CURRENT PROBLEMS IN RESEARCH

The Moon as a Collector of Biological Material

Terrestrial microorganisms may be found on the moon, but extra-solar-system biota would be undetectable.

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Several authors have discussed the possibility that the moon might serve as a repository for microorganisms from outside the solar system, or "astroplankton" (*1–4*). In considering the quantitative aspects of this idea, the first question to be asked is, what mass, W, of microorganisms needs to be ejected from an average planet in our galaxy to give the minimum detectable density of one microorganism per square meter of lunar surface (*1*), or 10^{-12} g/m^2. If this material were distributed uniformly on the moon, the total mass q of such viable microorganisms to be deposited on the moon during its existence would then be $\geqq 38$ grams.

For a single planet at a distance R from the moon, the solid angle subtended by the moon is $\pi r^2/4\pi R^2$, where r is the radius of the moon. If we approximate the galaxy by assuming a planar, uniform distribution of stars (*5*) centered on the moon, the number of stars between the limits R and $R + dR$ equals

$$N(R)\,dR = 2\pi R\beta dR \qquad (1)$$

where β, the density of stars per unit area, equals 1.4×10^{-25} star per square kilometer, for an effective galactic radius of 50,000 light years and a total star count of 10^{11}.

We shall henceforth make the optimistic assumption that the number of life-bearing planets in the galaxy also equals 10^{11}. The total mass of microorganisms deposited is then given by

$$q = \int W \frac{\pi r^2}{4\pi R^2}\, 2\pi\beta R dR$$

$$= \frac{\beta\pi W r^2}{2} \ln R + C \qquad (2)$$

Taking this integral between the limits 4.3 light years (the distance of α Centauri) and 50,000 light years, the effective radius of the galaxy, we obtain for W the value 6.0×10^{18} grams. This is the average mass of microorganisms that must be ejected from each of 10^{11} planets to give a density on the moon of one microorganism per square meter.

It is instructive to compare this figure with the mass of the earth's biosphere. The amount of carbon in the biosphere has been estimated (*6*) as 2.8×10^{17} grams, and the total mass of the biosphere may hence be perhaps ten times that amount, or 2.8×10^{18} grams. The mass of a planet's biosphere is dependent on the light flux, the rate of photosynthesis, the metabolic rate of its biota, the climatic conditions, and so on, but in the absence of further knowledge, one may perhaps consider the earth as typical. It then follows that, on the average, no less than twice the mass of a planet's biosphere must be ejected to give a detectable number of microorganisms on the moon's surface. This figure, moreover, makes no allowance for death during ejection, interstellar travel, arrival, and storage on the moon.

Capture and Ejection

We may next consider the processes of capture and ejection. Particles from outside the solar system will arrive on the moon with a velocity equal to the vector sum of the escape velocity from the solar system at 1 astronomical unit (42 km/sec), the earth's circumsolar velocity (30 km/sec), and the lunar escape velocity (2.4 km/sec). In the absence of an atmosphere, even very small particles will vaporize on impact. No information exists concerning the impact dynamics of gram- to kiloton-sized particles at these velocities, but if the data on the Canyon Diablo impact ($\sim 6 \times 10^4$ tons at 15 km/sec) may be used as a guide, more than 99 percent of the material may be expected to vaporize (*7*).

The ejection, whatever its mechanism, requires that the escape velocity from the combined gravitational fields of the planet and the central star be exceeded. The latter term is likely to be large for most life-bearing planets, since the requirement of surface temperatures permitting the existence of liquid water implies close proximity to the central star. Greater distances and lower escape velocities will be found only in the case of very luminous central stars of early spectral classification, since the temperature will vary approximately as the fourth power of the mass and the inverse one-half power of the distance, whereas the gravitational force will vary as the first power of the mass and the inverse second power of the distance. However, these stars remain on the main sequence of the Hertzsprung-Russell diagram only for times of $\leqq 10^8$ years, times which may not be sufficient for the development of life.

It is therefore necessary to consider ejection mechanisms that can propel at least some biological material to the required high velocities. Meteorite and comet impact appears to be the most promising possibility, as pointed out by O'Keefe (*8*), but one must not take it for granted that the sources of these objects, an asteroidal and a cometary belt, are indeed universal properties of all planetary systems. Moreover, the small mass deficit of lunar craters shows that the velocities imparted to the bulk of the material thrown out in such impacts are appreciably smaller than the lunar escape velocity (2.4 km/sec), though the length of Tycho's rays indicates that a moderate amount of material must have nearly reached circumlunar velocity (1.7 km/sec). For any reasonable velocity distribution peaking below 2 km/sec, only a minute fraction of the material is likely to attain the high velocities required to permit its escape from the gravitational field of the planet and its central star. To this factor one may add the effect of the drag of the planet's atmosphere, which will tend to prevent the escape of all but the largest fragments.

It might be argued that ejection in the direction of the planet's motion will permit escape from the system at lower ejection velocities. However, such an

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event requires a head-on collision with an object in a retrograde orbit. Such objects are exceedingly rare in our solar system, and it may not be unreasonable to suppose that they are rare in other systems as well.

It should be noted, incidentally, that this mechanism is operating on the earth not far from its maximum theoretical efficiency. Öpik (*9*) has calculated the frequency of collision with celestial bodies for the earth and finds that an impact resulting in a lethal area equal to the entire surface of the earth is likely to occur every 2.4×10^{10} years. Clearly, a substantially higher collision frequency would lead to the periodic obliteration of all life from a planet. If the intervals between these cataclysms become shorter than the time required for the reappearance of life (reappearance either by chance, divine force, or panspermia), the planet will remain permanently lifeless.

If this ejection mechanism is operating on the earth at close to peak efficiency, then the moon has been periodically contaminated with terrestrial life throughout geologic time. The solid angle subtended by the moon, as seen from the earth, is 5.12×10^{-6}. If the earth has ejected organic matter at the same rate as we assumed for 10^{11} other planets in the galaxy, one finds from the figures cited above that the ratio of terrestrial to extra-solar-system matter on the moon should be $\geqq 8 \times 10^{11}$. This ratio would be even greater if allowance were made for the lower escape and infall velocity of terrestrial matter.

Conclusions

As shown above, the absolute number of extra-solar-system microorganisms is likely to be below the threshold for detection by many orders of magnitude. Now it is clear, in addition, that these few strangers are vastly outnumbered by their terrestrial counterparts. This would also be true, though to a lesser degree, of any Martian microorganisms, which should be outnumbered by a factor of 3.3×10^{6}. Hence, the odds against a search for extra-solar-system biota being successful are overwhelming, but, as pointed out by Turkevich (*10*), the moon may well yield samples of terrestrial microorganisms now extinct on the earth. At the observed frequencies of meteorite infall (*11*), crater-forming impacts of the required magnitude may be expected at 10^{3}- to 10^{6}-year intervals, and a fraction of the debris ejected from the earth may ultimately reach the moon, after transit times ranging from a few days to $\sim 10^{7}$ years. Indeed, the latest addition to the moon may have taken place in this century, after the fall of the Tunguska meteorite (or comet) in 1908.

It would seem that these facts warrant a reconsideration of the goals of the lunar biology program. Aside from the possibilities discussed by Sagan (*1*), the principal remaining objective would be a test of the panspermia hypothesis, as provided by the presence or absence of terrestrial microorganisms (*4*). If a positive result could be predicted with certainty on the basis of present knowledge, the sterilization of lunar probes would no longer seem to be as necessary as it has sometimes been supposed to be (*2*), although a strong case could still be made for the sterilization of planetary probes.

In conclusion, it should be said that the foregoing calculations do not refute Arrhenius's panspermia hypothesis. It is true that the deposition of 3.8×10^{13} extra-solar-system microorganisms has been shown to be virtually impossible. But Arrhenius's hypothesis requires that only a *single* such spore arrive at the earth. The odds for such an event are quite favorable, and it may have occurred more than once in the earth's history. We may all be descendants of this spore (*12*).

References and Notes

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