Orbit and dynamic origin of the recently recovered Annama’s H5 chondrite

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ABSTRACT
We describe the fall of Annama meteorite occurred in the remote Kola Peninsula (Russia) close to Finnish border on 2014 April 19 (local time). The fireball was instrumentally observed by the Finnish Fireball Network. From these observations the strewnfield was computed and two first meteorites were found only a few hundred metres from the predicted landing site on 2014 May 29 and 30, so that the meteorite (an H5 chondrite) experienced only minimal terrestrial alteration. The accuracy of the observations allowed a precise geocentric radiant to be obtained, and the heliocentric orbit for the progenitor meteoroid to be calculated. Backward integrations of the orbits of selected near-Earth asteroids and the Annama meteoroid showed that they rapidly diverged so that the Annama meteorites are unlikely related to them. The only exception seems to be the recently discovered 2014UR116 that shows a plausible dynamic relationship. Instead, analysis of the heliocentric orbit of the meteoroid suggests that the delivery of Annama onto an Earth-crossing Apollo-type orbit occurred via the 3:1 mean motion resonance with Jupiter or the nu6 secular resonance, dynamic mechanisms that are responsible for delivering to Earth most meteorites studied so far.

Key words: meteorites, meteors, meteoroids – minor planets, asteroids, individual: 2014UR116.

1 INTRODUCTION
The recovery of a meteorite following an accurate trajectory reconstruction of its luminous bolide phase is rarely achieved. Recovery is even less frequent when the observations come from a continuous monitoring effort made by a ground-based fireball network. At the time of writing, 21 meteorites exist where the heliocentric orbit has been calculated from observations of the fireball generated by the passage of the meteoroid through the Earth’s atmosphere and details of these are given in Table 1. In order for a meteorite to survive the passage through the Earth’s atmosphere, the initial meteoroid must have been large, producing a very bright fireball or superbolides with a luminous magnitude over −16. These are rare and unpredictable both in time and location so that the accuracy and reliability of the observations vary widely from event to event. Some are relatively good while others are less trustworthy, depending on the type, quality and number of records. Some events were imaged by accident by untrained observers, but a significant number came about through programmes that regularly monitor the skies. Modern digital cameras have allowed casual images to be obtained even in day-time, producing valuable records of the luminous fireball phase that might be calibrated (see e.g. Trigo-Rodríguez et al. 2006). Even though the fireballs are extremely bright, the progenitor meteoroids...
Table 1. Chronologic list of recovered meteorites with accurate orbital information. The uncertainty in each orbital element is not given here for simplicity, but it is implicit in the last figure given, and in the respective references. The names of other H chondrite falls appear in bold. Concerning the meteorite classification shown in the third column (type), it has been updated for each meteorite to the currently accepted in the online Meteoritical Bulletin Database (http://www.lpi.usra.edu/meteor/metbull.php) from which the exact acronyms were adopted.

| Meteorite name      | Year of fall | Type | Vg (km s⁻¹) | q (au) | 1/a (au⁻¹) | Orbital elements | Reference |
|---------------------|--------------|------|-------------|--------|------------|------------------|-----------|
| Piébram             | 1959         | HS   | 17.43       | 0.789  | 51         | 0.416 0.6711 10.482 241.75 17.79147 | [1], [2] |
| Lost City           | 1970         | HS   | 14.2        | 0.967  |            | 0.602 0.417 12.0 161.0 283.0 | [3] |
| Innisfree           | 1977         | L5   | 14.2        | 0.986  |            | 0.534 0.4732 12.27 177.97 316.8 | [4] |
| Peekskill           | 1992         | H6   | 14.7        | 0.886  |            | 0.671 0.41 4.9 308 17.030 | [5] |
| Tagish Lake         | 2000         | C2-ung | 15.8     | 0.884  |            | 0.505 0.55 2.0 224.4 297.9 | [6] |
| Moravka             | 2000         | H5   | 19.6        | 0.982  |            | 0.541 0.47 32.2 203.5 46.258 | [7] |
| Neuschwanstein      | 2002         | EL6  | 20.94       | 0.7929 |            | 0.417 0.670 11.41 241.20 16.82664 | [2] |
| Park Forest         | 2003         | L5   | 16.1        | 0.811  |            | 0.395 0.680 3.2 237.5 6.1156 | [8] |
| Villalbeto de la Peña | 2004       | L6   | 16.9        | 0.860  |            | 0.435 0.63 0.0 132.3 283.6712 | [9] |
| Bunburra Rockhole    | 2007         | Ercrete | 13.4      | 0.6428 |            | 1.175 0.245 9.07 209.87 297.59528 | [10] |
| Almahata Sitta      | 2008         | Ureelite-an | 12.42  | 0.8999 |            | 0.7644 0.31206 2.5422 234.448 194.10114 | [11] |
| Buzzard Coulee      | 2008         | H4   | 18.0        | 0.961  |            | 0.8130 0.22 25.5 212.0 238.9 | [12] |
| Maribo              | 2009         | CM2  | 28.5        | 0.481  |            | 0.45 0.8 0.26 99.0 117.64 | [13] |
| Grimshy             | 2009         | H5   | 20.9        | 0.9817 |            | 0.490 0.518 28.07 159.865 182.9561 | [14] |
| Jesenice            | 2009         | L6   | 13.78       | 0.9965 |            | 0.571 0.431 9.6 190.5 19.196 | [15] |
| Mason Gully         | 2010         | HS   | 14.53       | 0.982 40 |            | 0.405 0.6023 0.832 18.95 203.2112 | [16] |
| Košice              | 2010         | HS   | 10.3        | 0.957  |            | 0.369 0.647 2.0 204.2 340.072 | [17] |
| Sutter’s Mill       | 2012         | C    | 28.6        | 0.456  |            | 0.386 0.824 2.38 77.8 32.774 | [18] |
| Novato              | 2012         | L6   | 13.67       | 0.9880 |            | 0.478 0.526 5.51 347.35 24.9900 | [19] |
| Chelyabinsk         | 2013         | LL5  | 19.03       | 0.738  |            | 0.581 0.571 4.98 107.67 326.459 | [20] |
| Annama              | 2014         | H5   | 24.2        | 0.634  |            | 0.503 0.69 14.7 264.8 28.611 | This work |

Note. Reference list: [1] Ceplecha (1961); [2] Spurný, Oberst & Heinlein (2003); [3] McCrosky et al. (1971); [4] Halliday, Blackwell & Griffin (1978); [5] Brown et al. (1994); [6] Hildebrand et al. (2006); [7] Borovička et al. (2003); [8] Brown et al. (2004); [9] Trigo-Rodríguez et al. (2006); [10] Bland et al. (2009); [11] Jenniskens et al. (2009) and NEO JPL database for 2008 TC3; [12] Milley et al. (2010) [13] Haack et al. (2010); [14]; [15] Spurný et al. (2011); [16] Borovička et al. (2013); [17] Jenniskens et al. (2012); [19] Jenniskens et al. (2014); [20] Borovička et al. (2013b).
also explore the possible existence of near-Earth asteroids (NEAs) capable of producing Annama’s meteoroid. The description of the observational methods, reduction procedures and results are given in next section. In Section 3, the discussion and main implications of the results are given in the context of the sources of meteorites reaching the Earth. Finally, some general conclusions on this new meteorite are presented.

2 OBSERVATIONS AND DATA REDUCTION

Continuous monitoring of the skies for meteor and fireball activity over Finland was initiated by Ilkka Yrjolä and has continued with different degrees of coverage from 1998. This became incorporated into the Finnish Fireball Network (hereafter, FN) in 2002. Today the network monitors a surface of about 400,000 km² with most of the observations made by amateur astronomers (Gritsevich et al. 2014b). The event under discussion, initially named the Kola Peninsula fireball (FN20140419), was imaged on 2014 April 18 at 22 h 14 m 09.3 ± 0.1 s UTC from three FN stations: Kuusamo, Muho and Mikkeli. It was fortunate that an additional dashcam recording was made by Alexandr Nesterov in Snezhnogorsk, Russia. The locations of these are given in Table 2, while an image from the dashcam is shown as Fig. 1. The general camera details and resolution computed from the calibrations are given in supplementary Table 2b.

After the initial registration of the fireball, the FB_ENTRY program which has been validated using different types of observational data, including most of the fireball cases imaged in Finland (Lyytinen & Gritsevich 2013), was used to analyse the observations. In the past, the program was applied to the number of cases, including observations which may not be accurately timed, some may be observations from one station only, while some of the observations only had directions in use. There are three basic functions in the FB_ENTRY program. One determines the general direction of the trajectory, its location and the velocity of the meteor along the early part of its path. The other two functions determine the individual velocities of the larger surviving fragments, when applicable. From this basic data, other physical parameters are determined using the methods described in Gritsevich (2007, 2009). The case of Annama was very interesting since the key scaling parameters as well as the terminal height of the fireball derived from our analysis were found to be practically the same as the corresponding values earlier reported by Gritsevich (2008) and Moreno- Ibáñez, Gritsevich & Trigo-Rodríguez (2015) for Innisfree, the only meteorite successfully recovered by the MORP monitoring programme (Halliday 1978).

All the images were calibrated using background star field, the astrometric measurements being made manually. The model assumes a symmetry point in the image that could be offset from the image centre. The radial distance from this point depends on the weighted average of the equidistant and gnomonic projections, which in many cases gives quite a good approximation. In the wide field cameras, the weight of the equidistant part is typically more than one and correspondingly the weight of the gnomonic part is negative. This radial model is further improved by means of a polynomial fit with powers up to either 5 or 7 as required. The pixel XY-ratio is also derived and in video cameras is often not 1.0.

Good calibrations (with an accuracy of a few hundredths of a degree) were obtained for both the Kuusamo and the Mikkeli cameras. In the Muho camera field of view, there were few stars near the fireball direction. This did not affect the final solution, because it was used mainly for checking purposes. The calibration of the video from Snezhnogorsk was much more difficult because of the lack of stars in the images. Stacking of a few frames might have been possible but because Jupiter just barely could be detected it was no hope of getting stars from only a few stacked images. Fortunately, Jupiter was found in a few frames before the main fireball outburst took place. The main calibration was made for one frame. The car location and azimuth directions were derived by means of Google-satellite images and Yandex images. All calibration directions were assigned with the azimuth and elevation values. It is very helpful, if the image contains vertical lines that can be measured at more than one point if the image is scarce in star data and this was the case with several buildings providing such vertical lines as can be seen in Fig. 1(b).

The actual horizon was not visible, but one point with elevation 0° was derived by means of some perspective properties of assumed horizontal directions such as roof-tops and window edges. The elevation of Jupiter was known. Jupiter was at a very different azimuth direction compared to the fireball, which has some disadvantages but also could be advantageous since the fit of this to other directions is quite sensitive to possible car location error. There were in all 13 calibration points, including Jupiter and the zero-elevation point (Fig. 1). One of the azimuth directions had three measure points at different elevation angles and three others had two. The pixel XY-ratio was assumed 1.00, but it was also tested to be a free variable and the resulting value was very close to this. For other nearby frames, the fireball direction was transformed to the calibration by means of some distant terrestrial reference points close to the direction where the car was moving. One of the fireball directions was shifted to this frame by means of cloud patterns very near the fireball. The video frames were measured from 1600 × 900 pixel size images. From this calibration, fireball directions for four different video frames were measured. The rms error in the azimuth calibration was 0.14, the largest being 0.34. The total azimuth directions span was more than 70°, also covering the measured fireball azimuth range. The scale in the image centre is 17.3 pixels deg⁻¹ (see Table 2b). However, the highest apparent error of this magnitude in the calibration is due to the uncertainty in the actual directions measurements (from Google images) and not associated with the astrometric video accuracy. The very first fireball direction was measured from a different car location and consequently the accuracy of this direction is not as good as the others and has been given a smaller weight in the trajectory derivation.

| Station # | Station (Province, country) | Camera operator | Longitude | Latitude (N) | Altitude (m) |
|-----------|-----------------------------|-----------------|-----------|--------------|--------------|
| 1         | Flotskaya str., 184682 Snezhnogorsk, Russia | Alexandr Nesterov | 33.241 40 | 69.194 84 | 80           |
| 2         | Kuusamo, FN, Finland         | Asko Aikkila     | 29.718 19 | 65.947 64 | 256          |
| 3         | Mikkeli, FN, Finland         | Aki Taavitsainen, Jani Lauanne | 27.239 53 | 61.684 40 | 148          |
| 4         | Muho, FN, Finland            | Pekka Kokko     | 26.013 37 | 64.954 93 | 71           |

Table 2. Locations of the FN stations and the Russian dashcam which collected the videotapes analyzed here.
The fireball trajectory was computed using the FB_ENTRY software developed by Lyytinen and Gritsevich (2013). In this case, the entry track result is very similar to that obtained using the method of planes developed by Ceplecha (1987). Later on the orbital elements were computed using the Spanish Meteor Network software (Madiedo, Trigo-Rodríguez & Lyytinen 2011) as well as with the recently developed and tested software 'METEOR TOOLKIT' (Dmitriev, Lupovka & Gritsevich 2014). The results are given in Tables 3 and 4.
Table 3. Mass, trajectory and radiant data for Annama’s bolide. $m_{abs}$ is the absolute magnitude, $M_b$ and $M_t$ are the computed initial and terminal masses, $H_b$, $H_{max}$ and $H_e$ are the height for the beginning, maximum and ending parts of the computed trajectory. The meteorite bulk density was measured in 3.5 g cm$^{-3}$ (Gritsevich et al. 2014a,b). Radiant is given for equinox (2000.0). Last three columns are the velocity at infinity, geocentric and heliocentric.

| Code         | $m_{abs}$ $\pm$ 100 kg | $M_b$ (kg) | $M_t$ (kg) | $H_b$ | $H_{max}$ | $H_e$ | $\alpha_{\gamma}$ ($^\circ$) | $\delta_{\gamma}$ ($^\circ$) | $V_{\infty}$ (km s$^{-1}$) | $V_g$ | $V_h$ |
|--------------|-------------------------|------------|------------|-------|-----------|-------|-------------------------------|-------------------------------|-------------------------------|------|------|
| FN20140419 (Kola) | 18.3 ± 0.7              | 472        | 12.5       | 83.9  | 34.6      | 21.8  | 213.03 ± 0.20                 | +8.7 ± 0.4                   | 24.2 ± 0.5                    | 21.5 | 36.3 |

Table 4. Orbital elements of Annama, and Apollo asteroid 2014UR116. Equinox (2000.00).

| Code         | $q$ (au)  | $a$ (au)  | $e$      | $i$ (°) | $\omega$ (°) | $\Omega$ (°) |
|--------------|----------|----------|---------|---------|--------------|--------------|
| FN20140419   | 0.634 ± 0.006 | 1.99 ± 0.12 | 0.69 ± 0.02 | 14.65 ± 0.46 | 264.77 ± 0.55 | 28.611 ± 0.001 |
| 2014 UR116   | 0.563 579 | 2.069 624 05 | 0.727 689 | 6.574 63 | 286.8123 | 6.0125 |

Figure 2. The heliocentric orbit of Annama meteoroid projected into the ecliptic plane and its relative position to the orbits of Mercury, Venus, Earth, and Mars. Grid corresponds to the ecliptic J2000 coordinate system.

3 DISCUSSION

When Drummond (1982) first calculated meteor radiants for bodies approaching within 0.2 au of the Earth’s orbit, the number of known asteroids was quite small, and only three orbits of meteorite-dropping bolides (Příbram, Lost City and Innisfree) were known as can be seen from the chronologic list shown in Table 1. Fortunately, present achievements in completing the NEO inventory and size distribution (Bottke et al. 2002) together with a significant increase in fireball studies and meteorite recoveries...
provide dynamic clues on the origin of metre-sized meteoroids that might be source of localized hazard (Chapman 2004, 2008; Brown et al. 2013).

3.1 Source regions for the Annama meteoroid

To study the origin of Annama in the Solar system we used an unpublished model based on the ideas developed by Morbidelli and Gladman (1998). Assuming Annama’s orbit was \((a, e, i) = (1.990 \text{ au}, 0.690, 11.650)\), we found that it was a 73 per cent chance of coming from the \(n6\) resonance, and 27 per cent chance of coming from the 3:1 resonance. On the other hand, we also looked at what would predict (Bottke et al. 2002) model even although it was meant for large bodies, not meteoroids, so results are given with caution here. The probabilities of having Annama coming from the JFC, outer main belt, 3:1 resonance, intermediate Mars-crossing region \(P_{MC}\), and the \(n6\) resonance \(P_{N6}\) were explored with such model. The model included a source called the ‘intermediate Mars-crossing region’ that is probably not applicable to metre-sized rocks, so we just add this probability to the \(n6\) resonance for clarity. By adding the \(P_{MC}\) and \(P_{N6}\) together, it looks like the strongest probability is that the Annama meteoroid came from the innermost region of the main belt (i.e. it escaped near the \(n6\) resonance). The probabilities for the 3:1 resonance are relatively low: about 10–26 per cent as a function of the uncertainty in Annama’s orbital elements. Consequently, both results about the origin of Annama are consistent and temptatively suggest that from a source standpoint, and for H chondrites, one could argue that Annama potentially came from the same broad source region as Lost City, Peekskill and Buzzard Coulee (Table 1). This result confirms the role of the \(n6\) secular resonance as source of meteorites envisioned long ago by Scholl and Frouschlé (1991). It is important to remark that Příbram, Moravka and Grimsby seem to have a different source because their orbits are more likely associated with the 3:1 resonance.

3.2 Orbital clues on the origin of Annama: Is there a link with known NEOs?

As can be seen in Fig. 2, the Annama meteoroid has an orbit that is quite similar to a typical Apollo NEO. For this reason, we searched through the NEO databases for asteroid orbits that could be regarded as a present-day match for the derived Annama orbit, using the \(D\)-criterion of Southworth and Hawkins (1963). In reality, any of the criteria outlined in Jopek and Williams (2013) could be used, but the Southworth and Hawkins criterion has been used several times before in this context (e.g. Trigo-Rodríguez et al. 2007; Madiedo et al. 2013, 2014).

As was pointed out by Porubcan et al. (Porubcan, Williams & Kronos 2004; Porubcan, Kronos & Williams 2006) before any association should be claimed, the orbital evolution should be similar for at least 5000 years back in time. First of all, we identified 12 potential candidates in the NeoDys (2007) data base having \(D\)-criterion lower than 0.2 among the currently known NEOs: 2000EJ26, 2002EB3, 2002GM5, 2003GR22, 2004HA1, 2004VY14, 2005TU50, 2006JO, 2006WK130, 2012TT5, 2013LY28 and the recently discovered 2014UR116. The evolution of the orbits of these NEOs was calculated by numerical integrations using the MERCURY 6 program (Chambers 1999), a hybrid symplectic integrator widely used in Solar system dynamics studies. The orbits of the Annama bolide

![Figure 3. Southworth–Hawkins dissimilarity criterion (\(D_{SH}\)) comparing with different Annama’s orbits generated by changing the pre-atmospheric velocity \(V_{\text{inf}}\) (in \(\text{km s}^{-1}\)) in the range given by the calibration uncertainty and 2014UR116 nominal orbit over 10 000 years.](https://academic.oup.com/mnras/article-abstract/449/2/2119/1074901)
Orbit and origin of Annama H5 chondrite fall

Figure 4. Numerical integration of $q$ (graph a), eccentricity (b) and inclination (c) for several orbits of Annama obtained for the plausible pre-atmospheric velocity $V_{\text{inf}}$ (in km s$^{-1}$) and asteroid 2014UR116 over 10 000 years. Perturbations from the planets Venus, Earth, Mars, Jupiter and Saturn were taken into account.

The $D$-criterion for all candidates was initially low at current time, but most exhibited a considerable divergence in few thousand years. However, that was not the case for the recently discovered PHA 2014UR116, where the $D$-criterion remained low throughout the
integration, thus there may be a plausible connection with Annama (Fig. 3). For showing better the evolution, this plot and the following one only goes backwards for 10 000 years that is enough for this overall discussion of the evolutionary trends. The results of these integrations for $q$, $e$ and $i$ are shown in Fig. 4 for the range of pre-atmospheric velocity ($V_{\text{int}}$) given by the uncertainty of Annama that we will call here ‘clones’ for simplicity. The general evolution of the inclination is remarkably similar to 2014UR116 and seems to get closer for the Annama clones derived for the higher $V_{\text{int}}$. This is what we should expect, since usually these measurements can underestimate the geocentric velocity at top of the atmosphere. From the inclination graph, it seems that the best $D$-criterion match occurs for a $V_{\text{int}} = 24.7$ km s$^{-1}$. On the other hand, the 24.6 km s$^{-1}$ clone exhibits very different evolution. This clone matches very well the $i$, $e$, $q$ values before diverging abruptly in inclination about 4500 years ago. Interestingly Fig. 3 shows that the lower $V_{\text{int}}$ clones have a lower $D$-criterion values ($D < 0.3$) over a short timescale of about 3000 years. However, the best short-term candidate is again the 24.6 km s$^{-1}$ clone, but the $D$-criterion increases very quickly probably because of a close approach to one of the terrestrial planets.

4 CONCLUSIONS

The pre-impact orbit derived for the Annama H5 chondrite and its backward analysis together with that of several NEAs give us the following clues on the origin of this meteoroid.

(a) The Annama fireball was produced by a meteoroid with significant initial velocity (24.2 km s$^{-1}$) that came from an Apollo-type orbit.

(b) Backward integration of the orbital elements of the progenitor meteoroid have identified that the PHA 2014UR116 could share a similar dynamic origin with Annama, but close approaches with terrestrial planets make it difficult to establish any other relationship among both bodies.

(c) Trajectory reconstruction of Annama’s bolide leaded to meteorite recovery of a meteorite that is the ninth H ordinary chondrite with accurate orbital elements. From the comparison with the eight previous H chondrites recovered, we can conclude that Annama comes from the same broad source region as Lost City, Peekskill and Buzzard Coulee, and it was delivered from a main belt resonance.

(d) Considering Annama’s orbital elements, a source probabilistic model suggests that the Annama meteoroid was delivered to Earth via the nu6 resonance with about a 70 per cent of probability.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 2b. Camera data. (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stv378/-/DC1).

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