The pre-atmospheric size of the Martian meteorite ALH 77005 progenitor

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Abstract

An upper mass estimate of 30 kg, corresponding to a diameter of order 26 cm, is derived for the progenitor meteoroid to Martian meteorite ALH77005. This estimate is derived upon the application of a cooling time model, constrained so as to allow for the observed partial recrystallization of plagioclase within the meteorite’s interior. This new estimate for the size of the progenitor to ALH77005 is some 2–3 times larger than that previously assumed by earlier researchers. Uncertainty in the value of the thermal diffusivity term appropriate to Martian meteorite material results in the cooling time model allowing for a possible precursor mass range of 25 and 110 kg. An Earth atmosphere interaction model has been applied against the cooling time model mass range, under the constraint that the most likely Earth encounter speed is less than 20 km/s, and that the parent body does not fragment in the Earth’s atmosphere. It is through the consideration of the fireball ablation model that the eventual upper bound of 30 kg is obtained.

1. Introduction

Impact cratering is a ubiquitous solar system process and it facilitates the exchange of surface material between planets and planetary satellites (Melosh, 2003; Fritz et al., 2005). Both lunar and Martian meteorites have been collected on the Earth’s surface (see e.g., McSween, 1999), and in the latter case the meteorites afford a ‘first study’ supply of Martian surface material for laboratory analysis. While a number of impact modeling papers have been published in recent years (e.g., Head et al., 2002; Artemieva and Ivanov, 2004) there are unfortunately very few observational constraints upon the model predictions concerning the amount of material and the size distribution of material that might be ejected into space following a Martian impact. In principle, one can attempt to constrain the ejecta size distribution by modeling the ablation losses suffered by Martian meteorites collected on Earth: that is, the pre-atmospheric size distribution of Martian meteorite progenitors is the same as the ejecta size distribution (here we assume that there are no transfer orbit collisional fragmentation processes at play). Unfortunately no fireball associated with the atmospheric flight of a Martian meteorite dropping event has ever been instrumentally recorded, and consequently there are no direct constraints upon the progenitor initial mass and the recovered meteorite mass.

Recently, Beech et al. (2007) have applied a ‘forensic style’ approach to determine the initial mass and size of the Chassigny Martian meteorite. Accordingly, they find an initial precursor meteoroid mass of between 5 and 15 kg, corresponding to an initial diameter some 15–20 cm across. In the Chassigny situation a forensic approach, in which unknown parameters are taken to correspond to the average values deduced for observed meteorite producing events, is feasible because there are a few eyewitness constraints. In this paper we consider the circumstances of the fall of the Martian meteorite ALH77005, and use a combination of experimental results and direct meteorite analysis to determine the most likely size and mass of its progenitor meteoroid.
2. Why ALH77005?

Martian meteorite ALH 77005 is a lherzolitic Shergottite that was found in the Allan Hills region of Antarctica during the 1977 collecting season of ANSMET (Meyer, 2003). The parent body to the meteorite formed from igneous rock that, based upon samarium-neodymium radioactive isotope measurements, cooled and crystallized on Mars some 173 \pm 6 \text{ Myr} ago. The parent body was ejected from the Martian surface an estimated 3.52 \pm 0.55 \text{ Myr} ago (Eugster et al., 1997), and the terrestrial residency time for the meteorite is estimated as being 190 \pm 70 thousand years (Schultz and Freundel, 1984). The recovered mass of ALH77005 amounts to 0.482 kg, and while the meteorite was slightly elliptical in profile before laboratory cutting took place, we take its characteristic semi-diameter to be that of a sphere of radius $R_{\text{max}} = 3.3 \text{ cm}$. In this latter size calculation we have adopted a grain density of $\rho_b = 3275 \text{ kg/m}^3$ and taken the porosity to be 50\%, which yields a bulk density of $\rho_b = 3111 \text{ kg/m}^3$; this density combined with the recovered mass provides the radius estimate. The grain density is based on the average of helium pycnometer measurements on bulk samples of DaG 489 and Zagami (their grain densities being 3130 and 3420 kg/m$^3$, respectively) both of which are Shergottite meteorites, and the porosity is based upon a scanning electron microscope analysis conducted on a thin section of ALH77005 (the experimental details behind these measurements are described in Coulson et al., 2007). The largest orthogonal dimensions of the recovered meteorite are given by Nishiizumi et al. (1994) as 9.5 \times 7.5 \times 5.25 \text{ cm}; the average of these diameters suggests a mean radius of 3.7 \pm 0.9 \text{ cm}, which is in reasonable agreement with our estimate given above.

Petrological studies indicate that ALH77005 is an olivine-rich cumulate (gabbroic) rock (Meyer, 2003), but of particular importance to this study the meteorite has also been highly shocked. Indeed, the olivine shows a distinct yellow–brown discoloration due to shock-induced oxidation (Ostertag et al., 1984). This shock processing will have taken place during the launch of the meteorite’s parent body from the surface of Mars. Fritz et al. (2005) estimate, in fact, that during the ejection process the parent body of ALH77005 was subjected to a peak shock pressure of some 50 \pm 5 \text{ GPa}. Combining this shock pressure with a set of experimentally determined equations of state, Fritz et al. (2005) find that the implied temperature of the meteorite’s progenitor body, immediately after the shock and ejection event, was approximately 900 \pm 100 \text{ K}. In addition to these observed shock effects, Ikeda (1994), Boctor et al. (1999) and Fritz et al. (2005) have all pointed out that partial recrystallization of plagioclase is evident in ALH77005—illustrated here in Fig. 1. The interpretation of this partial recrystallization feature envisions the initial generation of a shock-produced plagioclase melt pocket which then partially recrystallizes along its rim, the interior, however, being quenched as glass. Where this latter observation becomes particularly useful is that Ostertag (1982) has found from annealing experiments that the recrystallization of plagioclase will only occur if the temperature is kept above \sim 1000 \text{ K} for 0.5 \text{ h}. In contrast, complete recrystallization requires that the temperature remains above 1000 \text{ K} for at least 1 \text{ h}. At temperatures much below 1000 \text{ K}, the recrystallization of plagioclase takes many tens of hours to occur; indeed, at an annealing temperature of 900 \text{ K}, Ostertag finds the recrystallization time to be greater than 10 \text{ h}. Since it is anticipated that we are dealing with a relatively small meteorite-producing progenitor (certainly less than a few meters across) such long annealing times are unlikely. The recrystallized rim of birefringent plagioclase found in ALH 77005 suggests, therefore, that elevated temperatures (i.e., of order 1000 K; consistent with a 50 \pm 5 \text{ GPa launch and ejection shock}) must have prevailed for about 0.5 \text{ h}, but for no more than 1 \text{ h}, within the interior of its progenitor meteoroid (i.e., the body ejected from the Martian surface). With this experimental constraint in place, we present below a cooling time model for the progenitor body to ALH77005.

3. The cooling time model

Following ejection from the surface of Mars, the progenitor meteorite body will cool from its immediate post-shock heated temperature ($T_{\text{shock}}$) to that of space ($T_{\text{surface}}$). The cooling rate of a sphere of radius $R$ is described by the radial diffusion equation

$$\frac{\partial U(r, t)}{\partial t} = k \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial U(r, t)}{\partial r} \right), \quad (1)$$

where $k$ is thermal diffusivity, which is expressed according to the thermal conductivity $\kappa$, the density $\rho$ and the specific
heat capacity $C_p$ of the meteorite material:

$$k = \frac{k}{\rho C_p}.$$

(2)

The boundary conditions for Eq. (1) are

$$U(r, 0) = T_{\text{shock}} \quad \text{and} \quad U(R, t) = T_{\text{surface}},$$

(3)

which indicates a constant surface temperature, $T_{\text{surface}}$ and a constant initial temperature of $T_{\text{shock}}$ throughout the interior at time $t = 0$ (the moment of ejection from Mars). The solution to Eq. (1) can be found through the method of separating variables with $U(r, t) = R(r)T(t)$. Accordingly the standard solution to (1) is

$$U(r, t) = \sum_{n=1}^{\infty} a_n \sin \left( \left( \frac{\pi n}{R} \right) r \right) \frac{1}{r} \exp \left[ -\left( \frac{\pi n}{R} \right)^2 \frac{k}{C_p} t \right],$$

(4)

where the $a_n$ terms are the Fourier components that describe the temperature variation within the sphere at time $t = 0$. With the boundary conditions (3) we have

$$U(r, t) = T_{\text{surface}} + \frac{2R}{\pi} (T_{\text{shock}} - T_{\text{surface}})
\times \sum_{n=1}^{\infty} \left( \frac{-1}{n} \right)^{n-1} \sin \left( \left( \frac{\pi n}{R} \right) r \right) \frac{1}{r}
\times \exp \left[ -\left( \frac{\pi n}{R} \right)^2 \frac{2}{C_p} k t \right].$$

(5)

Solutions to Eq. (5) for $U(r, t)$ can be sought once the initial radius $R$, $T_{\text{shock}}$, $T_{\text{surface}}$ and the thermal diffusivity $k$ are described. In the following, the surface temperature and the immediate post-shock temperature are assumed fixed and accordingly set to 250 and 1000 K, respectively. The radius is taken to be a variable parameter and the thermal diffusivity is allowed to take on a range of representative values since no direct measurements of the thermal properties of Martian meteorites have ever been published. Fritz et al. (2005) argue that the thermal diffusivity for typical Earth mantle rocks is of order $7.0 \times 10^{-7}$ m$^2$/s, while Hevey and Sanders (2006) suggest a value of $7.6 \times 10^{-7}$ m$^2$/s for non-differentiated stony planetesimals. Direct laboratory measurement of eucrite meteorites (basaltic achnondrite meteorites derived from the asteroid Vesta) by Yokomogida and Matsui (1993) indicate a thermal diffusivity of $3.0 \times 10^{-7}$ m$^2$/s, whereas measurements performed on terrestrial basalts indicate a value of order $3.3 \times 10^{-7}$ m$^2$/s (Murase and McBirney, 1973). While the variously published results provide us with a range of values for the thermal diffusivity, it seems worthwhile to draw attention to the fact that there are very few data available in the literature concerning the laboratory measured thermal characteristics of meteorites (of any kind), and that this is an area where further work is required.

4. Numerical results

For an adopted value of the thermal diffusivity, solutions to Eq. (5) have been obtained for a range of parent bodies of radius $R_{\text{par}}$. For a given assumed radius we check to see if the central temperature constraint holds true; that is, is $T(r = 0, t)\approx 1000 K$ for at least half an hour. If the central temperature remains high for too long then $R_{\text{par}}$ is reduced and another trial run is performed. The procedure for finding $R_{\text{par}}$ when different values of the thermal diffusivity are used is simplified by a scaling condition allowed for by Eq. (5), which gives $(\pi/R_{\text{par}})^2 k = \text{constant}$. Table 1 indicates the range of estimated masses and radii for the parent meteoroid to ALH77005 according to the various thermal diffusivity values found in the literature.

Fig. 2 shows an example calculation for the variation in temperature at the center, the mid-point $r = 9$ cm and $r = R_{\text{net}} = 3.3$ cm when $k = 6.5 \times 10^{-7}$ m$^2$/s. The cooling time model indicates that the possible parent meteoroid masses for ALH77005 range from $\sim 25$ to $\sim 110$ kg. The range of possible parent meteoroid masses can be further paired-down, however, by considering the atmospheric interaction of the parent meteoroid prior to the meteorite hitting the ground.

Fig. 3 shows the locus for producing a meteorite of mass 0.482 kg in the initial meteoroid mass and initial meteoroid velocity plane. To determine this locus we have numerically integrated the standard equations of meteoroid ablation (see e.g., Bronshten, 1983) for a range of initial masses and velocities. In the calculations leading to Fig. 3 the enthalpy of fusion was taken as $Q = 5.0 \times 10^4$ J/kg, which is a representative value for terrestrial basalt (Yoder, 1976; Kojitani and Akaogi, 1995; Fukuyama, 1985). Following Passey and Melosh (1980) we assume a constant heat transfer coefficient $A = 0.02$ and adopt a constant drag coefficient of $\Gamma = 1.0$. The resultant ablation coefficient $\sigma = A/2\Gamma Q = 2 \times 10^{-8}$ s$^{-1}$m$^{-2}$ is, as would be expected, comparable to, but slightly larger than, that expected for stony meteorites, which produce so-called Type-I fireballs, but less than that expected for Type-II fireballs produced by highly ablative carbonaceous chondrite bodies. The atmospheric density versus height model used in our integration scheme is that of the MSIS-E-90 Earth

<table>
<thead>
<tr>
<th>$k$ (m$^2$/s)</th>
<th>$R_{\text{par}}$ (cm)</th>
<th>$M_{\text{par}}$ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.00 \times 10^{-7}$</td>
<td>12.4</td>
<td>26.4</td>
</tr>
<tr>
<td>$3.25 \times 10^{-7}$</td>
<td>12.9</td>
<td>29.7</td>
</tr>
<tr>
<td>$6.50 \times 10^{-7}$</td>
<td>18.3</td>
<td>84.7</td>
</tr>
<tr>
<td>$6.79 \times 10^{-7}$</td>
<td>18.7</td>
<td>90.4</td>
</tr>
<tr>
<td>$7.60 \times 10^{-7}$</td>
<td>19.8</td>
<td>107.3</td>
</tr>
</tbody>
</table>

The mass estimate (column 3) is based upon the radius of the parent $R_{\text{par}}$ (column 2) and an estimated bulk density of 3111 kg/m$^3$.
of terrestrial basalt with...move the locus slightly downward in the diagram.

Fig. 3. Locus for producing a meteorite of mass 0.482 kg. As the initial meteoroid mass increases, the initial velocity required to produce a meteorite of the specified mass also increases. The calculations take the ablation coefficient to be \( \sigma = 2 \times 10^{-8} \text{s/m}^2 \). The expected initial velocity range for progenitor meteoroids with space exposure ages less than 10 Myr is indicated by the extent of the brackets (Gladman, 1997). The point labeled ‘Basalt’ indicates the expected parent body mass when the composition is similar to that of terrestrial basalt and when the encounter speed is 20 km/s. This is in good agreement with the parent mass predicted by the cooling time model (see Table 1) when the thermal diffusivity is that of terrestrial basalt with \( k = 3.3 \times 10^{-7} \text{m}^2/\text{s} \). For a given entry velocity value, greater zenith angles of entry will shift the production locus upward (i.e., a larger mass progenitor will be required to produce the 0.482 kg ground-mass meteorite), smaller, near vertical, zenith angles of entry will move the locus slightly downward in the diagram.

5. Summary and discussion

The aim of this study has been to estimate the likely size and mass of the progenitor meteoroid to the Martin meteorite ALH77005. We have used a cooling time model to estimate the size of the progenitor under the constraint that partial, but not full, recrystallization of plagioclase has taken place. We have further reduced the range of possible progenitor masses by considering the atmospheric interaction of the parent meteoroid prior to the meteorite hitting the ground. In these latter calculations a dynamic constraint has been applied such that Martian ejecta, with space exposure ages less than \( \sim 10 \) Myr (encompassing the space exposure age measured for ALH77005), should
encounter the Earth’s atmosphere at speeds less than 20 km/s. With these constraints we place an upper limit of 30 kg (diameter ~26 cm) on the mass of the body that was ejected from Mars 3.5 Myr ago, and which ultimately produces the ALH77005 meteorite in Antarctica some 190,000 years back into our past. The upper bound derived for the mass of the parent meteoroid to ALH77005 indicates an ablative mass loss of about 98% during atmospheric passage, and implies that the eventual meteorite occupied the innermost 2% by volume of the parent meteoroid. It is worth re-iterating at this point that our fireball model suggests that no fragmentation of the parent meteoroid was likely as it descended through the atmosphere, since $P_{\text{ram}}(\text{max}) < P_{\text{ram}}(\text{frag})$ and consequently ALH77005 apparently constitutes the inner core of the initial body ejected from Mars. This being said, given the nature of Antarctic meteorite transport and recovery there is no direct observational support for this claim. Nishiizumi et al. (1986) have suggested an initial radius of 5–6 cm for ALH77005 on the basis that 1.5–2.5 cm was removed from the initial radius during atmospheric ablation. This seems to be a rather low estimate for ablative mass loss—amounting to the loss of only 75% of the initial mass. The small shielding depth adopted by Nishiizumi et al. is probably the reason why their estimated exposure age for ALH77005 is some 1 billion years shorter than that derived by Eugster et al. (1997), who assume that Martian meteorites have the same $^{22}\text{Ne}/^{21}\text{Ne}$ shielding with depth sensitivity as the HED achondrites. Head et al. (2002) have suggested an initial radius of 4 cm for the parent meteoroid of ALH77005 on the basis that only 50% of the mass is lost during atmospheric ablation, but this again seems to be a very low estimate for the ablative mass loss. In light of the observed recrystallization of plagioclase within ALH77005, the thermal cooling time model described above effectively rules out the latter two initial radii estimates as being far too small. Objects of just 4–6 cm in radius would cool off much too rapidly for the plagioclase recrystallization process to begin. Fritz et al. (2005) use the recrystallization of plagioclase and a thermal cooling time model to derive an initial radius of 22 cm (mass ~128 kg) for the parent meteoroid to ALH77005. Their mass value, we would suggest, is on the high side, since the Earth atmosphere entry velocity required to produce a meteorite with the same mass as ALH77005 would have to be of order 24.5 km/s (see Fig. 3), which is an uncomfortably high value with respect to the expected encounter speeds (Gladman, 1997). Eugster et al. (2002) have determined estimates to the size of precursor meteoroids for 7 Martian meteorites (unfortunately, ALH77005 was not one of them) by analyzing the neutron flux induced by cosmic ray interactions. They find typical minimum radii for the precursor meteoroids of 22–25 cm, corresponding to minimum masses of 150–220 kg. While objects with these masses might theoretically be ‘lifted’ from the surface of Mars during a large asteroid impact, the precursor sizes, according to our Earth atmosphere ablative mass loss analysis, appear rather large, and especially so if they are viewed as minimum sizes. In addition, we note that larger sized (and larger mass) meteoroids, according to the statistical distribution of defects theory of Weibull (see Beech, 2002), are more likely to fragment than smaller sized (lower mass) meteoroids. On this basis, the lower mass limit is at least consistent with our working hypothesis that ALH77005 is derived from a non-fragmenting parent meteoroid. It would be particularly valuable if neutron flux measurements could be made for ALH77005 since this would offer a direct comparison with the ablation and heating model presented here, and such measurements would also constrain the parent body’s initial burial depth on Mars.

Hydrodynamic Martian impact ejection models have recently been published by Head et al. (2002) and Artemieva and Ivanov (2004). A summary of the key results from these works is presented in Table 2. For a 200 m diameter asteroid striking Mars with an impact speed of 10 km/s, the models predict that ejecta ranging in size from ~5 to 30 cm across, that has suffered peak shock pressures ranging from 15 to 65 GPa, will be produced. Artemieva and Ivanov (2004) and Fritz et al. (2005) argue, however, that ejecta must be larger than ~10 cm in order to survive passage through the Martian atmosphere and the impact plume, which suggests that the ejecta size range for precursor bodies producing meteorites that have been highly shocked, such as in the case of ALH77005, might vary from ~10 to 30 cm. These theoretical results certainly encompass the mass and size range for the precursor meteoroid to ALH77005 derived above, and it would seem that, within a factor of about two, there is reasonable agreement between the various approaches to constraining the most likely pre-Earth atmosphere interaction size of Martian meteorite precursor meteoroids.

Table 2
Summary of hydrodynamic code modeling of Martian asteroid impacts with the resultant ejection of material into space

<table>
<thead>
<tr>
<th>Reference</th>
<th>$D_{\text{imp}}$ (m)</th>
<th>$V_{\text{imp}}$ (km/s)</th>
<th>Entry angle (deg)</th>
<th>Peak pressure (GPa)</th>
<th>Ejecta diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMI</td>
<td>150</td>
<td>10</td>
<td>90</td>
<td>45-65</td>
<td>7-10</td>
</tr>
<tr>
<td>HMI</td>
<td>200</td>
<td>10</td>
<td>90</td>
<td>50-60</td>
<td>5-30</td>
</tr>
<tr>
<td>AI</td>
<td>200</td>
<td>10</td>
<td>15-90</td>
<td>15-45</td>
<td>12-20</td>
</tr>
</tbody>
</table>

In column 1, HMI corresponds to Head et al. (2002), while AI refers to Artemieva and Ivanov (2004). $D_{\text{imp}}$ is the diameter of the impactor in meters, $V_{\text{imp}}$ is the impact velocity in km/s and the entry angle is measured in degrees, with 90° corresponding to a vertical impact. The last two columns indicated the predicted peak shock pressure in GPa experienced by ejecta in the diameter range specified in column 6.
Acknowledgments

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References