Reports

Dissipation of Planetary Atmospheres

Abstract. Escape-level density is approximately inversely proportional to gravity and with decreasing mass will tend toward that of interplanetary gas. When this value is reached, dissipation must cease. The minimum possible ground density of lunar air is calculated to be 10^{-12} that of the air at normal temperature and pressure. Ionization creates a binding electrostatic charge at the escape level.

Jeans' theory of molecular dissipation is of fundamental importance to the study of planetary atmospheres (*1*). It applies, however, to a greatly simplified atmospheric model and leaves many important aspects of the situation out of account.

Jeans considers an atmosphere in isothermal equilibrium which thins out upward according to the formula

$$\rho_z = \rho_0 e^{-2hmga\,[z/(a\,+\,z)]} \qquad (1)$$

where ρ_z is the atmospheric density at a height z above the surface of the planet; ρ_0 is the atmospheric density at ground level; e is the base of natural logarithms; h is $1/2RT$ (R being the gas constant and T the absolute temperature of the atmosphere, which is the same throughout by definition); m is the mean molecular weight of atmospheric gases; g is the surface gravity; and a is the semidiameter of the planet in question.

Now, a real planetary atmosphere is not even approximately isothermal, and Jeans' treatment is significantly wrong, as has been pointed out by Lyman Spitzer, Jr., (*2*), by reason of the difference in the temperature of the atmosphere at ground level and at the escape level where molecular collisions become so infrequent that they can be neglected in practice and where any molecule having an outward or "positive" velocity equal to or exceeding the velocity of escape will be lost to space.

It is clear that the actual rate of dissipation will depend on the conditions obtaining at the escape level; of these conditions, Spitzer considers only the temperature. There are three further important factors, which I will take up seriatim.

1) Let ρ be the atmospheric density at the actual escape level. In the atmosphere of a body of small attracting mass, this critical density will be reached at a greater height, both because of the flatter density gradient and because of the more marked drop in gravity over the increased height itself.

The important point, however, is that ρ will not be the same for different values of g, for the operative condition which any given atmospheric level must satisfy to be the escape level is that molecular collisions above it are so infrequent that they can be neglected in practice, which means that the number of molecules above it must be substantially the same in every case. ρ is proportional to the pressure p and *ceteris paribus* the latter is proportional to g, so that, to satisfy the above requirement, ρ must be inversely proportional to g.

Since, though, the rate of molecular dissipation per unit area must be proportional to ρ, it, too, will be inversely proportional to g at the escape level. In the particular case of the moon this means that the rate of dissipation assumed by Jeans is at least 6 times too high.

2) The atmosphere at escape level will be unshielded against short-wave radiations and exposed to bombardment by cosmic rays, so that it must be highly ionized. This will increase its molecular density ν, even though ρ remains the same, by increasing the number of free particles. The number of collisions will increase *pari passu*, so that the effective escape level will rise and the rate of escape will drop, although this effect will be counteracted by a fall in m, to which the rate of escape is very sensitive (*1*).

In such ionized gas, or plasma, every electron becomes an independent particle with a mass of about 1/1800 that of a hydrogen atom. The square of mean molecular velocity, $C^2 = 3RT/m$, and free electrons will be lost very quickly at the escape level. In view of their low collisional cross-section, they may be taken to diffuse equally up and down from the escape layer, so that one-half of all free electrons produced there will be lost to space and the other half to the immediately subjacent layer of the atmosphere.

As a result, the escape layer will acquire a strong positive electrostatic charge, and the underlying layer will become negatively charged. Thus we have here something like an electrophorus, whose charge will tend to grow up to a certain maximum, depending on the degree of ionization.

This, however, must generate a considerable electrostatic force binding the escape layer to the subjacent atmosphere. It will, of course, also tend to increase the density of this layer and, while the numerical consequences of this situation remain to be determined, it appears likely that the exosphere has a well-defined boundary, as indeed rocket data would seem to indicate.

3) It is usually assumed that interplanetary space is a perfect vacuum, but this is hardly true within the present terms of reference. Indeed, the molecular density of the interplanetary gas in the vicinity of the earth is about $10^3/\text{cm}^3$ (*3*).

This gas will offer some collisional opposition to the escape of atmospheric molecules and be itself subject to gravitational and electrostatic capture. The increment from this source may be not inappreciable, and for thin atmospheres it may become decisive.

We have seen under (*1*) that the rate of escape depends on the molecular density ν at the escape level, which decreases with the mass of the attracting body. In doing this it will steadily draw closer to the molecular density of the interplanetary gas, which will be able to offer an increasingly effective resistance to atmospheric dissipation.

No certain data are available here, and this reasoning is not exhaustive, but it is worth pursuing and leads to a somewhat paradoxical situation, for once ν has dropped to the density of interplanetary gas, dissipation becomes impossible. In other words, *the atmosphere of a body of sufficiently small mass becomes indestructible.*

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper.

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* **125**, 16 (1957)].

The critical mass is yet to be determined, but it appears that asteroids may be able to retain appreciable gaseous envelopes which they could have acquired by gravitational and electrostatic capture of interplanetary gas, its concentration by sorption on their surfaces [particularly effective if their surfaces are porous or dust-covered (*4*)], and radioactive decay of their lithosphere and the liberation of such gases as may be occluded in it. Yet such atmospheres would be substantially lost by more massive bodies.

Even so, the latter could not lose their atmospheres completely, for the agencies mentioned above will be at work on them as well. There must, therefore, exist a lower limit below which the ground atmospheric density cannot fall. This limit will depend on a host of factors, too numerous and too uncertain for generalization in useful mathematical terms. If, however, gravitational action is considered alone, the limiting ground density can be readily determined in the known case of the moon. The accuracy of such an estimate cannot go beyond the order of magnitude, so that there would be no point in more than a rough numerical calculation.

Let us assume that the moon is surrounded by an isothermal atmosphere obeying Eq. 1 at a temperature $T = 250°K$ and having a mean molecular weight 25 (it would be much higher in reality). By definition, this atmosphere is due solely to the gravitational concentration of interplanetary gas, the molecular density of which may be taken to be the same as it is in the vicinity of the earth, that is, about 10^3.

The atmosphere of the earth is known to extend in attenuated form up to 1000 km or so. That of the moon should extend farther out, owing to the lower surface gravity. To be on the safe side, we may take 1000 km $= 10^8$ cm as the upper limit z of this lunar atmosphere and put $g = 150 \text{ cm} \cdot \text{sec}^{-2}$ (below the real value).

Equation 1 may be written thus:

$$\nu_z = \nu_0 e^{-2hmga\,[z/(a\,+\,z)]} \qquad (2)$$

where ν_z is the molecular density at z and ν_0 is the molecular density at ground level. Our problem is to find ν_0.

$$\nu_0 = \nu_z e^{2hmga\,[z/(a\,+\,z)]} \qquad (2)$$

Numerically, putting $R \simeq 8 \times 10^7$ and $a \simeq 10^8$ cm,

$$\nu_0 = 10^3 \times e^{150/16}$$

whence, upon carrying out the operations, ν_0 is approximately 1.9×10^7.

The molecular density of any gas at normal temperature and pressure on the earth is given by Loschmidt's number $n = 2.69 \times 10^{19}$. Thus the ground density of lunar air resulting solely from the gravitational concentration of interplanetary gas would be of the order of 10^{-12} the terrestrial atmospheric density at sea level. It will be appreciated that this represents only the lowest possible limit, for it has been assumed above that the moon has never had any atmosphere of its own, that no gases, produced by radioactive decay or any other physicochemical processes or by meteoritic impacts, are liberated from its interior. The concentration of gas close to the lunar surface by the sorptive action of dust and porous pumice-like rocks of which this is expected to consist (*4*) is likewise disregarded. Moreover, if a convective atmospheric layer exists above the surface of the moon its density gradient will be higher than in the assumed isothermal atmosphere (*2, 4*).

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References

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3. *Observatory* **78**, 196 (1958).
4. V. A. Firsoff, *Strange World of the Moon* (Basic Books, New York, 1959).

4 May 1959

Escape and Avoidance Conditioning in Human Subjects without Their Observation of the Response

Abstract. An invisibly small thumb-twitch increased in rate of occurrence when it served, via electromyographic amplification, to terminate or postpone aversive noise stimulation. Subjects remained ignorant of their behavior and its effect. Their cumulative response curves resembled those obtained in similar work with animals. Other subjects, informed of the effective response, could not produce it deliberately in a size small enough to qualify for reinforcement.

When the human subject has "voluntary control" of the response to be conditioned, experimental results are in general less predictable and reproducible than those obtained from animals. This is commonly attributed to "self instruction"—that is, to variables experimentally uncontrolled. In the study reported here this problem was circumvented by working with a response so small as to preclude a history of strengthening through discriminable effect upon the environment—in fact, so small as to occur unnoticed by the subject.

The electromyographic setup employed was a modification of that previously reported (*1*). The subject sat in a shielded enclosure in a reclining chair. Recording electrodes were attached to the palmar base of the left thumb and to the medial edge of the left hand. Three additional sets of dummy electrodes were applied in some instances, to suggest that a comprehensive study of body tensions was being conducted. Muscle-action potentials across the left hand were amplified by a factor of 1 million and rectified, and their average momentary values were displayed on a meter. They were also permanently recorded by an Esterline-Angus recording milliammeter.

Twenty-four adults served as subjects. Records from 12 were ruined by apparatus failure, excessive artifact, or failure of the subject to sit still. Results are reported from eight men and four women ranging in age from 18 to 50 and divided into four groups of three each.

Group 1, with four sets of electrodes attached, were told that the study concerned the effects on body tension of noise superimposed on music. Their task was to listen through earphones and, otherwise, do nothing. Group 2, also with all electrodes attached, were told that a specific response, so small as to be invisible, would temporarily turn off the noise or, when the noise was not present, postpone its onset. Their task was to discover and make use of the response. Group 3 (with recording electrodes only) were informed that the effective response was a tiny twitch of the left thumb. Group 4 were given the same information as group 3 but had, in addition, a meter before them during the first half-hour of conditioning, which provided a potential basis for them to use the visual presentation of their response as a "crutch" for proprioceptive observation of the response.

Experimental procedure was identical for all groups. While the subject relaxed and listened to tape-recorded music through earphones, the experimenter watched the meter on his panel for 5 to 10 minutes to select for later reinforcement a response of a size occurring not more than once in 1 or 2 minutes. It was a ballistic swing of the pointer up and back over a few scale divisions. This represented, for a particular subject, a momentary voltage increment at the electrode of 1, 2, or 3 μv.

After the operant level for this response had been recorded for 10 minutes (*OL 1* in Fig. 1), conditioning was begun by superimposing on the music an aversively loud, 60-cycle hum.