MU radar head echo observations of the 2011 October Draconids

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ABSTRACT
On 2011 October 8, the Earth passed through a stream of dust ejected by the comet 21P/Giacobini–Zinner during its perihelion passage of the year 1900, causing an outburst of October Draconid meteors. 13 Draconids were observed among ~6300 meteor head echoes with precisely determined orbits during an observational campaign ranging from October 8 05:00 UT to October 9 13:00 UT with the Shigaraki middle and upper atmosphere (MU) radar in Japan (34°85 N and 136°10 E). The meteor outburst occurred while the Draconid radiant was descending below and 2 h later rising up above the horizon. Therefore, 11 of the detections were from very low (<15°) elevation. The detection altitudes of the Draconids were high compared to sporadic meteors of the same velocity and radiant elevation. The weighted mean geocentric velocity of the 13 Draconids was 20.6 ± 0.4 km s⁻¹, and the weighted mean radiant located at right ascension α = 263°3 ± 0.6 and declination δ = 55°8 ± 0.2.

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

1 INTRODUCTION
The Draconid meteor shower is also called the Giacobinids after its known parent comet 21P/Giacobini–Zinner. This short-period comet has currently an orbital period of 6.60 years and a perihelion distance of 1.03 au. It was discovered during its perihelion passage in 1900 December.

According to simulations, the dust ejected during the 1900 perihelion passage was predicted to cause a meteor outburst in 2011 October 8 around 20 UT (Maslov 2011; Vaubaillon et al. 2011b). The outburst level was expected to reach several hundreds of meteors per hour, but not approach the intense Draconid outburst rates of up to 10 000 h⁻¹ that occurred in 1933 and 1946 (Jenniskens 1995). Visual observations collected by the International Meteor Organization (IMO) largely agree with the predictions (Vaubaillon et al. 2011a). From 2164 visual Draconids reported to the IMO, G. Barentsen calculated that the peak zenith hourly rate (ZHR) reached 300 ± 30 h⁻¹ on 2011 October 8 at 20h03 min ± 10 min UT.

An event head echo is caused by radio waves scattered from the intense region of the plasma surrounding and convolving with a meteoroid during atmospheric flight. The Doppler shift and/or the range rate of the target can therefore be used to determine meteoroid velocity. The first head echoes were reported by Hey, Parsons & Stewart (1947) from observations conducted in 1946 October 7–11, covering the anticipated 1946 Draconid meteor outburst, with a 150-kW VHF radar system. A total of 22 events could be used for velocity determination, leading to a weighted mean Draconid velocity of 22.9 ± 1.3 km s⁻¹.

Since the 1990s, head echo observations have been conducted with most high-power large-aperture (HPLA) radar facilities around the world (Pellinen-Wannberg & Wannberg 1994; Mathews et al. 1997; Close et al. 2000; Sato, Nakamura & Nishimura 2000; Chau & Woodman 2004; Mathews et al. 2008; Malhotra & Mathews 2011). However, only a few observations of shower meteors have been published (e.g. Chau & Galindo 2008; Kero et al. 2011) and no reports have contained new data on the Draconids.

We conducted an observational campaign ranging from the period 2011 October 8 05:00 UT to October 9 13:00 UT with the Shigaraki middle and upper atmosphere (MU) radar in Japan (34°85 N and 136°10 E) to cover the expected 2011 Draconid outburst with some margin. Unfortunately, the expected and visually confirmed outburst occurred as the Draconid radiant was descending below and 2 h later rising up above the horizon. Therefore, only 13 Draconid meteors were observed among the 6300 meteor head echoes with precisely determined orbits, and 11 of the detections occurred when the radiant had very low elevation (<15°).

The observed weighted mean velocity and geocentric velocity, the latter corrected for the Earth’s encounter, were 23.5 ± 0.3 and 20.6 ± 0.4 km s⁻¹, respectively. The weighted mean radiant was located at right ascension α = 263°3 ± 0.6 and declination δ = 55°8 ± 0.2, in agreement with simulations of dust ejected in 1900 from comet 21P/Giacobini–Zinner (Vaubaillon, Watanabe & Sato 2010; Maslov 2011).

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The detection altitudes of the Draconids are higher than the average detection altitude of sporadic meteors of the same velocity and radiant elevation. High Draconid detection altitudes have previously been found, e.g., among photographic (Jacchia, Kopal & Millman 1950) and video meteors (Suzuki et al. 1999; Fujiwara et al. 2001; Koten et al. 2007).

2 RADAR EXPERIMENTAL SET-UP

The 46.5-MHz MU radar hardware comprises a 25-channel digital receiver system. It was upgraded from its original set-up (Fukao et al. 1985) in 2004 and is described by Hassenplug et al. (2008). Meteor head echo observations prior to the upgrade have been reported by Sato et al. (2000) and Nishimura et al. (2001). We have developed improved analysis algorithms and collected an extensive set of data (>500 h) between 2009 June and 2010 December. The analysis algorithms are detailed by Kero et al. (2012a), and Kero et al. (2011) present meteor head echoes associated with comet 1P/Halley dust of the 2009 Orionid meteor shower. An overview of some analysis parameters of Draconid number 10 in Tables 1 and 2: (a) range, (b) radial velocity, (c) meteoroid velocity, (d) transversal displacement from the beam centre in the west (black) and south (red) directions, (e) angle of the trajectory to the beam and (f) RCS (black) and S/N (red). The green markers in panel (b) trace the velocity determined from pulse-to-pulse phase correlation while open circles are Doppler estimates. The dotted lines in panels (c) and (e) show the estimated 95% confidence intervals of the meteoroid velocity uncertainty margin and the angle to the beam, respectively. One interpulse period (IPP) corresponds to 3.12 ms.

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3 DRACONID OBSERVATIONS

Fig. 2 presents the hourly rate of detected meteor head echoes with precisely determined orbits during the Draconid campaign. The number of meteors classified as Draconids is given numerically. The elevation of the Draconid radiant above the local horizon is plotted as a curve, and the visual ZHR determined by G. Barentsen from 2164 visual Draconids reported to the IMO is displayed as error bars.

The radiant distribution of the detected meteors is plotted in Fig. 3 in Sun-centred ecliptic coordinates. The Sun is located at 0° Sun-centred ecliptic longitude, regardless of the time of year. The direction of the apex is = 270° Sun-centred ecliptic longitude. In addition to the Draconids (DRA), a radiant enhancement also appears close to the expected radiant region of the South Taurids (STA).
According to model simulations by Vaubaillon et al. (2010), on 4 THE 2011 DRACONID RADIANT

zenith distance of their radiants are summarized in Table 1.

Table 1. Draconid time of observation (2011 October 8 and 9), right ascension (α), declination (δ), geocentric velocity (Vg), radar cross-section (RCS), initial detection height (Hδ), end height (Hβ), azimuth (αz) and zenith distance (ζe) of the radiant, and observed initial velocity (Vobs).

| Event | Time (UT) | α (°) | δ (°) | Vg (km s⁻¹) | RCS (dBsm) | Hδ (km) | Hβ (km) | αz (°) | ζe (°) | Vobs (km s⁻¹) |
|-------|-----------|-------|-------|-------------|------------|---------|---------|--------|-------|--------------|
| 1     | 16:24:12  | 262.9 ± 0.5  | 55.7 ± 0.3  | 21.1 ± 0.2   | -17        | 103.7   | 102.1   | 337.6 ± 0.2  | 76.4 ± 0.1 | 23.7 ± 0.2   |
| 2     | 17:30:44  | 263.0 ± 0.8  | 55.0 ± 0.7  | 19.4 ± 0.6   | -19        | 97.8    | 96.3    | 345.6 ± 0.3  | 80.2 ± 0.2 | 22.3 ± 0.6   |
| 3     | 17:32:06  | 262.8 ± 0.5  | 55.7 ± 0.4  | 20.3 ± 0.4   | -1         | 99.4    | 98.1    | 346.2 ± 0.2  | 80.2 ± 0.1 | 23.0 ± 0.4   |
| 4     | 17:49:34  | 262.4 ± 1.8  | 55.3 ± 1.1  | 19.7 ± 0.7   | -27        | 102.2   | 100.7   | 348.6 ± 0.8  | 81.1 ± 0.3 | 22.5 ± 0.7   |
| 5     | 18:51:12  | 263.8 ± 0.9  | 55.1 ± 1.4  | 19.6 ± 1.3   | -24        | 100.9   | 99.9    | 356.4 ± 0.4  | 82.8 ± 0.4 | 22.5 ± 1.3   |
| 6     | 18:58:30  | 261.9 ± 0.7  | 55.6 ± 0.8  | 20.5 ± 0.8   | -10        | 100.2   | 99.5    | 358.5 ± 0.4  | 83.0 ± 0.3 | 23.3 ± 0.8   |
| 7     | 20:13:51  | 261.3 ± 3.9  | 55.4 ± 1.9  | 19.6 ± 1.5   | -29        | 105.9   | 104.9   | 7.4 ± 1.9   | 82.3 ± 0.5 | 22.6 ± 1.5   |
| 8     | 20:31:47  | 263.8 ± 0.3  | 55.8 ± 0.2  | 20.6 ± 0.2   | 0          | 103.9   | 102.7   | 10.5 ± 0.1   | 81.9 ± 0.1 | 23.5 ± 0.2   |
| 9     | 20:49:02  | 261.3 ± 2.3  | 55.4 ± 1.2  | 20.7 ± 1.0   | -29        | 108.4   | 107.1   | 14.3 ± 1.0   | 81.3 ± 0.6 | 23.6 ± 1.0   |
| 10    | 21:48:44  | 263.5 ± 1.1  | 55.9 ± 0.6  | 20.5 ± 0.3   | -20        | 102.2   | 100.2   | 20.6 ± 0.5   | 78.0 ± 0.2 | 23.4 ± 0.3   |
| 11    | 22:20:11  | 263.5 ± 0.3  | 55.9 ± 0.2  | 20.5 ± 0.1   | -1         | 101.2   | 99.1    | 24.4 ± 0.1   | 76.0 ± 0.1 | 23.5 ± 0.1   |
| 12    | 00:15:33  | 263.9 ± 6.2  | 55.9 ± 3.4  | 18.9 ± 1.3   | -30        | 96.7    | 94.5    | 35.8 ± 2.6   | 64.9 ± 1.6 | 22.1 ± 1.3   |
| 13    | 06:26:31  | 262.0 ± 5.3  | 55.8 ± 2.9  | 20.9 ± 0.3   | -26        | 103.3   | 98.1    | 19.6 ± 5.9   | 21.3 ± 2.0 | 23.7 ± 0.3   |
| Mean  |           | 263.1 ± 1.0  | 55.6 ± 0.3  | 20.2 ± 0.7   |            | 102.0 ± 3.2 | 100.2 ± 3.4 |            | 23.0 ± 0.6  |
| Weighted mean | 263.3 ± 0.6  | 55.8 ± 0.2  | 20.6 ± 0.4   |            |            |            |            | 23.5 ± 0.3  |

The Draconid radiant enhancement is compact and therefore very clear, even though comprised of only 13 detections. A close-up of the Draconid radiant region in equatorial coordinates is provided in Fig. 4 and is further described below.

Fig. 5 shows a top-down projection of the meteor radiant distribution in a local horizontal coordinate system with zenith above the MU radar located at the centre of the plot; west is to the left and north is up. The path of the Draconid radiant region during the observation is plotted in green and detected Draconids as red dots. The exact time of the Draconid detections and the azimuth and zenith distance of their radiants are summarized in Table 1.

4 THE 2011 DRACONID RADIANT

According to model simulations by Vaubaillon et al. (2010), on 11 October 8 and 9, the Earth passed through several dust trails left by 21P/Giacobini-Zinner. The model predicted the two most prominent trails to be the 1900 and the 1887 ones. The 1900 trail passage was expected to give rise to an order of magnitude more meteors, ZHR ~ 600, than the 1887 one. The 1887 trail radiant region was located at α = 263.3 ± 0.1 and δ = 55.4 ± 0.2, while the 1900 one at α = 263.2 ± 0.2 and δ = 55.8 ± 0.2. These regions are marked in green in Fig. 4. The red shape shows the weighted mean of the 13 MU Draconid radiants with an estimated uncertainty region. Uncertainty calculations are detailed in Appendix A.

The weighted mean of the Draconid radiant agrees with the expected 1900 trail radiant region. However, the uncertainties of the individual radiants are large compared to the expected difference between 1887 and 1900 trail meteoroids. Also, some of the MU Draconids may have belonged to the 1887 trail rather than the 1900 one.

Nevertheless, the good agreement with the predictions, as well as with reported video observations (Vaubaillon et al. 2011a), shows that the small (radiator-sized) MU Draconids and larger meteoroids had similar orbital characteristics. The mean radiant region of small (radiator-sized) particles of the 2005 Draconid outburst observed with the Canadian Meteor Orbit Radar (CMOR) reported by Campbell-Brown et al. (2006) differed from the modelled and the optical (video and photographic) radiant with α = 1° and δ = 6° (Koten et al. 2007).
Figure 2. Histogram of the hourly meteor detection rate and the number of observed Draconids during the MU radar observation from 2011 October 8 05:00 UT to October 9 13:00 UT. The elevation of the Draconid radiant (red) peaks at \(\sim 70^\circ\) around 7 UT. The error bars show the ZHR calculated by G. Barentsen from 2164 visually observed Draconids collected by the IMO.

Figure 3. The radiant distribution of \(\sim 6300\) meteors plotted in Sun-centred ecliptic longitude and ecliptic latitude. The geocentric velocity is colour coded. The ecliptic longitude of the Sun at the moment of detection has been subtracted from each meteor radiant, positioning the Sun at 0\(^\circ\) regardless of the time of year. The direction of the apex is 270\(^\circ\) Sun-centred ecliptic longitude. The Draconid and the South Taurid shower radiants are marked by arrows.

5 DRACONID VELOCITY AND INITIAL ALTITUDE

Fig. 6 shows a histogram of the observed velocity distribution of all detected meteors. Each bar represents the number of detections in a bin of 1 km s\(^{-1}\) width. The red bars show the Draconids. Part of the spread in the Draconid velocity distribution correlates with the different initial heights of the detected meteors. Fig. 7 extends the initial altitude versus observed velocity (green) and versus geocentric velocity (blue), corrected for the Earth focusing (zenith attraction) and the Earth’s rotation following Szasz et al. (2008) and Szasz (2008).
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Figure 4. Scatter diagram of the MU Draconid radiants in equatorial coordinates. The red shape marks the weighted mean radiant with estimated uncertainty. The green shapes show expected radiant regions for meteors of the 1900 and 1887 trails of 21P/Giacobini–Zinner (Vaubillon et al. 2010).

Figure 5. Top-down view of the MU meteor radiant distribution. Zenith is located at the centre of the plot and the concentric circles correspond to zenith distances of $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$ and $90^\circ$, respectively. The green shape is the path of the Draconid radiant region, and red dots mark detected Draconids. The radiants are corrected for the Earth’s encounter. Error bars correspond to the estimated 95 per cent confidence interval of the velocity. The uncertainties of the measured altitudes are of the order of tens of metres and thus negligible.

The meteoroid velocity shows a clear dependence on the initial altitude. Plotted in Fig. 7 are linear least-squares fit to the data. The fitted observed/geocentric velocity is $23.7/20.9$ km s$^{-1}$, respectively, at an altitude of 108.4 km, and decreases with 0.11/0.10 km s$^{-1}$ each kilometre of a lower initial height. The decreasing velocity with altitude is likely a sign of small but significant deceleration before detection. If the initial detection altitude is equal to the beginning height of the meteor, the deceleration occurred before the start of substantial ablation. The fitted geocentric velocity at 108.4 km is identical to the predicted geocentric velocity of dust in the 1900 trail, 20.9 km s$^{-1}$ (Maslov 2011).

Figure 6. Histogram of the meteor initial velocity distribution (grey). The red bars show the Draconids.

Figure 7. Draconid initial detection altitude versus observed initial velocity (green) and versus geocentric velocity (blue) corrected for zenith attraction, aberration etc. Numbers refer to Table 1.

Fig. 8 is a scatter plot of the initial detection altitude versus observed meteoroid velocity, the Draconids plotted in a deviating colour. In order to investigate the fairly large spread of Draconid initial heights further, Fig. 9 shows scatter plots of the initial detection altitude versus radiant zenith distance, divided into different meteoroid velocity intervals. The Draconids are plotted in red in the top leftmost panel of Fig. 9. The average initial detection altitude is lower than that of the Draconids and only two meteors appear at a higher initial altitude, one of them likely belonging to the Southern Taurid (STA) meteor shower, the other one being a sporadic meteor.

A larger zenith distance means that a larger number of collisions with atmospheric constituents have taken place when a meteoroid has penetrated to a given altitude, thus a larger loss of momentum.
This could cause large zenith distance meteoroids to have higher average beginning heights. Fig. 9 does not show such a correlation between the initial detection altitude and zenith distance. One reason could be that a meteoroid of a certain mass and velocity does not give rise to a detectable head echo until it has reached down to a certain level of atmospheric density where the mean-free path of the ablated material fulfills a radar frequency-dependent condition (e.g., Close et al. 2004, 2007; Mathews 2004; Westman, Wannberg & Pellinen-Wannberg 2004; Mathews et al. 2008). The results given in Fig. 9 suggest that the effect of zenith angle is small compared to other factors.

At any rate, the average Draconid detection altitude is higher than that of other meteoroids of the same zenith angle and velocity. The spread of the initial detection altitudes among meteoroids of a similar velocity does not seem to be controlled by zenith distance. Other factors that may affect the beginning heights of meteorites are e.g., meteoroid density, composition, porosity and fragmentation characteristics. Ceplecha (1968) described discrete levels in the detection altitudes of McCrosky-Posen Super-Schmidt photographic meteors and divided these meteors into classes A, B, C1 and C2. Shower meteors generally fall into one of the C classes. The C classes contain the meteors observed at the highest beginning altitude. Draconids are an exception in that they begin as much as 7 km higher than an average C level meteor.

The MU radar Draconids have high, but not exceptionally high, initial detection altitudes. As is evident from Fig. 8, the Draconids seem to belong to a class of radar meteorites that span the whole velocity range and have initial altitude at a level distinctly above the bulk of the radar meteors. Note that only a small fraction of our total detected meteors belong to the class of high initial altitudes, whereas all detected Draconids belong to high initial altitudes.

6 DISCUSSION

Photographic (Jacchia et al. 1950) and also more recent video (Suzuki et al. 1999; Fujiwara et al. 2001; Koten et al. 2007)
observations during previous Draconid outbursts have revealed that the Draconid beginning heights are significantly higher than those of other established meteor showers and that of an average sporadic meteor. An explanation suggested by Jacchia et al. (1950) is that the Draconid meteoroids might be composed of soft materials and therefore more easily melt or vaporize, perhaps due to the recent dust release from the parent comet.

Beech (1986) compared observational data of Draconid meteors with the dustball meteor ablation theory of Hawkes & Jones (1975). According to the dustball theory, meteoroids are composed of grains held together by a lower boiling point component, and for meteors fainter than +5m these grains are completely detached before ablation (of the individual grains) commences. Beech (1984, 1986) found that the energy required to fragment a unit mass of the Draconid material is less than \( \sim 10^3 \text{ J kg}^{-1} \) and the bulk density is \( \gtrsim 200 \text{ kg m}^{-3} \).

Borovička, Spurný & Koten (2007) found that fragmentation into individual grains before ablation does not agree with their spectroscopic video observations of seven Draconid meteors. Instead, they developed a model of gradual fragmentation, where grains are released in different quantities at various heights. Furthermore, different grain mass distributions had to be applied to each individual meteor to fit the observed deceleration and light curves. Borovička et al. (2007) concluded that erosion starts when the meteoroid surface receives an energy of \( (1.0–1.6) \times 10^5 \text{ J m}^{-2} \) and that the total erosion energy lies in the range of \( (0.6–1.5) \times 10^3 \text{ J kg}^{-1} \), an order of magnitude higher than that found by Beech (1984).

The MU Draconids and some of the sporadic meteors in Fig. 7 have clearly higher initial detection heights than the bulk of the sporadic meteors. This is the first evidence of the Draconid head echo altitude distribution and its relation to other meteors.

7 CONCLUSIONS

We conducted an observational campaign ranging from 2011 October 8 05:00 UT to October 9 13:00 UT with the Shigaraki MU radar in Japan. An expected, and visually confirmed, outburst of meteors due to the Earth’s crossing a trail of dust released by comet 21P/Giacobini–Zinner during its perihelion passage in 1900 occurred at a time when the radiant was descending below and 2 h later rising up above the horizon. Of the 13 Draconid meteors observed, 11 were observed when the Draconid radiant was located at a large zenith distance (>75°).

The detection altitudes of the MU Draconids are high compared to sporadic meteors of similar velocity and zenith distance. Their weighted mean geocentric velocity is 20.6 ± 0.4 km s\(^{-1}\) and the weighted mean radiant is located at \( \alpha = 263.3 \pm 0.6 \) and \( \delta = 55.8 \pm 0.2 \), in good agreement with simulations (Vaubaillon et al. 2010, 2011b; Maslov 2011).

HPLA radar meteor head echo observations complement sporadic meteor trail radar orbital surveys (e.g. Galligan & Baggaley 2004; Brown et al. 2010), as a wealth of information can be determined from each particular head echo event (e.g. Kero et al. 2008) and because the observational biases are different.

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evaluate how this uncertainty affects the velocity curve and the radiant, we started by estimating confidence intervals (CIs) of the coefficients of the linear fit to the interferometric data.

Fig. 1(d) shows the interferometry data of the Draconid labelled as number 10 in Tables 1 and 2. The horizontal displacement of the meteor target from local zenith (centre of the radar beam) is given as east–west (blue) and north–south (red) components. The straight lines are least-squares fits to the position data. The CIs are constructed by calculating the standard errors of the ordinary least-squares solutions and multiplying them with the 95 per cent parameter of the student t distribution (e.g. Hamilton 1992). Fig. 1(e) shows the angle between the trajectory and the beam with the estimated uncertainty, in this case less than 0.2°.

Using the estimated CI for both zenith distance and azimuth, we construct an elliptical area (circular if the uncertainties in both directions are equal) containing the true meteoroid radiant with a 95 per cent certainty under the condition that the residuals of the interferometry data are random and normally distributed.

Fig. 1(c) shows the uncertainty of the meteoroid velocity, given that the very precise measured radial component reported in Fig. 1(b) is correct and projected on to possible trajectory directions within the radiant uncertainty region described above. The only necessary assumption for this conversion is that the trajectory has negligible curvature within the few kilometres it is observable. The algorithms used are further detailed by Kero et al. (2012a).

The 0.2 uncertainty of this particular case leads to a velocity uncertainty of ±0.3 km s⁻¹. Due to the large trajectory to the beam angle 76°–82° during the extent of the event, deceleration cannot be determined despite this quite small uncertainty. Depending on the trajectory, the total loss of velocity during detection is 0–1 km s⁻¹ (Fig. 1c), or equal to ~0–3 km s⁻². All 13 Draconids have a similarly large uncertainty. Deceleration is therefore not reported.

Error margins for the orbital parameters in Table 2 were found by assuming worst-case combinations of the estimated uncertainty of the observed velocity (Vobs), zenith distance (ze) and azimuth (az).

A1 Weighted mean radiant and velocity

The estimated uncertainty region of the weighted mean radiant plotted in Fig. 4 was determined by calculating the square root of the weighted variance. The weights, wi, used in the mean and variance calculations are equal to wi = 1/σ², where σi is the estimated 95 per cent CI of α and δ, respectively, drawn as error bars on the individual Draconid radiants in Fig. 4 and given numerically in columns 3 and 4 of Table 1.

For the weighted mean velocity and geocentric velocity we assumed σi equal to the 95 per cent CI of Vobs and Vg, respectively, drawn as error bars on the individual velocity data points in Fig. 7 and given numerically in columns 5 and 11 of Table 1.

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