broad range of optical applications, such as data storage and readout, medical diagnostics, surveillance imaging, and light-field photography.

References and Notes

1. J. H. van Hateren, in *Facets of Vision*, D. G. Stavenga, R. C. Hardie, Eds. (Springer-Verlag, Berlin, 1989), pp. 74–89.
2. M. F. Land, *Annu. Rev. Entomol.* **42**, 147 (1997).
3. D. G. Stavenga, J. H. van Hateren, *J. Opt. Soc. Am. A* **8**, 14 (1991).
4. A. W. Snyder, in *Comparative Physiology and Evolution of Vision in Invertebrates A: Invertebrate Photorecepters*, H. Autum, Ed. (Springer-Verlag, Berlin, 1979), pp. 225–314.
5. R. C. Hardie, in *Progress in Sensory Physiology*, D. Ottoson, Ed. (Springer-Verlag, Berlin, 1985), pp. 1–79.
6. R. C. Hardie, K. Vogt, A. Rudolph, *J. Insect Physiol.* **35**, 423 (1989).
7. J. Tanida *et al.*, *Appl. Opt.* **40**, 1806 (2001).
8. J. Duparre, P. Dannberg, P. Schreiber, A. Brauer, A. Tunnermann, *Appl. Opt.* **44**, 2949 (2005).
9. S. Ogata, J. Ishida, T. Sasano, *Opt. Eng.* **33**, 3649 (1994).
10. K. Hamanaka *et al.*, *Opt. Rev.* **3**, 264 (1996).
11. L. P. Lee, R. Szema, *Science* **310**, 1148 (2005).
12. D. G. Stavenga, *J. Comp. Physiol. A* **189**, 1 (2003).
13. J. Kim, K. Jeong, L. P. Lee, *Opt. Lett.* **30**, 5 (2005).
14. A. S. Kewitsch, A. Yariv, *Opt. Lett.* **21**, 24 (1996).
15. M. Kagami, T. Yamashita, H. Lto, *Appl. Phys. Lett.* **79**, 1079 (2001).
16. S. Shoji, S. Kawata, A. Sukhorukov, Y. S. Kivashar, *Opt. Lett.* **27**, 185 (2002).
17. U. Streppel, P. Dannberg, C. Wachter, A. Brauer, R. Kowarschik, *Appl. Opt.* **42**, 3570 (2003).
18. T. Yamashita *et al.*, *IEEE Photonics Technol. Lett.* **16**, 801 (2004).
19. Y. Xia *et al.*, *Science* **273**, 347 (1996).
20. R. Feng, R. J. Farris, *J. Micromechanics Microengineering* **13**, 80 (2003).
21. J. S. Sanders, C. E. Halford, *Opt. Eng.* **34**, 222 (1995).
22. B. Greiner, W. A. Ribi, E. J. Warrant, *Cell Tissue Res.* **316**, 377 (2004).
23. S. B. Laughlin, G. A. Horridge, *J. Comp. Physiol. A* **74**, 329 (1971).
24. A. W. Snyder, C. Pask, *J. Comp. Physiol. A* **80**, 51 (1972).
25. D. G. Beersma, B. J. Hoenders, A. M. Huiser, P. V. Toorn, *J. Opt. Soc. Am.* **72**, 583 (1982).
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A Population of Comets in the Main Asteroid Belt

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Comets are icy bodies that sublimate and become active when close to the Sun. They are believed to originate in two cold reservoirs beyond the orbit of Neptune: the Kuiper Belt (equilibrium temperatures of ~40 kelvin) and the Oort Cloud (~10 kelvin). We present optical data showing the existence of a population of comets originating in a third reservoir: the main asteroid belt. The main-belt comets are unlike the Kuiper Belt and Oort Cloud comets in that they likely formed where they currently reside and may be collisionally activated. The existence of the main-belt comets lends new support to the idea that main-belt objects could be a major source of terrestrial water.

Temperatures in the outer parts of the protoplanetary disk of the Sun, beyond a critical distance known as the snow line (*1*), were low enough for water to condense as ice. The icy planetesimals that formed beyond the snow line are the progenitors of today's comets—ice-rich bodies that sublimate when close to the Sun, producing distinctive unbound atmospheres ("comae") and tails (*2*). The active lifetimes [$\sim10^4$ years (*3*)] of comets that pass inside Jupiter's orbit are short relative to the age of the solar system (4.6×10^9 years). This means that currently active comets must have only recently arrived in the inner solar system from cold reservoirs elsewhere, otherwise they would have exhausted their volatile material long ago. Two such originating reservoirs are well established. The Kuiper Belt (*4*) beyond Neptune (~30 to 50 AU from the Sun) supplies the so-called Jupiter-family comets (JFCs), whereas the much more distant Oort Cloud (*5*) (~3000 to 50,000 AU) supplies the Halley-family and long-period comets (*3*, *6*).

Although the dominant cometary reservoirs are located beyond the orbit of Neptune, the main cometary volatile, water, is stable as ice down to much smaller heliocentric distances (*7*), and it has long been suspected that other populations (such as the Hilda asteroids at 4 AU and the jovian Trojans at 5 AU) might be ice-rich, dormant comets (*8*, *9*). However, the active comet population we see today consists mainly of objects from the Kuiper Belt and Oort Cloud that have been scattered onto Jupiter-crossing orbits by gravitational interactions with the giant planets (*3*, *10*). Even the dynamically peculiar comet 2P/Encke is believed to have originated in the Kuiper Belt, albeit with an orbital evolutionary history strongly influenced by nongravitational forces induced by cometary outgassing (*11*, *12*).

Despite occupying a thoroughly asteroidal orbit in the main belt between the orbits of Mars and Jupiter, asteroid 7968 Elst-Pizarro (also known as comet 133P/Elst-Pizarro) was observed to eject dust like a comet when near perihelion in both 1996 and 2002 (*13*, *14*).

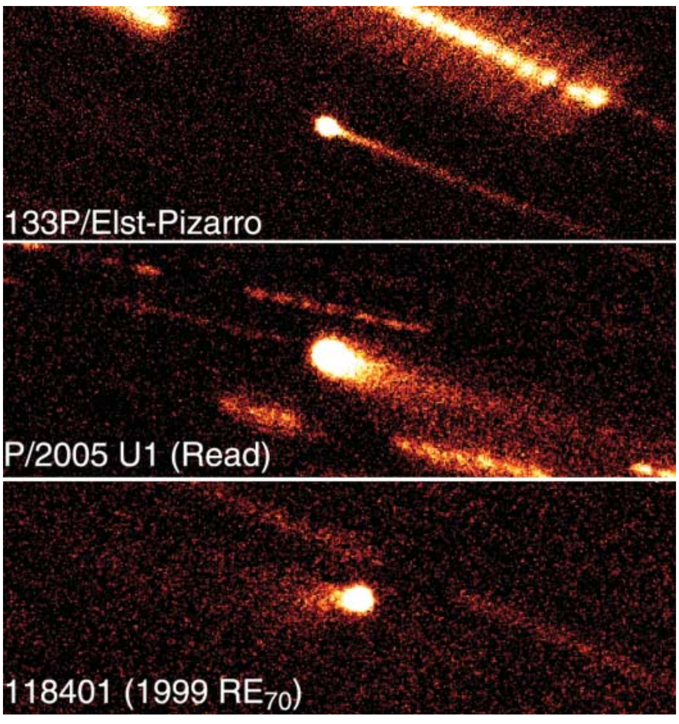

Fig. 1. *R*-band (wavelength 0.65 μm) images of MBCs 133P/Elst-Pizarro on 7 September 2002 (*14*), P/2005 U1 (Read) on 10 November 2005, and 118401 (1999 RE$_{70}$) on 27 December 2005 (all dates UT). All images are composites (0.5′ by 1.5′ in size, with north at the top and east to the left) from data taken at the University of Hawaii 2.2-m telescope on Mauna Kea, and represent 1.1 hours, 1.9 hours, and 2.8 hours of total effective exposure time, respectively. Streaked objects in each panel are background stars and galaxies that have been trailed by the nonsidereal motions of the comets. Geometric circumstances of these observations are given in Table 1.

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Motivated by these observations, we have been conducting an optical survey of asteroids in the main belt in search of similar behavior. In conducting this survey, we have used both small-aperture (1 to 2 m) and large-aperture (8 to 10 m) telescopes in Hawaii, Chile, and Taiwan, and have observed ~300 small (kilometer-sized) main-belt asteroids over the past 3 years.

Recently, two more main-belt objects—P/2005 U1 (Read) (*15*), discovered serendipitously, and asteroid 118401 (1999 RE_{70}), found to be active by our survey using the 8-m Gemini telescope—have been found with comet-like morphologies (Fig. 1 and Table 1). Together, these three objects (Table 2) form a new class of comets having stable orbits completely confined to the main asteroid belt: the main-belt comets (MBCs).

The image data (Fig. 1) leave no doubt that these asteroids are ejecting dust and so satisfy the observational definition of comets (*10*). Dust ejection velocities in the two most recently discovered MBCs were estimated from the sunward extents of their comae. The sunward extent of a coma is proportional to the square of the ejection velocity divided by the acceleration due to radiation pressure. Velocities estimated for the MBCs are $\sim$100 m s^{-1}, greatly in excess of the velocities that would be expected for electrostatic levitation [$\sim$1 m s^{-1} (*16*)] or rotational ejection (on the order of the escape velocity, or $\sim$1 m s^{-1} for an object of radius $\sim$1 km). Additionally, the activity of all three MBCs is observed to persist for several weeks or months, much longer than would be expected for impact-generated dust ejection but consistent with sublimation-driven dust ejection (*14*). In the case of Elst-Pizarro, activity is seen to recur over a finite portion of its orbit close to perihelion; this observation is again consistent with a sublimation-driven origin (*14*). Physically, the MBCs are bona fide comets. Dynamically, however, all three are completely asteroidal in character (Fig. 2), with orbits unlike those of any other known comets.

Could the MBCs be comets from the Kuiper Belt or Oort Cloud that have become trapped in asteroid-like orbits? Published dynamical simulations suggest that this is not the case, because they cannot reproduce the transfer of comets to main-belt orbits (*11*). Likewise, it is extremely unlikely that the MBCs could have resulted from collisional deflection of comets passing through the main belt, for two reasons: (i) the long time scales of such collisions (at least 10^7 times the dynamical lifetimes of the JFCs), and (ii) the implausibility of such collisions delivering fragments precisely onto nearly circular, low-inclination main-belt orbits, given the much more eccentric and more inclined orbits of the presumed parent comets. Unless nongravitational forces associated with asymmetric cometary outgassing can somehow be invoked to solve this problem, an origin for the MBCs in the Kuiper Belt or Oort Cloud appears improbable.

It is more likely that the MBCs are intrinsically icy bodies, formed and stored at their current locations, that have been activated by some recent trigger. A recent trigger is required because exposed, dirty water ice located at the subsolar point of an MBC at a heliocentric distance of 2.4 to 2.9 AU (Table 1) will sublimate and recede at a rate on the order of 1 m per year. Given the kilometer-scale sizes (Table 2) of the currently known MBCs, the active lifetimes of these objects once sublimation begins must be considerably shorter than 1000 years. Models show, however, that buried ice at these distances could be protected against sublimation over the entire age of the solar system by even a relatively thin ($\sim$1 to 100 m) layer of surface regolith (*17*). Sublimation could then be triggered by a collision able to penetrate this insulating inactive layer, exposing deeply buried ice to the heat of the Sun. The behavior of Elst-Pizarro suggests that the resulting activity might then continue for several months before subsiding, with recurring outbursts continuing on a seasonal basis for several more years (*14*).

The discovery of the MBC class is scientifically interesting on several levels. Geochemical and spectroscopic evidence for hydrated minerals on main-belt asteroids is best explained if those asteroids were once bathed in liquid water (*18*, *19*). The absence of hydration features in certain asteroids has been interpreted as a sign that their ice was never heated to the liquid phase and presumably remains frozen inside (*20*). The MBCs are optically faint and have not been spectroscopically studied to see whether they show hydration features. However, two-thirds of the asteroids in the region where the MBCs are found ($\sim$3 AU) show no evidence for hydration (*21*) and thus are candidates for containing water as ice.

Dynamically, two of the three MBCs (Elst-Pizarro and 118401) are associated with the Themis collisional family, with P/Read falling just outside this family because of its slightly high eccentricity. This family association may be simply an artifact of observational selection because our survey has been focused on Themis family objects, although a number of other main-belt asteroids were also observed. More observations are needed to determine the true distribution of MBCs; it is possible that non-Themis objects that outgas also exist but have so far escaped detection because they were not emphasized in our initial survey sample. The velocity dispersion among the known MBCs is $\sim$1 km s^{-1}, which is much larger than typical velocity dispersions among fragments of split comets ($\sim$1 m s^{-1}) but is comparable to the velocity dispersion expected from a collisionally shattered body. The collisional lifetime of a 5-km body in the main belt is

Table 1. Observational circumstances of MBCs during observed periods of activity. Position data shown are from JPL's online ephemeris generator and include heliocentric distance *R*, geocentric distance Δ, and phase angle α (Sun-object-Earth). For new observations of P/Read and 118401, we also report approximate mean *R*-band magnitudes (m_R) measured at the times of observation. ESO, European Southern Observatory; UH, University of Hawaii.

Object	UT date	Telescope	*R* (AU)	Δ (AU)	α (°)	m_R
133P/Elst-Pizarro	14 Jul 1996	ESO 1.0 m (*13*)	2.65	1.77	13.1	18.3
	19 Aug 2002	UH 2.2 m (*14*)	2.86	2.05	14.5	20.10 ± 0.10
	07 Sep 2002	UH 2.2 m (*14*)	2.89	1.94	8.2	19.70 ± 0.05
P/2005 U1 (Read)	24 Oct 2005	Spacewatch 0.9 m (*15*)	2.42	1.46	8.7	20.2
	10 Nov 2005	UH 2.2 m	2.44	1.45	0.6	19.28 ± 0.05
118401 (1999 RE_{70})	26 Nov 2005	Gemini 8 m	2.59	1.82	16.4	19.16 ± 0.05
	27 Dec 2005	UH 2.2 m	2.60	2.19	21.5	19.60 ± 0.05

Table 2. Orbital and physical parameters of MBCs. Orbital data are from JPL's online database and include semimajor axis *a*, eccentricity *e*, inclination *i*, Tisserand parameter T_J, perihelion distance *q*, and aphelion distance *Q*. The Tisserand parameter is an approximately constant dynamical quantity that reflects the degree of an object's dynamical coupling with Jupiter and is commonly used to classify orbits as cometary or asteroidal. Most comets have $T_J < 3$; most asteroids have $T_J > 3$ (*28*, *29*). We also report approximate effective diameters d_e for P/Read and 118401 estimated from apparent *R*-band magnitudes (Table 1) and an assumed geometric albedo of 0.04. The estimated contribution to object brightness due to coma (as determined from comparison of MBC surface brightness profiles to field star profiles) has been subtracted.

Object	*a* (AU)	*e*	*i* (°)	T_J	*q* (AU)	*Q* (AU)	d_e (km)
133P/Elst-Pizarro	3.156	0.165	1.39	3.184	2.636	3.677	5.0 (*14*)
P/2005 U1 (Read)	3.165	0.253	1.27	3.153	2.365	3.965	2.2
118401 (1999 RE_{70})	3.196	0.192	0.24	3.166	2.581	3.811	4.4

roughly 10^9 years (*22*). Thus, although it is possible that the MBCs are collisionally produced fragments of precursor asteroids, a recent disruptive collision is unlikely, and—given that observational selection effects can just as easily explain these objects' orbital similarity—we do not believe that the MBCs necessarily originated from a common parent.

The similarity of the semimajor axes of the MBCs (Table 2) may be important in other respects. Thermal averaging inside the nuclei will lead to deep interior temperatures near the local blackbody value. At 3.2 AU (the approximate semimajor axis of all three MBCs), this temperature is 155 K, at which ice is thermodynamically stable. At smaller distances, higher deep interior temperatures may prevent the survival of ice over the age of the solar system. Careful observations in search of comae on closer asteroids are needed. Present-day surface water ice and even possible water sublimation have been reported on 1 Ceres (*23*, *24*), although no visible cometary activity has ever been observed, as well as on Elst-Pizarro (*14*), the prototype MBC. Our observations show that the snow line was once within the asteroid belt and suggest that buried water ice in the main belt may be common.

The outer main belt has been proposed as a likely source of terrestrial water (*25*). In this regard, it would be valuable to determine the isotopic composition (especially D/H) in ice from the MBCs for comparison with the isotopic composition of the oceans. Given their proximity to Earth, the MBCs make attractive targets for spacecraft sampling missions having this scientific objective. In addition, the noble gases on Earth and the terrestrial planets may have been delivered by the impact of asteroids and comets (*26*). High-temperature ice from the main belt is a possible carrier of at least the less volatile noble gases and, again, in situ measurements would place useful constraints on the magnitude of a possible main-belt source.

Finally, the MBC class was identified from limited observational data. In our survey, we discovered one new MBC (asteroid 118401) from observations of ~300 main-belt objects (including ~150 Themis-family asteroids). Scaling to the currently known population of >50,000 small asteroids (with radii of <10 km) in the outer main belt beyond 3 AU (with ~2000 in the Themis-family region), we estimate that there could be 15 to 150 currently active MBCs. We caution, however, that our survey was designed to maximize the chances of finding new Elst-Pizarro–like objects, not to provide a statistically significant representation of the main-belt population. Furthermore, the number of dormant MBCs (i.e., icy asteroids that have not yet been collisionally activated) must certainly be larger than the number of currently active MBCs. More MBCs may soon be identified by synoptic all-sky survey telescopes currently under development, such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) (*27*).

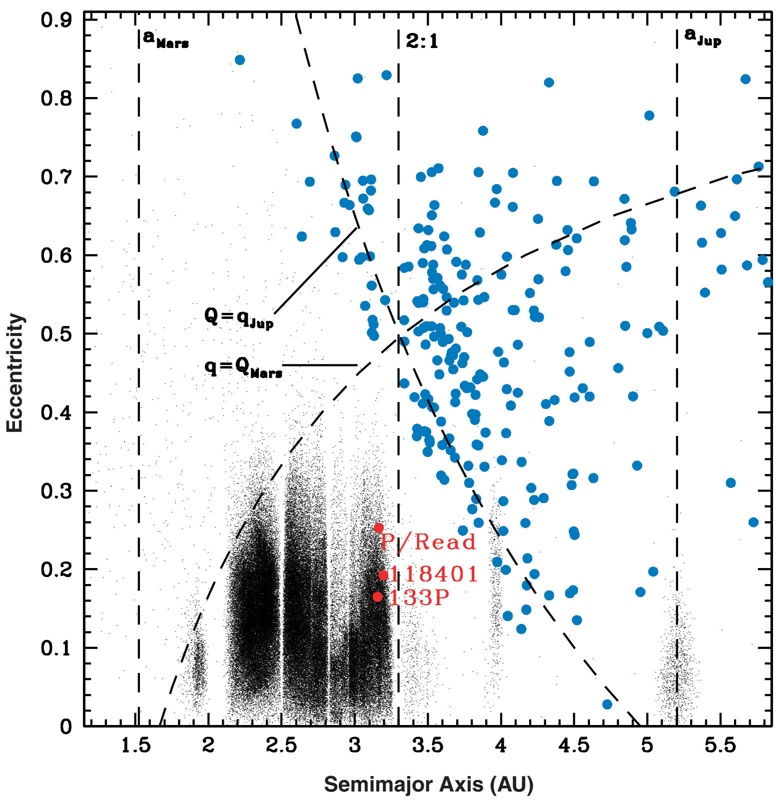

Fig. 2. Plot of semimajor axis versus eccentricity for all numbered asteroids (small black dots) and comets (large blue dots) tabulated by JPL as of 14 December 2005. MBCs 133P/Elst-Pizarro, P/2005 U1 (Read), and 118401 (1999 RE_{70}) are plotted in red. Vertical dashed lines mark the semimajor axes of Mars and Jupiter (a_{Mars}, a_{Jup}) and the 2:1 mean-motion resonance with Jupiter (commonly considered the outer bound of the classical main belt), as labeled. Curved dashed lines show the loci of orbits with perihelia equal to Mars' aphelion ($q = Q_{Mars}$) and orbits with aphelia equal to Jupiter's perihelion ($Q = q_{Jup}$). Objects plotted above the $q > Q_{Mars}$ line are Mars-crossers; objects plotted to the right of the $Q < q_{Jup}$ line are Jupiter-crossers. The MBCs, like the majority of main-belt asteroids, approach neither Mars nor Jupiter.

References and Notes

1. D. D. Sasselov, M. Lecar, *Astrophys. J.* **528**, 995 (2000).
2. F. L. Whipple, *Astrophys. J.* **111**, 375 (1950).
3. H. F. Levison, M. J. Duncan, *Icarus* **127**, 13 (1997).
4. D. Jewitt, J. Luu, *Nature* **362**, 730 (1993).
5. J. H. Oort, *Bull. Astron. Inst. Neth.* **11**, 91 (1950).
6. H. F. Levison, *ASP Conf. Ser.* **107**, 173 (1996).
7. K. E. Cyr, W. D. Sears, J. I. Lunine, *Icarus* **135**, 537 (1998).
8. R. P. Di Sisto, A. Brunini, L. D. Dirani, R. B. Orellana, *Icarus* **174**, 81 (2005).
9. D. C. Jewitt, J. X. Luu, *Astron. J.* **100**, 933 (1990).
10. D. C. Jewitt, in *Comets II*, M. C. Festou, H. U. Keller, H. A. Weaver, Eds. (Univ. of Arizona Press, Tucson, AZ, 2004), pp. 659–676.
11. J. A. Fernández, T. Gallardo, A. Brunini, *Icarus* **159**, 358 (2002).
12. E. M. Pittich, G. D'Abramo, G. B. Valsecchi, *Astron. Astrophys.* **422**, 369 (2004).
13. E. W. Elst *et al.*, *IAU Circ. 6456*, 1 (1996).
14. H. H. Hsieh, D. C. Jewitt, Y. R. Fernández, *Astron. J.* **127**, 2997 (2004).
15. M. T. Read, T. H. Bressi, T. Gehrels, J. V. Scotti, E. J. Christensen, *IAU Circ. 8624*, 1 (2005).
16. B. R. De, D. R. Criswell, *J. Geophys. Res.* **82**, 999 (1977).
17. F. P. Fanale, J. R. Salvail, *Icarus* **82**, 97 (1989).
18. B. A. Cohen, R. F. Coker, *Icarus* **145**, 369 (2000).
19. K. Keil, *Planet. Space Sci.* **48**, 887 (2000).
20. T. D. Jones, L. A. Lebofsky, J. S. Lewis, M. S. Marley, *Icarus* **88**, 172 (1990).
21. J. Carvano, T. Mothé-Diniz, D. Lazarro, *Icarus* **161**, 356 (2003).
22. A. F. Cheng, *Icarus* **169**, 357 (2004).
23. L. A. Lebofsky, M. A. Feierberg, A. T. Tokunaga, H. P. Larson, J. R. Johnson, *Icarus* **48**, 453 (1981).
24. M. F. A'Hearn, P. D. Feldman, *Icarus* **98**, 54 (1992).
25. A. Morbidelli *et al.*, *Meteorit. Planet. Sci.* **35**, 1309 (2000).
26. T. Owen, A. Bar-Nun, I. Kleinfeld, in *Comets in the Post-Halley Era*, R. L. Newburn Jr., M. Neugebauer, J. Rahe, Eds. (Kluwer Academic, Dordrecht, Netherlands, 1991), pp. 429–437.
27. K. Hodapp *et al.*, *Astron. Nachr.* **325**, 636 (2004).
28. S. Vaghi, *Astron. Astrophys.* **24**, 107 (1973).
29. L. Kresák, *Moon Planets* **22**, 83 (1980).

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