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Key Points:
- The ionization coefficient is evaluated in the low-velocity range (10–20 km/s) for incoming meteors
- Meteor velocity measurements from the Jicamarca HPLA radar, sensitive to meteor ionization on account of both long radar wavelength and exceptional aperture, are analyzed for the first time
- Velocity corrections to the Jicamarca HPLA radar data show consistent features independent of the model for $\beta(V)$ and independent of the inclusion of Na in the calculations

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Intercomparison of radar meteor velocity corrections using different ionization coefficients

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Abstract Sensitive long-wavelength radar observations of absolute velocity never previously published from Jicamarca are brought to bear on the long-standing problem of radar detection of slow-moving meteors. Attention is devoted to evaluating the ionization coefficient $\beta(V)$ in the critically important velocity range of 11–20 km/s in recent laboratory measurements of Thomas et al. (2016). Theoretical predictions for $\beta(V)$ based on the laboratory data, on Jones (1997), on Janches et al. (2014), and on Verniani and Hawkins (1964) are used to correct the incoming meteor velocities measured with the sensitive Jicamarca high-power, large-aperture radar operating at 6 m wavelength. All corrected distributions are consistent with the predictions of the Nesvorný model in showing pronounced monotonic increases down to the escape velocity (11 km/s). Such distributions may be essential to explaining the pronounced ledge in nighttime electron density and the rapid disappearance of electrons in meteor trails in the altitude range of 80–85 km.

Plain Language Summary Incoming meteors from space cannot be detected with radars unless the medium around the meteor is strongly ionized. In this study, the distribution of meteor velocities that are detected by the sensitive Jicamarca radar is corrected following theoretical models for the ionization coefficient, a measure of what fraction of the ablated meteor atoms are ionized. The results show that when the distribution of velocities is corrected, one is left with a large population of meteors that are entering the Earth's atmosphere close to the escape speed for the solar system which is 11 km/s.

1. Introduction

The continuous meteoric input to the terrestrial atmosphere from space is dominated by meteoroids in the size range of 100 μm [*Love and Brownlee*, 1993]. To be detected by sensitive radars, local ionization is needed (i.e., the presence of free electrons linked with ablation) to enhance the radar cross sections and the degree of ionization increases with meteor speed. The Rayleigh radar backscatter from the particles themselves is orders of magnitudes below any radar sensitivity. The long-standing and hotly debated question is whether or not the most sensitive radars are capable of measuring the incoming mass flux [*Hughes*, 1972, 1978; *Ceplecha et al.*, 1998; *Janches et al.*, 2015; *Plane et al.*, 2015] and to what extent that mass flux is dominated by low-speed meteors [*Nesvornỳ et al.*, 2010, 2011; *Carrillo-Sánchez et al.*, 2015]. The low-speed limit for incoming meteoroids is set by the terrestrial escape velocity, 11 km/s.

New measurements by *Thomas et al.* [2016] have been undertaken to shed new light on this long-standing unresolved issue. Their focus has been on the velocity-dependent ionization coefficient, henceforth denoted $\beta(V)$, defined as the ratio of the number of electrons produced to the number of vaporized atoms. This has been a controversial parameter in meteor physics for more than half a century [*Verniani*, 1970]. This problem is complicated because in the critical velocity range near the terrestrial escape speed of 11 km/s, the kinetic energies of meteoroid constituents are of the same order as the first ionization energies (5–35 eV). This circumstance is entirely fortuitous as the escape speed originates in Newtonian gravity and the ionization energies come from quantum physics. As shown by the experiments carried out by *Thomas et al.* [2016], iron atoms are more readily ionized because they are simultaneously massive and have low ionization energy. Iron is however a rather minor constituent of typical incoming chondritic meteors. In contrast, the element oxygen, whose atomic concentration in meteoric stone (57%) exceeds that of Fe (6.3%) by nearly an order of magnitude [*Öpik*, 1958], lacks the kinetic energy at the escape speed to ionize either oxygen or nitrogen.

This study is concerned with the implications of the laboratory measurements of $\beta(V)$ on the distribution of incoming velocities one obtains with ionization-sensitive radar observations at long radar wavelength

(6 m), characteristic of the Jicamarca meteor radar. Despite the exceptional aperture of Jicamarca (300 m × 300 m) and its long-standing interferometric capability for full velocity measurements of meteors, no velocity distributions have previously been published.

The first author's interest in the origin of the pronounced nighttime ledge in electron density near 85 km altitude [*Hale*, 1984; *Friedrich and Torkar*, 2001] initiated this inquiry into meteor ablation. *Whipple*'s [1955] finding of an abrupt increase in the rate of decay of meteor trail ionization below about 85 km was strongly motivational here for investigating meteoric debris/dust as an explanation for the ledge. This idea has been pursued further in more recent work by *Wu et al.* [2017].

2. Resurrection of Laboratory-Based Ablation Experiments by *Thomas et al.* [2016]

The experiments by *Thomas et al.* [2016] seek to duplicate the ablation and ionization of meteoroids in the laboratory. The new effort resurrects the experimental design of J. F. Friichtenicht and colleagues in the 1960s, involving the electrostatic acceleration of conductive particles of elemental material to meteor speeds with a Van de Graaff generator. The new experiments have been successful in showing reasonably good agreement on measurements of $\beta(V)$ for Fe particles. This success has led to the upholding of the *Jones* [1997] theoretical work on $\beta(V)$ for meteors in which a scaling constant had been estimated on the basis of the earlier laboratory measurements on Fe [*Slattery and Friichtenicht*, 1967].

Two shortcomings of the laboratory measurements for $\beta(V)$ in the context of the overriding problem of radar detection are worthy of emphasis. First of all, measurements have been largely confined to the ablation of pure materials (Fe, Cu, and LaB_6). Knowledge on the behavior of realistic meteoric material is needed for meaningful response in the radar context. *Friichtenicht and Becker* [1973] envisaged the measurement on a composite with their laboratory approach but this goal was evidently not achieved. Fortunately, *Jones* [1997] makes a theoretical prediction for composite behavior of $\beta(V)$ and that is followed up in the calculations described below.

The most serious shortcoming of all the laboratory measurements, also highlighted in *Thomas et al.* [2016], is the restriction on the velocity range for $\beta(V)$. The typical range of the measurement begins at 20 km/s and so the critical region down to the escape speed is not accessible. The mean speed of incoming meteors in the Nesvorný model is 14 km/s [*Carrillo-Sánchez et al.*, 2015] and so is centrally located in the unmeasured velocity range. This limitation on speed range in the laboratory measurement is imposed by fundamental considerations of energy conservation. The laboratory measurement of β, as the fraction of all ablated atoms that are ionized, requires the complete vaporization of the simulated meteoroid. The energy available for vaporization of all its atoms and for the ionization of a portion of them is derived from the initial kinetic energy of the simulated meteoroid.

$$½MV^2 = ½NmV^2 = \text{kinetic energy of ablated atoms} + N\,E_{\text{vap}} + \beta N\,E_{\text{ion}} + \text{other} \tag{1}$$

where M is the mass of the unablated particle, N is the number of constituent atoms in that particle, m is the mass of the Fe atoms, and E_{vap} and E_{ion} are the vaporization and ionization energies, respectively, per atom. The "other" term in this equation represents the translational and rotational kinetic energies of atmospheric constituents (prominently N_2 and O_2) with which the ablated atoms interact. Following equation (1), the fractional diminishment in kinetic energy, obtained by dividing through by the originally available kinetic energy (KE) is given by

$$\Delta\,\text{KE}/\left(½M\,V^2\right) = \left(N\,E_{\text{vap}} + \beta N\,E_{\text{ion}} + \text{other}\right)/\left(½\,mV^2\right) \tag{2}$$

For Fe, E_{vap} = 3.5 eV and the atom kinetic energy at the escape speed is 35 eV. Accordingly, by considering only the first term in ((2)), a lower bound on the fractional loss in kinetic energy just to vaporize the particle is 10% of the initial energy (at escape speed). If V doubles to enter the typical range of the laboratory measurement (20–40 km/s), the fractional kinetic energy loss drops to a few percent and then can be considered negligible. For an accurate measurement at any speed, the fractional change in KE and particle speed must by small and that condition is readily satisfied for $V > 20$ km/s. The only material for which $\beta(V)$ measurements have been achieved below 20 km/s with the laboratory method was copper [*Friichtenicht and Becker*, 1971], whose vaporization energy (3.1 eV) is less than for iron.

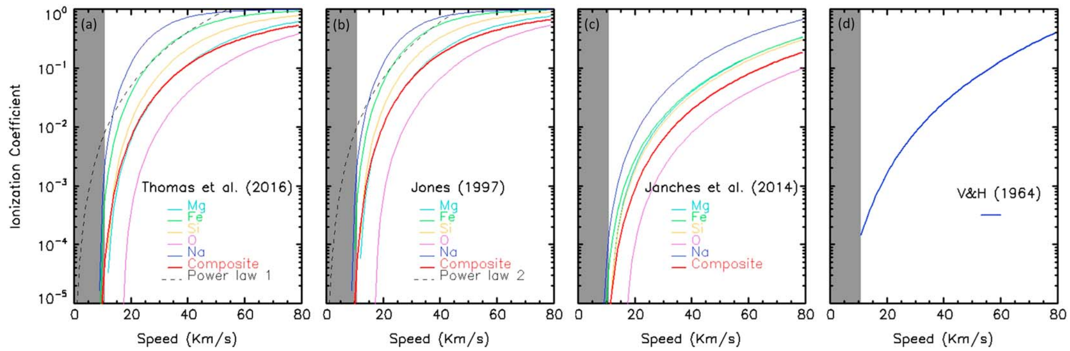

Figure 1. Ionization coefficient $\beta(V)$ for four models: (a) Theoretical calculations from *Jones* [1997, equation (25)] but with c parameters based on laboratory measurements of *Thomas et al.* [2016]. The contributions of all major atomic constituents of meteoric stone (Mg, Fe, Si, O, and Na) are included, as well as the composite result. The power law fit from the lab measurements on Fe is also shown as the dashed curve. (b) Theoretical calculations from *Jones* [1997, equation (25)] with the original c parameters. The contributions of all major atomic constituents of meteoric stone (Mg, Fe, Si, O, and Na) are included, as well as the composite result. The power law fit from the lab measurements on Fe from *Slattery and Friichtenicht* [1967] is also shown as the dashed curve. (c) Theoretical calculations from *Jones* [1997, equation (28)] based on atomic cross section measurements, following the work in *Vondrak et al.* [2008] and *Janches et al.* [2014]. The contributions of all major atomic constituents of meteoric stone (Mg, Fe, Si, O, and Na) are included, as well as the composite result. (d) The power law relation $\beta(V) = 1 \times 10^{-8}\, V^4$ based on optical and radio observations of meteors by *Verniani and Hawkins* [1964].

3. Evaluation of $\beta(V)$ Following *Jones* [1997] and *Thomas et al.* [2016]

The theory for ionization coefficient $\beta(V)$ in *Jones* [1997] can be used with the new measurements of *Thomas et al.* [2016] over the range of 20–45 km/s to extend the estimates for β for Fe downward into the unmeasured range of 11–20 km/s. The same approach to solving equation (25) in *Jones* [1997] as in *Thomas et al.* [2016] and in *Moorhead et al.* [2017] has been followed. (Typos are present in the equations (16) and (19) of *Moorhead et al.* [2017], but these errors did not impact their numerical calculations.)

$$\beta(v) = \beta_0(v) + (1 - \beta_0(v))\frac{(1+\mu)^2}{2v^2\mu}\int_{v_0}^{v}\beta(v')v'dv' \tag{3}$$

(equation (25) in *Jones* [1997]).

where

$$\beta_0 = \frac{C(v - v_0)^2 v^{0.8}}{1 + C(v - v_0)^2 v^{0.8}} \tag{4}$$

$\beta(V)$ for all other prominent meteoric constituents have also been computed following these equations. Since no laboratory measurements are available for the other constituents (Mg, Si, and O), the original estimates for the respective *c* values in *Jones* [1997] (see equation (4) above) have been scaled by the new *c* value for Fe in *Thomas et al.* [2016]. The ratio of the *c* values for Fe is Thomas/Jones = 19.65/34.5 = 0.57. The contribution of more volatile Na has also been included based on the recent estimates of *Moorhead et al.* [2017]. No laboratory measurement of $\beta(V)$ for Na has yet been achieved, no doubt because of its exceptional reactivity. The results are shown in Figure 1a. Included here is the power law fit ($\beta(V) = 6.224 \times 10^{-6}\, V^{3.003}$) of the laboratory measurements [*Thomas et al.*, 2016] as the dashed curve.

For purposes of correcting the radar-measured distribution of incoming meteor velocities, an estimate of composite $\beta(V)$ is needed for a realistic meteoroid composition. Appeal here is made to *Jones* [1997, equation (3)] to weight the β contributions from the main constituents (Fe, Mg, Na, Si, and O) proportional to their atomic abundance. The atomic weighting used for a cometary meteoroid by *Jones* [1997] is closely matched with other estimates [e.g., *Öpik*, 1958]. The calculation for the composite response is also included in Figure 1 a. The large ionization energy for O in comparison with its atomic kinetic energy, at speeds near the escape velocity, contributes to a marked decline in $\beta(V)$ in the critical velocity range (11–20 km/s).

The same set of $\beta(V)$ calculations for the original *Jones* [1997] implementation, for comparison with the inferences from the new laboratory measurements of *Thomas et al.* [2016] but with the Jones scaling parameters, as noted above and adjusted for the measurements on Fe, is shown in Figure 1b. Again, the $\beta(V)$ estimates for Na are taken from *Moorhead et al.* [2017]. The power law fit ($\beta(V) = 5.96 \times 10^{-6}\ V^{3.12}$) to the laboratory data on Fe from *Slattery and Friichtenicht* [1967], which Jones used earlier to compute his *c* value, is also included for comparison. As with the power law fit to data in Figure 1a, the *Jones* [1997] theory predicts a β value for iron near the escape speed which is an order of magnitude smaller than the extrapolation of the power law relationship.

4. Evaluation of $\beta(V)$ Following *Janches et al.* [2014] and *Vondrak et al.* [2008]

The *Jones* [1997] theory for $\beta(V)$ has been utilized earlier by *Vondrak et al.* [2008] and by *Janches et al.* [2014], but with a scaling based on experiments concerned with atomic collisions [*Cuderman*, 1972] rather than on macroscopic ablation results. It is important to note here that equation (28) from *Jones* [1997] was used in both Vondrak et al. and Janches et al. to calculate $\beta(V)$, rather than the more complicated (but more accurate at large speed) equation (25). This approach has led to substantially smaller scaling parameters (the *c* values in *Jones* [1997, equation (33)]) than ones determined from the laboratory ablation experiments. The calculations for all five main meteoric constituents (Fe, Mg, Na, Si, and O) are shown in Figure 1c, where in this case the $\beta(V)$ values for Na are taken from *Janches et al.* [2014] rather than from *Moorhead et al.* [2017]. The contrast in scaling between *Jones* [1997] and *Janches et al.* [2014] amounts to an offset in the $\beta(V)$ curves. The markedly reduced values of $\beta(V)$ over the entire velocity range in comparison with Figures 1a and 1b are attributable to the difference in the selection of scaling parameters *c*. For Fe, for example, $c = 19.65 \times 10^{-6}$ in *Thomas et al.* [2016] but in *Janches et al.* [2014] the selected value is $c = 1.5 \times 10^{-6}$, amounting to a difference of a factor of 13.

It is important to note here that the plotted values for $\beta(V)$ in Figure 19 of *Janches et al.* [2014] are not the β_{ip} values reported in their text as solutions for their equation (18), but instead represent values of β_o. Following equation (18) in that work, the latter values are always less than the β_{ip} values (note that β_{ip} in Janches et al. is identical with β in equation (3)) that are plotted in Figure 1c of the present work. The dashed curve for *K* in the top of their Figure 19 is identical with the solid curve for *K* in the bottom of Figure 19.

The same procedure as in *Jones* [1997] and in *Moorhead et al.* [2017] for estimating a composite behavior for $\beta(V)$ can by implemented with the calculations from *Janches et al.* [2014] for elemental meteoric constituents. This result is also included in Figure 1c. As with the calculation in Figure 1a pertaining to *Thomas et al.* [2016], $\beta(V)$ is declining markedly in the critical velocity range of 11–20 km/s. The general shape of $\beta(V)$ here is similar to that in Figures 1a and 1b, but as one can understand from the *Jones* [1997] theory, the overall curve is offset downward based on the use of different *c* scaling parameters.

5. Ionization Coefficient $\beta(V)$ Based on Earlier Direct Observations (Optical + Radar) on Meteors

The origin of the ionization coefficient in meteor physics derives not from laboratory measurements but from radar and optical measurements on real meteors in space. Extensive works by *Verniani and Hawkins* [1964] and *Verniani* [1970], making use of radio and photographic meteors over the full velocity range from 10 to 60 km/s, were used to obtain a power law fit for $\beta(V)$ of the form

$$\beta(V) = \left(1 \times 10^{-8}\right) V^4 (\text{with } V \text{ in km/s})$$

This power law relationship is plotted in Figure 1d for comparison with the earlier calculations in Figure 1. This relationship was used by *Southworth and Sekanina* [1973] and later by *Taylor* [1995] to correct the velocity distribution recorded with the Havana, Illinois, radar over the full range from 11 to 70 km/s. This corrected velocity distribution was later used by *Hunten et al.* [1980] in early estimates of the altitude distribution of meteor ablation and is the basis for one of the meteor velocity models [*McBride et al.*, 1999] favored by *Carrillo-Sánchez et al.* [2015]. It is interesting to note that the data point in *Verniani and Hawkins* [1964] for the lowest velocity range (10–20 km/s) lies below the power line fit, and so more consistent with the predictions of *Jones* [1997]. *Furman* [1967] noted a half-century ago that power law fits for ionization coefficient would not be reliable at low meteor speeds. It should also be noted that the contribution of Na is included naturally in the estimate of $\beta(V)$ based on real meteors.

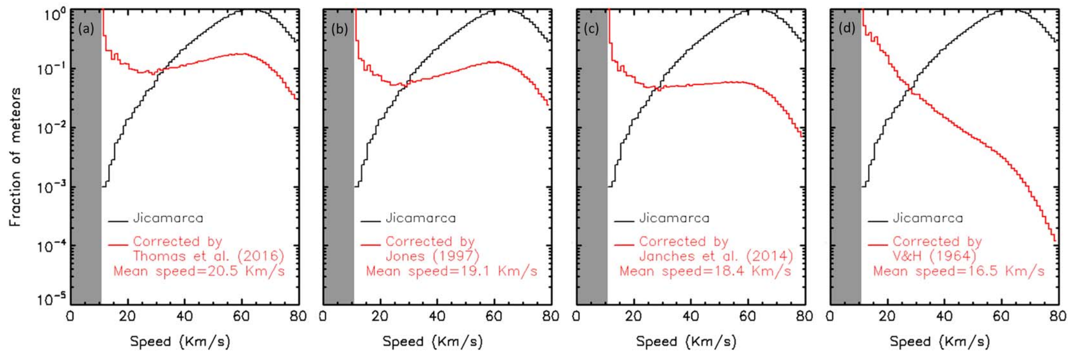

Figure 2. The velocity distribution measured by the Jicamarca radar (black) and corrected according to the ionization coefficients $\beta(V)$ documented in four models of Figure 1 (red): (a) Theoretical calculations from *Jones* [1997] but with c parameters based on laboratory measurements of *Thomas et al.* [2016], (b) theoretical calculations from *Jones* [1997] with the original scaling parameters, (c) theoretical calculations from *Jones* [1997] following *Janches et al.* [2014], and (d) empirical calculations following the power law relation from *Verniani and Hawkins* [1964]. Mean values for each corrected velocity distribution are given for each of the four calculations. The grey zones denote the range of speeds less than the terrestrial escape speed (11 km/s).

6. Correcting Meteor Velocity Observations With the Jicamarca Meteor Radar

Contemporary meteor velocity observations from the Jicamarca high-power, large-aperture (HPLA) meteor radar in Peru [*Chau et al.*, 2007] (wavelength 6 m, peak power 2 MW, antenna aperture 300 m × 300 m, and altitude coverage 80–130 km) have been used to apply corrections based on the foregoing $\beta(V)$ results. This radar was selected purposely in the present context for a number of reasons. First, the operating wavelength (6 m) is close to that used by the Havana, Illinois, radar (7.3 m) that was important in the earlier velocity corrections implemented by *Southworth and Sekanina* [1973], *Hunten et al.* [1980], *Taylor* [1995], and *McBride et al.* [1999]. More importantly, Jicamarca, with an aperture of 300 m × 300 m, is the world's most sensitive radar at this long wavelength. Most importantly, radars operating at longer wavelength are more sensitive to weaker ionization, all other things being equal. This provides greater sensitivity to slow-moving meteors. Evidence for this quantitative importance of ionization sensitivity is found in the work of *Close et al.* [2002] with the Advanced Research Project Agency Long-range Tracking and Identification Radar (ALTAIR). They found a mean wavelength dependence of $\lambda^{4.1}$ for the radar cross sections of head echoes. If this dependence can be extended to the 6 m wavelength of Jicamarca, one can infer a 21 dB advantage over ALTAIR ($\lambda = 1.86$ m) and a 38 dB advantage over Arecibo ($\lambda = 0.70$ m), on the basis of radar wavelength alone.

Previously published corrections of radar-based velocity observations [*Southworth and Sekanina*, 1973; *Taylor*, 1995; *McBride et al.*, 1999; *Hunt et al.*, 2004; *Close et al.*, 2007] have given attention to both the cumulative mass distribution of meteoroids, characterized by an exponent α, and to the ionization coefficient $\beta(V)$, and when given in power law form is characterized with an exponent γ. In the case of the cumulative mass distribution a selection of $\alpha = 1.0$ is consistent with known constraints [*Taylor*, 1995; *Close et al.*, 2007] for a meteoroid mass distribution peaking near 10^{-5} g [*Love and Brownlee*, 1993]. This selection for α leads to the much simplified correction procedure, of the same form as the original implementation in *Sida* [1969]:

$$N_C(V) = N_R(V)/\beta(V)$$

where $N_R(V)$ is the raw distribution of meteor velocities and $N_C(V)$ is the corrected distribution. This is a relative correction procedure for the velocity distribution.

For the corrections here, the raw velocity distribution is established by observations of 236,229 meteors with the Jicamarca HPLA radar over a period of 12 days (23–27 February 2005, 8–9 May 2006, 1 September 2007, 5–6 December 2007, 13–14 December 2008, and 26 June 2009), for a mean daily rate of 19,679 meteors per day. All absolute velocity calculations were made manually. The raw distribution $N_R(V)$ is plotted with 1 km/s binning in each of three panels of Figure 2, normalized to the maximum value near 64 km/s. Meteors with velocity magnitudes down to 11.7 km/s were detected, with a trajectory elevation angle of 90°.

The corrected distributions $N_C(V)$ are shown in Figure 2a for the Thomas et al. values of $\beta(V)$, Figure 2b for the original *Jones* [1997] calculations, Figure 2c for the Janches et al./Jones values of $\beta(V)$, and Figure 2d for the *Verniani and Hawkins* [1964] power law representation for $\beta(V)$. The corrected distributions are all consistent in showing a monotonic increase in counts down to the escape velocity of 11 km/s, precisely in the region of unmeasured $\beta(V)$ in the laboratory, and for convenience in illustration are all normalized to the maximum value there. Furthermore, the computed mean velocities for the four corrected distributions in Figure 2 (20.5, 19.1, 18.4, and 16.5 km/s, respectively) are closely matched and are all close to the mean speed of 18 km/s for the velocity distribution taken from *McBride et al.* [1999] and ultimately based on the Harvard Radar Meteor Project radar measurements [*Southworth and Sekanina*, 1973; *Taylor*, 1995]. The mean speeds from all four sets of calculations are all distinctly larger than the mean speed of 14 km/s for the Nesvorný model [*Carrillo-Sánchez et al.*, 2015] (Figure 1), but this value pertains to the particles produced by Jupiter family comets [*Nesvornỳ et al.*, 2010]. This mean speed is smaller than the mean values determined here, not because the distribution is less strongly peaked near 11 km/s but because the Nesvorný distribution is lacking in high-speed ($>$30 km/s) meteors.

7. General Discussion and Conclusion

The new laboratory-based results for $\beta(V)$ in *Thomas et al.* [2016] fall short of providing estimates in the velocity range (11–20 km/s) critical for resolving the outstanding questions about radar detection of slow-moving meteors. They do however provide an important basis for new theoretical calculations of $\beta(V)$ to be used for radar corrections. Comparisons can be made between lab measurements and theory in the velocity region of overlap, and in all cases [*Slattery and Friichtenicht*, 1967; *Friichtenicht and Becker*, 1971, 1973; *Thomas et al.*, 2016], the data points at the low end of the power law-fitted velocity interval fall below the mean fit line, in some cases quite conspicuously. The *Jones* [1997] theoretical predictions are not simple power laws, and all $\beta(V)$ predictions are concave downward on plots of log β versus log V, generally consistent with the lab observations, especially when a larger velocity range has been measured. Furthermore, for the measurements on Fe in *Thomas et al.* [2016], the power law slope (3.003) is greater for the low-V interval (20–45 km/s) than the value (2.068) for the high-velocity interval (20–90 km/s), pointing to an even greater slope in the unmeasured velocity interval. The extension of the dashed power law fit in Figure 1a to the unmeasured interval shows values larger than all other estimates. All theoretical $\beta(V)$ calculations based on *Jones* [1997] show local power law slopes greater than 3.003 in the unmeasured low-speed range (11–20 km/s). The steepening of the slope near 11 km/s is attributable to the similarity of atomic kinetic energies and ionization energies as noted earlier.

All velocity corrections show monotonic increases in numbers down to the escape velocity of 11 km/s. This is not a new result [*Sida*, 1969; *Southworth and Sekanina*, 1973; *McBride et al.*, 1999; *Hunt et al.*, 2004; *Close et al.*, 2007; *Moorhead et al.*, 2017], mainly because all treatments of ionization coefficient involve monotonic decreases down to the escape velocity. Increasingly well established on the basis the findings here and those of *Moorhead et al.* [2017] is the narrowing of the corrected velocity distribution near the escape speed, with local *e*-foldings of the distribution at the escape speed of less than 2 km/s. It is also remarkable how well the distributions in Figure 2 agree at low speed for all three sets of $\beta(V)$ devised after *Thomas et al.* [2016] and taken from the literature. The evidence here is that both theoretical and radio/optical experimental studies are getting the general shape of $\beta(V)$ correct in the unmeasured region, but that the general level of $\beta(V)$ still has substantial (and still unexplained) disagreement. In the context of *Jones* [1997], the level change in $\beta(V)$ is controlled by the fitting parameters (*c* values), for which considerable differences are apparent among approaches [*Jones*, 1997; *Vondrak et al.*, 2008; *Janches et al.*, 2014; *Thomas et al.*, 2016; *Moorhead et al.*, 2017].

Given the strong velocity dependence of β in the unmeasured velocity interval in all treatments, it is apparent that it is meaningless to discuss any particular radar's sensitivity as a threshold in meteoroid mass. At low speeds, velocity and attendant ionization take over as the main determinants of detectability. Very small masses can be detected if they have sufficient speed. It is also apparent that one needs to go beyond the behavior of Fe alone (a minor constituent of typical meteoroids in atomic counts) in the laboratory measurements to shed light on the long-standing questions pertaining to radar. The ionization coefficient for Na has not been measured in the laboratory, but appropriate scaling in the *Jones* [1997] approach and the most recent literature reference for $\beta(V)$ [*Moorhead et al.*, 2017] have been used in the calculations here.

This study adds evidence to other independent lines of support for the feature of the Nesvorny model showing an abundance of incoming meteoroids near the escape velocity [*Hunten et al.*, 1980; *Nesvornỳ et al.*, 2010, 2011; *Huang et al.*, 2015; *Carrillo-Sánchez et al.*, 2015; *Moorhead et al.*, 2017]. The physical basis for this anomaly at low speeds is the Poynting-Robertson effect acting on cometary debris over a long time period [*Nesvornỳ et al.*, 2010]. It is important to note that *Love and Allton* [2006] have provided evidence for a general absence of incoming velocities below 11 km/s but do not present strong constraints on the unmeasured velocity range of this study.

The evidence in all corrected velocity distributions in Figure 2 for both a narrowing and a marked reduction in mean velocity (both here and in *Moorhead et al.* [2017]), together with an inferred size distribution [*Love and Brownlee*, 1993] over which the ablation onset altitude is invariant [*Jones and Kaiser*, 1966], are consistent with findings in another recent study [*Carrillo-Sánchez et al.*, 2015] but with a different approach. The collective observational evidence serves to sharpen the increase in concentration of the ablation debris with decreasing altitude, without invoking additional modeling complications that are often overparameterized. The rich concentration of meteoric smoke particles noted initially in modeling studies by *Hunten et al.* [1980] may be a key aspect of the systematic ledge in electron density [*Plane et al.*, 2015] and electrical conductivity in the 80–90 km altitude range in the nighttime ionosphere [*Hale*, 1984; *Friedrich and Torkar*, 2001]. This concentrated deposition may also be important in explaining the more abrupt disappearance of electrons in meteor trails below 85 km reported earlier by *Whipple* [1955] and mentioned in section 1 [*Wu et al.*, 2017].

New laboratory emphasis on the previously unmeasured low-speed range in both *Slattery and Friichtenicht* [1967] and *Thomas et al.* [2016] is essential for comparison with the theoretical predictions for $\beta(V)$ by *Jones* [1997] and for the accurate correction of radar observations of incoming meteors where they may be most abundant.

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