FLIGHT FLOW REGIMES OF METEOROIDS DETERMINED FROM INFRASOUND DETECTION.

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Introduction: Low frequency sound (< 20Hz) that lies above the natural oscillation frequency of the atmosphere but below the human detectability is called infrasound. The shock wave generated during the interaction of a meteoroid and the Earth's atmosphere initially induce a highly non-linear strong overpressure in its vicinity. However, as the overpressure wave moves away from its source, it gradually decays, and eventually becomes a linear wave, which can be detected as infrasound at ground. A theoretical methodology to gain insight on meteor phenomena (optically detectable light production due to the meteoroid ablation [1]) and the meteoroid properties was outlined in [2, 3], and latter improved and validated by [4]. This theory is focused on a weak shock (once the highly non-linear strong shock has decayed) that arrives directly to the detector (no atmospheric bouncing shall occur), and comes from short-range sources (avoidance of large attenuation due to atmospheric propagation). Additionally, the altitude of the meteor generated shockwave was constrained in [5] by finding the point along the meteor trajectory from which infrasound signal originated. Although this altitude is not diagnostic of the initial onset of the shock wave, it represents the earliest known point for which the shock wave is determined to exist. Thus, the existence of a shock wave plus the infrasound detection provides a means to expand our understanding of the flow regime of meteors.

In this work, we discuss the suitability of the observational infrasound study to gain insight on the flow regimes of impacting meteoroids. Our data sample consists of 24 centimeter-sized meteoroids detected simultaneously by optical and infrasound systems, that belong to the wider data set used in [4] to validate the weak shock theory of [2, 3]. For this sample, the altitude at which the infrasound originated is accurately determined, although there is strong evidence suggesting that in some cases the onset of meteor shock waves could take place much earlier than predicted by classical methodologies ([6] and references therein). To our knowledge, this is the only well-documented and well-constrained set of such events to-date. We aim to elucidate the flow regimes associated with the onset of the meteor generated shockwaves by linking the observations to a new theoretical approach.

Knudsen number and flow regimes: The high altitude low density hypersonic air flow impacting the surface of centimetre-sized meteoroids ejects large number of meteoroid atoms, some of which are ionized. The ejected particles are efficient in braking down the air flow molecules, which eventually may not be able to reach the meteoroid surface. The accumulated number of particles in front of the meteoroid creates a vapour cap that acts as an "hydrodynamic shielding" [7], which initially expands (during high energy direct collisions and meteoroid surface evaporation) and compresses as a result of the descent into the more dense atmosphere and stronger evaporation. Strong heating results from irreversible adiabatic compression and subsequent changes in velocity, pressure and density in the vapour cap. At lower altitudes, when the pressure of the vapour gas in the flow field surrounding the meteoroid significantly exceeds that of the surrounding atmosphere by orders of magnitude, the vapour gas expands radially behind the shock envelope and can be considered as hydrodynamic flow into vacuum [7]. In a simple sense, that creates a shock discontinuity where the pressure, density and temperature experiences large jumps.

Indeed, for centimetre-sized meteoroids, the hydrodynamic shielding will alter the consideration of the flow regimes and consequently shift the continuous and transitional flow regimes upward in altitude.

The classification of the flow regimes relies on the Knudsen number (Kn), which is a dimensionless parameter defined as the ratio between the mean free path of the gas molecules (λ) to a physical length of the body immersed in the gas. Although it is quite common to use an equivalent radius of the meteoroid (L) as the physical length of the body, and thus $Kn=\lambda/L$, when a boundary layer exists (i.e., the body is contoured by a continuous flow), the thickness of the boundary layer (δ) formed in the vicinity of the body can be used as the characteristic length, $Kn=\lambda/\delta$. Provided the existence of strong ablation, it is recommended to express the Knudsen number as seen from the meteoroid (the reference frame is on the meteoroid surface) to account for the local physical phemomena in the neighbourhood of the meteor (see [8]) instead of using a reference frame fixed on the incoming fluid. This way, the mean free path of the reflected (evaporated) molecules relative to the impinging molecules (l_r) is considered instead of the mean free path of the gas molecules (l).

The flow regimes are studied using two classifications. On one hand, Tsien [9] accounted for the importance of these viscous effects and outlined a flow regime classification based on the comparison of the mean free path of the gas molecules (l) to the length of the boundary layer (δ). On the other, we consider a simplistic approach that allows a first approximation to the flow regimes, using the more general Knudsen scale that only accounts for number of intermolecular collisions within a specific time.

Results: Our results show that most of the meteoroids included in our sample are between slip-flow and continuum flight regime conditions [10]. Despite of some minor discrepancies, the results derived from the two classifications (Tsien's and general Knudsen scale) are quite similar. Furthermore, we analyzed the effect of varying some initial assumptions made on the general physical parameters (e.g., bulk density, meteoroid surface temperature, negligible deceleration) that may slightly vary for each sample member, only to find minor discrepancies [10].

Figure 1 compares the flight regimes of our meteoroid sample [10] with a Leonid meteoroid studied in [7]. The meteoroid radii and the altitude at which the shock wave was detected (shock source height) are plotted onto an adaptation of Figure 1 of [7]. Note that, as the altitude is a fixed value, the position of the meteoroids in the plot may only vary along the abscissa axis.

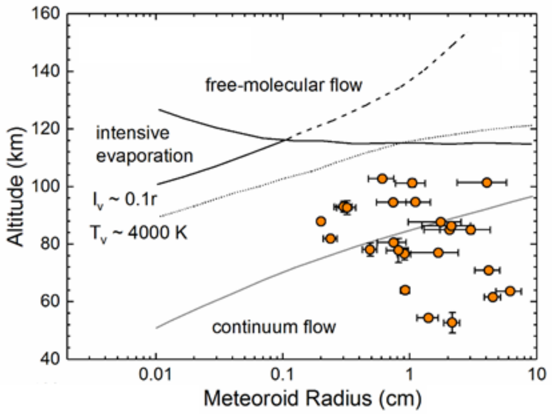

Figure 1. Adaptation of Figure 1 of [7]. The lines and regions are as in [7]: the intense evaporation line and the continuum flow boundary for the Leonid (0.01 cm sized meteoroid with entry velocity around 72 km/s); the boundary that indicates the moment the mean free path (l_v) becomes 0.1 times the meteoroid radius (l_v~0.1r); and the line below which the vapour temperature (T_w) exceeds 4000 K (dotted line). The horizontal error bars represent the standard error from the mean, and the altitude error. Note that some error bars are small and contained within the data points [10].

Given that the Leonids exhibit a smaller size and faster entry velocities, their continuum regime shall be reached earlier than for most of our meteor sample.Also, in line with Bronshten [8], we observe that the value of the Kn (defined with the reference frame on the meteoroid surface) is strongly influenced by the entry velocity and the atmospheric gas conditions at the height where the shock wave is detected. These parameters are principally gathered in the *Re* number. Moreover, the importance of the viscous effects that are already relevant in the expanding vapor gas is held in the *Re* number; this suggests that the use of the Tsien's scale is more appropriate for this kind of study. In agreement with what is commonly accepted, our results show that the use of a flow regime scale that accounts for the physics of the event is more adequate than a simplistic general approach.

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Acknowledgments: EAS gratefully acknowledges the Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship program for supporting this project. MG acknowledges support from the ERC Advanced Grant No. 320773, and the Russian Foundation for Basic Research, project nos. 16-05-00004, 16-07-01072, and 18-08-00074. JMTR thanks the support of the Spanish grant AYA2015-67175-P. MMI study was done in the frame of a PhD. on Physics at the Autonomous University of Barcelona (UAB).