DETECTION OF COMA ACTIVITY OF THE ACO/QUASI-HILDA OBJECT 212P/2000YN$_{30}$

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ABSTRACT

The quasi-Hilda object 212P/2000YN$_{30}$, which has a cometary-like orbit, was found to display a dust tail structure between 2009 January and March. From orbital calculations, it is shown that this object could have been an active comet in the past before being transported to its current orbital configuration in quasi-stable 3:2 resonance with Jupiter.

Key words: comets: general – Kuiper belt: general – minor planets, asteroids: general

1. INTRODUCTION

One basic question in connection to the origin of life and the development of a biosphere has to do with the source of the terrestrial ocean. For exogenic sources, ocean water could have come from either comets or asteroids. The idea that cometary water ice could be the main contributor (Chyba 1987; Ip & Fernandez 1988) has suffered a setback because the D/H isotope ratios measured in several comets are about a factor of two larger than the standard value $1.49 \pm 0.03 \times 10^{-4}$ for ocean water (Eberhardt et al. 1995; Meier et al. 1998; Crovisier et al. 2004; Jehin et al. 2009).

However, the recent report of the D/H ratio ($=1.61 \pm 0.24 \times 10^{-4}$) of the Jupiter family comet (JFC) 103P/Hartley 2 determined from Herschel observations has shed new light on the old issue of terrestrial water (Hartogh et al. 2011). The most recent report of a D/H ratio of $2.06 \pm 0.22 \times 10^{-4}$ for the Oort cloud comet C/2009 P1 (Garradd) by Bockelee-Morvan et al. (2012) has further underscored the point that comets could have a wider range of D/H ratios than previously thought. In any event, they could still make a contribution to the terrestrial water source reservoir within the dynamical constraint of being no more than 10% in total, as estimated by Morbidelli et al. (2000).

We note that among the seven other comets for which D/H ratios have been measured by pre-Herschel spacecraft observations or ground-based observations, C/1995 O1 Hale-Bopp, C/1996 B2 Hyakutake, C/2001 Q4 NEAT, and C/2002 T7 LINEAR are all long-period comets from the Oort cloud, and 1P/Halley, 8P/Tuttle, and 81P/Wild2 are short-period comets (see Jehin et al. 2009). The D/H ratios of the long-period comets—which presumably have a different condensation region from that of the Jupiter-family comets—now range from $2.06 \times 10^{-4}$ (Bockelee-Morvan et al. 2012), $3.3 \pm 0.8 \times 10^{-4}$ (Meier et al. 1998) to $4.6 \pm 1.4 \times 10^{-4}$ for C/2001 Q4 NEAT (Weaver et al. 2008). These values overlap with the range between $1.49 \pm 0.03 \times 10^{-4}$ for 103P/Hartley 2 (Hartogh et al. 2011) and $4.09 \pm 1.45 \times 10^{-4}$ for 8P/Tuttle (Villanueva et al. 2009).

Another basic question of equal importance is, therefore, how would JFCs that presumably originated from the trans-Neptunian region (Duncan et al. 1989; Ip & Fernandez 1991; Volk & Malhotra 2008) have such large differences in the D/H ratios? Could they have formed in different orbital positions in the outer solar nebula before being swept up by planet migration (Fernandez & Ip 1984; Malhotra 1995)? Tiscareno & Malhotra (2003), Di Sisto & Brunini (2007), and Volk & Malhotra (2008) considered the dynamical transformation of the trans-Neptunian objects into Centaur populations with orbits in the Jovian and Saturnian zones and then short-period comets in the inner solar system. Or, some of them could have formed in the asteroidal region but were later implanted in the Kuiper Belt after following a complex history of dynamical evolution. Di Sisto et al. (2005) studied the interesting issue of whether JFCs could be mixed with the Hilda asteroids and vice versa by performing numerical orbital calculations on a stably trapped population in 3:2 resonance with Jupiter and those quasi-stable populations. They found that the majority ($\sim 99\%$) of the escaping Hildas would be perturbed into JFC-like orbits but with perihelia $q > 2.5$ AU. This means that a small fraction ($\sim 1\%$) of them would become near-Earth objects with the possibility of hitting the Earth, according to this study. Whether the Hilda population could have significantly contributed to terrestrial ocean water thus depends very much on the total mass of the original population. Di Sisto et al. (2005) further estimated that at the present time the expected number of comet-sized Hilda asteroids in cometary-like orbits should be on the order of 143, in comparison to about 2800 dormant JFCs.

In a series of papers, Dahlgren & Lagerkvist (1995) and Dahlgren et al. (1997, 1999) reported on their photometric survey of the color distribution of the Hilda asteroids. In one study, they showed that about 36% of the Hildas could be classified as D-type, 28% as P-type, and only 2% as C-type (Dahlgren et al. 1999). The fact that both JFCs and Hilda asteroids share many of the characteristics of the D-type taxonomic class is another possible piece of evidence for a link between these two populations of small bodies. From this point of view, we might pose the hypothesis that comet 103P/Hartley 2 could be an escapee from the Hilda group if the D/H ratio of the Hildas is found to be the same as those of the CI–CM chondrites (Robert 2006).

The above discussion shows the new impetus in the study of asteroids in cometary orbits (ACOs) since they can provide hints on the nature and relationship between terrestrial water and planetesimals formed in the early solar system. This is also why the recent discovery of a small population of main-belt comets or active asteroids (Hsieh & Jewitt 2006; Jewitt 2012) has drawn so much attention. The main belt objects discovered by these authors are all located at the outer edge of the main asteroidal belt with semi-major axes between 3.156 AU and 3.196 AU and near-zero eccentricity. The detection of water ice and organics
The Observation log of 212P by Using the LOT Telescope at Lulin Observatory

| Date     | $R_0$ (AU) | $\Delta$ (AU) | $\alpha$ (deg) | $V$ (mag) | Remark                |
|----------|------------|----------------|----------------|-----------|-----------------------|
| 2009 Jan | 1.683      | 0.959          | 50.4           | 19.594 (±0.064) |                       |
|          | 1.688      | 0.948          | 29.6           | 19.548 (±0.070) | Close to a BG stellar  |
|          | 1.690      | 0.944          | 29.4           | 20.027 (±0.094) | Not photometric night  |
|          | 1.693      | 0.941          | 29.1           | 19.762 (±0.079) |                       |
| 2009 Mar | 1.950      | 1.107          | 20.7           | 20.700 (±0.130) |                       |
|          | 1.955      | 1.115          | 20.8           | 20.512 (±0.129) |                       |
|          | 1.960      | 1.123          | 20.9           | 20.504 (±0.132) |                       |

on the surface of the asteroid 24 Themis has further heightened the interest in this issue (Campsins et al. 2010; Rivkin & Emery 2010).

In our observational program at Lulin, the Tisserand parameter,

$$T_J = \frac{a_J}{a} + 2 \cdot \sqrt{\frac{(a/a_J)(1-e^2)}{2}} \cos i,$$

has been used to select the targets. In the above equation, $a_J$ is the semi-major axis of Jupiter, and $e$ and $i$ are the eccentricity and inclination, respectively, of the object in question. Vaghi (1973) examined the $T_J$ values of the 73 JFCs known at the time and found that the majority of them fall in the range of $2.450 < T_J < 3.032$, and further concluded that those with $T_J > 2\sqrt{2}$ must have originated from elliptical orbits instead of parabolic orbits. Kresak (1980) discussed the variation of the values of the Tisserand parameter among different groups of solar system small bodies and showed that the Hilda asteroids shared the same dynamical characteristics as those of the JFCs, even though not a single asteroidal-like object could be definitely identified as an ex-comet at that time. A recent study by Fernandez et al. (2005) comparing the albedos ($p_V$) and $T_J$ values of 26 asteroids in cometary orbits (including 6 Damocloids and 6 near-Earth asteroids) found the interesting result that there is a discontinuity in the albedo distribution as a function of $T_J$. That is, those with $T_J < 3.0$ would tend to have $p_V \sim 0.04$ and those with $T_J > 3.0$ would have $p_V > 0.2$, thus suggesting different physical origins. For these reasons, we are mainly interested in objects with $T_J < 3$.

In addition to the ACOs and Hilda asteroids, many objects called quasi-Hildas moving in the orbital region of the Hildas but without being stably trapped in the 3:2 mean motion resonance with Jupiter are also included in the Lulin target list according to their $T_J$ values. While Di Sisto et al. (2005) suggested that the Hildas and quasi-Hildas could be closely related to JFCs according to their dynamical behavior, Toth (2006) gave an update on the orbital properties of ecliptic comets in Hilda-like orbits and quasi-Hilda asteroids. Subsequently, Ohtsuka et al. (2008) showed that some of the quasi-Hildas (i.e., 147P/Kushida-Muramatsu) could be the progenitors of temporarily captured irregular satellites of Jupiter. Along the same line, Fernandez & Gallardo (2002) used an orbital integration method to trace the dynamical evolution of inactive JFCs and estimated that up to 20% of the near-Earth asteroid population with $T_J < 3$ could be of cometary origin. Thus, the intercomparison of the surface color variations and size distributions of Hildas/quasi-Hildas, JFCs, and ACOs might give us some hints on the evolution of the surface material and structures of cometary nuclei, namely, from youth to old age in case the ACOs are representative of defunct (i.e., inactive) cometary nuclei. The aim of our observational project is therefore to establish a comprehensive database of the sizes and surface colors of these populations of small bodies with the intention of comparing them to those of the JFCs (Lamy & Toth 2009).

In this work, we bring attention to the serendipitous discovery of the coma activity of an ACO. This object, previously known as 2000 YN$_{30}$ (212P hereafter), was a target in our survey program of ACOs using the LOT 1 m telescope at Lulin Observatory. It was first discovered by the NEAT (Near Earth Asteroid Tracking) group on 2000 December 1 as an asteroid when it was at a solar distance of 1.86 AU just before perihelion. Its orbital parameters of $a = 3.929$ AU, $e = 0.579$, and $i = 22:398$ with $T_J = 2.635$ make it a member of the ACOs. With an absolute magnitude $H = 16.76$ and an R-band geometric albedo $p_R$ of 0.096 ± 0.032, its size can be estimated to be $D = 1.7 \pm 0.3$ km (Fernandez et al. 2005). The fact that 212P has a larger eccentricity and higher inclination than the quasi-Hildas or the outliers listed in Toth (2006) might mean that it could actually be a weakly outgassing comet in transition to an inactive cometary nucleus. On the other hand, we note that two quasi-Hilda asteroids, 2004 FM$_{32}$ and 2002 CF$_{140}$ in Toth (2006), can be shown by numerical calculations to evolve into cometary-like orbits within a million years. Comet 212P might share the same dynamical origin as these two quasi-Hildas.

This paper is organized as follows. In Section 2, we will describe observations and images obtained at Lulin. Section 3 will be dedicated to the discussion of the orbital evolution of 212P. Finally, the summary and discussion will be given in Section 4.

### 2. Observations

The LOT telescope used in this project was equipped with the PI 1300B $1340 \times 1300$ pixels CCD camera. The image scale is 0.516 pixel$^{-1}$. The standard Asahi $BVRI$ broadband filters were used in the photometric measurements. The observational log is given in Table 1. Figure 1 shows the discovery image of 212P’s outgassing activity taken on 2009 January 2 (Cheng et al. 2009). A faint dust tail with a length of about 20′′ or 14,000 km appeared in the anti-sunward direction. Note that 6.5 hr prior to our observation, Gibbs (2009) detected the presence of a diffuse coma surrounding this object that was not there in the previous observational report in 2008 December (Marsden 2008). After confirmation by IAU Circulars, this object was renamed 212P/2000 YN$_{30}$ (NEAT) to reflect its cometary nature.

Since the first detection of the dust tail feature, 212P was routinely monitored at Lulin until March of the same year. As

![Figure 1](image-url)
Figure 2. Follow-up images of 212P from 2009 January 2, until March 17. All the images were composites of three $R$-band images of five minute exposure. North is up and east is to the right. The direction of the Sun is also indicated.

Table 2

| Date     | $r_h$ (AU) | $\Delta$ (AU) | $\alpha$ (deg) | $A_{\rho}$, 3'5 (cm) |
|----------|------------|---------------|----------------|-----------------------|
| 2009 Jan | 2          | 1.683         | 0.959          | 5.341                 |
|          | 5          | 1.688         | 0.948          | 4.712                 |
|          | 6          | 1.690         | 0.944          | 4.410                 |
|          | 7          | 1.693         | 0.941          | 4.927                 |
|          | 8          | 1.695         | 0.938          | 4.573                 |
| 2009 Feb | 17         | 1.822         | 0.945          | 20.0                  |
|          | 21         | 1.839         | 0.961          | 19.7                  |
|          | 23         | 1.848         | 0.969          | 19.6                  |
| 2009 Mar | 16         | 1.945         | 1.099          | 20.6                  |
|          | 17         | 1.950         | 1.107          | 20.7                  |
|          | 18         | 1.955         | 1.115          | 20.8                  |
|          | 19         | 1.960         | 1.123          | 20.9                  |
|          | 20         | 1.965         | 1.132          | 21.1                  |

This interpretation is also consistent with the finding that the $A_{\rho}$ (cm) value as determined according to A’Hearn et al. (1984) varies from 4.6 to 5.3 at the beginning of January to 3.4–4.6, and finally to about 2.8 in March as the comet moved away from the perihelion (see Table 2). The continuous presence of the dust tail between 2009 January and March suggests an uninterrupted emission process through this time interval according to the synchrone approach (Finson et al. 1968). However, we are unable to determine whether or not the dust emission was triggered by the recent excavation of some fresh active region by an impact event.

Next we check the colors of the dust coma. The aperture size of our photometric study is about 6–8 pixels (4200–5600 km) depending on the seeing conditions. The measured values of $B - V$ (0.995 ± 0.189), $V - R$ (0.678 ± 0.092), and $V - I$ (1.008 ± 0.106) at the optical center are consistent with those of the nuclei of JFCs (Lamy & Toth 2009). Because of the faintness of the dust tail, it is not possible to accurately estimate the color of the dust. In any event, the $B - R$ color at a location several arcseconds away from the central nucleus in the tailward direction can be estimated to be about 1.1 ± 0.1 (see Figure 3). This is consistent with the average value of about 1.1 ± 0.3 for cometary dust as summarized in Kolokolova et al. (2004) and the $B - R$ value of the dust tail of comet P/2010 TO20 LINEAR-Grauer which was found to be about 1.2 ± 0.2 (Lacerda 2013). Because the color remains nearly the same along the tail, where the brightness distribution has a much smaller slope as a function of the cometocentric distance than that of the gas coma, we believe that our measurements are not subject to strong contamination by gas emission.

Figure 4 summarizes the orbital positions of 212P during the Lulin observations. The orbits of a number of main-belt comets are also shown for comparison. It can be seen that the coma activity occurred a few days after perihelion and the dust coma remained detectable with LOT for the next two months. An enhanced level of solar heating for the nucleus surface could be the triggering mechanism of the dust tail formation. Other effects might also play a role. For example, the absence of a dust coma when 212P was discovered as an asteroid might have two possible reasons. First, the appearance of a diffuse coma and dust tail in 2009 January could be associated with an outburst of a pocket of volatile material similar to that of comet 17P/Holmes (Lin et al. 2009; Reach et al. 2010) but on a smaller
3. ORBITAL EVOLUTION

Table 3 shows the orbital parameters of 212P from the Jet Propulsion Laboratory (JPL-SBD). We used the Mercury integrator of the Bulirsch–Stoer algorithm (Chambers 1999) for the numerical orbit integrations. All planets from Mercury to Neptune are included in the computation. The step size employed was 0.05 days. The orbital evolution of 212P was traced backward and forward for 100,000 yr in each direction.

Table 3

| Parameter                      | JPL_SBD         |
|--------------------------------|-----------------|
| Perihelion, \(q\) (AU)        | 1.654234        |
| Eccentricity, \(e\)           | 0.578748        |
| Inclination, \(i\) (deg)      | 22.3980         |
| Argument of pericenter (deg)  | 15.0710         |
| Ascending node (deg)          | 98.9294         |
| Epoch of pericenter, \(T_p\) (JD) | 2454803.81008  |
| Orbital epoch (JD)            | 2454481.5       |

scale. Alternatively, the disappearance/non-detection of the dust features in earlier observations could be the result of a seasonal effect connected to the obliquity of the rotating nucleus (Hsieh et al. 2010). It is therefore interesting to know whether 212P is basically a defunct comet with its nucleus surface covered by a dust mantle or if it is of the nature of a new comet that has only recently reached the present perihelion distance. We used numerical computation to trace the dynamical history of 212P.
Figure 5 shows an example of the pattern of orbital evolution according to the JPL ephemeris. In the case of backward integration, 212P was captured into a “short-period” orbit with a \(< 20\) AU at \(T = -46,802\) yr ago as a result of a close encounter with Jupiter at a distance of 0.0063 AU. Its perihelion \((q)\) stays at about 4 AU and aphelion \((Q)\) at about 15 AU. Another close encounter with Jupiter at \(T = -18,250\) yr ago at a distance of 0.021 AU transforms the orbit into a quasi-Hilda orbit with the semi-major axis remaining at about 4 AU. Our calculation shows that repeated planetary perturbations will lead to long-term oscillations in the eccentricity and inclination, with periods varying between a few hundred years to about ten thousand years. At about \(t \sim -18,250\) yr ago, the eccentricity reaches values as high as 0.8, allowing 212P to attain a perihelion distance as close as 0.8 AU to the Sun. It is probably in this time interval that 212P begins its career as a short-period comet. This phase lasts about 250 yr. Subsequently, the orbit of 212P will be transformed to one that increasingly resembles that of a quasi-Hilda asteroid, with \(q\) being raised to larger values between 1 and 3.5 AU. At the present time, the orbital evolution of 212P is in transition from a punctuated long-term 3:2 libration to a relatively smooth long-term libration in \(e\) and \(i\) for the next \(10^5\) yr. According to this sample calculation with the JPL orbital data, 212P will be a very stable quasi-Hilda object from now on.

The study of the orbital evolution of this test particle gives us some idea of the possible origin and fate of an object like 212P. For example, it tells us how an object with a perihelion distance originally outside the orbit of Jupiter could be transformed into a quasi-Hilda in long-term stable 3:2 resonance with Jupiter. However, the orbital elements given in the JPL ephemeris have numerical uncertainties. Furthermore, additional numerical effects could be introduced in the direct integration scheme. It is therefore important to study the statistical pattern of the orbital evolution of 212P by running a number of its clones. The Monte Carlo simulation of the orbital histories of 100 clones of 212P was done by following the description in Bernstein & Khushalani (2000).

The global pattern of the dynamical evolution of 212P-like objects could be formulated by computing the relative fractions of time in the lifetimes of individual test particles (clones) spent in different combinations of orbital parameters. One method that is often used is the statistical distribution of the time intervals in the \(q\) (perihelion) and \(Q\) (aphelion) coordinate system divided into many grids with \(\Delta q = 1\) AU and \(\Delta Q = 1\) AU. The sum of the total time of duration in each grid therefore constitutes the probability, namely, the distribution of residence time or “footprint,” of the object during its orbital evolution.

Figure 6 compares the statistical distributions of the “footprints” of the 212P clones in the orbital space for the past and
future one million years, respectively. The gravitational influences of Jupiter and Saturn are clearly seen. In the cases of the backward and forward integrations, we find several strips and clusters confined within the $q$–$Q$ curve of Jupiter and then some others between those of Jupiter and Saturn, respectively. Similar features can be found between the $q$–$Q$ curves of Saturn and Uranus. Those are objects that are being temporarily trapped between the orbits of these two outer planets. In the forward integration, there are also two horizontal patterns, one has $q$ nearly being fixed at about 5 AU but $Q$ moving from $<10$ AU to $>1000$ AU, and the other one has $q$ being fixed at about 9 AU and $Q$ ranging from 10 AU to beyond 1000 AU. These two tracks are produced by the gravitational scattering of the test particles by Jupiter and Saturn, respectively, to large aphelion distances. Similar “footprint” structures in the backward integration can be understood in the same manner. Because of their large gravitational scattering effect, both Jupiter and Saturn effectively form barriers for further outward diffusion of the test particles to the orbital region of Uranus and Neptune. In the numerical simulations of the injection of trans-Neptunian objects into the inner solar system (see Tiscareno & Malhotra 2003), we would find the presence of “footprints” between the orbit of Neptune and that of Uranus simply because the source region is located in the vicinity of the trans-Neptunian region while Jupiter and Saturn form barriers to inward diffusion.

Therefore, the evolutionary behavior as shown in Figure 6 is what would be expected of short-period comets that are injected from the trans-Neptunian region. However, in our backward integration, random planetary encounters tend to produce a cutoff at Jupiter’s orbit, thus curtailing the reverse paths returning to the trans-Neptunian region and the transitory zone occupied by Centaurs (Tiscareno & Malhotra 2003). The orbital footprints from the forward integration show a pattern similar to that of the backward integration.

These results also indicate that the exact evolutionary histories of quasi-Hilda asteroids are very sensitive to the starting values of the orbital elements. Even small differences could lead to very different outcomes in the orbital integrations. On the other hand, it is interesting to note that in a statistical sense, some of the quasi-Hildas could have originated from the outer solar system via gravitational scattering by Jupiter. In this process, these objects, including 212P, would have moved in orbits with perihelia of less than 1 AU for some short intervals. This means that there is a fair chance that 212P had experienced ice sublimation and gas outgassing from its surface material.

According to estimates of the average physical lifetime of short-period comets (Fernandez 1984; Hughes 2003), the outgassing activity of those with perihelion $q < 1$ AU should decay away with a physical lifetime of $10^3$–$10^4$ yr due to the buildup of a dust mantle. For a short-period comet orbit of $a = 3$ AU and $e = 0.8$, the time spent inside 1 AU is about 0.4 yr per orbit with an orbital period of 5.2 yr. This means that objects with a cumulative time of $\Delta t > 80–800$ yr with $q < 1$ AU over their past orbital evolution would have a high probability of becoming inactive.

Figure 7 shows the statistical distribution of the cumulative time of the 212P clones as a function of heliocentric distance during their individual dynamical evolutions. Note that in our sample of “backward” test runs, a fraction ($\sim 30\%$) of the objects spend more than a total of $\Delta t \sim 100$ yr inside a 1 AU heliocentric distance. From this point of view, it is possible that 212P could have developed a partial dust mantle in its past history as a short-period comet.

4. SUMMARY AND DISCUSSION

In the present work, we report the serendipitous discovery of the coma activity of 212P, which is a quasi-Hilda object in cometary-like orbit. This object, with a diameter of $D = 1.7 \pm 0.3$ km, is the size of a cometary nucleus. The results of our orbital integration show that it could have been captured into a short-period orbit from a Centaur-like orbit. Subsequent close encounters with Jupiter could have transformed its orbit into that of a quasi-Hilda characterized by a 3:2 mean motion resonance. The exact dynamical origin and its fate depend sensitively.
on the starting orbital elements. Our study therefore shows that ACOs/quasi-Hilda asteroids are potentially important in tracing the transport process of volatile materials from the outer solar system to the inner solar system via planetary orbital migration and scattering. 212P will return to perihelion in 2016. Its brightness variation and the possible reappearance of the dust coma activity will be closely monitored so that we can know for sure whether its observed dust tail structure from last time was related to thermal sublimation or not. As for the larger issue of the Hildas and quasi-Hildas (and other classes of objects like the main-belt comets) as potential contributors to terrestrial oceans, we intend to follow up with model calculations of their orbital evolution with and without the possible effects of planetary orbital migration. The definite answer would probably need to wait for in situ (D/H) measurements (or sample returns) from these objects.

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