The Future of Planetary Entry Technology

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Abstract

This is a written version of an hour-long lecture delivered by the author on June 30, 2011, as Plasmadynamics and Lasers Award Lecture at the AIAA 2011 summer conference in Honolulu, Hawaii. The author proposes that two areas of planetary entry physics be pursued in the future: outer planet aero-capturing and study of aerodynamics of meteoroid entries, both for the purpose of advancing the understanding of the possible extraterrestrial seeding of building blocks of life. For outer planet aero-capturing, the author proposes to develop new shock tube facilities that will produce up to 30 km/s of shock speed without causing photo-ionization of the driven gas by the radiation from the hot driver gas. Regarding meteors, the author proposes to carry out laboratory testing of the Tunguska event and of the seeding of amino acid molecules using a ballistic range which shoots a snowball laden with amino acid molecules toward a water surface.

Key words: Entry technology, Exobiology, Tunguska event, Shock tube, Ballistic range

1. Amino Acid Story

1.1 The second space age

In the summer of the year 2011, the United States is in the middle of an economic and political panic: public debt has soared; balance of trade is lop-sided; natural disasters partly blamed on global warming are inflicting painful damages; and the discontentment in different parts of the world is harming and dragging the nation into unaffordable wars. In this midst, the space activity the nation has so splendidly excelled in the past seems a luxury. The United States is drastically curtailing its commitment to the space activity. The physicists, environmentalists, and biologists who inhabit the National Academy of Sciences and the present administration are skeptical especially of the manned space flight which makes up the heart of National Aeronautics and Space Administration(NASA)'s activities. We must conclude that the great space age of the twentieth century is coming to an end, with the last flight of the Space Shuttle.

But the space activity itself is not dying. Instead, the second round of space age is about to begin. The first round, the twentieth century version, was based on international conflicts. The nature of the second round will be determined by what we want it to be. We have before us the task of designing this round two of space age. Obviously, we expect China and India to play an important role in this second round. Manned space flight, the target of skepticism of so many scientists, is to be relegated henceforth to the private enterprise whose purpose at present is to construct a space tourism business. In fact, one is amazed by the inventiveness in Burt Rutan’s Spaceship Two: the vehicle is designed so safely that one wonders why NASA did not think of it before. But, regarding planetary exploration, the message is clear: everybody likes it because it brings new knowledge about planets and the universe and especially the position of us human beings in the universe. Expectation is high that such exploration would tell us whether we humans are alone in the universe.
1. 2 Left-handed amino acids

A few years ago, NASA administrator Dan Golden triggered excitement by declaring that something from out of space contained signs of past life. Many were skeptical. However, there is one line of evidence which is scientifically concrete. It concerns the chirality, i.e., left-handed or right-handedness, of amino acid molecules (Avetisov et al., 1991; Chyba, 1997a). All living things on Earth are made of left-handed amino acid molecules, called scientifically L-alanine. Its molecular structure is shown in the left of Fig. 1. In a laboratory, one can make amino acid molecules. The molecules so made contain the left-handed and the right-handed molecules, called D-alanine and shown in the right of Fig. 1, in equal numbers (Miller, 1953).

1. 3 Amino acids in space

Amino acid molecules were found in objects in space in several different forms. One of them is what is known as Murchison meteorite. In an area called Murchison in Australia, a meteorite fell on September 28, 1969. The fragments totaling about 100 kg of this meteorite were eventually recovered. The largest of these is shown in Fig. 2. It was chemically analyzed. Amino acid molecules mostly of left-running type were found in them (Engel and Nagy, 1982; Ilczuk, 1976). Question was raised as to whether these molecules were genuinely of extra-terrestrial origin. Isotopic analysis was made to confirm that the molecules are indeed of extra-terrestrial origin (Engel and Macko, 1997; Engel et al., 1990).

More recently, the Stardust space vehicle, which rendezvoused with comet Wild 2, brought back left-running amino acid molecules (Glavin et al., 2008). Presence of left-handed amino acids in other celestial bodies has also been studied to a great extent (Al-Mufti et al., 1982; Basiuk, 2001; Belloche et al., 2008; Bredehoefl and Meierhenrich, 2008; Breslow, 2011; Elsila et al., 2007; Goldanskii, 1977; Igesias-Groth et al., 2010, 2011; Knowles et al., 2010; Kobayashi et al., 2010; Lattelais et al., 2011; Lee et al., 2009; Martins, 2011; Meierhenrich, 2009; Munoz Caro and Martinez-Frias, 2007; Pilling et al., 2008; Suess et al., 2005; Vandenbussche et al., 2011). It seems firm that amino acids exist in abundance in space and they are mostly of left-running type. This is believed to be because radiation preferentially decomposes right-running amino acids.

1. 4 Looking for amino acids in space

Such finding prompted even space missions using spacecraft to look for the left-running amino acids (Kobayashi, 2008; Thiemann and Meierhenrich, 2001). The finding also prompted speculations about the origin of life on Earth. Could the left-running amino acids on Earth have been seeded by the extraterrestrial objects (Blank et al., 2001; Brack, 2007; Chyba et al., 1990; Cohen, 1995; Irwin and Schulze-Makuch, 2001; Meierhenrich, 2002; Oberbeck and Aggarwal, 1991; Pierazzo and Chyba, 1999; Steel, 1991; Zahnle and Grinspoon, 1990). If the answer is affirmative, naturally one could further speculate that life on Earth was seeded by extraterrestrial objects. However, in order to answer these questions, one must first find out whether the amino acid molecules can survive the entry flights of the objects.

In order for the extraterrestrial seeding could occur, the object must fall on the ocean because water is needed for biochemical evolution to begin. Principles of aerodynamics and entry aerothermodynamics tell us that heat transfer rate to an entry body is inversely proportional to the square-
root of its diameter. Therefore, small entry bodies will be vaporized before it can reach the ocean surface. Many geophysicists who were studying this question (Goldanskii, 1996; Meierhenrich, 2002; Oberbeck and Aggarwal, 1991; Pierazzo and Chyba, 1999; Steel, 1991; Winans et al., 2000; Zahnle and Grinspoon, 1990) seem to be in the opinion that large objects can safely deliver amino acids to the ocean surface. However, Ross (2006) who studied thermodynamics of the impact of an extraterrestrial object on ocean surface in detail, concluded that the heat generated at the moment of impact will decompose any organic molecules contained therein. This issue will be discussed further later in this lecture.

2. Aero-capturing in Outer Planets

2. 1 Planets and moons that may harbor amino acids

Several of the planetary exploration missions executed in the past and most of those planned for future are primarily for the purpose of answering the questions surrounding the existence and origin of life here on Earth and elsewhere. The questions are closely related to the issue of chirality of amino acid molecules. Search for the signs of past life has been in progress for Mars. Titan (Brack, 2000; Jones et al., 2011; Lunine, 2009; McKay and Smith, 2005; Neish, 2008; Norman, 2011; Raulin, 2008; Schulze-Makuch et al., 2002; Shapiro and Schulze-Makuch, 2009; Shaw, 2008; Simakov, 2004; Vazquez, 2005), a moon of Saturn, Europa (Chyba, 1997b, 2000; Irwin and Schulze-Makuch, 2001; Raulin, 2009; Schulze-Makuch et al., 2002; Shapiro and Schulze-Makuch, 2009; Vazquez, 2005), a moon of Jupiter, Io (Irwin and Schulze-Makuch, 2001; Schulze-Makuch et al., 2002; Vazquez, 2005), another moon of Jupiter, Enceladus (Raulin, 2009), a moon of Saturn, and Triton (Irwin and Schulze-Makuch, 2001; Shock and McKinnon, 1993), a moon of Neptune, have also been touted as places worthy of visiting for this purpose.

Except for Mars, all celestial bodies of interest are therefore moons of the outer planets, i.e., Jupiter, Saturn, or Neptune. Titan has been visited already, but doubtless will be visited again. These outer planet’s moons are interesting because they are far from the sun. The primitive icy objects are mostly in the region outside of the reach of the sun’s gravity, known as Kuiper Belt. If the building blocks of life came from celestial sources, then the objects in Kuiper Belt should contain them most. These Kuiper Belt objects become comets and enter into the solar system. Therefore, seeding of the planets and their moons, if true, would preferentially occur in these outer-lying celestial bodies (Owen, 2008).

2. 2 Planetary aero-capturing

In order to increase the payload for the spacecraft visiting these outer planet’s moons, aero-capturing would be desirable. What was envisioned in Arthur C. Clark’s 2010 Space Odyssey is the kind needed to increase the payload to these celestial bodies.

Entry flight in Jupiter has already been made in Project Galileo. That flight was a steep entry, producing very high pressures. In contrast, the aero-capturing maneuvers needed here will be a shallow entry, producing a dynamic pressure at most on the order of 0.1 atmospheres. It must be mentioned here that the Galileo Probe mission left us a homework problem to solve: the extent of ablation of the heat-shield was significantly different from the pre-mission calculations (Matsuyama et al., 2005); in fact the mission succeeded only because the thickness of the heat-shield was made twice the calculated needed thickness. Even that was barely: the downstream edge of the heatshield was almost burned through!

The easiest of these aero-capturing in the outer planet’s atmosphere will be that in Neptune, because it is the smallest of the three outer planets of interest. As mentioned, its moon Triton is one that is worth visiting. For this reason, some theoretical calculations have been made. In the following, these calculations will be described in the hope of highlighting what lies ahead in pursing such aero-capturing flights in outer planets:

2. 3 Ionization in H2 + He mixtures

The atmospheres of an outer planet consist typically of 80%H2 + 19%He + 1%CH4. Aero-capturing flight in an outer planet will occur at a very high speed. For Jupiter, the minimum energy trajectory leads to an entry speed of the order of 50 km/s. For Saturn, it is about 30 km/s. For Neptune, it is about 25 km/s. However, for Neptune, the actual entry speed will be faster. First, Neptune is so far from Earth that it will take excruciatingly long time to reach it unless the trip is made on a high energy trajectory. Such high energy trajectory can be attained through the use of a planetary swing-by. Second, the entry flight must be made in the retrograde direction, in the direction opposite to the direction of planet’s rotation, because its moon Triton is rotating in the retrograde direction. These two reasons compel the aero-capturing entries to be made at about 30 km/s. Thermally shielding the aero-capturing vehicle at such high speeds becomes the problem.

At such speeds, CH4 will quickly decompose into C and
H. C and H will both ionize; Helium will not. But, because the concentration of H is overwhelmingly large, most of electrons will be from H. Radiation intensity is approximately proportional to the square of electron density. Therefore the extent of ionization, and indirectly electron temperature, will dictate the radiative heat flux falling onto the heat-shield. Because chemical reactions take time, there will be a region immediately behind the bow shock wave where electron density and temperature will be different from the equilibrium values. In Earth entries, it is well known that this so-called nonequilibrium region produces radiation stronger than in the equilibrium flow, in a phenomenon known as nonequilibrium radiation overshoot. Characterizing this nonequilibrium radiation overshoot phenomenon becomes the problem of primary concern.

It is well known that ionization of an atom occurs primarily by the collisions of electrons with atoms, in a process known as electron-impact ionization \( \text{H} + \text{e} \rightarrow \text{H}^+ + \text{e} + \text{e} \). Because one such process produces an additional electron, electron density grows exponentially, in a process called avalanche ionization. But, for this avalanche ionization to start, there must first be an electron. Where this first electron comes from is the question. In air, conveniently a collision between N and O produces NO + and an electron. But, in the H2 + He + CH4 atmosphere, such process is not yet known.

2.4 Leibowitz and Livingston-Poon experiments

The nonequilibrium processes behind a shock wave is studied normally in a shock tube. But it is rather difficult to produce a speed of the order of 30 km/s in a shock tube. In order to produce such a high shock speed, it is customary to heat the driver electrically. In the 1970s, Leibowitz (1973) and Livingston and Poon (1976) carried out separately a shock tube experiment with an H2 + He mixture. The shock tubes they used are shown schematically in Figs. 2a and b.

As shown, the driver in Leibowitz’s shock tube was heated thermally by electric discharge. In the shock tube of Livingston and Poon, the driven gas was pushed by a combination of electrical heating of the driver and the magneto-hydrodynamic forces produced by a concentric electrode arrangement.

Leibowitz measured the time to reach equilibrium. Livingston and Poon measured not only the equilibration time but also the absolute values of electron density. When the equilibration times of the two sets of data, discrepancy was found (Park, 2010): equilibration was faster in Leibowitz’s experiment by a factor of about three. Moreover, the electron densities measured by Livingston and Poon were higher than the equilibrium values, which is theoretically impossible.

To understand these two experiments, Bogdanoff and Park (2002) tried to repeat Leibowitz’s experiment using a shock tube closely resembling Leibowitz’s, as shown in Fig. 3c. The electron density values in what looked like the equilibrium region (steady-state region) are shown in Fig. 4.

As seen in Fig. 4, the measured electron densities were up to 10 orders of magnitude higher than the theoretical equilibrium values. Various tests revealed that the hot driver gas radiatively ionized the driven gas through photo-ionization process. This result hinted strongly that the same phenomenon could have happened in the experiments by...
Leibowitz (1973) and by Livingston and Poon (1976). This prompted the present author and his associates to reexamine the data by these two sources and to reinterpret their data accounting for this driver irradiation phenomenon (Furudate et al., 2005; Kim et al., 2009, 2010; Park, 2004, 2010, 2011a, b, c). This led to a tentative theoretical model to describe the nonequilibrium phenomenon in an H₂ + He + CH₄ mixture.

The central part of this tentative theoretical model concerns description of nonequilibrium ionization phenomenon in an H₂ + He mixture. Because this model must describe ionization rate when there are no electrons, the model accounts for both the electron-impact ionization phenomenon and the heavy particle-impact ionization phenomena, H + H à H⁺ + H + e and H + He à H⁺ + He + e.

To determine the ionization rate, the number density of all electronic states of H are first determined by solving the so-called quasi-steady state population equation (Park, 1990). To do so, the rate of transition from one electronic state to another by collisions and by radiation must be known. The rate of collisional transitions by an electronic-impact is known accurately for H. The rate by heavy particle-impact is not known, and must be deduced from the experiments by Leibowitz and by Livingston and Poon. For convenience, this heavy particle-impact excitation is assumed to occur with a same cross section for all transitions. The rate of radiative transition from a high electronic state to a low electronic state is the transition probability, which is known accurately for H. However, there are transitions from a low state to a high state by radiation absorption. This transition is weak for all transitions except for the radiation at the wavelength of 121.6 nanometer which is known as Lyman-alpha radiation. To determine this quantity, one must first solve the radiative transfer problem over the entire flow-field.

When the quasi-steady state population calculation is made, there result eight rate coefficients, all of which are a function of five parameters, heavy particle temperature, heavy particles number density, electron number density, electron temperature, and the extent of Lyman-alpha absorption. In addition, there is the radiative cooling rate which is a function also of the five parameters. The absolute magnitude and temperature dependence of the heavy particle-impact transition rates are varied until the calculation reproduced the experimental data of Leibowitz and Livingston and Poon.

Because the radiation from the hot driver gas is influencing the flow, the driver irradiation phenomenon had to be accounted for also. Because of high pressure and relatively large volume of the driver, the driver radiation is assumed to be that of a black body. In the shock tube experiment by Leibowitz and by Livingston and Poon, presumably the driver temperature was different for each data point. This driver temperature must be guessed at this time in order to obtain any meaningful results.

This guess work was made, and the resulting ionization equilibration time and electron density were calculated for the two shock tube experiments (Park, 2010). In Fig. 5, the calculated radiation intensity at one wavelength, which is proportional to the square of electron density, are compared with the experimental data for Leibowitz’s experiment. As seen here, agreement is good. As indicated, this agreement is obtained by assuming the driver temperature to be 15,500 K.

In Fig. 6, the ionization equilibration times in the experiment by Leibowitz, indicated in Fig. 5, are compared between the measurement and the theoretical model.
2.5 Desirable experimental facilities

One can think of three different facilities that could be guessed. In reality, the cross section for heavy particle-irradiation impacts negligibly.

As Fig. 6 hints, the driver’s influence becomes negligible when the highest driver temperature is below 12,000 K. Calculation shows that when the driver temperature is 12,000 K, 30 km/s shock speed could be produced if the driver pressure is very high, i.e., of the order of 1,000 atm.

One can think of three different facilities that could produce 30 km/s shock speed without radiatively affecting the test gas, as shown in Fig. 9.

Fig. 7. Ionization equilibration distances in the experiment by Livingston and Poon (1976).

Fig. 8. Peak electron densities in the experiment by Livingston and Poon (1976).

Fig. 9. Three possible ways of producing 30 km/s without producing radiative heating of test gas.
In Fig. 9a, a double-diaphragm shock tube (expansion tube) is to be operated with hydrogen in the first and the second chambers. Pressure in the first chamber will have to be very high in order to produce 12,000 K in the second chamber. In Fig. 9b, the driver is filled with a gas of low ionization potential such as potassium-sodium KNa. The capacitance of the capacitor powering the driver will have to be small in order to finish electric discharge in a short time. Capacitor voltage must be high in order to deliver enough energy with such a small capacitance. In Fig. 9c, a hard material is accelerated to a very high speed using an explosive. This high speed matter compresses hydrogen to attain 12,000 K. The device will be destroyed in such an operation. That is, this is a disposable shock tube (Cooper et al., 1972).

2. 6 Effect of CH4

When C originating from CH4 collides with H, associative ionization C + H  à CH+ + e occurs. The coefficient for this reaction was deduced from its reverse reaction CH+ + e à C + H for which several data exist. This rate coefficient in the present model is compared with the experimental data in Fig. 10. As seen, the model is satisfactory.

2. 7 Application to flight

The theoretical model so developed was applied to the flight case (Park, 2011c). The case selected is one studied previously by Hollis et al. (2004). In Fig. 11, the radiative heat transfer rates calculated by the model are compared with those by Hollis et al. (2004). As indicated, the theoretical model developed leads to radiative heat transfer rate values some three times larger than that determined by Hollis et al. The heat load values shown are very large values needing a thick heat-shield. This shows the importance of carrying out new experiments in new facilities indicated in Fig. 9.

3. Entry Flights of Extraterrestrial Objects

3.1 Initial breakup of a meteor

Now we ask ourselves what we could do in order to further our understanding of life in the universe. Comets and asteroids in the solar system collide with Earth and other celestial bodies in the form of meteoroids. Comets could bring the primordial amino acids from outside of solar system. They are believed to be dirty snowballs entering Earth’s atmosphere typically at 40 km/s. Asteroids are recycled planets and enter into the atmosphere typically at 20 km/s.

Ross (2006) and most other geophysicists who tackled the problem of extraterrestrial seeding of life tried to answer the question regarding the survivability of amino acids contained in the extraterrestrial objects through the violent entry process. As mentioned, Ross determined that large meteorites which could reach the ocean surface would hit the ocean surface so hard that it would heat up instantly and therefore amino acids will all be destroyed.

However, Ross’ theory does not account for one important mechanical phenomenon. A large entry body will break up in the atmosphere and fragment into many small objects. These small fragments will slow down and vaporize fast. If the slowing down is faster than vaporizing, then there will be some small fragments that will reach the ocean surface at a small velocity. At such a small velocity, the impact will
be gentle and no heating will occur. Conversely, if vaporizing is faster than slowing down, then there will be nothing left to reach the ocean surface. If vaporization and deceleration are both slow, then the object will hit the ocean surface hard, resulting in instant rise of temperature and ensuing vaporization of amino acid molecules.

The phenomenon of breakup of meteoroids has been studied from the early times (Baldwin and Sheaffer, 1971; Fay et al., 1964; Romig, 1965). More recently, Hills and Goda (1993), Zdan et al. (2004a, b), and Stulov (2010) studied in more detail. The initial breakup of a meteoroid is reasoned to occur when the aerodynamic forces acting on the meteoroid exceed the strength of the meteoroid. The aerodynamic interactions among the fragments so formed cause forces to separate the fragments. These theories explain the breakup process up to the point where the distances between adjacent fragments are about five times the diameter of the fragments. Ross’s analysis accounts for this early breakup phenomenon. However, what happens after this initial breakup process has not yet been studied systematically.

3.2 Tunguska event

That this initial breakup alone cannot explain all aspects of breakup phenomena of a meteoroid is seen in the case of the well-known Tunguska event (Drobyshevski, 2009; Vasilyev, 1998). In the summer of 1908, in a Siberian region named Tunguska, shown in the map in Fig. 12, a large celestial object fell. Bright light resembling an explosion was seen. But there was no impact crater. Trees were felled, but there was no forest fire, as can be seen in Fig. 13, signifying that heat was not generated. The seismographs all over the world recorded Earth’s tremor due to the impact and the barometers all over the world recorded the pressure wave generated by the event. Moreover, the sky over the northern hemisphere was darkened. The seismographic analysis determined the vertical impulse to be $7 \times 10^{13}$ N-m and the horizontal impulse to be $1.4 \times 10^{13}$ N-m. The extent of the darkness of the sky was found to be equivalent to that due to 30 million tons of nitric oxide (Turco et al., 1981, 1982).

The people familiar with nuclear weaponry concluded that the damage done to the ground was equivalent to that produced by a nuclear bomb of 10 to 50 mega-ton TNT energy exploding at an altitude of 5 to 10 km (Drobyshevski, 2009). If the seismographic impulse is the initial momentum of the meteor, the meteor’s mass should be 3.5 million tons. If 15 mega-ton-TNT energy was the initial kinetic energy of the object, mass is calculated to be 8,000 tons. Chyba et al. (1993), Ivanov and Ryzhanskii (1995), and Melott et al. (2010) deduced different masses falling between these two limits. But, still no such theories can explain this large difference in the calculated entry mass and the three indirect but firm physical data of the event, i.e., the impulses, atmospheric pressure variation, and the nitric oxide production, in addition to what was observed on the ground, i.e., no crating and no fire.

The fact that there was no crater and no fire imply first that no hard material hit the Earth’s surface: the felling of the trees was due only to an air blast. The air blast was not hypersonic: a hypersonic flow would have produced high temperature and would have burned the trees. The solid fragments, if existed, must have been quite small or would have been moving quite slowly. This means that the breakup process continued much beyond the initial breakup to five-diameter inter-segment distances. So, if this is true, and if any solid fragments reached the ground at a low speed, amino acid molecules riding on them would have survived to reach the ground. Thus, the breakup phenomenon in the later portion of the entry trajectory is the crucial part of the equation.

3.3 Ballistic range experiment

The present author witnessed the phenomenon of spreading of such fragments in a laboratory. The experiment
was actually for testing the aerodynamics of the Galileo Probe vehicle which entered the atmosphere of Jupiter later. A scale model of the Galileo Probe vehicle made of graphite was flown in a ballistic range. In order to heat the model to a high temperature, the model was made to fly through a chamber filled with krypton or xenon, as shown schematically in Fig. 14 (Park and De Rose, 1980). Krypton or xenon produced radiative heating rates of several hundred kilowatts per square centimeter, which gave thermal shock to the flying body.

The shape of the unbroken model is shown in Fig. 15a. After passing through the krypton/xenon chamber, the model started breaking up as shown in Fig. 15b. Later, the model was fragmented into small pieces, as shown in Fig. 15c. Still later it became totally pulverized as shown in Fig. 15d. The overall diameter of the fragment cloud seen in Fig. 15d is quite large.

The surprising aspect of these figures is that the fragments spread not only in the initial phase but also in the later phase when the near-body interaction forces have died down.

3.4 Computational-fluid-dynamic calculation of spreading phenomenon

In order to find out the source of the forces causing the spreading in the later phase of the entry flight, a computational-fluid-dynamic (CFD) calculation was performed by the present author. The fragments were assumed to be so small in comparison with the diameter of the particle cloud that they could be taken to be dust particles. In this dust-laden hypersonic flow, flow momentum is affected by the drag produced by each dust particle, and the mass and energy are affected by the ablation of the each particle. The density of the particles is assumed to be 1,000 kg/m³. The drag of the particles is calculated assuming the drag coefficient to be unity. Ablation rate is determined by dividing the stagnation
point convective heat transfer rate by the heat of ablation. Convective heat transfer rate is calculated in turn by assuming the Nusselt number to be 0.002. Heat of ablation is assumed to be 10 kJ/kg.

The results of this calculation will be presented elsewhere. But a typical solution is shown in Fig. 16. In this case, the flow density is 10^-4 kg/m^3, corresponding to the altitude of 68 km, and the flight velocity is 5.280 km/s. The dust particles are a sphere of 1 mm diameter. There are 1,000 such spheres in 1 m^3. The cloud is in the shape of a sphere with a diameter of 8 meters. Figure 15 shows pressure distribution qualitatively.

As Fig. 16 shows, pressure is generally high along the centerline axis and decays in the radial direction. This pressure distribution is a result of the drag produced by each fragment. Though not shown, corresponding to this pressure distribution, there is a distribution of velocity vectors. Because pressure decreases with increasing radius, flow velocity has a radial component that increases with increasing radius. This radial component of flow velocity will push the fragments radially outward, causing spreading of fragments.

Simultaneously with this spreading, there will be ablation and breakup. The small fragments will have small ballistic coefficients and therefore will slow down rapidly. By accounting for this spreading, breakup, slowing down, and ablation, one should be able to determine how fast the particles are moving when they reach the ground, if at all, how large each particle will be, and how hot the particles will be. The problem is totally in the domain of entry physics, and should be studied by the entry physicists familiar with spacecraft entries. By performing such calculations for the Tunguska event and by comparing the resulting four quantities, i.e., impulses, atmospheric pressure propagation pattern, nitric oxide production, and ground damage, with the observation, one should be able to validate the calculation. Only when the validated solution is determined, can one determine whether the amino acid molecules in the object can survive the entry flight.

3.5 Desirable experiments

In order to partially validate the CFD calculation for Tunguska event, a ballistic range experiment could be performed. In this experiment, a model made of a snowball can be launched in a ballistic range. The snowball could really be a compacted ball of water snow particles or of an organic matter similar to water snow. The snowball will break up in the ballistic range as seen in Fig. 15. At the end of the range will be an inclined plate shown in Fig. 17. The fragments of the snowball will hit this inclined plate at an angle. The accelerometers attached to the plate will measure the response of the plate. From the response obtained, one shall determine the normal and tangential impulses. These impulses will be compared with the initial momentum of the snowball and with the results of the CFD calculation. By varying the characteristics of the snowball, one should be able to derive a mathematical model relating the breakup, spreading, and ablation phenomena of the snowball to the characteristics of the snowball.

In order to answer the question more directly as to whether amino acid molecules can survive an Earth entry, one could also carry out an experiment simulating the entire process as shown in Fig. 18. In this experiment, a two-stage light gas gun launches a model of a cometary or asteroidal meteoroid at an angle toward a water surface. The model is seeded with organic molecules such as amino acids. The model is made to fly through a space filled with atmosphere freely a certain distance so that it could break up and spread. After each flight, the water is analyzed to see whether the organic molecules originally contained in the

Fig. 16. Pressure distribution of a dust-laden hypersonic flow at flight speed of 5.28 km/s in air. Abscissa is longitudinal distance and ordinate is radial distance. Flow direction is from left to right. Flow density = 10^-4 kg/m^3; Particle diameter = 1 mm.

Fig. 17. Schematic of a ballistic range experiment of Tunguska event.
snowball survived the flight. Various different instruments can be placed at different positions along the flight path. The entire process, from beginning to end, of the flight of a meteoroid can be studied in this experiment, and new theoretical models describing the phenomena could be derived from this experiment.

4. Conclusions

Future entry technology research should be directed to improve our understanding of the existence and proliferation of life forms in the universe. One notices that the amino acid molecules present outside of the Earth is predominantly left-handed, and that all living things on Earth are made up of such left-handed amino acids, despite the fact that left-handed and right-handed amino acids are produced in equal numbers in a laboratory. Effort should be made to answer the question as to how likely it is for extraterrestrial amino acid molecules to have seeded the life forms in the solar system.

Two different directions are proposed. In the first, the search for life’s building blocks in outer planets and their moons is to be pursued. For this purpose, aero-capturing flights need to be carried out in outer planets. The heating environment in such flights must be defined. The past works on this subject are unsatisfactory. New types of shock tubes, which can produce a shock speed of 30 km/s without heating the driver gas beyond 12,000 K, must be developed to study the phenomenon.

Second, the question as to whether the amino acid molecules contained in the celestial bodies can survive the planetary entry flights should be studied. It is noted that, in the past research works on this subject, the fluid mechanical aspect of the spreading of the meteor fragments has not been studied thoroughly. A CFD study of the process of breakup, spreading, slowing down, and ablation will have to be made. Such calculation should be made first for the Tunguska event. The results of such calculation could be validated by comparing with the observed impulses, pressure records, nitric oxide production, and ground damage. Ballistic range experiment could be made to simulate the Tunguska event in order to partially validate the calculation. A full-fledged ballistic range experiment can be made to test the survivability of amino acid molecules in a dedicated inclined two-stage light gas gun range launching a snowball toward a water surface.

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