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The main-belt comets: The Pan-STARRS1 perspective

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ABSTRACT

We analyze a set of 760475 observations of 333026 unique main-belt objects obtained by the Pan-STARRS1 (PS1) survey telescope between 2012 May 20 and 2013 November 9, a period during which PS1 discovered two main-belt comets, P/2012 T1 (PANSTARRS) and P/2013 R3 (Catalina-PANSTARRS). PS1 comet detection procedures currently consist of the comparison of the point spread functions (PSFs) of moving objects to those of reference stars, and the flagging of objects that show anomalously large radial PSF widths for human evaluation and possible observational follow-up. Based on the number of missed discovery opportunities among comets discovered by other observers, we estimate an upper limit comet discovery efficiency rate of ~70% for PS1. Additional analyses that could improve comet discovery yields in future surveys include linear PSF analysis, modeling of trailed stellar PSFs for comparison to trailed moving object PSFs, searches for azimuthally localized activity, comparison of point-source-optimized photometry to extended-source-optimized photometry, searches for photometric excesses in objects with known absolute magnitudes, and crowd-sourcing. Analysis of the discovery statistics of the PS1 survey indicates an expected fraction of 59 MBCs per 10^6 outer main-belt asteroids (corresponding to a total expected population of ~140 MBCs among the outer main-belt asteroid population with absolute magnitudes of $12 < H_V < 19.5$), and a 95% confidence upper limit of 96 MBCs per 10^6 outer main-belt asteroids (corresponding to a total of ~230 MBCs), assuming a detection efficiency of 50%. We note however that significantly more sensitive future surveys (particularly those utilizing larger aperture telescopes) could detect many more MBCs than estimated here. Examination of the orbital element distribution of all known MBCs reveals an excess of high eccentricities ($0.1 < e < 0.3$) relative to the background asteroid population. Theoretical calculations show that, given these eccentricities, the sublimation rate for a typical MBC is orders of magnitude larger at perihelion than at aphelion, providing a plausible physical explanation for the observed behavior of MBCs peaking in observed activity strength near perihelion. These results indicate that the overall rate of mantle growth should be slow, consistent with observational evidence that MBC activity can be sustained over multiple orbit passages.

1. Introduction

1.1. Active asteroids: main-belt comets and disrupted asteroids

In recent years, an increasing number of objects have been discovered that occupy asteroid-like orbits in the main asteroid belt but have shown evidence of comet-like activity, typically in the form of transient comet-like dust emission. The suspected sources of this dust emission vary. Some instances of activity are believed to result from comet-like sublimation of volatile sub-surface ice (e.g., Hsieh et al., 2004; Hsieh et al., 2009a; Hsieh et al., 2010; Hsieh et al., 2011b; Hsieh et al., 2012b; Hsieh et al., 2012c; Hsieh et al., 2013a; Moreno et al., 2011; Moreno et al., 2013; Licandro et al., 2013a; Jewitt et al., 2014a; Jewitt et al., 2014b), and the objects exhibiting this type of activity have come to be known as main-belt comets (MBCs; Hsieh and Jewitt, 2006). For

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most MBCs, the presence of gas is only inferred by the presence and behavior of visible dust emission and is not directly detected. However, a direct detection of water vapor outgassing has recently been made for main-belt object (1) Ceres by the *Herschel Space Observatory* (Küppers et al., 2014), marking the first time that sublimation on a main-belt object has been unambiguously detected.

In other instances, apparent comet-like dust emission is found to be the result of impacts, rotational destabilization, or a combination of several of these types of effects (e.g., Jewitt et al., 2010; Jewitt et al., 2011; Jewitt et al., 2013b; Snodgrass et al., 2010; Bodewits et al., 2011; Ishiguro et al., 2011a; Ishiguro et al., 2011b; Stevenson et al., 2012; Moreno et al., 2011; Moreno et al., 2012; Moreno et al., 2014). In these cases, the objects can be referred to as disrupted asteroids (cf. Hsieh et al., 2012a). Instances where a combination of both sublimation and disruptive effects may be responsible for activity are also possible, such as the cases of 133P/Elst-Pizarro, for which rapid nucleus rotation may enhance the strength of its repeated dust emission events (Jewitt et al., 2014b), and P/2013 R3 (Catalina-PANSTARRS), for which rapid nucleus rotation may have induced its disintegration, but sublimation may have been responsible for ongoing post-disintegration activity (Jewitt et al., 2014a). In such cases, the inferred presence of ice is the defining characteristic, and as such, we still consider these objects as MBCs.

MBCs have attracted interest in astrobiology for their potential to constrain theoretical studies indicating that material from the asteroid belt region could have been a significant primordial source of the water and other volatiles on Earth (e.g., Morbidelli et al., 2000; Raymond et al., 2004; O'Brien et al., 2006; Hsieh, 2014a). The existence of water in the asteroid belt in the past has long been inferred from the existence of hydrated minerals in CI and CM carbonaceous chondrite meteorites believed to originate from main-belt asteroids (e.g., Hiroi et al., 1996; Burbine, 1998; Keil, 2000), as well as from spectroscopic observations of asteroids themselves (cf. Rivkin et al., 2002). If ice is still present today in the asteroid belt, as the MBCs and other recent work (e.g., Rivkin and Emery, 2010; Campins et al., 2010; Takir and Emery, 2012) suggests, it would represent a opportunity to probe a potential primordial water source through compositional and isotopic studies using either in situ measurements by a visiting spacecraft or some of the next-generation extremely large telescopes now in development. Icy asteroids also contain some of the least altered material from the inner part of the protosolar disk still in existence today, and could give insights into the early stages of the formation of our Solar System. The added bonus of their close proximity in the main asteroid belt means that in situ spacecraft studies are feasible given present-day technical capabilities.

Collectively, MBCs and disrupted asteroids comprise the class of objects known as active asteroids (e.g., Jewitt, 2012). Orbits of small Solar System bodies are typically classified as asteroidal or cometary using the Tisserand parameter, or Tisserand invariant, with respect to Jupiter, T_J, as the primary dynamical discriminant, where asteroids have $T_J > 3$ and comets have $T_J < 3$ (Kresák, 1972). As such, a full accounting of active asteroids includes not only objects found in the main asteroid belt, but also other comet-like objects such as (2201) Oljato, (3200) Phaethon, and 107P/(4015) Wilson–Harrington (Russell et al., 1984; Jewitt et al., 2013a; Bowell et al., 1992), which have $T_J > 3$ but whose orbits carry them well outside the asteroid belt. In this work here, however, we are primarily interested in objects in the main asteroid belt. The currently known active asteroids found in the main asteroid belt (as of 2014 August 1), along with their orbital elements and absolute magnitudes, are listed in Table 1. The most likely classification of each object as either a MBC or disrupted asteroid based on the available evidence (e.g., numerical modeling indicating whether dust production is impulsive or ongoing, photometric measurements showing steady, increasing, or decreasing dust cross-sections, or observations of repeated activity; cf. Hsieh et al., 2012a) is also indicated, except for 233P/La Sagra, for which no physical analysis is available at this time. We also plot the orbital elements of the known active asteroids in the main asteroid belt in Fig. 1.

Table 1
Known active main-belt asteroids[i].

Name	Type[a]	a[b]	e[c]	i[d]	T_J[e]	P_{orb}[f]	H_V[g]	Refs.[h]
(1) Ceres[j]	MBC	2.767	0.076	10.59	3.310	4.60	3.3	[1]
133P/Elst-Pizarro = (7968)[j]	MBC	3.160	0.162	1.39	3.184	5.61	15.9	[2]
176P/LINEAR = (118401)[j]	MBC	3.194	0.194	0.24	3.166	5.71	15.5	[3]
238P/Read	MBC	3.165	0.253	1.27	3.153	5.63	19.5	[4]
259P/Garradd	MBC	2.726	0.342	15.90	3.217	4.50	20.1	[5]
288P/2006 VW_{139} = (300163)[j]	MBC	3.051	0.201	3.24	3.203	5.32	16.9	[6]
P/2010 R2 (La Sagra)	MBC	3.099	0.154	21.40	3.099	5.46	18.8	[7]
P/2012 T1 (PANSTARRS)	MBC	3.154	0.236	11.06	3.135	5.60	>16.9	[8]
P/2013 R3 (Catalina-PANSTARRS)	MBC	3.033	0.273	0.90	3.184	5.28	>15.4	[9]
(596) Scheila[j]	DA	2.927	0.165	14.66	3.209	5.01	8.9	[10]
P/2010 A2 (LINEAR)	DA	2.290	0.125	5.25	3.583	3.47	22.0	[11]
P/2012 F5 (Gibbs)	DA	3.004	0.042	9.74	3.229	5.21	17.4	[12]
311P/PANSTARRS (2013 P5)	DA	2.189	0.115	4.97	3.661	3.24	>18.7	[13]
233P/La Sagra	?	3.037	0.409	11.28	3.081	5.29	>18.6	[14]

[a] Type of active asteroid (MBC: main-belt comet; DA: disrupted asteroid; ?: unknown).
[b] Osculating semimajor axis, in AU.
[c] Osculating eccentricity.
[d] Osculating inclination, in degrees.
[e] Tisserand parameter with respect to Jupiter.
[f] Orbital period, in years.
[g] Absolute *V*-band magnitude of nucleus.
[h] References: [1] Tedesco et al. (2004); Küppers et al. (2014); [2] Elst et al. (1996); Hsieh et al. (2010); [3] Hsieh et al. (2006); Hsieh et al. (2011a); [4] Read et al. (2005); Hsieh et al. (2011b); [5] Garradd et al. (2008); MacLennan and Hsieh (2012); [6] Hsieh et al. (2011c), Hsieh et al. (in preparation); [7] Nomen et al. (2010); Hsieh (2014b); [8] Wainscoat et al. (2012); Hsieh et al. (2013a); [9] Hill et al. (2013); Jewitt et al. (2014a); [10] Tedesco et al. (2004); Larson (2010); [11] Birtwhistle et al. (2010); Jewitt et al. (2010); [12] Gibbs et al. (2012); Novaković et al. (2014); [13] Bolin et al. (2013g); Jewitt et al. (2013b); [14] Mainzer et al. (2010).
[i] Objects known as of 2014 August 1. All osculating orbital elements provided by JPL's online small-body database browser (http://ssd.jpl.nasa.gov/sbdb.cgi).
[j] Previously known as an apparently inactive asteroid prior to discovery of comet-like activity.