THE ESCAPE OF PLANETARY ATMOSPHERES

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Abstract. The problem of escape of atmospheres from the Moon and planets has roots deep in ancient history. Many of the great philosophers of the past regarded the Earth's atmosphere as a medium extending to infinity, with a stationary Earth imbedded at the center. Indeed, it was this concept that led Ptolemy, among many others, to conclude that the Earth could not be moving, for otherwise it would be subject to a gale-force wind caused by its own motion. This idea fostered many of the early stories of interplanetary visitations. Lucian, for example, writing in the second century A.D., has his Icarome nippus fly to the Moon and beyond by means of wings attached to his body.

Not until Copernicus, did this concept of air as an universal medium completely die out, though men had by then become aware of the fact that atmospheric density is less over mountains than over the lowlands. The question then began to take form whether or not the Moon possessed an atmosphere. And this idea was gradually extended to other planets.

The lunar observers of the late eighteenth century set out to ascertain whether the Moon indeed showed visible traces of an atmosphere. In 1792, Schröter recorded what he interpreted as traces of a lunar twilight, which indicated the presence of a thin atmosphere some 29 times more tenuous than our own.

Bessel expressed doubts about this observation, basing his argument on the well-known instantaneous disappearance of a star occulted by the Moon. This argument, which I heard repeatedly in my youth, is not fully correct. A thin atmosphere, if it existed, would cause a delay in the disappearance, by refractive displacement of the star's position. But it would not cause the star to disappear gradually as proponents of the theory argued.

The lunar air battle, which endured for more than a century, involved dozens of famous scientists. The estimates of allowable surface density decreased. Bessel set the figure as 1/500 that of the Earth, in good agreement with the figure set by Newcomb of 1/400. Sir John Herschel urged a much lower figure, of 1/2000, a figure that Airy claimed was in accord with his occultation measures, which indicated the slight retardation of an occultation. Comstock, on similar grounds, reduced the figure to 1/5000.

Paul and Prosper Henry believed they had detected traces of twilight, caused by a thin lunar atmosphere. And W. H. Pickering, observing an occultation of Jupiter by the Moon, claimed to have detected traces of a distortion of the planet, which indicated a density of 1/4000. Yet even this minute amount, as Pickering typically pointed out, required the presence of 'hundreds of tons of atmosphere per square mile of lunar surface.' Pickering also accorded changes in the visibility of certain lunar fea-

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tures, which he ascribed in part to presence of lunar fog or clouds as well as to possible vegetation on the surface of the Moon.

In the midst of such arguments, Johnstone Stoney quietly called attention (in 1898) to the fact that the kinetic theory of gases implies that some fraction of molecules would acquire velocities in excess of the velocity of escape and that atmospheres of the Moon and planets would thus gradually evaporate into space. The speed of disappearance would depend on the body's gravitational potential and upon the boundary temperature of the atmosphere. Stoney elaborated his theories in a series of papers that appeared in the *Transactions of the Royal Society of Dublin* between 1898 and 1904.

In the modern era, Dollfus from measurements of polarization and brightness of the Moon, near quadrature, set the limiting density first at 10^{-6} and, later, 10^{-9} that of the Earth. Elsmore, from radio occultations of the Crab Nebula by the Moon set an even smaller limit.

Such scientists as Sir George Darwin, Cook, Bryan, Emden, and others also considered the problem of atmospheric escape. But it was Sir James Jeans who brought the studies into focus, in his book *Dynamical Theory of Gases*, published in 1916.

Jeans considered the escape of an isothermal atmosphere from a spherical planet. The calculation was a model of simplicity. He calculated the total amount of original atmosphere, figured the rate of escape, and then, dividing the first figure by the second, derived a mean time for atmospheric decay.

Nowhere does Jeans mention the well-known fact – of which he must have been aware – that the total mass of an isothermal atmosphere is infinite. He does not correct for the gravitational pull of the atmosphere upon itself. Indeed, he implicitly assumes that the atmospheric mass is zero. Jeans' formula also predicts an infinite rate of escape of such an atmosphere. The mean decay time, thus derived, is the result of dividing infinity by infinity, always a precarious procedure.

That Jeans was aware of this defect in his analysis I have no doubt. He writes paragraphs about the escaping atmosphere completely detached from the planet, apparently in an effort to justify his loose mathematical treatment of the subject. I have made a careful study of Jeans' argument and am forced to conclude that his times of decay have no physical significance whatever.

William H. Pickering noted that the value of gravity at the surface of a red giant star, such as α Orionis, would be far less than that of the Moon and hence such stars would be expected to dissipate rapidly into space. E. A. Milne pointed out that the rate of dissipation depends on the *gravitational potential* not on the *gravitational acceleration* at the surface. He then develops a modern theory of atmospheric escape, 'with special reference to the boundary of a gaseous star.' The analysis was performed with the 'elegance' characteristic of Milne.

Milne's analysis is applied specifically to a star, whose internal temperature varies according to the law of an Emden 'polytrope'. Milne applied his results to the Earth, but they seem to have largely escaped the attention of astrophysicists.

Spitzer made an important contribution, in analyzing the physical properties of the

Earth's *exosphere*. And various other scientists, especially Chamberlain, Öpik, Singer, and Lifshitz, have extended and improved earlier results.

The high-speed computer has attracted analysts. However, a computer is limited by the way in which the problem is given to it.

I have tried to improve on previous studies, by taking more properly into account the effects of atmospheric temperature gradient. The escape rates prove to be extremely sensitive to the model assumed. I have made some improvement, I think, by inventing a 'collision depth', analogous to 'optical depth' in the problem of radiative transfer.

I conclude, however, that no existing model properly allows for the known physical properties of the exosphere, including the ionosphere. The effect of the variable solar wind needs to be taken into account. Extrapolation backwards in time, from present physical conditions of a moon or planet, is also dangerous. I can construct models of the Moon, for example, which can retain an atmosphere – including water – for some thousands of millions of years. I do not insist that this proves anything, because I can find other models where the decay constant is thousands of times smaller. If we are to draw a conclusion from such studies, it would consist – I think – of a warning not to take too seriously the results from any given model. The Moon, planet, or the universe can readily find some method of evading the predictions made on almost any model.

DISCUSSION

McCrea: I have two questions: (a) It is widely believed that the Earth lost its original atmosphere; could this have happened in accordance with your theory? (b) Many years ago, E. A. Milne developed an extensive theory of the escape of atmospheres; is your work similar to Milne's?

Menzel: Milne's approach is similar to mine. But he was concerned with evaporation from a star and hence did not give a figure for lifetime of an atmosphere above a planet with a definite surface. I see no problem about escaping of the entire atmosphere and later reconstitution. There was probably a time when the Earth was quite hot.

Khodak: Comment to Dr Menzel's paper; The evolutionary and comparative approach is very important for studying planetary problems. For example, the terrestrial planets form a sequence, from the smaller, more primitive, and unevolved bodies like Mercury and the Moon (which lack atmospheres), through the intermediate level represented by Mars (with a thin CO_2 atmosphere and a frozen or liquid hydrosphere), to the largest and most complex planets, Venus and Earth. The dense CO_2 atmosphere of Venus represents a qualitatively new stage in planetary development after Mars; while the Earth, with an oxygen-nitrogen atmosphere, a global hydrosphere, and a biosphere, represents a still higher stage. Thus the evolution of a dense CO_2 atmosphere is to be sought between the levels of Mars and Venus, while the evolution of our present atmosphere lies in the stages between Venus and Earth, buried in the Earth's past. This problem is, simultaneously, relevant to the evolution of a biosphere.

An atmosphere, and the closely-related glacial or liquid hydrosphere (on Mars, Earth, and also, slightly, on Venus), should be treated *fundamentally* as results of endogenous (internal) processes of evolution. That is, they are results of geological outgassing of solid bodies; these atmospheres are secondary, by contrast with the primary atmospheres of the Jovian planets. Thus the straightforward approach needed for the study of planets and satellites is the historical, comparative study of all planetary data with the methods of structural geology and petrochemistry: the 'geology' of planets, planetology (see Yu. A. Khodak, 'Geography and Geology of Planets – Planetology', a course of lectures, Pedagogical Institute Press, Moscow, 1972).