A EUCRITE DELIVERED FROM AN ATEN-TYPE ORBIT: THE LAST LINK IN THE CHAIN FROM 4 VESTA TO EARTH.

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Introduction: Meteorites provide us with the only surviving physical record of the formation of our Solar System. But they are also unique - as geological materials - in that they come with virtually no spatial context to aid us in interpreting that record. There is a profound disconnect with possible asteroid parent bodies; we have no sample-return material; and orbital information for meteorite falls is largely absent. Although a primary motive behind fireball camera networks was the recovery of meteorites with orbital data [1], only four samples have been obtained. The reason for this low recovery rate relates to field areas: any vegetation makes looking for small meteorites extremely difficult. Our solution was to place a network in an area that has proved eminently suitable for locating meteorites: the Nullarbor Region of Australia. The aim of the Desert Fireball Network (DFN) is to deliver numbers of samples with precise orbits, providing a spatial context to aid in interpreting meteorite composition.

The first phase of the project involved designing and building a prototype automated fireball observatory, and testing this unit in the Western Australian desert. The second phase involved deploying a small preliminary network of these units in the Nullarbor: over a period of two years, four observatories were installed, the final station was set up in November 2007. During the past two years we recorded more than one hundred fireballs. However, the small size of the network meant that around half were recorded from only one station, or had a bad viewing geometry, limiting the dataset of complete and precise atmospheric trajectories, orbits, light curves, and dynamics to around 40 fireballs (this is the first orbital data for southern hemisphere fireballs). Five of the recorded fireballs had a computed terminal mass larger than 100 grams, two of which were in areas suitable for systematic searching. Observing several meteorites with significant terminal masses in the network area allowed us to move to phase three of the project: recovery of meteorite falls. The first organized search for a Desert Fireball Network fall took place in October 2008. Two fragments, totaling 324 grams, were recovered within 100m of the projected ground track. Extensive searching did not produce additional samples.

Results: This first DFN meteorite was delivered from an extremely unusual orbit. It is the first achondrite with an orbit, and the first meteorite with an orbit from the southern hemisphere. The fireball is designated DN200707; the meteorite, Bunburra Rockhole.

The orbit. The beginning of the fireball lightcurve for event DN200707 occurred at $19^h13^m53.2^s \pm 0.1^s$ (UT) on July 20th 2007 [2]. The object had an initial velocity of 13.40km/s; semimajor axis (AU): 0.851 ± 0.002; argument of perihelion (°): 209.9 ± 0.2; eccentricity: 0.245 ± 0.003; longitude of ascending node (°): 297.59525 ± 0.00010; perihelion distance (AU): 0.643 ± 0.004; inclination (°): 9.07 ± 0.17; aphelion distance (AU): 1.05997 ± 0.00014; period (years): 0.786 ± 0.003. All angular elements are given in J2000 equinox. This is one of the most precise orbits ever determined for a meteorite, but it is exceptional for another reason. It is an Aten-type orbit. Aten asteroids are near-Earth objects which have semi-major axes <1AU. In the case of DN200707, virtually the entire orbit was contained within the Earth's orbit (see Figure 1).

An orbital analysis was performed using the parameters defined above. The orbit is relatively chaotic, with a number of previous close approaches with Earth and Venus. Approaches as close as 0.04AU to Venus are possible; the most recent Venusian encounter occurred in September 2001. A search on the asteroid catalogue for objects with similar orbital elements resulted in several cases. However, given the relatively chaotic nature of these orbits it is rather unlikely that these objects are genetically related to our meteorite. Even so, as the meteorite is an unusual type, spectral observations of these asteroids may be worthwhile.

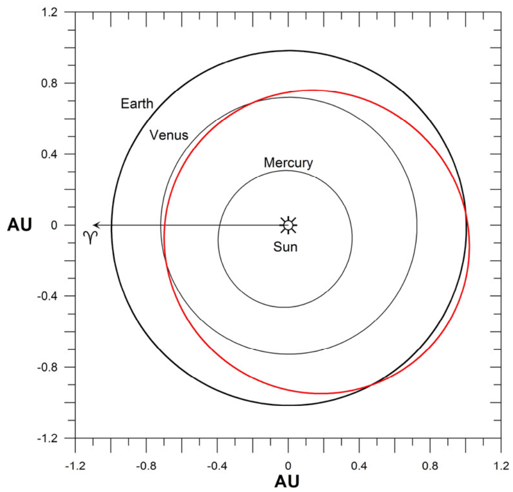

Figure 1. Orbit for DN200707 / Bunburra Rockhole.

The meteorite. Bunburra Rockhole is brecciated and contains numerous clasts. BSE images reveal three lithologies delineated by grain size (Figure 2). Mineralogy in all lithologies is similar, comprising pyroxene, plagioclase, and silica, with minor amounts of chromite, sulphide, and ilmenite. Pyroxene is Fe-rich and ranges from Ca-rich to Ca-poor ($Fs_{26.7}$ $Wo_{44.0}$ to $Fs_{63.6}$ $Wo_{2.3}$). Exsolution lamellae are apparent in all lithologies, but are most prominent in the medium-grained areas. Plagioclase ranges in composition from An_{85} to An_{91}. The Fe-rich composition of the pyroxenes indicates that Bunburra Rockhole is a basaltic eucrite.

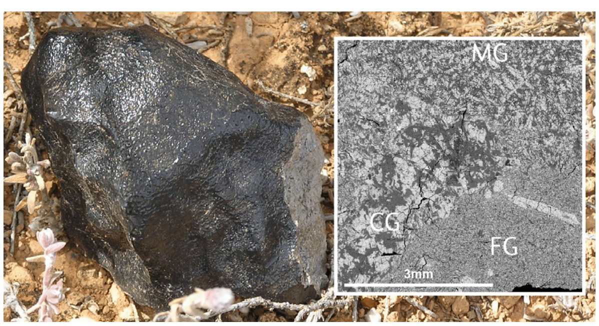

Figure 2. Bunburra Rockhole at the recovery site, and (inset) a BSE image showing lithologies (FG=fine grained; MG=medium grained; CG=coarse-grained).

Discussion: A number of workers (e.g. [3,4]) have explored the spectral similarities between 4 Vesta, Vestoids (small asteroids with spectra similar to that of 4 Vesta), and HED meteorites, noting the orbital association of Vesta and the Vestoids, and potential delivery pathways to Earth. However, until now, orbital data for HEDs was lacking. What does the recovery of a eucrite delivered from an Aten-type orbit offer us, in terms of the proposed Vesta/Vestoid/HED connection? Using the NEO model of [5] we can predict the probability that particular NEOs came from different NEO source regions using their present-day *a*, *e*, and *i* values. Making the assumption that small NEOs have the same orbital distribution as the observed km-sized NEOs, we find that the probability of Bunburra Rockhole coming from the innermost region of the main belt is 98%. There is a 72% probability that it was delivered from the ν_6 resonance, and a 26% probability that it came from the large number of small resonances located in the inner main belt. The probability that Bunburra Rockhole came from the 3:1 resonance is only 2%. It did not come from the outer main belt >2.8AU, or the Jupiter-family comet population. We note that both the 3:1 and ν_6 resonances are plausible sources for Vesta-derived ejecta: arguments have been presented which tend to favour the 3:1 resonance [3,6], the ν_6 [7], or both [8]. Certainly for our meteorite ν_6 is favoured. The most likely scenario appears to be that Bunburra Rockhole is a fragment of a Vestoid, derived from the innermost region of the main belt, delivered from the ν_6 resonance, evolving onto an Aten-type orbit, and finally entering the Earth's atmosphere over south-western Australia on July 20th 2007; in a sense, forging the last link in the chain from 4 Vesta to Earth.

Conclusions: This recovery is exceptional in several ways. It is the first achondrite with an orbit. The first Aten-type meteorite. The first meteorite with an orbit from the southern hemisphere. And one of the most precise orbits ever determined for a meteorite. But aside from its research value, Bunburra Rockhole represents a real validation of the basic premise of our project: the meteorite was found on our first organized search, indicating that an expanded Nullarbor network will be capable of delivering dozens of meteorites with orbits over the lifetime of the project.

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