A NOVEL TECHNIQUE TO DETERMINE ATMOSHPERIC COLUMN DENSITY USING A GAMMA-RAY AND NEUTRON SPECTROMETER DURING ATMOSPHERIC ENTRY. Steven V. Heuer, Patrick N. Peplowski, David J. Lawrence, Ralph D. Lorenz; Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723 (Steven.Heuer@jhuapl.edu).

Introduction: Gamma-ray and neutron spectroscopy is an established method in planetary science for determining the elemental composition of planetary surfaces. On airless bodies, the surface is exposed to bombardment by galactic cosmic rays (GCRs), which are high energy (~10 to ~10000 MeV) particles, usually (~95%) protons, which impact the surface and initiate nuclear reactions with the elements in the surface. GCR-induced reactions culminate in gamma-ray emission. The energy of the emitted gamma rays are characteristic to the element, and the gamma-ray flux can be used to derive elemental concentration at the surface [1–4]. This technique relies on GCRs having access to a planetary surface, as thick atmospheres like those around the Earth, Venus, and Titan absorb GCRs before they reach the surface. On worlds with thick atmospheres, landers can carry a neutron generator to produce high-energy neutrons which induce similar reactions to those initiated by GCRs, again resulting in characteristic energy gamma rays [5]. Without a neutron generator, it is still possible to determine the local abundance of natural radioactive elements on bodies with thick atmospheres using a gamma-ray spectrometer. Future missions to Titan (Dragonfly) and Venus (VICI) were proposed to the 2016 NASA New Frontiers mission opportunity with gamma-ray and/or neutron spectrometers on the planned payloads [6,7]. While the primary purpose of those gamma-ray and neutron spectrometers (GRNS) is to determine the elemental composition of a planet's surface, here we report the feasibility of using in-situ measurements of particle fluxes with a GRNS during atmospheric entry to provide valuable constraints on the bulk composition and as well as physical properties of the atmosphere.

Atmospheric Nuclear Spectroscopy Measurements: When a GCR enters any material, including a planetary atmosphere, it interacts with the constituent nuclei via a number of processes, many of which result in nuclear spallation. Spallation is a natural fission process where kinetic energy is transferred from the GCR to the incident nucleus via an internuclear cascade, resulting in particle emission (spallation). If these secondary particles are energetic enough, they can also induce spallation in other nuclei via intranuclear cascades. These cascades, which propagate downward into the atmosphere, are well studied on Earth and known as GCR air showers. There is a point in the atmosphere where the secondary particle production is balanced with particle losses within the atmosphere, creating a peak in particle flux known as the Regner-Pfotzer (RP) maximum [8]. The RP maximum is seen with a variety of measurables, including neutrons, line-emission gamma-rays, and continuum gamma rays. GCRs also show RP maximum behavior, but not necessarily at the same altitudes as other secondary-particle products. The altitude location of RP maxima is strongly dependent on the atmospheric column density, which varies in planetary atmospheres as a function of altitude. A GRNS collecting data during atmospheric entry samples the altitude-dependent profile of hadronic and electromagnetic particle populations in the atmosphere resulting from GCR air showers, data that serves as proxies for atmospheric density. Using the GEometry And Tracking (GEANT4) radiation transport code [9,10], we have simulated altitude-dependent particle production profiles within the atmospheres of Earth, Venus, Mars, and Titan. The simulation of Earth's atmosphere was compared to the neutron and proton profiles measured by a $CeBr_3$ and CLYC neutron and gamma-ray detectors flying on a stratospheric balloon, providing validation of our models for Venus, Mars, and Titan.

Balloon-Flight Measurements: As part of a sensor maturation project, two GRS/NS sensors ($CeBr_3$ and CLYC) were flown as a hosted payload on a stratospheric balloon for nearly 22 days over Antarctica in December of 2016 [11]. An example of a RP-maximum measurement from this balloon flight is shown in Figure 1, where the neutron count rate from the CLYC sensor is plotted versus balloon altitude. The measured count rate clearly shows a RP maximum at an altitude of 17

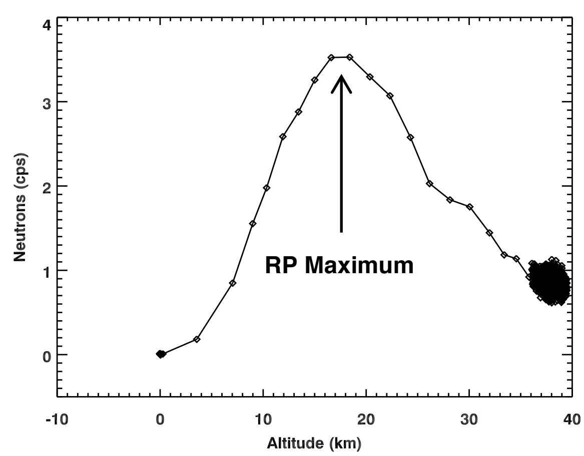

Fig. 1. Net measured neutron count rate from the CLYC sensor as a function of altitude, measured during a high-altitude balloon flight. The RP maximum is clearly seen at an altitude of ~17 km.

km. Other measurements from the CLYC and $CeBr_3$ sensors showed similar maxima [11].

Simulation Approach: Our GEANT4 simulations model GCR transport and interactions in the atmospheres of Earth, Titan, and Venus. Planetary atmospheres were modeled as cubes with dimensions dependent on the planet/moon of interest. The cubes were divided into surface and atmosphere layers. The surface volume had bulk surface properties for the simulated object, and the atmosphere volumes were divided layers (the exact number varying between models) with varying density, pressure, and temperature from an atmosphereic reference model. Model outputs are altitude-dependent particle flux profiles, which, when convolved with detector response models, simulate the measurements observed by a GRNS onboard a spacecraft entering a planetary atmosphere.

Results and Discussion: For Earth's atmosphere, the simulations predict a neutron RP maximum at an altitude of 16 km (Figure 2), which is in good agreement with the 17 km observed in flight data from the Antarctic balloon flight. The simulated GCR flux profile also shows good agreement with the data (not shown). The RP maximum at Titan is predicted to be at 84 km (Figure 3), which is in the same atmospheric region as the peak ionization observed at 60km by the Huygens atmospheric conductivity measurments [12]. The RP maximum at Venus is predicted to be at 52 km (not shown). Compared to Earth, the RP maximum at Titan is much higher because Titan's atmospheric density is larger than Earth, and its low gravity results in a more extended atmosphere.

These types of measurements, and more specifically their variation with altitude, may serve as an important constraint on the entry/descent trajectory reconstruction. For example, an accelerometer record indicates the density along the entry path, which depends on the flight path angle as well as the atmosphere profile, whereas the column mass (pressure) depends only on the profile directly above the probe location. In effect, the measurement acts as a static pressure sensor during the entry, and could improve the accuracy of trajectory reconstruction.

In principle, such a measurement could yield useful insights on any planetary entry/descent to ~1 bar altitude, such as the Dragonfly mission to Titan [13]. To our knowledge, such measurements have not been performed to date on any planet other than Earth. The Venera 9 and 10 GRS instruments were only turned on at a pressure of 7 bars (to measure the spacecraft background [14]), well below the cosmic ray interaction altitude. The Galileo probe had an Energetic Particle Instrument to map the Jovian radiation belts, but this was switched off before atmospheric entry.

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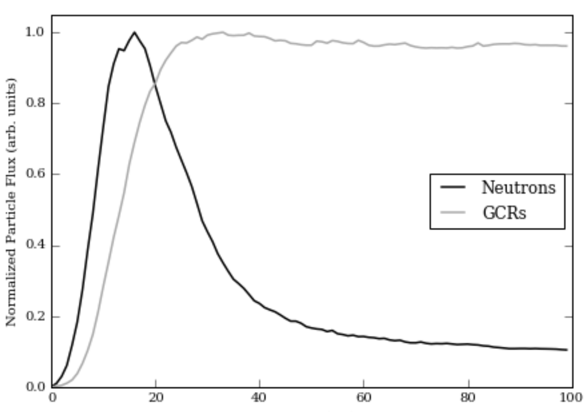

Fig. 2. Simulation GCR and neutrons flux in Earth's atmosphere. The RP maximum can be seen at 16 km, in good agreement with the 17 km altitude seen in flight data.

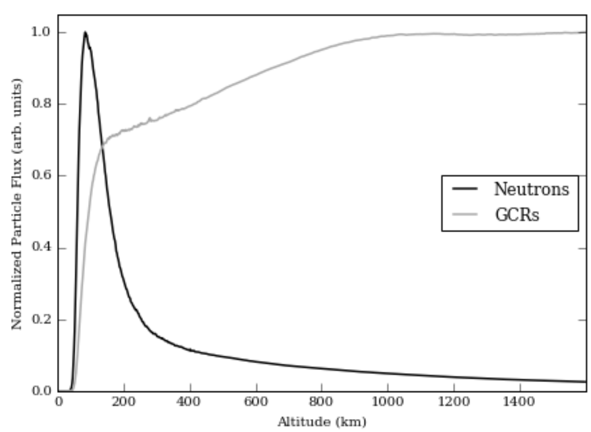

Fig. 3. Simulation GCR and neutrons flux in Titan's atmosphere. The RP maximum can be seen at 84 km.