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1.1 Introduction

The beginning of the space age 60 years ago brought about a new era of discovery for the science of astronomy. Instruments could now be placed above the atmosphere, allowing access to new regions of the electromagnetic spectrum and unprecedented angular and spatial resolution. But the impact of spacelight was nowhere as important as in planetary and space science, where it now became possible – and this is still the case, uniquely among astronomical disciplines – to physically touch, sniff and directly sample the bodies and particles of the solar system. A cursory reading of the chapters in this volume will show that meteor astronomy has progressed in leaps and bounds since the era of visual observations. Indeed, it has evolved into a true analytical science, on a par with sister disciplines such as cometary science and meteoritics. Unfortunately, instrumentation specifically designed to detect meteors on planets other than the Earth has yet to fly on a planetary mission.

Two factors have now brought the era of exo-meteor astronomy closer than ever before. One is the serendipitous detection of meteors and their effects in the relatively thick atmospheres of Mars and Jupiter as well as the tenuous exospheres of Mercury and the Moon, developments of sufficient import to warrant dedicated sections in this chapter. The other is technological advances in the detection of short-lived luminous phenomena in planetary atmospheres and a new understanding of the unique operational aspects of off-Earth meteor surveys. Throughout this chapter we use the term “extraterrestrial meteor” or “exo-meteor”. We base our use of this terminology on the distinction between meteoroids and meteors. While “meteoroid” refers to particulate matter in interplanetary space, a “meteor” is a phenomenon – the light emitted during the entry of a meteoroid into an atmosphere – that is intrinsic to that atmosphere. Therefore, the term “extraterrestrial meteor” as previously used in the literature (Selsis et al. 2003) and the principal subject matter of this chapter, uniquely defines meteors in planetary atmospheres other than the Earth’s.

Why study these meteors? Despite the current rapid progress of Earth-based meteor astronomy, our ability to do useful science will always be limited by the simple fact that we can only sample meteoroid populations with orbits that cross the Earth’s. Yet, there is every reason to expect, for instance, that the solar system is criss-crossed with a web of dust streams spread along cometary orbits, all-but-invisible except where the particles are packed densely enough to be detectable, typically near the comet itself (Sykes and Walker 1992; Reach and Sykes 2006; Gehrz et al. 2006). Extending meteor observations to other planetary bodies allows us to map out these streams and investigate the nature of comets whose meteoroid streams do not intersect the Earth. Observations of showers corresponding to the same stream at two or more planets will allow to study a stream’s cross-section. In addition, the models used to extract meteoroid parameters from the meteor data are fine-tuned, to a certain degree, for Earth’s atmosphere. Processing exo-meteor data with these same models will be particularly useful in demonstrating their robustness or uncovering as-yet-unknown limitations that will impact our Earth-centred understanding of the meteor phenomenon. Last but not least, observations of exo-meteors will promote the safety of deep space missions, both crewed and robotic, by identifying regions where the meteoroid flux is high enough to pose significant risk to people or machines.

It is fortuitous that the atmospheres of both our neighbouring planets lend themselves to meteor observations. Mars combines a predominantly clear atmosphere and a solid surface to serve as a stable observation platform. It is also the target of a vigorous international exploration program. Venus may, at first glance, not appear as appealing; apart from the extreme environmental conditions, the Venustian sky is perpetually hidden from the surface by planet-encircling cloud layers (Esposito et al. 1983). Yet this still leaves the possibility of observing meteors from above the atmosphere, a technique already employed in observing meteor showers at the Earth (Jenniskens et al. 2006).

1.2 Theoretical Expectations

Single body meteoroid ablation in the Martian atmosphere has been modelled by several workers (Apsitein et al. 1982; Adolfsson et al. 1996; McAuliffe 2006). Adolfsson et al. (1996) compared the height and brightness of meteors at Mars and the Earth, assuming that these properties do not sensitively depend on atmospheric composition. They found that, in general, meteors reach their maximum brightness within the same range of atmospheric density (Figure 1.1). Martian meteors ablate between altitudes of 90 and 50 km; fast (30 km s$^{-1}$); low-
density (0.3 g cm\(^{-3}\)) meteoroids in the two atmospheres generate meteors of similar brightness while slower, denser (3 g cm\(^{-3}\)) particles produce significantly fainter meteors at Mars. They were able to reproduce their numerical results with the intensity law

\[ I_m \propto m v^{3+n}/H \quad (1.1) \]

where \( m \) is the meteoroid’s mass, \( v \) its atmospheric impact speed, \( H \) the density scale height and \( n \) depends on the meteoroid type as described above. Christou (2004b) applied the same principles to the case of Venus, finding that, everything else being equal, Venusian meteors would be as bright or brighter than at the Earth but also shorter-lived. Using the same argument as Adolffson et al., whereby the meteoroid ablation rate peaks between \( 10^{-9.2} \) and \( 10^{-7} \) g cm\(^{-3}\), meteors would appear between 100 and 120 km in the venusian atmosphere and above the haze layer (Esposito et al., 1983), boding well for meteor searches from Venus orbit. McAuliffe and Christou (2006) confirmed these earlier conclusions with a numerical ablation model that takes into account radiative surface cooling and heat conduction within the meteoroid, effects not considered in Christou (2004b). Additional numerical work has been carried out in the context of the presence of layers of meteoric metals – in both neutral and ionic form – in the upper atmospheres of these planets with emphasis on Mars (e.g Pesnell and Grebowsky, 2000a, see Section 1.5). A first step for such studies has been to determine the mass deposition rate of individual atomic metal species (Fe, Mg) from the ablating meteoroid as a function of altitude. The deposition rates of these species represent different components of the gross ablation rate of the meteoroid, equivalent to meteor brightness in the single body ablation model. The results indicate – as in the earlier works – that the maximum brightness of martian meteors is reached \( \sim 10 \) km lower in the atmosphere and over a similar or somewhat broader range of altitudes compared to terrestrial meteors. Similar calculations were done as part of a recent study (Frankland et al., 2017) of O\(_2\) removal efficiency at Venus by CO\(_2\) oxidation on meteoric remnant particles. These show, as for Mars, that the maximum deposition rate of meteoric metals agrees with the earlier predictions from single body ablation modelling, but also indicate that significant ablation may be taking place at altitudes as high as 130–135 km.

### 1.3 Observational Record

As mentioned in the Introduction, no direct optical detection of exo-meteors has been achieved to-date. A transient event observed by the Optical and Ultraviolet Visible Spectrometer (OVUVS) instrument onboard the Pioneer Venus Orbiter on 1979 February 17 (Huestis and Slanger, 1993) was interpreted as a serendipitous detection of a meteor trail but remains unconfirmed. A detection of a meteor associated with a known Jupiter-family comet by the dual-eye PanCam imager onboard the Spirit rover on Mars was reported by Selsis et al. (2005). Later work by Domokos et al. (2007) showed that the claimed 2005 detection was most likely a cosmic ray hit on the PanCam detector. In addition, the non-availability of a broadband or clear filter on both PanCam eyes severely limited the scope of the search, which did not yield any definite detections. This highlights the need for dedicated instruments to carry out exo-meteor observations.

Although not a search for exo-meteors per se, it is worth mentioning here a successful recording of a meteor shower from space. The \( 13^\circ \times 10^\circ \) Wide Field Imager (WFI) channel of the Ultraviolet and Visible Imagers and SpectrographicImagers (UVISI) suite on board the Midcourse Space eXperiment (MSX) satellite logged 29 meteor detections during an effective observing time of \( \sim 20 \) min on 1997 November 17. The Leonid flux derived from these observations was \((5.5 \pm 0.9) \times 10^{-2} \text{ km}^2 \text{ hr}^{-1} \) down to a limiting absolute magnitude of \(-1.5^m\) and a population index of \( r=1.7\) (Jenniskens et al., 2000). It demonstrates that detection of even moderately strong meteor showers with instruments not specifically suited to the task is possible from orbit.

### 1.4 Predictions

#### 1.4.1 Observability

For Mars, Adolffson et al. (1996) estimated the flux of meteors of absolute visual magnitude \( m=-1^m-+4^m \) at Mars to be 50% of that at the Earth. Domokos et al. (2007) placed an upper flux limit of \( 4.4 \times 10^{-9} \text{ km}^2 \text{ hr}^{-1} \) for >4 g meteoroids, consistent with the Adolffson et al. prediction \((4 \times 10^{-7} \text{ km}^2 \text{ hr}^{-1})\) derived by their scaling of the Earth flux according to the Grün et al. (1983) model. Such flux estimates, though approximate, may be used to estimate sporadic meteor detection rates for a given camera system from specific vantage points. For instance, the expected detection rate by a meteor camera system specifically designed for operation in space (Smart Panoramic Optical Sensor Head or SPOS H): Oberst et al. (2011) is between 1 and 7 meteors per orbit or between 14 and 74 per Earth day (\( \sim 11 \) nightside passes) for a 400 km altitude circular orbit at a limiting apparent magnitude of \(+2^m\) (Christou et al., 2012). Bouquet et al. (2014) find a similar detection rate for a SPOSH-like system operating in Earth orbit.

For Venus, Beech and Brown (1995) investigated the feasibility of observing bright fireballs (entry mass of \( 10^4-10^7 \) kg) in the venusian atmosphere from the Earth. They found, for instance, that events with apparent magnitude \(+10^m\) – equivalent to an absolute magnitude of \(-24^m\) – or brighter will occur every three weeks whereas fainter, \(+15^m\) events of \(-19^m\) meteor absolute magnitude will occur every 2 days. The authors pointed out that the flux could be higher at times when streams rich in fireball-producing meteoroids cross the orbit of Venus and advocated long-term monitoring programmes to determine whether such fireball-rich streams exist. Interestingly, Hansell et al. (1993) reported the detection of seven flashes of \((1-20) \times 10^9\) J in luminous energy

\(^1\) The magnitude a visual observer would perceive of a meteor at 100 km distance and at the zenith
from narrowband observations at 777 nm with an effective observing time of 3 hr, a rate of $2.7 \times 10^{-12}$ km$^{-2}$ sec$^{-1}$ which they attributed to lightning. This is $6 \times (2 \times 24h)/3h = 100$ times the Beech and Brown rate for $-20^m$ fireballs assuming a $10^{-3}$ luminous efficiency.

### 1.4.2 Showers and Outbursts

It has been known since ancient times that meteor activity is not uniformly random but tends to concentrate around specific times of the year. The first association between a comet and a meteor shower was made 150 years ago Schiaparelli (1867) with the first systematic survey of meteor shower activity carried out in the middle of the 20th century Lovell (1949). Repeating the same exercise on other planets, we are faced with the added difficulty that there are essentially no observations, but a multitude of potential parent bodies that may be producing strong meteor activity or nothing at all. To illustrate the problem, consider the case of (3200) Phaethon associated with one of the most prolific annual showers, the December Geminids (Whipple 1983). The nature of this object has been debated for decades (Ryabova 2015, 2018). Recent observations from the Sun-orbiting spacecraft indicate activity of an exceptional type, not related to release of dust grains from within a sublimating matrix Li and Jewitt 2013. Arguably, the motivation to study and explain arose because of the “happy coincidence” whereby the Geminid stream intersects the orbit of the Earth.

The distance of the comet orbit to the planet orbit ($\Delta$) offers a necessary, but not sufficient, criterion for a comet to produce an observable meteor shower. Because it is computationally expedient to calculate it for a large number of orbits, it has been employed and again in the literature (Terentjeva 1993, Christou and Beurle 1999, Treiman and Treiman 2000, Larson 2001, Christou 2004b, Selsis et al. 2004, Neslusan 2003). A byproduct of these works is that we now have a fairly strong grasp on the population characteristics of planet-approaching comets for Mars, Venus and the outer planets as compared to the Earth’s. They allowed to identify the best candidate parent bodies as input to more sophisticated techniques.

The observational record at the Earth teaches us that the minimum approach – or its projection on the orbit plane – cannot be the sole discriminator for meteor activity. While it works for e.g. the Perseids in August (109P/Swift-Tuttle), Leonids in November (55P/Tempe-Tuttle) and Lyrids in April (C/1861 G1 (Thatcher)) in the sense that $\Delta$ takes particularly small values for these objects, it fails in several prominent cases such as the Taurids (2P/Encke), $\eta$ Aquariids and Orionids (1P/Halley) where $\Delta$ is of order 0.1 au or greater. An important additional factor is the dynamical type of the orbit. Because of the efficient action of Jupiter in rapidly scattering the orbits of dust grains away from the comet’s, annually recurring meteor activity from Jupiter Family comets is typically weak or non-existent and large numbers of meteors appear only during outbursts e.g. the Draconids in October (21P/Giacobini-Zinner) or the Bootids in June (73P/Schwassmann-Wachmann 3).

To identify the best shower candidates, Christou (2010) refined the $\Delta$-search technique by exploiting the tendency for strong meteor showers to be associated with Halley-type and Encke-type comets, rather than Jupiter-family and Long-period comets. The final distillation of the best candidates among potential parent bodies and their distribution along the planetary orbit is illustrated in Figure 1.2. Note the relative lack of objects on the left half of each orbit, suggesting a semi-annual modulation of the shower frequency. This is likely a consequence of the method since the observed level of terrestrial meteor activity is a contributing factor in the predictions. Future surveys at Mars and Venus should confirm this.

Arguably, modern meteor forecasting was brought on by (a) the advent of cheap computing power, and (b) adopting the so-called trail model of cometary dust evolution (Kondrateva and Reznikov 1984, McNaught and Asher 1999) where populations of meteoroids ejected from the comet at a given perihelion passage maintain their cohesiveness in space as distinct “trails” of particles over many orbital revolutions. The key result is that the dynamical evolution of trails is deterministic, so meteor outbursts can be reliably forecasted with numerical simulations of large number of test particles to serve as tracers of the dust evolution. The potential of this approach was spectacularly demonstrated during the Leonid meteor storms in 1999 and 2001. Guided by trail model predictions, observational campaigns are now routinely organised in advance to study debris reaching the Earth from the same comet at different years, from different comets as well as from different comet types (Wiegert et al. 2011, Koten et al. 2013, Ye et al. 2015).

It was only a matter of time until the trail method found application in exo-meteor shower prediction. It was used by Vaubaillon and Christou (2006) and Christou et al. (2007) to identify dust trail encounters between Jupiter-Family comets 45P/Honda-Mrkos-Pajdusakova with Venus and 76P/West-Kohoutek-Ikemura with Mars respectively, to simulate dust ejection from comet 1P/Halley $\sim$5,000 yr ago to form a model of the stream and study how the characteristics of the corresponding shower differ from Venus to Earth and to Mars.
The same approach was used by Christou and Vaubaillon (2011) on a study of larger scope, namely to simulate the meteoroid streams of the parent body candidates in Christou (2010). They found that particles from many of these comets physically approach Mars and Venus and do so year after year, suggesting the presence of annually-recurring activity. The typical efficiency of particle delivery – in other words the fraction of particles physically encountering a planet out of those ejected – is $\sim 10^{-4}$ per comet per planetary year. For six of these, however, the model dust distribution cross-section appears highly inhomogeneous, capable of producing outbursts of activity well above the annual level. We show one such case, the stream of comet C/2007 H2 (Skiff), in Figure 1.3. The dust distribution is reminiscent of that of the Leonids at the Earth and suggests that our planet is not alone in possessing annual showers that produce outbursts on certain years. Tables 1.1 and 1.2 show forecasts for Mars and Venus for the coming years, in addition to those in the literature (e.g. Christou 2010; Christou and Vaubaillon 2011). Interestingly, the width of a meteoroid trail decreases when its heliocentric distance decreases, leading to higher Zenithal Hourly Rate ($ZHR$) and shorter duration showers at Venus than at Mars. However, as pointed out by Christou (2004a), since the number of Mars-crossing is greater than Venus-crossing comets, we expect more meteor showers at Mars than at Earth and Venus. These two factors combine and we observe that the number of showers at Venus is quite small, and the $ZHR$ low, simply because the odds to encounter the planet are lower for Venus than for Mars.

The most recent work to model the meteoroid influx from individual comets on a planetary body has focused on the very close approach of comet C/2013 A1 (Siding Spring) to Mars (Moorehead et al., 2014; Farnocchia et al., 2014; and an enhancement of the release rate of metallic species in Mercury’s tenuous exosphere probably caused by particles from 2P/Encke (Killen and Hahn, 2013; Christou et al., 2013). These are described in more detail in Sections 1.5.3 and 1.7 respectively.

A question linked to the orbital simulations is that of the ensemble atmospheric properties of the hypothetical showers and their detectability. This problem admits to Monte Carlo simulations and has been investigated either parametrically, by varying pertinent detector properties such as field-of-view (FOV), limiting magnitude and orbital vs surface-based vantage point (McAuliffe, 2006; McAuliffe and Christou, 2006) or by using specific instruments as the baseline (Christou et al., 2012). To indicate what is possible, we quote here some results for the annual Leonid shower from Appendix C of McAuliffe. A zenith-pointed instrument with 60° FOV and limiting magnitude of +2.0m will detect 70 meteors per hr and 51 meteors per orbital revolution respectively from the Earth’s surface and from Earth orbit. The respective figures for Mars are 25 and 15 while from Venus orbit, 215 detections per orbital revolution are expected. For orbital detection, a lesson that applies to all these planets is the crucial role of the shower population index i.e the slope of the meteoroid magnitude distribution and the speed. For a given Earth $ZHR$, fast showers with shallow magnitude distribution yield the highest number of detections. In this case, a large field-of-view is preferable to high sensitivity on account of the numerous bright meteors occurring far from nadir, a finding also true for sporadics (Bouquet et al., 2014). Surface-based meteor cameras at Mars will have to contend with the varying amount of atmospheric dust. While they may achieve several tens to a few hundreds of detections per hr at times when the atmosphere is clear (dust optical depth $\tau = 0.5$), during periods of high dust loading ($\tau = 3.0$) the detection rate drops to a few per hr at best.

In conclusion, work done so far suggests that (a) with the exception of a surface camera at Venus, camera systems specifically designed for meteor work will be no less useful at Venus and Mars than at the Earth, and that (b) one should expect comparable detection rates for orbital and surface-based meteor surveys.

1.5 Ionospheric Layers from Meteor Ablation

1.5.1 Overview and State-Of-The-Art

Meteoroid ablation deposits all species common in meteoroids, such as O, Na, Mg, Al, Si, K, Ca, Ti, and Fe, into the upper atmosphere (Plane et al., 2018). Since oxygen is already present in a typical atmosphere, trace amounts of meteoroid-derived oxygen have little effect. The metal species, however, are exotic constituents of atmospheres. They behave differently from the major constituents and trace amounts of metal species can have noticeable effects. These metallic species are deposited at altitudes where the neutral atmosphere is already weakly ionised by sunlight’s ultraviolet photons. They can themselves be ionised by sunlight, by chemical reactions with existing atmospheric ions, or directly during ablation. Metallic species tend to form atomic ions like Mg$^+$ and Fe$^+$, whereas the ambient ionosphere at ablation altitude is dominated by molecular ions (Schunk and Nagy, 2006). They are destroyed by transport downwards into denser regions of the atmosphere where atomic metal ions undergo three-body reactions to form molecular ions that are quickly neutralized by dissociative recombination with an electron (Molina-Cuberos et al., 2003).

Since atomic ions cannot dissociatively recombine like molecular ions, atomic metal ions tend to be long-lived and a slow production rate of atomic ions can maintain a significant plasma population. Consequently, meteoroids affect the structure, chemistry, dynamics, and energetics of Earth’s ionosphere. Compositional profiles have been obtained by 50 (as of 2002) sub-orbital rocket flights with in situ mass spectrometers (Grebowsky and Aikin, 2002). They consistently show a metal ion layer a few km wide located between 90 km and 100 km. Observed properties are highly variable. The
many ground-based ionosondes in continuous operation regularly detect post-sunset narrow plasma layers that contain long-lived atomic metal ions at the same altitudes. These are called Sporadic E layers. Models of terrestrial metal ion layers rely on wind shear in a strong and inclined magnetic field to organize ions into narrow layers (e.g., Carter and Forbes, 1999).

Do meteoroids also produce similar layers of metal ions in the ionospheres of other solar system objects? The basic input exists throughout the solar system as meteoroids enter all solar system atmospheres at orbital speeds. However, ionospheric chemistry and magnetically-controlled plasma dynamics will differ between Earth and other objects (Molina-Cuberos et al., 2008; Schunk and Nagy, 2009). Theoretical models of the effects of meteoroids have been developed for many solar system ionospheres (e.g., Lyons, 1993; Pesnell and Grebowsky, 2000a; Kim et al., 2001; Molina-Cuberos et al., 2004; Moses and Bass, 2000; Whalley and Planck, 2010; Molina-Cuberos et al., 2008, and references therein). In general, these models predict that the ablation of meteoroids should produce a narrow plasma layer a few neutral scale heights below the main ionospheric peak. For simplicity, these models generally focus on Mg and Fe, which are cosmochemically abundant, well-known from Earth observations, and readily ionised, but other metal species will also be present.

Section 1.5.2 presents observations of candidate metal ion layers throughout the solar system. Section 1.5.3 describes MAVEN observations of metal ions at Mars. Section 1.5.4 discusses the ionospheric effects of the encounter of Mars with comet C/2013 A1 (Siding Spring) in 2014.

1.5.2 Pre-MAVEN Observations of Possible Metal Ion Layers

Radio occultation experiments have been responsible for most measurements of extra-terrestrial ionospheres (e.g., Winters, 2010). These measure vertical profiles of electron density, but cannot provide any compositional information. They have observed narrow layers of plasma near predicted ablation altitudes on many objects (e.g., Waite and Cravens, 1987; Winters et al., 2013). However, since many processes can produce, transport, and destroy ionospheric plasma, definitive confirmation of the presence of plasma of meteoric origin in an extraterrestrial ionosphere requires the detection of metal ions. Since most ionospheric observing methods detect electrons, rather than ions, direct compositional information is rare for planetary ionospheres. Furthermore, in situ compositional measurements by retarding potential analyzers and ion mass spectrometers are generally made at altitudes above the putative altitudes of metal ion layers.

Here we summarize observations of potential metal ion layers in solar system ionospheres, with the exclusion of observations made at Mars by the MAVEN mission. Since MAVEN is the only mission to provide relevant ion compositional information, MAVEN’s observations and their implications will be presented in Section 1.5.3.

At Venus, Pesnell and Grebowsky (2000a) suggested that some nightside Pioneer Venus Orbiter (PVO) electron density profiles contain meteoric layers, and Butler and Chamberlain (1976) had earlier suggested that meteoroid influx could produce the surprisingly dense nightside ionosphere. However, recent work has not favored these earlier conclusions (Fox and Kliore, 1997; Winters et al., 2008). On the dayside, Witaske and Nagy (2003) suggested that two PVO electron density profiles near the terminator (Solar Zenith Angle (SZA) of 85.6° and 91.6°) contain meteoric layers (Winters et al., 2008). Winters et al. (2013) identified 13 candidate meteoric layers at Venus in Mariner 10, Venera 9/10, and Pioneer Venus Orbiter data. However, the most convincing detection of a plasma layer whose altitude is consistent with ions derived from meteoroids is that of Pätzold et al. (2009), who used Venus Express radio occultation electron density profiles. They identified 18 instances of low-altitude plasma layers, but only at solar zenith angles between 55° and 90°. Typical peak plasma densities of $10^{10}$ m$^{-3}$ are reached between 110 and 120 km altitude, peak electron densities increase with decreasing solar zenith angle, and layer shapes are symmetric with respect to peak altitude. This work was based on early Venus Express observations in 2006–2007; a comprehensive survey of the full Venus Express dataset has not yet been published. The in situ Pioneer Venus Orbiter Retarding Potential Analyzer (ORPA) and Ion Mass Spectrometer (OIMS) did not report any detections of metal ions at their altitudes above 150 km (e.g., Brace et al., 1983, and references therein).

At Mars, Fox (2004) suggested that a Mars Global Surveyor electron density profile displayed a plasma layer near 90 km with a density of $5 \times 10^9$ m$^{-3}$ that “could be attributed to meteoric ions”. Pätzold et al. (2005) surveyed 120 Mars Express electron density profiles and found that 10 of them contained a low-altitude plasma layer between 65 km and 110 km with an average peak electron density of $8 \times 10^9$ m$^{-3}$. Subsequently, Winters et al. (2008) conducted a comprehensive survey of the entire set of 5600 electron density profiles observed by Mars Global Surveyor. They found low-altitude plasma layers in 71 of the 5600 profiles, a significantly lower detection rate than for Mars Express. An example is shown in Figure 1.4. The mean altitude of the meteoric layer was 91.7±4.8 km. The mean peak electron density in the plasma layer was $(1.33 \pm 0.25) \times 10^{10}$ m$^{-3}$ and the mean width of the layer was 10.3±5.2 km. Pandya and Haider (2012) investigated these low altitude plasma layers using the integrated total electron content between 80 km and 105 km, found a higher occurrence rate of candidate low-altitude layers than did Winters et al. (2008), and concluded that the total electron content in this altitude range increased by a factor of 1.5–3.0 when these layers were present. They suggested that some observed increases in total electron content were associated with the predicted occurrence of meteor showers, but did not show that these increases happened in multiple Mars Years. Searches for potential metal ion layers in earlier Mars datasets have been inconclusive. Using published images of electron density profiles, Winters et al. (2013) identified one candidate from Mariner 7 and seven candidates from Mariner 9. Yet when the actual data from the Mariner 9 profiles were acquired and an-
alyzed, Withers et al. (2015) concluded that “no meteoric layers have been firmly identified in the Mariner 9 dataset”. The two pre-MAVEN observations of ionospheric composition, made by retarding potential analyzers on the two Viking Landers, did not detect any metal ions in their profiles that extended down to 110 km (Hanson et al., 1977). In a series of conference abstracts, Aikin and Maguire (2003); Maguire and Aikin (2004) reported the detection of infrared emissions from the Mg$^+$ CO$_2$ ion, but this work has not yet passed through the peer-review process. We note that considerable effort has been expended to search for correlations between temporal variations in the properties of these low-altitude plasma layers and the predicted occurrence of meteor showers, but no significant relationships have been identified (Espley et al., 2007; Withers et al., 2008; Pandya and Haider, 2012; Withers et al., 2013, and Section 1.3).

At Jupiter, Pioneer 10, Pioneer 11, Voyager, and Galileo radio occultation profiles commonly show plasma layers that have widths of 10 km and densities of $10^{10}$–$10^{11}$ m$^{-3}$ at altitudes of a few hundred kilometers (Fieldho et al., 1975; Hinson et al., 1997, 1999a; Yelle and Miller, 2004). At Saturn, Pioneer 11, Voyager, and Cassini radio occultation profiles commonly show narrow plasma layers with densities of $10^{10}$ m$^{-3}$ around 1000 km altitude (Lindal et al., 1983; Nagy et al., 2006; Kliore et al., 2009). Similar narrow plasma layers were also seen by Voyager 2 at Uranus and Neptune (Lindal et al., 1987; Lindal, 1992; Tyler et al., 1989). Cassini was able to make in situ measurements of the composition of Saturn’s ionosphere during its proximal orbits, but was not able to search for metal ions. The high speeds of these atmospheric passes restricted the Cassini ion mass spectrometer (INMS) to observations at masses below 7 daltons (pers. comm., Moore, 2018).

At Titan, several Cassini radio occultation profiles have been classified as “disturbed” (T31N, T31X, T57X) (Kliore et al., 2008, 2011). The two T31 profiles display a broad plasma layer at 500–600 km altitude with peak density of 2–3×10$^9$ m$^{-3}$. The published T57 profile is not shown below 800 km (Kliore et al., 2011). Several hypotheses have been proposed for the plasma layer at 500–600 km, including meteoroid ablation (Molina-Cuberos et al., 2001, 2008) and ion precipitation (Cravens et al., 2008). Relative to the neutral scale height, this plasma layer on Titan is somewhat broader than the putative metal ion layers identified on other solar system objects. Cassini in situ observations by its mass spectrometer (INMS) that extend down to altitudes around 900 km have not detected metal ions (Vuitton et al., 2009; Cravens et al., 2010).

No features in the two Voyager 2 radio occultation electron density profiles from Triton have been suggested to be metal ion layers (Tyler et al., 1989). With a surface pressure of 1–2 Pa, it is not clear that Triton’s atmosphere is sufficiently dense to ablate meteoroids before they impact the icy surface (e.g., Moses and Bass, 2000). No features in radio occultation electron density profiles of the Galilean satellites have been suggested to be metal ion layers. There are 10 Galileo profiles for Ganymede (Kliore et al., 2001a,b), 6 Galileo profiles for Europa (Kliore et al., 1997), 8 Galileo profiles for Callisto (Kliore et al., 2002), and two Pioneer 10 and ten Galileo profiles from Io (Kliore et al., 1974, 1976; Hinson et al., 1998a). Due to the rarefied neutral atmospheres of these satellites, little ablation of meteoroids will occur prior to meteoroid impact. Furthermore, since these atmospheres are ballistic, not collisional, ablated metal species will not be suspended in the atmosphere (but see Section 1.7).

Narrow plasma layers have been observed below the main ionospheric peak in many solar system ionospheres. These have often been interpreted as being metal ion layers caused by meteoroid ablation, but direct evidence for the presence of metal ions is lacking. It is worth considering why the meteoroid hypothesis for the origin of these plasma layers is quite widely accepted, despite the absence of direct composition measurements. Two factors seem significant: (1) the existence of meteoroid-derived metal ion layers on Earth that appear analogous to these extraterrestrial plasma layers; and (2) the paucity of verifiable non-meteoroid explanations for these low-altitude plasma layers. Yet recent observations of ionospheric composition at Mars have shed new light on these issues.

1.5.3 MAVEN Observations of Metal Ions at Mars

The MAVEN spacecraft is a Mars orbiter that makes extensive measurements of the ionosphere (Jakosky et al., 2013). Two MAVEN instruments are able to detect metal ions. In situ measurements by the mass spectrometer (Mahaffy et al., 2015; Benna et al., NGIMS: 2015) are sensitive to metal ions above spacecraft periapsis (nominally 150 km, occasionally as low as 120 km) and remote sensing observations by the ultraviolet spectrometer (UVS, McClintock et al., 2014) are sensitive to Mg$^+$ ions down to approximately 80 km altitude. Both instruments have detected metal ions.

The NGIMS instrument found that metal ions Na$^+$, Mg$^+$, and Fe$^+$ are continuously present down to the lowest altitudes sampled (120–130 km) (Grebowsky et al., 2017). Densities of Mg$^+$ and Fe$^+$ are, on average, approximately equal. This was unexpected – “one might expect Fe$^+$ to be less dominant with increasing altitude because of the gravitational mass separation anticipated for diffusion processes” (Grebowsky et al., 2017). Ionospheric models also predicted that Mg$^+$ would be appreciably more abundant than Fe$^+$ (Whalley and Pland, 2010). However, the Mg$^+$/Fe$^+$ ratio on an individual orbit may vary significantly from its long-term average. Densities of Mg$^+$ and Fe$^+$ are, on average, proportional to the density of the dominant neutral constituent, CO$_2$. This was also unexpected – on Earth, “observations made above the main ionospheric metal ion layer are often characterized by complex layers associated with electrodynamic sources, with no clear trend of ordered metal ion concentration decreases with increasing altitude” (Grebowsky et al., 2017). Furthermore, “isolated metal ion layers mimicking Earth’s sporadic E layers occur despite the lack of a strong magnetic field as required at Earth” (Grebowsky et al., 2017). These metal ion layers are seen at altitudes around 140–170 km and have widths of 10 km.
The in situ NGIMS observations were unable to address how the trend of exponential increase in metal ion density with decreasing altitude continued below the 120 km limit of periapsis. Remote sensing observations are required to do so. The IUVS instrument found that Mg\(^+\) ions are continuously present in the ~75–125 km altitude range (Fig. 1, top panel; Crismani et al., 2017). Crismani et al. (2017) reported that Mg\(^+\) ions formed a layer with peak density 2.5 \times 10^{8} \text{ m}^{-3}, peak altitude of 90 km, and full-width at half-maximum of approximately 30 km. The layer shape appears symmetric with distance from the peak, distinct from the strikingly asymmetric shape of a Chapman layer.

Based on Grebowsky et al. (2017) and Crismani et al. (2017), the NGIMS and IUVS observations of Mg\(^+\) appear to be consistent, but further work is needed to synthesize them into a coherent picture of the vertical profile of Mg\(^+\) density from 75 km to 175 km.

Both radio occultation experiments and MAVEN IUVS have observed a plasma layer at 90 km altitude. However, radio occultation experiments observe a sporadic layer of electrons with peak density in excess of 10^{10} \text{ m}^{-3} and width of 10 km, whereas IUVS observes a continuous layer of Mg\(^+\) ions with peak density that is 50 times smaller and width that is three times larger. The persistent presence of Mg\(^+\) ions in IUVS observations is consistent with terrestrial experience, where metal ions are a ubiquitous feature of the ionosphere. They derive predominantly from steady influxes of sporadic meteoroids, rather than shower meteoroids whose influx varies greatly with time. Shower meteoroids, although visually striking, contribute only a small fraction of the steady-state mass flux (e.g., Brown et al., 2008). Readers should note the potential for confusion between the “sporadic” occurrence of low altitude electron density layers in radio occultation profiles and the “sporadic” meteoroid population, which supplies a relatively stable influx of interplanetary dust.

If the sporadic low-altitude plasma layers seen by radio occultation experiments are generated by meteoroid influx, then their chemistry must be such that metal ions like Mg\(^+\) rapidly transform into other ion species that are much longer-lived. That possibility is extremely inconsistent with current understanding of the effects of meteoroids on planetary atmospheres (e.g., Whalley and Plant, 2010). Furthermore, their irregular occurrence must be reconciled with the constant influx of interplanetary dust. The other possibility is that the sporadic low-altitude plasma layers seen by radio occultation experiments are caused by other mechanisms, such as enhancements in the precipitation rate of charged particles of suitable energy to deposit their energy at these altitudes.

In light of the MAVEN IUVS observations, we judge that the cause of the sporadic low-altitude plasma layers seen at Mars by radio occultation experiments is currently unknown. Given the similarities between the ionospheres of Venus and Mars, caution should also be applied to the interpretation of the analogous layers in the ionosphere of Venus. However, given the many major differences between giant planets and terrestrial planets, these Mars findings should not necessarily be extended directly to the giant planets.

Nevertheless, it is important to note that direct evidence for metal ions in giant planet ionospheres is absent.

### 1.5.4 Encounter of Mars with Comet C/2013 A1 (Siding Spring)

On 2014 October 19, Mars experienced a remarkably close encounter with comet C/2013 A1 (Siding Spring) at a distance of approximately 135,000 km (e.g., Withers, 2014, and references therein). As Mars passed through the comet’s coma, the dust influx on Mars increased substantially. This was expected to affect the distribution of metal ions in the planet’s ionosphere. This encounter occurred when several spacecraft were operational at Mars and able to perform relevant observations. MAVEN, which arrived at Mars only weeks earlier, searched for metal ions using the NGIMS and IUVS instruments discussed above. The MARSIS topside radar sounder on Mars Express measured the peak density of the ionosphere. The SHARAD radar sounder on Mars Reconnaissance Orbiter measured the total electron content of the ionosphere.

MAVEN IUVS observed enhanced densities of Mg\(^+\) (Figure 1.5, bottom panel) and Fe\(^+\) ions after the encounter (Schneider et al., 2015). (Note that Fe\(^+\) was not discussed by Crismani et al. (2017) in their survey of the long-term behavior of Mg\(^+\) ions.) A typical vertical profile of Mg\(^+\) density several hours after closest approach revealed a layer with a peak density on the order of 10^{10} \text{ m}^{-3}, peak altitude of 120 km, symmetric shape, and full-width at half-maximum of approximately 10 km. Relative to observations under normal conditions, the peak density is larger, the peak altitude is higher, and the width is narrower. The increase in peak density is expected from the increase in dust flux. The increase in peak altitude is expected from the increase in dust speed from sporadic meteoroids at a few km s\(^{-1}\) to cometary dust at 55 km s\(^{-1}\). The decrease in peak width has not been explained. Schneider et al. (2015) found that Mg\(^+\) densities were enhanced globally for 1–2 days.

The MAVEN NGIMS instrument observed enhanced densities of a tremendous range of metal ions (singly ionised Na, Mg, Al, K, Ti, Cr, Mn, Fe, Co, Ni, Cu, and Zn, and possibly Si and Ca) at 185 km after the encounter (Benna et al., 2015). Observations did not extend below 185 km, which was the periapsis altitude at this early stage of the mission. In these observations, the most abundant metal ions were Na\(^+\), Mg\(^+\), and Fe\(^+\), but in different proportions to those seen in normal circumstances. Here Na\(^+\) was the most abundant ion (roughly 3 times as abundant as Fe\(^+\)) and Mg\(^+\) was the next most abundant (roughly 2 times as abundant as Fe\(^+\)). That may reflect compositional differences between fresh dust from comet C/2013 A1 (Siding Spring) and background interplanetary dust. The Mg\(^+\) density at 185 km shortly after the encounter (153.6 \pm 7.5 \times 10^{6} \text{ m}^{-3}) was increased from its normal value by approximately three orders of magnitude, which illustrates the dramatic impact of this comet on the distribution of metal species in the ionosphere and atmosphere. The Mg\(^+\) density at 185 km decreased exponentially after the encounter with a time constant of 1.8 days.
Electron densities in the ionosphere of Mars were observed by other orbital instruments during the encounter. The MARSIS toposide sounder on Mars Express observed peak electron densities of \(1.5-2.5 \times 10^{11}\ m^{-3}\) at 80–100 km altitude and solar zenith angles of 75–110° (Gurnett et al., 2013). Under normal conditions, the peak electron density and peak altitude at these solar zenith angles are 0.1–1.0 \(\times 10^{14}\ m^{-3}\) and greater than 140 km, respectively. Although the ionospheric composition was not simultaneously observed for these electron density observations, it seems likely that metal ions constituted a significant fraction of the total ion density.

The SHARAD radar on Mars Reconnaissance Orbiter measured the vertical total electron content of the ionosphere at solar zenith angles of 94° and 113° shortly after the encounter (Restano et al., 2015). It found total electron content values on the order of \(4\times10^{15}\ m^{-2}\) (94°) and \(2\times10^{15}\ m^{-2}\) (113°). Under normal conditions, total electron contents at these solar zenith angles are approximately \(2\times10^{15}\ m^{-2}\) (94°) and \(0.5\times10^{15}\ m^{-2}\) (113°). The corresponding peak electron density can be estimated from the fact that the total electron content is usually on the order of \(4NH\) where \(N\) is the peak electron density and \(H\) is the neutral scale height (10 km) (Withers, 2011). The inferred peak electron densities are \(10^{14}\ m^{-3}\) (94°) and \(5\times10^{10}\ m^{-3}\) (113°), which are reasonably consistent with the MARSIS peak density measurements when allowance is made for plausible spatial and temporal variations in ionospheric conditions during this unusual event.

The overall picture of the ionosphere of Mars suggested by the MAVEN IUVS, MAVEN NGIMS, Mars Express MAR-SIS, and Mars Reconnaissance Orbiter SHARAD observations is of enhanced plasma densities at relatively low altitudes, altered ion composition, and substantial spatial and temporal variations. Realistic numerical simulations of the global-scale, time-varying picture of ionospheric properties during the cometary encounter have not yet been conducted. Such simulations, though technically challenging, are necessary to synthesize the disparate measurements available for this unique event.

In conclusion, metal ion layers are likely to exist in all planetary ionospheres, but the narrow electron density layers that have been observed throughout the solar system and suggested as being meteoric have not been proven to contain metal ions. In view of the difficulty of in situ sampling of composition at relevant pressure levels, remote sensing by ultraviolet spectroscopy offers the most promising path for detecting metal ions in planetary ionospheres.

1.6 Impact Flashes at Jupiter

The giant planet Jupiter is observed every year by thousands of amateur astronomers who acquire video observations of its atmosphere. Their images provide a nearly continuous observational record that is widely used to study the atmospheric dynamics of the planet (Hueso et al., 2010a, 2018b; Mousis et al., 2014). Since the year 2010 some of these video observations have resulted in the serendipitous discovery of energetic flashes of light that last from 1 to a few seconds and with visual brightness comparable to stars of magnitude +6⁰ or brighter. Although Jupiter impacts visible from Earth are caused by asteroids or comets, not meteoroids, they do nevertheless produce meteor phenomena. The first of these optical flashes was discovered on 2010 June 3 and was simultaneously recorded by two observers (Anthony Wesley from Australia discovered the flash and Christopher Go from Philippines confirmed this with his own observation acquired at the same time). This bolide appeared as a bright flash that lasted about 2 seconds and did not leave any observable trace on the atmosphere afterwards. A large follow-up campaign of observations using telescopes such as the Very Large Telescope (VLT) or Hubble Space Telescope (HST) did not find any debris in the atmosphere (Hueso et al., 2010a). The analysis of the light-curve of the observations yielded an estimated energy of the impact of \((1.9-14) \times 10^{14}\ J\) which in turn corresponds to an object of \(1.05-7.80 \times 10^{3}\ kg\) with a diameter range of \(4.7-18\ m\) depending on the density (Hueso et al., 2010a, 2013).

Since then, other instances of energetic flashes on Jupiter have been found, totalling 5 different events observed by a total of 12 amateur observers. The light-curves of these events have been analyzed by Hueso et al. (2013) and Hueso et al. (2018a) and interpreted as being caused by the impact of large meteoroids with diameters of \(5-20\ m\). We note that these actually qualify as small asteroids or cometary fragments rather than meteoroids according to the IAU definition.

The estimated masses and energies released in Jupiter’s atmosphere by these impacts are summarized in Table 1.3 where we also compare with previous impacts in Jupiter: the meteor observed by Voyager 1 in 1981 (Cook and Duxbury, 1981), the impacts of the D/1993 F2 (Shoemaker-Levy 9) fragments in 1994 (Hammel et al., 1995; Harrington et al., 2004) and the 500-m diameter object that impacted Jupiter in 2009 (Sánchez-Lavega et al., 2010), the latter also recorded by Anthony Wesley one year before his discovery of the bright flash.

Remarkably, each of these bolides was first noted by a single observer who detected the flash and issued an alert. The alert quickly resulted in reports from other observers who found the flashes in their video observations acquired on the same night and at the precise time of the reported flash. This occurs because most video recordings are obtained over several minutes and it is difficult to manually scrutinise video observations frame by frame in search of an unremarkable short-lived feature such as a flash. Software tools that process video observations to detect flashes are now available at, eg, http://www.astrosurf.com/planetessaf/doc/project_detect.php and http://pvo12.ehu.eus/psws/jovian_impacts/ (André et al., 2013). However, the availability of these tools has not produced further detections, probably due to their limited usage up to now.

The brightest flash occurred in 2012 September and is discussed in Hueso et al. (2013). Figure 1.6 shows the frame
with the peak of the flash, a synthetic image of the made by stacking the different frames where the flash is visible and a light-curve of this event. Analysis of the light-curve following photometric calibration of the video indicates a mass of about \(5.00-9.50 \times 10^5\) kg for the impactor.

[Hueso et al. (2013)] present a numerical simulation of the airbursts produced by objects equivalent to the 2012 impact and colliding with Jupiter at velocities of \(60\) km s\(^{-1}\). Objects of this size begin to break up at about \(3\) mbar pressure (120 km above the 1-bar level) and deposit most of their energy at the \(5-6\) mbar level (100 km height) where they break up in successive events. These result in light-curves that may show significant structure if observed with sufficient time resolution.

The latest analysis of the frequency of such impacts on Jupiter results in an estimate of 4-25 detectable events per year [Hueso et al. (2018a)]. Given that these flashes have to be found right at the moment they occur, and we may only observe one side of Jupiter and for a limited period of time every year, the total number of events on Jupiter’s atmosphere should be 10-70 impacts per year. This impact rate is in basic agreement with expectations from dynamical studies of comets [Levison et al. (2000)]. The contribution of impacts of this size range to the abundance of well-characterized exogenic species (mainly O atoms in CO and H\(_2\)O molecules; Lellouch et al. (2002); Moses and Popp (2015)) in Jupiter’s upper atmosphere is probably limited [Hueso et al. (2018b)].

We expect that the number of detections in the next few years will increase. On the one hand, the new generation of sensitive cameras used by amateur astronomers will allow to detect impacts by slightly smaller objects. On the other hand, Jupiter oppositions in the next few years will occur in spring and summer in the North hemisphere, where most of the regular observers of Jupiter are located. Additionally, improvements in the software tools used by the amateur community to systematically search for more flashes are underway, and will allow to improve the detectability of these events, providing better constraints on the flux of impacts in Jupiter. Finally, similar impacts are also expected to occur on Saturn [Tiscareno et al. (2013)]. Their discovery from ground-based observations is not beyond the capability of equipment used by amateurs to discover bolide impacts on Jupiter.

1.7 Impact-Derived Species Within Airless Body Exospheres

Objects such as the Moon, Mercury and asteroids that lack atmospheres in the traditional sense, host instead tenuous Surface-Bounded Exospheres (SBEs), the result of a delicate balance between poorly-understood sources and sinks.

Models of SBEs have extremely varied estimates of the importance of surface Impact Vapourisation (IV). Although is an established field of study [Melosh (1989); Pierazzo and et al. (2008); Hermalyn and Schultz (2010)] uncertainties regarding the importance of impact vapourisation on extraterrestrial bodies include the uncertainty in impact rates for both interplanetary dust and larger meteoroids and comets [Cremonese et al. (2016)], the relative amounts of melt and vapor produced in an impact [Pierazzo et al. (1995)], the temperature of the vapor – which affects escape rates (e.g. Cintala (1992); Rivkin and Pierazzo (2005)), the relative amount of neutral vs. ionised ejecta [Hornung et al. (2000)], and the gas-surface interaction of the downwelling ejecta [Yakshinskiv and Madey (2007)]. The importance of impact vapourisation as a source of exospheric neutrals has been constrained in part by observation of the escaping component of the exospheres – the Mercurian tail [Schmidt et al. (2013)], the Ca exosphere of Mercury [Burger et al. (2014)] and the lunar extended exosphere and tail [Wilson and Smith (1999)]. These results all depend critically on the assumed temperature or velocity distribution of the initial vapor plume, which has been variously assumed to be between 1500 K to 5000 K or non-thermal. They also depend critically on the assumed photoionisation rate. Values of the Na photoionisation rate have varied by a factor of three, and values of the Ca photoionisation rate have varied by a factor of 4.4 (e.g. see Killen et al. (2019)). This obviously introduces a huge uncertainty in the escape rate, and hence the source process.

Colaprete et al. (2016) conclude, based on observations of the UV spectrometer onboard the LADEE mission, that there is a pronounced role for meteoroid impact vapourisation and surface exchange in determining the composition of surface-bounded exospheres. Most interestingly, the simulations show that a release of ejecta from a single injection will persist in the SBE-surface system for much longer than the ionisation lifetime. Their nominal model shows that about 30% of Na released is still adsorbed on the surface after 100 days (3 lunations). Residence times in the lunar environment of 45 to 90 days (mainly on the lunar surface) can be expected before escape to the solar wind, which would explain the long-term smooth increase and decrease in the Na column density observed as the result of meteoroid streams. This is the result of each particle residing in the soil for approximately an ionisation lifetime (i.e., several days) between bounces, combined with the many bounces that it has to take before being lost from the SBE. Although Leblanc and Johnson (2010) conclude that thermal desorption and Photon-Stimulated Desorption (PSD) are the dominant source processes for the Na exosphere of Mercury, they introduce a source term equivalent to the amount of fresh material required to maintain the SBE. This source is not identified but is required to maintain a surficial reservoir.
of adsorbed atoms containing at least 2000 times as many atoms as the exospheric content.

A pronounced increase in K was observed by LADEE during the Geminid meteor shower while no increase was seen in Na. Given that Na is more volatile than K, it is not obvious that the peaks are the result of the meteoroid streams as opposed to whatever is causing the monthly variation. Given the long residence time of Na on the surface deduced by both Leblanc and Johnson (2003) and Colaprete et al. (2016), it has been suggested that impacts are the primary source of atoms from the regolith to the extreme surface, and these atoms feed the subsequent release by photons or thermal processes. If this is the case, then micrometeoritic impacts play the dominant role in maintaining the SBEs while the less energetic processes such as PSD and thermal desorption serve to keep the atoms in play until they are destroyed by photoionisation.

Schmidt et al. (2012) studied the extended sodium tail of Mercury and concluded that both photon-stimulated desorption and micrometeoroid impacts are required to simulate the ∼20% loss of Mercury’s sodium atmosphere, depending on orbital phase, and that the two mechanisms are jointly responsible for the observed comet-like tail as driven by solar radiation pressure. Roughly three times as many atoms would have to be ejected by PSD than by IV at 3000 K to accomplish a similar loss rate. The velocity distribution for PSD was required to have a low energy maximum (900 K) and high energy tail similar to that measured by Yakshinsky and Matey (2004) for electron-stimulated desorption from a lunar sample at 100 K.

The distant sodium tail of the Moon has been observed by looking in the direction opposite the sun (Wilson and Smith, 1999). They concluded that the Na escape rate increased by a factor of 2–3 during the most intense period of the 1998 Leonid meteor shower. The changes in the lunar exosphere itself were not quantified, as the escape rates only constrain that fraction of the velocity distributions above 2.1 km s⁻¹. Nevertheless, the observation is evidence for a strong influence of meteor impacts on the lunar sodium exosphere and its escape rate.

The calcium exosphere of Mercury exhibits several attributes that point to meteoritic impact as the source of the calcium exosphere (Figure 1.4). First, the calcium source peaks strongly on the dawn side of the planet, exhibiting the same morphology seen in the lunar dust observed by the LADEE spacecraft (Szalay et al., 2013; Szalay and Horányi, 2013; Januches et al., 2018). The variation of the calcium exosphere with True Anomaly Angle (TAA) was modeled independently by Killen and Hahn (2015) and Pokorný et al. (2018), indicating that the calcium source rate could be the result of impacts from the interplanetary dust disk except for a dramatic increase near TAA of 20°–30°. This increase was attributed to the intersection of Mercury’s orbit and that of comet Encke (Killen and Hahn, 2015) and further shown to be consistent with the evolution of the dust stream by the influence of planetary perturbations and Poynting-Robertson drag (Christou et al., 2015).

Although much of the literature concerning impact vapourisation on airless bodies relates to the ejection of sodium, potassium or calcium, the origin of schreibersite, a phosphide common to impact breccias at all Apollo sites, has been proposed to be a meteoritic contaminant, or alternatively produced in situ by reduction on the lunar surface. Pasek (2013) proposed that schreibersite and other siderophelic P phases have an origin from impact vapourisation of phosphates at the lunar oxygen fugacity. Phosphorus has not been observed in any SBE but that may be due to the difficulty in observing it.

1.8 Exo-Meteor Observations: Future Prospects

In the near future, we will continue to rely on serendipity for in situ detection of exo-meteors, either directly or indirectly. The MAVEN orbiter continues to monitor the metal content of Mars’ upper atmosphere for increases of similar magnitude and character to the C/2013 A1 (Siding Spring) event that would indicate passage through a comet’s dust stream. At the surface, the Opportunity and Curiosity rovers regularly image the Martian sky but confirmation of a martian meteor will require the fortuitous interruption of the trail by a foreground object, such as a rock, a mountain or part of the spacecraft structure (Christou and 10 co-authors, 2007). The InSight lander scheduled to land on the Martian surface in late 2018 will be equipped with seismometers that will detect atmospheric entry of large meteoroids (Stevanović et al., 2017). Optical cameras are also present on the spacecraft, but are not designed for night time observations and therefore will most likely not deliver many meteor images. Closer to the Sun, the JAXA Akatsuki spacecraft finally entered orbit around Venus in 2015 November, at the end of an extended cruise period. The Lightning and Airglow Camera (LAC) is a 12° FOV high-speed imaging system onboard the orbiter that searches for rapidly-varying luminous phenomena in the night-time Venusian atmosphere (Takahashi et al., 2008). The instrument has been active since 2016 December, observing Venus for ∼30min every 10-day orbit (Takahashi et al., 2017) and may detect bright meteors if, or when, their frequency is sufficiently high. In the meantime, valuable operational experience in this type of observation is being gained by ongoing – as well as planned – spaceborne monitoring of the atmosphere of our own planet for meteor events (Arai et al., 2014; Abdellaoui et al., 2017). These efforts are complemented by ground-based monitoring of the atmosphere of Jupiter by amateur and professional astronomers for impact flashes, possibly to be extended to the other giant planets as well as the Venusian nightside atmosphere. Numerical modeling and supporting laboratory work is also likely to continue. Many aspects of recent MAVEN observations of metal ions at Mars have yet to be reproduced or explained by numerical models. In particular, rate coefficients for many relevant chemical reactions involving metal species and ambient atmospheric molecules are not well-known. Previous laboratory work has naturally focused on reactions involving the nitrogen and oxygen species preva-
lent in Earth’s atmosphere, not the carbon and hydrogen species common in other atmospheres.
Abdellaoui, G., Abe, S., and Acheli, A. et al. 2017. Meteor studies in the framework of the JEM-EUSO program. *Planet. Space Sci.*, 143, 245–255.

Adolfsson, L., Gustafson, B. A. S., and Murray, C. D. 1996. The Martian atmosphere as a meteoroid detector. *Icarus*, 119, 144–152.

Aikin, A. C., and Maguire, W. C. 2005. Detection in the infrared of Mg$^+$-CO$_2$ ion produced via meteoritic material in the martian atmosphere. *American Astronomical Society DPS Meeting*, 37, 33.37.

Aikin, A., Christou, A. A., and Beurle, K. 2008. Prospects for meteor shower activity. *Earth Moon & Planets*, 97, 457–473.

Alam, N., and Chambers, J. E. 1979. The daytime meteor shower from comet C/1976 S1 (Gehrels). *Planet. Space Sci.*, 27, 139–151.

André, N., Grande, M., Achilleos, N. et al. 2018. Virtual Planetary Space Weather Services offered by the Europlanet H2020 Research Infrastructure. *Planetary and Space Sci.*

Aspinal, A., Clegg, J. A., and Lovell, B. 1949. The daytime meteor shower from comet P/Halley 1946 IV. *Mon. Not. R. Astron. Soc.*, 109, 495–513.

Arai, T., Kobayashi, M., Yamada, M., Matsui, T., and COMETSS project team. 2014. Meteor observation HDTV camera onboard the International Space Station. 45th Lunar Planet. Sci. Conf., Abstract 1610.

Aplin, A., Clegg, J. A., and Lovell, B. 1949. The daytime meteor streams of 1948-1. Measurement of the activity and radiant positions. *Mon. Not. R. Astron. Soc.*, 109, 352–358.

Aplin, A., Clegg, J. A., and Lovell, B. 1949. The daytime meteor streams of 1948-2. Measurement of the activity and radiant positions. *Mon. Not. R. Astron. Soc.*, 109, 359–368.

Beech, M., and Brown, P. J. 1995. On the visibility of bright Venusian fireballs from Earth. *Earth, Moon & Planets*, 68, 171–179.

Benn, M., Mahaffy, P. R., Grebowsky, J. M. et al. 2015. Metallic ions in the upper atmosphere of Mars from the passage of comet C/2013 A1 (Siding Spring). *Geophys. Res. Lett.*, 42, 4670–4675.

Bouquet, A., Baratoux, D., Vaubaillon, J. et al. 2014. Simulation of the capabilities of an orbiter for monitoring the entry of interplanetary matter into the terrestrial atmosphere. *Planet. Space Sci.*, 103, 238.

Brace, L. H., Taylor, H. A., Gombosi, T. I. et al. 1983. The ionosphere of Venus: Observations and their interpretations. Pages 779–840 of: Hunten, D. M., Colin, L., Donahue, T. M., and Moroz, V. I. (eds), *Venus*. University of Arizona Press.

Brown, P., Weryk, R. J., and Wong, D. K. et al. 2008. A meteoroid stream survey using the Canadian Meteor Orbit Radar I. Methodology and radiant catalogue. *Icarus*, 195, 317–339.

Butler, D. M., and Chamberlain, J. W. 1976. Venus’ night side ionosphere — Its origin and maintenance. *J. Geophys. Res.*, 81, 4757–4760.

Carter, L. N., and Forbes, J. M. 1999. Global transport and localized layering of metallic ions in the upper atmosphere. *Ann. Geophys.*, 17, 190–209.

Christou, A. A. 2004a. Predicting martian and venusian meteor shower activity. *Earth Moon & Planets*, 95, 425–431.

Christou, A. A. 2004b. Prospects for meteor shower activity in the venusian atmosphere. *Icarus*, 168, 23–33.

Christou, A. A. 2010. Annual meteor showers at Venus and Mars: lessons from the Earth. *Mon. Not. R. Astron. Soc.*, 402, 2759–2770.

Christou, A. A., and Beurle, K. 1999. Meteoroid streams at Mars: possibilities and implications. *Planet. Space Sci.*, 47, 1475–1485.

Christou, A. A., and Vaubaillon, J. 2011. Numerical modeling of cometary meteoroid streams encountering Mars and Venus. In: *Meteoroids: the smallest solar system bodies* (Cooke, W. J., Moser, D. E. and Hardin, B. F. and Janches, J., eds), NASA/CP-2011-216469, 26–30.

Christou, A. A., Vaubaillon, J., and Withers, P. 2007. The dust trail complex of comet 79P/du Toit-Hartley and meteor outbursts at Mars. *Astron. Astrophys*, 471, 321–329.

Christou, A. A., Vaubaillon, J., and Withers, P. 2008. The P/Halley Stream: Meteor Showers on Earth, Venus and Mars. *Earth, Moon & Planets*, 102, 125–131.

Christou, A. A., Oberst, J., Elgner, S. et al. 2012. Orbital observations of meteors in the Martain atmosphere using the SPOSHE camera. *Planet. and Space Sci.*, 60, 229–235.

Christou, A. A., Killen, R. M., and Burger, M. H. 2015. The meteoroid stream of comet Encke at Mercury: Implications for Mercurian regoliths. *Earth, Moon & Planets*, 136, 1485–1492.

Cook, A. F., and Duxbury, T. C. 1981. A fireball in Jupiter’s atmosphere. *J. Geophys. Res.*, 86, 249–252.

Cravens, T. E., Robertson, I. P., Ledvina, S. A. et al. 2008. Energetic ion precipitation at Titan. *J. Geophys. Res.*, 113, A4004.

Cravens, T. E., Robertson, I. P., Ledvina, S. A. et al. 2008. Energetic ion precipitation at Titan. *J. Geophys. Res.*, 113, A4004.

Cintala, M. J. 1992. Impact-induced thermal effects in the Lunar and Mercurian regoliths. *J. Geophys. Res.*, 97, 947 – 973.

Colaprete, A., Sarantos, M., Wooden, D. H. et al. 2016. How surface composition and meteoroid impacts mediate sodium and potassium in the lunar exosphere. *Science*, 351, 249–252.

Cook, A. F., and Duxbury, T. C. 1981. A fireball in Jupiter’s atmosphere. *J. Geophys. Res.*, 86(Sept.), 5435–5439.

Cravens, T. E., Robertson, I. P., Ledvina, S. A. et al. 2008. Energetic ion precipitation at Titan. *J. Geophys. Res.*, 113, A4004.

Cravens, T. E., Robertson, I. P., Ledvina, S. A. et al. 2008. Energetic ion precipitation at Titan. *J. Geophys. Res.*, 113, A4004.

Cremone, G., Borin, P., Lucchetti, A., Marzari, E., and Bruno, M. 2016. Micrometeoroids flux on the Moon. *Astron. Astrophys.*, 551, id. A27.
Kliore, A. J., Anabtawi, A., Herrera, R. G. et al. 2002. Ionosphere of Callisto from Galileo radio occultation observations. J. Geophys. Res., 107, 1407, 10.1029/2002JA009365.

Kliore, A. J., Nazy, A. F., Marouf, E. A. et al. 2008. First results from the Cassini radio occultations of the Titan ionosphere. J. Geophys. Res., 113, A09317, 10.1029/2007JA012965.

Kliore, A. J., Nazy, A. F., Marouf, E. A. et al. 2009. Midlatitude and high-latitude electron density profiles in the ionosphere of Saturn obtained by Cassini radio occultation observations. J. Geophys. Res., 114, A04315.

Kliore, A. J., Nazy, A. F., Cravens, T. E., Richard, M. S., and Rymer, A. M. 2011. Unusual electron density profiles observed by Cassini radio occultations in Titan’s ionosphere: Effects of enhanced magnetospheric electron precipitation? J. Geophys. Res., 116(A15), A11318.

Kondrateva, E. D., and Reznikov, E. A. 1985.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.

Kondrateva, E. D., and Reznikov, E. A. 1985. . Solar Sys. Res.

Koten, P., Vaubaillon, J., Margonis, A. et al. 2015. Double station Solar Sys. Res.
Withers, P., Mendillo, M., Hinson, D. P., and Cahoy, K. 2008. Physical characteristics and occurrence rates of meteoric plasma layers detected in the martian ionosphere by the Mars Global Surveyor Radio Science Experiment. *J. Geophys. Res.*, 113, A12314, 110.1029/2008JA013636.

Withers, P., Christou, A. A., and Vaubaillon, J. 2013. Meteoric ion layers in the ionospheres of Venus and Mars: Early observations and consideration of the role of meteor showers. *Adv. Space Res.*, 52, 1207–1216.

Withers, P., Weiner, S., and Ferreri, N. R. 2015. Recovery and validation of Mars ionospheric electron density profiles from Mariner 9. *Earth, Planets, and Space*, 67, 194.

Yakshinskiy, B. V., and Madey, T. E. 2004. Photon-stimulated desorption of Na from a lunar sample: Temperature-dependent effects. *Icarus*, 168, 53–59.

Yakshinskiy, B. V., and Madey, T. E. 2005. Temperature-dependent DIET of alkalis from SiO2 films: Comparison with a lunar sample. *Surface Sci.*, 593, 202–209.

Ye, Q-Z., Brown, P. G., Bell, C. et al. 2015. Bangs and meteors from the quiet comet 15P/Finlay. *Astrophys. J.*, 814 (Aug.), id 79.

Yelle, R. V., and Miller, S. 2004. Jupiter’s thermosphere and ionosphere. Pages 185–218 of: Bagenal, F., Dowling, T. E., and McKinnon, W. B. (eds), *Jupiter: The planet, satellites, and magnetosphere*. New York: Cambridge University Press.
Table 1.1. *Meteor showers at Mars in the next few years, from the method described in Vaubaillon et al.* (2005) and *Vaubaillon and Christou* (2006). “parent body” is the parent body of the stream causing the shower, “d” the minimum distance between the center of the stream cross-section and the planet (negative if the stream crosses inside the planet’s orbit and positive otherwise), “Date” the epoch of the shower, α and δ the sky location of the radiant in J2000 Earth equatorial coordinates, $V_p$ the planetocentric velocity and “conf_id” the confidence index as defined by Vaubaillon (2017).

| parent body | d (au) | Date (UT) | α (deg) | δ (deg) | $V_p$ (km sec$^{-1}$) | ZHR | conf_id |
|-------------|--------|-----------|---------|---------|----------------------|-----|---------|
| 252P/       | −0.0260| 2019-11-17T07:32 | 70.2    | −45.0   | 14.8                | 28  | GYO1/60CU22.8 |
| 3D/         | 0.0004 | 2019-12-11T22:27 | 20.1    | −2.0    | 22.6                | 22  | SYO0/1CE0.0   |
| 49P/        | −0.0006| 2019-06-11T13:02 | 22.3    | −67.0   | 16.4                | 1164| SYO0/1CE0.0   |
| P/2012 S2   | 0.0616 | 2020-12-23T07:44 | 254.8   | −40.8   | 16.4                | 917 | SYO0/1CE0.0   |
| 156P/       | −0.0855| 2020-11-06T13:56 | 311.5   | −79.5   | 12.6                | 67  | GYO0/43CU0.0  |
| 156P/       | −0.0807| 2020-11-06T20:36 | 312.4   | −79.7   | 12.6                | 25  | SYO0/1CE0.0   |
| 156P/       | −0.0855| 2020-11-06T20:31 | 314.8   | −79.7   | 12.6                | 115 | SYO0/1CE0.0   |
| 156P/       | −0.0970| 2020-10-31T14:47 | 292.3   | −74.1   | 11.6                | 138 | SYO0/1CE0.0   |
| 156P/       | −0.0698| 2020-11-06T09:52 | 320.1   | −81.8   | 13.1                | 57  | SYO0/1CE0.0   |
| 10P/        | −0.0358| 2020-06-16T05:31 | 244.8   | 25.6    | 10.4                | 231 | GYO20/56CU0.0 |
| C/2007 H2   | 0.0009 | 2021-10-28T16:58 | 39.9    | −55.2   | 34.4                | 122 | GYO0/4CU0.0   |
| 304P/       | 0.0035 | 2021-01-25T01:47 | 280.8   | −19.1   | 13.5                | 610 | SYO0/1CE0.0   |
| 304P/       | −0.0057| 2021-01-31T01:44 | 280.8   | −19.3   | 13.9                | 1640| SYO0/1CE0.0   |
Table 1.2. Future meteor showers at Venus. See Table 1.1 for explanations.

| parent | d   | Date       | α      | δ      | $V_p$ (km sec$^{-1}$) | ZHR | conf id |
|--------|-----|------------|--------|--------|-----------------------|-----|---------|
| 2008 BO$_{16}$ | −0.0739 | 2019-08-18T08:36 | 295.6   | −11.7  | 24.9                  | 1   | GYO1/9CU0.0 |
| 2008 BO$_{16}$ | −0.0620 | 2019-06-16T13:58 | 287.8   | −11.1  | 24.8                  | 1   | SYO0/1CE0.0 |
| 2008 ED$_{60}$ | −0.006 | 2019-07-09T04:58 | 247.5   | 63.0    | 22.9                  | 1   | GYO0/4CU12.7 |
| 2013 CT$_{36}$ | −0.0377 | 2019-10-12T01:55 | 261.1   | 21.9    | 12.5                  | 8   | GYO0/19CU0.0 |
| 2013 CT$_{36}$ | −0.0620 | 2019-06-16T13:58 | 287.8   | −11.1  | 24.8                  | 4   | SYO0/1CE0.0 |
| 2013 CT$_{36}$ | 0.0190 | 2019-12-08T00:21 | 241.5   | 27.2    | 12.6                  | 1   | SYO0/1CE0.0 |
Table 1.3. Summary of impacts on Jupiter

| Date     | Mass (kg) | Reference                  |
|----------|-----------|----------------------------|
| 81-03-05 | 11        | Cook and Duxbury (1981)    |
| 94-07-16 | $1.0 \times 10^{12}$ | Hammel et al. (1995),      |
|          | – 24      | Harrington et al. (2004)   |
| 09-07-19 | $6.0 \times 10^{10}$ | Sánchez-Lavega et al. (2010)|
| 10-06-03 | $1.05-7.80 \times 10^{3}$ | Hueso et al. (2010a, 2013)|
| 10-08-20 | $2.05-6.10 \times 10^{3}$ | Hueso et al. (2013)        |
| 12-09-10 | $5.00-9.50 \times 10^{3}$ | Hueso et al. (2013)        |
| 16-03-17 | $4.03-8.05 \times 10^{3}$ | Hueso et al. (2018b)       |
| 17-05-26 | $0.75-1.30 \times 10^{3}$ | Hueso et al. (2018b)       |
Figure 1.1. Atmospheric density-height profiles for different planets. From top to bottom: Venus (“nightside” atmospheric model by Seiff (1983) – dark grey line), Earth (US Standard Atmosphere 1976 – moderate grey line) and Mars (Mars Pathfinder entry profile – light grey line). The horizontal bands indicate the respective height ranges – corresponding to the same density range – at which meteors reach maximum luminosity. Adapted from Christou (2004b).
Figure 1.2 Locations of meteoroid streams encountering the orbits of Earth (blue), Venus (green) and Mars (brown) based on data from Christou (2010). The First Point of Aries is towards the right. Open symbols correspond to Encke-type Comets, filled symbols to Intermediate Long Period and Halley Type Comets. The size of each symbol is proportional to the encounter speed while the brightness indicates the solar elongation of the radiant.
Figure 1.3 Left: Nodes of test particles from comet C/2007 H2 (Skiff) that encounter Mars between the years 2000 and 2050. The points represent cartesian heliocentric J2000 coordinates and units of au, as the particles cross the martian orbit plane. The black curve is the orbit of Mars, with the planet’s direction of motion being from top to bottom. Note the numerous concentrations of particles within the stream’s cross-section.

Right: Histogram of those particles on the left panel that approach the planet’s orbit to within 0.005 au as a function of solar longitude in degrees. Each bin corresponds to a time interval of one hour. After Christou and Vaubaillon (2011).
Figure 1.4 Mars Global Surveyor Radio Science profile 5127R00A.EDS showing a low-altitude plasma layer between 80 and 100 km. It was measured at latitude 66.0°N, longitude 2.4°E, 14.4 h LST, Solar Longitude = 206.8°, and SZA = 81.6° on 2005 May 7. The nominal profile is the solid line, and 1σ uncertainties in the electron densities are indicated by the grey region. After Withers et al. (2008).
Figure 1.5  Top: $\text{Mg}^+$ altitude profiles derived from MAVEN IUVS at orbit 3040 compared with the model prediction. Note that Mg is not detected despite large predicted concentrations. From Crismani et al. (2017). Bottom: Temporal evolution of the abundances of $\text{Mg}^+$ measured by MAVEN/NGIMS at periapsis from 2014 October 18 to 2014 October 23. The exponential decay can be fitted by a time constant of 1.8 days. The dashed line marks the predicted time of maximum flux of C/2013 A1 dust. Predicted signal levels were derived by a 1-D model. Error bars reflect $3 \times$ standard deviation of the sampled data due to counting statistics. Instrument background is 10–100 counts/s. From Benna et al. (2015).
Figure 1.6 The 2012 September impact on Jupiter. This was the most energetic flash of light at Jupiter. (a) Brightest video frame in the recording; (b) Image composite made by stacking all frames where the flash is visible and 1000 frames for the planet. (c) Light-curve of the impact. The impact partially saturated some pixels at the peak of its brightness. Points represent the flash intensity measured over the different frames, the dashed line is a gaussian fit to the data and the continuous line is a weighted average of the photometric values. Further evidence of the flash is visible in the data at the level of the photometric noise. Based on data from [Hueso et al.] [2013].
**Figure 1.7** Left panel: Total planetary calcium source rate to Mercury’s exosphere is a periodic function of the planet’s TAA. Mercury is at perihelion when TAA=0° and at aphelion when TAA=±180°. The black curve is this total rate summed over the planet at each TAA, derived from observations obtained by the MESSENGER MASCS spectrometer 2011 March – 2013 March (from Burger et al., 2014). The red line is the modeled contribution from a cometary dust stream with peak density at TAA=25° plus that due to an interplanetary dust-disk. The green line is the contribution from the disk. Adapted from Killen and Hahn (2015). Right panel: Encke’s orbit (red) along with those of Mercury (blue), Venus and Earth (in grey). After Killen and Hahn (2015).