Earth, Moon, and Planets (2005)
DOI 10.1007/s11038-005-5041-1

THE VELOCITY DISTRIBUTION OF METEOROIDS AT THE EARTH AS MEASURED BY THE CANADIAN METEOR ORBIT RADAR (CMOR)

P. BROWN, J. JONES, R. J. WERYK AND M. D. CAMPBELL-BROWN
Department of Physics and Astronomy, University of Western Ontario, London, Ontario, N6A 3K7, Canada

(Received 18 October 2004; Accepted 5 April 2005)

Abstract. The velocity distribution of meteoroids at the Earth is measured using a time-of-flight measurement technique applied to data collected by the CMOR radar (29.85 MHz). Comparison to earlier velocity measurements from the Harvard Radio Meteor Project suggests that HRMP suffered from biases which underestimated the number of fragmenting meteoroids. This bias results in a systematic underestimation of the numbers of higher velocity meteoroids. Other works (cf. Taylor and Elford, 1998) have also found additional biases in the HRMP which suggest the original HRMP meteoroid velocity analysis may have underestimated the fraction of high velocity meteors by factors up to 10^4.

Keywords: meteoroid, radar, velocity distribution

1. Introduction

An accurate measure of the velocity distribution of meteoroids at the Earth is important for addressing a number of critical questions in meteor astronomy. The origin of various meteoroid populations is related intrinsically to their observed velocity at the Earth. All retrograde particles, for example, must have observed velocities in excess of approximately 32 km s^{-1} (with a variation of $\sim$0.5 km s^{-1} during the year due to the non-zero eccentricity of the Earth's orbit) and these are all related to comets. The meteoroid velocity distribution is central to interpreting the distribution of micro-craters on the moon, the height deposition of meteoric metal atoms in the upper atmosphere, the total meteoroid mass influx to the Earth and crucial to engineering estimates of the meteoroid impact hazard to satellites orbiting the Earth.

The meteoroid velocity distribution at the Earth has been previously measured using photographic and radar techniques. Erickson (1968) used a random sample of Super-Schmidt data to estimate the true velocity distribution of sporadic meteoroids to a constant limiting mass at the top of Earth's atmosphere. The primary limitation of his work was the small number statistics involved (286 sporadic meteors) and the lack of daytime coverage. The Harvard Radio Meteor Project (HRMP) has become the other source of meteoroid velocity information at the Earth (cf. Sekanina and Southworth, 1975). Recently, Taylor (1995) re-examined the HRMP velocities and found several errors in the original analysis. One result of these recent corrections was to increase the number of higher velocity meteoroids ($v > 60$ km s^{-1}) by as much as two orders of magnitude. However, the HRMP data suffer from additional biases not accounted for in the Taylor (1995) re-analysis including the effects of fragmentation, Faraday rotation attenuation (cf. Ceplecha et al., 1998) and unequal diurnal coverage, though some of these and other effects were taken into account by the analysis of Taylor and Elford (1998). In particular, the use of the Fresnel oscillations in signal amplitude to measure the velocities for HRMP and the requirement that at least three complete Fresnel oscillation cycles from three stations be visible before a velocity measure is made (Hawkins et al., 1964) produce a severe bias. Since fragmentation causes much smearing of the individual Fresnel cycles, such a restriction will almost completely eliminate meteoroids which fragment.

Here we have attempted to measure the true out-of-atmosphere velocity distribution of meteoroids encountering the Earth using the Canadian Meteor Orbit Radar (CMOR). Details of the radar system hardware, analysis software and system operation are given in Jones et al. (2004) and Hocking et al. (2001). This analysis represents our preliminary estimate of the velocity distribution using all calibrations and bias corrections presently available. We expect to make another revision to this work once additional calibration data (particularly simultaneous optical – radar observations and a revision of the initial trail radius correction) are gathered. Another recent velocity analysis based on extensive radar data gathered by the Advanced Meteor Orbit Radar (AMOR) presented by Galligan and Baggaley (2004) has found similar general conclusions to the present work.

2. Data Selection, Corrections and Analysis

Velocity data from CMOR using time-of-flight (tof) measurements from three stations collected from May, 2002 to September, 2004 were used in the present study. A total of 1.5 million echoes with tof velocities were selected initially for this survey. From this initial population only echoes with radiants north of the ecliptic plane were retained to avoid large corrections that must be applied when dealing with deep southern radiants which have small integrated daily collecting areas. This restricts our analysis to only meteoroids with descending nodes at the Earth. The assumption is made that the velocity distribution is symmetric with respect to ecliptic plane.

Computing the true out-of-atmosphere velocity for each echo requires an estimate of the deceleration which has occurred in the atmosphere. To perform this correction, we examined 13 showers visible with CMOR having previously well-measured geocentric velocities from photographic or video techniques since early portions of the shower meteor trail (where deceleration is least) can be used and/or decelerations directly measured. Examining those meteors associated with each shower, a generally linear trend in apparent velocity vs. height was noted. That is, shower members observed at lower heights had (on average) lower velocities than those at higher heights, as would be expected. Using data for each of the 13 showers, combined from all years in which each shower was observed by CMOR, a linear fit of the observed geocentric velocity vs. height per shower was constructed. Comparing this fit to the accepted geocentric velocity of the shower, an estimate of the height at which no measurable deceleration occurs per shower (i.e. where the observed geocentric velocity equals the literature value) and the loss of speed at that height is made. Figures 1 and 2 show the resulting fits. By combining data from all 13 showers used in this way, a single velocity correction factor was found of the form:

$$\Delta V_{obs} = -((-0.0050098 V_{obs} + 0.5142)(h - (0.3362 V_{obs} + 86.6039))) \quad (1)$$

where ΔV_{obs} is the expected change in the apparent velocity (in km s^{-1}) for an echo observed at a height h (in km). Note that this deceleration applies specifically to the CMOR system (29.85 MHz) and its range of observed

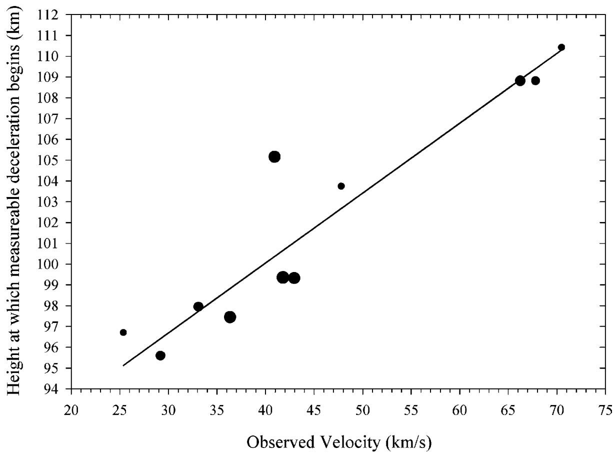

Figure 1. The apparent height at which noticeable deceleration begins for 13 different showers measured by CMOR. Apparent height is defined as the height at which the best fit line of measured velocity vs. height intersects the accepted out-of-atmosphere velocity for the shower. The size of each point is proportional to the log of the number of echoes used in the distribution to determine the intersection height. The solid line is the number weighted least-squares best fit.

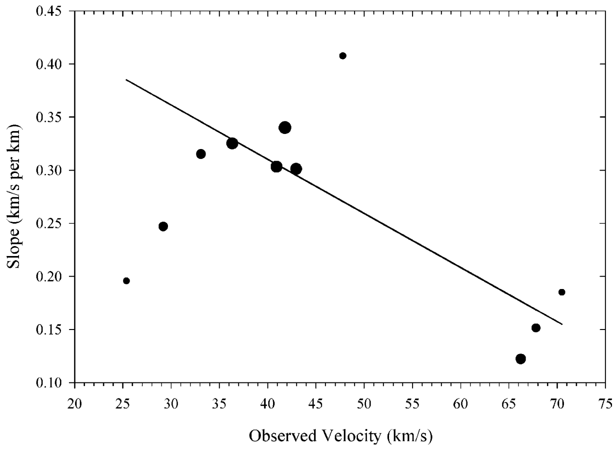

Figure 2. The slope of the change in deceleration as a function of measured velocity for 13 major showers observed by CMOR. The symbol sizes and line have the same meaning as in figure 1.

masses with height. Other systems with different sensitivity limits and different wavelengths would not necessarily see the same behaviour. We have also examined the dependence of entry angle on velocity – this shows a much smaller correlation with decelerations in the population as a whole noticeable only at low ($< 20^\circ$) radiant elevations. We have thus ignored this correction. Note that when Equation (1) becomes positive (which would signify an increase in speed), we set ΔV_{obs} to zero, following figure 1. The average correction varies from about 1 km s^{-1} at the lowest observed velocities to nearly 2.5 kms^{-1} at a velocity of 50 km s^{-1}. Thus this correction is comparable to or smaller than the mean error in speeds (~ 5%) at lower velocities, but nearly negligible relative to the error spread in speeds at higher velocities.

In addition to correcting for deceleration, each observed echo is inversely weighted according to the daily integrated collecting area appropriate to its apparent radiant. Details of the procedure for computing collecting area can be found in Brown and Jones (1995). For northern ecliptic radiants, the integrated daily collecting area varies between the limits 1500 km^2 to 5500 km^2.

Finally, each echo is inversely weighted according to the attenuation in signal amplitude produced by four different effects: initial trail radius, interpulse period detectability, diffusion due to finite velocity and Faraday rotation of the radio wave. Details of these effects and the numerical expressions used to quantify the degree of attenuation can be found in Ceplecha et al. (1998) and Cervera et al. (2004). For readers not familiar with these effects we will briefly and qualitatively describe each.

The initial trail radius effect is arguably the most important effect and also the most difficult to quantify (cf. Ceplecha et al., 1998). This effect results in an attenuated signal amplitude when the physical radius of the meteor trail exceeds $\lambda/2\pi$, where λ is the radar wavelength. Classically, this radius has been assumed to be limited by the thermalization scale of ablated atoms, however more recently it has become clear that the effect is probably dominated by fragmentation effects (Campbell-Brown and Jones, 2003; Cervera and Elford, 2004). Still a poorly constrained effect, we adopt the radius dependence of Cervera and Elford, (2004) and compute the attenuation assuming a Gaussian distribution of electrons across the trail (cf. Cervera and Elford, 2004 for more details). The initial trail radius effect remains the most serious shortcoming of the present analysis; once a more complete description of the effects of initial fragmentation radius is known, this analysis should be redone.

The inter-pulse period attenuation reflects the fact that a trail which diffuses to $\lambda/2\pi$ in a time which is short compared to the time between radar samples will be strongly biased against detection. For CMOR, detection occurs if a potential echo remains above the background for more than four consecutive samples. Echoes with decay times less than ~0.01 sec will not be readily detected.

For meteoroids moving at slower velocities, the time to cross the central Fresnel zone (where almost all of the backscatter signal arises) may be longer than the diffusion timescale at that height. In such cases, the fact that the meteor has a finite velocity in crossing the central Fresnel zone will lead to decreasing contributions to the scattered signal from those portions of the trajectory earlier in flight. This results in a reduced signal amplitude at the receiver in comparison to the case where the meteor velocity is neglected (i.e. the meteor is treated as though it has an infinite velocity).

Finally, linearly polarized radio waves propagating in a magnetized plasma experience a rotation in their plane of polarization (cf. Ceplecha et al., 1998). As rotation of the radio wave occurs, the returned signal will be attenuated, with essentially no signal detected if rotations of 90° or 270° occur between transmission and reception. As CMOR uses linear dipole type antennae for both receiving and transmitting this is a potential source of echo attenuation. The magnitude of the rotation depends (among other things) on the electron content of the ionosphere. At CMOR's frequency there is almost no Faraday rotation during nighttime hours. However, the effect of Faraday rotation can be important for CMOR echoes over an altitude of ~95 km during daytime ionospheric conditions. Here we adopt the International Reference Ionosphere – 2000 (IRI) model (Bilitza, 2000) and use it to provide the electron content along each transmit – receive echo path and measure the expected attenuation for each observed echo.

All four of these attenuations are multiplied together and each velocity measure is then weighted by the inverse of the product. Echoes which have total attenuations of more than 100 are removed from the analysis.

Finally, to produce a velocity distribution for a single mass limit, we follow the procedure outlined in Taylor (1995) which was used to correct the HRMP data. In this approach, all echo masses are referenced to the equivalent limiting threshold mass at 30 kms^{-1}, which for CMOR is approximately 4×10^{-7} kg. We have also adopted the same constants used in Taylor's re-analysis of HRMP for the cumulative mass distribution index ($\alpha = 1.36$) and for the ionization production exponent of $\gamma = 4.25$ (i.e. ionization $\propto m^{0.92} v^{3.91}$ with $\gamma = 3.91/0.92 = 4.25$)). Thus the cumulative number of meteoroids with mass greater than the threshold mass of 4×10^{-7} kg at 30 km s^{-1} (m_{30}) as a function of velocity is given by:

$$N(m > m_{30}) = \left(\frac{v}{30}\right)^{-\alpha\gamma} \quad N(m > m_v) \tag{2}$$

relative to the number measured in velocity bin v (see Taylor (1995) equation 6). Physically, this weighting accounts for the fact that faster meteoroids produce more ionization per unit mass, the radar being more sensitive to smaller, fast meteoroids and seeing "deeper" into the distribution of small particles at higher velocities.

3. Results and Discussion

To understand the connection between the original HRMP results and our data, we first attempt to reproduce the results from HRMP. One advantage of this comparison is that both stations are at nearly the same latitude (HRMP 40N, CMOR 43N) and both have similar limiting mass thresholds (10^{-4} g for data used in the HRMP velocity survey and 10^{-5} g for CMOR). As stated earlier, we suspect that the technique used to measure velocities by HRMP (Fresnel oscillations) suffers from a hidden bias in that heavily fragmenting meteoroids will not be selected for measurement due to the strict selection criteria applied to the original HRMP data. Such echoes will be detected by the system, but the Fresnel oscillations will be "smeared" out by the presence of multiple, overlapping Fresnel patterns from different fragments in the vicinity of the main trail. From general physical considerations, we may expect that cometary meteoroids would be more prone to such fragmentation, so we would expect the greatest underestimatation to occur at the highest velocities where high inclination/cometary meteoroids predominate.

To test this notion, we make use of a hybrid-Fresnel velocity measurement technique introduced by Hocking (2000). This velocity technique uses Fresnel oscillations in both amplitude and phase and determines the speed using a Fourier transform approach. The selection criteria applied by this technique is such that only 5% of all detected CMOR echoes have sufficiently "clean" Fresnel oscillations to permit measurement. For comparison, ~1% of all echoes detected by HRMP met all selection criteria and were used in their final velocity analysis (Lacy, 1966; Cook et al., 1972). While it is not possible to know the exact correspondence between the different selection procedures applied by each algorithm, the fact that only a small fraction of all echoes are accepted for reduction in both cases and that both rely on the presence of Fresnel oscillations for measurements should render the two at least qualitatively similar. Figure 3 shows the velocity distribution for HRMP as given by Taylor (1995) and the velocity distribution produced from 7.5×10^4 echoes analysed from CMOR using the hybrid-Fresnel technique. Both distributions have been normalized to the number of echoes in the 20 km s^{-1} bin. The general shape and relative proportion of echoes is very similar for both distributions across the velocity range shown. The only major deviations are at the lowest velocities (<18 km s^{-1}), where the number of echoes detected by the CMOR hybrid-Fresnel is ~2 times less than the HRMP numbers and at the highest velocities where CMOR is almost a factor of five above HRMP values. It is worth noting that the number of echoes in the HRMP survey with velocity above 65 km s^{-1} is less than 100 (Sekanina and Southworth, 1975), so the statistics at the high end of the range are very poor. For comparison, over 3000 echoes with velocities above 65 km s^{-1} had hybrid-Fresnel velocity measurements from CMOR. It is also important to recognize that the Fresnel method begins breaking down at the very highest speeds due to inadequate sampling of the Fresnel cycles between successive pulses. This may be another explanation for the under-representation of higher velocity echoes.

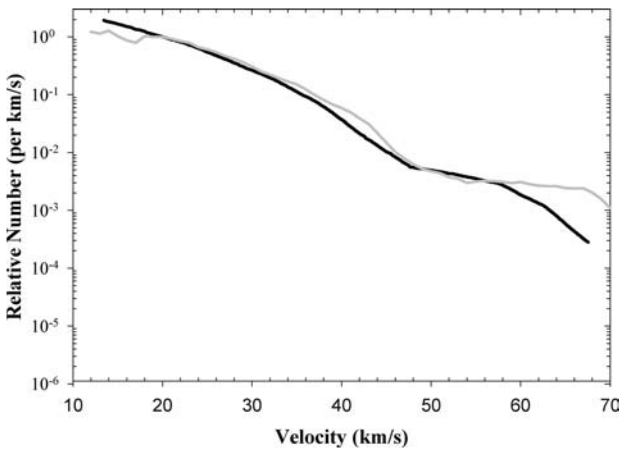

Figure 3. The relative number of meteoroids as a function of velocity for HRMP (solid black line) and CMOR measured using the hybrid Fresnel technique (gray line). Both distributions are normalized to the 20 km s^{-1} velocity bin.

Having established that the Fresnel technique is inherently biased against high velocity meteors and showing that we can reproduce its general shape, we examine the HRMP distribution in comparison to the complete CMOR distribution using the tof velocity measurements in Figure 4. Also shown is the photographically measured velocity distribution for larger (mass ~1g) meteors in the Erickson (1968) sample. The main feature is the systematically higher number of meteors with velocities > 40 km s^{-1} in the CMOR sample compared to HRMP from Taylor (1995). This reaches more than an order of magnitude difference in the 60 to 70 km s^{-1} velocity range. We also note that the more recent HRMP velocity distribution corrected according to the methodology in Taylor and Elford (1998) (their Figure 3) shows a small increase for speeds in excess of 45 km s^{-1}, giving a "knee" at 45–50 km s^{-1} as is also evident in the CMOR and Erickson distributions.

The implication is that the numbers of cometary meteoroids in the original HRMP survey were underestimated, perhaps by as much as an order of magnitude. Interestingly, the Super-Schmidt data, with much poorer statistics agree on the relative numbers of very fast meteors in comparison with CMOR, though the numbers of medium velocity particles are generally lower throughout the entire Erickson (1968) distribution.

4. Conclusions

The velocity distribution of meteoroids at the Earth as given by the HRMP survey underestimates the contribution from high velocity, fragmenting

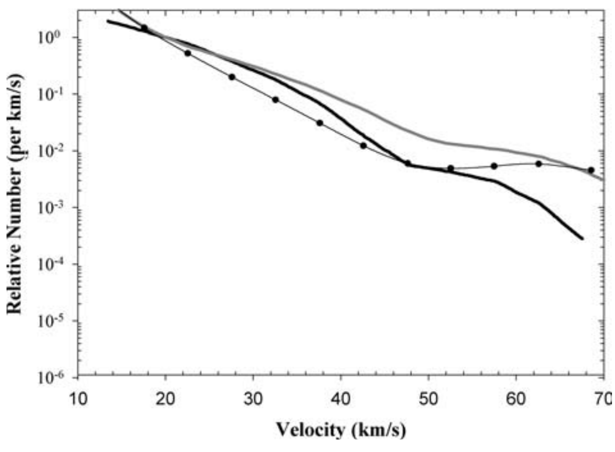

Figure 4. HRMP velocity distribution (black line), the CMOR time-of-flight velocity distribution (gray line) and the photographically determined velocity distribution from Erickson (1968) (solid circles with thin line). All distributions are normalized to the number of meteors in the 20 km s^{-1} bin.

cometary meteoroids as compared to measurements from the CMOR survey which uses a different velocity measurement technique (time-of-flight). More recent measurements (Baggaley, 1998) suggest that the cumulative mass distribution index is closer $\alpha = 1.0$ and hence that the value used in the HRMP analysis may have been too high. A change to smaller mass indices will further increase the true propotion of faster meteoroids.

The change in ionization efficiency with velocity remains poorly constrained at higher velocities as does the true effect of initial fragmentation radius on echo attenutation. As these two effects are better quantified, a re-analysis of the velocity distribution would be warranted.

Acknowledgements

The authors wish to thank the NASA Space Environment and Effects program for substantial funding support to operate and maintain the CMOR radar facility. PGB thanks the Canada Research Chair program and the Natural Sciences and Engineering Research Council for additional funding support. Two anonymous refrees provided extensive constructive comments to an earlier version of this manuscript.

References

Baggaley, W.: 1998 in Baggaley, W., Porubcan V., eds, Meteoroids 1998. Tatranska Lomnica, Slovakia, p. 311.

Bilitza, D.: 2000, *Radio. Sci.* **36**, 261–275.

Brown, P., and Jones, J.: 1995, *EMP* **68**, 223–245.

Campbell-Brown, M., and Jones, J.: 2003, *MNRAS* **343**, 775–780.

Ceplecha, Z., Borovicka, J., Elford, W.G., Revelle, D.O., Hawkes, R.L., Porubcan, V., and Simek, M.: 1998, *Space Sci Rev*. **85**, 327–471.

Cervera, M.A., and Elford, W.G.: 2004, *PSS* **52**, 591–602

Cook, A.E., Flannery, M.R., Levy, H., McCrosky, R.E., Sekanina, Z., Shao, C.-Y., Southworth, R.B.,, and Williams, J.T.: 1972, *Meteor Research Program*. Cambridge, MA: NASA CR-2109, Smithsonian Institution.

Erickson, J.E.: 1968, *JGR* **73**, 3721–3726.

Galligan, D., and Baggaley, W.J.: 2004, *MNRAS* **353**, 422–446.

Hawkins, G.S., Southworth, R.B., and Rosenthal, S.:1964, Preliminary Analysis of Meteor Radiants and Orbits, Harvard Radio Meteor Project Research Report No. 7, Smithsonian Institution, Cambridge, MA.

Hocking, W.K.: 2000, *Radio. Sci.* **35**, 1205–1220.

Hocking, W.K., Fuller, B., and Vandepeer, B.: 2001, *JATP* **63**, 155–169.

Jones, J., Brown, P., Ellis, K.J., Webster, A.R., Campbell-Brown, M.D., Krzemenski, Z., and Weryk, R.J.: 2005, The Canadian Meteor Orbit Radar (CMOR): System Overview and Preliminary Results, Planetary and Space Science, **53**, 413–421.

Lacy, R.G.: 1966, *A tabulation of Meteor-Echo Rates July 1965 – June 1966 Harvard Radio Meteor Project Research Report No. 13.*. Cambridge, MA: Smithsonian Institution.
Sekanina, Z., and Southworth, R.B.: 1975, *Physical and Dynamical Studies of Meteors: Meteor Fragmentation and Stream Distribution Studies, NASA CR 2615*. Cambridge, MA: Smithsonian Institution.
Taylor, A.D.: 1995, *Icarus* **116**, 154–158.
Taylor, A.D., and Elford, W.G.: 1998, *Earth Planets Space* **50**, 569–575.