Radar observations of the 2011 October Draconid outburst

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ABSTRACT
A strong outburst of the October Draconid meteor shower was predicted for 2011 October 8. Here we present the observations obtained by the Canadian Meteor Orbit Radar (CMOR) during the 2011 outburst. CMOR recorded 61 multistation Draconid echoes and 179 single-station overdense Draconid echoes (covering the magnitude range of +3 ≤ MV ≤ +7) between 16 and 20 h UT on 2011 October 8. The mean radiant for the outburst was determined to be αg = 261°9 ± 0°3, δg = +55°3 ± 0°3 (J2000) from observations of the underdense multistation echoes. This radiant location agrees with model predictions to ∼1°. The determined geocentric velocity was found to be ∼10–15 per cent lower than the model value (17.0–19.1 km s−1 versus 20.4 km s−1), a discrepancy we attribute to undercorrection for atmospheric deceleration of low-density Draconid meteoroids as well as to poor radar radiant geometry during the outburst peak. The mass index at the time of the outburst was determined to be ∼1.75 using the amplitude distribution of underdense echoes, in general agreement with the value of ∼1.72 found using the diffusion-limited durations of overdense Draconid echoes. The relative flux derived from overdense echo counts showed a similar variation to the meteor rate derived from visual observations. We were unable to measure the peak flux due to the high elevation of the radiant (and hence low elevation of specular Draconid echoes). Using the observed speed and electron line density measured by CMOR for all underdense Draconid echoes as a function of height as a constraint, we have applied the ablation model developed by Campbell-Brown & Koschny. From these model comparisons, we find that Draconid meteoroids at radar sizes are consistent with a fixed grain number ngrain = 100 and a variable grain mass mgrain between 2 × 10−8 and 5 × 10−7 kg, with bulk and grain density of 300 and 3000 kg m−3, respectively. One particular Draconid underdense echo displayed well-defined Fresnel amplitude oscillations at four stations. The internal synchronization allowing us to measure absolute length as a function of time by combining the absolute timing offsets between stations. This event showed clear deceleration and modelling suggests that the number of grains for this meteoroid was of the order of 1000 with grain masses between 10−10 and 10−9 kg, and a total mass of 2 × 10−6 kg.

Key words: comets: individual: 21P/Giacobini-Zinner – meteorites, meteors, meteoroids.

1 INTRODUCTION

1.1 A brief history of Draconids
Although quiet in most years, the October Draconid meteor shower (sometimes shorted to ‘Draconids’, and also referred to in older literatures as the ‘Giacobinids’, after its parent body 21P/Giacobini-Zinner) has produced several of the most spectacular meteor storms in modern astronomical history. It is also among the very first (if not the first) meteor shower to be predicted on the basis of the parent comet’s proximity to Earth’s orbit prior to the shower being widely observed.

21P/Giacobini-Zinner was discovered by Michel Giacobini in 1900, before any modern observations of the Draconids. Because of limited observations, the exact orbit of the comet was unknown until Ernst Zinner recovered it in 1913 (Kronk 2008). The orbital period was determined to be ∼6.5 yr, identifying the comet as a Jupiter-family comet, a major comet family that occasionally experience strong perturbations from Jupiter. The possibility of a meteor shower generated by the comet was first proposed by Davidson (1915), years before Denning (1926)
first observed the meteor shower in either 1920 or 1926 (Denning only saw five meteors in 1920, therefore the linkage is questionable). The maximum zenith hourly rate (ZHR) in 1926 was reported to be 17 (Denning 1926). Before the historic Draconid meteor storm in 1933, no other definitive observations of the shower had been reported.

The 1933 Draconid meteor storm was largely a surprise as no specific prediction suggested an unusually intense shower that year. The meteor rate reported by European and American observers was between 2400 and 5400 h^{-1} (Watson 1934; Nijland & van der Bilt 1935), while more recent estimates have suggested 10000 ± 2000 (Jenniskens 1995). The apparent radiant was measured to be near α₀ = 266°, δ₀ = +59° by Nijland & van der Bilt (1935), with a relatively large diameter (∼10'). Fisher (1934) suggested as many as six possible historical sightings before 1920, with the earliest sighting dating back to Chinese observations in 585 AD, although later studies do not support that hypothesis (e.g. Imoto & Hasegawa 1958).¹

A Draconid outburst at 21P/Giacobini-Zinner’s 1939–1940 apparition was predicted by Watson (1939), but no activity was observed in either year. However, Watson made a successful outburst prediction for 21P/Giacobini-Zinner’s 1946 apparition (Watson 1946). The Draconid meteor storm again favoured American and European observers, with maximum activity at around 10 h UT on 1946 October 10 and a ZHR of 12 000 ± 3000 (Jenniskens 1995). It was also a landmark in meteor studies, not only because it was the first time that radars were deployed to observe a meteor shower (Hey, Parsons & Stewart 1947; Lovell, Banwell & Clegg 1947; Stewart et al. 1947), but also because during this meteor storm many precise photographic records of bright Draconid meteors were obtained (e.g. Jacchia, Kopal & Millman 1950).

The 1946 Draconid meteor storm was the second and the last recorded Draconid meteor storm in the 20th century. 21P/Giacobini-Zinner’s apparitions in 1985 and 1998 were accompanied with substorm outbursts with a maximum ZHR of ∼700 (Lindblad 1987; Arlt 1998). Moderate activity was detected by radar in 1952, 1972 and 2005 (Davies & Lovell 1955; Hughes & Thompson 1973; Campbell-Brown et al. 2006), but the associated visual activity was either unreported (1952), very weak (1972) or moderate (2005) with ZHR ~ 40 (Maley & Saulietis 1972; Campbell-Brown et al. 2005). In other years, the hourly rates of Draconids were no more than a few meteors per hour.

¹ The Chinese observations were quoted from Sui Shu (the Book of Sui), Vol. XXI, Section 3, which recorded that a meteor outburst took place on 585 AD September 23, approximately corresponding to λ₀ = 202° in 12000 epoch. Most studies mentioning this event quote Biot: ‘...hundreds of meteors fled in every direction.’ But there was one sentence from the original Sui Shu text omitted by Biot: ‘(astrologers) divined and said: “small meteors fled in every direction.”’ Apparently indicating the meteors were mostly faint. Jenniskens (2006) suggested a linkage to the Orionids; but given the fact that the moon was at its last quarter, and the Orionid radiant did not rise until midnight, the event was unlikely to take place other than in the early evening as the moon would wash out most faint meteors. Since the observations were conducted in the capital of Sui, which was Chang’an (today’s Xi’an); at a latitude of 34°N, the radiant of the Draconids would be high enough for the described viewing geometry (‘fled in every direction’), therefore a linkage of the 585 AD observation to Draconids cannot be ruled out.

1.2 Dynamical modelling of the Draconid stream

An important aspect of meteor physics is that it can reveal physical properties of small Solar system bodies without the cost of a spacecraft mission. Meteoroid streams are formed from ejections occurring during multiple perihelion passages of a parent body as well as occasionally through catastrophic break-ups. The meteoroids released during each ejection epoch will undergo a slightly different orbital evolution compared to the parent body, depending on their mass and ejection state, but generally they are diluted into the background (annual) stream which is usually too sparse to allow a statistically sufficient sampling of shower meteoroids and typically includes meteoroids from many ejection eras. However, recently ejected material from the parent body may encounter the Earth and produce a meteor outburst, often comprising material from a single-ejection epoch. Observations of such outbursts allow us to directly sample a large number of meteoroids of known age from the parent body. The interaction of these meteoroids with the Earth’s atmosphere can reveal clues about their properties, such as mass and chemical composition, which are directly related to the parent body. For example, the mismatch of visual and radar activity in the 2005 Draconid outbursts may suggest that the 2005 return was dominated by an abundance of subvisual meteoroids from the 1946 perihelion passage of 21P/Giacobini-Zinner (Campbell-Brown et al. 2005).

The dust trail theory of meteor outbursts/storms developed in the 1990s turned out to be a robust way to understand the linkage between outbursts of meteor showers and both the activity and ejection age from the parent body (Emel’janenko 1992; Arlt et al. 1999; Asher 1999). However, to apply such a theory with confidence, sufficient observations of the meteor shower itself and its parent body are needed as constraints. Virtually, no meteor showers can satisfy this requirement except the Leonids, mostly because of a lack of significant trail encounters and outbursts that might allow us to accumulate sufficient observations about individual dust trails.

Prior to the late 1990s, potential Draconid outbursts were predicted by considering the distance between the orbits of 21P/Giacobini-Zinner and the Earth, the time difference between the arrival of the two bodies to the intersection point, and the geometry of comet’s perihelion relative to the Earth’s orbit. The predictions of Draconid outbursts in 1946, 1985 and 1998 using this method were in good agreement with observations (Watson 1946; Spalding 1985; Langbroek 1997), while the predictions for 1952, 1959, 1972 and 1979 did not agree. This reflects the value of applying the dust trail model to young, outburst streams such as the Draconids.

1.3 Outburst predictions for 2011

Sato (2003) first applied the dust trail theory to the Draconids and studied the trail encounter situations in 1998 and 1999, while Campbell-Brown et al. (2006) adopted a stream model proposed by Vaubaillon, Colas & Jorda (2005) to study the unexpected outburst of the Draconids in 2005. Further numerical simulations were carried out by a number of researchers (see Table 1 for a summary), and Earth’s encounter of 21P/Giacobini-Zinner’s ejections from 1866 to 1907 (hereafter the 1866–1907 ‘trails’) were predicted to occur between 16 and 20 h UT, 2011 October 8. The associated peak visual rate predictions ranged from 50 (Maslov 2011) to 600 h^{-1} (Vaubaillon et al. 2011b). Almost all observing techniques, including airborne missions, were deployed for the outburst, and preliminary analyses indicate that the outburst arrived more or less as predicted (Vaubaillon et al. 2011a). At the Canadian Meteor Orbit
Table 1. Summary of Draconid 2011 outburst predictions of time and radiant position for individual trail encounters. The forecast data from Lyytinen and Moser are quoted from http://draconids.seti.org/ (accessed 2013 March 17).

| Trail    | Reference            | Predicted \(\alpha_g, \delta_g\) (J2000) | Predicted maximum (October 8 UT) |
|----------|----------------------|-----------------------------------------|----------------------------------|
| 1866     | Vaubaillon et al.    | 263:3, +55:3                            | 16:13                            |
| 1873     | Vaubaillon et al.    | 263:2, +55:4                            | 16:29                            |
| 1880     | Vaubaillon et al.    | 263:2, +55:4                            | 16:53                            |
|          | Sato (2003)          |                                         | 19:04                            |
| 1887     | Vaubaillon et al.    | 263:2, +55:4                            | 17:25                            |
|          | Sato (2003)          |                                         | 17:05                            |
|          | Lyytinen             |                                         | 17:02                            |
|          | Maslov (2011)        | 263:2, +55:4                            | 17:04                            |
| 1894     | Vaubaillon et al.    | 263:2, +55:4                            | 18:45                            |
|          | Maslov (2011)        |                                         | 18:06                            |
| 1900     | Vaubaillon et al.    | 263:2, +55:8                            | 20:01                            |
|          | Sato (2003)          |                                         | 20:36                            |
|          | Moser                |                                         | 19:52                            |
|          | Lyytinen             |                                         | 20:12                            |
|          | Maslov (2011)        | 263:3, +55:8                            | 20:42                            |
| 1907     | Vaubaillon et al.    | 262:5, +55:4                            | 19:26                            |
|          | Sato (2003)          |                                         | 19:59                            |
|          | Maslov (2011)        | 262:2, +55:8                            | 21:05                            |

Radar (CMOR), for example, a meteor rate of \(~140\,h^{-1}\) was observed around 19 h UT, 2011 October 8, indicated an unusually high activity comparing to past non-outburst years (\(~26\ and \sim 39\,h^{-1}\ in 2009 and 2010, for example).

In this paper, we present the observation and analysis of the 2011 Draconid outburst as recorded by the CMOR. We focus on the following topics:

(i) characteristics of the outburst, such as radiant, velocity distribution, mass distribution and flux variation;
(ii) comparison with dynamical stream model predictions;
(iii) meteoroid structure as revealed through ablation modelling.

2 Radar INSTRUMENTATION

2.1 The CMOR system

The CMOR is an interferometric backscatter meteor radar located near London, Ontario, Canada that is designed to observe meteor echoes and perform basic analysis continuously and automatically. It is based on the commercially available SKiYMET system (e.g. Hocking, Fuller & Vandepeer 2001) with some modifications to optimize for astronomical meteor echo detection (e.g. Jones et al. 2005; Weryk & Brown 2012). Currently it consists of six sites (Fig. 1) and operates at 29.85 MHz at 12 kW peak power (Table 2). The radar detects meteors through reflection of a transmitted pulse from the ionization trail left behind during meteor ablation and subsequently received after specular reflection by receivers. Meteors observed by the radar from the main station (Zehr) are always 90° from the apparent radiant. Because of this geometry, the underdense echo rate for radar observations has a secondary minimum when the radiant has a zenith angle \(<~20°\) due to lower elevations and larger ranges to the echo, as opposed to visual, photographic and video meteor observation, where the minimum in apparent rates typically occurs when the radiant is near the horizon.

If the echo from a meteor is detected at \(N\) sites (\(N \geq 3\)), we can optimize for astronomical meteor echoes and perform basic analysis continuously and automatically. The time differences between the three observations, together with the interferometric direction measured from the main site, can be used to construct the trajectory of the meteor.

\(^2\) The system also operates in 17.45 and 38.15 MHz, but only data at 29.85 MHz is used in this study.

Figure 1. Location and geographic distribution of the main CMOR station (Zehr) and other remote sites as of 2011 October.

Figure 2. Simplified example of how CMOR measures meteor trajectories. In this example, three sites detect signals reflected from the meteor trail at different points as the meteoroid moves in the atmosphere. The time differences between the three observations, together with the interferometric direction measured from the main site, can be used to construct the trajectory of the meteor.

Table 2. Basic specification of the 29.85 MHz CMOR system, adapted from Weryk & Brown (2012).

| Parameter      | Value             |
|----------------|-------------------|
| Frequency      | 29.85 MHz         |
| Range interval | 15–255 km         |
| Range resolution | 3 km             |
| Pulse frequency | 532 Hz           |
| Peak power     | 12 kW             |
| Noise floor    | \(-107\, \text{dBm})\) |
| Dynamic range  | 33 dB             |
| Beam size      | 55° at \(-3\, \text{dB point})\) |
distribution resembles a bubble rather than a uniform distribution. This not only affects the number of meteors detected with respect to different ranges, but also affects the determination of the physical properties of individual meteoroids. One of the most significant properties of any specular radar echoes is the trail type of the meteor, namely underdense or overdense.

An underdense trail occurs when radio waves scatter from all the individual the electrons in the trail. In contrast, an overdense echo occurs when the radio wave cannot completely penetrate the meteor trail due to the trail plasma frequency being higher than the radar wave frequency. Strictly speaking, the boundary between underdense and overdense echoes is a continuum; in between is transition echoes, which can exhibit characteristics from the other two types, but for simplicity we also consider them as overdense echoes in this study.

Visually, the amplitude-time series of an overdense echo will appear as ‘flat’ (i.e. does not decay) for some time until ambipolar diffusion makes the trail underdense. Since overdense echoes have higher electron line density than underdense echoes, for a fixed velocity, overdense echoes tend to be generated by a larger meteoroid. They represent a higher fraction of echoes in regions where the radar gain is low, since fainter echoes will not be observed in these regions.

Examples of underdense and overdense echoes are shown in Fig. 3. Detailed theory of these two echo types is beyond the scope of this paper, but interested readers may refer to McKinley (1961, section 8) or Ceplecha et al. (1998, section 4) for details. The CMOR automatic detection algorithms are tuned to accept underdense echoes but generally suppress overdense-type echoes.

### 3 OBSERVATIONAL METHODOLOGY

#### 3.1 Selection of Draconid echoes

For our study, we first separated the Draconid meteor echoes from other echoes. To include as many Draconid meteors as possible, we use two methods to select underdense and overdense Draconid echoes, respectively; this is briefly described below and summarized in Table 3.

For multistation echoes, we developed user-interactive software to view, select and analyse the geometry and trajectory of meteors automatically detected in the raw data stream. These are mainly underdense echoes with some overdense echoes included as well. We consider any meteor radiant within $5^\circ$ and 20 per cent of the predicted 1900-trail geocentric radiant (i.e. $\alpha_g = 263.2^\circ$, $\delta_g = +55.8^\circ$, J2000), and geocentric velocity $v_g = 20.4$ km s$^{-1}$ (Jenniskens 2006) to be Draconid candidates. The velocity constraint is broad as Draconids are more fragile than other meteor streams (Jacchia et al. 1950; Fiocco & Colombo 1964), leading to larger uncertainty in measured velocity as a result of deceleration with height of detection. Using this method, we selected 61 Draconid candidates, including 39 underdense echoes and 22 overdense echoes. We refer to these as the COMPLETE data set.

#### Table 3. Summary of the two data sets used in our study.

|       | COMPLETE data set | OVERDENSE data set |
|-------|-------------------|--------------------|
| Underdense | 39                | -                  |
| Overdense (definite) | 22               | 148                |
| Overdense (possible)    | -                 | 31                 |
| Total                  | 61                | 179                |

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**Figure 3.** A typical Draconid underdense echo (above), overdense echo (middle) and wind twisted overdense echo (below). We define these by the shape of their amplitude–time series (see Section 2.2).
Since the echo line where all Draconid meteors detectable by CMOR is at a low elevation (<∼20°) and a larger range around the outburst (∼20 h UT), only the meteors which scatter the most power will be detectable (i.e. overdense echoes). However, as some non-specular overdense echoes are detected through wind-twisting or development of plasma irregularities (Fig. 3), they can be difficult to detect and measure in an automated fashion. Therefore, we manually examined the raw data from the main site (Zehr) between 2011 October 7 and 9 at 15–20 h UT each day for overdense Draconid echoes. The trajectories of the trails were manually determined for cases when they were well observed at other remote sites. This permitted us to isolate overdense Draconids. Trails with observations from less than three stations but with interferometric position consistent with Draconid meteor (i.e. at right angles to the Draconid radiant), were marked as ‘possible’ Draconids. Following this method, we identified 148 overdense specular Draconid echoes as well as 31 possible Draconid echoes, which formed another sample (Fig. 4; referred to as the OVERDENSE data set). This includes the 22 overdense echoes in the COMPLETE data set. For the relative flux analysis, the number of possible overdense echoes on 2011 October 8 is subtracted from echoes from the same periods on 2011 October 7 and 9, to correct for possible sporadic overdense contamination.

### 3.2 Uncertainties

As the COMPLETE data set was measured in an automatic fashion, it is possible to objectively estimate the uncertainty in the data. This involves an estimate of the uncertainty of the position of \( t_0 \) (the specular point at each station) and the interferometric direction, both of which are directly measured, to estimate the error in the TOF velocity. To do this, we used an echo simulator, which constructs a synthetic echo based on the observing geometry and strength of the measured signal assuming a Gaussian distribution of noise (see Weryk & Brown 2012). Each pseudo-echo is then analysed using the same detection/measurement algorithm that is used for real observations. A comparison is then made between the measured model results and the ‘true’ (input) state to determine the expected random observational error in radiant and speed measurements, under the assumption of a perfect underdense specular echo. We ran the simulation 65 536 times\(^3\) for each echo and recorded the standard deviation to be the uncertainty in speed and radiant. We were able to use this technique on 41 echoes in the COMPLETE data set; for the other 20 echoes in the COMPLETE data set, we found it necessary to manually revise the time pick for reliable results, so no uncertainty can be estimated for these echoes. We believe the error estimation for the 41 echoes is representative of the uncertainty of the entire COMPLETE data set.

The velocity of each echo in the COMPLETE data set is determined using the TOF method (Baggaley et al. 1994). To verify that the TOF method yields accurate velocity measurements, we also use the Fresnel phase-time method (Cervera, Elford & Steel 1997) to measure the velocities of echoes in the COMPLETE data set that exhibit such features. This method works as shown in Fig. 5: when a specular meteor echo exhibits characteristic phase changes before the specular \( (t_0) \) point, we can determine the speed of the meteor by

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\(^3\) This number is arbitrary chosen so that it is large enough to be statistically meaningful for the Monte Carlo uncertainty analysis.
4 ANALYSES, RESULTS AND DISCUSSION

4.1 Radiant and orbits

The weighted mean geocentric radiant for all echoes in the COMPLETE data set was determined to be $\alpha_g = 261.9 \pm 0.3, \delta_g = +55.3 \pm 0.3$ (J2000), as shown in Table 4 and Fig. 8. The radiant errors reflect the scatter in individual radiances weighted by individual radiant errors found through simulation as described in Section 3.2. We also examined the meteors detected around the time of two predicted main peaks (see Table 1), namely the expected peaks from the 1873–1894 and the 1900–1907 trails. We examined subsets of the COMPLETE data set that spanned these predicted trail passage times and found the weighted (inversely by error) geocentric radiants. Comparing these to the predictions summarized in Table 1, the radiants determined from our observations match the model prediction reasonably well ($\sim 1^\circ$), and are comparable to the observations of Shigaraki middle and upper atmosphere (MU) radar (Kero et al. 2012) (Fig. 8; we note that the MU results span a large period of time and thus represent a mixture of meteoroids from both 1873–1894 and 1900–1907 trails).

The multistation observations in the COMPLETE data set also allow determination of the orbits. The distribution of $a$, $e$ and $i$ is shown as Fig. 9. We also selected a set of echoes with $\Delta a/a$ is below 0.2 ($\Delta a$ was determined by the echo simulator as described in Section 3), defining a set of high-quality multistation orbits. The distribution of these orbits is shown in Fig. 10. We also plot the range of $a$, $e$ and $i$ of the simulated particles by Vaubaillon et al. (2011b) as shaded bars in each graph. It can be seen that most echoes are located in $a \in (2, 3)$ which is smaller than the $a \sim 3.5$ of the simulated particles, as well as the parent body.

What is the cause of this difference in $v_o$ and $a$ between observation and theoretical values? One possible explanation for the smaller observed $a$ (and hence smaller $v_o$) as compared to modelling, as noted by Brown et al. (2004) and Campbell-Brown et al. (2006), is an underestimation of the deceleration correction for Draconid echoes using the standard deceleration correction applied to CMOR echoes as a whole. Since the correction was derived from other showers which are not as fragile as the Draconids (e.g. Fiocco & Colombo 1964), the out-of-atmosphere velocity ($v_{\infty}$) for Draconids may therefore be underestimated, resulting in a lower apparent initial velocity corresponding to a smaller $a$. As shown in Fig. 11, instead of the corrected $v_o$ showing no height trend, we observe a slowly increasing $v_{\infty}$ with respect to height, indicating a stronger deceleration to the meteoroids than the Brown et al. (2004) algorithm predicts.

However, from Table 4 we also notice that the observed $v_o$ for Draconid echoes occurred during the times of the expected arrival of the 1873–1894 and 1900–1907 trails are even lower than the overall $v_o$. A quick data check shows that the echoes detected during the passage of the two trails were roughly 10–15 per cent slower than the those detected in the early hours of October 8 (the weighted mean of echoes detected before 12 h UT is $v_o = 19.6 \pm 0.7$ km s$^{-1}$). Although a difference in physical properties between these two trails and the Draconid background is a possible explanation, we suggest that the contribution of a small radiant zenith angle ($\eta$) (Fig. 12) is more convincing. Because of a higher radiant elevation, the meteoroid trajectory is more vertical, resulting in a deeper penetration through the atmosphere (Fig. 13; see also Verniani 1973, equation 25). We note that the $v_o$ for 1900–1907 trails derived from European video observations agrees the expected value ($v_o = 20.9 \pm 1.0$ km s$^{-1}$ as given by Jenniskens, Barentsen & Yrjola 2011) which supports our

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Footnote:

4 There is another Fresnel method called the amplitude-time method (see Ceplecha et al. 1998, section 4.6.1); however, only seven echoes in our sample exhibited such a feature, and therefore we did not use this method. We note that the small number of Draconid echoes displaying Fresnel amplitude variations is another indication of the widespread fragmentation behaviour of the Draconids.
Table 4. CMOR-observed weighted mean geocentric radiant and velocity for all detected Draconid meteors. Also shown are average radiants and speeds expected to be associated with the 1873–1894 and 1900–1907 trails based on the echo time of appearance in comparison to the model in the complete data set.

| Time period | $\alpha_g$, $\delta_g$ (J2000) | $v_g$ (km s$^{-1}$) | $N$ |
|-------------|---------------------------------|---------------------|-----|
| Annual radiant by Jenniskens (2006) | 264.1, +57.6 | 20.4 | |
| CMOR observation: October 7–9 | 261.9 ± 0.3, +55.3 ± 0.3 | 19.1 ± 0.3 | 61 |
| Vaubaillon’s prediction for 1873–1894 trails | 263.2, +55.4 | | |
| CMOR observation: October 8 16:19–18:55 UT (1873–1894 trails) | 262.2 ± 0.4, +54.9 ± 0.4 | 18.3 ± 0.4 | 32 |
| Vaubaillon’s prediction for 1900–1907 trails | 262.8, +55.6 | | |
| CMOR observation: October 8 19:00–20:00 UT (1900–1907 trails) | 262.5 ± 0.6, +55.3 ± 0.8 | 17.0 ± 0.5 | 16 |

Figure 8. CMOR-observed weighted mean geocentric radiant for the 1873–1894 trails (upper left), the 1900–1907 trails (upper right) and all echoes in the complete data set (lower left). Uncertainty bars based on echoism results for individual radiants are plotted where applicable. Grey circles indicate a 5° circle within the predicted mean radiant of the model predicted respective trail or annual radiant. Shaded grey dots in the upper two figures represent the radiant of pseudo-particles in the mass range of $10^{-10}$–$10^{-1}$ kg as simulated by Vaubaillon et al. (2011b) (assuming a bulk density of 300 kg m$^{-3}$). The overall comparison between observations of CMOR and MU radar (Kero et al. 2012), as well as the prediction by Vaubaillon et al. (2011b), is given in lower right of the figure.

argument that the CMOR speeds are lower due to underestimation in deceleration.

4.2 Mass distribution

One of the diagnostic parameters one can get from statistical analysis of a meteor outburst is the mass distribution index $s$. The mass index is a measure of mass distribution of the meteoroids; it is defined such that the number of meteoroids between mass interval $m$ and $m + dm$ is a power law described by $m^{-s}$.

It is very difficult from specular radar echoes to directly measure $m$ for each meteoroid; however, in radar theory, $m$ and the electron line density $q$ are linearly related under certain assumptions (e.g. McKinley 1961, sections 7.3–7.5). Considering that $q$ is proportional to echo amplitude for underdense echoes, we can simply substitute amplitude for $m$, and use the slope of cumulative logarithmic amplitude distribution to derive $s$ (McIntosh 1968; Simek & McIntosh 1968). For overdense echoes, a diffusion-limited echo duration implies $\tau \propto q$ (McKinley 1961, section 8.9), and we can use echo duration instead of amplitude to estimate $s$ (McIntosh 1968) independently.

We have few underdense echoes due to the poor radiant geometry at the outburst peak for CMOR, therefore, we first use the echo duration method to estimate $s$. However, since overdense echoes
are much more likely to be affected by winds (Fig. 3; which do not affect very short-lived underdense echoes), and are more prone to secondary specular point development (see McKinley 1961, sections 4.9 and 8.11) and the radiant may not be properly determined, leading to possible sporadic contamination. To address this issue, we manually inspected every echo for its pre-φ₀ phase feature (Fig. 5). Only specular echoes exhibit such a feature, and therefore we can remove non-specular echoes. In the end, we selected a total of 155 Draconid overdense echoes on October 8 in the OVERDENSE data set.

The identification of an overdense echo is rather subjective, leading to doubt as to whether some underdense echoes may have been confused with short-duration overdense echoes. However, unlike the duration of overdense echoes, which depends on radar wavelength, ambipolar diffusion coefficient, and electron line density, the duration of underdense echoes only depends on the radar wavelength and ambipolar diffusion coefficient (and hence height), as shown in McKinley (1961, section 8.5). Combining this with the
empirical diffusion coefficient formula derived by Massey, Burhop & Gilbody (1971), we have
\[ t_{ud} = \frac{\lambda^2}{16\pi^2} \times 10^{0.006 - 4.74}, \tag{1} \]
where \( t_{ud} \) is the duration and \( \lambda \) is the radar wavelength, both in SI units, and \( h \) is the height in kilometres. With \( \lambda \sim 10 \text{ m} \) and a lower limit of \( h \sim 75 \text{ km} \) (Fig. 14), we see the upper limit of \( t_{ud} \) to be \( ~1 \text{ s} \). Based on this result, it is reasonable to label any CMOR echo with duration longer than \( ~1 \text{ s} \) as an overdense echo.

We found \( s = 1.72 \pm 0.01 \) by fitting the linear portion of diffusion-limited overdense duration data points with Fig. 15 and using the relation \( N \propto t^{3.1 - s/2} \) (Weiss 1961), where \( N \) is the cumulative number of echoes. The uncertainty here only depicts the uncertainty of least-squares fit.

Figure 14. The height range of the selected overdense echoes in OVERDENSE data base. It can be seen that the lower limit of echo height is \( \sim 75 \text{ km} \). The shaded area marks the overdense region defined by equation (1). We note that if this population were mainly underdense, a clear duration versus height trend would be present.

Figure 15. The mass index of Draconids on October 8 determined with selected echoes in the OVERDENSE data set. The turnover from diffusion-limited to chemistry-limited duration (the duration of meteor echo limited by dissociating recombination between meteoric ions and atmospheric ozone molecules; cf. Jones & Jones 1990) can be seen at \( t_r = 2.7 \text{ s} \). The mass distribution index determined by fitting the diffusion-limited portion is \( 1.72 \pm 0.01 \).

We can also measure \( s \) using the underdense echo amplitudes detected at the main site (Zhr). The advantage of this method is that it will include more events, including the possible Draconids that were filtered out in multistation trajectory measurements. Sporadic contamination is possible, but given the low background rates at this time of the day (\(~15 \text{ h} \text{ local time}\)), we expect it to be representative of the mass index of the outburst. We select all the echoes perpendicular to within \( 5^\circ \) of the apparent radiant and \( v_g = 20.4 \text{ km s}^{-1} \) (derived using rise-time estimation which can be applied to single-station data) over a range of 10 per cent. We find 84 single-station echoes match our acceptance criteria for the period of October 7–9, and the mass index is determined by using the relation \( N \propto A^{1-s} \) (McIntosh 1968) (where \( N \) is the cumulative number of echoes exceeds amplitude \( A \)). As shown in Fig. 16, the mass index determined in this way for October 8 was \( s = 1.75 \pm 0.01 \). The uncertainty given here is from least-square fitting only and is several times smaller than the real uncertainty given the small sample size (see Blaauw, Campbell-Brown & Weryk 2011, for discussion). The mass indices for October 7 and 9 appear to be higher than October 8, possibly suggesting sporadic contamination, but they are subject to low confidence since the sample sizes are too small for quantitative estimates of \( s \) (14 for October 7 and 16 for October 9). We are unable to compare this with the mass indices determined from overdense echoes for those two days, as there are also very few Draconid overdense echoes (<10) for either of the days.

The \( s = 1.75 \) on October 8, the peak, is low compared to that found by Simek (1994) \( (s = 2.06 \) for underdense echoes, \( s = 2.11 \) for overdense echoes) for the 1985 Draconid outburst. This implies that the 2011 outburst was richer in bright meteors than the 1985 outburst. Of course, such a conclusion is weakened by the small sample size that we used, but we note that it is consistent with the theoretical suggestion by Maslov,\(^5\) whose model suggested that the 1985 outburst was composed of ‘quite faint meteors’ while the 2011 outburst was relatively rich in bright meteors. Combining the value derived from OVERDENSE and single-station data, we suggest the 2011 outburst had \( s \sim 1.75 \), appropriate to \( +3 \leq M_v \leq +7 \).

4.3 Flux

We counted the events in the OVERDENSE data set and selected events around the time of the maximum in the effective specular collecting area (17:30–18:30 UT) to compare to the zenith hourly rate (ZHR) by guest on 30 July 2018
published by the International Meteor Organization (IMO),⁶ shown in Fig. 17. As noted in previous sections, the main peak measured with visual data for the 2011 outburst occurred under very poor specular scattering geometry for CMOR, such that only the outburst rise is measurable. However, the scaled ZHR from the overdense radar data shows a similar variation to the visual data.

4.4 Meteoroid structure inferred from ablation modelling

The meteoroid ablation model developed by Campbell-Brown & Koschny (2004) was used to explore the structure of radar-detected Draconid meteoroids. We can use the velocities and electron line densities measured from different radar stations as constraints, and fit the model to match the observations. The velocity used here is the TOF velocity described in Section 3; the electron line density is computed from the amplitude/power of the echo (see Ceplecha et al. 1998, sections 4.2 and 4.3). The computation of electron line density differs between underdense and overdense echoes. Following the definition of classic radar meteor theory, we use the underdense formula for echoes with $q < 2.4 \times 10^{14} \text{m}^{-1}$ and vice versa (McKinley 1961, equations 8–29). In this way, we perform the ablation entry modelling using two approaches: (i) modelling the Draconids as a ‘mean’ population using all events; (ii) modelling individual events that showed noticeable deceleration across multiple stations.

4.4.1 Modelling Draconids as a population

In this approach, we mainly focused on two meteoroid structural parameters: grain number ($n_{\text{grain}}$) and grain mass ($m_{\text{grain}}$); for other tunable parameters, we either use the known properties of Draconids or those used by Campbell-Brown & Koschny (2004), as summarized in Table 5.

First, we find starting values for ($m_{\text{grain}}, n_{\text{grain}}$). We fix the total meteoroid mass in the range ($10^{-6}$–$10^{-4}$ kg), and plot the results of three combinations with ($m_{\text{grain}}, n_{\text{grain}}$) ranging from ($10^{-4}$ kg, 1) to ($10^{-10}$ kg, 10 000) to compare with radar observations, as shown in Fig. 18. Our best fit is near $m_{\text{grain}} \in [10^{-8}, 10^{-6}$ kg] and $n_{\text{grain}} = 100$, though the solution is not unique and we emphasize that we are in effect trying to fit an average Draconid, when there may be significant variation within the stream.

Next we want to see which of the two parameters ($m_{\text{grain}}, n_{\text{grain}}$) dominates the process. We investigate this by fixing either $m_{\text{grain}}$ (to $10^{-7}$ kg) or $n_{\text{grain}}$ (to 100), letting the other parameter, as well as total meteoroid mass, being variable as summarized in Table 6. The results are shown in Figs 19 and 20. For both the electron line density and velocity simulations, we see a trend that fixed-$n_{\text{grain}}$ curves match the observations better; for the fixed-$m_{\text{grain}}$ curves,
the sharp maximum of electron line densities near 93 km does not match the observed data points over the same height range. Also the velocity simulation showed little variation with different $n_{\text{grain}}$ in contrast to the observation.

4.4.2 Modelling individual Draconid echoes

As the time and phase measurements in CMOR data are synchronized, it is possible to use the Fresnel amplitude fluctuation features
Table 6. Summary of parameters for the sensitivity test of $m_{\text{grain}}$ and $n_{\text{grain}}$ for Figs 19 and 20.

| Figure | $m_{\text{grain}}$ (average) | $n_{\text{grain}}$ | Total mass  |
|--------|-----------------------------|----------------|----------------|
| Fig. 19 | $10^{-7}$ kg (fixed)       | 20              | $2 \times 10^{-6}$ kg |
|        |                             | 500             | $5 \times 10^{-5}$ kg |
| Fig. 20 | $2 \times 10^{-8}$ kg      | 100 (fixed)     | $2 \times 10^{-6}$ kg |
|        |                             | 5 $\times 10^{-7}$ kg | $5 \times 10^{-5}$ kg |

Figure 19. Modelling results with fixed $m_{\text{grain}} = 10^{-7}$ kg and variable $n_{\text{grain}} = 20$ and 500, corresponding to total masses of $2 \times 10^{-6}$ and $5 \times 10^{-5}$ kg. Size and colour of data points in velocity figure indicate number of sites: darker and larger points indicate more sites and vice versa. The vertical line for each data point depicts the height range constrained by multisite observations. Curves depict modelling solutions under different $n_{\text{grain}}$. Comparing with Fig. 19, we see a better match to the observations especially at middle and lower heights.

Figure 20. Modelling results with fixed $n_{\text{grain}} = 100$ and variable $m_{\text{grain}} = 5 \times 10^{-7}$ and $2 \times 10^{-8}$ kg, corresponding to total masses of $2 \times 10^{-6}$ and $5 \times 10^{-5}$ kg. Size and colour of data points in velocity figure indicate number of sites: darker and larger points indicate more sites and vice versa. The vertical line for each data point depicts the height range constrained by multisite observations. Curves depict modelling solutions under different $n_{\text{grain}}$. Comparing with Fig. 19, we see a better match to the observations especially at middle and lower heights.

Figure 21. Example of an underdense Draconid echo with four Fresnel maxima amplitude features noted (marked by arrows).

...and the $t_0$ point (Fig. 21) to precisely measure the positions (see Cephecha et al. 1998, section 4.6.1 and references therein); we therefore searched in the complete data set for any echo showing significant deceleration using this method. We have many echoes which show no measurable deceleration, but this does not provide a strong constraint on the entry model parameters, so we focus instead on events with clear deceleration. Since the same meteor seen at different sites usually corresponds to different positions on the trail, if the Fresnel feature shows up in observations from more than one site, we can obtain a series of contiguous position measurements along the trail. If there is no deceleration, then the position should increment linearly with time; therefore, by plotting position–time series, we can readily see if there is any deceleration. This is analogous to the distance along trail versus time plots used by Borovička et al. (2007) for video data to reveal meteoroid deceleration. In this way, we identified one event (detected on 17:31:47 UT on October 8 ...
and grain density to the one recommended by Borovička et al. (2007) (i.e. the one used in the previous section, $\rho_{\text{bulk}} = 300 \, \text{kg m}^{-3}$ and $\rho_{\text{grain}} = 3000 \, \text{kg m}^{-3}$), then tune $n_{\text{grain}}$ and $n_{\text{grain}}$ until a minimum difference between the modelling and the observation is achieved. The second approach leaves both the bulk and the grain density as well as the zenith angle and entry velocity flexible to eliminate any remaining differences. The results found with the two modelling approaches, as well as the input parameters, are given in Fig. 23 and Table 7.

4.4.3 Comparison and discussion

We compare our observational and modelling result to Borovička et al. (2007), who reported six decelerated Draconid meteors with sizes comparable to radar meteors, detected by double-station video system during the 2005 Draconid outburst. Their grain masses were in the range of $10^{-11} - 10^{-8}$ kg, with $\rho_{\text{bulk}} = 300 \, \text{kg m}^{-3}$ with the assumption of $\rho_{\text{grain}} = 3000 \, \text{kg m}^{-3}$, and total number of grains between $10^4$ and $10^6$. These six meteors all showed significant deceleration with turnover height (i.e. the height that $\dot{v}$ becomes significant) around 95 km. The differences with our results include a much smaller grain number ($10^2$) and a much larger grain mass (at the order of $10^{-3}$ kg) despite the density configurations being similar. Our 17:31:47 event also showed a slightly lower turnover height (~93 km) than the video meteors.

How to explain these differences? One possibility is the outbursts from 2005 to 2011 were ejected by Comet Giacobini-Zinner in different years: the material encountered in 2011 was ejected earlier than 2005 (1873–1907 versus 1946; Campbell-Brown et al. 2006; Vaubaillon et al. 2011b). However, we note that it is still difficult at this stage to uniquely define the physical properties of meteoroids in this way due to the lack of observational constraints. For example, the statistical model fits shown in Fig. 18 are broad averages which allow much uncertainties; for the modelling of the 17:31:47 event we have shown that a reasonable fit can be found with different sets of parameters, and similar phenomenon have been noted by the Borovička et al. (see section 7.1 of their paper). All these factors cast doubts on whether we are indeed seeing the physical differences between meteoroids or just fit variations admissible within the uncertainties. However, we still see that it is possible to use the observations to broadly constrain meteoroid properties to some extent, and we feel encouraged by the fact that our results have shown basic agreement to the earlier work of Borovička et al. (2007).

Furthermore, we do not have sufficient constrains on the chemical state of the meteor with radar observations, which prevent us from considering more chemistry-enhanced model, such as the differential ablation model developed by Vondrak et al. (2008). Future multi-instrumental observations, for example simultaneous radar-spectral observations, will be helpful to solve this problem and give more insights on the chemical state of the meteoroids.

5 CONCLUSIONS

In this study, we have analysed CMOR observations of the 2011 Draconid outburst, including 61 multistation specular echoes and 179 single-station overdense echoes. Our main results are the following.

(i) The radiant of the outburst was determined to be $\alpha_s = 261.9 \pm 0.3$, $\delta_s = +55.5 \pm 0.3$ (J2000) with the multistation echoes, which agreed with earlier modelling forecasts to $\sim 1^\circ$.

(ii) The averaged velocity determined from the CMOR data was by $\sim 10–15$ per cent smaller than the expected value (17.0–19.1 km s$^{-1}$ versus 20.4 km s$^{-1}$), likely due to the undercorrection of deceleration, combined with the effect of radiant geometry during the peak hours.

(iii) The mass distribution index determined from 155 overdense echoes was $s = 1.72 \pm 0.01$ assuming the echoes used for such determination were diffusion dominated. Alternatively, we selected 54 possible Draconids in the sample of single-station underdense echoes and determined the mass index to be around 1.75. Combining
Table 7. Input parameters of two approaches used to model the ablation of the 17:31:47 event. For the first approach, the bulk and grain densities are set to those given by Borovička et al. (2007), while for the second approach the two are fit by the model.

| Parameter                      | First approach | Second approach |
|--------------------------------|----------------|-----------------|
| Number of grains, $n_{\text{grain}}$ | 800            | 4000            |
| Grain mass (average), $m_{\text{grain}}$ (kg) | $3 \times 10^{-9}$ | $5 \times 10^{-10}$ |
| Grain mass range (kg) | $[10^{-9}, 4 \times 10^{-9}]$ | $[3 \times 10^{-10}, 5 \times 10^{-10}]$ |
| Total mass, m (kg) | $2.4 \times 10^{-6}$ | $2 \times 10^{-6}$ |
| Deceleration corrected apparent velocity, $v_{\infty}$ (km s$^{-1}$) | 24.30 | 24.50 |
| Zenith angle, $\theta$ | 38.3 | 36.8 |
| Bulk density, $\rho_{\text{bulk}}$ (kg m$^{-3}$) | 300 | 500 |
| Grain density, $\rho_{\text{grain}}$ (kg m$^{-3}$) | 3000 | 1500 |

Newtonian calculations suggest that the mass index of the 2011 outburst to be $s = 1.75$ for the magnitude range of $+3 \leq M_V \leq +7$.

(iv) We compared the counts of overdense echoes to the visual data, and a clear consistency can be noted. Unfortunately, the peak time of the outburst occurred with very poor scattering geometry for CMOR, such that no comparison can be made at the peak time. However, the rise of the meteor rates between the radar and visual results was highly comparable.

(v) We used the meteoroid ablation model developed by Campbell-Brown & Koschny (2004) to explore the structure of dense meteoroid Draconid meteoroids. Assuming bulk and grain densities to be 300 and 3000 kg m$^{-3}$, respectively, the model seems to infer that the grain number of CMOR-observed Draconid meteoroids is $\sim 100$ regardless of meteoroid sizes.

(vi) We also identified a Draconid meteor that showed clear deceleration. Two modelling approaches were attempted, suggested the grain numbers to be $\sim 1000$, grain mass between $10^{-10}$ and $10^{-9}$ kg and the total mass to be around $2 \times 10^{-5}$ kg, which were in close agreement with the video results reported by Borovička et al. (2007).

As this paper was being finished, an unexpected and much more intense Draconid outburst was detected by CMOR on 2012 October 8. Preliminary analysis suggests a spectacular ZHR at the order of 8000, far above the storm level. In-depth investigation of the 2012 event will be addressed in a separate paper.

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Campbell-Brown M. D., Koschny D., 2004, A&A, 418, 751
Campbell-Brown M., Brown P., Wiegert P., Arlt R., Vaubaillon J., 2005, Cent. Bureau Electron. Telegrams, 255, 1
Campbell-Brown M., Vaubaillon J., Brown P., Weryk R. J., Arlt R., 2006, A&A, 451, 339
Cephecha Z., Borovička J., Elford W. G., Reveille D. O., Hawkes R. L., Porubčan V., Šimek M., 1998, Space Sci. Rev., 84, 327
Cervera M. A., Elford W. G., Steel D. I., 1997, Radio Sci., 32, 805
Davidson R. M., 1915, J. British Astron. Association, 25, 292
Davies J. G., Lovell A. C. B., 1955, MNRAS, 115, 23
Denning W. F., 1926, MNRAS, 87, 104
Emel‘Ianenko V. V., 1992, Celest. Mech. Dyn. Astron., 54, 91
Fiocco G., Colombo G., 1964, J. Geophys. Res., 69, 1795
Fisher W. J., 1934, Harvard College Obser. Bull., 894, 15
Hey J. S., Parsons S. J., Stewart G. S., 1947, MNASS, 107, 176
Hocking W. K., Fuller B., Vandeper B., 2001, J. Atmos. Sol.-Terr. Phys., 63, 155
Hughes D. W., Thompson D. A., 1973, MNARS, 163, 3 p
Imoto S., Hasegawa I., 1958, Smithsonian Contr. Astrophys., 2, 131
Jacchia L. G., Kopal Z., Millman P. M., 1950, ApJ, 111, 104
Jenniskens P., 1995, A&A, 295, 206
Jenniskens P., 2006, Meteor Showers and Their Parent Comets. Cambridge Univ. Press, Cambridge
Jenniskens P., Barentsen G., Yrjola I., 2011, Cent. Bureau Electron. Telegrams, 2862, 1
Jones W., Jones J., 1990, J. Atmos. Terr. Phys., 52, 185
Jones J., Brown P., Ellis K. J., Webster A. R., Campbell-Brown M., Krzeminski Z., Weryk R. J., 2005, Planet. Space Sci., 53, 413
Kero J., Fujiwara Y., Abo M., Szasz C., Nakamura T., 2012, MNARS, 424, 1799
Kronk G. W., 2008, Cometography. Cambridge Univ. Press, Cambridge
Langbroek R., 1997, WGN, J. Int. Meteor Organization, 25, 37
Lindblad B. A., 1987, A&A, 187, 928
Lovell A. C. B., Banwell C. J., Clegg J. A., 1971, MNARS, 107, 164
McIntosh B. A., 1968, in Kresak L., Millman P. M., eds, Proc. IAU Symp. 33, Physics and Dynamics of Meteors. Reidel, Dordrecht, p. 362
Spalding G. H., 1985, J. British Astron. Association, 95, 211
Stewart J. Q., Ference M., Slattery J. J., Zahl H. A., 1947, AJ, 52, 158
Vaubaillon J., Colas F., Jorda L., 2005, A&A, 439, 751
Vaubaillon J., Koten P., G erding M., Johannink C., Langbroek M., Latteck R., Brown P., Jenniskens P., 2011a, Cent. Bureau Electron. Telegrams, 2862, 2
Vaubaillon J., Watanabe J., Sato M., Horii S., Koten P., 2011b, WGN, J. Int. Meteor Organization, 39, 59
Verniani F., 1973, J. Geophys. Res., 78, 8429
Vondrak T., Plane J., Broadley S., Janches D., 2008, Atmos. Chem. Phys., 8, 7015
Watson F., Jr., 1934, Harvard College Obser. Bull., 895, 9
Watson F., 1939, Nat., 144, 482
Watson F. G., 1946, Sky Telesc., 5, 5
Weiss A. A., 1961, Aust. J. Phys., 14, 102
Weryk R. J., Brown P. G., 2012, Planet. Space Sci., 62, 132

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