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An Anomalous Basaltic Meteorite from the Innermost Main Belt

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Triangulated observations of fireballs allow us to determine orbits and fall positions for meteorites. The great majority of basaltic meteorites are derived from the asteroid 4 Vesta. We report on a recent fall that has orbital properties and an oxygen isotope composition that suggest a distinct parent body. Although its orbit was almost entirely contained within Earth's orbit, modeling indicates that it originated from the innermost main belt. Because the meteorite parent body would likely be classified as a V-type asteroid, V-type precursors for basaltic meteorites unrelated to Vesta may reside in the inner main belt. This starting location is in agreement with predictions of a planetesimal evolution model that postulates the formation of differentiated asteroids in the terrestrial planet region, with surviving fragments concentrated in the innermost main belt.

Meteorites, except those coming from Mars or the Moon, record the conditions that existed during the formation of the solar system. They can be thoroughly analyzed in the laboratory, but there is virtually no constraint on where they come from. Although the value of combined orbital and compositional data is clear (*1*, *2*), it remains difficult to recover those meteorites for which precise orbits have been determined. Of the 1076 documented meteorite falls that have been observed over the past several centuries (*3*), there are reliable orbits for only a handful (*1*). Dedicated observing networks, designed to image fireballs, triangulate trajectories, and determine orbits and fall positions, have succeeded in recovering four meteorites with orbits (*1*), but recovery rates from these networks are extremely low. Here, we report data on a meteorite recovered from the Nullarbor Desert of Australia after being recorded by the Desert Fireball Network (DFN) as it entered the atmosphere. The DFN is located in an area that has proved suitable for locating meteorites (*4*) and currently comprises four automated fireball observatories.

The fireball was observed over southwestern Australia on 20 July 2007 at $19^{h}13^{m}53.24^{s} \pm 0.05^{s}$ UT (the time of the beginning of the event), recorded by two eastern stations of the DFN (Fig. 1). The object, with initial mass of ~22 kg, began a luminous trajectory at an altitude of 62.83 km, and after a 64.7-km-long flight (which included several fragmentation events) terminated at an altitude of 29.59 km. The most probable mass for the largest individual meteorite fragments calculated from our models was in the range 100 to 250 g. The search strategy was focused around the projected highest-probability fall line (*5*), bounded by these mass limits. The first stone (150 g) was found 97 m southward from the predicted central line; the second stone (174 g) was found 39 m northward from the central line. The meteorite is designated Bunburra Rockhole (BR) after a nearby landscape structure.

This first DFN sample is an igneous achondrite. Initial petrography indicated that BR is a brecciated eucrite containing numerous clasts; backscatter electron images revealed three lithologies delineated by grain size (fig. S1). Eucrites are part of a larger clan (the howardites, eucrites, and diogenites, or HEDs) that has been linked, via similarities in reflectance spectra, to asteroid 4 Vesta (*6*, *7*). The lithological diversity and impact history of HED samples require them to have come from a relatively large parent body; 4 Vesta is the largest intact differentiated asteroid in the main belt.

However, BR is not a typical eucrite. It has a distinct oxygen isotopic composition, plotting significantly above the HED mass fractionation line

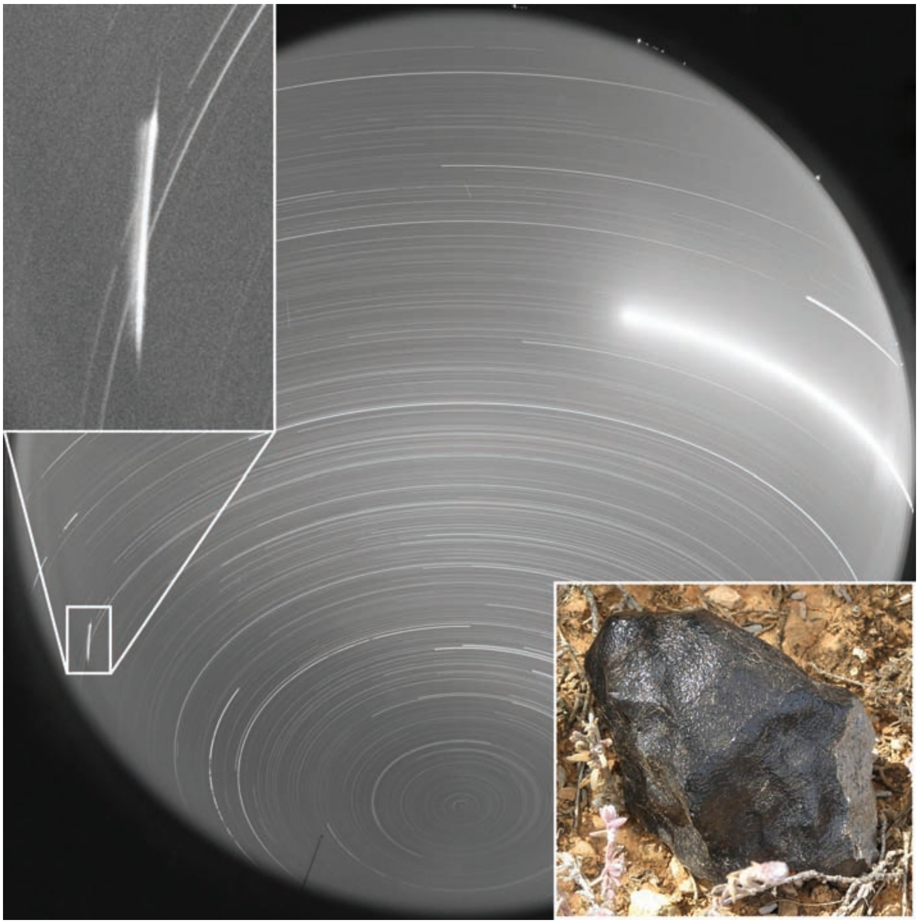

Fig. 1. All-sky image from the easternmost station in the Desert Fireball Network, showing the track of the fireball at left (and **inset**), close to the horizon, and Bunburra Rockhole (BR) at the recovery site (**inset**).

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(Fig. 2). North West Africa 011 (NWA 011, a meteorite found in the Sahara in 1999) was the first of these anomalous eucrite-like basaltic meteorites to be identified (*8*). On the basis of its unusual oxygen isotope composition, NWA 011 was presumed to derive from a basaltic parent asteroid other than 4 Vesta (*8*). NWA 011 has $\Delta^{17}O = -1.80$ per mil (‰) (*8*, *9*), whereas HEDs define a mass fractionation line of $\Delta^{17}O = -0.242 \pm 0.016$‰ (2σ) (*10*, *11*). Data from nine replicate analyses (table S1), taken from coarse, medium, and fine textural subtypes, indicate that BR has $\Delta^{17}O = -0.112 \pm 0.042$‰ (2σ) (Fig. 2). Following NWA 011, a further five anomalous eucrite-like basaltic meteorites were identified on the basis of their oxygen isotope compositions (and, in some cases, unusual mineralogy): Ibitira (a meteorite that fell in Minas Gerais, Brazil, in 1957), Asuka-881394 (found in the Queen Maud Land region of Antarctica, 1988), PCA 91007 (found in the Pescora Escarpment region of Antarctica, 1991), Pasamonte (fell in New Mexico, USA, 1933), and NWA 1240 (found in the Sahara, 2001) (*11*–*15*). Of these six, only three (Ibitira, Asuka-881394, and NWA 011) diverge sufficiently from the HED mass fractionation line to unambiguously require distinct parent asteroids (*11*). BR is the fourth.

BR also appears to be unusual among these anomalous achondrites in displaying substantial variations in $\Delta^{17}O$ values between lithological subtypes. The oxygen isotopic composition within other HEDs or anomalous eucrite-like basalts shows little heterogeneity [e.g., dark clast and light matrix in Pasamonte are virtually identical, with $\Delta^{17}O$ values of –0.198‰ and –0.206‰, respectively (*11*)]. In contrast, $\Delta^{17}O$ values in BR range from –0.092‰ in the fine-grained lithology to –0.131‰ in the coarse-grained lithology. The average $\Delta^{17}O$ value for BR is 0.112 ± 0.021‰ (1σ), which is a larger 1σ value than observed in any of the HEDs or anomalous eucrite-like basaltic achondrites analyzed in recent studies (*11*–*13*). The relatively high level of oxygen isotope heterogeneity displayed by BR lends further support to the suggestion that this meteorite comes from a separate source from that of other basaltic achondrites. It has been proposed that complete oxygen isotope homogenization on 4 Vesta occurred during an early-stage, large-scale melting event, which may equate with the development of a magma ocean (*10*). The oxygen isotope heterogeneity exhibited by BR indicates that its parent body may have experienced substantially less early-stage melting than 4 Vesta. By analogy with the primitive achondrites, it would indicate that the body had not completely equilibrated with respect to oxygen isotopes.

The major-element composition and mineralogy of the six anomalous eucrite-like basalts are similar to those of normal eucrites (with the exception of the Fe/Mn ratio for NWA 011 and Ibitira pyroxenes, and plagioclase composition in Asuka-881394). Likewise, BR has mineral composition (fig. S2) (*16*), mineral abundance (*17*), and petrography similar to those of normal eucrites. This suggests that different parent bodies had very similar histories. However, it has been shown that eucrite-like and angrite-like partial melts can be generated from the same starting material simply by changing oxygen fugacity (*18*): Eucritic melts are produced at low fugacities (IW–1), angritic melts at higher fugacities (IW+2). By extension, melts forming at similar oxygen fugacities but on different parent bodies may have similar major-element chemistries.

In the case of BR we have determined its orbit, which means we can trace its orbital history. BR was delivered from an unusual, Aten-type orbit (Fig. 3). Aten asteroids are near-Earth objects (NEOs) that have semimajor axes of <1 AU. In this case, virtually the entire orbit was contained within Earth's orbit (Fig. 3). Although orbital data for achondrites have been lacking, it has been suggested that symmetric ante meridiem and post meridiem achondrite fall times can

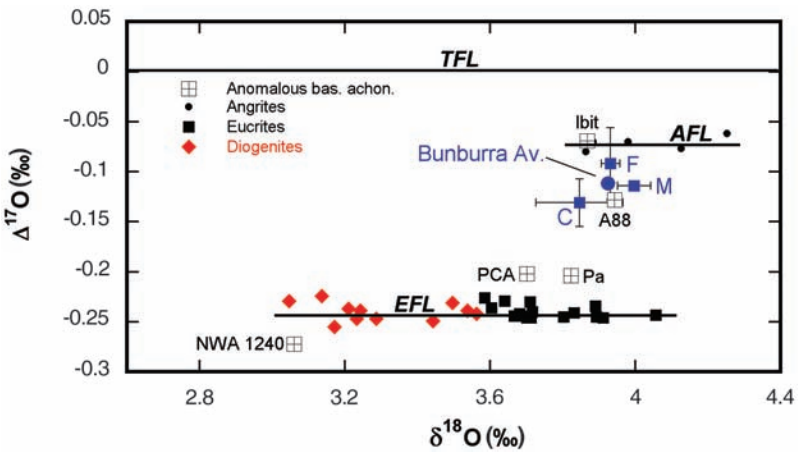

Fig. 2. Oxygen isotopic composition of BR relative to eucrites and diogenites (meteorites associated with 4 Vesta), the angrite group, and anomalous eucrite-like basaltic achondrites [other meteorite data from (*10*, *11*)]. Three distinct lithologies are present in BR (C, coarse-grained; M, medium-grained; F, fine-grained), each having slightly different but overlapping oxygen isotope compositions. BR plots off the eucrite mass fractionation line (EFL) (*10*, *11*). It also plots well away from the anomalous eucrite-like basalts NWA 1240, PCA 91007 (PCA), and Pasamonte (Pa). The BR fine-grained lithology shows slight overlap with the angrites and Ibitira (Ibit) in terms of $\Delta^{17}O$ values. Only the anomalous eucrite-like basalt A-881394 (A88) plots close to the BR average composition. TFL, terrestrial fractionation line; AFL, angrite fractionation line (*10*). Error bars are 2σ.

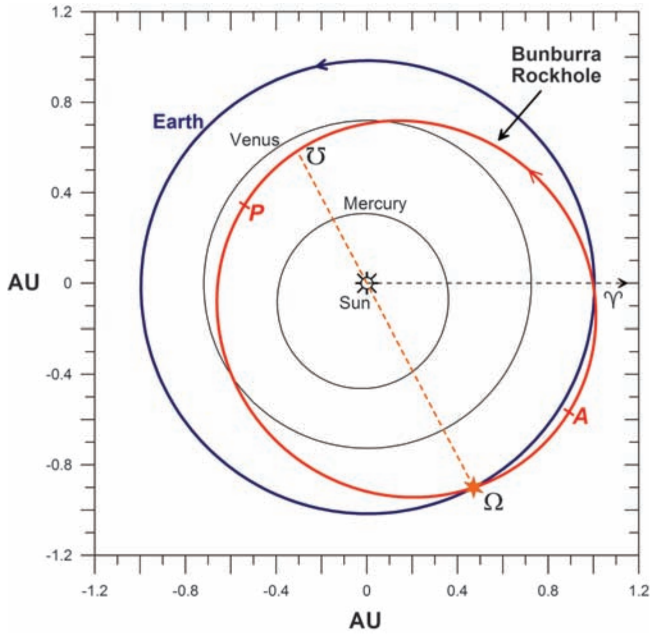

Fig. 3. Orbit of BR projected on the plane of the ecliptic, with orbits of Earth, Venus, and Mercury. P and A are the positions of perihelion and aphelion, respectively, of the BR orbit; ☊ and ☋ are the ascending and descending nodes, showing which part of the orbit is above or below the plane of the ecliptic (the position of the ascending node also defines the collision point of BR with Earth); the arrow labeled ♈ shows the direction to the point of equinox. Orbital parameters: initial velocity = 13.40 ± 0.02 km/s; semimajor axis = 0.8514 ± 0.0009 AU; argument of perihelion = 209.87° ± 0.11°; eccentricity = 0.2450 ± 0.0013; longitude of ascending node = 297.59528° ± 0.00004°; perihelion distance = 0.6428 ± 0.0018 AU; inclination = 9.07° ± 0.07°; aphelion distance = 1.05996 ± 0.00012 AU; period = 0.7856 ± 0.0012 years. Angular elements are in J2000 equinox.

occur only if orbital maturity has been achieved (*19*, *20*). The fact that BR was on a mature Aten orbit supports this suggestion. We explored BR's most recent orbital history, finding approaches as close as 0.04 AU (distance to within a factor of 2) for an encounter with Venus in September 2001, and earlier close approaches with Earth [a search for BR precursor objects in NEO space was also made (*5*)]. In addition, we used a numerical method designed to model the evolution of NEO orbits (*21*) to determine the probability that BR came from a specific NEO source region, given its present-day semimajor axis, eccentricity, and inclination (this approach is based on the assumption that small NEOs have the same orbital distribution as observed kilometer-sized NEOs). The probability of BR 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, a 26% probability that it came from one of the numerous small resonances in the inner main belt, and a 2% probability that it came from the 3:1 resonance. The outer main belt (>2.8 AU) and the Jupiter-family comet population can be ruled out as possible sources.

The BR parent body would likely be classified as a V-type asteroid. The characteristics of a reflectance spectrum are largely controlled by the major-element chemistry of the dominant phases, principally pyroxene (*7*). Because the major-element composition of BR's pyroxene (and plagioclase) (fig. S2) (*16*), modal mineral abundance (*17*), and grain size (fig. S1) are similar to those of normal eucrites, the reflectance spectrum should also be very similar to that of normal eucrites (i.e., it should match that of V-type asteroids). There are few V-type asteroids that are dynamically distinct from 4 Vesta (*22*, *23*). In the inner main belt, most V-types are part of the Vesta dynamical family [the proximity of a few V-types to resonances was a fundamental link in the conceptual chain connecting 4 Vesta with HED meteorites (*3*)]. Even for those inner main belt V-types that are not currently part of the Vesta dynamical family, it is difficult to exclude an origin at Vesta (*24*–*26*). In the case of BR, compositional as well as orbital data indicate that basaltic asteroids unrelated to 4 Vesta reside in the innermost main belt, and that these bodies are delivering material (most likely via the ν_6 resonance) into Earth-crossing orbits.

Finally, the predicted source region of BR is consistent with a recent planetesimal evolution model (*27*). In this model, planetesimals forming in the terrestrial planet region, which would have had fast accretion times relative to main belt objects, would also have been more likely to melt (from decay of short-lived radionuclides such as ^{26}Al) than later-accreting chondrites. The collisional evolution of these planetesimals would result in fragments, some of which (according to numerical simulations) would have been scattered into the main belt via interactions with planetary embryos (*27*). The model provides an explanation both for the paucity of differentiated asteroids in the main belt and for the anomalously old ages for differentiated meteorites [e.g., (*28*)]. The greatest concentration of surviving fragments should be in the innermost main belt (*27*), the most probable starting location for the BR precursor.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/325/5947/1525/DC1
Materials and Methods
Figs. S1 and S2
Table S1
References

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Evidence for Obliquity Forcing of Glacial Termination II

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Variations in the intensity of high-latitude Northern Hemisphere summer insolation, driven largely by precession of the equinoxes, are widely thought to control the timing of Late Pleistocene glacial terminations. However, recently it has been suggested that changes in Earth's obliquity may be a more important mechanism. We present a new speleothem-based North Atlantic marine chronology that shows that the penultimate glacial termination (Termination II) commenced 141,000 ± 2500 years before the present, too early to be explained by Northern Hemisphere summer insolation but consistent with changes in Earth's obliquity. Our record reveals that Terminations I and II are separated by three obliquity cycles and that they started at near-identical obliquity phases.

During the Late Pleistocene, the period of glacial-to-interglacial transitions (or terminations) has increased relative to the Early Pleistocene [~100 thousand years (ky) versus 40 ky] (*1*, *2*). A coherent explanation for this shift still eludes paleoclimatologists (*3*). Although many different models have been proposed (*4*), the most widely accepted one invokes changes in the intensity of high-latitude Northern Hemisphere summer insolation (NHSI). These changes are driven largely by the precession of the equinoxes (*5*), which produces relatively large