DISCOVERY AND CHARACTERISTICS OF THE RAPIDLY ROTATING ACTIVE ASTEROID (62412) 2000 SY178 IN THE MAIN BELT

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ABSTRACT

We report a new active asteroid in the main belt of asteroids between Mars and Jupiter. Object (62412) 2000 SY178 exhibited a tail in images collected during our survey for objects beyond the Kuiper Belt using the Dark Energy Camera on the CTIO 4 m telescope. We obtained broadband colors of 62412 at the Magellan Telescope, which, along with 62412’s low albedo, suggests it is a C-type asteroid. 62412’s orbital dynamics and color strongly correlate with the Hygiea family in the outer main belt, making it the first active asteroid known in this heavily populated family. We also find 62412 to have a very short rotation period of 3.33 ± 0.01 hours from a double-peaked light curve with a maximum peak-to-peak amplitude of 0.45 ± 0.01 mag. We identify 62412 as the fastest known rotator of the Hygiea family and the nearby Themis family of similar composition, which contains several known main belt comets. The activity on 62412 was seen over one year after perihelion passage in its 5.6 year orbit. 62412 has the highest perihelion and one of the most circular orbits known for any active asteroid. The observed activity is probably linked to 62412’s rapid rotation, which is near the critical period for break-up. The fast spin rate may also change the shape and shift material around 62412’s surface, possibly exposing buried ice. Assuming 62412 is a strengthless rubble pile, we find the density of 62412 to be around 1500 kg m⁻³.

Key words: comets: general – comets: individual (62412) – Kuiper belt: general – minor planets, asteroids: general – minor planets, asteroids: individual (62412) – Oort Cloud

1. INTRODUCTION

Comets are generally defined as objects that display dust and/or gas emitting from their surfaces. Observationally, this means detecting either a coma or tail from the object. The main source of the observed activity in most comets is likely the sublimation of water ice. Comets are traditionally thought to originate in the Kuiper Belt as short-period comets or in the Oort cloud as long-period comets. Some comets could also originate in the Trojan regions of the giant planets, but no definitive examples are known. Elst et al. (1996) reported activity around a main belt asteroid now called 133P/Elst-Pizarro. Hsieh & Jewitt (2006) detailed the observed activity around a few main belt asteroids (MBAs) between Mars and Jupiter. Hsieh & Jewitt (2006) coined these objects main belt comets (MBCs) as it was thought that MBAs would not be able to sustain any observable activity since water ice should be unstable on their surfaces. There are now at least 12 known objects well within the main belt asteroid that have shown significant activity over the past several years. The source of this activity may be different for the various objects and could include ice sublimation, impact ejecta, or rotational breakup (Jewitt 2012; Capria et al. 2012). Because the source of the observed activity in these main belt objects may be unrelated to cometary ice sublimation, these objects are now collectively called active asteroids. The MBCs are a subset of the active asteroids in which water ice is thought to be the source of the activity observed for the objects. It is important to determine whether or not the observed activity in an asteroid is driven by volatile inventory as ices are important for understanding the chemistry of the early solar nebula and planet formation (Castillo-Rogez & Schmidt 2010; Schmidt & Castillo-Rogez 2012).

Impacts have been inferred for a few active asteroids, such as (596) Scheila and P/2012 F5 (Gibbs), because of the large brightening and quick fading indicative of an impulsive event like an impact (Jewitt et al. 2010, 2011; Snodgrass et al. 2010; Ishiguro et al. 2011; Hainaut et al. 2012; Hsieh et al. 2012; Kim et al. 2012; Moreno et al. 2012; Stevenson et al. 2012; Agarwal et al. 2013; Kleyna et al. 2013). Ice sublimation is inferred for some active asteroids, such as 133P and 238P, because of repeated and prolonged activity only seen near the perihelion of the objects (Hsieh et al. 2010, 2011). Newly discovered active asteroid P/2014 S4 (Gibbs) near the outer main belt EOM family complex could also be from water ice sublimation as activity was first seen near perihelion, very similar to the nearby MBC P/2012 T1 (PanSTARRS; Gibbs et al. 2014; Hsieh et al. 2013). Though water ice is unstable at the surface of an MBA, it could survive a few ms below the surface for billions of years (Schorghofer 2008; Priailnik & Rosenberg 2009). To date, no direct or spectroscopic ice detection has been made for an active asteroid, but this is not unexpected because of the estimated low activity and low active surface areas of these objects (Hsieh et al. 2011; O’Rourke 2013; Jewitt et al. 2014).

The known active asteroids are unlikely to have recently arrived at their locations but have been within the main asteroid belt for billions of years. Thus, these objects are not dynamically related to the current short- or long-period comet populations (Levison et al. 2006; Haghighipour 2009). It is thought that these asteroids likely formed near their present locations but it is possible some could have originated in the outer solar system and became captured in their current orbits very early in the solar system’s history during the planetary migration era (Levison et al. 2009; Walsh et al. 2011, 2012). It is of interest to know whether the active asteroids formed near their present locations or if they were captured from the outer solar system as any volatile
Table 1
Geometry of the 62412 Observations

| UT Date     | R  (AU) | Δ  (AU) | α  (deg) | Plane (deg) | True (deg) | PAnut (deg) | PA (deg) | Active |
|-------------|---------|---------|----------|-------------|------------|-------------|----------|--------|
| 2012 Jan 25.307 | 3.102   | 3.028   | 18.4     | -0.64       | 277.3      | 68.5        | 246.3    | No     |
| 2013 Jan 04.407 | 2.900   | 1.950   | 6.12     | -1.69       | 344.4      | 271.4       | 287.6    | No     |
| 2013 Mar 21    | 2.892   | 2.357   |          |             |            |             |          |        |
| 2014 Mar 28.245 | 3.062   | 2.144   | 8.78     | 1.35        | 74.4       | 300.9       | 291.8    | Yes    |
| 2014 May 01.192 | 3.088   | 2.101   | 4.44     | 2.15        | 80.6       | 84.9        | 293.8    | Yes    |
| 2014 May 02.005 | 3.089   | 2.104   | 4.75     | 2.16        | 80.8       | 87.0        | 293.9    | Yes    |
| 2014 Aug 29.246 | 3.184   | 3.534   | 16.2     | -0.15       | 101.8      | 111.7       | 291.2    | No     |
| 2016 Jan 10    | 3.411   | 4.332   |          |             |            |             |          |        |

Note. Quantities are the heliocentric distance \( R \), geocentric distance \( Δ \), phase angle \( α \), the orbit plane angle which is the angle between the observer and target orbital plane \( \text{Plane} \), true anomaly \( \text{True} \), position angle of the antisolar vector as projected in the plane of the sky \( \text{PA}_{\text{Sun}} \), and position angle of the negative velocity vector as projected in the plane of the sky \( \text{PA} \). UT Date shows the year, month, and time of day at the start of the observations on each night it was observed. Individual exposure times used for colors and the light curve measurements on 2014 May 2 were 30 s in the \( g' \), \( r' \), \( i' \), and \( z' \) filters and they were rotated after each observation to prevent any rotational light curves from influencing the color calculations.

content within them may have played an important role in the formation of the terrestrial planets, including water delivery to Earth (Mott et al. 2007; O’Brien et al. 2014).

We have discovered a new active asteroid in the outer main belt of asteroids. (62412) 2000 SY178 joins the other 12 objects known to show activity in the main belt and thus can help us further understand these unusual objects. We obtained detailed follow-up observations of 62412 after the initially observed activity from the object.

2. OBSERVATIONS

The main belt asteroid (62412) 2000 SY178 was serendipitously imaged three times on UT 2014 March 28 at the CTIO 4 m telescope with the Dark Energy Camera (DECam) during our ongoing survey to find objects beyond the Kuiper Belt (see Trujillo & Sheppard (2014) for details of the survey). DECam is a wide-field optical imager that covers about 2.7 square degrees per image using 62 2048 × 4096 CCD chips. The pixel scale is 0.263 arcsec per pixel. Activity was seen on three DECam images of 330–420 s taken using the very wide VR filter with seeing at about 1 arcsec FWHM. The faint tail was observed at a position angle of 295 ± 2 degrees extending about 1 arcmin from the nucleus of 62412.

Follow-up observations of 62412 were obtained with the IMACS camera on the 6.5 m Magellan-Baade telescope on UT 2014 May 1 and 2 (Table 1). IMACS has eight CCD chips of 2048 × 4096 with a pixel scale of 0.20 arcsec per pixel. Standard image reduction techniques were used, including bias subtraction and flat-fielding from dithered twilight images. A clear tail for 62412 was evident at a position angle of 297 ± 2 degrees and extending about one arcminute from the object in six 420 s images in the VR filter (Figure 1). There was no evident anti-tail on the opposite side of the main tail of the object. The width of the tail is similar to the FWHM of the images, suggesting it is not resolved. Once it was confirmed that 62412 was an active asteroid, it was routinely observed using 30 s exposures over about an 8 hour time span on 2014 May 2 in 0.8 arcsec seeing (Table 2). Most of these observations were taken in the \( r' \) band to look for variability, but some were obtained in the \( g' \), \( i' \), and \( z' \) bands to measure the color of the surface of the object. There is no obvious coma with only a faint tail observed near 62412 and thus the photometry of the nucleus should not be significantly contaminated (Figure 2). We used an aperture of radius 3 arcsec for photometry and the Sloan standard star field around DLS-1359 for photometric calibration.

Four 200 s images of 62412 in the VR filter were obtained on UT 2014 August 29 at the 8.2 m Subaru Telescope on Mauna Kea in Hawaii. The Suprime-Cam imager was used with a pixel scale of 0.20 arcsec per pixel in 0.7 arcsec seeing. No coma or tail was evident around 62412, suggesting the activity slowed or is no longer present. We also found 62412 at two epochs on archived images from the MegaCam imager on the Canada–France–Hawaii Telescope (CFHT) using the Solar System Object Image Search tool (Gwyn et al. 2012). MegaCam has a pixel scale of 0.187 arcsec per pixel. On UT 2012 January 25 the main image was a 384 s exposure in the \( r' \) band. 62412 was easily detected but no obvious coma or tail was seen in 1.1 arcsec seeing, indicating the object was not active. On UT 2013 January 4, several \( i' \)-band exposures of 560 s each were obtained with 62412 in the field. No visible coma or tail was observed in 0.8 arcsec seeing in any of the \( i' \)-band images, suggesting the object had yet to become active just before perihelion.

3. RESULTS AND ANALYSIS

3.1. Orbit

The newly identified active asteroid 62412 has been observed without activity identification for over 15 years and thus has a well-determined orbit in the outer MBAs (Table 3). 62412 has a Tisserand parameter of 3.20, which is larger than 3 as is typical for MBAs but not short-period comets (Fernandez et al. 2002). Several previous active asteroids in the outer main belt have been identified within the Themis family, but 62412’s current inclination is too high for this association (Figure 3). In order to determine the proper orbital elements of 62412 and look for family membership, we numerically integrated its orbit under the influence of the planets using the Mercury program (Chambers 1999). We found the orbit of 62412 to be stable for the age of the solar system with its proper orbital elements shown in Table 3.

62412’s proper inclination puts the object within the highly populated Hygiea family (Carruba 2013; Masiero et al. 2013; Milani et al. 2014). The Hygiea family is named after 10 Hygiea, which is a C-type asteroid and likely the parent body of most of the family members in this region (Parker et al. 2008; Carruba et al. 2014). This is the first known active
3.2. Colors, Albedo, and Size

The WISE survey serendipitously observed 62412 in 2010 May when the object was near aphelion (Masiero et al. 2011). Masiero et al. (2011) found an effective radius of 5.187 ± 0.171 and optical albedo of 0.0653 ± 0.0097 for 62412 using an H magnitude of 13.5. This makes 62412 the second largest known active asteroid (Bauer et al. 2012). The largest active asteroid, (596) Scheila, is believed to have activity caused by a

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Table 2 (Continued)

| Airmass | Exp \(^a\) | UT Date \(^b\) | Mag. \(^c\) | Err \(^d\) |
|---------|-------------|---------------|------------|------------|
|         | (s)         | yyyy mm dd.dddd | (m\(\prime\)) | (m\(\prime\)) |
| 1.821   | 30          | 2014 05 02.319919 | 18.44      | 0.01       |
| 1.842   | 30          | 2014 05 02.321238 | 18.44      | 0.01       |
| 1.862   | 30          | 2014 05 02.322546 | 18.39      | 0.01       |
| 1.884   | 30          | 2014 05 02.323854 | 18.40      | 0.01       |
| 1.907   | 30          | 2014 05 02.325231 | 18.34      | 0.01       |
| 1.929   | 30          | 2014 05 02.326539 | 18.32      | 0.01       |
| 1.953   | 30          | 2014 05 02.327859 | 18.26      | 0.01       |
| 1.977   | 30          | 2014 05 02.329167 | 18.26      | 0.01       |
| 2.001   | 30          | 2014 05 02.330475 | 18.20      | 0.01       |
| 2.027   | 30          | 2014 05 02.331840 | 18.19      | 0.01       |
| 2.054   | 30          | 2014 05 02.333160 | 18.17      | 0.01       |
| 2.080   | 30          | 2014 05 02.334468 | 18.14      | 0.01       |
| 2.108   | 30          | 2014 05 02.335775 | 18.10      | 0.01       |
| 2.137   | 30          | 2014 05 02.337095 | 18.11      | 0.01       |
| 2.168   | 30          | 2014 05 02.338472 | 18.08      | 0.01       |
| 2.198   | 30          | 2014 05 02.339792 | 18.10      | 0.01       |
| 2.232   | 30          | 2014 05 02.341192 | 18.05      | 0.01       |

\(^a\) Exposure time for the image.
\(^b\) Decimal universal time at the start of the integration.
\(^c\) Apparent magnitude in \(r\)-filter.
\(^d\) Uncertainties on the individual photometric measurements.

Table 3

| Type | \(a\) (AU) | \(e\) | \(i\) (deg) | \(q\) (AU) | \(Q\) (AU) | \(P\) (yr) | \(T\)_j |
|------|------------|------|-----------|----------|----------|--------|------|
| Current | 3.151 | 0.082 | 4.74 | 2.892 | 3.410 | 5.6 | 3.20 |
| Proper | 3.147 | 0.114 | 5.64 | 2.790 | 3.506 | 5.6 | 3.19 |

Note. Quantities are the semimajor axis (\(a\)), eccentricity (\(e\)), inclination (\(i\)), perihelion distance (\(q\)), aphelion distance (\(Q\)), period (\(P\)), and Tisserand parameter with respect to Jupiter (\(T_j\)). Current orbital elements are from the Minor Planet Center. Proper orbital elements are from our 4.6 billion year numerical integration using the Mercury code (Chambers 1999).

Figure 2. Relative surface brightness profile of 62412 (red squares) and the average of 7 field stars (green diamonds) on the combined 41 30 s \(r\)-band exposures from Magellan. There is no apparent extended brightness for 62412 compared to the field stars. This indicates 62412 has little to no coma surrounding the nucleus.

Figure 3. Semimajor axis vs. inclination for known active asteroids (open circles), known asteroids in a family (red dots), and new active asteroid 62412 (solid blue square). 62412 is the first active asteroid known in the Hygiea family.

3.3. Rotation

We used the phase dispersion minimization (PDM) method to determine possible periodicity in the light curve of 62412.
Semimajor axis vs. eccentricity with symbols the same as in Figure 3. 62412 has one of the lowest known eccentricities of an active asteroid, which is currently around 0.082 though its proper eccentricity averaged over 100 Myr is shown here as 0.114 (see Table 3).

(Stellingwerf 1978). In PDM, the metric is the $\Theta$ parameter, which is essentially the variance of the unphased data divided by the variance of the data when phased by a given period. The best fit period should have a very small dispersion compared to the unphased data and thus $\Theta \ll 1$ indicates that a good fit has been found.  

From Figure 7, it is apparent that a single-peaked period of 1.665 hours and a double-peaked period of 3.33 hours are the best fits to the light curve of 62412. When phasing the data together (Figure 8), it is obvious that the double-peaked period is the best fit as the two minimum peaks have different amplitudes. A double-peaked periodic light curve is produced when an elongated object’s effective radius to our line of sight changes as the object rotates. That is, the projected cross section of an object would go between two minima (short axis) and two maxima (long axis) during one complete rotation. A single-peaked light curve is likely caused by albedo or surface variations.

Thus, we find a double-peaked period of $3.33 \pm 0.01$ hours with a maximum peak-to-peak amplitude of $0.45 \pm 0.01$ mag for 62412. The two brightest peaks, which are when the two opposite sides of maximum surface area of the object are visible, appear to be similar. The two fainter peaks of the light curve are different by about 0.05 mag, showing the object has an elongated irregular shape.

62412 is small enough that its spin is not likely primordial and thus has been modified over the age of the solar system (Steinberg & Sari 2014). The large size and distant orbit of 62412 make it less sensitive to the YORP spin-up effect than the other mostly smaller active asteroids (Nesvorny & Vokrouhlicky 2007; Marzari et al. 2011; Jacobson et al. 2014). The size of 62412 is very near the transition radius where YORP is expected to significantly modify the spins of asteroids (Bottke et al. 2002, p. 395; Pravec et al. 2002, p. 113; Carbognani 2011; Steinberg & Sari 2011). Thus, the short rotation period of 62412 could be from the YORP effect, but, if not from YORP, an impact and/or sublimation of ice off the surface could have initially spun up 62412 to the state it is now (Polishook 2014; Wiegert 2014).

Note. The Sloan colors converted to BVRI using Smith et al. (2002) are $R = 18.02 \pm 0.01$ with $B - R = 1.00 \pm 0.02$, $V - R = 0.36 \pm 0.02$, and $R - I = 0.35 \pm 0.02$. The error on $m_i'$ is large because of the significant light curve while the error on $M_R(1,1,0)$ is shown to be much smaller as we use the mean of the light curve.

3.4. Shape, Critical Period, and Density

For an object that is elongated, the peak-to-peak amplitude of the rotational light curve allows for the determination of the projection of the body shape into the plane of the sky. Assuming we are viewing the object equatorially, the lower limit on the $a$ to $b$ axis ratio is $a/b = 10^{0.4\Delta m}$ (Binzel et al. 1989), where $a \geq b \geq c$ are the semi-axes with the object in rotation about the $c$ axis and $\Delta m$ is expressed in magnitudes. If...
the light curve amplitude of 62412 is caused by an elongated shape, 62412 has \(a/b \geq 1.51\). Using the effective radius of 5.2 km, we get \(a \sim 6.4\) km and \(b \sim 4.2\) km.

An object will be near breakup if it has a rotation period near the critical rotation period \(P_{\text{crit}}\) at which centripetal acceleration equals gravitational acceleration toward the center of a rotating spherical object,

\[
P_{\text{crit}} = \left( \frac{3\pi}{G\rho} \right)^{1/2}.
\]

where \(G\) is the gravitational constant and \(\rho\) is the density of the object. With \(\rho = 2000\) kg m\(^{-3}\), which is on the high end of C-types but about the density of 10 Hyggea and Ceres (Baer et al. 2011; Carry 2012), the critical period is about 3.3 hours. At shorter periods, the object may break apart while slightly longer periods the equilibrium figures are triaxial ellipsoids which are elongated from the large centripetal force (Weidenschilling 1981; Holsapple 2001).

For an elongated strengthless object, the critical period of break-up will occur at a slower spin period (Samarasinha et al. 2004; Jewitt 2012)

\[
P_{\text{crit}} = \left( \frac{a/b}{\rho} \right) \left( \frac{3\pi}{G\rho} \right)^{1/2}.
\]

For 62412, \(a/b \geq 1.51\) and thus \(P_{\text{crit}} \geq 3\) hours for a density of \(2000\) kg m\(^{-3}\). Thus, 62412’s period appears to be near the critical period for break-up and thus the object should be unstable to rotational fission, especially if its density is less than \(2000\) kg m\(^{-3}\), as expected for most C-type asteroids (Mainzer et al. 2012). Holsapple (2004) found that the spin period for instability should be even slower than the simple discussion above, making it even more likely that 62412 is spinning faster than the critical period, though unknown cohesive forces will be important (Richardson et al. 2009; Chang et al. 2014; Rozitis et al. 2014).

Assuming 62412 is at \(P_{\text{crit}}\) and is a strengthless rubble pile, we find from Equation (2) that the density would be about \(1500\) kg m\(^{-3}\), which is significantly greater than expected for comets (Thomas et al. 2013) and as expected for C-type asteroids of 62412’s size (Baer et al. 2011; Carry 2012).

4. DISCUSSION

4.1. Cause of 62412’s Tail

Above we show that 62412 is likely spinning near or faster than its critical speed for breakup. This strongly suggests that the tail observed for 62412 is in part created by its rapid rotation. The observed tail is aligned with the negative velocity vector, which usually means relatively large particles in the orbital plane (Finson & Probststein 1968; Hsieh et al. 2004; Lisse et al. 2004; Moreno et al. 2011a). These large particles could be the remnants of an earlier outburst or slow moving ejected material from 62412’s rapid rotation (see Jewitt et al. 2010; Snodgrass et al. 2010).

Some of the active asteroids appear to show activity within a few months of perihelion, which has been attributed to water ice sublimation (Hsieh et al. 2010, 2011, 2013). For 62412, the first detection of activity was in early 2014, over a year after perihelion (Figure 9). 62412 showed no activity leading up to and just before perihelion in early 2013 from deep images similar to ours that were serendipitously obtained at the CFHT telescope during this time. Thus, the activity likely started or occurred around perihelion or afterwards. It is possible that 62412 has a high thermal inertia since it was not active just before perihelion but is active well beyond perihelion, suggesting heat took awhile to penetrate to depth where ice could be.

The short rotation period may or may not be directly ejecting material off the surface of 62412, but it has likely changed the shape and is shifting or has shifted material around the object (Bottke et al. 2002; Richardson et al. 2005; Minton 2008; Harris et al. 2009; Scheeres 2009; Statler 2009; Holsapple 2010; Walsh et al. 2012; Cotto-Figueroa et al. 2013; Richardson & Bowling 2014). If ices are contained within 62412, this shifting of material could expose fresh ice to the surface, which could then sublimate away dragging material with it. The changing shape and shifting of material from the rapid rotation may be an
ongoing process that could constantly expose new ice. 62412 is a good candidate to have ice buried just under its surface since it is relatively large and the parent body 10 Hygiea was recently shown to have a 3 μm spectral feature indicative of water ice (Takir & Emery 2012).

Our last observations of 62412 in late 2014 August found no obvious tail near the object. Further monitoring of 62412 is necessary to better determine the cause of its activity. If the activity is seen sporadically throughout 62412’s orbit, fissioning of material off the surface is most likely. If the activity only appears near or just after perihelion, ice sublimation would be the most likely cause, though helped by the short rotation period. If no further activity is observed, it is possible 62412 experienced a recent impact that lifted material from the surface.

4.2. Comparison to Other Active Asteroids and Comets

Rapid rotation has been suggested as the cause for the multiple tail features observed for the active asteroid P/2013 P5 PanSTARRS, though no rotation period has been measured to confirm this (Jewitt et al. 2013; Hainaut et al. 2014; Moreno et al. 2014). Active asteroids P/2012 A2 LINEAR and P/2013 R3 Catalina-PanSTARRS have also been suggested as possible rotationally unstable objects, though, again, no rotation periods are known for these objects and impact-generated activity is a more likely scenario for P/2012 A2 LINEAR (Jewitt et al. 2010, 2011; Snodgrass et al. 2010; Hainaut et al. 2012; Hirabayashi et al. 2014). Asteroid pairs, which are asteroids not bound to each other but on very similar orbits with very similar colors, could also have formed from rotational-fission or impacts (Vokrouhlicky & Nesvorny 2008; Pravec & Vokrouhlicky 2009; Pravec et al. 2010; Jacobson & Scheeres 2011; Moskovitz 2012; Jacobson et al. 2014; Polishook et al. 2014; Wolters et al. 2014).

The Themis family member active asteroid 133P has a period of 3.471 hours with an axis ratio greater than 1.45 (Hsieh et al. 2004), which are characteristics similar to 62412. There is no obvious coma around 62412 or 133P, indicating extremely low ejection velocities for dust particles (Jewitt et al. 2014). Both 62412 and 133P are very fast rotators compared to known comets (Jorda & Gutierrez 2000; Samarasinha et al. 2004), and because of their aspherical shapes, are likely near or faster than the critical rotational speed for breakup. Jewitt et al. (2014) suggest the high centripetal acceleration from 133P’s rapidly rotating nucleus aids in the escape of near-surface water ice and dust from the object.

Using data from the updated Asteroid Lightcurve Database (LCDB: Warner et al. 2009), Figure 10 shows that 62412 has the fastest known rotation speed of any object in the mostly C-type Hygiea and Themis families. The active asteroid 133P has the next fastest known rotation of any of these objects. This strongly suggests that these short rotation periods are an important part of the activity seen in these objects.

62412 has a much higher density than any known short- or long-period comet. The short- and long-period comets appear to have densities closer to 1000 kg m\(^{-3}\), which is thought to be because of their more distant formation in the ice-rich outer solar system (Weissman et al. 2004, p. 337). The C-type asteroids probably consist of much more rock giving them a density closer to 2000 kg m\(^{-3}\) (Baer et al. 2011; Carry 2012). Thus, 62412 likely formed in a much different location than the short or long period comets. See Figure 11.

4.3. Number of Active Asteroids

We have observed about 700 square degrees of sky to deeper than 24th magnitude during our ongoing survey for objects beyond the Kuiper Belt edge (Trujillo & Sheppard 2014). The survey has generally been between 5 and 20 degrees from the ecliptic. Because of the depth and large area, our survey has an unprecedented ability to see faint coma and tails around objects that other surveys would not detect. This increased sensitivity means we can detect lower activity active asteroids, which are also likely to be older as activity is expected to decrease over time. Though we would only detect the coma and/or tail of an active object by serendipitous visual inspection, it is generally obvious to identify activity while looking through the survey images. We have looked at all survey images visually while searching for distant solar system objects. In this way we not
only observed a tail to 62412 but also discovered comet C/2014 F3 Sheppard-Trujillo as well as detected many known comets (Sheppard & Trujillo 2014). The faint tail of 62412 was not detected by any other survey even though it was within several automated surveys fields of view and has been imaged many times in the last 15 years.

In this crude way, we can put order of magnitude constraints on the number of possible active asteroids in the MBAs. We detected about 15,000 MBAs and one active asteroid. This detection rate gives a ratio of active asteroid to MBA of 1:15,000. Thus, with about 1–2 million MBAs larger than 1 km predicted (Tedesco et al. 2005), we would expect about 100 active asteroids, which is consistent with earlier estimates (Hsieh 2009).

The Hygiea family likely has about 10,000 members larger than 1 km (Tedesco et al. 2005) and thus we should only expect one as an active asteroid. The Themis family is 100 times larger and thus we expect this family to have the majority of the active asteroids, in which it appears this is the case as 3–5 of the known active asteroids out of 13 total are near the Themis family (Figure 3). This, of course, assumes all asteroids are just as likely to become active. In reality, the spin state, collisional environment, surface properties, and volatile content of the asteroids are very important factors in determining what objects become active. This should favor more MBCs in the outer belt as they are the most likely to have retained water ice over the age of the solar system as shown by the recent possible detections of water ice on Ceres, Themis, and Cybele (Campins et al. 2010; Rivkin & Emery 2010; Licandro et al. 2011; Kuppers et al. 2014).

5. SUMMARY

We report the thirteenth known active asteroid in the main asteroid belt, (62412) 2000 SY178. There is no obvious coma around the object but it exhibits a faint tail. 62412 is about 5 km in radius, making it the second largest known active asteroid. The main results of this paper are as follows.

1. The orbit of 62412 is stable for the age of the solar system and has a Tisserand parameter greater than 3, which is typical of MBAs. We determine that proper orbital elements for 62412 make it the first known active asteroid in the Hygiea family in the outer belt of asteroids.
2. The optical colors of 62412 match those of typical primitive C-type asteroids, which is the dominant type of asteroid in the Hygiea family.
3. 62412 has the highest perihelion and one of the lowest eccentricities of the known active asteroids. The observed tail was first seen over 13 months after perihelion with no activity observed just before perihelion.
4. We find a rapid rotation of 3.33 ± 0.01 hours for 62412. The double-peaked peak-to-peak light curve amplitude of 0.45 ± 0.01 mag suggests 62412 is an elongated object with an a to b axial ratio greater than or equal to 1.51.
5. 62412 is likely rotating faster than the critical period for rotational breakup of a strengthless body. To prevent rotational fission, it must have a density of about 1500 kg m⁻³. This is typical for C-type asteroids and well above known short- and long-period comet densities.
6. 62412 has the fastest spin rate of any known member of the Hygiea or Themis asteroid families as well as any long- or short-period comet. This suggests the spin state may be the cause or is at least a major factor in the observed activity. The rapid rotation may allow particles to directly escape from the surface and likely causes changes in the shape and shifts material around on 62412, which could expose possible buried ices.
7. The number of active asteroids in the main belt is likely to be around 100 objects, consistent with previous estimates.

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