THE VIABILITY WITH RESPECT TO TEMPERATURE OF MICRO-ORGANISMS INCIDENT ON THE EARTH'S ATMOSPHERE *

(Letter to the Editor)

F. HOYLE, N.C. WICKRAMASINGHE and S. AL-MUFTI
Department of Applied Mathematics and Astronomy, University College, Cardiff U.K.

Abstract. Using laboratory measurements of the resistance of *E. coli* to flash-heating, it is shown that a large fraction of interplanetary micro-organisms in prograde orbits could be added to the Earth without losing viability due to beating by the atmospheric gases.

1. Model for a Micro-Organism Impacting the Terrestrial Atmosphere

The micro-organism will be taken to be a sphere of radius a and specific gravity s. The radius a is considered to be so small that thermal conductivity easily maintains a uniform body temperature, say T, as the frictional resistance of the atmosphere generates heat at the surface of the organism. The temperature rises to a maximum and declines thereafter in a time scale of a few seconds. Since the heat capacity is small, T is determined by the condition that the rate of radiation equals the rate of heat production, evaporation being omitted because the micro-organism is taken to be initially dry and because T does not become so high that biomaterial is subjected to appreciable evaporation.

The geometry of impact is illustrated in Figure 1, the micro-organism being instantaneously at the point P with velocity $v(x)$, which will be considered large enough for the path of the organism to be essentially a straight line, intersecting the Earth diameter AB at N, where $ON = r < R$, R being the radius of the Earth. Writing $OP = R + h$, the density of the atmosphere at P is of the form $\alpha \exp(-h/H)$, where α is some constant and H is the scale height of the atmosphere in the neighbourhood of P. The co-ordinate x is the distance from P to N.

The mass of air impacting the organism per unit time is $\pi a^2 \alpha \exp(-h/H) v$. The molecules of air will be taken to acquire the velocity v in the direction P to N, following which they move away from the organism – after becoming co-moving they evaporate away, leaving the organism to continue its journey. Momentum balance then requires

$$\frac{4\pi}{3} a^3 s[v(x+dx) - v(x)] = -\pi a^2 \alpha \exp(-h/H)\, v^2\, dt, \quad (1)$$

* 1986, *Earth, Moon, and Planets* **35**, 79–84.

Astrophysics and Space Science is the original source of publication of this article. It is recommended that this article is cited as: *Astrophysics and Space Science* **268:** 45–50, 1999.

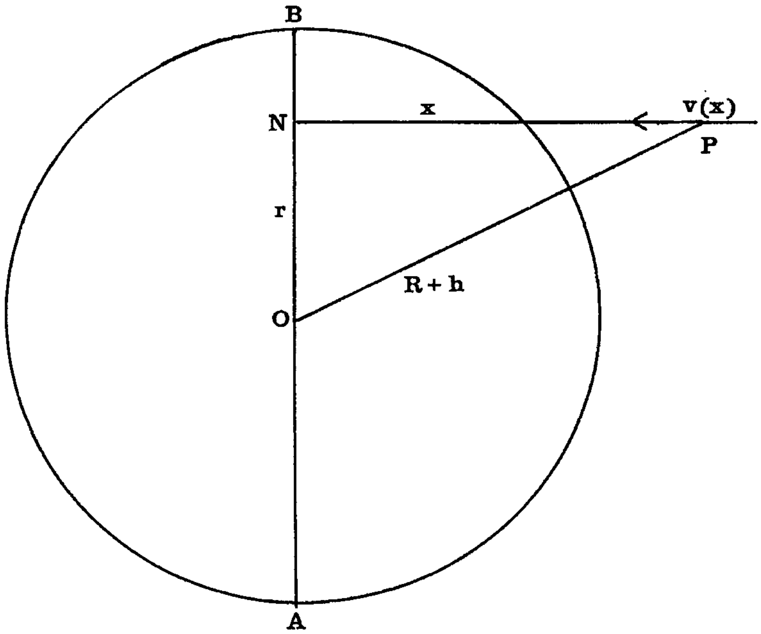

Figure 1.

with $\nu(x) = -dx/dt$, so that

$$d \ \ln \ \nu/dx = \frac{3}{4}(\alpha/as) \exp(-h/H). \tag{2}$$

When $r < R$, Equation (2) can be integrated subject to a slight approximation. Since triangle OPN is right-angled $(R+h)^2 = x^2 + r^2$. The range of h over which a micro-organism is 'stopped' by atmospheric resistance $\sim$ 150 km down to $\sim$ 120 km, over which range $h \ll R$. Thus in the important range of x we can take $(R+h)^2 = R^2 + 2Rh$, i.e. the relation between x and h is to sufficient accuracy

$$\frac{h}{H} = \frac{x^2 + r^2 - R^2}{2RH}, \tag{3}$$

whence (2) becomes

$$\frac{d \ln \ \nu}{dx} = \frac{3\alpha}{4as} \exp\left(\frac{R^2 - r^2 - x^2}{2RH}\right). \tag{4}$$

Writing $\nu(\infty) = \nu_0$, we therefore obtain,

$$\ln \frac{\nu}{\nu_0} = -\frac{3\alpha}{4as} \exp\left(\frac{R^2 - r^2}{2RH}\right) \int_x^\infty \exp - \left(\frac{y^2}{2RH}\right) dy. \tag{5}$$

Now because $r < R$, and $x^2 > 2Rh \gg 2RH$, the integral in (5) can be approximated as follows,

$$\int_x^\infty \exp -\left(\frac{y^2}{2RH}\right) dy = \exp -\frac{x^2}{2RH}\int_0^\infty \exp\frac{-2xz - z^2}{2RH}dz$$

$$\cong \exp -\frac{x^2}{2RH}\int_0^\infty \exp\left(-\frac{xz}{RH}\right) dz \tag{6}$$

$$= \frac{RH}{x}\exp -\frac{x^2}{2RH}.$$

Hence

$$v(x) = v_0 \exp\left\{-\frac{3\alpha}{4as}\cdot\frac{RH}{x}\exp\frac{R^2 - r^2 - x^2}{2RH}\right\}. \tag{7}$$

The relation (7) holds over the range of x in which the micro-organism is 'stopped'.

2. The Maximum Rate of Release of Heat

If a body of small mass m at rest impacts a larger body of mass M moving with speed v, with the small body brought up to speed with the large one, the kinetic energy of the translation of the system is reduced from $\frac{1}{2}Mv^2$ to $\frac{1}{2}Mv^2(1 - m/M)$, the lost kinetic energy, $\frac{1}{2}mv^2$, of translation appearing as heat.

In a similar way, an incoming micro-organism brings the impacting atmospheric gases up to speed with itself, at a rate $\pi a^2\alpha v \exp -h/H$. Hence the rate of release of heat is $\frac{1}{2}\pi a^2\alpha v^3 \exp -h/H$. The heat is partly taken up by the micro-organism itself and partly by the impacting gases, which carry away a share of the heat as they evaporate from the organism. Assigning one-half of the heat to the evaporation of atmospheric gases and one-half to the organism itself the rate of heating of the latter is

$$\frac{1}{4}\pi a^2\alpha v^3 \exp(-h/H). \tag{8}$$

We now determine the maximum value of (8). Inserting (7) for v and (3) for h/H, (8) takes the form

$$\frac{1}{4}\pi a^2\alpha v_0^3 \ \exp\left[-\frac{9\alpha}{4as}\frac{RH}{x}\exp\frac{R^2 - r^2 - x^2}{2RH}\right] \exp\left[\frac{R^2 - r^2 - x^2}{2RH}\right] \tag{9}$$

By differentiating (9) with respect to x and remembering that $x^2 \gg RH$, we find it straightforward to show that the maximum of (9) occurs for

$$x \cong \frac{9\alpha RH}{4as}\exp\frac{R^2 - r^2 - x^2}{2RH}. \tag{10}$$

Substituting (10) in (9) gives

$$\frac{1}{4}\pi a^2 \alpha v_0^3 \exp\left[\frac{R^2 - r^2 - x^2}{2RH} - 1\right]. \tag{11}$$

Again using (10) to eliminate $\exp[(R^2 - r^2 - x^2)/2RH]$, the maximum rate of heat addition to the microorganism can be written as

$$\frac{4}{3}\pi a^3 s \times \frac{1}{12e} v_0^3 \times \frac{x}{RH}. \tag{12}$$

So long as r is not too close to R, $x^2 + r^2 = (R + h)^2 \cong R^2$, giving $x/R = (1 - r^2/R^2)^{1/2}$, and (12) can be written in the form

$$\frac{4}{3}\pi a^3 s \times \frac{k^{1/2}}{12e} \times \frac{v_0^3}{H}. \tag{13}$$

where $k = 1 - r^2/R^2$ is the fraction of a parallel beam of micro-organisms of uniform density that impacts the Earth over a silhouette area consisting of a circular ring of inner radius r and outer radius R. The result (13) is the maximum rate of heat production for any of the micro-organisms impacting this ring.

3. Laboratory Experiments to Determine Tolerance to Flash Heating

A series of laboratory experiments were carried out to test the viability of bacteria after brief exposures to high temperatures, as may be expected in the atmospheric re-entry problem. About 2 mg of freeze-dried *E. coli* (types ATCC/0537 and ATCC/35218) were placed inside a sterilised test tube, vacuumed and sealed. Next, an oven was pre-heated to a temperature accurately set in the range 400–800 K. (The upper bound of this range was set by the practical difficulty of reaching and measuring higher temperatures with the equipment available.) The tube was then placed inside the pre-heated oven for varying lengths of time, taking account of the time taken for the test tube to reach the oven temperature, which was found to be a few seconds. In all cases we found that the bacteria appear charred at their surface after exposure to heat. The bacteria in each experiment were then transferred into sterilised flasks containing nutrient broth.

We found that approximately 80% of the bacteria exposed to a temperature of 800 K for 25 s are viable, although they required approximately 20 hr to begin regrowth. For bacteria exposed to the same temperature for 35s the percentage regrown was found to be $\sim$ 30%.

On examining the regrown cultures microscopically it was found that bacterial morphologies and initial replication patterns are altered in a very similar way to what was earlier found for bacteria subjected to high pressures (Al Mufti *et al.*, 1984).

Another set of experiments was carried out in which bacteria were exposed to heat in two stages. In the first stage, the test tube containing the bacteria was placed in an oven at a temperature of 450 K for 0.5 to 1.0 min. It was then allowed to re-cool to room temperature and then re-exposed to heat at 800 K. We now found that $\sim$ 80% viability was obtained after longer exposures up to $\sim$ 45 s. This could be due to the formation of a thin carbon skin in the first stage, that acted as a partial shield in the second stage of heating.

In sum, the upshot of our experiments was to show that micro-organisms typified by *E. coli* survived heating under vacuum conditions to temperatures of 800 K for durations of time ranging from 25–35 s. In a two-stage heating process, even longer exposures ($\sim$ 45 s) to a temperature of 800 K led to significant survival. We stress, however, that our results establish the survival of bacteria on flash heating in a vacuum to at least 800 K. Our experimental procedure did not permit us to reach temperatures significantly higher than 800 K or to expose the micro-organisms to much briefer time intervals. It could well be that micro-organisms could survive a temperature of 1000–1200 K for time scales of the order of 1s. Further experiments to test this possibility are currently in progress.

4. The Maximum Temperature Attained by an Impacting Micro-Organism

Suppose the mass absorption coefficient κ of the material of a microorganism to be independent of the electromagnetic wavelength λ. Then for a microorganism which is small enough to be optically thin in itself the emission rate of radiation at temperature T is

$$\frac{4}{3}\pi a^3 s \times \kappa \times acT^4. \tag{14}$$

Equating to (13) gives

$$v_0^3 = \frac{12e}{k^{1/2}} \times \kappa H \times acT^4, \tag{15}$$

a result independent of the radius a. If v_0 is specified, (15) gives the maximum temperature attained by the micro-organism.

Alternatively, we can insert in (15) the laboratory determination, $T \cong 800$ K, at which *E. coli* could be projected into the atmosphere without significant loss of viability. Bacteria flash-heated to 800 K emerged from the furnace with noticeable charring of their cell walls. Graphite, which is optically similar to the charred material, has an average mass absorption coefficient of $\sim$ 40 000 cm^2 g^{-1} over the wavelength range 3–6 μm (Taft and Phillipp, 1965), the relevant wavelength range for emission for $T \approx 800$ K. If the charred material were ten percent of the total, $\kappa = 4\,000$ cm^2 g^{-1} would be an appropriate value to be inserted in (15). Putting $k = 0.1$, $H = 25$ km, we then obtain

$$v_0 \cong 46 \text{ km s}^{-1}. \tag{16}$$

The choice for k implies that 10% of all the microorganisms incident on the Earth with speed 46 km s^{-1} would retain viability. At $v_0 = 40$ km s^{-1} essentially all the microorganisms would retain viability. The choice $H = 25$ km for the scale height is appropriate for micro-organisms stopped at an altitude $h \cong 130$ km. It may be noted that whereas *E. coli* was flash-heated in our experiments for 25 to 60 s, the atmospheric heating for the present values of H and v_0 would only have a duration of order 1 s. Thus our estimates are markedly on the safe side.

A particle falling towards the Sun from rest at large distance that encountered the Earth would do so at closely the speed given by (16), while particles in prograde orbits would have lower speeds. It follows that essentially all micro-organisms in prograde orbits could be added to the Earth without losing viability due to heating as they were slowed by the atmospheric gases.

References

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