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Physical Characteristics of Kazan Minor Showers as Determined by Correlations with the Arecibo UHF Radar

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Abstract In the northern hemisphere, the month of February is characterized by a lack of major meteor shower activity yet a number of weak minor showers are present as seen by the Kazan radar. Using the Feller transformation to obtain the distribution of true meteor velocities from the distribution of radial velocities enables the angle of incidence to be obtained for the single beam AO (Arecibo Observatory) data. Thus the loci of AO radiants become beam-centered circles on the sky and one can, with simple search routines, find where these circles intersect on radiants determined by other means. Including geocentric velocity as an additional search criterion, we have examined a set of February radiants obtained at Kazan for coincidence in position and velocity. Although some may be chance associations, only those events with probabilities of association > 0.5 have been kept. Roughly 90 of the Kazan showers have been verified in this way with mass, radius and density histograms derived from the AO results. By comparing these histograms with those of the "background" in which the minor showers are found, a qualitative scale of dynamical minor shower age can be formulated. Most of the showers are found outside the usual "apex" sporadic source areas where it is easiest to detect discrete showers with less confusion from the background.

Keywords Meteor shower · Sporadic source · AO · Kazan · HPLA · Radar

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1 Introduction

In a series of papers Sidorov et al. (see Sidorov et al. 2004a, b for example) and his coworkers at Kazan have resolved structure in the radar meteor sporadic background they called "microshowers" (=very weak minor showers). The configuration of these sources was determined using interferometric observations obtained with a classical trail scattering low-power, wide-beam, VHF radar operated by the Kazan State University. The Arecibo Observatory (AO) UHF radar on the other hand is a High Power Large Aperture (HPLA) facility and does not yet have full interferometric capability. In spite of this, the AO UHF radar has been used to study several important meteor properties using head echo scattering to determine radial velocities and in some cases decelerations (Janches et al. 2001; Mathews et al. 2003; Mathews 2004). These observations established that the majority of AO returns were from very small objects with radii on the order of microns, hence the name micrometeors was applied in publications. It was further determined that approximately 3% of the AO meteors were on hyperbolic heliocentric paths and hence candidates as interstellar particles (Meisel et al. 2002a, b). But because at AO, the angle that the meteor path makes with the beam axis is not directly observed, such observations, while reaching to extremely small masses, are always suspected of harboring unknown biases. In an effort to better understand the AO single beam data, a statistical reevaluation of the observing and data reduction methodologies was begun in 2004. Rather than being a guide to the methodologies themselves, this short paper illustrates one of the immediate consequences of the revised data reduction techniques including the ability to discern a beam inclination and its effects on derived meteoroid physical parameters. More detailed discussions of the methodologies are in preparation.

2 Sketch of the New Methodologies

There were three main breakthroughs in this data reevaluation. First a highly efficient and reliable automated meteor signature search algorithm was devised and perfected (Briczinski et al. 2006, 2007a,b). Next a pronounced correlation among decelerating meteors was discovered (Briczinski et al. 2007b) using the new search algorithm that tied together velocity (V), radius derived from the momentum equation utilizing the measured deceleration (r), and height ($\ln \frac{V^2}{r}$ versus height in the atmosphere). Residuals from this correlation have been used to estimate micrometeor mass densities at the time of radar visibility. The final breakthrough was the use of Feller's random vector theorem (Feller 1966) to transform observed radial velocities (and hence also decelerations) into actual meteor trajectory velocities. It also meant that derived quantities such as particle radius and mass density were estimates of the true quantities, not just upper limits.

Feller was able to reduce 3D random walks to 1D walks using a scheme of multidimensional projection. His random vector theorem uses the same technique to project 3D random vectors onto a fixed 1D axis. Thus if you know the random distribution of vector lengths in 3D you can by projection find the corresponding distribution in 1D, i.e. a radial direction. Feller showed that his transformation is invertible. Given an observed distribution of 1D vector components along a fixed axis, the theorem allows the reconstruction of the distribution of the vector lengths in 3D. Assigning a true length to each component is done through the standard statistical comparison of point position on the corresponding cumulative distributions.

Comparison of these transformed velocities with the original radial velocities gives the angles that the trajectory makes with the radar beam. In practice, subdividing the AO data into 2 h long segments seems to give the best balance between the needed Feller transform histogram resolution and the within-bin number of events for good Poisson statistics as needed for the proper operation of the transform technique. This 2 h partitioning of the data obtained Feb 24–26, 2006 08–15 h UTC was adopted for the results described here. The approximate mean error on each derived inclination angle as determined using the Feller procedure for these dates is $\pm 2.5°$. The range of inclinations in the 2 h intervals are usually 0–40° to 0–60°. With inclinations available, all the derived quantities including mass, density, deceleration (and hence also radius), and velocity are estimates of the true quantities corrected rigorously for angle-to-the-beam effects. This also means that discovery of actual radiant directions is much enhanced compared with the down-the-beam assumptions that at best could tell inclinations in 15–25° wide bins and which had no corrections for angle made in the results as was done for the data used here.

3 Searching for Shower Associations

Without the Feller transformation, the work described here would not have been possible. Of course, the Feller transform applied to single, vertical, fixed beam observations does not result in a full 3D reconstruction, but only a 2D one. Thus while the beam inclination angle and the total meteor velocity can now be determined, the trajectory azimuth around the beam cannot. If the AO radar had a second beam of equal power sensitivity to that of the main beam but offset to it and pointed to a common volume with the main antenna, then a 3D reconstruction would be possible. But under present circumstances, instead of there being a point radiant for each trajectory, there is a circle of equal beam inclination angle (hereinafter called CEBIA for short) or in this case of zenith pointing, equal zenith distances as displayed in Fig. 1. In the absence of further information, we must calculate circle averaged orbital elements of a specified number of sample points whose means correspond to the previously studied cases obtained by assuming purely down-the-beam trajectories. But such a procedure will have large errors. Here we present an alternative that utilizes previously determined radiants as constraints.

If there are known radiants including velocities, as obtained by other independent optical or radar interferometric observations for example, we can straightforwardly determine the probability of source membership for each event. First the spatial intersection point of the observationally determined CEBIA and the great circle joining the antenna beam center and the radiant center gives the most likely place where the individual meteoroid comes from, if truly associated with the radiant. Comparison of the velocity values gives an independent filter from which a subset of meteors can be selected. The Kazan radiants having high probability of AO point associations are plotted as large open circles in Fig. 2 using an Aitoff projection centered on the apex. The positions and areas of the sporadic sources (open ellipses) are also indicated (Chau et al. 2007) with the ellipses representing standard deviation contours of meteor density around each center (star).

4 Determining Shower Membership

The postulated minor showers as mentioned above are specified in a geocentric, moving, ecliptic system of reference. The minor showers themselves are modeled as concentrations

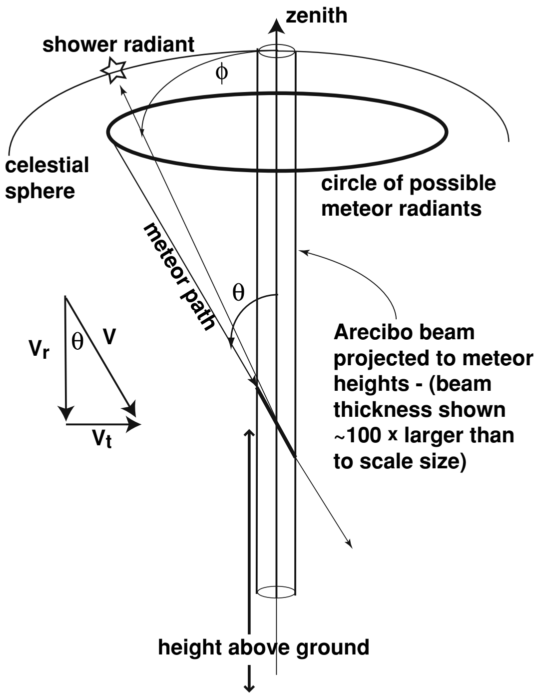

Fig. 1 Diagram showing the spatial configuration of the Arecibo beam (magnified here by about a factor of 100 for clarity), the meteor trajectory, the circle of possible radiants (denoted in the text as the CEBIA), and a shower radiant (shown as a five-point star) on the celestial sphere. Also shown are the velocity components of the meteor: V_r = the observed radial velocity, V_t = the inferred transverse velocity, and V = the meteor true or total velocity as inferred from the Feller transform (see the text). The angle θ = the inclination angle of the meteor path with respect to the beam axis (obtained by comparing V_r and V), the angle ϕ = the inclination of the shower radiant with respect to the beam axis. The probability of shower association is calculated from the absolute value of the minimum ϕ, θ difference. The actual meteor path as illuminated by the UHF radar is shown with a thick line segment. In actual practice, the meteor path can be offset from the beam axis (not shown). The offset angle can be estimated by a comparison of the observed duration with the duration calculated from the beam diameter and V_t

with the number densities of individual radiants specified by exponential radial functions. The algorithm we have adopted goes through the entire list of showers (in this case a special February list compiled from Kazan data by Sidorov to match the dates of the AO observations), whether deceleration was observed directly or not, and finds the source center that is closest to each of the resulting meteor intersection points (as described above). The resulting distance is then converted into a probability of membership resulting from an exponential probability assumption involving distance from the source center. In a parallel analysis, we have also investigated the associations of AO data with (a) the sporadic sources postulated by Jones and Brown (1993) and more recently detected with the HPLA radar at Jicamarca (see Chau et al. 2007) and (b)"major" showers as tabulated by Cook (1973) with the results mentioned here for comparison purposes. The sporadic source dimensions given by Chau et al. (2007) are used to estimate the variances of the exponentials for those identifications. For showers, the spatial probabilities are based on a 1/e radiant radius of 6°. This may seem a bit generous, but since small particles such as those that predominate the AO sample are subject to large perturbations it does not seem unreasonable.

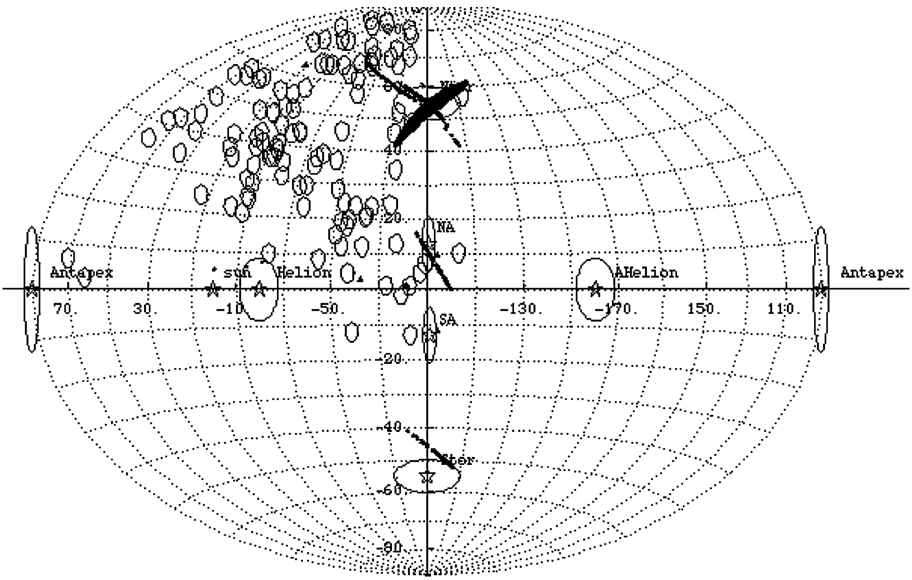

Fig. 2 Aitoff projection showing the positions of the AO CEBIA (circle of equal beam inclination angle) intersections relative to the sun-centered positions of the Kazan sources (open circles), the Jones and Brown (same as Chau et al.) sporadic sources (open ellipses with five pointed star symbols at the center) and the Cook radiants (small filled triangles). The AO point loci (strings of filled dots) attributed to sporadic sources are for Feb 24–26, 2006 during 08h–14h UTC on those days. Note that the Kazan sources for February do not fill the northern sky, but seem concentrated mostly in the north helion part of the sky and few overlap with the sporadic source positions. This makes it easier to distinguish them from the usual sporadic source distribution

Shower identifications involve not only spatial association but also velocity association. For the probability of velocity association, a Gaussian distribution centered on the velocity given for each shower is assumed with a 1/e width of $(2\ \mathrm{km/s})^2$. This arises because the velocity errors at Kazan and Arecibo are both about 1 km/s or less. The total shower probability is the product of the spatial probability and the velocity probability. Sporadic source probabilities have only a spatial part because their velocity distributions are too wide to be useful as a criterion of association. In Fig. 2, the Kazan sources that had probabilities of association with AO intersections greater than 0.5 are plotted as open circles. Notice that individual intersection points for the Kazan radiants are NOT shown because it interferes with the visibilities of the radiant symbols (circles).

Since the use of the Feller theorem is a bit exotic, there may be some doubt concerning its validity. Thus the CEBIA intersection points (with spatial probability $P > 0.1$) for the Chau et al. (2007) sporadic source positions are also plotted as strings of small filled dots in Fig. 2. Note how the loci of the AO points cross the source areas with excellent agreement in the two northernmost areas. The same type of loci for the Southern Toroidal source seems to be a bit off but data is incomplete there because of a limitation by the southern horizon as seen in February from AO. The South Apex source seems to have no associated points. While there may be a true lack of micrometeors from that direction, it is more likely that the search method has problems when the positions of two closely spaced sources are aligned along nearly the same CEBIA relative to the beam center. In such cases, the source closest to the beam center will always have the highest probability of association. While micrometeors associated with the South Apex source were indicated by the search techniques, the probabilities obtained were below the chosen threshold. Because of this ambiguity, neither results for the South Apex or the South Torodial sporadic sources have been included in the analysis described below. It might seem that confirmation of the Feller method could be obtained by analyzing data obtained with a HPLA interferometer such as at Jicamarca or the tristatic EISCAT UHF system. But while such an experiment might be interesting to try, it must be pointed out that the Feller method needs higher data rates in a 1 or 2 h period than can be obtained at either of those facilities. Instead we intend to reanalyze AO data obtained during major showers as calibrations of the method as is standard practice with specular radars.

5 Data Analysis and Results

The Arecibo UHF radar is able to detect returns from meteoroid masses far smaller than those reported for most HPLA facilities and classical meteor interferometers. That means we can more reliably derive at each observing epoch, the individual physical properties (velocity, radius, density, and mass) of a much larger sample of events for each source than can usually be obtained directly from the Kazan radar interferometer observations themselves.

Once the AO particles that have the highest probability of association have been identified, histograms of the physical states of the associated particles can be constructed. The three quantities obtained from the revised AO analysis were mass, radius, and density. Although a formal error analysis has not yet been carried out, we estimate errors between 10% and 20% for these three quantities after corrections for inclination effects have been applied. Since there resulted associations for some 87 of 114 Kazan radiants, to display all these histograms (nearly 270, all will be available on the internet) would have been tiresome and not very informative. Our more meaningful comparison involves what are considered "core" objects ($P > 0.5$) versus "halo" objects ($0.5 > P > 0.1$). While the eye may spot subtle differences in the various histograms had we been able to present them, to quantitatively compare the resulting histogram plots, we used the Student *t*-test (Burington and May 1953) between two sample means since it incorporates the variances of each sample and is relatively insensitive to differing and possibly small sample numbers. The final results are expressible in terms of probabilities.

In actual practice, we examined the distributions of $\log_{10}$mass (kg), $\log_{10}$radius (μm) and $\log_{10}$density (g/cc) to obtain the probability of difference for each property. A single "total" probability of difference (P_{tot}) was obtained by taking the products of the three individual probabilities of the properties for each shower. Also we found the ratio of the number of "halo" events (N_{halo}) to the number in the "core" (N_{core}).

6 Interpretation and Discussion

In Fig. 3 we give only the two final quantities, $\log_{10} P_{tot}$ and $\log_{10} \frac{N_{halo}}{N_{core}}$. $\mathrm{Log}_{10} P_{tot}$ is an indication of how different the "core" particle properties are from the "halo" ones while $\log_{10} \frac{N_{halo}}{N_{core}}$ is a crude measurement of how closely packed the "halo" is compared with the "core". We show data for the observed Kazan microshowers (black dots) and for the δ Cancri shower, the North Apex sporadic source (NA) and the North Toroidal sporadic source (Ntor) (open circles). It can be seen that the open circles are all to the right of the

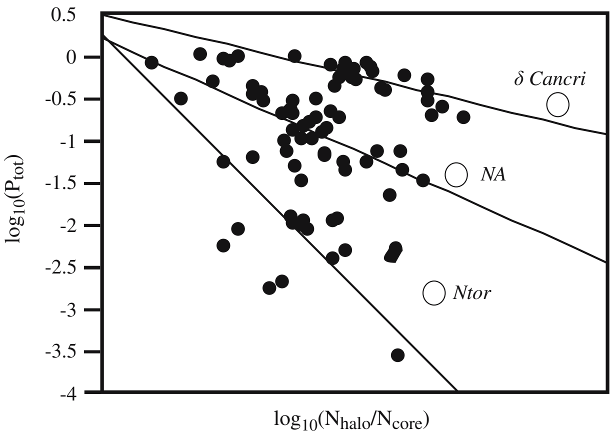

Fig. 3 Probability of different properties (P_{tot}) for halo and core particle as a function of shower/source concentration showing three possible sequences. The Kazan sources are shown as dots while the δ Cancri shower (Cook 1973), and the North Apex and the North Toroidal sources (Jones and Brown 1993) are shown as circles (in order from top of graph). Assuming a diffusion of meteors outward from the core center implies a time increase from left to right along each sequence and a time difference between sequences. See text for further details

other dots. Since N_{halo}/N_{core} is a measure of central concentration of each radiant, we conclude that the δ Cancri and sporadic sources are much less concentrated than the Kazan sources. The pattern of points is not random with what appears visually to be at least three sequences running from upper left to lower right. The reality of these sequences was verified using cluster analysis. To aid the discernment of these sequences, the points in each sequence were isolated and analyzed separately. Each sequence contains only one of the sporadic/δ Cancri points, but because the lines shown were determined by least squares, these extreme points played a critical role in the determination of the solutions. The linear correlation coefficients of the lines shown exceeded 0.9.

Given that the lines "diverge" from the upper left where the maximum contrast between the "core" regions and the "halo" regions occurs, a suggested explanation is that each sequence is a time-line along which radiant behavior "flows" from compact and contrasting to diffuse and more homogeneous. Apparently the three sequences depend on the rate of dissolution with the upper one "slow" and the lower one "rapid". The suggested temporal relationship along a sequence is that objects toward the right are older than objects to the left. Of course in the absence of a quantitative theory of meteor stream diffusion, age assignment cannot be done unambiguously. In ordinary diffusion, the rate of diffusion declines with time so that would mean the lower sequence is youngest with the top sequence being the oldest. But that would make the δ Cancri shower older than the sporadic sources which is not likely. That is why a quantitative dynamical study is needed. So why are there three sequences in the first place? Since the mean densities are all very close to a common value of about 0.5 g/cc, a characteristic of cometary material, it is speculated that these sequences are perhaps (in order) long period comets, short period comets, and sun-grazers, but more work is needed to establish such a relationship. Given the richness of this data shown by these preliminary *t*-test results, future ANOVA and multidimensional cluster analysis (Drummond 2000) seem warranted.

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