Introduction: Meteor Astronomy in the Twenty-First Century

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We can only speculate how long ago a human first consciously noticed a shooting star in the sky. Writings go back thousands of years. The Egyptian hieratic papyrus of the Hermitage museum in St. Petersburg (archive number 1115) dates from between the twentieth and seventeenth centuries BC and mentions a falling star in the "Tale of the Shipwrecked Sailor" (Astapovich, 1958). Aristotle hypothesised on the nature of meteors, though the correct scientific basis and the connection with meteorites had to wait until Ernst Chladni's work two hundred years ago: see Beech (1995), and chapter 3 of Littmann (1998). For a long time there had been civilisations around the world that kept careful and extensive records that we can now recognise relate to meteor outbursts, meteor showers or fireballs. Notable among such ancient records are those from China, Japan and Korea (Imoto and Hasegawa, 1958; Zhuang, 1977; Ahn, 2005). Many records include exact dates, of immense value in modern studies to test our ideas of how processes in space have operated over millennia. More about the history of meteor observations and meteor work can be found in Williams and Murad (2002), chapter 1 of Jenniskens (2006) and references therein. Humans have seen meteors for millennia; since Chladni it has been known that underlying the meteor phenomenon is the existence of solid objects in space, which we call meteoroids.

The fundamental scientific study is concerned with meteoroids; meteors are the light, ionisation, sound and other phenomena produced when meteoroids collide with a planetary atmosphere. Recently, the International Astronomical Union updated the definitions of meteor and meteoroid, motivated by the blurring of the line between asteroids and meteoroids. When the previous definitions were put in place in 1961, a meteoroid was defined as "a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and considerably larger than an atom or molecule" (Millman, 1961). This worked well until improvements in asteroid searches began to find many objects smaller than 100 m, some as small as a few metres (Beech and Steel, 1995). The Chelyabinsk impact was caused by an object 19 m in diameter; according to the old definitions it could not be called an asteroid because it was not observed in interstellar space, while the smaller, $\approx$3 m 2008 TC_3, which struck the Earth one day after it was discovered (Jenniskens et al., 2009), was an asteroid.

In order to resolve this, Commission F1 of the IAU proposed to establish a size threshold to divide asteroids from meteoroids (Borovička, 2016). There is no natural size limit, as the population is continuous from small to large objects, so an arbitrary limit of 1 metre was chosen; objects larger than this are asteroids (or comets, if they show activity). At the smaller end, a division was introduced between meteoroids and interplanetary dust; in this case, the natural division is the size at which a particle is too small to produce light and ionisation when it strikes a planetary atmosphere. This limit depends on the speed of the object, but an arbitrary limit of 30 μm was chosen as being characteristic. Remarks to the definitions include some elasticity, so that any object that causes meteor phenomena may be called a meteoroid; the Chelyabinsk impactor was both an asteroid and a meteoroid. Also, any natural object observed in space, even if below the 1-metre threshold, may be called an asteroid.

Although the science is of *meteoroids*, with meteors a manifestation thereof, the term 'meteor science' is often used to encompass the study of meteoroids. Meteor science continues to be studied for scientific and practical reasons. The practical includes the development of the ability to mitigate effects of impacting meteoroids when potentially harmful: the hazard on Earth and to spacecraft must be understood over a wide size range of impactors. Scientifically, the motivation is to understand ongoing processes in nature: how comets and asteroids evolve, or what happens to their debris, in space and in planetary atmospheres. As in other sciences, observation or experiment combine with theory to elucidate what processes really occur. Models fits data if given processes operate. Theory suggests that various forces in principle could act on particles moving in the Solar System (e.g., radiative, electrostatic, relativistic). If the forces are not directly observable, a model should predict an observable consequence. For example, if the radiative Poynting–Robertson effect influences the dynamical evolution of small grains (meteoroids) in space, this can help to explain observations at the Earth relating to the Geminid stream (Jakubík and Neslušan, 2015) or at Mercury relating to the Taurids (Christou et al., 2015). Despite the fact that cometary dust trails have been observed, the dust particle concentrations in space cannot be detected by modern instruments, as a rule. Therefore studies of the dynamics and structure of meteoroid streams, and particularly the orbital resonances that operate, are important (Soja et al., 2011; Kortenkamp, 2013). A good model of the composition and structure of the meteoroids themselves can predict how they will interact with the atmosphere, including the early release of volatiles like sodium (Vojáček et al., 2019). The interaction strongly depends on fragmentation, which affects both the meteor light and the dynamics of the meteoroid (Ceplecha and Revelle, 2005; Borovička et al., 2007).

The twenty-first century brings great opportunities to advance meteor science. Modern astronomy has been characterised by each new generation of telescopes seeing fainter and with better resolution, allowing discoveries that drive the theoretical understanding. In the study of meteors, this new century has seen both increased observational precision and huge increases in the size and availability of databases. This has improved the reliability with which orbits are computed and streams are identified, and the details of physical processes during the meteor flight, such as fragmentation. Computer speed, including access to supercomputers where necessary, leads to more elaborate models better able to match observations. The space age has brought space telescopes and missions that provide *in situ* data. The missions can be to the parent bodies that are the source of meteoroids, or to other planets where the effects of the meteoroids impacting the atmosphere or surface are detectable by various means. The spacecraft themselves can carry dust detection instruments (examples in Grün et al., 2002). We develop these points in the following text.

Observations in Earth's Atmosphere and Elsewhere

Theory is often data driven: observation and datasets are the basis for our science. The ionisation trails of meteors scatter radiation very efficiently, and can be used to calculate shower and sporadic meteor activity. The ionised region around the head of the meteor is smaller, but high-power, large-aperture radars are capable of tracking these faint objects and have opened up the very smallest meteor-producing cosmic particles for study (see Chapter 3, Kero et al., 2019). The light from meteors can be used to characterise nighttime meteor sources, and can provide strong constraints to ablation modelling, particularly when spectral data are gathered (more details in Chapter 4, Koten et al., 2019). Lidars can be used to study the deposition of meteoric material in the atmosphere, and large meteoroids produce shockwaves detectable at the surface through infrasound and seismic observations. All observing techniques have different strengths and weaknesses, so multi-technique observations have great value to cross-calibrate measurements and to provide a wealth of information about single events, particularly meteorite-dropping bolides.

Away from Earth, naturally, much less has been observed, but this is changing. The meteor phenomenon is in principle observable on other planets with atmospheres. Moreover, if the meteors are not observed, their aftereffects can be: ablating meteoroids cause layers of metal atoms and ions to be deposited in planetary atmospheres (Chapter 5, Christou et al., 2019). Airless bodies provide a different environment for impacting meteoroids. It is possible to detect both the impact phenomenon itself, in the form of impact flashes on hitting the surface (Chapter 6, Madiedo et al., 2019), and the aftereffects, one source of neutrals in the exospheres coming from impact vaporisation when the surface is bombarded (Christou et al., 2019, see Section 5.7). Of course impact flashes on Jupiter (Christou et al., 2019, see Section 5.6) are a meteor (superbolide) phenomenon, not surface impacts.

Until recently, the lunar dust cloud had only been expected to exist. The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission discovered it and mapped its density distribution. Moreover, several meteoroid streams were detected, and the Geminid stream radiant was determined (Szalay and Horányi, 2016). It has been realised that "the Moon can be used as an enormous meteoroid detector" (Szalay, 2017).

Detection of meteoroid influx to the Earth and other worlds can be viewed from complementary perspectives: a means to study the meteoroids or an effect on the target bodies themselves. Internal sources of oxygen are apparently inadequate to explain levels of oxygen-bearing species on Titan and the giant planets (Plane et al., 2018) and delivery by meteoroids provides a possible external source. Infalling matter may have had an important role in delivering organics to the early Earth (chapter 34 of Jenniskens, 2006).

The properties of asteroid (3200) Phaethon, including its small orbit and small perihelion distance, as well as its association with one of the most prominent annual meteor showers, the Geminids, have prompted much debate about its nature (chapter 22 of Jenniskens, 2006). The study of Phaethon is an excellent example of the value of space-based telescopes, with the mass loss observed by STEREO (Chapter 8, Kasuga and Jewitt, 2019, see Section 8.3.1). Moreover we expect to learn about the dust from Phaethon *in situ* with JAXA's DESTINY+ mission. Another example of STEREO's results was the discovery of the existence of a dust ring at the orbit of Venus (Jones et al., 2013). Such a resonance ring is known to exist around the Earth's orbit. The observations of the venusian dust ring should lead to improved understanding of the factors influencing its formation.

That will not be the first mission to a parent body of meteoroids and dust; plenty of others have given valuable scientific results (Chapter 2, Borovička et al., 2019, see Section 2.2.4), including ESA's recent Rosetta mission to comet 67P/Churyumov-Gerasimenko. This comet's perihelion distance is presently above 1.2 AU so that although its activity releases meteoroids, it is not apparently a source of meteors on Earth. However, being a typical Jupiter family comet, its orbit can change substantially within decades or centuries (Królikowska, 2003) and the unstable nature of its meteoroid stream is confirmed by dynamical modelling (Soja et al., 2015).

Meteoroid Ablation Modelling and Stream Modelling

Major meteor showers have always been relatively easy to identify in datasets around the time of their maxima, when stream meteoroids greatly outnumber sporadics. Minor streams and showers (Chapter 9, Williams et al., 2019) are now increasingly identified as datasets grow and powerful search techniques are developed. Meteor velocity measurements are one of the best examples of the importance of observational precision enhancing theoretical understanding. Critical in evaluating the existence of hyperbolic meteoroids with an interstellar origin (Chapter 10, Hajduková et al., 2019), sufficient velocity accuracy will also help to characterise, for example, trail structure within meteoroid streams (Chapter 7, Vaubaillon et al., 2019, see Section 7.7). Our mathematical models need more precise data than has been available to date, so the parameters in the models are often poorly constrained. However, the advent of high-precision data allows the range of errors to be narrowed (e.g. Abedin et al. 2015). Modern computer power not only enables the processing of massive observational datasets; it can greatly improve the reliability of physical models. To model the meteoroidal influx to the Earth or other planets (Wiegert et al., 2009; Pokorný et al., 2017), the evolution of particles is modelled beginning with their creation from the parent body populations, through streams and later dispersion into the sporadic background.

Interpretation of observational data is based strongly on physical models. The interaction between meteoroids and the atmosphere depends on many factors, including the size and speed of the meteoroid and the height at which ablation takes place. Small meteoroids may interact with individual air molecules, while larger, more deeply penetrating meteoroids form a shock front that changes the rate of energy and momentum transfer (Chapter 1, Popova et al., 2019). Fragmentation is a particularly difficult issue to handle, which can affect conclusions about the density and structure of meteoroids (Chapter 2, Borovička et al., 2019). High-precision observations are a significant advantage in constraining the many free parameters in ablation models, including deceleration and fragmentation, and telescopic tracking systems may be particularly useful in this context (Campbell-Brown et al., 2013).

Practical Applications

Although the nineteenth century brought the realisation that the Earth's passage through cometary debris streams causes annual meteor showers, it is essentially at the start of the twenty-first century that outburst forecasts have become routine. The reliability of forecasts depends on a number of factors, often relating to the parent comet (Vaubaillon, 2017). Providing a forecast for human observers to view one of the sky's great displays can be regarded as a practical application of meteor astronomy. A high level meteor storm is not only a visual spectacle to be witnessed just a few times in a lifetime by travelling to the right point on Earth; in the space age it can very briefly increase the hazard to spacecraft by orders of magnitude (Ma et al., 2007). But such a storm is of short duration, with the Earth traversing the really dense region of space perhaps in under an hour. Overall, the risk to spacecraft is dominated by the sporadic background (Chapter 11, Drolshagen and Moorhead, 2019, see Section 11.5.2.4). The hazard is not restricted to spacecraft orbiting Earth; the 2014 approach of Comet C/2013 A1 (Siding Spring) to Mars showed the importance of computing dust and meteoroid impact risks to spacecraft elsewhere (Moorhead et al., 2014).

A detailed understanding of the inner Solar System meteoroid population has become essential to modern society. Models are now available which quantitatively map the temporal and spatial density variations of meteoroids in interplanetary space (see Chapter 11, Drolshagen and Moorhead, 2019, and Chapter 7, Vaubaillon et al., 2019, Section 7.4.8).

The discovery of lunar water (Pieters et al., 2009) has renewed interest in colonising the Moon. In this regard estimation of the meteoroid flux to the lunar surface becomes a practical task. Until LADEE, it was monitored by observations of visual light flashes from large meteoroids with masses > 1 kg (Suggs et al., 2014). Our understanding of meteoroid and dust fluxes on airless bodies has improved in the last two decades (see Szalay et al., 2018, and references therein).

Incidentally, spacecraft themselves yield extensive data on occasions when they re-enter Earth's atmosphere (Yamamoto et al., 2011) behaving like large fireballs and detectable via the various phenomena associated with such events. There is, moreover, the advantage of known entry parameters.

The other category of hazard is at larger sizes. Near-Earth asteroid surveys beginning in the 1970s and continuing today have catalogued potential impactors, gradually extending the size limit downwards as advancing survey capabilities scan more sky to deeper magnitudes. The more likely occurrences remain those at intermediate sizes (Tunguska, Chelyabinsk) and even if the individual events are unforeseen, research gives an understanding of their frequency and effects (Chapter 12, Svetsov et al., 2019).

Meteor Showers and Meteor Nomenclature

With the most famous showers, there is never ambiguity as to what is being referred to, e.g., the Perseids are the debris of comet 109P/Swift-Tuttle. One theme of this book is that well-defined or well-structured streams eventually disperse into the sporadic background. Inevitably some showers are hard to detect or define. In such cases it may be unclear whether or not different authors are writing about the same shower. The common use of a shower or stream list as standards would help to promote clarity in the literature. Over the years some lists of showers or streams have become widely used, e.g., the list of Cook (1973) and the International Meteor Organization's "Working list of meteor showers" (Rendtel, 2014).

In addition to its efforts to formalise what we mean by a meteor shower and a meteoroid stream (Chapter 9, Williams et al., 2019, see Section 9.2), the IAU, via its Meteor Data Center (MDC), now maintains a shower list (see Section 9.4.3) which can serve as a standard in shower nomenclature. Provisional names are assigned to newly discovered showers. The IAU's Commission F1 operates a Working Group on Meteor Shower Nomenclature, which recommends the showers that are well enough established to be officially approved by the IAU. There are presently 112 established showers (see Tables 9.2, 9.3 and 9.4). As has been traditional (though not quite universal, which is one of the problems when no standard exists), the shower name relates to the part of the sky from which the shower's meteors appear to radiate (Jenniskens, 2008), the radiant being a well-defined direction for meteoroids arriving on similar orbital paths. As well as the name, the MDC ensures that every shower has a unique three-letter code (relating to the name as far as the uniqueness constraint allows), and a unique number which can exceed three digits, as at the time of writing, the number in the list of provisional and established showers has just passed a thousand. The reader will see the IAU number and/or three-letter code widely used in the chapters in this book. For example, the Phoenicids are PHO/254 or #254. As noted by Jenniskens (2008), this system is certainly clearer than the same shower being variably described as the Draconids, γ-Draconids, October Draconids, Giacobinids or Giacobini-Zinnerids.

Meteoroids: Sources of Meteors on Earth and Beyond

The subsequent chapters present twelve aspects of meteoroid research, concentrating on recent and current developments. A chosen feature of the book is that every chapter concludes with a section envisaging the most important future research directions. We can foresee that future advances will come from space missions, or ground-based observational surveys, or outburst predictions, that we know are going to be undertaken. Other advances will be serendipitous: Asteroid 2008 TC_3 and the Almahata Sitta meteorite notwithstanding (Chapter 4, Koten et al., 2019, see Section 4.3.3.2), we do not know when the next spectacular bolide or meteorite fall will be. Meteor science will move in exciting directions in the twenty-first century.

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Part I

Meteor Physics

1

Modelling the Entry of Meteoroids

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1.1 Introduction

1.1.1 Ablation and Fragmentation

Meteoroids represent the material remaining from the formation of the solar system and carry unique information on the earliest forming solids. They enable the study of the structure and composition of these small-scale solids, which form the seeds of planets. Meteoroids are most easily studied using the atmosphere as a detector, as they produce light, ionisation and sonic waves during interaction with the atmosphere. Under the right conditions, the passage of the meteoroid through the atmosphere may result in a meteorite falling to Earth or even the formation of an impact crater (Svetsov et al., 2019), but in most cases only the luminosity and ionisation are available for analysis. Therefore, meteoroid properties (physical, chemical and all other possible properties) need to be determined through observations. The most obvious way to evaluate meteoroid properties based on observational data is to apply a model to fit the data.

The mass loss process is called *ablation*. Ionised and luminous areas, metal layers and smoke dust appear in the atmosphere due to ablation. Meteoric material is involved in atmospheric chemistry (Dressler and Murad, 2001; Plane et al., 2018, and references therein). Meteor spectra confirm the presence of Fe, Si, Mg, H, Na, Ca, Ni, Mn, Cr, Al, Ti, FeO, AlO, MgO, OH due to ablation (Ceplecha et al., 1998). Meteors are sometimes considered as a source of organic material deposited into the atmosphere during ablation (Jenniskens et al., 2000b).

Ablation is dependent on the meteoroid size and mass, the entry velocity, the altitude of flight and the meteoroid properties. The ablation rate determines the deposition of mass, and influences the momentum and energy release into the atmosphere. Meteor radiation and ionisation, which allow us to observe meteor phenomena, are controlled by the ablation rate:

$$I = -\tau \cdot \frac{dE_k}{dt} = -\tau \cdot \left(\frac{V^2}{2} \frac{dM}{dt} + MV \frac{dV}{dt} \right); \qquad q = -\frac{\beta}{\mu V} \frac{dM}{dt} \tag{1.1}$$

here E_k, V and M are the meteoroid kinetic energy, velocity and mass, τ is the luminous efficiency and β is the ionising efficiency, q is the linear electron concentration, μ is the average mass of an ablated meteoroid atom and I is the intensity of radiation.

The classical models of meteor ablation use conservation of energy and momentum to determine the light and/or ionisation produced by a meteoroid as a function of time. Different physical processes causing mass loss are taken into consideration in the dependence on entry conditions. Meteoroids lose mass mostly as a result of vapour production. The strongly temperature-related meteoroid mass loss processes are generally called thermal ablation and other processes are usually excluded from consideration except for special cases when they are important.

The total size range of meteoroids entering the Earth's atmosphere is very large. Their sizes range from about micron dust to 10-km impactors. For some of these objects ablation in the atmosphere doesn't play a role. Analysis based on meteor physics equations similar to that introduced in the 1960s (see e.g. Popova (2004) and references therein), shows that for an impact speed of 40 km s^{-1}, stony objects ($\leq 10^{-6}$ m) decelerate before being substantially heated, and the heating of objects with radius $R \leq 10^{-4}$ m is limited by thermal re-radiation. The recent analysis of micrometeoroids collected on arctic surface snow point to mechanical destruction and weathering (Duprat et al., 2007). Rietmeijer (2002) points out that even certain classes of interplanetary dust particles that are collected almost intact in the Earth's atmosphere show traces of flash heating to 300–1000°C. For a large-scale impact it should be mentioned that cosmic objects larger than about one hundred meters will lose only a small part of their mass and energy in the atmosphere (at average impact velocity and entry angle). So, ablation is most important for cosmic objects roughly in the range of 10^{-4}–100 m. Note that the largest annual event appears to have initial kinetic energy of about $E_k \sim 5-10$ kt TNT (Nemtchinov et al., 1997; Brown et al., 2002b) (i.e. mass $M \sim$ 150–300 t and diameter $\sim$ 4–5 m).

In addition to the basic equations of ablation for a single particle, fragmentation must be taken into account. Evidence for fragmentation may be direct (observed breakups in flight, meteorite strewn and crater fields) or inferred from multiple differences between theoretical predictions and observations. For example, numerous studies of the light curves of faint meteors (e.g. Jacchia, 1955; Jones and Hawkes, 1975; Fleming et al., 1993; Murray et al., 1999; Koten et al., 2004, and others) have shown that light curve shapes are extremely variable, and do not match the light curve predicted by the single-body model. Irregular ionisation profiles, the scatter of underdense decay times in radar meteors and short trails, flashes and flares on light curves, luminosity in shutter breaks, the difference between dynamic and photometric masses and other data may be explained by fragmentation. So modelling of meteoroid entry includes fragmentation models.

Different fragmentation mechanisms are considered when interpreting observations and modelling. Disruption due to heating or due to aerodynamical loading are the main ones. Several types of fragmentation, which include decay of a meteoroid into few non-fragmenting pieces; progressive disintegration into successively disintegrating fragments; quasi-continuous fragmentation (a gradual release of the smallest fragments from the body and their subsequent evaporation) and simultaneous ejection of large number of small particles (giving rise to meteor flares), are usually considered. Various combinations of these types may be observed and included in modelling for the same body.

The ablation and fragmentation proceed at the altitudes of optical and radio meteor observations, i.e. mainly at 130–20 km. High-altitude meteors were registered as high as 200 km (see Section 1.2.1). For a specific object the ablation and fragmentation altitudes are dependent on its size (larger bodies penetrate deeper), on entry velocity (the higher the velocity, the higher the aerodynamical loading and the higher the incoming energy flux) and on the meteoroid origin, composition and structure (cometary material is deposited higher than asteroidal matter: Rietmeijer, 2000).

Small and large meteoroids in the atmosphere are observed by different methods, have different ablation altitudes, and their interaction with the atmosphere occurs in different flow regimes (see Subsection 1.1.2). The physical conditions during meteoroid entry change considerably as a function of altitude and different processes are responsible for ablation at different stages of meteoroid flight. Different models are used to describe the entry of small and large meteoroids. Many models aim to reproduce meteoroid behavior in the atmosphere (deceleration and/or light curves) in different flow conditions. Other models are trying to describe the physical conditions that occur around the meteor body. The main goal of this chapter is to describe the current state of modelling of different scale meteor phenomena, to review current entry models, and to discuss their boundaries and limitations.

Following an introduction of ablation theory and description of the flow regimes and their boundaries (Subsections 1.1.2–1.1.4), the chapter is broken up into three sections covering different regimes of meteoroid-atmosphere interaction: free molecular flow (Section 1.2), the transition regime (Section 1.3), and continuous flow (Section 1.4). Subsections are devoted to the main issues of each flow regime. Sputtering (Subsection 1.2.1), luminous and ionisation efficiencies (Subsection 1.2.2), and head echoes and ionisation radius (Subsection 1.2.3) are included in the free molecular flow section. Fragmentation of small meteoroids as well as the parameters of the luminous area are discussed in Subsections 1.2.4 and 1.2.5. The formation of the screening vapour cloud around the meteoroid and current modelling efforts in the transition regime (including heat transfer coefficient estimates, description of the conditions in the luminous area, etc.) are presented in Section 1.3. In the continuous flow section, the ablation coefficient and luminous efficiency are discussed in Subsections 1.4.1 and 1.4.2. Modelling of spectra, fragmentation models and a short description of hydrodynamical modelling are described in Subsections 1.4.3–1.4.5. The subsections for different regimes are not the same, since different emphasis is placed on different issues in each regime. The ionisation efficiency has been studied for free molecular flow since radars observe faint meteors, and there are no detailed studies of ionisation in bolides. In contrast, spectral modelling has been done primarily for bolides, since these spectra are rich and thermal equilibrium conditions can be assumed. Concluding remarks are presented in Section 1.5.

1.1.2 Different Regimes of Meteoroid Interaction with the Atmosphere

The physical conditions during meteoroid entry change considerably as a function of altitude; in the range of ablation altitudes, the atmospheric density varies by orders of magnitude (from 10^{-10} kg m^{-3} at 200 km altitude down to 1 kg m^{-3} at the ground). Corresponding momentum and energy fluxes are equal to $\rho_a V^2$ and $\rho_a V^3/2$ in the absence of meteoroid surface shielding, where ρ_a is the atmosphere density at the altitude of flight. For a meteor radiating between 130 and 80 km altitude the fluxes increase more than 3000 times from the beginning height to the end. This large variation in the fluxes leads to the fact that the conditions of meteoroid-atmosphere interaction change along the trajectory.

The local flow regime around the falling body determines the heat transfer and mass loss processes. Two limiting cases are evident in the meteoroid interaction with the atmosphere. If the meteoroid is small enough, or the altitude of flight is large enough, the mean free path of the air molecules is larger than the meteoroid size. The flow can be considered to be individual particles moving in straight lines, and the meteoroid is effectively under particle bombardment, which causes the meteoroid heating and an appearance of evaporated atoms/molecules with thermal velocities (Figure 1.1). The appropriate gas dynamic regime is determined by the magnitude of a Knudsen number, which represents the ratio of the molecule mean free path l to a characteristic body dimension R: $Kn = l/R$. The free-molecular flow corresponds to $Kn > 10$, where interparticle collisions are negligible. As the atmosphere density increases, the mean free path decreases. When the Knudsen number becomes small compared to unity, of the order of $Kn \leq 0.1$, the medium can be treated as a continuous one and described in terms of the macroscopic variables: velocity, density, pressure and temperature. The reduction of the free path length with a decrease of flight altitude leads first to the formation of a viscous layer around the body and then to the formation of a shock wave in front of it. A large meteoroid at a relatively low altitude (where the shock wave is formed) is satisfactorily described by hydrodynamic models.

However, the Knudsen number for undisturbed air is insufficient to describe air-meteoroid interaction because the presence of evaporated molecules affects the flow.

Bronshten (1983) suggested using a modified Knudsen number Kn_r: $Kn_r = (V_r/V)Kn$, which takes into account the increase in the concentration of evaporated molecules near the meteoroid due to the difference between the thermal velocity V_r and the meteoroid velocity V. This correction shifts the boundaries between the flow regimes upward in height. Since the difference between the thermal velocity and the velocity of the meteoroid affects the physics of the interaction process, these boundaries depend on both the size and the speed of the meteoroid. In the process of modelling the transition flow

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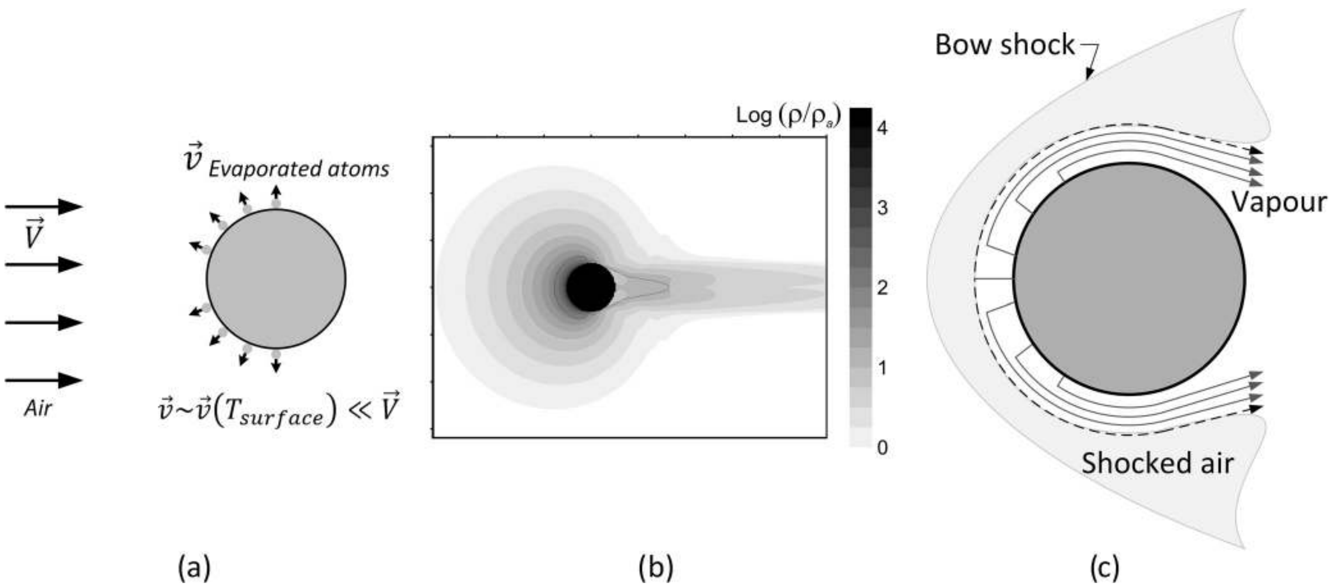

Figure 1.1. Schematic picture of the interaction of a meteoroid with the atmosphere in different flow regimes; (a) free molecular regime, where air particles reach the meteoroid surface, causing the appearance of evaporated atoms; (b) in the transition regime a vapour cloud is formed in front of the meteoroid, density distribution according the air-beam model (see Section 1.3) is shown; (c) a shock wave is formed in the continuous flow conditions.

conditions, it is necessary to take into account the shielding of the meteoroid surface by evaporated material and the subsequent reduction of the heat transfer coefficient (Popova, 2004 and references therein).

There are independent estimates of the boundary between the free-molecule and transition regimes (Popova et al., 2000, 2001; Stokan and Campbell-Brown, 2015). The high velocity of fast meteors produces a high evaporation rate and the vapour pressure exceeds aerodynamical loading (Popova et al., 2000). A vapour cloud is formed around the body and screens the surface from direct impacts of incoming air molecules. The corresponding upward shift in the flow regime boundaries is consistent with the estimate from the modified Knudsen number Kn_r (Popova et al., 2000, 2001; Popova, 2004). For example, for the most part in Leonids (larger than about 10^{-3} m) the interaction takes place in the transition regime from free-molecule flow to continuous due to their high entry velocity (Figure 1.2).

Stokan and Campbell-Brown (2015) compared the number density of atmospheric and evaporated particles at first collision. They found that for a representative meteoroid travelling at 40 km s^{-1} with a radius of 10^{-3} m (corresponding to an approximate mass of 10^{-5} kg with a density of 1000 kg m^{-3}), the shielding of the meteoroid surface should be taken into account below about 105 km altitude, which is in agreement with other estimates (in Figure 1.2 these estimates are recalculated for 70 km s^{-1} velocity).

Thus, the ratio of the meteoroid size to the atmospheric mean free path at different altitudes, corrected for the meteoroid velocity, determines the mode of interaction with the atmosphere and the character of the ablation (Bronshten, 1983; Popova, 2004). Large meteoroids lose most of their mass in the continuum flow regime, whereas small meteoroids interact with the atmosphere mainly in the free molecular flow or transition flow regimes. Very roughly, the boundary may be estimated as ~1 cm (Borovička, 2005a). Large meteoroids spend a longer time in the atmosphere before they disintegrate and give rise to more phenomena; they can be significantly decelerated, produce more complex light curves, and can drop meteorites in some cases.

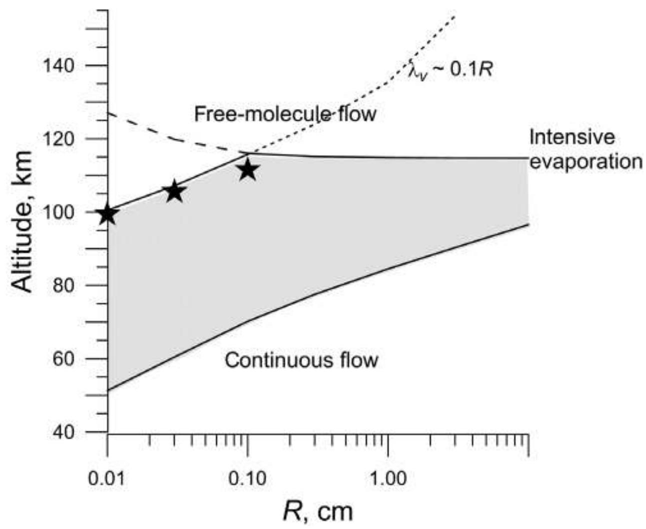

Figure 1.2. Boundaries of different flow regimes taking into account the presence of an ablation vapour cloud in front of a meteor. The intensive evaporation altitude and the line where the free path length in vapour λ_v is ten times smaller than meteoroid size R, are shown (Popova et al., 2000). The estimates correspond to 70 km s^{-1} entry velocity and cometary meteoroid composition. Stars mark the altitudes where the ratio of evaporated to atmospheric particles is significant according to the estimates by Stokan and Campbell-Brown (2015). Grey area corresponds to transition regime.

1.1.3 Main Equations Used in Modelling

The physical conditions during the meteoroid entry change considerably as a function of altitude and different processes may be responsible for ablation at different stages of meteoroid flight through the atmosphere. Therefore, we must emphasise that it is incorrect to apply the approximations/equations obtained for one regime to another.

The thermal energy received by the meteoroid from the impinging air molecules is balanced by radiative loss, temperature increase, melting, phase transitions, and by vapourisation of the meteoric constituents (Levin, 1956; Jones and Kaiser, 1966; Lebedinets et al., 1973). The standard heat balance equation for a spherical particle may be written as follows:

$$\pi R^2 \Lambda \frac{\rho_a V^3}{2} = 4\pi R^2 \varepsilon \sigma_b (T_s^4 - T_0^4) + \frac{4}{3}\pi R^3 \rho_m c \frac{dT_s}{dt} - Q\frac{dM}{dt} \qquad (1.2)$$

The energy flux received from the impacting air molecules ($1/2 \cdot \Lambda \rho_a V^3$) is used for thermal radiation cooling, meteoroid heating and ablation. Here Λ is the accommodation coefficient (or heat transfer coefficient), which determines the fraction of incoming energy flux reaching the meteoroid surface. The heat transfer coefficient Λ is often denoted as C_h, especially in papers devoted to modelling in the continuous flow conditions. If there is no shielding in free molecular flow, the Λ value is equal to unity. The first term on the right-hand side of the equation is the radiation loss, where ε is the emissivity coefficient, σ_b is the Stefan-Boltzmann constant, and T_s and T_0 are the temperature of the particle surface and the atmospheric environment, respectively. The second term is the heat consumed to increase the temperature of the particle (c is the bulk specific heat, ρ_m is the particle density). The last term is the heat consumed in the transfer of particle mass into the gas phase, where Q is the ablation heat including all the energy needed to melt and/or vapourise meteoroid material.

A meteoroid, even one that is only 1 mm in size, will not heat uniformly. To determine the temperature at the surface, the thermal conduction equation may be solved in the meteoroid interior simultaneously with the modelling of the entry (Čapek and Borovička, 2017), or a simplification can be used. It is assumed that a shell of the meteoroid, the thickness of which is determined by the material parameters, heats uniformly, while the interior remains cool (Love and Brownlee, 1991; Campbell-Brown and Koschny, 2004; McAuliffe and Christou, 2006).

Mass is considered to be lost through sublimation and evaporation, vapour thus being the final stage of majority of the ablated material. It is often assumed that sublimation begins as soon as the meteoroid temperature starts to rise (Lebedinec and Šuškova, 1968; Lebedinets et al., 1973; Love and Brownlee, 1991; Moses, 1992; Adolfsson et al., 1996; Campbell-Brown and Koschny, 2004; Rogers et al., 2005, and many others) with the temperature dependent mass loss rate being modelled using the Knudsen–Langmuir formula (Bronshten, 1983):

$$dM/dt = -4\pi R^2 p_v(T_s)\sqrt{\frac{\mu}{2\pi k_b T_s}}, \qquad \log_{10} p_v = A_v - B_v/T_s. \qquad (1.3)$$

Here k_b is the Boltzmann constant, p_v is the saturated vapour pressure and A_v and B_v are empirically or theoretically determined constants for specific substance. The influence of external gas pressure on the evaporation is neglected, i.e. this approach is fully justified in the frame of free molecular flow and can't be applied in the continuous flow conditions. In the transition regime the application of (Equation 1.3) is limited by increasing counterpressure.

The energy equation (Equation 1.2) is widely used in numerous papers devoted to the entry of small meteoroids. Its right-hand side is modified by different authors depending on the purpose of the study and the size of meteoroids under consideration. For example, the absorption of solar radiation may be included (Moses, 1992; McAuliffe and Christou, 2006), and the atmosphere radiation may be excluded (Love and Brownlee, 1991; Moses, 1992, and others). In the case of small particles, along with thermal cooling, it is necessary to take into account the energy and the mass lost to sputtering. Neither process is significant in the case of large meteoroids.

McNeil et al. (1998) calculated vapour pressures of the various melt constituents and introduced the concept of differential ablation. They assumed sequential release of different compounds according to their volatility. A current example of an ablation model which also predicts the injection rates of individual elements is the Chemical Ablation MODel (CABMOD) (Vondrak et al., 2008). Genge (2017) incorporated partial melting behaviour of particles to study micrometeorite formation.

In addition, other energy and mass losses are considered and corresponding terms are included in Equations (1.2) and (1.3). At high temperatures, meteoroids may lose mass through spraying of the melted layer on the surface (Bronshten, 1983; Campbell-Brown and Koschny, 2004; Briani et al., 2013; Čapek and Borovička, 2017). The deeper the meteoroid penetrates into the atmosphere, the larger the received energy flux will be. The altitude at which the received energy flux exceeds the energy losses from meteoroid heating and thermal radiative cooling may be called the height of intensive evaporation. For porous bodies with $R \sim 0.1$–10 cm this altitude is about 110–130 km (Lebedinets, 1980; Bronshten, 1983). Below this altitude the incoming energy contributes mainly to ablation; heat conduction and the thermal radiation can be excluded from consideration (Lebedinets, 1980; Bronshten, 1983). Equation (1.2) is transformed into the following mass loss equation:

$$\frac{dM}{dt} = -\Lambda \cdot \frac{\pi R^2 \rho_a V^3}{2Q} \qquad (1.4)$$

which is correct after the beginning of intensive evaporation. The conditions in the body itself usually are not of interest, it is assumed that the meteoroid surface temperature remains at the melting/boiling value. Ablation modelling of bolides and photographic meteors is usually restricted to this equation; the stage of meteoroid heating is not included into the modelling (Ceplecha et al., 1998). An additional mechanism was included in Equation (1.4) by Borovička et al. (2007). The authors suggested that small fragments can be detached from the meteoroid, producing additional mass losses, and called this process erosion.

The dominant role of thermal ablation in meteoroid mass loss has been questioned by some authors. Spurný and Ceplecha (2008) proposed triboelectric charging as the most important