THE LUNAR ATMOSPHERE AS A COSMIC-RAY DETECTOR. T. L. Wilson[1], [1]NASA, Johnson Space Center, Houston, Texas 77058 USA.

Introduction: The recent discovery of a tenuous sodium (Na) atmosphere on the Moon [1,2] and Mercury [3] has renewed interest in studying the lunar atmosphere [4-7] since the physics involved for the two bodies is thought to be of similar nature [8,9]. Na came as a surprise because it had been missed by *in situ* UV measurements made during the Apollo program [10,11]. The new lunar observations involve the visible D_1 (5896 Å) and D_2 (5890 Å) wavelengths which are highly efficient at scattering sunlight. Although its lunar source and morphology is still not completely understood [12], Na is present as a collisionless exosphere - apparently in the form of a cometary-type coma with a tail that can extend hundreds of lunar radii during Leonid showers [13,14]. The global shape of the atmosphere, in particular for the shaded antisolar side, has been modelled by Smyth [9, 8]. Since planetary atmospheres can be used as cosmic-ray (CR) spectrometers by means of their fluorescence excited by CR-induced air shower particles, the subject of the Moon's atmosphere as a CR detector will be discussed here.

Sodium in the Lunar atmosphere: The spectroscopic techniques used in these studies [1-7] examined Na and potassium (K) emission intensities induced by sunlight. Insight into the formation and dynamic maintenance of planetary exospheres was a consequence of this work. For example, scale heights, temperatures, radial extent, and luminescence of atomic and molecular constituents were investigated.

It was determined that lunar atmospheric Na density was ~ 50 atoms/cm^3, placing it lower than the Earth's atmospheric density of ~ 10^{19} molecules/cm^3 by a factor of 10^{-17}. Nevertheless, the sunlit Na and K resonances are clearly visible from Earth and needless to say the Moon.

Preliminary analysis found that the total Na (D_1 + D_2) brightness levels can be represented by a power law, $I(r) = I_o r^{-\alpha}$, where r is the distance from the center of the Moon in lunar radii R_m, I_o is the equivalent brightness at the limb, and $\alpha = 4$. Further modelling of the data sets showed that there is a latitudinal effect where χ is the solar zenith angle (latitude) on the Moon. At the poles the power law changes to $\alpha = 2$.

Merging the image analysis into the power law formula, the following fit was found [4]:

$$I(r, \chi) = I_o r^{-\alpha} \tag{1}$$

where $I_o = (1 + 6\cos^8\chi)$ is measured in kilorayleighs (kR) and $\alpha = 2(1 + \cos^3\chi)$. The intensity plot for (1) is simply a log-log graph with a Na (D_1 + D_2) brightness level of 10 kR at the sunlit surface along the lunar equator, decreasing radially to 1 kR at an altitude of r = 10 R_m as shown in Figure 1.

Assuming hemispheric symmetry, the Na scale height H at the lunar equator where $\alpha = 4$ is approximately 1000 km (temperature T = 4500 K). The rapid power-law decrease softens as one approaches the poles, where $\alpha = 2$ and H as well as T double in value.

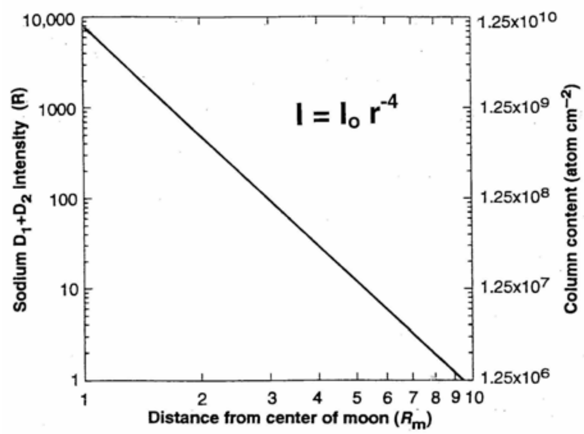

Figure 1. Data compilation of the radial profile of Na intensities for the $\alpha = 4$ power law in Equation (1) at the lunar equator (χ=0). Adapted from [4].

Atmospheric Spectrometers like Fly's Eye and OWL: The use of atmospheric fluorescence as a means of studying Extensive Air Showers (EASs) has a long history motivated primarily by the search for the Greisen-Kuz'min-Zatsepin cutoff in the CR energy spectrum around 10^{19} eV [15]. From early names such as Volcano Ranch the technology evolved into the first successful atmospheric EAS fluorescence detector, Fly's Eye in Utah [16-18].

Technically demanding and illustrated in Figure 2, the task is to pick out a faint, fast signal from background atmospheric noise as an incoming CR primary collides with a molecule of air and starts a highly-energetic cascade of secondary particles that create the shower S. Fly's Eye photodetectors D sense the light signals produced by various mechanisms involved in these collisions. They are UV nitrogen (N) fluorescence (3100-4400 Å), direct Cerenkov light, and Cerenkov light produced by molecular Rayleigh scattering and aerosol Mie scattering.

A next-generation concept inspired by the atmospheric fluorescence technique is an Orbital Wide-

Angle Light Collector (OWL) which investigates EASs by looking down on the Earth's atmosphere from space [19]. Depicted in Figure 3, it takes advantage of a larger area of the atmosphere by stereoscopically making measurements of a volume of a planetary atmosphere. A precursor study of OWL known as the Extreme Universe Space Observatory (EUSO) has been planned for the International Space Station (ISS) [20].

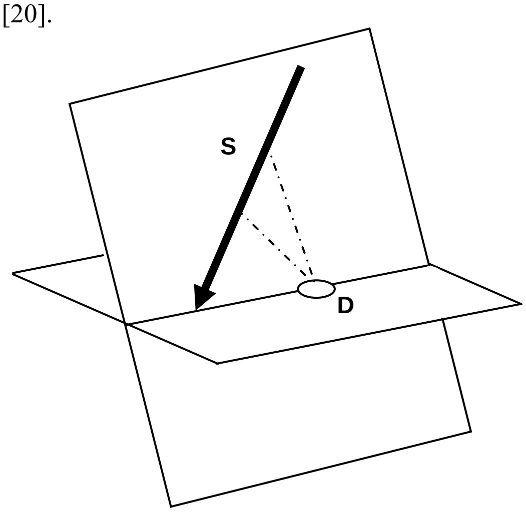

Figure 2. Geometry for an EAS trajectory S with respect to a surface Fly's Eye detector D in the SD plane.

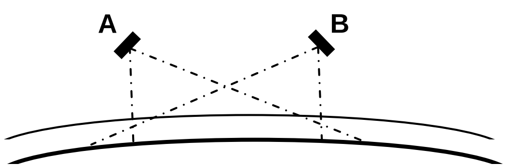

Figure 3. OWL geometry for a spectroscopic array of two satellites A and B observing atmospheric fluorescence from above in space. For the Moon, the array would actually be moving through the Na exosphere.

Exospheric Particle Detectors?: The Earth's nighttime atmosphere is obviously superior for studying EASs, with a density of 10^{19} molecules/cm^3 compared to 10^5 molecules/cm^3 on the Moon during a lunar night [21].

Limitations. There are at least three serious constraints on using atmospheric fluorescence on the Moon as a means for CR detection. (a) Air shower physics is a very mature subject [22], coupled closely to advances in high-energy particle physics, and Earth-based experiments have made significant progress. Why do this on the Moon? (b) Fluorescence yields and efficiencies are probably the most severe constraints on the detectability of CR-induced Na resonance lines in a rarefied lunar exosphere. There must be sufficient yield to avoid backgrounds. How rarefied can a Na gas be and still absorb incoming CR energy, then resonance fluoresce or scintillate photons at Stokes-shifted (longer) wavelengths? (c) Observable events may prove to be extremely rare, not justifying the cost of such a system.

Summary: The Moon's Na exosphere has been discussed as a possible fluorescent particle detector. Further study necessarily requires the use of a Monte Carlo such as FLUKA (www.fluka.org) or laboratory measurements before one can advocate such a system. Since the Earth also has an exosphere, EUSO might provide pertinent experimental data at ISS altitudes in the thermosphere although it is currently designed to search in the UV for N lines and not visible Na lines. It should be noted that the atmospheric Na D_2 emission is stronger on the Moon than on Earth [11].

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