



Active Neutron and Gamma-Ray Measurements of Icy Planetary Surfaces

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Introduction & Applications for Planetary Investigations

Gamma-ray and neutron spectrometers (GRNS) can be used to determine the hydrogen content and elemental abundances within the top ~tens of centimeters of planetary surfaces. Through the added use of a DT (Deuterium-Tritium, 14.1 MeV) **pulsed neutron generator (PNG)**, GRNS can more rapidly characterize planetary surface materials; this makes active GRNS useful for roving and landed missions [1, 2]. The first planetary active neutron investigation, the Dynamic Albedo of Neutrons, is returning significant scientific results from the surface of Mars [3, 4]; the recently selected Dragonfly mission to Saturn's Titan will also carry an active GRNS instrument (DraGNS) [5]. In addition, several other active neutron and gamma-ray instruments are in development [6, 7]. We investigated the response of an active GRNS system to analog materials relevant to planetary science missions such as basalt (volcanic, extrusive), granite (crustal, intrusive, high Th & K), iron blocks (meteorite falls), milorganite organic fertilizer (carbon-rich with 5wt% N, 2wt% P, 0.32wt% K, 2.1wt% Ca, 0.58 wt% S, 0.68wt% Mg, 4wt% Fe, and trace amounts of Zn, Cu, B, and Cl), and polyethylene (ice, water, hydrated material simulant) for our measurements. These experiments and simulation studies contribute to a better understanding of the active GRNS data that will be collected on future landed missions to Mars, the Moon, Titan, and other planetary bodies using these types of instruments.

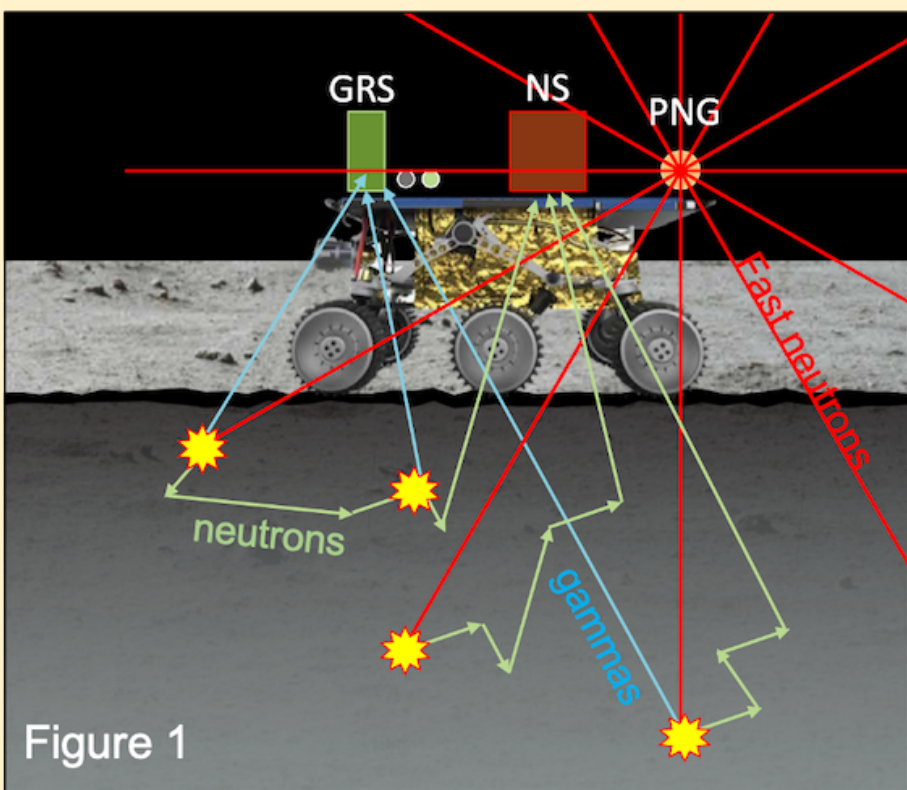
Nuclear Interactions with Matter

In passive systems:

- **High energy galactic cosmic rays (GCRs)** penetrate the surface (~1m) of solar system objects that have little or no atmosphere.
- GCRs liberate neutrons from nuclei within the surface material in a process called spallation.
- Liberated neutrons then continue to interact with other nuclei, resulting in neutrons of lower energy (**thermal neutrons**) and/or the emission of **gamma-rays** [8].

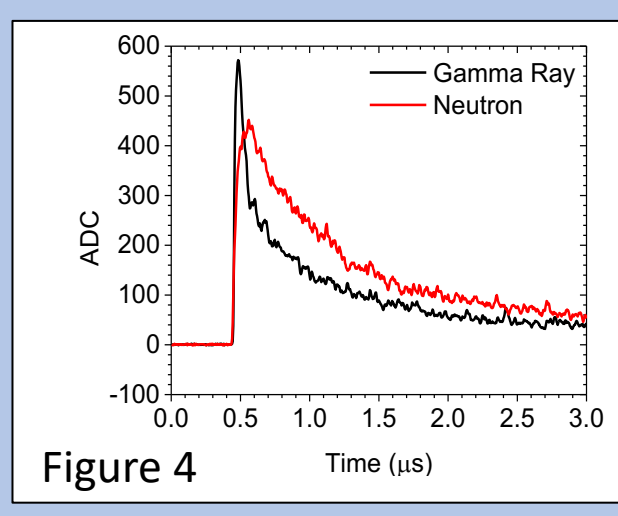
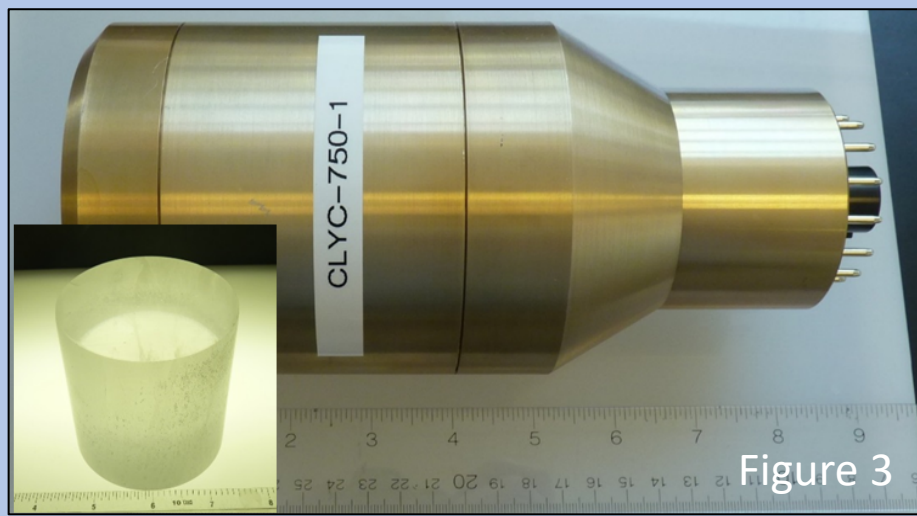
In active systems:

- A neutron generator is used to create the source term in place of GCRs. The neutrons then interact with the nuclei of the material in the surface of a body (up to ~ 1 meter in depth), resulting again in the emission of **thermal neutrons** and/or **gamma-rays** [1,2].
- Neutron die-away experiments count neutrons by their arrival time (time resolved data) after the PNG pulse and are used to determine the hydrogen abundance, the hydrogen distribution with depth, and the macroscopic absorption cross section of planetary surfaces [1, 3, 4, 6].



Instrumentation

- We used the SINGR (CLYC) instrument (Fig. 3), an n-type HPGe, and a DT pulsed neutron generator (PNG, Fig. 2) to study neutrons and gamma-rays emitted as a result of DT irradiation onto our icy planetary analogs.



- We used a Thermo MF Physics Model MP320 PNG that uses a deuterium-Tritium (DT) neutron tube to generate up to 10⁸ neutrons/s (14 MeV) with a frequency range of 250 – 1000 Hz.
- SINGR uses a relatively new scintillator material, an elpasolite called **Cs₂YLiCl₆:Ce (CLYC)**; the **⁶Li(n,α)t reaction** allows SINGR to detect neutrons, Fig. 4 shows the difference in signal for gammas & neutrons.
- SINGR has an **energy resolution** for gamma-rays, 4% full-width-at-half-maximum at 662 keV; both $\phi 2'' \times 2''$ and $\phi 3'' \times 3''$ CLYC crystals were tested.
- A technique called **Pulse Shape Discrimination (PSD)** is used to distinguish between neutron and gamma-ray events [9].
- Measurements were taken with an FPGA DAQ (250 MSPS, 1024 channels).

Experimental set-up & test site

- Data with active GRNS instrumentation was acquired at the NASA Goddard Space Flight Center (GSFC) Goddard Geophysical and Astronomical Observatory (GGAO) outdoor test site.
- Experiments were performed at the GGAO in summer of 2019 using the Colombia River basalt monument and granite monument with varying amounts of polyethylene, fertilizer, basalt, granite, and iron blocks layered on top of and within the monument [7]. Figure 6 shows a typical set-up.
- Hydrogen is an efficient neutron moderator; neutron moderators shift the population of fast (high-energy) neutrons towards thermal (low) energies.
- Altering the amount of polyethylene in layers serves as a proxy for varying the H content (reported as water-equivalent-hydrogen (WEH)) with depth on a planetary surface.
- We used six different polyethylene geometry set-ups (Figure 5 below) to simulate an increase in wt% H abundance, including one buried polyethylene set-up to demonstrate H distribution with depth.

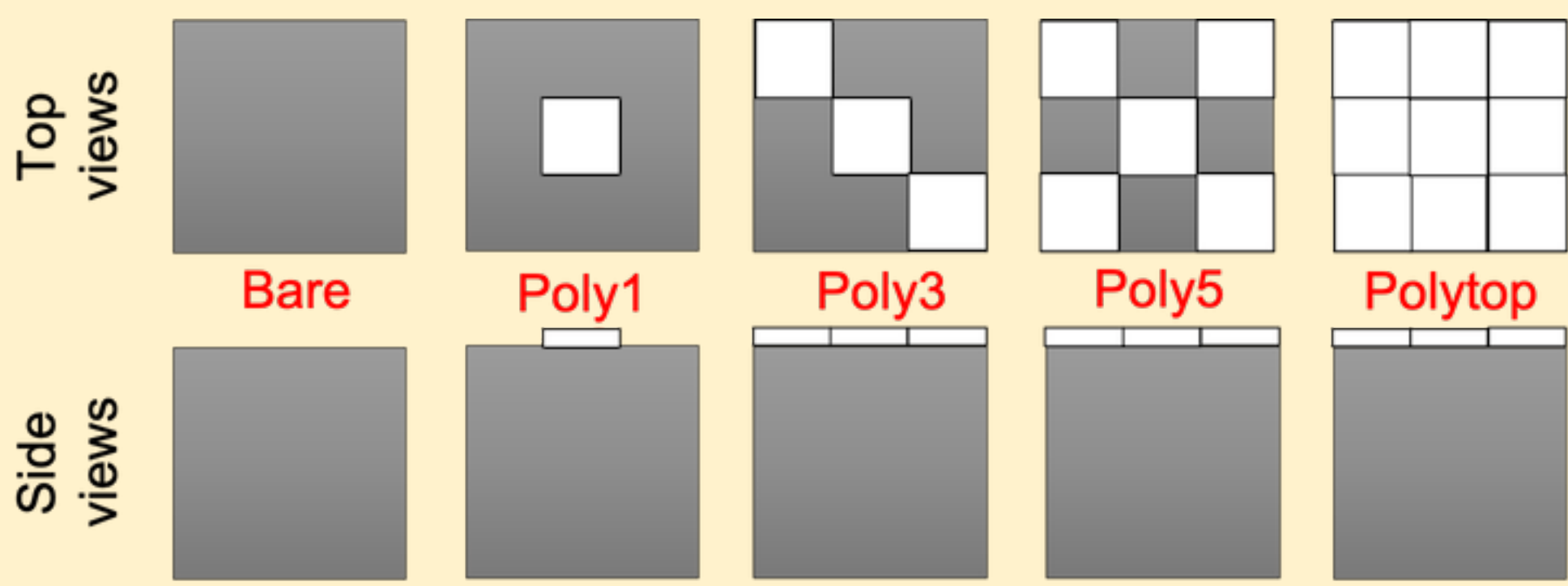


Figure 5

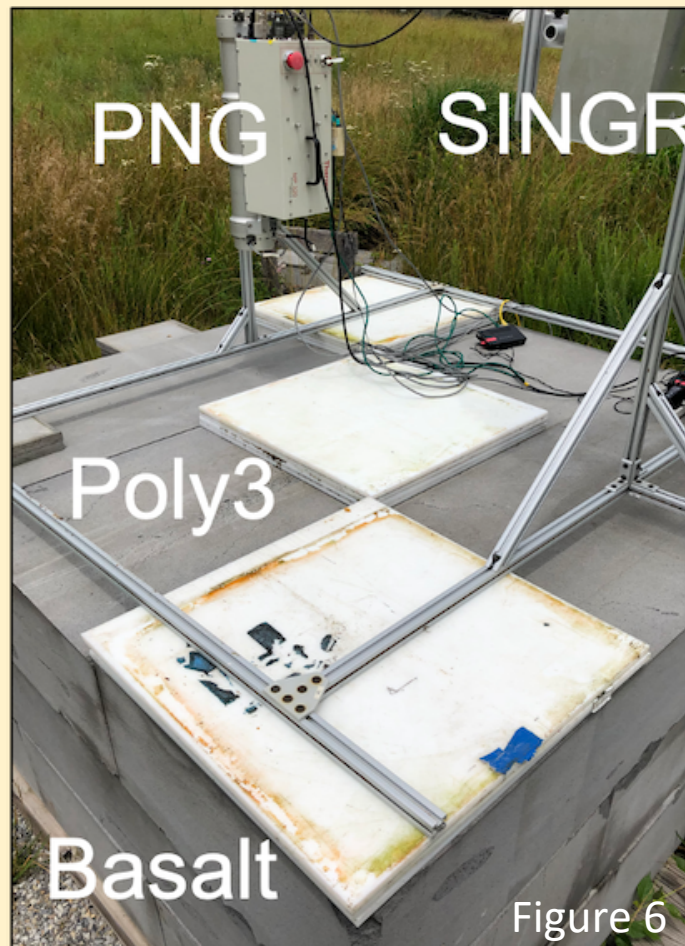


Figure 6

Experiment: High-hydrogen environments

In H-rich environments, the emission of fast neutrons emitted by the PNG are moderated to lower energies, resulting in a higher amount of thermal neutrons scattered back to the GRNS after each pulse. The shape and magnitude of the neutron die-away curve changes as H increases from 0 to 25 wt.% WEH [1].

The shape of the neutron die-away curve changes significantly for low amounts of H (~0 to 6 wt.% WEH in top 2'' layer), as shown in Figure 7 for the bare and poly1 set-ups. However, for high amounts of H (≥ 10 wt.% WEH in top 2'' layer) the normalized curves are no longer distinguishable between measurements (poly1 through 3 and polytope, Fig. 7B).

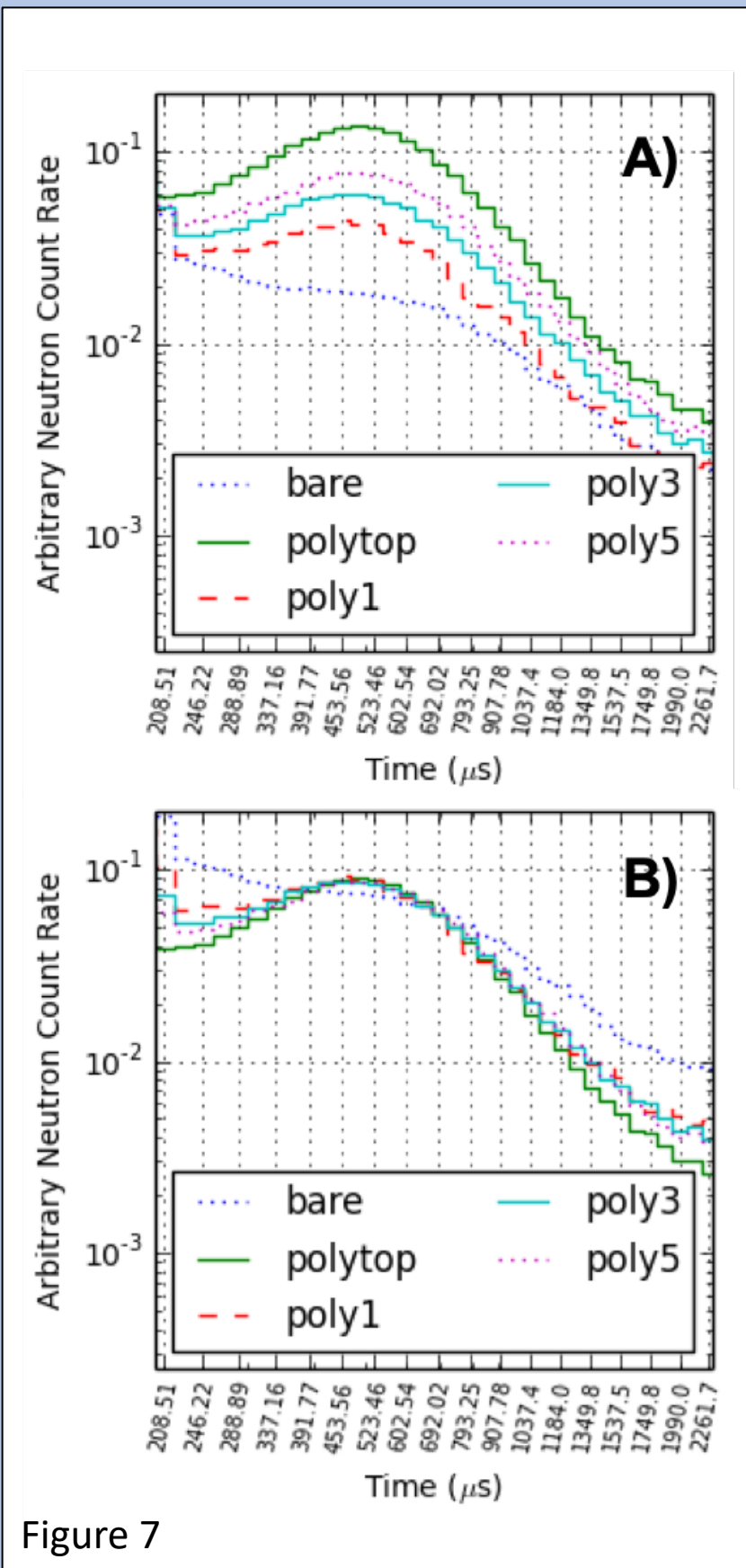


Figure 7

At high H abundance, the total *magnitude* of the thermal neutron die-away curve is the main indicator of H content. In the absence of information about the neutron output of the PNG, the shape of the thermal neutron die-away curve can be used to determine H abundance, however, normalized curves require additional counting statistics and longer integration times to statistically separate from one another. This work demonstrates that in high-H environments (~10 wt.% WEH or more), the *shape* of the neutron die-away curve does not significantly change with WEH and would be more representative of the abundance of neutron absorbing elements [11].

Neutron die-away curves have been used to determine burial depth of H [3, 4]; to test this in high-H environments we buried a large amount of H under varying amounts of milorganite fertilizer and constructed neutron die-away curves, shown in Figure 8. We observed both a suppression of neutrons and an expected shift in time for the returning thermal neutron peak using a thin layer (2'') of fertilizer on top of a stack of polyethylene blocks. However, for large amounts of fertilizer we observed more of a peak broadening in time, rather than a peak shift, this is presumably due to some H existing within the fertilizer. We observed a suppression of the total thermal neutron output for both thicknesses of fertilizer.

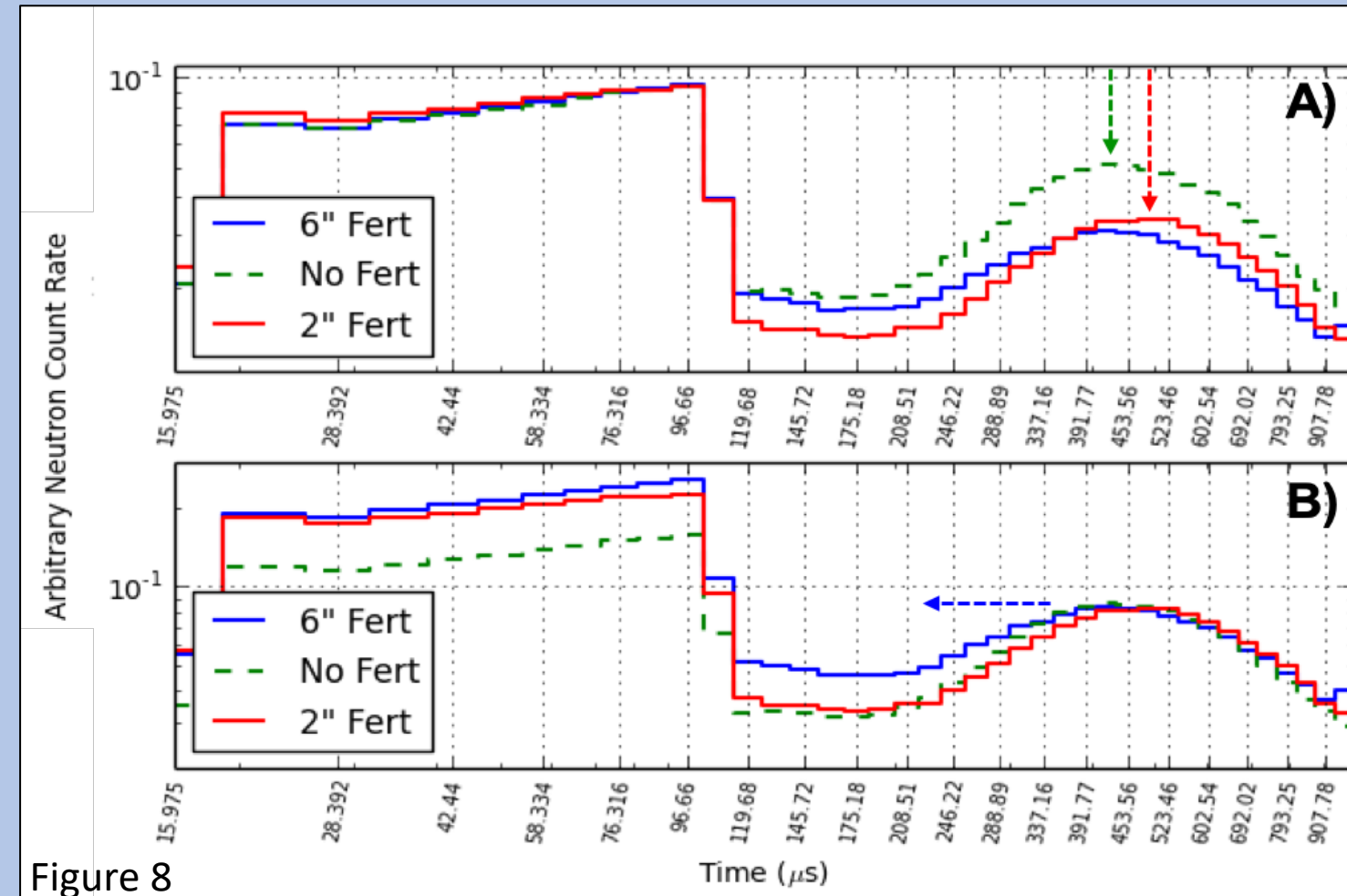


Figure 8

Bonus Simulations: Can a planetary body's dense atmosphere affect its neutron environment?

- We want to determine if atmospheric density has a significant effect on the local neutron environment on a planetary body, using active interrogation (a PNG).
- Target planetary body case study: Titan (atmospheric density = 0.00539 g/cc), whose atmospheric properties were measured using the Cassini-Huygens mission probe [12 - 15].
- The atmosphere on Titan is dominated by nitrogen (~97 wt%) with some small amounts of hydrogen (<1 wt%) and carbon (<2 wt%) which tend to condense in the atmosphere, creating tholin hydrocarbons which later rain down to the surface [13].

Assumptions:

- Inferred Titan's surface composition to be a dune-like mixture of methane water-ice ([CH₄]4[H₂O]₂₃), and tholin hydrocarbons (C₆H₆ & C₃HN) based on hypotheses from various studies of Huygens probe data [13, 14, 15-21].
- Modeled spherical worlds using MCNP 6.1 that consisted of:
 - Fully atmospheric Titan world
 - ½ atmospheric ½ dune world (Figure 9)
- Compared Titan simulation results to that of other planetary compositions from Mars and the Moon, Figure 10.
- We also studied how the neutron energy spectrum changes over time for a variety of planetary scenarios and PNG pulse widths, Figure 11 shows the results of a 50us pulse on a ½ atmospheric ½ dune world.

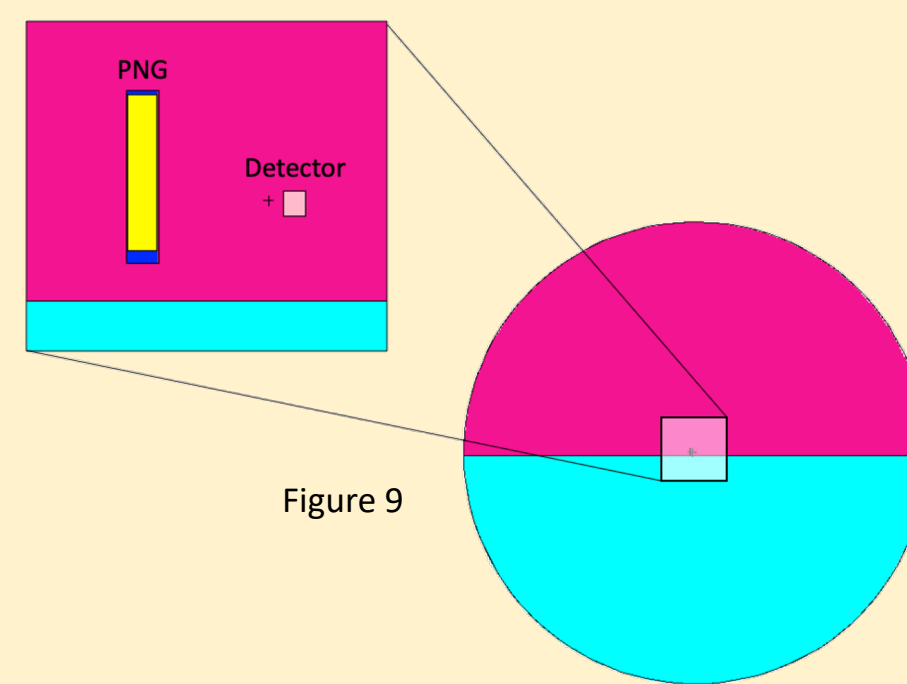


Figure 9

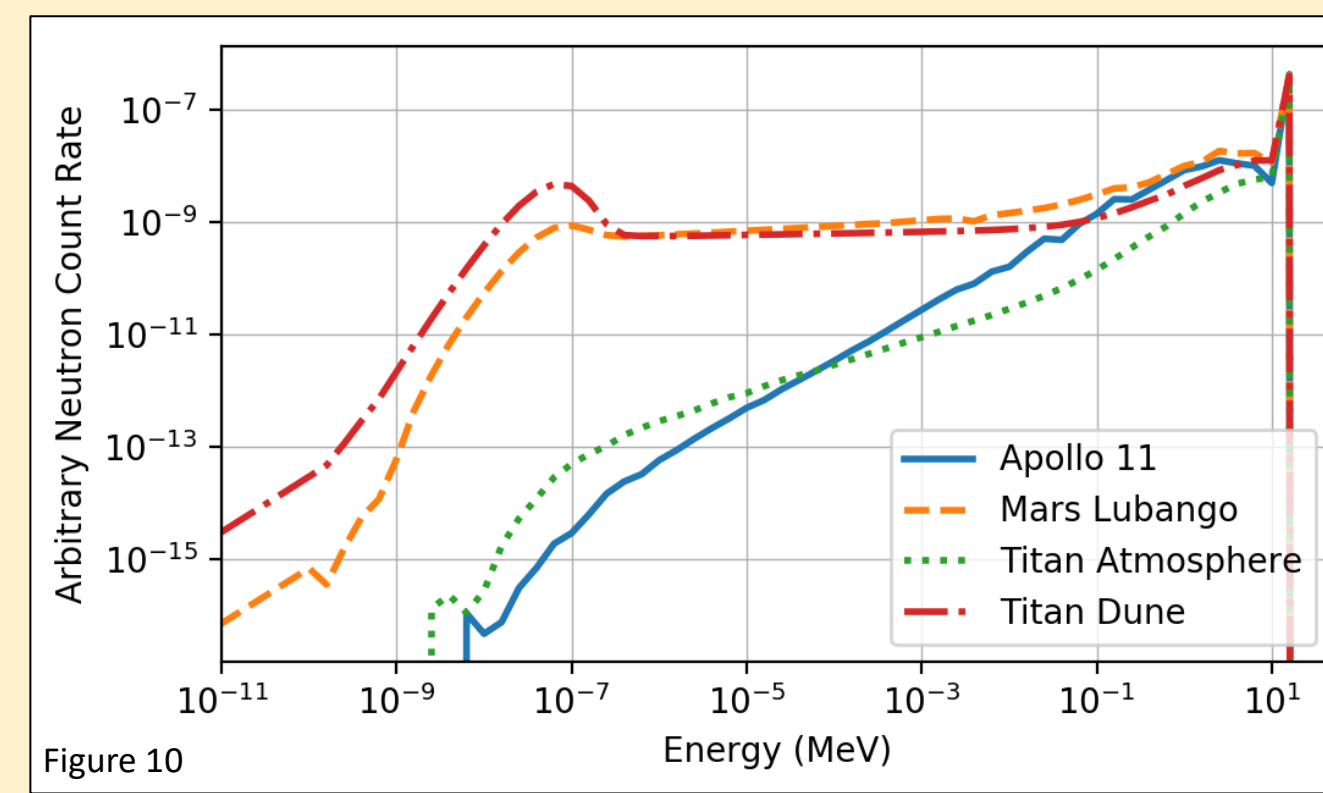


Figure 10

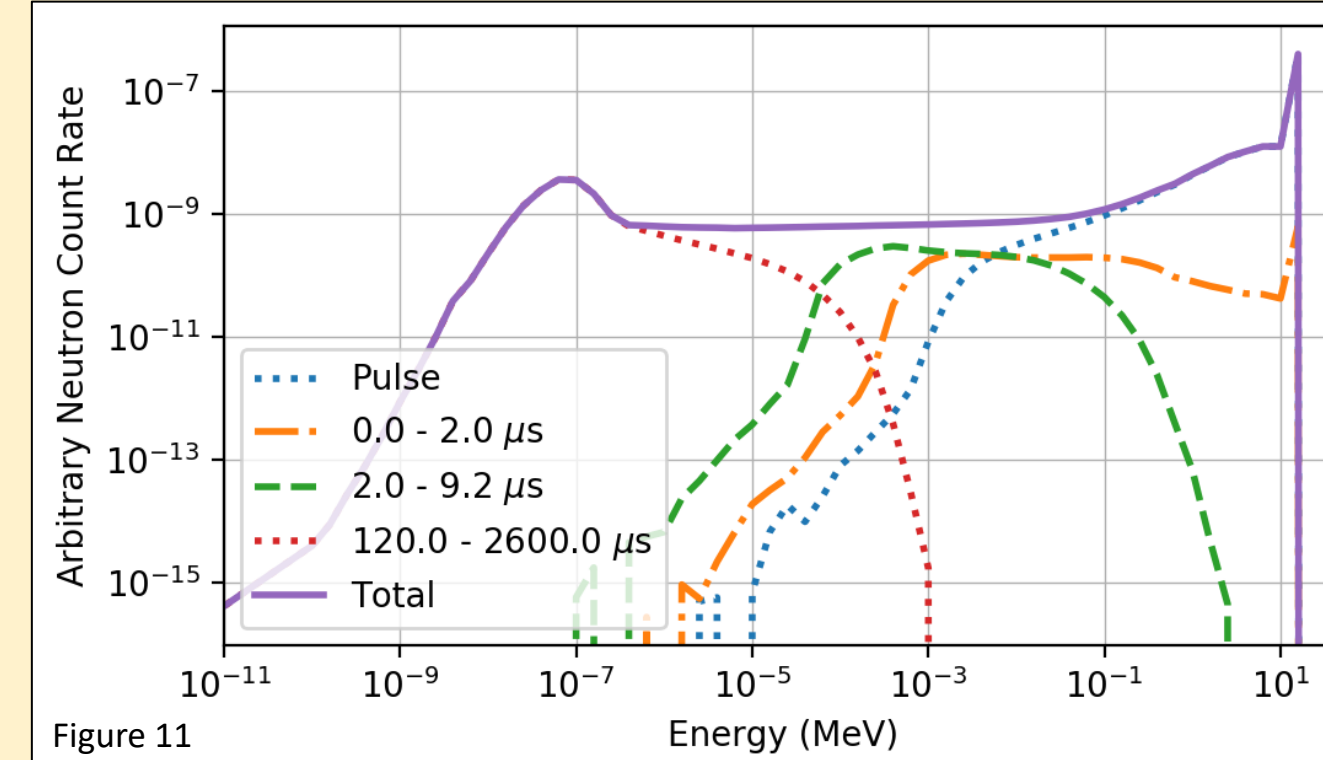


Figure 11

Does neutron die-away inform gamma-ray measurements?

Using the SINGR instrument with a $\phi 3'' \times 3''$ CLYC crystal, we gathered event-by-event, time resolved data for neutron and gamma-ray events. We plotted the gamma-ray events much like that of a neutron die-away curve (Fig. 12A), then segmented the gamma-ray spectra in accordance with a typical neutron die-away profile (Fig. 12B-E). The detector experiences high event rates during the pulse (0 – 200 μ s) out to high channels (9000), suggesting that the detector may be experiencing event saturation or an inability to distinguish between individual event pulses due to rapid arrival time of particles during pulses. Data from Fig. 12D-E suggests that time gating gamma-ray events in conjunction with the neutron die-away curve or the PNG output pulse may allow for GRS data to be taken with decreased detector saturation, increased efficiency, and increased overall sensitivity.

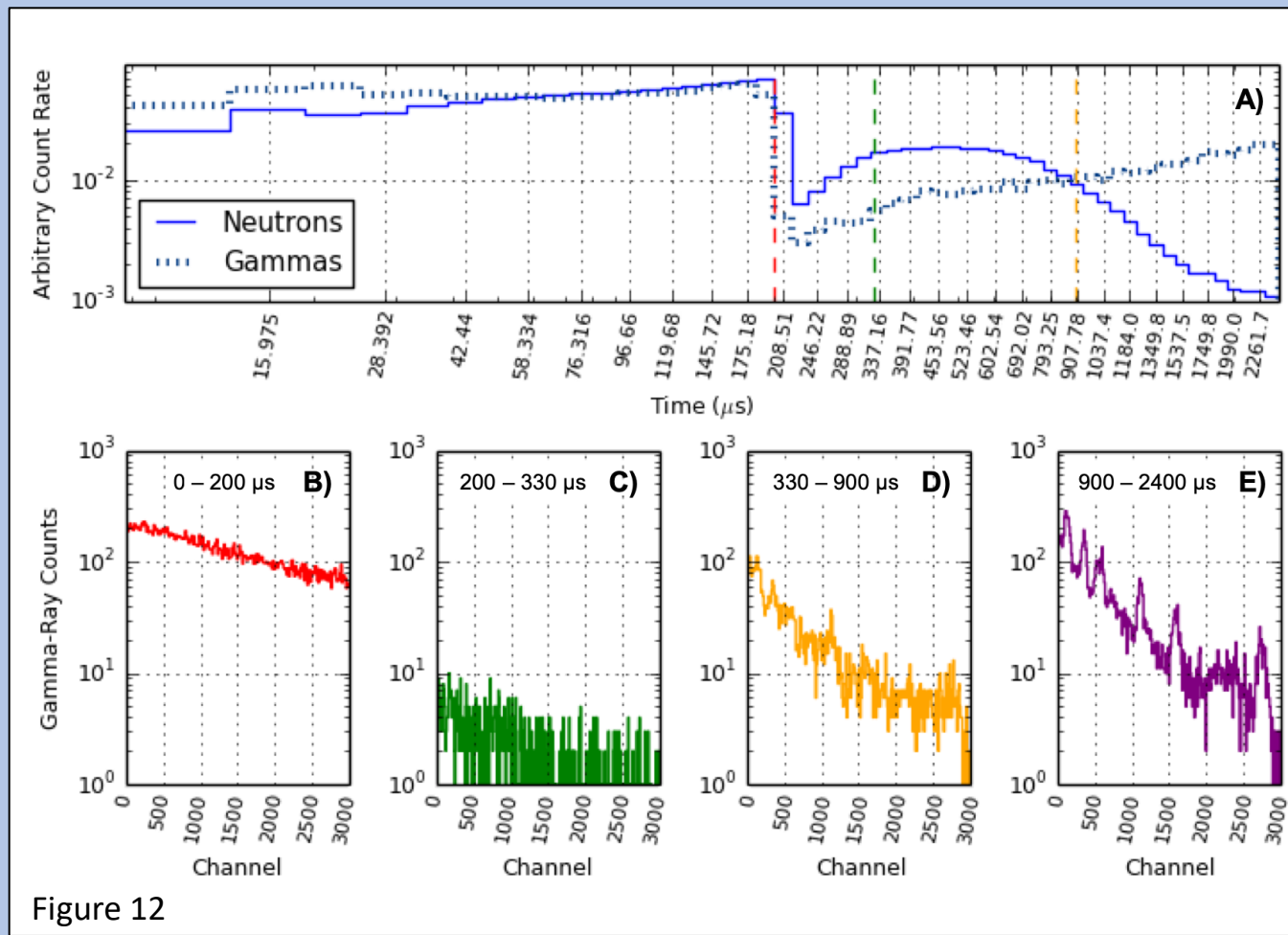


Figure 12

Summary & Implications for Future Missions

- Neutron die-away curves can be used to inform near-surface hydrogen H content as well as compositional information (e.g. neutron absorbers) wt% in high-H environments.
- Integrated thermal neutron albedo (without timing) can be used to estimate the H abundance, however, additional information about near-surface neutron absorbing elements may be gained through analysis using neutron die-away.
- Due to the reduced effect on curve shape at high-H, it is important that if this technique is used in high-H environments there must be monitoring of the neutron output of the PNG for determination of bulk H content.
- The PNG output can degrade over time due to the short half-life of tritium; Abstract #2888 by T.S.J. Gabriel discusses this issue regarding the DAN instrument onboard the Mars Curiosity Rover.
- Dense atmosphere may have a non-negligible effect on active neutron measurements, as shown in Figure 10 the atmospheric world is comparable to dry lunar regolith (Apollo 11).
- Gating gamma-ray measurements based on the PNG output or neutron die-away curve may be beneficial for increasing overall measurement sensitivity (though it is important to note these measurements were taken using CLYC, other GRS may have faster timing capabilities to avoid event saturation).

References

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