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Letter to the Editor

Evidence for a source of H chondrites in the outer main asteroid belt*

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ABSTRACT

Aims. In this paper we report near-infrared spectroscopic observations of one of the largest potentially hazardous asteroids, (214869) 2007 PA8. Mineralogical analysis of this object was followed by the investigation of the dynamical delivery mechanism from its probable source region, based on long-term numerical integrations.

Methods. The spectrum of (214869) 2007 PA8 was analysed using the positions of 1 μm and 2 μm bands and by curve-matching with RELAB meteorites spectra. Its dynamical evolution was investigated by means of a 200 000-year numerical integration in the past of 1275 clones followed to the source region.

Results. (214869) 2007 PA8 has a very young surface with a composition more akin to H chondrites than to any other type of ordinary chondrite. It arrived from the outer Main Belt in the near-Earth space via the 5:2 mean motion resonance with Jupiter by eccentricity pumping. Identification of its source region far from (6) Hebe raises the possibility of the existence of a second parent body of the H chondrites that has a radically different post-accretion history. Future spectroscopic surveys in the 5:2 resonance region will most likely discover other asteroids with an H chondrite composition.

Key words. minor planets, asteroids: general – techniques: spectroscopic – celestial mechanics – methods: numerical

1. Introduction

Ordinary chondrites (OC) dominate the current meteorite collections with almost 80% of the total falls (Burbine et al. 2002). Their subclasses defined on the basis of Fe content – H (high Fe), L (low Fe), and LL (low Fe, low metallic Fe) represent 48%, 43%, and 9% of the OC-group meteorites (Grady 2000).

Despite their relatively high proportion among OC, H chondrites (HC-like) asteroids remain elusive. Following the identification of (6) Hebe as the putative parent body of HC (Gaffey & Gilbert 1998) it is only recently that Dunn et al. (2013), based on mineralogical analysis, has found six near-Earth asteroids (NEA) with spectral parameters consistent with HC in a set of 47 NEA with OC-like analogs. Another NEA with a composition between H and L chondrites was identified by Sanchez et al. (2013) in a group of 14 NEA and Mars-crossing asteroids. Overall, HC-like asteroids are uncommon in the NEA population dominated by LL-chondrite mineralogies (de León et al. 2010), a finding at odds with their prevalence among OC meteorites.

In this paper we report the serendipitous discovery of an unweathered NEA with an HC-like composition – (214869) 2007 PA8 (hereafter 2007 PA8). Mineralogical analysis of this object was followed by the investigation of dynamical delivery mechanism from its probable source region based on long-term numerical integrations. Finally, we discuss the results and their implication for the history of the HC parent body and its location.

* Figure 2 is available in electronic form at http://www.aanda.org

2. Observations

The asteroid 2007 PA8 has an orbit with (a, e, i) = (2.823 AU, 0.662, 1.984°) and a Tisserand parameter (T_J) of 2.947 marginally indicating an association with Jupiter family comets (JFCs). Although T_J alone is not a reliable indicator of a primitive composition of an asteroid (Stuart & Binzel 2004 find that 25% of NEA have both $T_J \leq 3$ and a C, D, or P taxonomic type), 2007 PA8 remained an interesting object. With an absolute magnitude H = 16.4 and a MOID value of 0.024 AU, it is among the largest 5% potentially hazardous asteroids (PHAs). It is also a relatively accessible target of space missions with a minimum required $\Delta V = 6.8\,\mathrm{km\,s^{-1}}$.

Its recent close approach to Earth on 5 November 2012 (the last one until 2084) prompted many observations. It was the subject of an extensive radar campaign that revealed a slow rotating, 2 km-wide, elongated, asymmetric object (Brozovic et al. 2013). Based on spectrophotometric observations, Godunova et al. (2013) obtained an S-type taxonomic classification, while Hicks et al. (2012) inferred an Xc spectral type from broadband photometry. From polarimetric and spectroscopic data, Fornasier (in prep.) finds an albedo of 0.21 ± 0.03 and a spectrum typical of OC for 2007 PA8.

We observed 2007 PA8 on 15 September 2012 using the spectrograph SpeX at the 3-m NASA Infrared Telescope Facility (IRTF) located in Mauna Kea, Hawaii (Rayner et al. 2003). The observations were performed in remote mode from the Astronomical Institute of the Romanian Academy Remote Observing Center, Bucharest (AIRA ROC). Instrument configuration for the run and the data reduction procedure are described elsewhere (Nedelcu et al. 2007).

Table 1. General circumstances of 2007 PA8 spectroscopic observations.

Date (UT)	RA [h m s]	Dec [° ′ ″]	ϕ [°]	r [AU]	Δ [AU]	M_V	Airmass	Standard star
2012/09/16.530	00 43 58	+00 13 35	12.23	1.37	0.38	15.73	1.13	HD 7983

Notes. The columns in order: UT date for the middle of exposure interval, asteroids right ascension and declination (J2000), phase angle, heliocentric and geocentric distances, magnitude, airmass value, and the solar analog star used in spectra reduction.

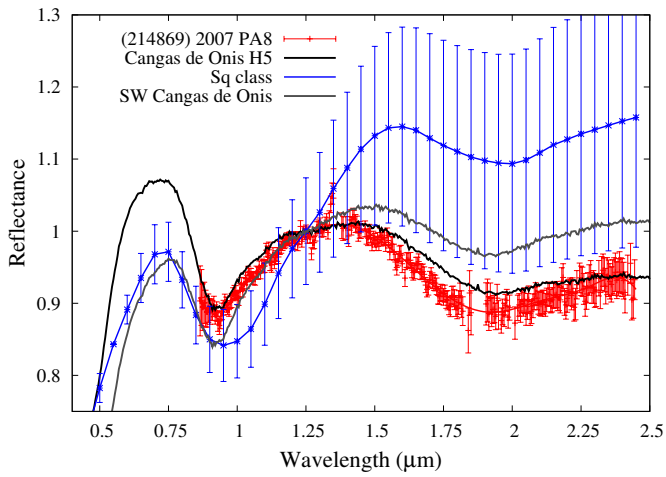

Fig. 1. Near-infrared (0.8−2.5 μm) spectrum of (214869) 2007 PA8 (red) and of Cangas de Onis H5 ordinary chondrite from RELAB (black). The average Sq-type spectrum from DeMeo et al. (2009) is displayed for comparison. A space-weathered spectrum of Cangas de Onis computed using the model of Brunetto et al. (2006) with $C_s = -0.2$ is displayed in gray. All spectra were normalized at 1.25 μm.

All spectra were acquired under good observing conditions (seeing 0.7″, airmass 1.13) with the asteroid and the solar analog star (HD 7983) at the same airmass (Table 1). The calibrated 0.8−2.5 μm near-infrared spectrum of 2007 PA8 is presented in Fig. 1.

3. Results

3.1. Mineralogical analysis

For spectral analysis we used the Modeling for asteroid spectra (M4AST) package, a tool available via a web interface[1]. M4AST streamlines spectroscopic investigation of asteroids by providing applications that cover aspects related to taxonomy, curve matching with laboratory spectra, space-weathering models, and mineralogical diagnosis (Popescu et al. 2012).

The 2007 PA8 spectrum (Fig. 1) has a slightly negative slope of $-0.03\,\mu\mathrm{m}^{-1}$. It presents two absorption bands located at $\sim$1 μm and $\sim$2 μm associated with Fe^{2+} crystal field transitions in the chondritic minerals olivine and pyroxene (Burns 1970).

We calculated band centers from the minima of cubic spline fits resampling the entire spectrum and, as a check, by fitting a second-degree polynomial to the lower half of the bands. Both methods produced similar results. The difference between band minima and actual band centers is always smaller than 0.01 μm even for objects with steep spectral slopes (Burbine et al. 2009). Band centers and their corresponding errors are BI = 0.92 ± 0.02 μm and BII = 1.95 ± 0.01 μm for Bands I and II, respectively.

[1] http://m4ast.imcce.fr

The lack of visible spectrum and accordingly of spectral data shortward of 0.8 μm precludes the accurate determination of the Band I center and of the band area ratio (BAR). We note, however, that from a set of 48 OC meteorites samples spanning petrologic types 4−6, Dunn et al. (2010) obtained for H, L and LL chondrites band centers at $BI_H = 0.939 \pm 0.006\,\mu$m, $BII_H = 1.925 \pm 0.014\,\mu$m, $BI_L = 0.956 \pm 0.011\,\mu$m, $BII_L = 1.944 \pm 0.020\,\mu$m, and $BI_{LL} = 0.998 \pm 0.016\,\mu$m, $BII_{LL} = 1.962 \pm 0.030\,\mu$m respectively. This result makes 2007 PA8 more akin to HC than to other ordinary chondrite types.

Another line of evidence for an HC composition of 2007 PA8 is M4AST curve matching with laboratory spectra. The best fit among meteoritic material is represented by Cangas de Onis H5 chondrite (Fig. 1). Its reflectance in the visible domain (0.55 μm) is 0.16, a value compatible with the inferred 2007 PA8 albedo (Fornasier, in prep.). In contrast, we found no reasonable match for 2007 PA8 among DeMeo et al. (2009) taxonomic classes. The closest taxonomic type that our object could be assigned to is Sq, but the average spectrum of this class is considerably redder than Cangas de Onis. Furthermore there is a significant mismatch in the visible domain.

We interpret these findings as evidence of a very young surface for 2007 PA8. Using the model of Brunetto et al. (2006) to produce a "space-weathered" spectrum for Cangas de Onis we find that a parameter $C_s = -0.2$ is sufficient to "redden" this HC to a typical Sq spectrum. Owing to an unknown past orbital evolution of the asteroid, it is, however, difficult to associate an irradiation time-scale to this C_s value. Giving the fast action of solar wind as a space-weathering agent (Vernazza et al. 2009), we can however establish an upper limit of 10^6 years for 2007 PA8 surface age.

3.2. Dynamical modeling

From 641 optical astrometric positions reported to MPC we computed the orbital elements of 2007 PA8 at the epoch JD = 2 456 600.5, $(a, e, i, \Omega, \omega, M) = (2.822816$ AU, 0.661989, 1.98386°, 142.6593°, 292.2879°, 70.7095°), with a 1σ variation of $\sigma_{ast} = (2.97 \times 10^{-8}$ AU, 8.58×10^{-9}, 1.44×10^{-6}°, 6.45×10^{-5}°, 6.50×10^{-5}°, 1.25×10^{-6}°).

In order to explore the dynamical evolution of the asteroid in a meaningful way, we generated a population of 1275 clones using a Gaussian distribution in the six orbital elements with the corresponding standard deviation $\sigma_{clones} = 3 \times \sigma_{ast}$. The clones were integrated backward in time for 200 000 years using a realistic dynamical model of the solar system described by Nedelcu et al. (2010) modified to use an 80-bit extended precision data type.

The result of the run is presented in Fig. 2. An Apollo type asteroid for the past 500 years, 2007 PA8 oscillated between Apollo and Amor classes beginning with 1500 years ago. Since this behavior is followed by the entire population of clones, we infer this to be a real stage in the dynamical evolution of 2007 PA8. The deterministic evolution (in terms of orbital elements) broke around 2000 years ago when clones split between Amor and Apollo classes (on average fractions of 80%, 20%).

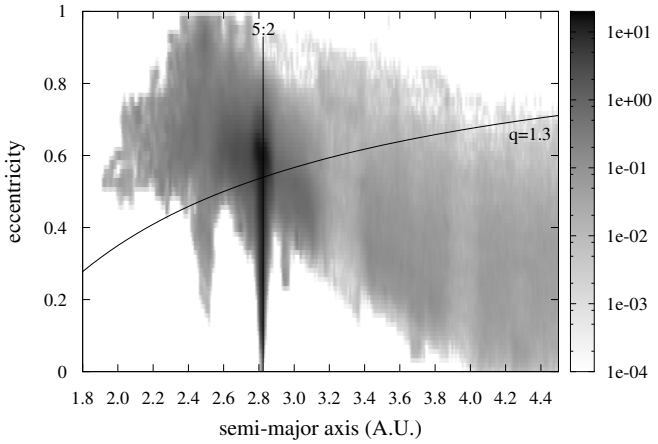

Fig. 3. Residence time of (214 869) 2007 PA8 clones expressed as the average number of clones per century for each (a, e) bin of size (0.02 AU, 0.02).

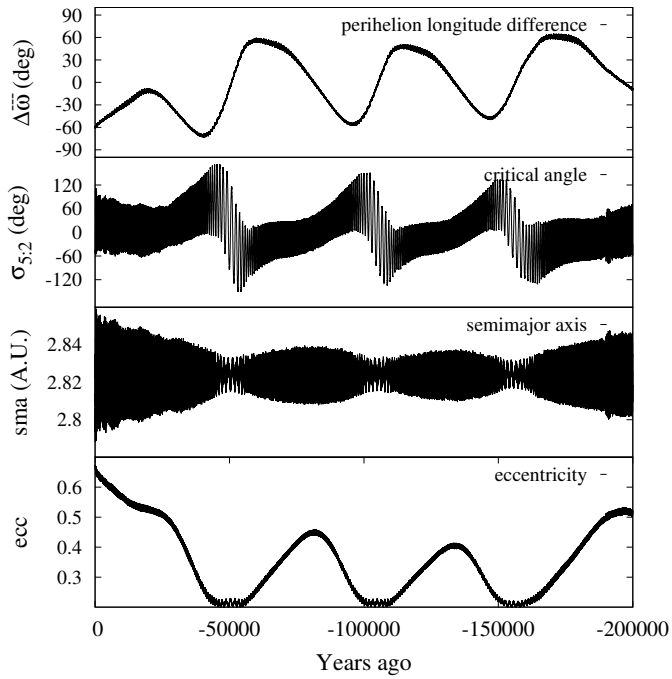

Fig. 4. Orbital evolution of one clone still locked in the 5:2 resonance at the end of 200 000 years backward numerical integration: $\Delta\varpi = \varpi_J - \varpi_{ast}$, difference in the longitudes of perihelion of Jupiter and clone (*first panel*), critical argument $\sigma_{5:2J} = 5\lambda_J - 2\lambda_{ast} - 3\varpi_{ast}$ (*second panel*), semimajor axis and eccentricity (*third and fourth panels*).

The Amor population of clones starts decaying rapidly beyond 5000 years ago as objects move to moderate eccentricities and consequently leave NEA space. In contrast, the population of Apollo-type asteroids has a much slower declining rate.

At the end of our 200 000-year numerical integration, only 14% of the initial clones are still NEA (8.8% Apollo, 5.2% Amor). Asteroids reaching $q \leq 0.02$ AU (4%) or $Q \geq 50$ AU (56%) were considered "lost" and removed from integration when they crossed the stated limits during the run. Finally, 36% of the objects evolved toward Main Belt orbits.

To quantitatively evaluate the dynamic of 2007 PA8, we calculated the residence time of clones in the admissible region of movement of the (a, e) space as the number of clone per century for each (a, e) bin of (0.02 AU, 0.02) size. The result, presented in Fig. 3, shows that for our 200 000-year run, the evolution of clones mainly took place in a narrow region at $a = 2.824$ AU that corresponds to the 5:2 mean motion resonance with Jupiter. Looking at the end state of the run, we find that out of 560 objects that "survived" for 200 000 years, 163 are within the borders of the 5:2 orbital resonance.

This mean motion resonance has been a subject of dynamical studies for a long time. Based on semi-analytical models and numerical integrations, Yoshikawa (1991) found that eccentricities of asteroids in 5:2 resonance change largely on a time sale of 10^5 years. Numerical integration of fictious asteroids placed in the 5:2 resonance explored the boundaries of the associated Kirkwood Gap and obtained a similar time scale for eccentricity increasing from an initial average $e_0 \leq 0.15$ to $e_{max} \geq 0.7$ (Ipatov 1992). Using the Wisdom (1982) perturbative method, Yokoyama & Balthazar (1992) determined that, unlike the 7:3 resonance, the 5:2 has no "safe zones". Asteroids eccentricity will reach planet-crossing values even starting from initial values e_0 near zero. Taking the role of overlapping ν_5 and ν_6 secular resonances in the region of the 5:2 mean motion resonance into account, Moons & Morbidelli (1995) found a large scale chaotic region that produces large jumps in eccentricities, a result usually obtained in realistic, full solar system numerical simulations.

In summary, the 5:2 resonance provides an effective pathway for asteroids to reach the inner solar system region with objects injected into it having the shortest half lives and the shortest time for crossing the orbits of terrestrial planets (Gladman et al. 1997; Morbidelli & Gladman 1998). Resonant asteroids will eventually become Earth- and Mars-crossers with future planetary close approaches slowly depleting the resonance region. The 5:2 resonance alongside the 3:1 and 2:1 mean motion resonances and the ν_6 secular resonance is one of the important sources of Earth-crossing objects (Bottke et al. 2002; de Elía & Brunini 2007).

If we turn to the numerical integration results, we find that the nominal orbit represents an object currently trapped in the 5:2 mean motion resonance with Jupiter with critical angle $\sigma_{5:2J} = 5\lambda_J - 2\lambda_{ast} - 3\varpi_{ast}$ (λ_J, λ_{ast}, and ϖ_{ast} are the mean longitude of Jupiter, mean longitude, and perihelion longitude of the asteroid) undergoing libration around 0° with a period of about 200 years. Orbital evolution of one typical clone surviving for 200 000 years in the 5:2 resonance is presented in Fig. 4. Critical angle $\sigma_{5:2J}$ librates around an oscillating libration center whose evolution correlates to that of semimajor axis and eccentricity. The difference in the longitudes of perihelion of Jupiter and clone librates with the same 52 000 year period seen for semimajor axis and eccentricity, thus effectively protecting asteroid from multiple close approaches with Jupiter.

Based on these known results on the 5:2 resonance and on our numerical integration run, we can now propose a plausible scenario for the dynamical evolution of 2007 PA8. Following the injection of the asteroid in resonance (via collisions in nearby families, Yarkovsky effect, gravitational scattering by large asteroids), it evolved rapidly on a time scale of 10^5 years toward higher eccentricities. It progressed from Main Belt to Mars-crossing region to enter NEA space as an Amor-type asteroid. Five hundred years ago, 2007 PA8 moved to Apollo class, and is currently one of the largest PHAs. The Bottke et al. (2002) NEO model finds for 2007 PA8 a probability of origin in the JFC region of 0.534 and in the outer main asteroid belt region of 0.438. Although we cannot completely exclude an outer solar system origin of 2007 PA8, its spectral data clearly indicates an origin in a region bordering the 5:2 resonance.

4. Discussion

The discovery of an unweathered NEA with an HC-like composition and identification of its source region in the outer Main Belt provide important constraints on the nature of HC parent body. Its composition, internal structure, and evolution have lately been topics of several debates (Harrison & Grimm 2010; Monnereau et al. 2013; Ganguly et al. 2013 and references within). The common understanding is that an "onion-shell" structure (Minster & Allegre 1979), i.e. petrographic type inversely correlated with metallographic cooling rate, has existed at least in an early stage of its formation. Whether this concentric layered structure has survived until today is still an open question. The scenario is complicated by the existence of HC samples with thermo-chronological data that are inconsistent with numerical models of an onion-shell body thermal history (Taylor et al. 1987; Scott et al. 2011). Our best fit for 2007 PA8, Cangas de Onis, for example, includes H6 clasts with diverse cooling rates, suggesting a wide range of depth origins, as expected from catastrophic fragmentation and subsequent reaccretion of its parent body (Williams et al. 1985). The HC group as a whole does not appear to conform to a single thermal evolution model, even if additional parameters, such as regolith insulation (Harrison & Grimm 2010), body size, and accretion time (Monnereau et al. 2013), are considered.

Based on the spectroscopic signature and on its location near the powerful 3:1 and ν_6 resonances, the large asteroid (6) Hebe has been proposed as the parent body of HC (Gaffey & Gilbert 1998). This link was strengthened by the identification of six HC meteorites with pre-atmospheric entry orbits originating in the two resonances zones (Bottke et al. 2010).

Although not excluding it, Monnereau et al. (2013) raises several arguments against this identification. Numerical models of thermal evolution placed H6 chondrites at greater depths, unlikely to be sampled by impacts without a total disruption of the parent body. Hebe's high bulk density of 3.77 g cm^{-3} (Baer et al. 2011), implying a low porosity, is also incompatible with the rubble-pile structure of HC material.

The discovery of a large, HC-like NEA with an outer Main Belt source region could provide a framework for interpreting this conflicting data. Thus the large majority of HC verifying the onion-shell model could have indeed originated on (6) Hebe where they accreted, cooled largely undisturbed, and were sampled by subsequent impacts. The remaining few samples left unexplained by this thermal model will then be derived from a second parent body shattered and reassembled in a rubble-pile structure immediately after a rapid accretion. The relative proportion of these two populations can be explained by a more favorable location of (6) Hebe for meteorites injection. The young surface of 2007 PA8 may be the result of an impact that sent it in the resonance or of close planetary encounters that followed the delivery of the asteroid in NEA space (Binzel et al. 2010; Nesvorný et al. 2010).

5. Conclusions

In this paper we report near-infrared spectroscopic observations of one of the largest PHAs – (214869) 2007 PA8. Mineralogical analysis reveals an object largely unaffected by space weathering with a spectrum directly matched by RELAB spectrum of Cangas de Onis H5 chondrite. The upper limit of surface age of 10^6 years is consistent with its rapid delivery from the outer Main Belt in the NEA space via 5:2 resonance by eccentricity pumping. Identification of its source region far from (6) Hebe raise the possibility of existence of a second parent body of the H chondrites that experienced a radically different post-accretion history. Future spectroscopic surveys in the 5:2 resonance region will most likely discover other asteroids with an H chondrite composition.

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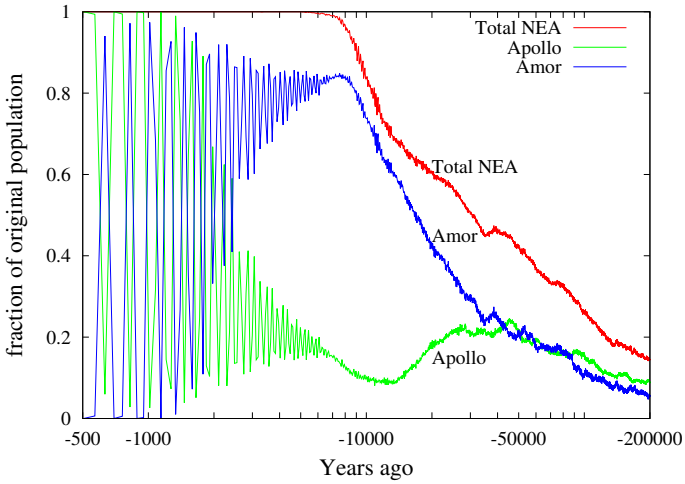

Fig. 2. Evolution of the original population of 1275 clones for asteroid 2007 PA8 during a backward numerical integration.