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Searching for main-belt comets using the Canada–France–Hawaii Telescope Legacy Survey

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ABSTRACT

The Canada–France–Hawaii Telescope Legacy Survey, specifically the Very Wide segment of data, is used to search for possible main-belt comets. In the first data set, 952 separate objects with asteroidal orbits within the main-belt are examined using a three-level technique. First, the full-width-half-maximum of each object is compared to stars of similar magnitude, to look for evidence of a coma. Second, the brightness profiles of each object are compared with three stars of the same magnitude, which are nearby on the image to ensure any extended profile is not due to imaging variations. Finally, the star profiles are subtracted from the asteroid profile and the residuals are compared with the background using an unpaired T-test. No objects in this survey show evidence of cometary activity. The second survey includes 11438 objects in the main-belt, which are examined visually. One object, an unknown comet, is found to show cometary activity. Its motion is consistent with being a main-belt asteroid, but the observed arc is too short for a definitive orbit calculation. No other body in this survey shows evidence of cometary activity. Upper limits of the number of weakly and strongly active main-belt comets are derived to be 630 ± 77 and 87 ± 28, respectively. These limits are consistent with those expected from asteroid collisions. In addition, data extracted from the Canada–France–Hawaii Telescope image archive of main-belt Comet 176P/LINEAR is presented.

1. Introduction

Historically, asteroids and comets have been thought as two separate populations in the Solar System. Having differing volatile fractions, a common distinction between the two is comets display a coma, while asteroids do not. In addition, the two populations differ dynamically. A standard criterion used to differentiate between a cometary or asteroidal orbit is the Tisserand parameter with respect to Jupiter,

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

where a_J is the semi-major axis of Jupiter, and a, e, and i are the semi-major axis, eccentricity, and inclination of the object, respectively. Comets typically have $T_J < 3$, while asteroids have $T_J > 3$.

Recently, surveys such as those discussed in Fernández et al. (2005), Jewitt (2005), and Licandro et al. (2008) have discovered a significant number of asteroids in comet-like orbits. There are also objects in asteroid-like orbits that show bursts of cometary activity (7968 = 133P/Elst-Pizzaro; Elst et al., 1996) or are associated with meteor streams (near Earth object 3200 Phaethon; Whipple, 1983). These observations have made the boundary between comets and asteroids less obvious. Intermediate objects may be comets that are extinct, dormant, or dead. Conversely, they may be asteroids with higher volatile content.

Objects that display activity but are in asteroid-like orbits are known as main-belt comets (MBCs) or activated asteroids (AAs) (Hsieh and Jewitt, 2006a). These objects are most likely native to the asteroid belt (Fernández et al., 2002) and may be activated by a collision with a small body (Boehnhardt et al., 1998; Toth, 2000). Hsieh and Jewitt (2005, 2006) carry out the first survey to search for MBCs and, as of this writing, only three MBCs have been found: 133P/Elst-Pizzaro (Elst et al., 1996), P/2005 U1 (Read et al., 2005) and 176P/LINEAR (Hsieh and Jewitt, 2006a).

In this paper, we present a study using the Canada–France–Hawaii Telescope (CFHT) Legacy Survey data to search for cometary activity in dynamically asteroidal bodies. The first (smaller) data set is subjected to stringent tests designed to detect weak activity. These objects are examined by comparing their full-width-half-maximum (FWHM) measurements and brightness profiles to those of stars of similar magnitude. If the profile of the asteroid is broader than those of the stars, it may indicate the presence of a coma. For such objects, the star profiles are subtracted from the profile of the asteroid, and an unpaired T-test is used to compare the residuals with the background to determine whether they are significantly different. A second (larger) data set is visually exam-

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ined for evidence of stronger cometary activity. Using results from both methods, upper limits are derived for the number of weakly and strongly active MBCs and are compared to those expected from collisional activation of asteroids. Finally, we present measurements of the known MBC 176P/LINEAR in the CFHT archive.

2. Observations and data reduction

All images were acquired with MegaCam on the 3.6-m CFHT in Hawaii. The images were taken as part of the Very Wide (VW) segment of the CFHT Legacy Survey (CFHTLS; Jones et al., 2006). The asteroids forming the first data set were observed on 2004 December 15–16, 2005 January 16–17, and 2006 May 1–2 and 25–26. All observations were taken in either the g' or r' filters, with exposure times of 90 s and 110 s, respectively. The limiting magnitude for a 90% probability of a 3σ detection in the g' filter was 22.5, and 21.75 for the r' filter. The average seeing size was $1''$ in both filters.

The observations for the second data set were taken on various dates between August 2003 and January 2008. The exposure times for the g' and r' filters were 70–110 s and 110–180 s, respectively, yielding comparable limiting magnitudes to the observations above.

The images were pre-processed using the Elixer pipeline (Magnier and Cuillandre, 2004). A fine astrometric correction was applied by the TERAPIX data-processing center, and the data was stored at the Canadian Astronomical Data Centre (CADC). Source Extractor (Bertin and Arnouts, 1996) and additional software designed for detecting moving bodies were used to find asteroidal objects. A more detailed explanation of the observations and data reduction process for the smaller data set are found in Wiegert et al. (2007), which used that data to investigate the size distribution of kilometer-sized main-belt asteroids (MBAs) as a function of color.

For both data sets, each field was typically observed three times on the first night, approximately 45 min apart, and once the following night. This allowed for a reasonable determination of orbit parameters for main-belt objects. The observations were taken at opposition and were not selected based on their possible main-belt content. Unlike other searches for MBCs, which focus on individual objects (Chamberlin et al., 1996; Luu and Jewitt, 1990) or asteroid families (Hsieh and Jewitt, 2006a), this was a relatively unbiased survey of the main-belt. This allowed for a determination of the upper limit of MBCs expected for the whole main-belt, rather than for a sub-population. In this study, observations from the first night were utilized to search for cometary activity. When a second night of data was acquired, it was used for orbit refinement.

3. Data analysis

3.1. Three-level analysis

To determine whether an asteroid showed evidence of cometary activity, three levels of analysis were chosen, each refining the number of possible MBC candidates. The investigation began with 1468 asteroids that were determined to be small bodies in the main-belt by visual inspection of image triplets (Wiegert et al., 2007) (each of these objects were also included in the visual investigation discussed below). The analysis was limited to objects with magnitudes less than 21.5 since the wings of the seeing profiles of fainter asteroids became too noisy for reliable examination in subsequent stages. Applying this limit left 952 objects to be examined.

In the first level of analysis the FWHM measurements of the objects and stars were compared. Each asteroid image was rotated by the angle of the direction of motion, calculated from the RA and Dec coordinates, such that the direction of motion lied on the horizontal axis. The FWHM was measured perpendicular to the direction of motion using IRAF's IMEXAMINE tool. The FWHM along the direction of motion of the asteroid was not measured, since the images were trailed.

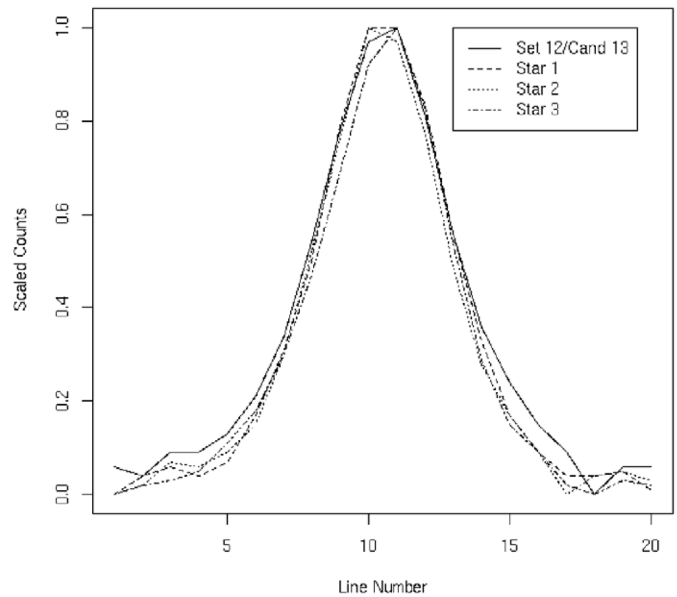

Fig. 1. The solid black line represents the brightness profile of an asteroid in the sample, while the three dotted lines represent the profiles of three comparison stars on the same chip. The asteroid shows slightly more counts in the wings, possibly due to a coma.

All stars in the image were divided into magnitude bins (0.25-mag wide) and the median FWHM of each bin was calculated. The FWHMs of each asteroid and stars in the same magnitude bin were compared. If the FWHM of the asteroid was greater than 110% of the FWHM of the stars in two or more observations the asteroid was passed to the next analysis level. The arbitrary limit of 110% was chosen to provide a substantial number of asteroids with the highest FWHMs. Of the initial 952 asteroids, 415 passed this test.

In the second level of analysis, the brightness profile of each asteroid was compared to three stars of similar magnitude (± 0.25 mag) on the same image and CCD chip. This eliminated the effect of imaging variances across the CCD. The brightness profiles were created from a 20×20 matrix of pixel counts. The counts of the columns were averaged, the background was subtracted and the columns were plotted as a function of the line number. Each profile was subsequently scaled to a height of unity.

The profiles of the asteroids were examined for interesting features (i.e., extended wings) when compared visually to the stars. Although this process was subjective, the intention was to select objects having scaled counts in the wings more than 0.05 higher than the stars. An example of a typical extended profile that passed this test is shown in Fig. 1. There were 65 asteroids that showed a similar feature to Fig. 1, and subsequently passed this test.

In the third level of analysis, the three star profiles were subtracted from the asteroid profile and an unpaired T-test was used to compare the residuals with the background noise. Using this method, 14 objects had residuals that were significantly different (i.e., $T > 2$ for $\alpha = 0.05$) from the background in at least two observations.

The images of those 14 objects were examined more carefully. All of the asteroids were either overlapping or near a background object, internal reflections, or artifacts due to bright stars, thus making the object appear more extended. Therefore, no asteroids