bulk densities, rubble-pile structures could not survive such high rotation rates, indicating cohesive force is required in addition to gravity to preserve the structures of these objects (Holsapple 2007; Hirabayashi 2015; Hu et al. 2021).

Table 1

| Block ID | R.A. (deg) | Decl. (deg) | JT Cloud | Number of Pointings | Filter | Exposure Time (s) | Limiting Magnitude | Cadence (minutes) | Date | Exposures per Pointing | Time Span (hr) |
|----------|------------|-------------|-----------|---------------------|--------|-------------------|-------------------|------------------|------|------------------------|---------------|
| 19Apr    | 197.526    | −6.763      | L5        | 5                   | g      | 90                | 24.5              | 10               | 2019-04-10 | 53          | 8.8            |
| 20May    | 224.351    | −14.596     | L5        | 2                   | r2     | 300               | 25.6              | 11               | 2020-05-19 | 23          | 3.8            |
| 20Aug    | 341.656    | −6.039      | L4        | 3                   | r2     | 300               | 25.6              | 16               | 2020-08-21 | 16          | 4.5            |
| 20Oct    | 10.119     | 5.754       | L4        | 3                   | r2     | 150               | 25.5              | 15               | 2020-10-14 | 24          | 3.4            |

While the wide-field surveys for asteroid rotation periods referenced above have helped to understand their bulk densities and interior structures, this kind of survey has not been conducted for JTs. Ryan et al. (2017) and Szabó et al. (2017, 2020) reported a possible rotation-period lower limit of \( \approx 5 \) hr for JTs using the K2 data set. However, their JT samples were limited to diameters \( D > 10 \) km, and these relatively large JTs have probably not been accelerated by the Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) effect (Rubincam 2000) to reach their spin-rate limit.

The YORP effect is a mechanism to change the spin state of an object due to sunlight absorption and reemission. Assuming circular orbits, the acceleration of the YORP effect on the spin rate can be expressed

\[
\frac{d\omega}{dt} \propto \frac{1}{\rho a^2 D},
\]

where \( \rho \) is the bulk density, \( a \) is the orbital semimajor axis, and \( D \) is the diameter of that moving object (Rozitis & Green 2013). The YORP timescale to double the spin rate of a 10 km diameter MBA is around a few hundred million years, and subsequently they have been sufficiently influenced by the YORP effect to reach their 2 hr spin-rate limit. In comparison, for JTs with similar densities and diameters of \( D \sim 10 \) km, it would take about a billion years to reach such a high angular velocity, and therefore the previously measured JT spin rate could very well be underestimated. Spin-rate measurements of smaller JTs are thus necessary to obtain a more accurate estimate of the true spin-rate limit.

To achieve this goal we used Subaru and HSC (Furusawa et al. 2018; Komiya et al. 2018; Kawanomoto et al. 2018; Miyazaki et al. 2018) to conduct a wide-field survey, from which dense lightcurves with durations from one to three nights were collected to measure rotation periods for small JTs (\( D \leq 10 \) km). A total of 53 rotation periods out of 1241 observed JTs were obtained by this survey.

This paper is organized as follows. The observations, data reduction, and lightcurve extraction are described in Section 2. The rotation-period analysis is discussed in Section 3. The results and discussion are presented in Section 4, and a summary is given in Section 5.

2. Observations and Data Reduction

High-cadence observations were performed on four blocks of pointings targeting the L4 and L5 JT clouds. The details of observations can be found in Table 1. Observations were conducted using Subaru/HSC during 2019 April 10 (19Apr), 2020 May 18–19 (20May), 2020 August 20–22 (20Aug), and
The g-band filter was used for the 19Apr observations, and the r2 band was used for the other three blocks. The observation time spans were roughly 8 hr for 19Apr and 4 hr each night for the observations conducted in 2020 (other than the last two nights of the 20Oct block, where the time was reduced due to poor weather).

The 19Apr data are from a previous observing run, and were not part of the original FOSSIL proposal. However, given that every one of the proposers for the 19Apr observations is a member of the FOSSIL collaboration, these data were combined with the FOSSIL data set.

FOSSIL was originally awarded four nights in both May (2020A) and September (2020B) when the L5 and L4 JT clouds, respectively, were at opposition. However, we lost three of our four nights of scheduled observations in 2020A because of the shutdown of Maunakea due to the COVID-19 pandemic, and our 2020B nights were rescheduled to August and October due to necessary Subaru maintenance that had been deferred due to the pandemic. The change in our observing schedule necessitated the cancellation of our planned JT color measurements, but we were still able to make useful JT lightcurve measurements during the time we managed to observe.

The number of selected pointings and the exposure time of each frame were adjusted for each block as we learned from our experience from the analysis of the previously observed blocks. For each block, exposures were cycled through the selected pointings repeatedly throughout each night. The typical limiting magnitudes were 24.5 mag for 19Apr and 25.4–25.7 mag for the others (except for the last two nights of the 20Oct block observations where the limiting magnitude dropped to 24 mag due to poor weather conditions). A total of 13 pointings were used, for a total sky coverage of 37.7 deg². Of this, 17.4 deg² covered the L4 cloud and 20.3 deg² covered L5.

All the images were processed using the official HSC pipeline, hscPipe v8.3 (Bosch et al. 2018), with astrometry and photometry calibrated against the Pan-STARRS1 catalog (Chambers et al. 2017). For each pointing, hscPipe was used to build a template image in order to produce differential images. The differential images were then processed by the same pipeline to generate source catalogs of potential moving objects.

Since the observations were carried out using relatively long exposure times, the images of the moving objects with relatively short geocentric distance were trailed. In order to improve the photometry for the trailing moving objects, the trailed source fitting software package TRIPPy (Fraser et al. 2016a, 2016b) was used to measure the magnitudes of the moving object candidates. For each CCD in the HSC focal plane, TRIPPy creates a point-spread function (PSF) model for each exposure based on the PSFs.
from a subset of stars on the same chip. This PSF model is then used along with the measured rate of motion of the relevant JT to create a trailing aperture for the moving object. The background is calculated as the median pixel value in the differential image from a set of pixels separated from the trailed PSF based on the FWHM of the model PSF. An aperture correction based on the FWHM is then applied to the resulting photometric measurement. Photometric uncertainties are estimated based on the signal-to-noise ratio. The intra-night detections of the moving objects would appear as linear sequences with correlated epochs. The Hough transform (Hough 1959; Duda & Hart 1972), an algorithm for line detection in images, was thus utilized to correlate the linear intra-night detections and find moving objects. This procedure is described in detail in Chang et al. (2019).

Since observations were conducted near opposition, we are able to use the rates of motion along the ecliptic longitude and latitude to distinguish different populations of moving objects (e.g., Yoshida & Terai 2017). The arc lengths of the observed objects are limited to 1–3 days and, therefore, cause a relatively large uncertainty in orbit determination. Therefore, the ecliptic motion is used to select JT samples. As shown in Figure 1, the observed moving objects can be classified as MBAs, Hildas, JTs, and trans-Neptunian objects (TNOs). Moreover, several near-Earth asteroids (NEAs) and Centaurs are also evident. We used the objects corresponding to the orange points in Figure 1 as our sample of JTs for further rotation-period analysis, and the JTs for which we found periods are indicated by the green dots. In total, 1241 JTs (hereinafter FOSSIL JTs) with detections in five or more epochs were chosen, including 63 previously known JTs. (Note that no rotation periods had been measured for these 63 objects.)

In order to estimate the diameters of the FOSSIL JTs, the distance to each object must be estimated. To that end, we assume a constant semimajor axis of $a = 5.2$ au and eccentricity $e = 0$ for each JT. Since the phase angles of FOSSIL JTs only have small changes during our observations, we simply estimate their absolute magnitudes using a fixed $G$ slope of 0.15 in the $H$–$G$ system (Bowell et al. 1989). Diameters were then estimated (Yoshida & Terai 2017) as

$$\log D = 0.2m_\odot + \log 2r - 0.5 \log p - 0.2H,$$

(2)

where $m_\odot$ is the apparent magnitude of the Sun, $r$ is the heliocentric distance of Earth in the same unit as $D$, $p$ is the geometric albedo, and $H$ is the absolute magnitude of the JT in the observed band. We adopt $m_\odot = 27.04$ for the $r$ band and $-26.34$ for the $g$ band (Willmer 2018), and we set $p = 0.05$ (Romanishin & Tegler 2018) for both bands.

3. Rotation-period Analysis

To measure rotation period, we attempted to follow the method of Harris et al. (1989) and performed a second-order Fourier series fit to the lightcurves of FOSSIL JTs:24

$$m_j = \bar{m} + \sum_{k=1}^{2} \left( \frac{2\pi k}{P} \sin \left[ \frac{2\pi k}{P} (t_j - t_0) \right] \right) + C_k \cos \left[ \frac{2\pi k}{P} (t_j - t_0) \right],$$

(3)

where $m_j$ are the apparent magnitudes in the observed band, $t_j$ is the observing epoch for measurement $j$, $B_k$ and $C_k$ are the coefficients of the second-order Fourier series, $P$ is the rotation period, $t_0$ is an arbitrary epoch, and $\bar{m}$ is the mean magnitude of the JT. The spin rate ($f = 1/P$) was explored from 0.25 to 50 day$^{-1}$ using a step size of 0.01 day$^{-1}$, where $\bar{m}$ is the mean magnitude of the JT.

To determine whether the algorithm gives a good fit to the lightcurve, we calculate the difference between the reduced $\chi^2$ of the best-fit period and that of a fit to the mean magnitude. We found that when the difference is $>2$, the fitting shows a convincing folded lightcurve.

Based on the assumption of ellipsoidal shapes for JTs, a folded lightcurve with two minima and two maxima is expected. However, the best-fit (i.e., the minimum reduced $\chi^2$) period of this algorithm returns two types of folded lightcurves: double peaked and single peaked. Two conditions can give rise to a single-peaked lightcurve: first, when all of the data are contained in the same half of the phased double-peaked lightcurve, and second, when the two halves of the double-peaked lightcurve are very similar. To distinguish between the two cases, we look at the amplitudes of each phase $k$ of the Fourier series fit

$$A_k = (B_k^2 + C_k^2)^{1/2}. $$

(4)

For a double-peaked lightcurve, the amplitude of the $k = 2$ Fourier component is larger, with a smaller correction by the $k = 1$ component. When a single-peaked folded lightcurve is found, the opposite is true. We can then distinguish between the two cases by defining a folded lightcurve as double peaked when $A_2 > A_1$ and single peaked when $A_1 \geq A_2$. Figure 2 shows a plot of $A_1$ versus $A_2$ for the JTs where a good fit was found, and Figure 3 shows example double- and single-peaked folded lightcurves. Note that in most cases it is obvious if the fit lightcurve is single or double peaked, but there are some

![Figure 2](image_url)

Figure 2. Amplitude $A_2$ vs. $A_1$ for the folded lightcurves. Double-peaked lightcurves (green dots) have $A_2 > A_1$, while the single-peaked folded lightcurves (blue dots) have $A_2 < A_1$.  

24 The correction for the light-traveling time was not applied here because the resulting changes are negligible for short time-span surveys (i.e., 1–3 days).
marginal cases when the amplitude is low, and this method also facilitates automation of the analysis.

When the best-fit period gives a single-peaked lightcurve, the next best local minimum of the reduced $\chi^2$ versus $P$ curve with a longer period is selected as the preferred solution. However, this does not always work well when there is not sufficiently full coverage of the single-peaked folded lightcurve. To eliminate such cases, we divide each single-peaked folded lightcurve into four sections bounded by the minimum, maximum, and the two points where the fit lightcurve crosses the mean magnitude $\bar{m}$ (see Figure 3). We require that there be at least two points in each section; otherwise, we reject the lightcurve since we cannot be confident of the fit period. Finally, when using the second local minimum for the period, in some cases unrealistic fit parameters are returned (e.g., a lightcurve amplitude of 80 mag). In such cases, we have found that the fit period is always more than three times the fit period for the original single-peaked folded lightcurve. We thus reject any fits where the new period is three times longer than that from the original single-peaked fit. Uncertainties in the periods are estimated following the process described in Polishook et al. (2012).

From the lightcurves of the 1241 FOSSIL JTs, we obtained 40 double-peaked folded lightcurves that passed our selection criteria. In addition, we found 13 single-peaked folded lightcurves from which we were able to recalculate double-peaked lightcurves that passed the cuts outlined above. The main reason for the low rate of successful period fitting is due to the fact that most of the detections are of fainter objects, and the lightcurves of these objects are therefore too noisy to obtain an accurate fit given the short span of our observations. In addition, due to the short time span of our observations at each block, our analysis is insensitive to longer period rotation curves.

Photometric data for these 53 lightcurves are presented in Table 2. Diameters, rotation periods, lightcurve amplitudes, and folded lightcurve fit parameters for each of these objects are available in machine-readable format.

### Table 2

| JD     | Mag       | Mag Error |
|--------|-----------|-----------|
| 245883.857932 | 20.9790 | 0.0062     |
| 245883.864924 | 20.9308 | 0.0061     |
| 245883.885930 | 20.8650 | 0.0059     |
| 245883.892958 | 20.8545 | 0.0058     |
| 245883.900007 | 20.8459 | 0.0058     |
| 245883.907036 | 20.8728 | 0.0059     |
| 245883.914078 | 20.9097 | 0.0059     |
| 245883.921106 | 20.9317 | 0.0060     |
| 245883.928126 | 21.0006 | 0.0062     |
| 245883.938686 | 21.0513 | 0.0065     |
| 245883.945697 | 21.1222 | 0.0069     |
| 245883.952704 | 21.2509 | 0.0070     |
| 245883.959705 | 21.3866 | 0.0078     |
| 245883.966701 | 21.4131 | 0.0078     |
| 245883.973695 | 21.4045 | 0.0078     |
| 245883.980718 | 21.3482 | 0.0080     |
| 245883.987715 | 21.3897 | 0.0076     |
| 245883.994707 | 21.3218 | 0.0074     |
| 245884.001710 | 21.2038 | 0.0072     |
| 245884.008693 | 21.0953 | 0.0070     |
| 245884.015689 | 21.0485 | 0.0068     |
| 245884.022678 | 20.9955 | 0.0068     |
| 245884.029678 | 20.9469 | 0.0066     |
| 245884.036667 | 20.9121 | 0.0065     |
| 245884.043656 | 20.8982 | 0.0063     |
| 245884.050641 | 20.8427 | 0.0062     |
| 245884.057636 | 20.8129 | 0.0062     |
| 245884.047127 | 20.8376 | 0.0063     |
| 245884.078620 | 20.8561 | 0.0065     |
| 245884.085612 | 20.8340 | 0.0067     |
| 245884.092621 | 20.9180 | 0.0069     |
| 245884.099606 | 20.9786 | 0.0070     |
| 245884.106602 | 20.9651 | 0.0078     |
| 245884.113589 | 21.0144 | 0.0079     |

**Note.** This is an example for a single object; all measurements from all 53 objects are available in machine-readable format.

(This table is available in its entirety in machine-readable form.)
| JT ID          | MPC Designation | Block | $H$ (mag) | $D$ (km) | $\sigma_D$ (km) | $P$ (hr) | $\sigma_P$ (hr) | $\dot{m}$ (mag) | $\dot{h}$ (mag) | $B_1$ | $C_1$ | $B_2$ | $C_2$ |
|----------------|-----------------|-------|-----------|----------|-----------------|----------|-----------------|-----------------|----------------|--------|-------|--------|-------|
| FSAU01020120   | 20Aug 14.5       | 6.52  | 0.29      | 8.51     | 0.06            | 21.5     | 0.13            | 0.17            | 0.02           | 0.07   | 0.14  | 0.05   | 0.09  |
| FSAU02030015   | 20Aug 13.5       | 10.52 | 0.85      | 8.42     | 0.15            | 20.2     | 0.03            | 0.11            | 0.02           | 0.07   | 0.13  | 0.01   | 0.05  |
| FSAU02032023   | 20Aug 13.0       | 13.4  | 1.1       | 13.52    | 0.72            | 19.6     | 0.09            | 0.02            | 0.09           | 0.06   | 0.18  | 0.06   | 0.06  |
| FSAU03020042   | 20Aug 15.7       | 3.76  | 0.30      | 6.115    | 0.09            | 22.4     | 0.02            | 0.03            | 0.10           | 0.02   | 0.10  | 0.02   | 0.02  |
| FSAU03020082   | 20Aug 15.6       | 3.97  | 0.32      | 11.43    | 0.28            | 22.3     | 0.08            | 0.01            | 0.17           | 0.18   | 0.17  | 0.17   | 0.18  |
| FSAU03020359   | 20Aug 17.1       | 1.98  | 0.16      | 6.115    | 0.39            | 23.8     | 0.05            | 0.01            | 0.18           | 0.10   | 0.10  | 0.10   | 0.10  |
| FSOCL010307    | 20Oct 7.3        | 1.06  | 0.14      | 11.39    | 0.34            | 23.7     | 0.06            | 0.04            | 0.03           | 0.22   | 0.22  | 0.22   | 0.22  |
| FSOCL010310    | 20Oct 7.2        | 1.06  | 0.14      | 11.39    | 0.34            | 23.7     | 0.06            | 0.04            | 0.03           | 0.22   | 0.22  | 0.22   | 0.22  |
| FSOCL010314    | 20Oct 7.2        | 1.06  | 0.14      | 11.39    | 0.34            | 23.7     | 0.06            | 0.04            | 0.03           | 0.22   | 0.22  | 0.22   | 0.22  |
| FSOCL010317    | 20Oct 7.2        | 1.06  | 0.14      | 11.39    | 0.34            | 23.7     | 0.06            | 0.04            | 0.03           | 0.22   | 0.22  | 0.22   | 0.22  |
| FSOCL010343    | 20Oct 15.8       | 3.65  | 0.30      | 7.218    | 0.055           | 22.5     | 0.01            | 0.01            | 0.19           | 0.18   | 0.18  | 0.18   | 0.18  |
| FSOCL010389    | 20Oct 15.7       | 3.77  | 0.30      | 4.229    | 0.037           | 22.4     | 0.02            | 0.02            | 0.01           | 0.08   | 0.08  | 0.08   | 0.08  |
| FSOCL03030078  | 20Oct 13.4       | 40.3  | 3.3       | 8.571    | 0.077           | 21.7     | 0.01            | 0.05            | 0.07           | 0.04   | 0.04  | 0.04   | 0.04  |
| FSOCL0303164   | 20Oct 16.6       | 2.46  | 0.20      | 7.500    | 0.059           | 23.3     | 0.04            | 0.04            | 0.03           | 0.17   | 0.17  | 0.17   | 0.17  |
| FSOCL0303176   | 20Oct 13.5       | 10.52 | 0.85      | 6.194    | 0.040           | 20.2     | 0.01            | 0.02            | 0.13           | 0.09   | 0.09  | 0.09   | 0.09  |
| FSOCL0303942   | 20Oct 16.2       | 2.99  | 0.24      | 7.33     | 0.16            | 22.9     | 0.01            | 0.03            | 0.13           | 0.02   | 0.02  | 0.02   | 0.02  |
| FSA0P06010005   | 20Sep 13.6       | 3.34  | 0.27      | 16.13    | 1.81            | 22.7     | 0.21            | 0.14            | 0.26           | 0.06   | 0.06  | 0.06   | 0.06  |
| FSA0P06010194   | 20Sep 15.0       | 9.12  | 0.31      | 11.23    | 0.70            | 21.7     | 0.06            | 0.00            | 0.22           | 0.23   | 0.23  | 0.23   | 0.23  |
| FSOCL0102033   | 20May 17.1       | 1.51  | 0.12      | 12.89    | 0.54            | 24.4     | 0.52            | 0.39            | 0.43           | 0.16   | 0.16  | 0.16   | 0.16  |
| FSOCL0102090   | 20May 16.6       | 2.50  | 0.20      | 9.95     | 0.30            | 23.3     | 0.15            | 0.05            | 0.14           | 0.07   | 0.07  | 0.07   | 0.07  |
| FSOCL0103144   | 20May 14.3       | 7.16  | 0.58      | 18.29    | 0.99            | 21.0     | 0.01            | 0.33            | 0.08           | 0.14   | 0.14  | 0.14   | 0.14  |
| FSOCL0103697   | 20May 15.0       | 5.25  | 0.42      | 6.91     | 0.15            | 21.7     | 0.00            | 0.02            | 0.08           | 0.09   | 0.09  | 0.09   | 0.09  |

Table 3: Physical Parameters for FOSSIL JTJs for which Rotation Periods Were Obtained.
### Table 3 (Continued)

| JT ID               | MPC Designation | Block   | $H$ (mag) | $D$ (km) | $\sigma_D$ (km) | $P$ (hr) | $\sigma_P$ (hr) | $\delta m$ (mag) | $\bar{m}$ (mag) | $B_1$ | $C_1$ | $B_2$ | $C_2$ |
|---------------------|-----------------|---------|-----------|----------|-----------------|----------|-----------------|-----------------|----------------|-------|-------|-------|-------|
| FOSL02010203        | (457150) 20May 13.9 | 8.84   | 0.71      | 12.63    | 0.34            | 0.27     | 20.6            | $-0.03$         | $0.01$         | $0.03$ | $-0.09$ | $0.27$ |       |
| FSAU01020025        | 20Aug 16.1      | 3.14   | 0.25      | 9.75     | 0.19            | 0.69     | 22.8            | $0.01$          | $0.03$         | $-0.02$ | $0.07$ | $-0.10$ |       |
| FSAU01030234        | 20Aug 14.9      | 5.55   | 0.45      | 11.71    | 0.60            | 0.23     | 21.6            | $-0.06$         | $0.01$         | $-0.02$ | $0.07$ |       |       |
| FSOC02010222        | 2015 FP40 14.3  | 7.08   | 0.57      | 9.84     | 0.10            | 0.21     | 21.0            | $-0.01$         | $0.01$         | $-0.02$ | $0.07$ |       |       |
| FSOC02010348        | 20Oct 16.0      | 3.35   | 0.27      | 7.90     | 0.13            | 1.09     | 22.7            | $-1.02$         | $-0.43$        | $-0.67$ | $-0.04$ |       |       |
| FSOC03010169        | (295699) 20Oct 14.2 | 7.71   | 0.62      | 10.91    | 0.13            | 0.60     | 20.9            | $-0.01$         | $-0.04$        | $-0.28$ | $-0.09$ |       |       |

**Note.** Minor Planet Center (MPC) designations are provided for previously known JTs. (This table is available in its entirety in machine-readable form.)

**Figure 4.** Forty folded lightcurves of JTs where a double-peaked fit was returned. The object ID and derived rotation period are indicated on each plot. Different colors represent data points obtained from different nights. The gray lines are the fitting results. Photometric errors are too small to be seen in the plots.
are shown in Table 3, and the folded lightcurves themselves are shown in Figures 4 and 5.

4. Results and Discussion

Figure 6 shows a plot of diameter versus rotation period for the FOSSIL JTs where full and half rotation periods are found. For comparison, the values for previously measured rotation periods for JTs and MBAs are also shown. The FOSSIL data set extends the range of diameters of JTs with measured rotation periods from $D \lesssim 10$ km down to $D \lesssim 1$ km for the first time. We note that there is a clear lack of long-period detections in the FOSSIL data. This is due to biases against long periods in our survey arising from the short time span of observations at each block of pointings.

In the sample of smaller diameter JTs found by FOSSIL, five of them have rotation periods faster than the previously suggested 5 hr limit, three out of which have rotation periods of $\sim 4$ hr. The diameters of these three $4$ hr rotation-period JTs are around 5 km, where the size range is expected to have sufficient YORP acceleration to reach the JT spin-rate limit, as mentioned in Section 1. We also note that the upturn in the spin rates shown among MBAs with diameters around 30–40 km is possibly seen for JTs around diameters 10–20 km as well. This might indicate the diameter ranges where the YORP effect starts to affect the spin rates in both populations and, moreover, the diameter ranges follows the simple relation of the YORP acceleration as discussed in Section 1.

Assuming a rubble-pile structure for JTs, the minimum bulk density to withstand these spin rates can be calculated using

$$P = 3.3 \left( \frac{1 + \delta m}{\rho} \right)^{\frac{1}{2}},$$  \hspace{1cm} (5)

where $P$ is the period in hr, $\rho$ is the bulk density in g cm$^{-3}$, and $\delta m$ is the lightcurve amplitude in mag. We estimate the lightcurve amplitude $\delta m$ as 95% of the difference between the brightest and faintest measurements for each object, given that the folded lightcurve fits sometimes significantly overestimate the amplitudes. Figure 7 shows a plot of spin rate versus lightcurve amplitude for both the FOSSIL JTs and previously measured JTs, along with limits on bulk density calculated from Equation (5). Given the rotation rates measured for the FOSSIL JTs, these objects need a bulk density of at least $\approx 0.9$ g cm$^{-3}$, a value consistent with the measurements of $\sim 0.8$–1.0 g cm$^{-3}$ (Marchis et al. 2006; Mueller et al. 2010; Buie et al. 2015; Berthier et al. 2020) from the binary JT system, (617) Patroclus–Menoetius system and much higher than that derived from the 5 hr spin-rate limit (i.e., $\sim 0.5$ g cm$^{-3}$; Ryan et al. 2017; Szabó et al. 2017, 2020; Kalup et al. 2021). The favored formation scenario (Nesvorný et al. 2013) suggests that JTs and dynamically excited Kuiper Belt objects (KBOs) were populated from the same primordial planetesimal reservoir. Our findings point to a tension with this idea when considering the densities of KBOs; small KBOs ($D \lesssim 300$ km) have significantly lower bulk densities $\rho \sim 0.7$ g cm$^{-3}$ (Grundy et al. 2019) than Patroclus–Menoetius and JT bulk densities derived here assuming rubble-pile structures.

Figure 5. Thirteen folded lightcurves of JTs where a single-peaked fit as returned. The top plots in each frame show the results from the original single-peaked fits, and the bottom plots show the folded lightcurves when a double-peaked period was found in a second round of fitting. The object ID and half period are indicated in each plot. Symbols are the same as in Figure 4. Photometric errors are too small to be seen in the plots.

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25 Previously known JT and MBA rotation periods were obtained from the Asteroid Lightcurve Database (LCDB Warner et al. 2009), which can be found at https://sbn.psi.edu/pds/resource/lc.html. Note that only the rotation periods with quality code of $U \geq 2$ are used.
Possible solutions to this tension include the possibility that KBOs of the same size as the Trojans considered here have similarly higher densities. The fact that Patroclus–Menotius has a higher bulk density than similar sized KBOs, however, disfavors this possibility. Collisional evolution (Wong et al. 2014) may be responsible for raising the densities of KBOs.
(Fraser & Brown 2018), but it remains to be seen whether collisional evolution sufficient to raise densities by \( \sim 1/3 \) would not also unbind the Patroclus–Menoetius system.

5. Summary and Conclusions

Using the Subaru/HSC, a wide-field high-cadence survey, part of which was to measure rotation periods of small JTs, was conducted in 2019 and 2020. From this survey, we report the detection of 1241 JTs, only 63 of which are found in the Minor Planet Center (MPC) database. We were able to obtain rotation periods for 53 of the 1241 JTs, the vast majority of which were measured on objects with diameters \( D < 10 \) km, an order of magnitude smaller than previously accomplished. We found a number of objects with periods near 4 hr, significantly lower than the suggested limit of 5 hr. Under the assumption of a rubble-pile structure for JTs, a bulk density of \( \approx 0.9 \) g cm\(^{-3} \) is required to maintain their structure at that rotation-period limit. This value is comparable to the measurements of \( \sim 0.8–1.0 \) g cm\(^{-3} \) (Marchis et al. 2006; Mueller et al. 2010; Buie et al. 2015; Berthier et al. 2020) from the binary JT system, (617) Patroclus–Menoetius.

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