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SPECIAL REPORT

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A BRIEF HISTORY OF DATA AND THEORY PERTAINING TO THE ATMOSPHERE OF THE MOON

Submitted by:

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May 5, 1972

Baltimore, Maryland 21218

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To: Distribution

From: Wm. G. Fastie, Principal Investigator

Subject: Special Report on a Brief History of Data and Theory Pertaining to the Atmosphere of the Moon.

We submit herewith a special report prepared by G. F. Thomas, University of Colorado (co-investigator). This report presents some information about the atmosphere of the moon and includes a bibliography on the subject.

Wm G Fastie
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Apollo 17 UV Experiment

April 23, 1972

I. Introduction

This report consists of a brief historical resume of data and theory for the lunar atmosphere existing prior to the Apollo program. It is intended to be a summary of the most important pre-Apollo research, rather than an exhaustive bibliographical study, and constitutes a supporting analytical study for the Apollo 17 UV Spectrometer Experiment.

II. Experimental Data on the Lunar Atmosphere

All Earth-based experiments designed to measure atmospheric density on the Moon have led only to upper limits. The first attempts by early astronomers to detect twilight effects or the bending of light during stellar occultations met with failure, and led only to estimates of upper limits of about 10^{-4} atm (Opik, 1962). Efforts to detect lunar auroras (Khan, 1946) have always given negative results. This has led to an estimation of the upper limit on lunar density to be that of the Earth's atmosphere in the altitude range where auroras occur (100 - 120 km implying a density range of $\sim 10^{-7}$-10^{-8} atm, according to present knowledge). However this limit implicitly assumes the same energetic particle flux impinging on the Moon as in the Earth's auroral zones. The lack of a reliable detection of lunar meteors (although see the discussion by Opik (1962) of the observations of W. H. Haas) leads to a more definite upper limit corresponding to an altitude on Earth of about 90 km (where the density is $\sim 10^{-5}$ atm).

More sensitive tests for a lunar atmosphere were introduced by Fessenkopf (1943) who placed an upper limit of 1.3×10^{-7} atm, on the basis of a lack of polarization on the dark side of the lunar terminator. This conclusion was strongly criticized by Lyot and Dollfus (1940) because of Fessenkopf's assumption that the ashen light was unpolarized. Dollfus (1952) using a Savart-Lyot polariscope at Pic-du-Midi showed that the lack of polarization in the twilight zones near the poles implied an upper limit of 10^{-9} atm. Using an improved technique he later extended this limit to 10^{-10} atm (Dollfus, 1956). A lack of extension of the terminator at the edge of the visible disk led Opik (1955) to place an upper limit of 10^{-6} atm. A widely-quoted observation by Kozyrev (1959) of a spectrogram of an "eruption" from the central peak of the crater Alphonsus points out the possibility of occasional local enhancements of atmosphere density by volcanism.

Gringauz et al (1961) reported direct measurements of ion densities at 10 Moon radii exceeding the interplanetary density, with an indication of an increasing density with decreasing altitude. Recent measurements using radio astronomy techniques have been reported by Elsmore (1957a, 1957b), Risbeth and Little (1957), Hazard et al (1963), and Pomalaza-Diaz (1967) which involve the refraction of signals from radio star sources or from spacecraft during lunar occultations. The earlier occultation measurements indicated ion densities less than 10^2 -10^3 cm^{-3}. The most accurate to date are from measurements of radio signals from Pioneer VII indicating less than 40 ions-cm^{-3} (Pomalaza-Diaz, 1967). A deduction of neutral density must be made from considerations of ionization sources and losses. The degree of ionization has sometimes been assumed to be that in the Earth's atmosphere near the F-2 peak (1×10^{-3}), which gave 10^5 -10^6 cm^{-3} for the neutral gas (Ellsmore, 1957b). However as Johnson (1972) has pointed out, this degree of ionization is unrealistically high, as lunar ions have a much shorter lifetime than do those in the Earth's ionosphere. Depending upon the photo-ionization time and the loss times due to the ion being swept up by the magnetic field in the solar wind, the degree of ionization varies between 5×10^{-7} for atomic hydrogen (H) to 2×10^{-4} for Argon (A). Thus more modest upper limits must be placed on the lunar atomsphere from such experiments. For H, this upper limit is therefore about 8×10^7 cm^{-3}, not much smaller than the upper limit of $\sim 2 \times 10^9$ cm^{-3} imposed by Dollfus, (1956) optical limits.

III. Theoretical Studies of the Lunar Atmosphere

Before the discovery of the solar wind, most speculations on the origin of a lunar atmosphere centered about the possibility of outgassing from the lunar interior, volatilization of meteors, and radioactivity decay (for example the product of radioactive potassium K^{40} is A^{40}.) The primeval atmosphere was considered largely in the light of evaporative loss processes. Thus on the basis of the time constants for thermal escape from an exosphere (Spitzer, 1952, Biutner, 1958, 1959), it was generally expected that since for the rare gases Krypton (Kr) and Xenon (Xe) (mean atomic weights 83.8 and 131.3 respectively) the depletion time exceeded the lunar age of 5×10^9 years, these gases would be the principal constituents of the lunar atmosphere. However such calculations refer to an average lunar surface temperature of 400°K. Opik and Singer (1960) pointed out that the expected pressure of 10^{-13} atmosphere of Xe and Kr (Edwards and Borst, 1958) would lead to an atmosphere in which the temperature is comparable to the exospheric temperature of Earth (~1500°K). This higher temperature would reduce the escape times to 170 years and 4×10^6 years for Kr and Xe respectively. This result would indicate that the lunar atmosphere would adjust itself to a density ($<10^{14}$ atoms-cm^{-2}-column) low enough for its temperature to be that of the surface itself; in other words the entire atmosphere is an exosphere. Opik and Singer also calculated the effect of the loss of photoelectrons produced at the surface by solar extreme ultraviolet. They estimated that an electric potential of 20-25 volts (positive) would exist at the lunar surface, and that most Kr^+ and Xe^+ ions formed in the region where the potential is not yet screened would pick up sufficient energy (2.4 and 3.7 ev respectively) for escape. For an estimated screening thickness of 4 meters the lifetimes of Kr or Xe atoms were estimated to be about 3000 years. Thus it became clear that an independent lunar atmosphere (either of primeval origin or due to slow outgassing from the interior) cannot exist because of non-thermal loss processes even for the heaviest gases.

The discovery of the solar wind led to the possibility of an atmosphere formed from solar wind accretion (Gold, 1959; Opik, 1962; Nakada and Mihalov, 1962; Weil and Barasch, 1963; Bernstein et al, 1963; Hinton and Taeusch, 1964; Michel, 1964; Vogel, 1966) and an additional loss process from solar-wind "scavenging" (Herring and Licht, 1959; and above references). The usual method is to use the known (or parameterized) solar wind flux, assume cosmic abundance of the rare gases in the solar wind, and from a balance of all gains and losses, to extract the average surface density. The most complete study was that of Hinton and Taeusch who considered the following losses: photoionization and subsequent escape, thermal escape (which is the most important loss for hydrogen and helium), and charge exchange and impact ionization from the solar wind. The sources assumed by Hinton and Taeusch were either solar wind or volcanism (the latter scaled from the known rates for Earth).

IV. Recent Theoretical and Experimental Results

Quantitative studies of the horizontal and vertical distribution of the lunar atmosphere began with Hodges and Johnson (1968), who showed that due to lateral transport, the horizontal variation of gases heavier than helium goes like $T_s^{-5/2}$, where T_s is the surface temperature. More recently Hodges (1972) has extended this work in terms of a generalized diffusion model. Gott and Potter (1968) presented detailed calculations of H and H_2 distributions in a hypothetical lunar atmosphere, and the Lyman alpha brightness expected from resonance scattering of solar Lyman alpha emission.

Very recently, there have appeared two papers, the first a review paper by Johnson (1971) who calculates surface densities from solar wind accretion using recent knowledge of solar wind fluxes (Bame et al, 1970) and ionization rates. Using the $T_s^{-5/2}$ law of Hodges and Johnson (1968) he predicts that the daytime lunar atmosphere is composed of Ne (6×10^4 cm^{-3}), He (6×10^3 cm^{-3}), H (5×10^3 cm^{-3}) and A (1.2×10^3 cm^{-3}) with traces of Kr (8 cm^3) and Xe (1.3 cm^{-3}). The nighttime densities, because of the $T_s^{-5/2}$ law for the heavier constituents, are expected to be much greater for Ne (1.5×10^6 cm^{-3}) and A (3×10^4 cm^{-3}). H and He densities do not follow the above law since they do not satisfy the assumption that the average horizontal distance travelled in the exosphere is small. However the behaviour should still be inversely dependent on temperature. A very different boundary condition for the H and He fluxes was given by Vogel (1966), who assumed a steady daytime flux varying as the cosine of the solar zenith angle. Yeh and Chang (1972) have recently used this as a lower boundary condition and calculated the three-dimensional spatial variation of H in the lunar atmosphere. As expected this yields a surface density that decreases into the night-side, by a factor of ~4. However a realistic lateral transport model for H and He has yet to be calculated.

Hodges and Johnson (1968) pointed out that such gases as Kr and Xe, which liquefy at temperatures encountered on the nightside, are subject to surface adsorption causing them to essentially vanish from the nightime lunar atmosphere. Rapid heating at sunrise would release most of these adsorbed gases producing a sharp maximum near the sunrise terminator. This expectation was not borne out by actual measurements through sunrise by the cold cathode gauge experiment placed on the Moon by Apollo 14 (Johnson et al, 1972). Instead of a gradual rise in density as the sun rose, there appeared a very steep rise in density from the nightime value of 2×10^5 cm^{-3} to $\sim 10^7$ cm^{-3}. The daytime value is believed to be a result of solar-induced outgassing of some contaminant in the vicinity of the landing area. The low nightime density is attributed by Johnson et al to the fact that the surface material is not saturated with neon. (In other words, the Moon is a sink of neon atoms given off by the sun.) This possibility was suggested in a more general context by Gutkin et al (1969).

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