



The Dingle Dell meteorite: A Halloween treat from the Main Belt

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Abstract–We describe the fall of the Dingle Dell (L/LL 5) meteorite near Morawa in Western Australia on October 31, 2016. The fireball was observed by six observatories of the Desert Fireball Network (DFN), a continental-scale facility optimized to recover meteorites and calculate their pre-entry orbits. The 30 cm meteoroid entered at 15.44 km s⁻¹, followed a moderately steep trajectory of 51° to the horizon from 81 km down to 19 km altitude, where the luminous flight ended at a speed of 3.2 km s⁻¹. Deceleration data indicated one large fragment had made it to the ground. The four person search team recovered a 1.15 kg meteorite within 130 m of the predicted fall line, after 8 h of searching, 6 days after the fall. Dingle Dell is the fourth meteorite recovered by the DFN in Australia, but the first before any rain had contaminated the sample. By numerical integration over 1 Ma, we show that Dingle Dell was most likely ejected from the Main Belt by the 3:1 mean motion resonance with Jupiter, with only a marginal chance that it came from the v₆ resonance. This makes the connection of Dingle Dell to the Flora family (currently thought to be the origin of LL chondrites) unlikely.

INTRODUCTION

As of mid-2017, there are nearly 60k meteorite samples classified in the Meteoritical Bulletin Database.¹ However, aside from a handful of Lunar (~300) and Martian ($\simeq 200$) meteorites that have a well-known origin, the link with other solar system bodies is limited. From the instrumentally documented fall of the Příbram meteorite in 1959 (Ceplecha 1961), we learned that chondritic material comes from the asteroid Main Belt. The way this material evolves onto an Earth crossing orbit starts with a disruption in the Main Belt. The small members of the debris field can be strongly affected by the Yarkovsky effect (Farinella et al. 1998) and as a consequence their semimajor axis is continually altered. If the debris field is close to a powerful resonance (in semimajor axis, inclination, eccentricity space), the breakup event feeds material into that resonance, which will in turn push the debris' perihelia into the inner solar system. This can occur on a time scale of less than a million years in some cases (Morbidelli et al. 1994).

Calculating the orbit of a meteoroid using only the luminous trajectory as the observation arc is in most cases not precise enough to allow unequivocal backtracking into a specific region of the Main Belt, hence the statistical results reported by Bland et al. (2009); Brown et al. (2011); Jenniskens et al. (2014); and Trigo-Rodríguez et al. (2015). In order to understand the origin of the different groups of meteorites from the main asteroid belt, it is therefore essential to collect several dozen samples with orbits and look at source regions in a broader, statistical way.

Dedicated Networks to Recover Meteorites with Known Provenance

In the decade following 2000, the recovery rate of meteorites with determined orbits has dramatically increased (Borovička et al. 2015), without a significant increase in collecting area of the major dedicated fireball

¹https://www.lpi.usra.edu/meteor/metbull.php

networks. While the initial phase of the Desert Fireball Network (DFN) started science operations in December 2005, covering 0.2×10^6 km² (Bland et al. 2012), other major networks ceased operations. The Prairie network in the United States (0.75×10^6 km² [McCrosky and Boeschenstein 1965]) shut down in 1975, the Canadian Meteorite Observation and Recovery Project (MORP)— 1.3×10^6 km²—stopped observing in 1985 (Halliday et al. 1996), and the European Network's covering area of ~ 1×10^6 km² has not significantly changed (Oberst et al. 1998). If not due to a larger collecting area, this increase can be explained by other factors as follows.

- 1. Existing networks improving their data reduction techniques (Spurný et al. 2014).
- Democratization and cheap operating cost of recording devices (surveillance cameras, consumer digital cameras, etc.) (Borovička et al. 2003).
- 3. Use of Doppler radar designed for weather observations to constrain the location of falling meteorites (Fries and Fries 2010; Jenniskens et al. 2012; Fries et al. 2014).
- 4. Deployment of the Desert Fireball Network expressly on favorable terrain to search for meteorites. In its early stage, within its first 5 years of science operation, the DFN yielded two meteorites (Bland et al. 2009; Spurný et al. 2011), while MORP only yielded one (Halliday et al. 1981) in 15 years of operations over a larger network.
- 5. To a lesser extent, development of NEO telescopic surveillance programs. One single case so far (the Catalina Sky Survey detecting the Almahata Sita meteoroid several hours before impact [Jenniskens et al. 2009]); however, this technique is likely to yield more frequent successes with new deeper and faster optical surveyors, like LSST, which comes online in 2021 (Ivezic et al. 2008).

The DFN started developing digital observatories to replace the film-based network in 2012 with the goal of covering 10^6 km^2 , the more cost-effective than expected digital observatories allowed the construction of а continent-scale network covering over $2.5 \times 10^6 \mbox{ km}^2$ (Howie et al. 2017a). This program rapidly yielded results, less than a year after starting science operation (in November 2014). One of the observatories lent to the SETI institute in California was a crucial viewpoint to calculating an orbit for the Creston fall in California in October 2015 (Meteoritical Bulletin 2015), and the first domestic success came 2 months later with the Murrili meteorite recovery on Kati Thanda-Lake Eyre (Devillepoix et al. 2016; Meteoritical Bulletin 2016). We report here the analysis of observations of a bright fireball that led to the fourth find by the Desert Fireball Network in Australia: the Dingle Dell meteorite. Dingle Dell was originally classified as an LL ordinary chondrite, petrographic type 6 (Meteoritical Bulletin 2017). However, further analysis revealed that it in fact sits on the L/LL boundary (Benedix et al. 2017). The sample has experienced a low level of shock, but has been heated enough to show recrystallization of minerals and matrix. There is no evidence of terrestrial weathering visible on the metal or sulfide grains, which is consistent with its extremely fast retrieval from the elements.

Current Understanding of the Origin of the Main Groups of L and LL Chondrites

L Chondrites

L chondrites represent 32% of total falls. Schmitz et al. (2001) first identified a large amount of fossil L chondrites meteorites in $\simeq 467$ Ma sedimentary rock, which suggests that a breakup happened not too long before, near an efficient meteorite transport route. From spectroscopic and dynamical arguments, Nesvorný et al. (2009) proposed that the Gefion family breakup event, close to the 5:2 MMR with Jupiter, might be the source of this bombardment, given the rapid delivery time, and a likely origin of L chondrite asteroids outside of the 2.5 AU. Most shocked L5 and L6 instrumentally observed falls also seem to come from this breakup, with an 39 Ar- 40 Ar age around \simeq 470 Ma ago: Park Forest (Brown et al. 2004), Novato (Jenniskens et al. 2014), Jesenice (Spurný et al. 2010), and Innisfree (Halliday et al. 1981). Only the Villalbeto de la Peña L6 (Trigo-Rodríguez et al. 2006) does not fit in this story because of its large cosmic ray exposure age (48 Ma), inconsistent with a 8.9 Ma collisional lifetime (Jenniskens 2014).

LL Chondrites

Thanks to Vernazza et al. (2008), we know that Sand Q-type asteroids observed in NEO space are the most likely asteroidal analog to LL-type ordinary chondrites. The Hayabusa probe returned samples from S-type (25143) Itokawa, finally unequivocally matching the largest group of meteorites recovered on Earth (ordinary chondrites) with the most common spectral class of asteroids in the Main Belt (Nakamura et al. 2011). The sample brought back from Itokawa is compatible with LL chondrites. Indeed, LL compatible asteroids make up two thirds of near-Earth space. The spectrally compatible Flora family from the inner Main Belt can regenerate this population through the v_6 secular resonance. But one large problem remains: only 8% of falls are LL chondrites (Vernazza et al. 2008). The orbits determined for some LL samples have so far not helped solve this issue. If we exclude Benešov (Spurný et al. 2014), which was a mixed fall, scientists had to wait until 2013 to get an LL sample with a

precisely calculated orbit: Chelyabinsk (Borovička et al. 2013; Brown et al. 2013). The preatmospheric orbit and composition of the Chelyabinsk meteorite seems to support the Flora family origin for LL chondrites, although a more recent impact could have reset the cosmic ray exposure age to 1.2 ± 0.2 Ma, and the presence of impact melts (very rare in ordinary chondrites due to the large impact velocities required [Keil et al. 1997]). Reddy et al. (2014) argued that an impact melt such as the one observed in the Chelyabinsk meteorites, or shock darkening, can alter the spectra of an S/O-type asteroid to make it look like a C/X-type spectrally. The implication of this is that the Baptistina family members (C/X-type), which overlaps dynamically with the Flora (S-type), could be the remains of a large impact on a Florian asteroid, and meteorites from both families can be confused both in their spectral signature and dynamical origin. It must be noted however that Reddy et al. (2014) do not make any conclusions on the origin of Chelyabinsk from the Baptistina family. The Chelyabinsk meteorite is also not a typical LL sample found on Earth, because of its size $(\simeq 17 \text{ m})$ and the presence of impact melts.

Based on its classification, we put the orbit of the Dingle Dell meteorite in context with other calculated orbits from L and LL chondrites and discuss the resonances from which it may have originated.

FIREBALL OBSERVATION AND TRAJECTORY DATA

On Halloween night shortly after 8 PM local time, several reports of a large bolide were made via the *Fireballs In The Sky* smartphone app (Sansom et al. 2016) from the Western Australian Wheatbelt area. These were received a few hours prior to the daily DFN observatory reports, apprising the team of the event expeditiously. The DFN observatory sightings are routinely e-mailed after event detection has been completed on the night's data set. It revealed that six nearby DFN observatories simultaneously imaged a long fireball starting at 12:03:47.726 UTC on October 31, 2016 (Fig. 1).

Instrumental Records

The main imaging system of the DFN fireball observatories is a 36 MPixel sensor: Nikon D810 (or D800E on older models), combined with a Samyang lens 8 mm F/3.5. Long-exposure images are taken every 30 s. The absolute and relative timing (from which the fireball velocity is derived) is embedded into the luminous trail by use of a liquid crystal (LC) shutter between the lens and the sensor, modulated according to a de-Brujin sequence (Howie et al. 2017b). The LC



Fig. 1. Cropped all-sky images of the fireball from the six DFN observatories. Images are of the same pixel scale with the center of each image positioned at the observatory location on the map (with the exception of Perenjori, whose location is indicated). The Badgingarra image is cropped because the sensor is not large enough to accommodate the full image circle on its short side. The saturation issue is exacerbated by light scattered in the clouds on cameras close to the event, this is particularly visible on the Perenjori image. The black blotch in the Perenjori image is an artifact that thankfully did not extend far enough to affect the quality of the data. Approximate trajectory path shown by orange arrow. Location of the recovered meteorite is shown by the red dot.

shutter operation is tightly regulated by a microcontroller synced with a Global Navigation Satellite System (GNSS) module to ensure absolute timing accurate to ± 0.4 ms. For further details on DFN observatory specifications, see Howie et al. (2017a).

Some DFN observatories also include video systems operating in parallel with the long-exposure photographic imaging system (Table 1). The video cameras are Watec 902H2 Ultimate CCIR (8 bit 25 interlaced frames per second), with a Fujinon fisheye lens. Originally intended as a backup device for absolute timing, these video systems have been retained for future daytime observation capabilities. Here we make use of the video data to acquire a light curve, as the event saturated the still camera sensors. The closest camera system to this event was in Perenjori (Table 1), located almost directly under the fireball, and was the only station to image the end of the luminous trajectory (Fig. 1). Other nearby camera sites were overcast and did not record the event. In order to triangulate the trajectory of the fireball, distant stations had to be used, all over 200 km away. The Hyden, Kukerin, and Newdegate systems were all around 500 km from the event and, although still managing to capture the fireball, were too low on the horizon for accurate calibration (Fig. 2).

Astrometry

All images captured by the DFN observatories are saved even when no fireball is detected. This is possible thanks to the availability of large-capacity hard drives at reasonable costs. Not only does this mitigate event loss during initial testing of detection algorithms but it also gives a snapshot of the whole visible sky down to 7.5 point source limiting magnitude, every 30 s. The astrometric calibration allows the points picked along the fireball image to be converted to astrometric sky coordinates. The associated astrometric uncertainties are dominated by the uncertainty on identifying the centroids along the segmented fireball track.

We have carried out studies on the long-term camera stability by checking the camera pointing using astrometry. On the outback system tested, the pointing changed less than 1' over the 3-month period assessed. The pointing is therefore remarkably stable, and the relevant fireball image can thus be astrometrically calibrated using a picture taken at a different epoch.

Table 1. Locations and nature of instrumental records. We use cameras <400 km away for trajectory determination.

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Observatory	Instruments	Latitude	Longitude	Altitude (m)	Distance ^a (km)
Perenjori	P, V	29.36908 S	116.40654 E	242	91
Badgingarra	Р	30.40259 S	115.55077 E	230	204
Northam	Р	31.66738 S	116.66571 E	190	323
Hyden	Р	32.40655 S	119.15325 E	390	484
Kukerin	Р	33.25337 S	118.00628 E	340	520
Newdegate	Р	33.05436 S	118.93534 E	302	534

P = Photographic record (exposures: 25 s, 6400 ISO, F/4.); V = video record.

^aDistance from the meteoroid at 70 km altitude.



Fig. 2. Configuration of DFN station observations for the Dingle Dell fireball. White rays show observations used in triangulation of the trajectory (approximated to the yellow line, starting NE and terminating to the SW of Perenjori). Hyden, Newdegate, and Kukerin stations were all around 500 km away from the event and were not used in triangulation.

This is particularly useful when a bright fireball overprints nearby stars, and especially in this case where clouds are present. In general however, we aim to use a calibration frame taken as close as possible from the science frame, particularly when studying an important event, such as a meteorite fall. In the following paragraph, we present the methods used for astrometrically calibrating the still images, using as an example the Perenjori data. This technique is implemented in an automated way in the reduction pipeline for all detected events.

The astrometric solution for the Perenjori camera is obtained using an image taken a few hours after the event, once the clouds had cleared (2016-10-31T16:00:30 UTC), containing 1174 stars of apparent magnitude $mV \in [1.5, 5.5]$. A third-order polynomial fit is performed to match detected stars to the Tycho-2 star catalogue. The transformation is further corrected using a second-order polynomial on the radial component of the optics. The stability of the solution can be checked at regular intervals. The slight degradation in altitude precision for altitudes below 20° in Fig. 3 is due to a partly obstructed horizon from this camera (e.g., trees, roofs). This degradation usually starts around 10° on cameras with a clear horizon, as is the case for most outback systems.



Fig. 3. Residuals on the global astrometric solution for the Perenjori camera. The pixel size at the center of the FoV is shown by the gray square in order to gauge the quality of the solution, as well as the 1σ residual bars on the stars. The azimuth residuals are artificially large around the pole of the spherical coordinate system, so we have multiplied them by cos(elevation) to cancel out this artifact.

The beginning of the fireball on the Perenjori image is partially masked by clouds, yielding only a handful of points. The middle section is not usable as the sensor was saturated in large blobs, rendering impossible timing decoding or even reliable identification of the center of the track. However, the Perenjori image provides a good viewpoint for the end of the fireball.

Well-calibrated data were also obtained from the Badgingarra camera, before it went outside the sensor area at 30.6 km altitude. Although the Northam camera was very cloudy, we were able to pick the track of the main meteoroid body without timing information, and use it as a purely geometric constraint. Hyden, Kukerin, and Newdegate also picked up the fireball; however, the astrometry so low on the horizon ($<5^{\circ}$) was too imprecise (between 2 and 4 arcminutes) to refine the trajectory solution.

Photometry

The automated DFN data reduction pipeline routinely calculates brightness for nonsaturated fireball segments. For this bright event however, the brightness issue was exacerbated by large amounts of light scattered in the clouds (Fig. 1), so it was impossible to produce a useful light curve from the photograph. On the other hand, the Perenjori observatory recorded a low-resolution compressed video through the clouds. Although it is not possible to calibrate this signal, we can get a remarkably deep dynamic range reading of the all-sky brightness, thanks to the large amount of light scattered in the numerous clouds. By deinterlacing the analog video frames, we were able to effectively double the time resolution (25 interlaced frames per second to 50 fields per second, which are equally as precise for all-sky brightness measurements). To correct how the auto-gain affects the signal, we perform aperture photometry on Venus throughout the event. The analog video feed is converted to digital by the Commell MPX-885 capture card, and then processed by the compression algorithm (H264 VBR, FFmpeg ultrafast preset) (Howie et al. 2017a) before being written to disk, divided into 1 minute long segments. The PC clock is maintained by the Network Time Protocol (NTP) service, fed with both GNSS and network time sources. However, the timestamp on the file created by the PC suffers from a delay. We measured the average delay using a GPS video time inserter (IOTA-VTI) on a test observatory. This allowed us to match the light curve obtained from the video to astrometric data to within 20 ms. Peak A in Fig. 4 is visible on the photographs from both Badgingarra and Hyden. These are used to validate the absolute timing alignment of the video data.



Fig. 4. All-sky brightness (sum of all the pixels) from the video camera at the Perenjori observatory. The light curve is corrected to take into account the effect of auto-gain.

Eye Witnesses

Three anecdotal reports of the fireball were received via the *Fireballs in the Sky* smartphone app (Paxman and Bland 2014; Sansom et al. 2016) within 2 hours of the event (Table 2). The free app is designed to enable members of the public to easily report fireball sightings. Phone GPS, compass, and accelerometers are utilized to report the direction of observations, while a fireball animation aids users in estimating the color, duration, and brightness of the event. This app is an interactive alternative to the popular web-based reporting tool of the International Meteor Organization (Hankey and Perlerin 2015).

The app reports were the first notification of the fireball received by the DFN team, even before the receipt of daily e-mails from the fireball observatories. The azimuth angles reported by the observers were not sufficiently consistent to enable a triangulation based on app reports alone.

The fireball was also reported by several nearby witnesses, and was described in detail by an eye witness only 7.4 km from the fall position (Table 2) who also reported hearing sounds, which due to the time of arrival may have been electrophonic in nature (Keay 1992).

FIREBALL TRAJECTORY ANALYSIS

Geometry

To determine the trajectory of the fireball through the atmosphere, we used a modified version of the Borovička (1990) straight-line least squares (SLLS) method. This involves creating a radiant in 3-D space that best fits all the observed lines of sight, minimizing the angular residuals between the radiant line and the observed lines of sight. While angular uncertainties will be similar across different camera systems, the effect of distance results in larger cross-track errors for more distant observatories (Fig. 5), and therefore less influence on the resulting radiant fit. The end of the fireball from the Perenjori image was used, along with Badgingarra and Northam camera data to triangulate the geometry of the fireball trajectory. The inclusion of astrometric data from Hyden, Kukerin, and Newdegate (see the Astrometry section) degraded the solution: the cross-track residuals from all viewpoints increased significantly, suggesting a systematic issue with the abovementioned camera data. Therefore, we only used the trajectory solution yielded by the three closest view points (Fig. 5). The best combination of viewpoints (Perenjori and Badgingarra) yields an excellent convergence angle of 86°. The trajectory solution points to a moderately steep entry with a slope of 51° from the horizon, with ablation starting at an altitude of 80.6 km and ending at 19.1 km (see Table 3).

Dynamic Modeling of the Trajectory, Including Velocity and Mass Determination

Filter Modeling

The method described in Chapter 4 of Sansom (2016) is an iterative Monte Carlo technique that aims to determine the path and physical characteristics such as shape (A: the cross section area to volume ratio), density (ρ_m), and ablation coefficient (σ) of a meteoroid from camera network data. In this approach, one is able to model meteoroid trajectories based on raw astrometric data. This avoids any preconceived constraints imposed on the trajectory, such as the

Table 2. Observer reports from eyewitness accounts and *Fireballs in the Sky* app (FITS).

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Reporting means	Report time (UTC)	Location	Approx. distance from event (km)	Reported duration (s)	Reported brightness (stellar Mag)	Reported color
FITS	12:04	Perth region	300	2.6	-8	Orange
FITS	12:59	Ballidu	150	6.4	-7	Green
FITS	13:35	Dowerin	230	8.6	-9	Pink
Eye witness	N/A	Koolanooka Hills	7.4	>5	>-12.6 (full moon)	



Fig. 5. Cross-track residuals of the straight-line least squares fit to the trajectory from each view point. These distances correspond to astrometric residuals projected on a perpendicular plane to the line of sight, positive when the line of sight falls above the trajectory solution. Note that the larger residuals on the Northam camera do not equate to larger astrometric uncertainties, but rather reflect a rather large distance from the observatory. The distances in the legend correspond to the observation range [highest point– lowest point].

straight-line assumption used in the Geometry section. Unfortunately, this requires multiple viewpoints with accurate absolute timing information to record the meteoroid position. For this event, timings encoded in the trajectory were distinguishable for only the initial 4.2 s by the Badgingarra system (before any significant deceleration) and for the final 1.1 s by the Perenjori system. In this case, we must rely on the straight-line least squares (SLLS) triangulation to determine meteoroid positions (see the Geometry section). We therefore applied the three-dimensional particle filter model outlined in Chapter 4 of Sansom (2016) using triangulated geocentric instead coordinates as observation measurements. Uncertainties associated with using pretriangulated positions based on an assumed straight-line trajectory are incorporated. The distribution of particle positions using such observations will be overall greater than if we had been able to use the raw measurements.

As a straight line may be an oversimplification of the trajectory to most reliably triangulate the end of the

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luminous flight using the SLLS method, the final 1.1 s was isolated (this being after all major fragmentation events described in the Atmospheric Behavior section). The filter was run using these positions and initiated at $t_0 = 5.0$ s (2016-10-31T12:03:52.726 UTC). Particle mass values at this time would be more suitably initiated using a logarithmic distribution in the range from 0 kg to 1000 kg. The initiation of other filter parameters. including the multimodal density distribution, are described in Sansom et al. (2017) with ranges given in table 1 of their work. As a calibrated light curve was not attainable, brightness values were not included in this analysis, making it a purely dynamic solution. The adaptive particle filter technique applied here uses the same state vector and three-dimensional state equations as in Chapter 4 of Sansom (2016) to evaluate the meteoroid traveling through the atmosphere. As we are using pretriangulated geocentric positions as observations, the measurement function here is linear. The particles are still allowed to move in 3-D space, and an evaluation of the model fit is performed as the absolute distance between the pretriangulated SLLS point and the evaluated particle position. This is shown in Fig. 6 for all particles, with the distance to the mean value also shown. Mean particle positions show a good fit to the SLLS triangulated observations, with a maximum of 30 m differences early on, decreasing to 6 m at the end.

The filter estimates not only the position and velocity of the meteoroid at each observation time but also the mass; ablation coefficient, σ ; and shape density coefficient, κ . At the final observation time $t_f = 6.1$ s (2016-10-31T12:03:53.826 UTC), the state estimate results in weighted median values of mass_f = 1.49 ± 0.23 kg, speed_f 3359 ± 72 m s⁻¹, $\sigma_f = 0.0154 \pm 0.0054$ s² km⁻², and $\kappa_f = 0.0027 \pm 0.0001$ (SI). Although κ may be used to calculate densities for a given shape and drag coefficient, to avoid introducing assumptions at this stage we may gauge its value by reviewing the density with which surviving particles were initiated. The distribution of final mass estimates is plotted against this initial density attributed to each given

Table 3. Summary	table of brigh	it flight events.	. Fragmentation ev	vent letters are defined	on the light	curve (Fig. 4	+).

Event	Time ^a (s)	Speed (m s^{-1})	Height (m)	Longitude (°E)	Latitude (°N)	Dynamic pressure (MPa)
Beginning	0.0	15443 ± 60	80594	116.41678	-28.77573	
А	1.20	15428	65819	116.36429	-28.86973	0.03
В	1.72	15401	59444	116.34151	-28.91045	0.08
С	1.96	15378	56531	116.33108	-28.92909	0.11
D	4.08	13240	32036	116.24270	-29.08672	2.28
Е	4.58	10508	27302	116.22547	-29.11738	3.09
F	4.84	8988	25019	116.21716	-29.13217	3.27
Terminal	6.10	3243 ± 465	19122	116.19564	-29.17045	

^aPast 2016-10-31T12:03:47.726 UTC.



Fig. 6. Position residuals of the 3D particle filter fit to the SLLS triangulated observations for the final 1.1 s of the luminous trajectory. Individual particle weightings are shown in grayscales, with weighted mean values shown in red.

particle in Fig. 7, along with the recovered Dingle Dell meteorite mass of 1.150 kg and bulk density of 3450 kg m⁻³. In this figure, the distribution of the main cluster of particles is consistent with the recovered mass; however, the initial densities are lower. The weighted median value of initial bulk densities (at $t_0 = 5.0$ s) for all particles resampled at t_f is 3306 kg m⁻³. It is expected that the bulk density of a meteoroid body may slightly increase throughout the trajectory as lower density, more friable material is preferentially lost. This could justify the slightly lower bulk densities attributed at t_0 .

In order to obtain the entry speed of the meteoroid with appropriate errors, we apply an extended Kalman smoother (Sansom et al. 2015) to the straight-line solution for the geometry, considering the timing of the points independently for each observatory. Of the two cameras that have timing data for the beginning of the trajectory, only Badgingarra caught the start, giving an entry speed of $15402 \pm 60 \text{ m s}^{-1}$ (1 σ) at 80596 m altitude. To determine whether speeds calculated are consistent between observatories, the first speed calculated for Perenjori—15384 ± 64 m s⁻¹ at 75548 m altitude—is compared to the Badgingarra solution at this same altitude $-15386 \pm 43 \text{ m s}^{-1}$. The results are

remarkably consistent, validating the use of a Kalman smoother for determining initial velocities.

Dimensionless Coefficient Method

As a comparison to the particle filter method, the dimensionless parameter technique described bv Gritsevich (2009) was also applied. The ballistic parameter (α) and the mass loss parameter (β) were calculated for the event, resulting in $\alpha = 9.283$ and $\beta = 1.416$ (Fig. 8). As the particle filter technique in this case was not able to be performed on the first 5.0 s of the luminous trajectory, these parameters may be used to determine both initial,² and final³ main masses, given assumed values of the shape and density of the body. Using the same parameters as Gritsevich (2009) ($c_d = 1$, A = 1.55) along with the density of the recovered meteorite, $\rho = 3450 \text{ kg m}^{-3}$ gives an entry mass, $m_{\rm e} = 81.6$ kg, and a $m_{\rm f} = 1.4$ kg. Varying the shape of the body to spherical values, A = 1.21 (Bronshten 1983) gives an initial mass of $m_e = 38.8$ kg. Instead of assuming values for c_d and A, we can also insert the κ value calculated by the particle filter to give

²See equation 14 in Gritsevich (2009).

³See equation 6 in Gritsevich (2009).



Fig. 7. Results of the 3D particle filter modeling, showing the distribution of final mass estimates along with the densities with which particles were initiated at $t_0 = 5$ s. Mass estimates are consistent with the recovered meteorite mass found (red cross), with initial densities slightly below the bulk rock value.

 $m_{\rm e} = 41.1$ kg. These results can be approximated to a 30 cm diameter initial body. Note that this method is the most reliable for calculating a minimum entry mass of the Dingle Dell meteoroid. The photometric method would require a calibrated light curve, and the particle filter method requires good astrometric data coverage



Fig. 8. Trajectory data from both Perenjori and Badgingarra observatories, with speeds normalized to the speed at the top of the atmosphere (15.443 km s⁻¹; Table 3), V_0 , and altitudes normalized to the atmospheric scale height, $h_0 = 7.16$ km. The best fit to equation 10 of Gritsevich (2009) results in $\alpha = 9.283$ and $\beta = 1.416$ and is shown by the blue line. These dimensionless parameters can be used to determine the entry and terminal mass of the Dingle Dell meteoroid.

where significant deceleration occurs (the missing data between 4.2 and 5.0 s).

Atmospheric Behavior

In Table 3, we report the ram pressure $(P = \rho_a v^2)$ required to initiate the major fragmentation events labeled on the light curve in Fig. 4. The density of the atmosphere, ρ_a , is calculated using the *NRLMSISE-00* model of Picone et al. (2002), and v is the calculated speed. The meteoroid started fragmenting quite early (events *A*, *B*, and *C*), starting at 0.03 MPa. These early fragmentation events suggest that the meteoroid had a much weaker lithology than the meteorite that was recovered on the ground. Then no major fragmentation happened until two very bright peaks in the light curve: *D* (2.28 MPa) and *E* (3.09 MPa). These large short-lived peaks suggest a release of a large number of small pieces that quickly burnt up. A small final flare (*F* -3.27 MPa) 1.26 s before the end is also noted.

DARK FLIGHT AND METEORITE RECOVERY

The results of the dynamic modeling (Fig. 7) are fed directly into the dark flight routine. By using the state vectors (both dynamical and physical parameters) from the cloud of possible particles, we ensure that there is no discontinuity between the bright flight and the dark flight, and we get a simulation of possible impact points on the ground that is representative of the modeling work done on bright flight data.

Wind Modeling

The atmospheric winds were numerically modeled using the Weather Research and Forecasting (WRF) software package version 3.8.1 with the Advanced Research WRF (ARW) dynamic solver (Skamarock et al. 2008). The weather modeling was initialized using global 1° resolution National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) Operational Model Global Tropospheric Analysis data. As a result, a 3 km resolution WRF product with 30 minutes history interval was created and weather profile at the end of the luminous flight for 2016-10-31T12:00 UTC was extracted (Fig. 9). The weather profile includes wind speed, wind direction, pressure, temperature, and relative humidity at heights ranging up to 30 km (Fig. 9), providing complete atmospheric data for the main mass from the end of the luminous phase to the ground, as well as for fragmentation events E and F(Table 3). Different wind profiles have been generated. by starting the WRF integration at different times: 2016 October 30d12h, 30d18h, 31d00h, 31d06h, and 31d12h UTC. Three of the resulting wind models converge to a similar solution in both speed and direction (30d12h, 31d00h, 31d12h) and will be hereafter referred to as solution W1 (Fig. 9). The other two models from 30d18h (W2) and 31d00h (W3) differ significantly. For example, the maximum jet stream strength is $\simeq 47 \text{ m s}^{-1}$ for W1, $\simeq 34$ m s⁻¹ for W3, and $\simeq 29$ m s⁻¹ for W2. To discriminate which wind profile is closer to the truth, we ran the model next to the Geraldton balloon launches of 2016 October 31d00h and 31d06h UTC, but no discrepancy was noticeable between all five scenarios. Considering that three model runs clump around W1, whereas W3 and W2 are isolated, we choose W1 as a preferred solution. The investigation of why W3 and W2 are different is beyond the scope of this paper, nonetheless we discuss how these differences affect the dark flight of the meteorites in the next section.

Dark Flight Integration

The dark flight calculations are performed using an eighth-order explicit Runge-Kutta integrator with adaptive step-size control for error handling. The physical model uses the single body equations for meteoroid deceleration and ablation (Hoppe 1937; Whipple 1939). In this model, rotation is accounted for such that the cross-sectional area to volume ratio (*A*) remains constant throughout the trajectory. The variation in flow regimes and Mach ranges passed

through the body alter the values used for the drag coefficient, which can be approximated using table 1 in Sansom et al. (2015). The integration of all the particles from the Dynamic Modeling of the Trajectory, Including Velocity and Mass Determination section allows the generation of probability heat maps to maximize field searching efficiency. The ground impact speed for the mass corresponding to the recovered meteorite is evaluated at 67 m s⁻¹.

In calculating a fall line for an arbitrary range of masses, the assumed shape of the body and the wind model used both affect the final fall position. However for a given wind model, a change in shape only shifts the masses along the fall line.

We also calculate dark flight fall lines from fragmentation events that happened within the wind model domain: E and F. Unsurprisingly, the main masses from those events are a close match to the corresponding main mass started from the end of the visible bright flight. However, small fragments are unlikely to be found as they fell into the Koolanooka Hills bush land (Fig. 10).

Search and Recovery

Within 2 days, two of the authors (PB and MT) visited the predicted fall area, about 4 hours' drive from Perth, Western Australia to canvas local farmers for access and information. Having gained landowner permission to search, a team was sent to the area 3 days later. Searching was carried out by a team of four (MT, BH, TJS, and HD), mostly on foot and with some use of mountain biking in open fields. The open fields' searching conditions were excellent, although the field boundaries were vegetated. The team managed to cover about 12 ha per hour when looking for a >1 kg mass on foot. On the second day, a meteorite was found (Fig. 11) close to the Dingle Dell farm boundary, at coordinates $\lambda = 116.215439^{\circ}$ $\varphi = -29.206106^{\circ}$ (WGS84), about 130 m from the originally calculated fall line, after a total of 8 h of searching. The recovered meteorite weighs 1.15 kg, with a rounded brick shape of approximately $16 \times 9 \times 4$ cm, and a calculated bulk density of 3450 kg m⁻³ (Fig. 11). The condition of the meteorite is excellent, having only been on the ground for 6 days, 16 h. Discussion with the local landowner, and checking the weather on the nearest Bureau Of Meteorology observation station (Morawa Airport, 20 km away) showed that no precipitation had fallen between times of landing and recovery. The meteorite was collected and stored using a Teflon bag, and local soil samples were also collected in the same manner for comparison. No trace of impact on the ground was noticed. The meteorite was found intact (entirely



Fig. 9. Wind model profile WI, extracted as a vertical profile at the coordinates of the lowest visible bright flight measurement.

covered by fusion crust) on hard ground, resting upright (Fig. 11), and covered with dust. So it is possible that the meteorite fell a few meters away in softer ground and bounced or rolled to the recovered position.

PRE-ENCOUNTER ORBIT

The backward propagation of the observed trajectory into an orbit requires the calculation of the direction of the fireball (known as the radiant), and the position and speed at the top of the atmosphere. The associated uncertainties on these two components are mostly uncorrelated. In order to minimize issues associated with the oversimplified straight-line trajectory for orbit purposes, we retriangulate the observations using only points that fall >60 km altitude on the initial triangulation. In this case, as the trajectory is fairly steep, the difference in apparent radiant between the two solutions is less than 5 arcmin. To calculate the errors on the radiant, we use the covariance matrix from the least squares trajectory fit (see the Geometry section), this gives us the apparent radiant: slope to the horizontal = $51.562 \pm 0.002^\circ$, azimuth of the radiant (East of North) = $206.17 \pm 0.03^\circ$, which corresponds to $(\alpha = 173.38 \pm 0.02^{\circ}, \delta = -6.34 \pm 0.01^{\circ})$ in equatorial J2000 coordinates.

To calculate the formal uncertainty on the initial velocity, we apply the Kalman filter methods of Sansom et al. (2015) as outlined in the Dynamic Modeling of the Trajectory, Including Velocity and Mass Determination section. Using the time, position, radiant, speed, and associated uncertainties, we determine the preatmospheric orbit by propagating the meteoroid trajectory back through time, considering the atmospheric effects, Earth's oblate shape effects (J2), and other major perturbing bodies (such as the Moon and planets), until the meteoroid has gone beyond $10\times$ the Earth's sphere of influence. From here, the meteoroid is propagated forward in time to the impact epoch, ignoring the effects of the Earth–Moon system. Uncertainties (Table 4) are calculated using a Monte Carlo approach on 1000 test particles randomly drawn using uncertainties on the radiant and the speed (Fig. 12).

We scanned the Astorb⁴ asteroid orbital database (Bowell et al. 2002) for close matches in a, e, i, ω, Ω orbital space using the similarity criterion of Southworth and Hawkins (1963). The closest match is the small (H = 24.6) 2015 TD179 asteroid that came into light in November 2015 when it flew by Earth at ≈ 10 lunar distances. But the large difference between these orbits, D = 0.04, makes the dynamical connection between the two highly unlikely.

To calculate the likely source region and dynamical pathway that put the meteoroid on an Earth crossing orbit, we use the Rebound integrator (Rein and Tamayo 2015) to backward propagate the orbit of the meteoroid. We use 10,000 test particles randomly selected using the radiant and speed uncertainties as explained above, as well as the major perturbating bodies (Sun, eight planets, and Moon). The initial semimajor axis (Table 4) is close to the 7:2 (2.25 AU) and 10:3 (2.33 AU) mean motion resonances with Jupiter (MMRJ). These minor resonances start to scatter the eccentricity of a large number of test particles very early on, but neither are strong enough to decrease it significantly enough to take the meteoroid outside of Mars' orbit. Because of the interactions with the inner planets, the particle cloud rapidly spreads out, and particles gradually start falling into the two main dynamical pathways in this region: 3:1 MMRJ (2.5 AU) and the v_6 secular resonance. These resonances rapidly expand the perihelia of particles out of the Earth's orbit initially, and eventually out of Mars' orbit and into the Main Belt.

During the integration over 1 Myr, we count the number of particles that have converged close to stably populated regions of the Main Belt, and note which dynamical pathway they used to get there. This gives us the following statistics:

^{1.} v₆: 12%

^{2. 3:1} MMRJ: 82%

^{3. 5:2} MMRJ: 6%

⁴ftp://ftp.lowell.edu/pub/elgb/astorb.html, downloaded June 24, 2017.



Fig. 10. Fall area around Dingle Dell farm and Koolanooka Hills. Fall lines in yellow represent different wind model solutions: WI (bottom), W2 (middle), and W3 (top). Mass predictions for the preferred wind model are shown for spherical (light blue markings; A = 1.21) and cylindrical (white markings; A = 1.5) assumptions. The particle filter results are propagated through dark flight using wind model WI, and are shown as a heat map. The location of the recovered meteorite (red dot) is ≈ 100 m from the WI fall line.

CONCLUSIONS

Dingle Dell is the fourth meteorite with an orbit recovered by the DFN in Australia. Its luminous trajectory was observed by six DFN camera stations up to 535 km away at 12:03:47.726 UTC on 31 October, 2016. Clouds severely affected the observations, but enough data were available to constrain the search area for a swift recovery, and determine one of the most precise orbits linked to a meteorite. The surviving rock was recovered within a week of its fall, without any precipitation contaminating the rock, confirming the DFN as a proficient sample recovery tool for planetary science. This recovery, in less than ideal conditions, also validates various choices in the design and operations of the Desert Fireball Network:

- 1. Use of high-resolution digital cameras to enable reliable all-sky astrometry for events up to 300 km away.
- 2. Uninterrupted operation even when a large portion of the sky is cloudy for individual systems.

3. Archiving of all raw data to mitigate event detection failures.

While the method of Sansom et al. (2017) was still in development at the time of the fall, the reanalysis of the fireball with this new technique is remarkably consistent with the main mass found, requiring just a small number of high-quality astrometric data points. This validates the method, and will drastically reduce the search area for future observed falls.

After a 1 million year integration of 10,000 test particles, it is most likely that Dingle Dell was ejected from the Main Belt through the 3:1 mean motion resonance with Jupiter rather than the v_6 resonance (82% for the 3:1 MMRJ compared to 12% probability for v_6). This also means that L/LL Dingle Dell is unlikely to be associated with the Flora family, likely source of most LL chondrites (Vernazza et al. 2008), as the most efficient mechanism for getting Florian fragments to near-Earth space is the v_6 secular resonance. This fall adds little insight into the Flora/LL link (Fig. 13), but 2016 was rich in instrumentally



Fig. 11. Dingle Dell meteorite as it was found. Image available at https://commons.wikimedia.org/wiki/File:Dingle_Dell_meteorite_as_it_was_found.jpg under a Creative Commons Attribution-ShareAlike 4.0 International.



Fig. 12. Ecliptic projection of the pre-encounter orbit of Dingle Dell. The shades of gray represent the likelihood as calculated from 1000 Monte Carlo simulations based on formal uncertainties on the radiant and the speed.

Table 4. Pre-encounter orbital parameters expressed in the heliocentric ecliptic frame (*J2000*) and associated 1σ formal uncertainties.

Parameter	Unit	Value	
a	AU	2.254 ± 0.034	
е		0.5904 ± 0.0063	
i	0	4.051 ± 0.012	
ω	0	215.773 ± 0.049	
Ω	0	218.252 ± 0.00032	
q	AU	0.92328 ± 0.00032	
Q	AU	3.586 ± 0.067	
$\alpha_{\rm g}$	0	354.581 ± 0.037	
δ_{g}	0	13.093 ± 0.081	
Ŭ _g	$m s^{-1}$	10508 ± 87	
T_{J}		3.37	

observed LL falls, which might yield clues to help confirm this connection in the near future: Stubenberg (LL6) (Spurný et al. 2016; Bischoff et al. 2017), Hradec Králové (LL5) (Meteoritical Bulletin 2017), and Dishchiíbikoh (LL7) (Meteoritical Bulletin 2017; Palotai et al. 2018).

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Fig. 13. The orbit of Dingle Dell in context with other L and LL ordinary chondrite falls. References for L and LL orbits are in the introduction.

reporting their sightings through the Fireballs In The Sky program, and other volunteers that have made this project possible. This research was supported by the Australian Research Council through the Australian Laureate Fellowships scheme and receives institutional data support from Curtin University. The DFN reduction pipeline makes intensive use of Astropy, a community-developed core Pvthon package for Astronomy (Astropy Collaboration et al. 2013). The authors also thank J. Borovička and J. Vaubaillon for their valuable comments and suggestions, which improved the quality of the paper.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:.

Table S1.AstrometricdataforBadgingarracamera.

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Table S2. Astrometric data for Perenjori camera.

Table S3. Astrometric data for Northam.

Table S4. Trajectory solution.

Table S5. Weather model profile W1.

File S6. Meteorite searching GPS tracks.