The 2009–2010 MU radar head echo observation programme for sporadic and shower meteors: radiant densities and diurnal rates

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ABSTRACT

The aim of this paper is to give an overview of the monthly meteor head echo observations (528.8 h) conducted between 2009 June and 2010 December using the Shigaraki Middle and Upper atmosphere radar in Japan (34°85 N, 136°10 E). We present diurnal detection rates and radiant density plots from 18 separate observational campaigns, each lasting for at least one diurnal cycle. Our data comprise more than 106 000 meteors. All six recognized apparent sporadic meteor sources are discernable and their average orbital distributions are presented in terms of geocentric velocity, semimajor axis, inclination and eccentricity. The north and south apex have radiant densities an order of magnitude higher than other apparent source regions. The diurnal detection rates show clear seasonal dependence. The main cause of the seasonal variation is the tilt of the Earth’s axis, causing the elevation of the Earth’s apex above the local horizon to change as the Earth revolves around the Sun. Yet, the meteor rate variation is not symmetric with respect to the equinoxes. When comparing the radiant density at different times of the year, and thus at different solar longitudes along the Earth’s orbit, we have found that the north and south apex source regions fluctuate in strength.

Key words: meteorites, meteors, meteoroids.

1 INTRODUCTION

Sporadic meteors are those that cannot be directly ascribed to a parent body. The first observational evidence of the Solar system sporadic meteoroid distribution not being isotropic was provided by Hawkins (1956). Investigating meteor trail detection rates recorded using a radar system at Jodrell Bank, Cheshire, UK, Hawkins found three concentrations of sporadic meteor radiants towards the ecliptic plane in the directions of the apex, the Sun (helion) and the antihelion points. An isotropic distribution would have yielded a concentration towards the apex only, due to the Earth’s orbital motion around the Sun.

Stohl (1968) extended the number of apparent source regions to four, by identifying a concentration around ecliptic latitude $\beta \simeq +60^\circ$ in data collected using the Springhill meteor radar in Canada. This concentration is called the north toroidal source.

Jones & Brown (1993) investigated ten meteor surveys available through the IAU Meteor Data Center (Lindblad 1987). They showed that the apex source could be divided into a north and a south component. Furthermore, they found a complementary source to the north toroidal source around ecliptic latitude $\beta \simeq -60^\circ$, termed the south toroidal source. The current number of recognized apparent source regions is thus six.

Investigations of the annual variations and orbital characteristics of the apparent sources have been conducted using, e.g., the Canadian Meteor Orbit Radar (CMOR; Campbell-Brown & Jones 2006; Campbell-Brown 2008; Campbell-Brown & Wiegert 2009) and the Advanced Meteor Orbit Radar (AMOR; Galligan & Baggaley 2004, 2005). These surveys show that some of the apparent sources, when observed with specular meteor radar (SMR) systems, vary in strength and location throughout the year, i.e. as a function of solar longitude.

Chau, Woodman & Galindo (2007) reported the first observational evidence of the sporadic source regions seen in SMR data also being discernable in interferometric meteor head echo data, in agreement with the modelling work by Janches et al. (2006). Using the 50 MHz high power large aperture (HPLA) radar of the

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Jicamarca Radio Observatory (JRO), Chau et al. found enhanced radiant densities within all six source regions. However, the relative strength of the north and south apex regions was much higher than in results obtained using SMR systems (Campbell-Brown 2008).

We have conducted a systematic set of monthly meteor head echo observations, between 2009 June and 2010 December, except 2009 August, with the 46.5 MHz Middle and Upper atmosphere (MU) radar near Shigaraki, Japan. The MU radar and the experiment setup we have used are presented in Section 2, and in more detail in a previous paper where we compared sporadic to Orionid meteor detections observed during the 33 h campaign in 2009 October (Kero et al. 2011).

In this paper, we present diurnal detection rates and radiant density plots from 18 separate observational campaigns, comprising more than 106 000 meteors in total. The diurnal detection rates show clear seasonal dependence and are reported in Section 3. The seasonal variation of the diurnal detection rates largely agrees with the observations and modelling work by Janches et al. (2006), Fentzke & Janches (2008), Fentzke, Janches & Sparks (2009), who found that ∼60–70 per cent of the total number of observable HPLA radar head echoes are associated with the apex sources.

Our observed radiant distribution and an explanation of how long different parts of the celestial sphere were observed during the experiments is provided in Section 4. A description of how we have calculated radiant density, and a comparison of the radiant density with modelling work is given in Section 5. Orbital element distributions are reported in Section 6.

The north and south apex apparent sporadic meteor source regions have radiant densities an order of magnitude higher than other apparent source regions. In Section 7, we compare the radiant density at different times of the year, and thus at different solar longitudes along the Earth’s orbit. We have found that the north and south apex source regions fluctuate significantly in strength.

The variation of the apparent source strength, location and shape depends on the number and approximate orbits of the parent bodies (Campbell-Brown 2008). Investigations of such properties therefore provide important input to dynamical modelling of the sporadic meteoroid complex (e.g. Wiegert, Vaubaillon & Campbell-Brown 2009).

2 MU EXPERIMENT

The Shigaraki 46.5 MHz MU radar in Japan is located at 34°85′N and 136°10′E. In total, 528.8 h of data and >106 000 meteor head echoes with precisely determined orbits were recorded. Fig. 1 compares the length and Fig. 2 the number of detected meteors of each experiment. Fig. 3 displays the diurnal meteor count rate per experiment. From this plot, it is clear that the detection rates are seasonally dependent. More meteors are observed around autumnal equinox than around vernal equinox.

Our goal has been to cover at least one diurnal cycle during each observational campaign. This we have achieved for most measuring campaigns. The shortest campaign is 2009 December, comprising 21.0 h of data and almost 5000 head echoes. The longest campaign, 2010 October, resulted in 69.1 h of data and more than 23 000 head echoes.

The radar is stopped and restarted every full hour to reboot the system and avoid memory buffer overflow, an occasional consequence of the data rate being close to the system limit. Due to this procedure, we have no data for the first 1–2 min of every full hour. This is taken into account when calculating the hourly rates presented in Section 3.
The MU radar was running in the general head echo mode briefly described below and detailed by Kero et al. (2012). The radar experiment ran with an identical setup each month for the whole duration of the observation programme. We originally designed the measurement mode for sporadic meteor head echo detections but it has also been shown to be very useful to observe shower meteors with. For example, Kero et al. (2011) present results from 2009 October, concentrating on the 2009 Orionid meteor shower. For the remainder of this paper, shower meteors are not discussed separately. Sporadics are the most numerous among our observed particles, and the main contributors to the mass influx into the Earth’s atmosphere.

The interferometric capabilities of the MU radar, described by Hassenpflug et al. (2008), make it an excellent tool for meteor head echo observations. It is a circular phased array antenna with a diameter of 103 m, consisting of 475 crossed Yagi antennas with one transmitter/receiver module each (Fukao et al. 1985). Previous meteor head echo observations with the MU radar have been reported by Sato, Nakamura & Nishimura (2000) and Nishimura et al. (2001). In our experiment, the output from 25 subgroups of 19 Yagi antennas each was stored as the data of separate digital channels.

The beam width of the MU radar system is wider than for most other HPLA radar systems, with a one-way full width at half-maximum of \(3.6^\circ\). This gives a comparatively large observing volume and, thus, longer event durations. During the experiments described in this paper, the radar beam was pointed towards zenith.

Head echoes are detected over the entire experiment height range 73–127 km, limited by the experiment settings adapted to the maximum data rate of 20GB h\(^{-1}\) (Kero et al. 2012). We transmitted 13-bit Barker-coded pulses with a total pulse length of 156 \(\mu\)s and interpulse period of 3.12 ms to use the 5 per cent duty cycle. The received data were stored as 85 range values from each transmitted pulse, sampled at 6 \(\mu\)s intervals. The sampling corresponded to a range resolution of \(6 \times 10^{-6} c_0/2 \approx 900\) m, where \(c_0\) is the speed of light. The range of meteor targets was determined with a precision of the order of 10 m, or to within about one-hundredth of a range gate, using a range interpolation technique described in detail by Kero et al. (2012).

Indeed, our analysis procedure computes the meteoroid range, velocity and deceleration as functions of time with unprecedented accuracy and precision. This is crucial for estimations of orbital parameters and meteoroid mass using dynamical modelling (Kero et al. 2008b), as well as investigations into meteoroid–atmosphere interaction processes (e.g. Kero et al. 2008a).

### 3 DIURNAL DETECTION RATES

Figs 3 and 4 report histograms of the diurnal detection rates of meteor head echoes observed using the MU radar. Fig 3 displays the total number of meteors recorded during one diurnal cycle (24 h) for each experiment, while Fig. 4 shows the hourly rates.

As evident from Fig. 1, most measurements cover one diurnal cycle only, but some are longer. There is only one experiment significantly shorter than 24 h. For presentation purposes and to facilitate comparison, the diurnal detection rates were calculated from dividing the total number of meteors during each 1 h bin of local time by the total observation time during that particular 1 h bin of the day. The 2010 October experiment has a 69.1 h time span, but contains no data from 12 to 20 Japan Standard Time (JST). It was scheduled to cover five Orionid shower radiant culminations and the radar was switched off from 12 to 20 JST. The 2009 December observation...
The diurnal detection rates are clearly dominated by a peak at the culmination of the apex, which occurs at ~06 JST. The MU radar is located at longitude 136.1° E, corresponding to 9144°25′ east of Greenwich. JST is always UT+9 h, and daylight saving time is not used.

The seasonal variation of the diurnal detection rate is asymmetric with respect to the equinoxes. The total diurnal number (Fig. 3) and the daily maxima (Fig. 4) are higher in the months preceding vernal equinox than in the succeeding months.

In Kero et al. (2011), section 5, we reviewed how the radar cross-section (RCS) of MU radar meteors was estimated and defined the noise temperature, $T_{\text{noise}}$, as the sum of the noise of the radar hardware and the cosmic radio background. The diurnal variation of $T_{\text{noise}}$ is provided in Fig. 4 in this paper. We found that $T_{\text{noise}}$ is dominated by the passage of two strong radio sources close to zenith, Taurus-A and Cygnus-A. The peak-to-bottom variation of $T_{\text{noise}}$ is $\simeq 3$ dB and could in principle modulate the low-RCS event rate. The culmination of the radio sources, and thus the modulation of $T_{\text{noise}}$, is shifted by about 2 h in a month.

An inspection of the diurnal event rates and the timing of the noise temperature variation in Fig. 4 reveals no significant detection rate modulation caused by the variation of $T_{\text{noise}}$. However, some hints of small dips in the detection rates at the culmination of Cygnus-A exist, e.g. in the 2010 March to May data. We will make a full investigation of the RCS distribution dependence on $T_{\text{noise}}$ in a future publication.

### 4 RADIANT DISTRIBUTION

Fig. 5 shows the individual radiants of all $>106,000$ meteors detected during the 2009–2010 MU radar head echo observation programme. The meteor radiants are expressed in terms of the Sun-centred ecliptic longitude and ecliptic latitude, and colour-coded geocentric velocity (the Earth’s velocity not subtracted). The position of the ecliptic longitude of the Sun at the moment of detection has thus been subtracted from each meteor radiant, positioning the Sun at 0° ecliptic longitude regardless of the time of year. The direction of the apex is 270° Sun-centred ecliptic longitude. The geocentric velocity and radiants in the figure were calculated using the routines described in Szasz et al. (2008) and Szasz (2008). Several compact radiant concentrations due to meteor showers are clearly discernable in Fig. 5 and will be treated in future publications. A review of the 2009 Orionid shower has already been reported (Kero et al. 2011).

The solid lines in Fig. 5 show the total observation time in hours for different regions of the celestial sphere, taking the elevation ($e_l$) above the local horizon into account. 1 h in the plot corresponds to 1 h in zenith for that particular region of the celestial sphere.

If a region spends 1 h at an elevation of, e.g., $e_l = 45°$, the time in the plot would be $1 \times \sin^{1.5} 45° = 0.6$ h. We have used here the radiant altitude dependence $\gamma \sim 1.5$ that we found for the 2009 Orionids (Kero et al. 2011), which happens to be equal to that of visual meteors found by Zvolankova (1983). To calculate the equivalent time in zenith, we divided the celestial sphere into a grid...
of \(1 \times 1\) cells, and integrated \(\sin^{1.47}\) of each cell for the total duration of the observation programme.

The meaning of different values of \(\gamma\) is worth some digression. If \(\gamma = 1\), the rate of detected meteors is equal to the number of meteoroids that passes through a horizontal area in the atmosphere above the observer.

A value of \(\gamma > 1\) therefore effectively means that the detection probability increases with increasing meteor radiant elevation. This is the case for visual meteors (e.g. Jenniskens 1994), most likely because identical meteoroids give rise to brighter meteors with increasing radiant elevation.

In the case of radar observations with a narrow beam system like the MU radar, the beam geometry may give rise to an effect that introduces a similar bias; a meteor trajectory originating from a low-elevation radiant crosses the beam on a large angle. Thus, the probability of successfully determining the trajectory decreases as the beam has a large vertical extension but is limited in the horizontal direction. This would explain why we found \(\gamma > 1\) for the MU radar (Kero et al. 2011), even though meteor head echo targets are virtually independent of aspect angle (Kero et al. 2008c and references therein).

5 RADIANT DENSITY

The radiant density presented in Fig. 6 was calculated by counting the number of meteors in Fig. 5 within cells of equal area, corresponding to \(3.5^\circ \times 3.5^\circ\) at the ecliptic plane, and dividing by the equivalent time in zenith. To achieve equal area of the cells, their outer limits were defined in Hammer–Aitoff coordinates,

\[
x = \frac{2\sqrt{2} \cos(\beta) \sin\left(\frac{\lambda_\odot}{2}\right)}{\sqrt{1 + \cos(\beta) \cos\left(\frac{\lambda_\odot}{2}\right)}},
\]

\[
y = \frac{\sqrt{2} \sin(\beta)}{\sqrt{1 + \cos(\beta) \cos\left(\frac{\lambda_\odot}{2}\right)}},
\]

where \(\beta\) is the ecliptic latitude and \(\lambda_\odot\) is the Sun-centred ecliptic longitude. The cells were quadratic in the Hammer–Aitoff projection and had a width of \(\approx 0.061\) in both the \(x\) and \(y\) directions. Their area corresponds to a solid angle of \(12.25\) degree\(^2\).

Since the radiant density is far higher in the north and south apex regions than elsewhere (except for the compact Perseid, Orionid and Geminid meteor shower radiants), it is displayed in the logarithmic scale. It is evident from Fig. 6 that the north and south apex regions have a radiant density about an order of magnitude higher than the other apparent sources.

A ring depleted of meteor radiants at a radius of about 55\(^\circ\) from the apex was first reported by Campbell-Brown (2008). The same kind of structure is visible in the MU radiant data in Figs 5 and 6. Wiegert et al. (2009) show that the ring may be a dynamical phenomenon resulting from the Kozai effect.

Janches et al. (2006) presented a model of the global micrometeoroid input function in the upper atmosphere. The model is based on diurnal curves obtained at different seasons and locations using the

**Figure 6.** Logarithm of the radiant density of the (>106 000) meteors detected during the 2009–2010 MU radar head echo observation programme plotted in Sun-centred ecliptic coordinates. The radiant density is expressed in no/h/cell of equal area, where a cell of equal area corresponds to a solid angle of 12.25 degree\(^2\). The radiant densities of the north apex (NA) and the south apex (SA) sources are an order of magnitude higher than in the helion (H), antihelion (AH), north toroidal (NT) and south toroidal (ST) source regions. The Perseid (PER), Orionid (ORI) and Geminid (GEM) meteor showers are visible as compact regions of high radiant density.

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430 MHz Arecibo radar in Puerto Rico (AO), the 1.29 GHz Sondrestrom radar in Greenland and the JRO. They found that the apparent apex sources account for \( \sim 70 \) per cent of the observed meteors. In a later development of the model, Fentzke & Janes (2008) revised the apex sources’ ratio of the total number of meteors to \( \sim 60 \) per cent.

The radiant density presented in Fig. 6 enables an independent validation of this model. Fentzke & Janes (2008) assumed a Gaussian-shaped apex source width of \( \pm 32^\circ \) and \( \pm 19^\circ \) ecliptic latitude and longitude, respectively. The MU radiant density within this region constitutes \( \sim 60 \) per cent of the total radiant density (with contribution from the Orionids removed). An \( \sim 70 \) per cent ratio is reached if the area around the apex is extended to \( \pm 40^\circ \) in both ecliptic latitude and longitude. This comparison shows that the MU radar observations largely agree with the apex source part of the modelling results by Janes et al. (2006) and Fentzke & Janes (2008). According to both models the remaining 30–40 per cent of the HPLA radar meteors detected as head echoes mainly originate from the helion and antihelion sources, with a small contribution also from the south and north toroidal sources. However, the relative contribution from within these source regions to the MU radar observations are less than \( \sim 2 \) per cent per region. When adding the north and south toroidal, the helion and the antihelion sources to the extended (\( \sim 70 \) per cent) apex region described above and including the total contribution from meteor showers, the sum is still lower than \( \sim 80 \) per cent. The remaining \( \sim 20 \) per cent of the meteors are sporadic detections from outside the defined source regions.

It should be pointed out that the fraction of apex meteors in this context refers to what is observed by the radar systems, not the fraction of meteoroids in the Solar system at 1au. These two differ due to observational biases, the ionization efficiency in collisions between ablated meteoric constituents and the atmosphere being highly velocity dependent (e.g. Jones 1997; Janes, Close & Fentzke 2008). Higher velocity gives rise to more ionization per collision. Apex meteoroids have a velocity distribution that is higher than the velocity distributions of all other apparent sporadic sources, and therefore lower mass apex meteoroids give rise to detectable head echo target plasmas. Fentzke & Janes (2008) estimated the ratio of apex meteoroids in the Solar system at 1au to \( \sim 33 \) per cent.

However, an assumption they make is an empirical atmospheric filtering effect, introduced to take into account how the meteor detection rate from a source region varies with elevation \((el)\) above the radar site local horizon. Janes et al. and Fentzke & Janes assume that meteors with radiant elevations below \( el < 20^\circ \) should be completely neglected due to the electron production mechanism of such meteors and/or their ablation taking place at higher altitude than the ablation of meteoroids on trajectories with \( el > 20^\circ \).

We have not found any such filtering effect of meteor radiants with \( el < 20^\circ \) in the MU radar data. Kero et al. (2011) showed that for detections of Orionid meteors, the detection rate varied approximately as \( \sin 1.5 el \), virtually all the way down to zero elevation of the radiant. There is no cutoff at or near \( 20^\circ \). The following two examples provide further verification, not only that meteors from low elevation can be detected with the MU radar, but also the quality of the low-elevation radiant data.

(1) The south toroidal meteor source as seen from Shigaraki is always below \( el < 10^\circ \) and is only visible above the local horizon around autumnal equinox for a short period of each diurnal cycle. Fig. 5 displays the equivalent time in the zenith of different regions of the celestial sphere. It shows that the south toroidal region equivalent observation time is less than \( \sim 30 \) h, estimated using the relation \( \sin 1.5 el \). From Fig. 9, further described in Section 6, it is clear that the south toroidal source is well discernible in the MU radar data despite its low radiant elevation. Its orbital properties agree with the orbital properties of the north toroidal source. Even their relative strengths are equal when the very disparate equivalent observation times of their respective location on the celestial sphere is taken into account.

(2) Kero et al. (2012) report observations of the 2011 October Draconid meteor outburst, which occurred at a time when the Draconid radiant was descending below and 2 h later rising up above the local horizon in Japan. 11 of the 13 Draconids detected with MU were therefore from very low radiant elevations \((el < 15^\circ)\). Yet, their geocentric velocity and radiant could be accurately determined. The Draconid weighted mean geocentric velocity was 20.6 \( \pm 0.4 \) km s\(^{-1}\) and the weighted mean radiant was located at right ascension \( \alpha = 263:3 \pm 0.6 \) and declination \( \delta = 55:8 \pm 0.2 \), in excellent agreement with simulations of dust released by comet 21P/Giacobini–Zinner during its perihelion passage in the year of 1900 (Vaubaillon, Watanabe & Sato 2010; Maslov 2011; Vaubaillon et al. 2011).

The filtering effect suggested by Janes et al. (2006) is therefore not a physical property of meteoroids from low-elevation radiants, but perhaps a system-dependent detection criteria or a modelling presumption. The reason for differences in detection capabilities between the radar systems used by Janes et al. and Fentzke & Janes, and the MU radar may lay in the comparatively wide MU radar beam width. A meteoroid from a low-elevation \((el \lesssim 20^\circ)\) radiant passes very quickly through a narrow and vertically pointed radar beam, as that of AO where less than 1 km of trajectory generally is detectable. The narrower the radar beam width, the more severe will be the suppression of the low-elevation meteor head echo detection probability.

Another feature well worth further investigation is the contribution of meteors from outside the defined source regions present in the MU data but not included in the models.

### 6 ORBITAL ELEMENTS

Table 1 presents a summary of the number of meteors, the equivalent time in zenith and the estimated relative strengths of the MU apparent sporadic source regions. The positions and widths are adapted to enable comparisons with table 1 by Campbell-Brown (2008), summarizing relative strengths in CMOR, AMOR (Galligan & Baggaley 2004, 2005) and JRO (Chau et al. 2007) data, as well as orbital properties calculated from CMOR, AMOR and HRMP (Taylor & Elford 1998) observations.

The apex regions are divided into two parts: the narrow central features first described by Chau et al. (2007) is here termed north/south apex narrow, and the broader apex regions found in specular meteor data are called north/south apex broad. We derived the north/south apex broad distributions by subtracting the meteors within the narrow regions from the full apex regions. The relative strengths of the narrow regions are 6 per cent each, compared to the broad regions with 23 per cent. All north/south apex source pairs are symmetric in terms of relative strength, as are the north and south toroidal sources (see Table 1). The helion to antihelion relative strength ratio of 0.91 differs the most. In CMOR data, the helion to antihelion relative strength ratio is 0.84, while in AMOR data it is only 0.77.

Figs 7, 8 and 9 display the orbital parameter distributions within all source regions defined in Table 1. Fig. 7 contains the apex...
Table 1. Number of meteors, equivalent time in zenith and relative strengths (in per cent of total) for the apparent sporadic sources, with positions and widths adopted from Campbell-Brown (2008). The NA/SA broad components are defined as all meteors within the north and south apex regions outside the NA/SA narrow central regions.

| Source            | \(\lambda_\odot\) position (°) | \(\beta\) position (°) | \(\lambda_\odot\) width (°) | \(\beta\) width (°) | No. of meteors | Equivalent time (h) | Relative strength [per cent] |
|-------------------|---------------------------------|-------------------------|-----------------------------|---------------------|-----------------|---------------------|---------------------------|
| North apex (NA)   | 270                             | 18                      | 20                          | 18                  | 41 000          | 170                 | 170                       | 29                        |
| (NA narrow)       | 270                             | 13                      | 3                           | 9                   | 8400            | 170                 | 170                       | 6                         |
| (NA broad)        | 270                             | 18                      | –                           | –                   | 32 000          | 170                 | 170                       | 23                        |
| South apex (SA)   | 270                             | –18                     | 20                          | 18                  | 26 000          | 110                 | 110                       | 29                        |
| (SA narrow)       | 270                             | –13                     | 3                           | 9                   | 5600            | 110                 | 110                       | 6                         |
| (SA broad)        | 270                             | –18                     | –                           | –                   | 21 000          | 110                 | 110                       | 23                        |
| Helion            | 340                             | 0                       | 15                          | 10                  | 1900            | 110                 | 110                       | 2                         |
| Antihelion        | 200                             | 0                       | 15                          | 10                  | 2600            | 140                 | 140                       | 2                         |
| North toroidal    | 270                             | 55                      | 15                          | 10                  | 1900            | 210                 | 210                       | 1                         |
| South toroidal    | 270                             | –55                     | 15                          | 10                  | 280             | 30                   | 30                        | 1                         |

Figure 7. Raw orbital parameter distributions for the north and south apex sporadic meteor sources, divided into narrow and broad parts.

Figure 8 contains the helion/antihelion sources and Fig. 9 the toroidal sources. The figure panels show geocentric velocity, semimajor axis, inclination and eccentricity with the same parameter range and distribution as the equivalent figs 11, 13 and 15 by Campbell-Brown (2008) to facilitate comparison. The error bars represent Poisson errors (\(\sqrt{n}\), where \(n\) is the number of meteors in each bin) normalized to number fraction.

Campbell-Brown (2008) found virtually no prograde apex meteors in the CMOR data while significant numbers of prograde apex meteors appear in AMOR and HRMP data.
The MU apex data (Fig. 7) contain very few (0.3 per cent) pro-grade orbits.

The AMOR inclination distribution of the helion source showed an excess of higher inclination orbits when compared to the CMOR distribution. Also in this respect, the MU distribution (Fig. 8) agrees with the CMOR rather than the AMOR results in there being no excess of high inclination helion orbits.

Campbell-Brown (2008) also found that the south toroidal source orbital parameters are identical to those of the north toroidal source, though noisy due to small collection area in the southern part of the celestial sphere and a consequently small number of such meteors. The MU data displayed in Fig. 9 also agrees with this finding.

As a matter of fact, each MU north/south source pair, as well as the helion/antihelion source pair, has pairwise nearly identical orbital properties when Poisson errors are taken into account. The only exception is the inclination distribution of the broad north/south apex source pair displayed in Fig. 7c. The broad south apex distribution has clearly higher inclination than the broad north apex. The reason for this is likely the same as stated by Campbell-Brown (2008) regarding the similar north/south apex disparity found in CMOR data, namely that the portion of the south apex source closer to the ecliptic (where the inclination is closest to 180°) is better sampled with a radar located on the Northern hemisphere, such as CMOR and MU, than the more southern part is. As can be seen in Fig. 5, the equivalent observation time quickly drops with decreasing ecliptic latitude below +30°.

7 NORTH AND SOUTH APEX SEASONAL VARIATION

Figs 10 and 11 show the meteor radiant density around the apex from 2009 June to 2010 March (except 2009 August), and from 2010 April to December, respectively, in Sun-centred ecliptic coordinates. The solid lines display the equivalent time in zenith explained in Section 5. The total number of meteors that was observed within each cell can be deduced from Figs 10 and 11 by multiplying the visualized radiant density with the equivalent time in zenith. For example, the number (N) of observed meteors within the cell in the north apex region with maximum radiant density was N = 75 in 2009 November and N = 65 in 2009 December.

One can easily see that the north and south apex regions contain very narrow structures. Such kinds of features were first reported by Chau et al. (2007), who suggested that each of the apex sources in JRO meteor head echo data could be divided into a wide circular...
and a narrow elliptical shaped component. Figs 10 and 11 of this paper show that the narrow components change in strength and shape throughout the year.

Brown & Jones (1995) reported a strong and consistent asymmetry in strength between the north and south apex sources detected with radars at Springhill, Canada (45° N, 76° W), and Christchurch, New Zealand (44° S, 173° E). It should in this context be pointed out that in contrast to the Brown & Jones (1995) result, the overall strengths of the MU north and south apex sources are equal, as reported in Section 5. It is mainly the narrow components that change in strength and which of the south and north narrow component that dominates varies with solar longitude. On average, also the narrow features are of virtually equal strength throughout the year.

To see if the radiant density variations in Figs 10 and 11 depend on the assumed radiant altitude exponent $\gamma = 1.47$, we have produced similar sets of plots with different values of $\gamma$ in the interval $1–2$. We found that a value of $\gamma = 1$ gives an overall $\sim 20$ per cent decrease, while $\gamma = 2$ gives a $\sim 20$ per cent increase, of the radiant density within the region of the celestial sphere displayed in Figs 10 and 11. However, the seasonal variation of the strengths and shapes of different features are well preserved. An incorrectly estimated exponent does therefore not have a significant impact on the result. Figs 10 and 11 are quite well representative of $\gamma = 1$ if the colour-coded radiant density is scaled down to a maximum value of 8, and representative of $\gamma = 2$ if it is scaled up to a maximum value of 12. Naturally, the number of observed meteors $N$ within each cell does not depend on $\gamma$, but the equivalent time in zenith does.

Wiegert et al. (2009) suggest that narrow features of the north and south apex sources can be explained as small ($\leq 100\mu$m), old ($\geq 10^5$ yr) and dynamically evolved meteoroids originating from 55P/Tempel–Tuttle or an orbitally similar object.

### 8 CONCLUSIONS

This paper extends an overview of the 2009–2010 MU radar head echo observation programme for sporadic and shower meteors. Data were collected using the same experiment setup at 18 separate observational campaigns, each campaign aimed to cover at least one diurnal cycle, and comprises a total number of more than 106 000 meteors.

All six previously recognized apparent sporadic meteor source regions are discernable, as well as a ring depleted of meteor...
Radiants at a radius of about 55° from the apex first reported by Campbell-Brown (2008). The north and south apex regions have radiant densities an order of magnitude higher than other apparent source regions have, and contain narrow structures that vary in strength with solar longitude.

The detection rates show clear diurnal and seasonal dependences. These dependences are dominated by the visibility of the north and south apex regions above the local horizon, but are also affected by the radiant density variations of their narrow structures.

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Figure 11. Meteor radiant density around the apex for the campaigns 2010 April to 2010 December plotted in ecliptic coordinates. A cell of equal area corresponds to a solid angle of 12.25 degree$^2$. The solid lines indicate the equivalent time in zenith (explained in Section 5).

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REFERENCES
Brown P., Jones J., 1995, Earth Moon Planet, 68, 223
Campbell-Brown M. D., 2008, Icarus, 196, 144
Campbell-Brown M. D., Jones J., 2006, MNRAS, 367, 709
Campbell-Brown M., Wiepert P., 2009, Meteorit. Planet. Sci., 44, 1837
Chau J. L., Woodman R. F., Galindo F., 2007, Icarus, 188, 162
Fentzke J. T., Janches D., 2008, J Geological Res., 113, A03304
Fentzke J. T., Janches D., Sparks J. J., 2009, J. Atmos. Solar-Terr. Phys., 71, 653
Fukao S., Sato T., Kato S., Wakasugi K., Makihiira T., 1985, Radio Sci., 20, 1155
Galligan D. P., Baggaley W. J., 2004, MNRAS, 353, 422
Galligan D. P., Baggaley W. J., 2005, MNRAS, 359, 551
Hassenplug G., Yamamoto M., Luce H., Fukao S., 2008, Radio Sci., 43, 24
Hawkins G. S., 1956, MNRAS, 116, 92
Janches D., Heinselmann C. J., Chau J. L., Chandran A., Woodman R., 2006, J. Geological Res., 111, A07317
Janches D., Close S., Fentzke J. T., 2008, Icarus, 193, 105
Jenniskens P., 1994, A&A, 287, 990
Jones W., 1997, MNRAS, 288, 995
Jones J., Brown P., 1993, MNRAS, 265, 524
Kero J., Szasz C., Pellinen-Wannberg A., Wannberg G., Westman A., Meisel D. D., 2008a, Geophys. Res. Lett., 35, L04101
Kero J., Szasz C., Pellinen-Wannberg A., Wannberg G., Westman A., Meisel D. D., 2008b, Ann. Geophys., 26, 2217
Kero J., Szasz C., Wannberg G., Pellinen-Wannberg A., Westman A., 2008c, GRL, 35, L07101
Kero J. et al., 2011, MNRAS, 416, 2550
Kero J., Szasz C., Nakamura T., Terasawa T., Miyamoto H., Nishimura K., 2012, Ann. Geophys., 30, 639
Kero J., Fujiwara Y., Abo M., Szasz C., Nakamura T., 2012, MNRAS, in press (doi:10.1111/j.1365-2966.2012.21255.x
Lindblad B. A., 1987, Publ. Astron. Inst. Czech. Acad. Sci., 67, 201
Maslov M., 2011, WGN, J. Int. Meteor Org., 39, 64
Nishimura K., Sato T., Nakamura T., Ueda M., 2001, IEICE Trans. Communications, E84-C, 1877
Sato T., Nakamura T., Nishimura K., 2000, IEICE Trans. Communications, E83-B, 1990
Szasz C., 2008, PhD thesis, Swedish Institute of Space Physics
Szasz C., Kero J., Meisel D. D., Pellinen-Wannberg A., Wannberg G., Westman A., 2008, MNRAS, 388, 15
Taylor A. D., Elford W. G., 1998, Earth, Planets, Space, 50, 569
Vaubaillon J., Watanabe J., Sato M., 2010, BAAS, 42, 950
Vaubaillon J., Watanabe J., Sato M., Horii S., Koton P., 2011, WGN, J. Int. Meteor Org., 39, 59
Wiegert P., Vaubaillon J., Campbell-Brown M., 2009, Icarus, 201, 295
Zvolankova J., 1983, Bull. Astron. Inst. Czech., 34, 122

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