Modeling the Entry of Micrometeoroids into the Atmospheres of Earth-like Planets

A. R. Pevyhouse • M. E. Kress

Abstract The temperature profiles of micrometeors entering the atmospheres of Earth-like planets are calculated to determine the altitude at which exogenous organic compounds may be released. Previous experiments have shown that flash-heated micrometeorite analogs release organic compounds at temperatures from roughly 500 to 1000 K [1]. The altitude of release is of great importance because it determines the fate of the compound. Organic compounds that are released deeper in the atmosphere are more likely to rapidly mix to lower altitudes where they can accumulate to higher abundances or form more complex molecules and/or aerosols. Variables that are explored here are particle size, entry angle, atmospheric density profiles, spectral type of the parent star, and planet mass. The problem reduces to these questions: (1) How much atmosphere does the particle pass through by the time it is heated to 500 K? (2) Is the atmosphere above sufficient to attenuate stellar UV such that the mixing timescale is shorter than the photochemical timescale for a particular compound? We present preliminary results that the effect of the planetary and particle parameters have on the altitude of organic release.

Keywords atmospheric entry · micrometeor · modeling · organic chemistry

1 Introduction

Micrometeorites ~200 μm in diameter carry most of the incoming mass to the modern Earth, approximately 30 million kg annually [2]. Love and Brownlee (1991) [3] found that micrometeors in this size range experience severe heating upon atmospheric entry. Peak heating occurs at an altitude of > 85 km within seconds of atmospheric entry, typically to temperatures in excess of 1600 K, sufficient to melt silicate and metals [3].

Recent experiments have simulated the flash-heating experienced by micrometeors upon atmospheric entry [1], [4]. Both of these groups found that methane is released, and Kress et al. [1] also found that other light hydrocarbons and a variety of more complex organics are released at temperatures of ~ 500 to 1000 K. In the current study, we identify the altitudes at which these temperatures are reached, which is an essential first step to determining the ultimate fate of these compounds.

The influence that PAHs and methane could have on a planetary atmosphere depends on the altitude at which they are released from an incoming particle. The altitude at which a molecule is released determines its fate. Vertical mixing will bring a molecule deeper down into the atmosphere, where its photochemical lifetime is longer. The photochemical lifetime of a substance is the time it takes for destruction mechanisms to reduce its concentration to 1/e its original amount. The deeper in the atmosphere an organic compound is released, the greater the probability of it being vertically mixed. Methane, CH_4, for example, will be broken into residual compounds by photolysis if released above Earth's stratopause due to Lyman-alpha radiation (λ = 121.6 nm). Methane also is destroyed at this

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altitude by reactions with O(^{1}D) and OH [5]. After several steps, these reactions will convert methane to CO_2. However, if released at an altitude of 70 km or lower, methane has a long enough photochemical lifetime to allow mixing [5].

We first apply the atmospheric entry model to the Earth. We then extend this study to plausible Earth-like planets of different masses and atmospheric densities to identify the parameter space in which micrometeors release organics close to a planet's surface. Varying planet mass was found to not result in organics being ablated under a greater portion of atmosphere.

We find that, for the modern Earth, organics are typically released at an altitude such that the timescale for methane to mix lower into the atmosphere is very long compared to its photochemical destruction timescale at that altitude [5].

2 Modeling the Atmospheric Entry of Micrometeorites

In this study, infalling micrometeorites were simulated numerically to generate temperature profiles for a variety of particle sizes and entry parameters. Entry parameters of interest were initial velocity and entry angle. The physics of atmospheric entry is that of Love and Brownlee (1991) [3].

Numerical modeling using an Euler algorithm was done to simulate atmospheric entry of micrometeorites. This model takes a continuous evaporation approach while the particle is treated as an isothermal sphere of density $\rho_{met} = 3$ g/cm^3. Incoming micrometeorites are heated due to collisions with atmospheric molecules. Particle temperature is determined by balancing the power imparted to it from atmospheric molecules, P_{in}, to the rate at which thermal energy is being dissipated by radiative and evaporative mechanisms, such that

$$P_{in} = 0.5\rho_{atm} s v^3 \tag{1}$$

and

$$T = \left(\frac{P_{in}}{4\pi r^2 \sigma\varepsilon}\right)^{1/4} \tag{2}$$

where ε is the emissivity of the particle, T is the particle's temperature, σ is the Stefan-Boltzmann constant, s is the particle's geometric cross section, v is the particle's velocity with respect to the atmosphere and ρ_{atm} is the density of the atmosphere (a function of altitude). The change in velocity due to atmospheric drag and gravity is

$$d\mathbf{v} = \left(-0.75\frac{\rho_{atm}v^2}{\rho_{met}r}\hat{v} + \mathbf{g}\right)dt \quad . \tag{3}$$

We first reproduced the Love and Brownlee (1991) [3] results using the United States Standard Atmosphere of 1976 [6] as the atmospheric model. These calculations served as a benchmark for those for hypothetical earth-like planets, whose mass and surface atmospheric density were treated as free parameters, and whose atmospheric density was assigned a simple exponential decay law.

To estimate the altitude at which organic compounds may be released in the atmospheres of hypothetical Earth-like planets, atmospheric pressure and planetary mass were treated as free parameters. The atmospheric density profiles for these worlds were approximated by assigning a simple exponential decay function. This exponential decay model treated the atmosphere as isothermal at a temperature of 288.15 K with a constant molecular weight of 28.97 g/mol. Using this atmospheric profile, the effect of varying a planet's mass and atmospheric pressure on the altitude at which a micrometeorite first reaches 500 K was investigated. Results obtained for a world with 1 Earth mass and 1 atm surface pressure were compared against the results obtained using the U.S. 1976 Standard Atmosphere [6].

3 Results

The altitude at which volatile organic compounds are released is defined as the altitude range for which an incoming particle would be between 500 and 1000 K.

Results for a 1 Earth mass planet with 1 atm atmospheric pressure were compared to those of Love and Brownlee (1991) [3] who used the 1976 Standard Atmosphere as the atmospheric model. Use of an exponential decay function to model a planetary atmosphere consistently resulted in a higher calculated altitude of organic release compared to the altitude calculated using the U.S. 1976 Standard Atmosphere [6] (Figure 1). Heating rates also differed between the two atmospheric models. A 100 µm diameter particle entering at 80 deg and 20 km/s experienced a heating rate of 56 K/s under the exponential decay model compared to 43 K/s using the U.S. 1976 Standard Atmosphere [6]. Heating rates were determined between 500 to 1000 K.

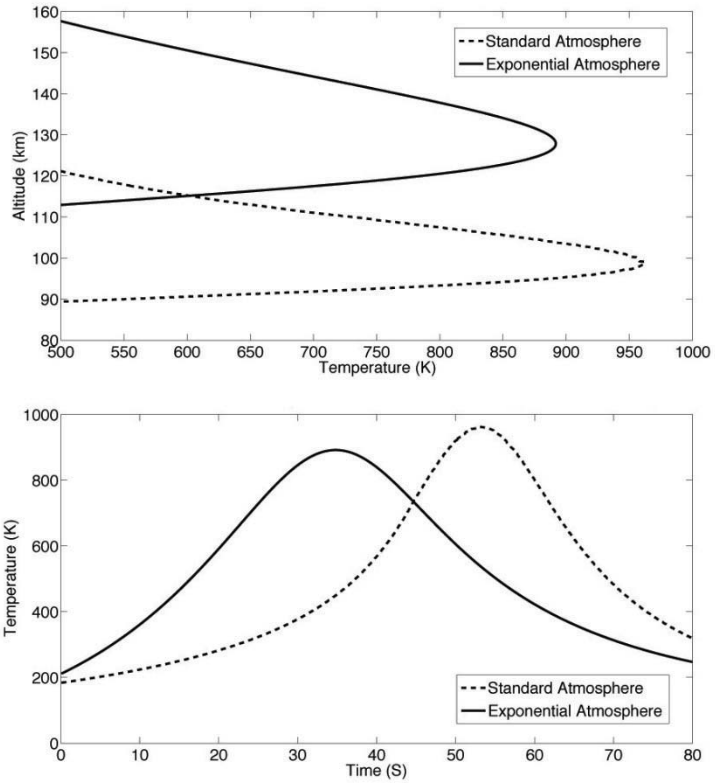

Figure 1. Comparison of results from the U.S. 1976 Standard Atmosphere [6] and exponential decay model for a 50 µm diameter particle entering at 80 deg and 12 km/s. Top: Particle temperature as a function of altitude. Bottom: Particle temperature as a function of time. Note that the particle reached its peak temperature later when in the standard atmosphere compared to an atmosphere whose pressure is exponentially decaying.

Figure 2 shows the dependence of organic release altitude on planetary mass and atmospheric pressure. Planetary mass was shown to have a greater effect on the altitude of organic release compared to planetary surface pressure. A micrometeorite falling through the atmosphere of a planet with a mass of 0.1 Earth mass and 0.1 atm surface pressure first reached 500 K at an altitude of 345 km. Increasing atmospheric pressure to 10 atm increased this altitude to 494 km. The same difference in atmospheric surface pressure resulted in only an 11 km difference for a planet of 10 Earth masses.

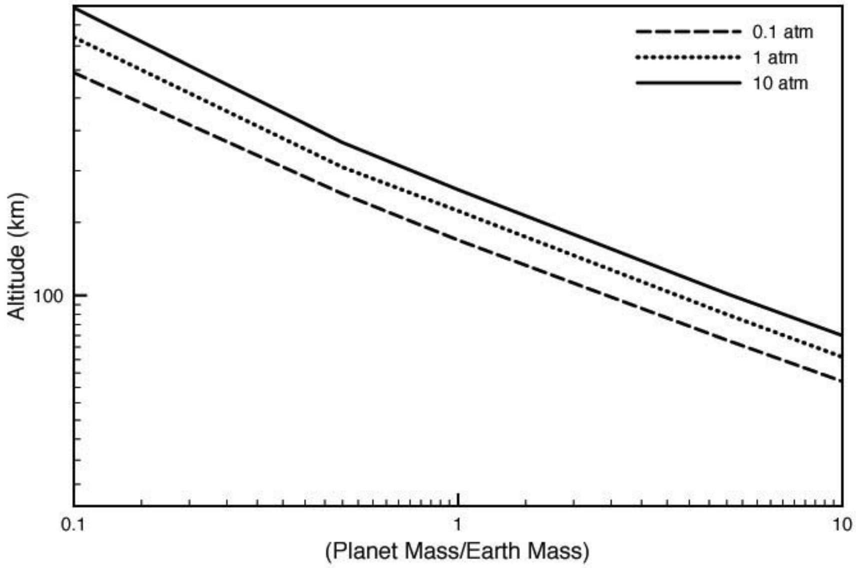

Figure 2. The altitude at which a 100 μm diameter particle first reaches 500 K as a function of planetary mass. The initial velocity of the particle is 12 km/s with an entry angle of 45°. Note the effect of increasing planetary mass on lowering the altitude at which a particle first reaches 500 K.

4 Discussion

Approximately 2 × 10^7 kg/yr of extraterrestrial material is deposited into Earth's atmosphere each year. The amount of organic carbon deposited can be estimated to be 10% of this total [2]. The level of ablated micrometeoritic organic compounds in a planetary atmosphere is determined by the competing rates of material deposition and degradation. Degradation of organic molecules occurs by photolysis due to exposure to solar UV radiation and chemical reactions with atmospheric molecules. The rate of this degradation depends on the altitude at which these organic compounds are released.

Uncertainties in the determination of the altitude range volatile organics are released from incoming micrometeorites originate from four factors.

The first factor is the Love and Brownlee (1991) [3] model. It does not take into account that meteorites have more than one phase. Micrometeorites in this model are treated as generic silicates. Therefore, an organic phase that evaporates at lower temperatures compared to silicates is not taken into consideration. The limitation of this model comes from the physics of the micrometeorite being determined to the 90% level by the silicates that are present. In reality, the loss of organics and ice will keep the particle cooler for longer due to the energy used for the phase change of these components. This lower temperature will allow for the particle to reach a lower altitude before reaching 500 K. The use of the Love and Brownlee (1991) [3] should therefore be considered as providing a conservative estimate on the altitude at which organics are released from micrometeorites.

The atmospheric model used is the second factor. The size of micrometeorites makes them very sensitive to any changes in atmospheric density. The difference in results between the U.S. 1976 Standard Atmosphere [6] and the Exponential Decay model makes the point that better representations of exoplanet atmospheres should be used.

The other two factors are the estimation of a heat transfer coefficient and lack of a rate equation for the release of volatile organics. A heat transfer coefficient will determine the percentage of input power that goes into heating the particle. A rate equation for the evaporation of organics determines were in the temperature range 500 to 1000 K organics are released. This is critical in determining the lower altitude boundary a particle will release organics. The need for an organic evaporation rate equation is discussed below.

The rate at which a particle is heated will determine the range of time organic compounds are released. Slow heating rates will give more time for volatile organics to be outgassed from a particle compared to quicker rates. Heating too quickly can result in organic compounds in the particle to be transformed to char before they are able to diffuse out of the particle.

A particle entering at 12 km/s and an angle of 0 deg was found to have a heating rate ~ 300 K/s. The same 12 km/s particle entering at 80 deg had a reduced heating rate of ~ 40 K/s. The heating rate of 500 K/s used by Cody was higher than any rate found for particles with an initial velocity less than 20 km/s. Such a high heating rate should be considered a worse case scenario of heating. Under such a high rate of heating, it is unknown if the volatile organics contained in a particle are all outgassed before being charred.

Further experiments on Murchison samples are needed to determine a rate equation for the evaporation of organic compounds. A rate equation will give insight into where in the temperature range of organic release organics are ablated. It is unknown if the majority of organics are released when a particle reaches 500 K, volatilization of organics is a continuous process over the entire temperature range of organic release, or if the majority of organics are ablated as the particle approaches 1000 K.

4.1 Effect of Stellar Class on Lyman-alpha Exposure

The further into a planetary atmosphere micrometeorites release organics, the greater the protection from lyman-alpha radiation. Lyman-alpha will degrade organic molecules on a time scale less than atmospheric vertical mixing times if released under too little atmosphere. The intensity of planetary exposure to Lyman-alpha depends on the temperature of a planet's home star and its distance to it. The liquid water habitable zone (LW-HZ) is defined as the region in space around a star in which a planet would be able to maintain liquid water on its surface [7]. Figure 3 shows the continuum flux of Lyman-alpha through the LW-HZ of F0, G2, and M0 stars as defined by Kasting et al. [7].

M-stars comprise about 75% of all main-sequence stars. Their hydrogen burning lifetimes are much longer than G2V stars like our Sun. Comparison of the intensity of Lyman-alpha radiation between a G star and an inactive M dwarf indicates ~ 10^{-7} reduction in Lyman-alpha intensity. This reduction in Lyman-alpha could slow the rate of rate of organic degradation in the atmosphere on an M-star planet. However, too low a level of UV radiation has been thought to inhibit the biogenesis of complex macromolecules. The volatile UV output from M-star flares have been hypothesized to be needed for the synthesis of large complex macromolecules [8].

The spectral distribution of radiation incident on an M-star planet has been theorized to result in a thicker ozone layer compared to the Earth [9]. A broader ozone layer could increase the photochemical lifetime of ablated molecules.

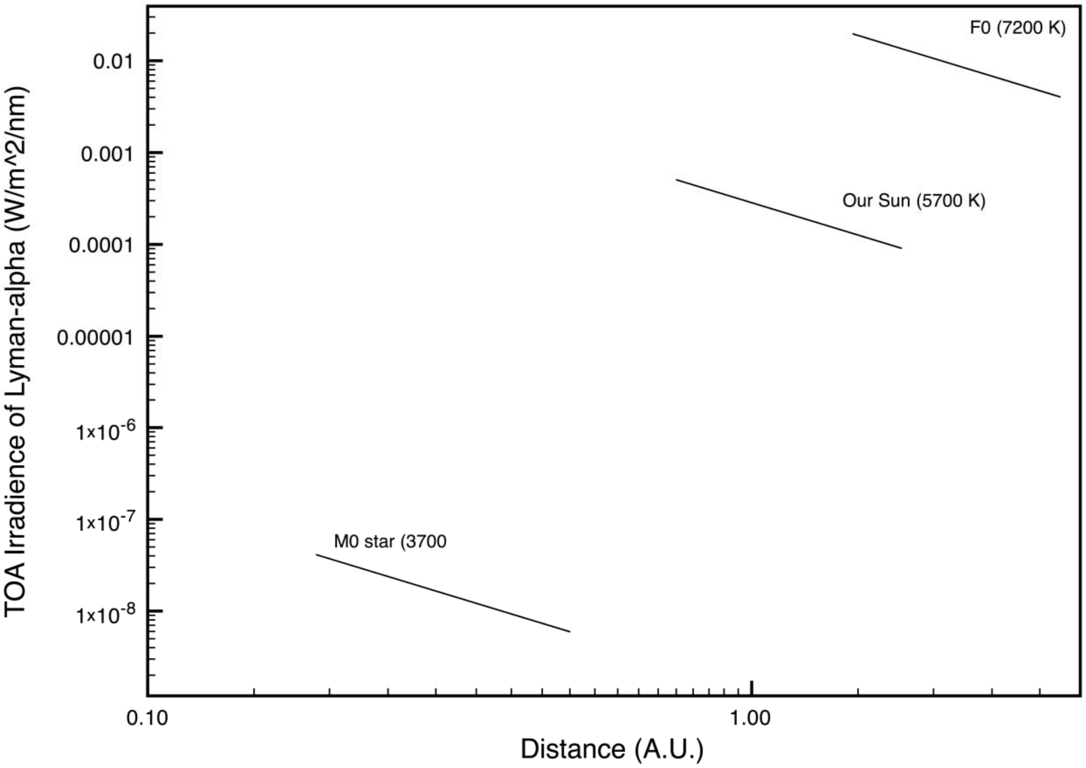

Figure 3. Irradiance at the top of the atmosphere (TOA) of Lyman-alpha for M0, G2, and F0 stars. Irradiance values were calculated from Planck's function. The range of habitable zone for each stellar class follows those published by Kasting et al. [7]

Another source of protection could come from the high probability of planets with the LW-HZ being tidally locked. Synchronous rotation does not necessarily mean atmospheric freeze out [10]. Therefore, the side of the planet always facing away from the star could provide a protected environment for ablated volatile organics. Future work should include modeling atmospheric mixing on tidally locked planets to investigate further the micrometeoritic contribution of volatile organics to these worlds.

5 Conclusion

For organic compounds to reach altitudes were exposure to UV radiation is low enough that it will not degrade, the compounds need to be either photochemically stable (e.g. PAHs) or the parent micrometeorite reaches 500-1000 K at lower altitudes. Although survival of methane in our modern atmosphere looks grim, that does not mean the release of organics in other atmospheres is not important. Smaller stars radiating less UV than our Sun may provide a longer time frame for ablated material to be vertically mixed into the atmosphere. At constant planetary density, increasing planet mass lowers the altitude 500 K and is first reached by an incoming particle but does not necessarily result in organic ablation occurring under a greater percentage of a planets atmosphere.

The need for atmospheric models of exoplanets was demonstrated in this study. Results differed by 35 km in altitude between the U.S. 1976 Standard Atmosphere [6] and exponential decay model atmosphere. This is due to the exponential decay model calculating a denser atmosphere compared to the U.S 1976 Standard Atmosphere [6] for altitudes above 100 km. This result was independent of entry angle for a 50 µm diameter particle entering at 12 km/s.

Progress into the micrometeoritic contribution of volatile organics to the atmosphere of planets and moons has been made in this study. Heating rates for further lab experiments have been clarified as well as the need to determine a rate equation for the release of volatile organics. Determination of an upper altitude for when a particle first reaches 500 K under a worst case scenario of heating has been made. Although progress has been made, further work needs to be done in three main areas: (1) determine a rate equation for the evaporation of organics under different rates of heating. (2) investigate the altitude range a particle first reaches 500 K while varying the heat transfer coefficient. (3) use the exponential model to simulate atmospheres with various combinations of atmospheric temperature and pressure that are favorable for liquid water to be present on a planetary surface. This will allow the study to be extended to a broader variety of exoplanets.

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