Discovery of a young asteroid cluster associated with

P/2012 F5 (Gibbs)

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Abstract

We present the results of our search for a dynamical family around the active asteroid P/2012 F5 (Gibbs). By applying the hierarchical clustering method, we discover an extremely compact 9-body cluster associated with P/2012 F5. The statistical significance of this newly discovered Gibbs cluster is estimated to be $> 99.9\%$, strongly suggesting that its members share a common origin. The cluster is located in a dynamically cold region of the outer main-belt at a proper semi-major axis of $\sim 3.005$ AU, and all members are found to be dynamically stable over very long timescales. Backward numerical orbital integrations show that the age of the cluster is only $1.5 \pm 0.1$ Myr. Taxonomic classifications are unavailable for most of the cluster members, but SDSS spectrophotometry available for two cluster
members indicate that both appear to be $Q$-type objects. We also estimate a lower limit of the size of the parent body to be about 10 km, and find that the impact event which produced the Gibbs cluster is intermediate between a cratering and a catastrophic collision. In addition, we search for new main-belt comets in the region of the Gibbs cluster by observing seven asteroids either belonging to the cluster, or being very close in the space of orbital proper elements. However, we do not detect any convincing evidence of the presence of a tail or coma in any our targets. Finally, we obtain optical images of P/2012 F5, and find absolute $R$-band and $V$-band magnitudes of $H_R = 17.0 \pm 0.1$ mag and $H_V = 17.4 \pm 0.1$ mag, respectively, corresponding to an upper limit on the diameter of the P/2012 F5 nucleus of $\sim 2$ km.

Key words: Asteroids, dynamics; Comets; Photometry

1 Introduction

Asteroid families are believed to originate from catastrophic fragmentations of single parent bodies (Zappalà et al., 2002). They are very useful for studying various open problems in asteroid science (Cellino and Dell’Oro, 2010), and have been extensively investigated for almost a century. In principle, it is clear that “fresh” young families, only slightly evolved since the epoch of their formation, may provide more direct information about the collisional events from which they originated. In the last decade, our knowledge about such young families has been increased significantly. Several new ones have been discovered (e.g., Nesvorný et al., 2002, 2003, 2006; Nesvorný and Vokrouhlický, 2006; Nesvorný et al., 2008; Pravec and Vokrouhlický, 2009; Novaković, 2010; Vokrouhlický and Nesvorný, 2011; Novaković et al., 2012a,b), and many have been the subjects of detailed investigations (e.g., Vernazza et al.)

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Still, the search for new young families is very important in many respects. For instance, there is a lack of young and dynamically stable groups belonging to the taxonomic \(C\)-class, as was noted by Novaković et al. (2012b), who found the first such example.

Another reason why young asteroid families are important is their likely relation with a new class of asteroids identified in recent years, collectively known as \textit{active asteroids} (Jewitt, 2012). Active asteroids are objects which move along typical asteroid orbits, but exhibit observable comet-like activity, i.e., mass loss, due to one or more of different physical mechanisms as discussed by Jewitt (2012). The two most plausible explanations for the activity observed for most active asteroids are the sublimation of water ice and the impulsive ejection of material by an impact. The main belt asteroids whose activity driver is most likely to be sublimation are referred to as \textit{main-belt comets} (MBCs; Hsieh and Jewitt, 2006). Objects displaying likely impact-driven activity are known as \textit{impacted asteroids} or \textit{disrupted asteroids}.

The existence of active asteroids, and MBCs in particular, challenges the traditional view that asteroids and comets are two distinct populations, and supports asteroid-comet continuum hypotheses (e.g., Gounelle et al., 2008; Briani et al., 2011). So far, only a little more than a dozen active asteroids have been discovered, but their number is constantly increasing with ongoing survey work (e.g., by the Catalina Sky Survey, Pan-STARRS, and others) and the improvement of the telescopes, detectors, and automated comet-detection algorithms used in such surveys.

The assumption that MBC activity is driven by volatile sublimation implies that
volatile compounds, i.e., ices, must be present on or immediately beneath the surfaces of these objects. It is difficult, however, to explain the survival of ices or other volatiles on (or close to) the surfaces of objects orbiting at the heliocentric distances of the main asteroid belt over Gyr time-scales (Hsieh, 2009; Capria et al., 2012). In fact, sublimation is expected to deplete the volatile content of the external layers of main belt objects over much shorter time scales. Hence, it has been suggested that MBCs could be preferentially found among young asteroid families, since the recently-formed members of these young families could still retain significant reservoirs of volatile material immediately below their surfaces which were previously deeply buried in the interior of the original parent bodies (Nesvorný et al., 2008; Hsieh, 2009; Novaković et al., 2012a).

So far, links between MBCs and young families have been shown in only two cases. 133P/Elst-Pizarro belongs to the young Beagle family, which is estimated to be less than 10 Myr old (Nesvorný et al., 2008). The second example is that of P/2006 VW₁₃⁹, which is a member of a small cluster of objects estimated to be just 7.5 Myr old (Novaković et al., 2012a). If more cases of MBCs belonging to young families can be found, it would lend strong support to the hypothesis that these families could preferentially contain more MBCs than the general asteroid population, which could in turn lead to more efficient searches for even more MBCs and also to greater insights into the physical conditions that give rise to MBC activity. Thus, each time a new MBC is discovered, it is extremely important to check whether or not an associated young asteroid family can be found.

Another reason why one could expect a cometary activity to be shared by different members of a very young family is that a statistical analysis has shown the occurrence of a strong enhancement in the rate of mutual, low-energy collisions among the members of newly-formed families (Dell’Oro et al., 2002). Although the pe-
period during which the intra-member collision rate is enhanced over the background collision rate is found to last only a relatively short time, and is expected to have only a minimal effect on the long-term collisional evolution of the family, this effect could nonetheless have consequences on the cratering record on the surfaces of family members, and could potentially enhance the likelihood of comet-like activity arising on these objects.

Active asteroid P/2012 F5 (Gibbs) (hereafter P/2012 F5) was discovered last year in Mt. Lemmon Survey data (Gibbs et al., 2012). To date, it has been the subject of two published studies (Stevenson et al., 2012; Moreno et al., 2012), both suggesting it is a disrupted asteroid, rather than a MBC. Before the origin of the activity of P/2012 F5 had been conclusively determined, however, we had already begun the search for a dynamical family associated with the object for the reasons described above. We describe the results of that search in this paper.

The paper is organized as follows. First, in Section 2 we compute both the osculating and proper orbital elements of P/2012 F5. We then employ the hierarchical clustering method to search for a family around P/2012 F5, successfully identifying an associated young asteroid cluster that we have named the Gibbs cluster. In Section 3, we determine the age of the Gibbs cluster, and in Section 4 we analyze some of its physical properties. In Section 5 we present the results of an observational search for new MBCs in the region occupied by the cluster, and finally, in Section 6 we discuss our results and conclusions.
2 Search for a dynamical family associated with P/2012 F5 Gibbs

2.1 Determination of orbital elements

To study the dynamical environment of P/2012 F5, we need reasonably good orbital elements for the object. This includes both osculating and proper elements. However, shortly after its discovery, the orbit of P/2012 F5 was still characterized by relatively large uncertainties. Thus, we made an effort to improve this situation as much as possible.

For the purpose of orbit determination, we used three sets of astrometric observations collected over a period of \(~3.6\) years from 2009 September 17 to 2013 May 12. The largest portion of the dataset consists of 125 observations obtained by various observing stations during the discovery apparition in 2012. In addition, 7 recovery observations were obtained by the authors in 2013 using the 3.6 m Canada-France-Hawaii Telescope and the University of Hawaii 2.2 m telescope on Mauna Kea. Finally, 17 precovery observations of this object were also found in Pan-STARRS1 survey data, and were submitted to the Minor Planet Center by the authors, adding an additional 2.4 years to the total observed arc for this object.

This total sample of 149 observations has been used in this work to carry out a refined determination of P/2012 F5’s orbit. The full dataset was first fit to a purely gravitational orbit by weighting every observation according to the average historical performances of the observational station that obtained it. Gravitational perturbations for all of the major planets and the three most massive main belt asteroids were included in the computation. Astrometric residuals for each astrometric position were then computed, and observations showing an offset in excess of \(2''\) were
removed from the sample used to obtain the solution. A new orbit was then computed, and this iterative process was repeated until a stable solution was achieved. The final solution was found after rejecting 37 out of the 149 observations, where all of the rejected observations were obtained in 2012 when the object was active. The anomalous abundance of large outliers during this period is likely due to the peculiar morphology of the object during its active phase, since the long tail structure and the lack of a clearly defined central condensation made it difficult to locate the object’s photocenter (especially for small-aperture telescopes), in turn causing a significant number of inaccurate positions to be reported to the Minor Planet Center. In fact, among the rejected positions, some show astrometric residuals in excess of 10 arcsec, mostly in the tail-ward direction. The resulting osculating orbit (Table 1) includes 112 positions, spanning an arc of 1333 days, and has an RMS of about 0′′.656. The addition of non-gravitational terms following the usual A1/A2 formalism does not improve the orbital fit, and no significant detection of non-gravitational accelerations can therefore be extracted from this dataset.

Having obtained good osculating elements we can then proceed to the determination of proper orbital elements, which we did by applying the methodology developed by Milani and Knežević (1990, 1994). We compute P/2012 F5’s proper semi-major axis (a_p), eccentricity (e_p), and inclination (i_p) and list their values in Table 2.

2.2 Application of the Hierarchical Clustering Method

The next step in our study was to search for the presence of a dynamical asteroid family around P/2012 F5. Families form dense clusters in the three-dimensional space of proper semi-major axis (a_p), proper eccentricity (e_p), and proper inclina-
Table 1

The osculating orbit parameters and their corresponding formal errors at epoch JDT 2456400.5 (2013 Apr 18.0 TT) for active asteroid P/2012 F5.

| Orbital element       | Symbol | Value     | Error    | Units |
|-----------------------|--------|-----------|----------|-------|
| Semi-major axis       | $a$    | 3.0050440 | 9.78e-7  | AU    |
| Eccentricity          | $e$    | 0.0417036 | 2.22e-7  | -     |
| Inclination           | $i$    | 9.73869   | 0.000026 | deg   |
| Argument of perihelion| $\omega$ | 177.82221 | 0.0007   | deg   |
| Longitude of node     | $\Omega$ | 216.85955 | 0.00012  | deg   |
| Mean anomaly          | $M$    | 210.98151 | 0.0008   | deg   |
| Perihelion distance   | $q$    | 2.87972262 | 1.21e-6 | AU    |
| Aphelion distance     | $Q$    | 3.13036534 | 1.15e-6 | AU    |
| Perihelion passage    | $t_p$  | 2457188.112002 | 0.00472 | JD    |

(tation ($i_p$), and can be identified by analyses of the distribution of objects in proper element space to search for such clusterings. In our analysis, we apply the hierarchical clustering method (HCM) to perform this analysis and adopt the ‘standard’ metric, $d_c$, proposed by Zappalà et al., 1990, 1994.

The HCM identifies groupings of objects having mutual separations below a threshold ‘distance’ ($d_c$), which, adopting standard conventions, has units of m s$^{-1}$. We apply the HCM to a catalog of analytically-determined proper elements (Milani and Knežević, 1990, 1994) available at the AstDyS web repository as of November 2012 (http://hamilton.dm.unipi.it/astdys/). Analytical proper elements are reasonably accurate for objects with low to moder-
ate orbital eccentricity and inclination. We use them because they are available for both numbered and multi-opposition asteroids. The proper elements of P/2012 F5 that we obtained here are also added to the catalog.

We carry out our HCM analysis by testing a range of cutoff distances from 5 to 70 m s\(^{-1}\) and noting the number of asteroids that the analysis links to P/2012 F5 at those separations. At the beginning of our search, we change \(d_c\) in discrete steps of 1 m s\(^{-1}\), but after identifying the family at 7 m s\(^{-1}\), we switch to steps of 5 m s\(^{-1}\). Our results are shown in Figure [I]. We find that a cluster of asteroids around P/2012 F5 does indeed exist, and hereafter will refer to it as the Gibbs cluster. This cluster is extremely compact and is clearly separated from background objects in proper element space. Given how compact the core of the cluster is, we do not believe that the asteroids associated with the cluster for \(d_c > 40\) m s\(^{-1}\) are real members.

The structure of the cluster in the space of proper orbital elements is shown in Figure [II]. In this figure, all asteroids located in the region of the Gibbs cluster are shown in two planes (semi-major axis vs. eccentricity and semi-major axis vs. sine of inclination), and by using two different scales. In the plots, the superimposed ellipses represent equivelocity curves, computed according to the Gauss equations (Morbidelli et al., 1995). These ellipses are obtained assuming a velocity change \(\Delta v = 10\) m s\(^{-1}\), argument of perihelion \(\omega = 90^\circ\), and true anomaly \(f = 90^\circ\). The ellipses are shown as an illustration of the limiting distance between the parent body and the other fragments in the isotropic ejection field. However, the ejection field of the Gibbs cluster is clearly asymmetric, a property that is usually interpreted as

\[1\] The usual practice is to name asteroid families after their lowest numbered member. However, for groups that are known to contain an active asteroid and that are discovered as the result of a search around that active asteroid, we have decided to name them after the member known to be active.
Fig. 1. Number of asteroids associated with P/2012 F5 as function of cut-off distance (in velocity space), expressed in m s$^{-1}$. The dominant feature is the existence of a small group consisting of nine members. These objects are very tightly packed in proper orbital element space. 

indicating that a family is the result of a cratering event (Vokrouhlický and Nesvorný, 2011; Novaković et al., 2012b).

2.3 Statistical significance of the cluster

An important additional step in any family identification analysis is evaluation of the statistical significance of any identified groups in order to avoid confusing true families (i.e., clusters of asteroids sharing a mutual collisional origin) with groupings which are simply statistical flukes. To evaluate the significance of the Gibbs cluster, we first note that its members are extremely tightly packed in proper orbital element space. We further note that the density of asteroids in the immediate vicinity of the Gibbs cluster is relatively low. This can be seen by looking at the four plots shown in Figure 2. There are a few background asteroids located inside the equivelocity ellipses in one plot or another, but these are not the same objects in both planes. As such, none of these objects are actually located within the proper
Table 2
List of asteroids belonging to the Gibbs cluster.

| Asteroid a | $a_p$ b | $e_p$ c | $sin(i_p)$ d | $H_e$ e | $D_1$ f | $D_2$ g | $T_{lyap}$ h |
|------------|---------|---------|--------------|---------|---------|---------|-------------|
| 20674      | 3.00423 | 0.02324 | 0.17974      | 12.6    | 17.9    | 9.0     | 0.65        |
| 140429     | 3.00381 | 0.02315 | 0.17972      | 15.0    | 5.9     | 3.0     | 3.33        |
| 177075     | 3.00509 | 0.02289 | 0.17973      | 15.6    | 4.5     | 2.3     | 0.63        |
| 249738     | 3.00481 | 0.02294 | 0.17971      | 15.7    | 4.3     | 2.2     | 0.68        |
| 257134     | 3.00514 | 0.02300 | 0.17970      | 15.8    | 4.1     | 2.1     | 0.67        |
| 321490     | 3.00514 | 0.02299 | 0.17971      | 15.8    | 4.1     | 2.1     | 0.65        |
| 2007 RT$_{138}$ | 3.00484 | 0.02310 | 0.17969      | 15.7    | 4.3     | 2.2     | 0.65        |
| 2002 TF$_{325}$ | 3.00503 | 0.02288 | 0.17968      | 17.1    | 2.3     | 1.1     | 0.67        |
| P/2012 F5  | 3.00386 | 0.02274 | 0.17972      | 17.4    | 2.0     | 1.0     | 0.83        |

a Asteroid number or provisional designation  
b Proper semi-major axis in AU  
c Proper eccentricity  
d Sine of proper inclination  
e Absolute magnitude  
f Diameter in km, when an albedo of $p_v = 0.05$ is assumed  
g Diameter in km, when an albedo of $p_v = 0.2$ is assumed  
h Lyapunov time in Myr

Relatively close to the Gibbs cluster, there is the very large Eos family. This family is among the largest and oldest groups in the main belt (Vokrouhlický et al., 2006). However, the eccentricities of asteroids belonging to the Gibbs cluster are substantially lower than those of Eos family members, even when a possible ex-
Fig. 2. The region of the main asteroid belt in which the Gibbs cluster is located. The plots represent the space of proper orbital elements, in two different planes (top/bottom) and scales (left/right). The members of the cluster are shown as black filled circles, and the size of their symbols is proportional to the corresponding diameter. Nearby background asteroids are shown as gray filled triangles. For the meaning of the elliptical curves, see the text.

ternal halo of Eos family members is considered (Brož and Morbidelli, 2013). We therefore consider the Gibbs cluster to be clearly separated from the Eos family, and likely completely unassociated with it. Moreover, the little spectroscopic data available for the Gibbs cluster also seem to rule out any relation with the Eos family (discussed below).

Nesvorný et al. (2002) furthermore showed that, even within the borders of the large and dense Koronis family, using a very low critical distance threshold for family identification of $d_c = 10 \text{ m s}^{-1}$, clusters of only up to 5 members could be
found by chance. This result suggests that a concentration of asteroids as tight and
dense as the Gibbs cluster is not easily achievable, even within very densely popu-
lated volumes of proper element space, including those occupied by extremely large
asteroid families like Eos, Themis and Koronis, further suggesting that the Gibbs
cluster is a true asteroid family, and not a statistical fluke, and that its members
share a common collisional origin.

To make a more quantitative assessment of the significance of the Gibbs cluster, we
also perform the following test. First, in the space of proper orbital elements, we
generate 1000 different synthetic main asteroid belts, each one including 336 555
fictitious objects drawn from a quasi-random distribution (QRD) fitting the distri-
butions of \( a_p, e_p, \) and \( \sin(I_p) \) exhibited by the known asteroids in the real main
asteroid belt. By doing this, we are able to experiment with different random pop-
ulations while still taking into account the structure of the real asteroid belt. The
complete procedure to obtain the QRD is described in Novaković et al. (2011). We
then apply the HCM to each of our 1000 synthetic main belts. Using the cut-off
distance of 7 m s\(^{-1}\) (the level at which the Gibbs cluster is detected), we fail to
find any group with at least 9 members. We therefore conclude that the statistical
significance of the Gibbs cluster is \( > 99.9\% \).

Despite the results presented above, one should keep in mind that the high statistical
significance of the cluster itself does not imply that there are no interlopers. A priori
we cannot exclude a possibility that any single member is an interloper.
The most appropriate and accurate way to determine the age of a young family is the so-called backward integration method (BIM; Nesvorný et al. (2002)). The strategy behind the BIM relies on the fact that immediately after the disruption of a parent body, the orbits of the fragments are nearly identical (being determined by the ejection velocities through the Gauss equations), but then tend to diverge as a function of time due to planetary perturbations and non-gravitational effects. Consequently, two secular angles that determine the orientation of an orbit in space, namely the longitude of the ascending node ($\Omega$) and the argument of perihelion ($\omega$), for different objects evolve with different, but nearly constant, speeds. After some time, this effect tends to spread out the distributions of $\Omega$ and $\omega$ of the family members uniformly over $360^\circ$. Therefore, the age of a young asteroid family can be determined by numerically integrating the orbits of its members backwards in time until the orbital orientation angles cluster around single values. Of course, this can be reliably done only when a family is sufficiently young that the dynamical evolution of its members, following fragmentation of the parent body, has not yet completely erased information about the primordial orbits.

This method, either in its original form or with some variations, has been used many times in the last decade to estimate the age of young families. For example, the BIM has been used to determine the ages of the Karin cluster (Nesvorný et al., 2002), Veritas family (Nesvorný et al., 2003), Datura cluster (Nesvorný et al., 2006), Theobalda family (Novaković, 2010), and Lorre cluster (Novaković et al., 2012b). Here, we obtain the age of Gibbs cluster using two approaches based on the BIM. First, we determine the cluster’s age by numerically integrating the orbits of the nominal cluster members, as originally proposed by Nesvorný et al. (2002). Second, we re-
fine our estimate using orbital and Yarkovsky clones of the real cluster members, in a way similar to that proposed by Vokrouhlický and Nesvorný (2011).

3.1 Orbital evolution of the cluster members

In our first application of the BIM, only the orbits of real family members are used to estimate the family age. In order to apply the BIM, two conditions must be fulfilled: (1) the family must be young (up to about 10 Myr); and (2) the family members must be dynamically stable. The first condition is nearly certainly satisfied based on the very tight packing of the Gibbs cluster members in the proper orbital space as discussed in Section 2. The fulfillment of the second condition is verified by calculating Lyapunov times ($T_{\text{lyap}}$) for all objects belonging to the cluster. In practical terms, for the purpose of this study, objects are considered stable if $T_{\text{lyap}} > 10^5$ yr. This condition is satisfied for all members of the cluster (see Table 2).

The evolution of the average of the mean differences in the two secular angles, derived from the numerical integration of the orbits of the cluster members, is shown in Figure 3. The results clearly show a tight clustering (within 7 degrees) of both angles at $\sim 1.5$ Myr in the past. This clustering very likely corresponds to the time of family formation. Such a conclusion is additionally supported by the past evolution of individual orbits of all 9 members of the cluster. As it is shown in Fig. 4, both secular angles, the nodal longitudes and arguments of perihelion, were very close at this time. Furthermore, the latter result also indicates that all 9 asteroids are likely real members of the Gibbs cluster.
Fig. 3. The average of differences in the mean longitudes of the ascending nodes $\Omega$ (top), and arguments of perihelion $\omega$ (bottom), for the 9 nominal members of the Gibbs cluster. These results are obtained in a purely gravitational model. The most important feature (clearly visible in both plots) is a deep clustering of both angles occurring about 1.5 Myr in the past.

Fig. 4. The plot shows past orbital evolutions of nodal longitudes, $\Omega$ (top) and arguments of perihelion, $\omega$ (bottom) at about 1.5 Myr ago for all 9 members of the Gibbs cluster. At this time both angles of all 9 asteroids were nearly the same, suggesting that the cluster was created by a recent catastrophic collision.
3.2 Orbital and Yarkovsky clones

To further refine our BIM determination of the age of the cluster, we use a methodology first proposed by Nesvorný and Vokrouhlický (2006) and used in the past to estimate the ages of some young clusters (e.g., Vokrouhlický and Nesvorný, 2011; Novaković et al., 2012b). Thus, we refer the reader to these papers for additional information about the method. In principle, the BIM is affected by two major sources of error. These are due on one hand to unavoidable uncertainties in the orbital elements of known family members, and on the other hand to a well-known secular evolution of the semi-major axis caused by the Yarkovsky thermal force (Bottke et al., 2006). The latter depends, in turn, upon the thermal properties of the objects’ surfaces and on the value of the obliquity angle. As a consequence of the Yarkovsky mechanism, the semi-major axis can either increase or decrease with time. In order to account for the above effects, we extend our analysis by considering a large sample of synthetic clones.

For this analysis, we generate a set of statistically equivalent orbital and Yarkovsky (hereafter ‘yarko’) clones. Specifically, for each nominal member of the Gibbs cluster, we create 10 orbital clones, and for each of the orbital clones, we generate 10 different yarko clones corresponding to different possible drift rates of the orbital semi-major axis. Orbital clones are generated using $3\sigma$ uncertainties of each cluster member’s osculating orbital elements, assuming Gaussian distributions. Yarko clones are distributed randomly over the interval $\pm(da/dt)_{max}$, where $(da/dt)_{max}$

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2 A better way to produce orbital clones would be to use random distribution based on the full correlation matrix. The approach we used here makes clones somewhat more dispersed, resulting in slightly larger uncertainty of the age than necessary. Still, we used this method due to its simplicity.
is the maximum expected value of the semi-major axis drift speed caused by the
Yarkovsky effect. This random $da/dt$ distribution corresponds to an isotropic dis-
tribution of spin axes. At the location of the Gibbs cluster, for a body of $D = 1$ km
in diameter, we use a value of $(da/dt)_{max} = 4 \times 10^{-4}$ AU/Myr, which scales as
$1/D$. This drift limit was determined assuming thermal and physical parameters
appropriate for C-type asteroids (see e.g. Brož and Vokrouhlický, 2008). Note also
that we only take into account the diurnal component of the Yarkovsky effect, be-
cause the seasonal variant is negligible for the objects of these sizes (Bottke et al.,
2006). In this way, we assign a total of 100 statistically equivalent clones to each
real member of the cluster.

We then numerically integrate the orbits of all clones backward in time for 2 Myr
using the ORBIT9 software package (Milani and Nobili, 1988). The adopted dy-
amical model includes four major planets, from Jupiter to Neptune, as perturbing
bodies, and accounts for the Yarkovsky effect.

The age of the cluster is defined as the minimum of the function

$$
\Delta V = na \sqrt{(\sin(i)\Delta \Omega)^2 + 0.5(e\Delta \varpi)^2}
$$

(1)

where $na \approx 17.2$ km s$^{-1}$ is the mean orbital speed of the asteroids in the Gibbs clus-
ter, and $\Delta \Omega$ and $\Delta \varpi$ are the dispersions of the longitude of node and the longitude
of perihelion, respectively (Vokrouhlický and Nesvorny, 2011). We then obtain the
final age of the cluster by performing $10^6$ trials of this procedure, randomly se-
lecting one clone of each member, and determining the minimum of the function
defined above for all of the clone combinations.

The histogram of the ages we obtain using this method is shown in Figure 5. We
find the age of the Gibbs cluster to be $1.5 \pm 0.1$ Myr.
Unfortunately, very little physical and spectral information about the members of the Gibbs cluster exists. The only data at our disposal come from SDSS spectrophotometric observations and corresponding taxonomic classification. Specifically, Gibbs cluster members (140429) 2001TQ$_{96}$ and (177075) 2003FR$_{36}$ are both classified as $Q$-class objects, although with probabilities of only 32% and 13% respectively (see Carvano et al., 2010, for more details on the classification). If these classifications are correct, we might expect all Gibbs cluster members to be $Q$-type asteroids since the members of an asteroid family tend to share similar spectral properties (e.g. Cellino et al., 2002).

This would be a very interesting result because $Q$-type asteroids are spectroscopically more similar to ordinary chondrite meteorites than any other asteroid class (Bus and Binzel, 2002), and it has been suggested that $Q$-class asteroids, which are most common among near-Earth objects (NEOs), have young surfaces. As a consequence, space weathering (SW; Gaffey, 2010; Marchi et al., 2012) has presumably...
not had sufficient time to transform the surfaces of \textit{Q}-class asteroids into those typical of classical and more common \textit{S}-type asteroids. The timescale for an asteroid to transition from \textit{Q}-type to \textit{S}-type is still not well understood. Cellino \textit{et al.} (2010) did not find differences in polarimetric properties of equal-sized members of the Koronis and Karin families, implying that SW acts on timescales shorter than the age of the Karin family, or about 6 Myr. Vernazza \textit{et al.} (2009) claimed that SW rapidly reddens asteroid surfaces in less than 1 Myr. However, this may be inconsistent with the observed fraction of \textit{Q}-type asteroids among NEOs. To reconcile this problem, Binzel \textit{et al.} (2010) proposed that during close encounters between NEOs and the Earth-Moon system, tidal forces could cause surface shaking that rejuvenates the surface regolith of these objects, thus, returning them from \textit{S}-types back to \textit{Q}-types. On the other hand, recent work by Nesvorný \textit{et al.} (2010) suggests a timescale longer than 1 Myr for SW to affect NEO spectra, so there may be no conflict to resolve after all.

Interestingly, the first examples of main belt \textit{Q}-type asteroids were found just recently among the members of very young asteroid families (Mothé-Diniz and Nesvorný, 2008). In this respect, our findings for the Gibbs cluster could be interpreted as an indication that, at these heliocentric distances, SW mechanisms require longer than 1.5 Myrs (our derived age of the family) to change the spectrophotometric properties of bodies having an overall composition similar to that of ordinary chondrites.

However, taxonomic classifications based on multi-band photometry covering only a few color channels are obviously not as precise as classifications derived from full reflectance spectra, and so therefore caution is required to avoid over-interpreting the scarce data at our disposal.

We note that Rivkin \textit{et al.} (2011) analyzed some members of the Koronis family (about 1-2 billion years old) and found that \textit{Q}-type asteroids are also present in the
main-belt among asteroids smaller than about 4 km (see also Thomas et al., 2011, 2012). These results are not necessarily at odds with our conclusions about possibly young surfaces among Gibbs cluster members, but they do perhaps indicate that more work is needed to better understand the nature of \( Q \)-type asteroids.

Other physical parameters can be derived for the members of the Gibbs cluster based on their absolute magnitude values taken from catalogs, and making assumptions about albedo and composition. Given the uncertainties on the few available spectrophotometric data, we decided to assume two different values for the geometric albedo \( p_v \) and the density \( \rho \), assuming two possible physical situations. As such, we consider the case of primitive \( C \)-type objects having low albedo and density \((p_v = 0.05 \text{ and } \rho = 1.3 \text{ g cm}^{-3})\) and the case of \( S \)-type asteroids with higher albedos and densities \((p_v = 0.2 \text{ and } \rho = 2.5 \text{ g cm}^{-3})\) (Carry, 2012).

First, for both sets of physical parameters, we compute the diameters of all cluster members using the absolute magnitudes provided by the AstDyS website. These results are also given in Table 2. It should be noted that the largest member, asteroid (20674) 1999 VT\(_1\), is significantly larger than all other members, about 3 times larger than the second largest member, asteroid (140429) 2001 TQ\(_{96}\). This situation is unlikely to be the consequence of observational incompleteness because all asteroids with \( H < 15 \) at heliocentric distances of \( \sim 3 \) AU are believed to have been discovered (Gladman et al., 2009).

Next, we estimate a lower limit for the diameter of the parent body \( D_{PB} \) (assuming a spherical shape) by summing-up the volumes of all known members. We find that \( D_{PB} \geq 18.3 \text{ km} \) or \( D_{PB} \geq 9.1 \text{ km} \), depending on the albedos assumed for cluster members. Corresponding escape velocities are \( \sim 7.8 \text{ m s}^{-1} \) or \( \sim 5.4 \text{ m s}^{-1} \), respectively for the two cases, taking into account the assumed density values mentioned.
above. We also note that if we follow the arguments developed by Tanga et al. (1999), the parent body’s diameter could not have been less than the sum of the sizes of the two largest members. The resulting parent body size turns out therefore to be on about 24 km (assuming $p_V = 0.05$) or about 12 km (assuming $p_V = 0.2$).

As we have already noted, asteroid 20674 is by far the largest member of the Gibbs cluster. The mass ratio between the largest fragment and the parent body is $M_{LF}/M_{PB} \approx 0.9$. Based on these findings, the collision producing the Gibbs cluster should be considered to be between a catastrophic disruption and a cratering event. Additional information, such as the discovery of more cluster members or better observational data for the cluster members, is certainly needed to better constrain the nature of the initial family-forming fragmentation event.

5 The observations

5.1 Search for new main-belt comets

Young asteroid families located in the outer regions of the asteroid main belt are thought to be the best candidates to look for new main-belt comets (Hsieh, 2009). For these reasons, we have carried out observations of 5 members of the Gibbs cluster and of 2 additional nearby background objects.

From the observational point of view, the major difficulty in identifying new MBCs is that of being able to detect their elusive cometary-like activity that is both weak and transient. Several techniques to attack this problem have been used so far (see Hsieh, 2009; Sonnett et al., 2011; Waszczak et al., 2013, and references therein).

The approach that we followed here includes optical imaging and adopts two dif-
different search methods. The first method is based on the so-called Stellarity Index, derived from SExtractor (Bertin and Arnouts, 1996). This is designed to discriminate between the images of point-like and extended sources. The second method consists in comparing surface brightness profiles of both the target and a nearby reference star (Hsieh and Jewitt, 2005). A possible excess in an asteroid’s profile, would be diagnostic of the presence of a comet-like coma.

We obtained $R$-band imaging of seven targets using the Imager/Low Resolution Spectrograph Do.Lo.Res of the 3.6 m Telescopio Nazionale Galileo (TNG) located at the Observatorio del Roque de los Muchachos (ORM) at La Palma, Canary Islands. Do.Lo.Res (Device Optimized for the Low Resolution) is a focal reducer instrument installed at the Nasmyth B focus of the TNG. The detector is a $2048 \times 2048$ E2V 4240 thinned back-illuminated, deep-depleted, Astro-Broadband coated CCD with a pixel size of 13.5 $\mu$m. The plate scale is $0''252$ pixel$^{-1}$, yielding a field of view of about $8.6' \times 8.6'$. Observations were carried out in service/queue mode between August 2012 and January 2013. Observational circumstances are listed in Table 3.

All the observing nights were photometric, with sub-arcsecond seeing. Seeing data were available in real-time from the TNG DIMM and extinction data in the SDSS $r$ band were available from the webpage of the Carlsberg Meridian Circle telescope at the ORM. For all targets, the same observation sequence was adopted of 12 exposures of 300 s each (total integration time of 3600 s) while tracking each asteroid with its proper differential motion. During each night, a photometric standard star field (Landolt, 1992) was observed to derive the average zero-point. We estimate the errors of the photometric calibration of the fields to be 0.03 mag or less for all fields. Images were reduced following standard procedures using IRAF routines. First, a master bias frame was created for each night by averaging all bias frames obtained...
Table 3

Observational circumstances of the 7 targets observed at the TNG. All observations were obtained using $R$-Johnson filter.

| UT date  | UT time | Target     | Ext.  | DIMM | t  | R  | $\Delta$ | $\nu$ |
|----------|---------|------------|-------|------|----|----|----------|------|
| 17/08/2012 | 2.5579  | 2002 TF$_{325}$ | 0.147 | 0.75 | 3600 | 3.001 | 1.999 | 271.4 |
| 17/08/2012 | 3.8192  | 2007 RT$_{138}$ | 0.147 | 0.75 | 3600 | 2.989 | 2.019 | 278.8 |
| 19/09/2012 | 1.5640  | 16290      | 0.129 | 0.85 | 3600 | 2.851 | 2.123 | 34.2  |
| 19/09/2012 | 2.9158  | 82522      | 0.129 | 0.85 | 3600 | 2.889 | 2.206 | 37.9  |
| 25/09/2012 | 4.3553  | 140429     | 0.171 | 0.90 | 3600 | 2.875 | 2.693 | 40.9  |
| 12/01/2013 | 4.1661  | 177075     | 0.087 | 0.75 | 3600 | 3.025 | 2.283 | 107.8 |
| 12/01/2013 | 5.5408  | 249738     | 0.087 | 0.75 | 3600 | 3.030 | 2.358 | 109.9 |

a Date of the observation
b Universal time of the observation in hrs
c Asteroid (target) number or provisional designation
d Extinction in mag/airmass
e Differential Image Motion Monitor seeing in arcsec
f Total integration time in sec
g Heliocentric distance in AU
h Geocentric distance in AU
i True anomaly in degrees

that night. All images were then bias-corrected by subtracting the corresponding master bias. A master flat-field frame was obtained by averaging the bias-corrected flat-field images and normalizing to the median intensity value. Images were then corrected for pixel-to-pixel response variations dividing by the corresponding flat-field frames. Given the non-negligible apparent differential motion of the asteroids with respect to the background star field, a suitable non-zero differential R.A./Dec.
tracking rate was applied to the telescope TCS for each target. This produces a field where only the asteroid is a point-like source while all the other sources are trailed. The final 3600 s image of each asteroid was obtained by aligning, registering and stacking each 300 s image to the position of the asteroid on the CCD corresponding as measured in the 6th image (i.e. the middle of the acquisition sequence).

The next step is to check for possible signs of cometary activity of the observed objects. Our first approach utilizes SExtractor \cite{1996A&AS..117..393B}, a software package developed to detect, measure and classify sources from astronomical images. Having been originally designed to distinguish between stars and galaxies, it allows users to discriminate between point-like and extended objects.

We use SExtractor to derive all the photometric/morphological parameters such as flux, background level, $R$-band magnitude, FWHM, ellipticity and Stellarity Index (SI). These results are shown in Table 4.

In particular, the latter parameter has been used to discriminate between point-like and extended sources. This parameter is the result of a supervised trained neural network to perform star-galaxy classification. In theory, SExtractor considers objects with SI=0.0 to be galaxies and those with SI=1.0 to be stars. In practice, objects are classified as stars by selecting SI $\geq 0.9$. Since the SI depends on the assumed FWHM of the stars in the image and the 3600 s exposures of our targets only have the target itself as the sole non trailed source, we also acquired a short 20 s exposure of each field so that the differential tracking rate would not produce any smearing of the stars and derived the average FWHM from that image. We take into account any fluctuation of the seeing during the $12 \times 300$ s sequence by checking the DIMM seeing. Despite a differential tracking rate was applied to the TCS we found that 4 out of 7 targets do have a quite elongated PSF (ellipticity values between
Table 4

Photometric Data for our 7 target asteroids. The \( R \)-band magnitude of each object is shown, as well as the \( 5\sigma \) detection limit magnitude for point-like and extended sources in each frame. Stellarity Indices are reported to discriminate between point-like and extended objects.

| Target    | FWHM\(^a\) | \( m_R \)^\(b\) | Limit mag 1\(^c\) | Limit mag 2\(^d\) | SI\(^e\) |
|-----------|------------|-----------------|-----------------|-----------------|----------|
| 2002 TF\(_{325}\) | 0.92       | 21.13           | 24.61           | 25.14           | 0.98     |
| 2007 RT\(_{138}\)   | 0.88       | 19.70           | 24.60           | 25.08           | 0.98     |
| 16290     | 1.21       | 19.12           | 24.12           | 24.95           | 0.97     |
| 82522     | 1.09       | 18.57           | 24.44           | 25.16           | 0.99     |
| 140429    | 1.40       | 20.37           | 23.69           | 24.67           | 0.98     |
| 177075    | 0.93       | 20.31           | 24.67           | 25.21           | 0.98     |
| 249738    | 0.99       | 20.70           | 24.40           | 25.01           | 0.98     |

\(^a\) FWHM in arcsec
\(^b\) \( R \)-band apparent magnitude
\(^c\) \( 5\sigma \) \( R \)-band detection limit magnitude for point-like sources
\(^d\) \( 5\sigma \) \( R \)-band detection limit magnitude for extended sources in mag/arcsec\(^2\)
\(^e\) Sextractor Stellarity Index

0.110 and 0.155). However, we attribute this elongation most likely to the presence of aberrations in the telescope optics, since no Shack-Hartman analysis was performed before observations. This is why we adopted a flexible elliptical aperture (Kron, 1980) instead of a simple circular aperture for photometry. Moreover, this is the best choice when any object could have a intrinsic diffused/elongated structure.

All our targets are found to have SI values of \( \geq 0.97 \). As a result, we conclude that none of the asteroids observed in our program show any evidence of cometary-like activity.
To confirm the above conclusions based on the Stellarity Index, we also analyze all obtained images by comparing surface brightness profiles of each asteroid and a corresponding reference star. This technique is best suited for detecting coma that extends radially in all directions from an object, or directed emission not aligned with the direction of the object’s apparent motion. It cannot be used to detect emission oriented along the direction of an object’s apparent motion.

We combine individual images of each object into a single high signal-to-noise ratio composite image to search for any features that would indicate comet-like activity. In each case, images are shifted and aligned on corresponding object’s photocenter using a fifth-order polynomial interpolation and averaged. As was found by Hsieh and Jewitt (2005), this process produces less noisy profiles than median combination. Additionally, all images are shifted and aligned on the photocenter of a nearby reference field star. We can then obtain one-dimensional surface brightness profiles by averaging over horizontal rows over the entire widths of the object and reference star, and by subtracting sky background sampled from either side of the object or star. These profiles are then normalized to unity and shown together in Figure 6 to search for dissimilarities. Specifically, we looked for excess flux in each asteroid’s profile that would imply the presence of a coma. By analyzing Figure 6 we note that some scatter is present in the wings of some of the asteroid profiles, but we attribute this to low signal-to-noise ratios far from the nucleus. Thus, we conclude that no coma is found, in agreement with results we obtained using method based on the SExtractor.
Fig. 6. Comparison of the surface brightness profiles of the composite images of observed asteroids and corresponding reference stars. Surface brightness is normalized to unity at each profiles peak and is plotted on a logarithmic scale against angular distance in the plane of the sky.

5.2 Observations of P/2012 F5 Gibbs

We also obtained 8 $R$-band images totalling 4080 s of effective exposure time on UT 2013 May 12, and 6 $R$-band images totalling 1800 s of effective exposure time on UT 2013 May 13 of P/2012 F5 using the University of Hawaii (UH) 2.2 m telescope on Mauna Kea. Obtained under photometric conditions, these observations utilized a Tektronix 2048×2048 pixel CCD with an image scale of $0''219$ pixel$^{-1}$ and a Kron-Cousins $R$-band filter. Standard bias subtraction and flat-field reduction
were performed on all images, where flat fields were constructed from dithered images of the twilight sky. Photometry of Landolt (1992) standard stars was obtained by measuring net fluxes (over sky background) within circular apertures, with background sampled from surrounding circular annuli. Asteroid photometry was performed similarly, except that to avoid the contaminating effects of any near-nucleus dust, background sky statistics were measured manually in regions of blank sky near, but not adjacent, to the object. Several (5-10) field stars in the object images were also measured and used to correct for minor extinction variation during each night.

We use these observations to estimate the absolute magnitude of P/2012 F5, finding $H_R \approx 17.0 \pm 0.1$ mag and $H_V \approx 17.4 \pm 0.1$ mag in $R$- and $V$-band respectively, assuming $G = 0.15$ for both filters. While the object appears point-source-like in these images, very large dust grains ejected during P/2012 F5’s original outburst event in 2012 could have a dissipation rate from the nucleus that is slow enough that they had not yet drifted beyond the seeing disk of the nucleus at the time of our observations. If this is the case, their additional scattering surface area could have contributed to the total flux observed from the nucleus, even though no observable evidence of residual activity (either in the form of visible coma or a non-stellar PSF) was present. As such, we cannot absolutely rule out the presence of unresolved large dust grains in the seeing disk of the nucleus. Based on these absolute magnitude limits, we set an upper limit on the diameter of the nucleus of $\sim 2$ km (see Table 2).
Our discovery of a young cluster associated with P/2012 F5 opens many different opportunities for future work. In this respect, three characteristics of the cluster are of particular importance. First, it is extremely compact in proper orbital elements, and its statistical significance is very high, meaning that its members are very likely to be fragments originating from a common parent body. Second, the Gibbs cluster is very young, being only about 1.5 Myr old. Third, it is located in a dynamically cold region of the main-belt, and thus its post-impact evolution is bounded. The study of young and well preserved families like the Gibbs cluster are essential for studies of impact physics, space weathering effects, and dynamical evolution.

In terms of studying space weathering, it is clear that the Gibbs cluster deserves further observations in the near future. In particular, we encourage observations aimed at developing better physical characterizations of the members of the Gibbs cluster, either via broadband photometry or spectroscopy. In this regard, high quality reflectance spectroscopy of the largest member, asteroid (20674) 1999 VT₁, would be extremely valuable. A good opportunity to obtain such spectroscopy will be in September 2014, during the asteroid’s next opposition.

Currently available SDSS data for two Gibbs cluster members suggest that 1.5 Myr is an insufficient length of time at these heliocentric distances to transform ordinary anchondrite spectra into more typical S-type spectra. As we have already cautioned though, these conclusions are based on uncertain data and should be considered preliminary. Fortunately, uncertainties in the physical properties of the cluster members has only limited influence our determination of the age of the cluster. However, as the physical properties of the cluster affect our estimates of the size of the par-
ent body, better physical characterizations of cluster members would certainly be
useful for refining our understanding of the initial family forming event.

As explained in Section 5, we were unsuccessful in our attempts to detect comet-
like activity among other members of the Gibbs cluster. This can be interpreted
either as a consequence of the fact that some faint activity could actually be present,
but it was below the detection limits of our observations. The other possibility is
that activity was actually absent, at least at the times when our observations were
carried out. Activity is known to be transient even for currently active MBCs (e.g.,
Hsieh et al., 2010, 2011), and only three of our targets were observed within the
approximate true anomaly range (−50° ≲ ν ≲ 90°; i.e., close to and following peri-
helion) where other MBCs have shown activity in the past (Hsieh et al., 2012).

However, perhaps the most important issues to keep in mind when interpreting
the lack of any detected activity in our observations of fellow cluster members of
P/2012 F5, is their composition as well as the active nature of P/2012 F5 itself. The
MBCs are expected to be low-albedo, icy-bearing objects, with spectra most closely
resembling that of C-type asteroids. If it turns out that the Gibbs cluster is indeed
composed of Q-type objects, as suggested by SDSS data, this would explain why
we did not find any activity in these asteroids. This hypothesis is supported by the
studies by Stevenson et al. (2012) and Moreno et al. (2012) who found that P/2012
F5’s activity was most likely due to an impact from another asteroid and not comet-
like sublimation of volatile ices.

Thus, while we did not successfully detect any new comet among the Gibbs cluster,
this result does not necessarily invalidate the hypothesis that young asteroid fami-
lies and main-belt comets are linked, as there are several plausible explanations for
why no activity was detected. In fact, if P/2012 F5’s activity was due to an impact
and not sublimation, making it a disrupted asteroid and not a comet, we perhaps
would not even expect to find other similar instances of comet-like activity given
the low likelihood of impacts in the asteroid belt, even in families as young as the
Gibbs cluster. As such, while the Gibbs cluster will certainly be an interesting sub-
ject for further studies of space weathering and catastrophic collisions in the main
asteroid belt, confirmation of the hypothesized link between young families and
main-belt comets will likely have to come from elsewhere.

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