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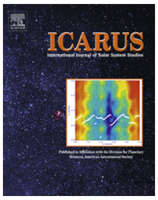

Hungaria asteroid family as the source of aubrite meteorites

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ABSTRACT

The Hungaria asteroids are interior to the main asteroid belt, with semimajor axes between 1.8 and 2 AU, low eccentricities and inclinations of 16–35°. Small asteroids in the Hungaria region are dominated by a collisional family associated with (434) Hungaria. The dominant spectral type of the Hungaria group is the E or X-type (Warner et al. [2009]. Icarus, 204, 172–182), mostly due to the E-type composition of Hungaria and its genetic family. It is widely believed the E-type asteroids are related to the aubrite meteorites, also known as enstatite achondrites (Gaffey et al. [1992]. Icarus, 100, 95–109). Here we explore the hypothesis that aubrites originate in the Hungaria family. In order to test this connection, we compare model Cosmic Ray Exposure ages from orbital integrations of model meteoroids with those of aubrites. We show that long CRE ages of aubrites (longest among stony meteorite groups) reflect the delivery route of meteoroids from Hungarias to Earth being different than those from main-belt asteroids. We find that the meteoroids from Hungarias predominantly reach Earth by Yarkovsky-drifting across the orbit of Mars, with no assistance from orbital resonances. We conclude that the CRE ages of aubrites are fully consistent with a dominant source at the inner boundary of the Hungaria family at 1.7 AU. From here, meteoroids reach Earth through the Mars-crossing region, with relatively quick delivery times favored due to collisions (with Hungarias and the inner main-belt objects). We find that, after Vesta, (434) Hungaria is the best candidate for an asteroidal source of an achondrite group.

1. Introduction

Hungarias are a dynamical group of asteroids interior to the asteroid belt but exterior to the orbit of Mars (in the 1.8–2 AU range). Most stable Hungarias have high inclinations (16–35°) and low eccentricities (<0.1). Hungarias are bordered in inclination by multiple secular resonances, separated from the main asteroid belt by the ν_6 secular resonance and the 4:1 mean-motion resonance with Jupiter, with a less well-defined inner boundary forced by close encounters with Mars (Warner et al., 2009; Milani et al., 2010).

Unlike the main asteroid belt, Hungarias are not stable over the age of the Solar System, but are escaping into the Mars-crossing region with a half-lives in the 500–1000 Myr range (Milani et al., 2010; McEachern et al., 2010). In the early Solar System the proto-Hungarias were shown to be orders of magnitude more numerous, and are proposed to be the main source of the Late Heavy Bombardment (Ćuk, 2012; Bottke et al., 2012). Hungarias may be depleted remnants of primordial Mars-crossers (Ćuk, 2012), or survivors from the extinct innermost part of main asteroid belt perturbed by late planetary migration (Bottke et al., 2012). Hungarias may therefore contain survivors from ancient collisional families which are now almost completely extinct via this large-scale dynamical depletion. This may help resolve some paradoxes in the meteorite–asteroid connection, like the lack of an extant suitable candidate for the mesosiderite parent body (Ćuk, 2012).

While they inhabit a single island of relative dynamical stability, Hungarias are not all compositionally uniform, with most common asteroid types being S and E (Carvano et al., 2001; Warner et al., 2009). A significant fraction of Hungarias belong to the Hungaria Genetic Family (HGF), centered on (434) Hungaria (Williams, 1992; Lemaitre, 1994; Warner et al., 2009).[1] This family consists of otherwise rare E-type asteroids, which are a proposed source of aubrite meteorites (Gaffey et al., 1992). Apart from the HGF, Hungarias may contain another collisional family at slightly higher inclinations, comprised of S-type asteroids (Williams, 1992; Milani et al., 2010). As this group is relatively spread out and S-types

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[1] In this paper, "Hungaria" and "Hungarias" refer to all relatively stable asteroids in the Hungaria zone 1.8–2 AU, regardless of the spectroscopic type; we use "(434) Hungaria" for their largest member and "HGF" for its collisional family.

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are common in the inner asteroid belt, it is not yet established that this is a real genetic family, and we will not address it here.

Aubrites, or enstatite achondrites, are the second most common group of achondrites, after the HED complex (Lorenzetti et al., 2003). Most aubrites are thought to originate from a single parent body, a large differentiated planetesimal that was disrupted soon after the formation of the Solar System. The immediate precursor bodies of aubrites can therefore be much smaller than the original progenitor, which was likely lost during the turbulent early history of the Solar System. The anomalous Shallowater aubrite, however, likely derives from the separate parent body from most aubrites (Keil et al., 1989).

E-type asteroids are widely seen as likely source of aubrites, as their spectra are consistent with high-albedo iron-poor minerals like enstatite that dominate the aubrites (Zellner, 1975; Zellner et al., 1977; Gaffey et al., 1992; Cloutis and Gaffey, 1993; Pieters and McFadden, 1994; Fornasier and Lazzarin, 2001; Burbine et al., 2002; Kelley and Gaffey, 2002; Clark et al., 2004; Fornasier et al., 2008). Three spectral sub-types of E-type asteroids have been identified in the literature (Clark et al., 2004; Fornasier et al., 2008). E [I] asteroids have featureless spectra characteristic of aubritic pyroxene plus feldspar assemblage; E [II] presents the strong absorption at 0.49 μm due to sulfide such oldhamite and occasionally at 0.90–0.96 μm; E[III] have absorption bands in the 0.9 and 1.8 μm region, indicating a silicate mineralogy higher in iron than the mineral enstatite. These subgroups likely possess distinct surface mineralogies, and more than one sub-type is identified within the HGF (Fornasier et al., 2011). While the surface of (434) Hungaria itself may contain heterogenities (Fornasier et al., 2008), most recent data indicate that Hungaria exhibits 0.49 μm band typical of the E [II] subtype (Fornasier et al., 2011). Some of E-types (notably 44 Nysa) appear to have hydration feature in the infrared (3-μm band), which is not consistent with aubrite composition (Rivkin et al., 1995). However, alternative explanations for the presence of this band have also been put forward, in which case at least a partial aubrite composition cannot be excluded (Gaffey et al., 2002). Clark et al. (2004) find that E-types within the HGF typically match aubrite visible and near-infrared spectra significantly better than non-Hungaria E-type asteroids (like 44 Nysa and 64 Angelina), as spectra of both E [II] asteroids and aubrites tend to be featureless. However, some individual aubrites can be well matched by main belt E-type asteroids (Fornasier et al., 2008).

Apart from spectroscopy, aubrites' long Cosmic Ray Exposure (CRE) ages indicate that they may be delivered through a distinct dynamical route from most stony meteorites (Lorenzetti et al., 2003; Eugster et al., 2006; Keil, 2010). Aubrites have median cosmic ray exposure ages of 50 Myr (Table 1), significantly longer than those of other stony meteorites. Median CRE ages for *H*, *L*, and *LL* ordinary chondrites are 7 Myr, 20 Myr and 15 Myr, respectively (Marti and Graf, 1992; Eugster et al., 2006), and about 20 Myr for HED meteorites (Eugster et al., 2006). Differences in CRE ages of stony and iron meteorites imply that collisional destruction plays the major role in limiting the lifetime of small meteoroids (Morbidelli and Gladman, 1998). There is however no reason to think that highly brecciated aubrites are stronger than other stones, so their long CRE ages would more likely be a consequence of their orbital history (Herzog, 2003). A unique orbital history could be consistent with an origin in a distinct dynamical group such as Hungarias, rather than the main asteroid belt, where the overwhelming majority of meteorites originate.

Since Hungarias are interior to strong jovian resonances but adjacent to Mars, the primary route for their escape (and potential Earth impact) is through Mars-crossing orbits. Median aubrite CRE ages of 50 Myr are comparable to typical Mars-crosser dynamical lifetimes of 80 Myr (Ćuk, 2012), supporting a possible Hungaria–aubrite connection. The Mars-crossing region is also depleted in meteoroidal debris, allowing for much longer collisional lifetimes of stony meteoroids on low *e*-orbits, than is possible in the main asteroid belt (or Hungarias).

Table 1

CRE ages of 15 brecciated aubrites reported by Lorenzetti et al., 2003. Anomalous Shallowater and Mt. Egerton aubrites were excluded as they may have originated on other parent bodies. Asterisk marks CRE ages that are an average between values for multiple fragments listed by Lorenzetti et al., 2003.

Meteorite	CRE age (Myr)
ALH 78113	21.2
ALH 84007/84008/84011/84024	19.6*
Aubres	12.6
Bishopville	52.0
Bustee	52.6
Cumberland Falls	60.9
EET 90033/90757	32.2
Khor Temiki	53.9
LEW 87007	53.9
Mayo Belwa	117
Norton County	111
Pena Blanca Springs	43.2
Pasyanoe (light/dark)	45.1*
QUE 97289/97348	40.6
Y 793592	55.0

In contrast to Mars-crossers, Earth-crossers have shorter dynamical lifetimes, with an average of 15 Myr (Gladman et al., 2000). This short lifetime of Near-Earth Asteroids (NEAs) was not recognized until the late 1990s when direct integrations replaced Öpik-type calculations. Previous suggestions of aubrite origin on (3101) Eger (Gaffey et al., 1992), or any other NEA, are thus not consistent with the modern understanding of NEA dynamical timescales.

In this paper, we will study the Hungaria–aubrite connection using numerical simulation of the motion of test particles originating among Hungarias and subject to planetary perturbations. These simulated meteoroids are also subject to two non-gravitational effects: the Yarkovsky drift (Farinella and Vokrouhlicky, 1999) and collisional removal. In the following sections we will explore how different starting points of meteoroids and models of these two processes affect the postulated Hungaria–aubrite connection. In particular, we will attempt to find a self-consistent model of aubrite delivery which could explain the CRE ages of known aubrites.

2. Dynamics of meteoroids launched from (434) Hungaria

The first numerical experiment aimed at testing the Hungaria–aubrite connection involved the integration of 4800 test-particles using SWIFT-rmvsy integrator (Brož, 2006). This integrator is based on the standard SWIFT-rmvs3 mixed-variable symplectic algorithm which is capable of integrating close approaches between planets and small bodies (Levison and Duncan, 1994), and is further modified by incorporating the Yarkovsky thermal recoil force on small bodies (Rubincam, 1995; Farinella and Vokrouhlicky, 1999; Bottke et al., 2006). This force depends on the size and spin properties of the body; we assumed uniform sizes with radii $R = 1$ m, obliquities of 45° and spin period of about 1 min with half of the sample being direct and half retrograde rotators. Bodies with radius $R = 1$ m were used as they are likely the largest (and therefore longest lived) meteoroids that are fully penetrated by cosmic rays. For SWIFT-rmvsy input, we used specific heat of 1000 J kg^{-1} K^{-1}, and thermal conductivity of 0.1 W m^{-1} K^{-1} (previously found appropriate for stony meteoroids by Bottke et al., 2006), with uniform density of 3000 kg m^{-3}, implying solid–rock composition. In this regime the seasonal Yarkovsky effect dominates and all bodies migrate inward, toward the Sun (Bottke et al., 2006). The test particles were affected by the gravity of the