NITROGEN CONTENT OF VENUS' UPPER ATMOSPHERE FROM THE MESSENGER NEUTRON SPECTROMETER. Patrick N. Peplowski[1*], David J. Lawrence[1], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 ([*]Patrick.Peplowski@jhuapl.edu)

Introduction: Nitrogen, in the form of N_2, is the second-most abundant compound in the Venusian atmosphere. Despite being a principle component of the atmosphere, its concentration is surprisingly uncertain. The most recent (and robust) N_2 measurements were made in December 1978, when the Pioneer Venus and Venera atmosphere entry probes sampled the atmosphere via mass spectroscopy and gas chromatography. A review of these measurements led *von Zahn et al.* [1] to adopt a reference value of 3.5±1.8 v% N_2 for the Venusian atmosphere. Note that the full, one-standard-deviation range of this value is 46%. Furthermore, this value is for altitudes <45 km only [1], a point that is not generally acknowledged in the literature.

At higher altitudes (>45 km), higher concentrations of N_2 (~4.5 v%) are reported. Unfortunately, the number of measurements in this region is limited. A precise measurement of the N_2 content at altitudes >45 km is needed to 1) reduce the uncertainties in our knowledge of absolute concentration of N_2, and 2) test the possibility that N_2 varies as a function of altitude within the atmosphere.

MESSENGER at Venus: During its 6.6-year-long interplanetary cruise to Mercury, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft performed two flybys of Venus. During the second Venus flyby (V2; 5 June 2007), MESSENGER's payload was active as the instruments performed a rehearsal for science operations during the upcoming MESSENGER M1 flyby. During V2, MESSENGER overflew the night side of Venus, with a closest approach altitude of 338 km over the surface (at 12.171° S, 164.952° E, just east of Aphrodite Terra).

During V2, MESSENGER's Neutron Spectrometer (NS) acquired time-series measurements of neutrons originating from Venus. NS is sensitive to neutrons in three distinct energy bins: thermal (E <1 eV), epithermal (1 eV < E < 0.5 MeV), and fast (E >0.5 MeV). Neutron emissions from Venus are the result of the dissociation of atomic nuclei by high-energy (10-10,000 MeV) galactic cosmic ray (GCRs) protons. On Venus, the atmosphere prevents the GCRs from reaching the surface, and neutron production occurs in the upper atmosphere (altitudes >60 km).

Atmosphere composition from neutrons: In 1963, *Lingenfelter, Hess, and Canfield* [2] noted that the magnitude of Venus' thermal neutron flux would be highly sensitive to the bulk N content of the atmosphere. This is because nitrogen is highly effective at absorbing neutrons (via the $^{14}N+n \rightarrow ^{15}N$ reaction) as compared to the dominant elements in the Venusian atmosphere – C and O. As a consequence small changes in the N content of the atmosphere result in large changes to the magnitude of the neutron flux. A similar principle led to a derivation of Ar concentrations within the CO_2-dominated Martian atmosphere using Mars Odyssey Neutron Spectrometer measurements [3].

Lingenfelter, Hess, and Canfield [2] suggested placing a lightweight neutron spectrometer in close proximity to Venus as a means of deriving the N_2 content of the atmosphere. Although no such dedicated experiment was conducted, 54 years after their suggestion the MESSENGER NS fortuitously made this measurement during the V2 flyby.

Analysis: In order to derive a N_2 content for the upper Venusian atmosphere from NS data, we compared time-series measurements of neutron fluxes acquired during the V2 flyby to radiation transport models of neutron production and transport within the Venusian atmosphere. The analysis follows prior work examining NS flyby datasets [4]. Our atmosphere model consisted of 10 discrete layers whose temperature and density were adopted from the Venus International Reference Atmosphere, derived from the December 1978 measurements [5]. Our atmosphere composition is based on [1], however we varied the N_2 content of the atmosphere within our models to 1) characterize the sensitivity of neutron fluxes to N_2 and 2) facilitate comparison to the NS V2 data as a means of deriving the best-fit N_2 content.

Model outputs are produced in units of neutrons per incident GCR particle and therefore require normalization prior to comparison to the V2 data. To derive this normalization, we benchmarked our model to NS data acquired during the M1 Mercury flyby data. The M1 measurements are ideal for benchmarking our models given that 1) Mercury's surface composition is now well known (e.g. [6]), 2) the M1 data was acquired with a measurement geometry comparable to that of V2, and 3) GCR conditions (the magnitude and spectral shape of the GCR flux) was virtually identical for the V2 and M1 timeframes. Comparison of the models to M1 data led to the derivation of a precise normalization factor for the radiation transport models. This normalization was subsequently applied to the Venus models prior to comparison to NS data.

Results: Figure 1 shows a comparison of the N_2-dependent model neutron count rates to the V2 data. Least squares minimization was used to find the best match between the modeled and measured count rates. When plotted as a function of N_2 content (Figure 2), a clear local minimum is observed at 3.49 wt% N_2 (5.38 v%). We assign one-standard-deviation statistical error of 0.29 v% to this result, and are currently evaluating the systematic uncertainties. For example, the normalization applied to the modeled neutron count rates leads to a systematic uncertainty that is not yet quantified.

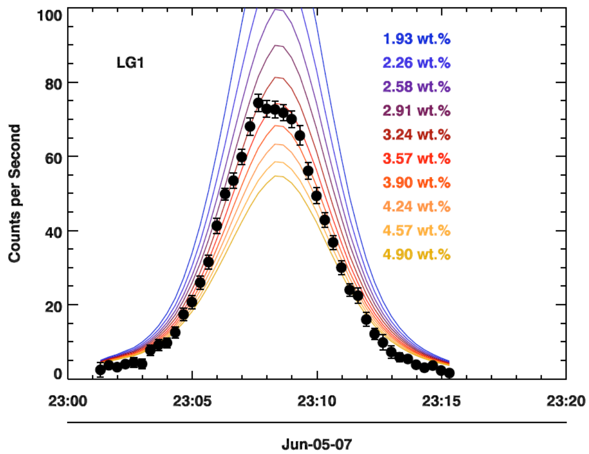

Figure 1. Neutron count rates, measured by the MESSENGER NS (from "LG1" detector) during the V2 flyby. Measured values and one-standard-deviation statistical errors are shown in black. Neutron models are shown as colored lines, with each color representing a different N_2 concentration. LG1 was the NS sensor most sensitive to thermal neutrons during V2.

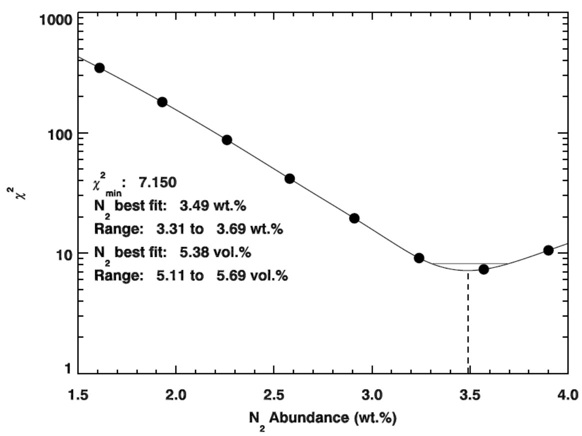

Figure 2. Reduced chi-squared (χ^2) values for the modeled versus measured neutron measurements, as a function of model N_2 abundance.

Discussion: Our derived N_2 value for Venus' atmosphere is 5.38±0.29 v%. Our models indicate that the thermal neutrons originate from altitudes of 60-70 km, above the noted discontinuity in N_2 concentrations [1]. Figure 3 plots the NS measurement and prior N_2 measurements as a function of altitude, and highlights the fact that our data cover an altitude range not previously sampled.

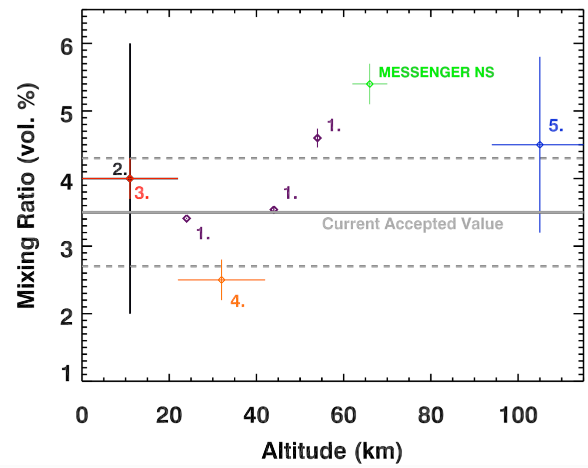

Figure 3. Altitude-dependent N_2 concentrations from the December 1978 measurements, MESSENGER NS, and the accepted value. 1978 measurements are: 1. Pioneer Venus Large Probe Gas Chromatograph, 2. Pioneer Venus Large Probe Mass Spectrometer, 3. Venera 11 and 12 Mass Spectrometer, 4. Venera 12 Gas Chromatograph, and 5. Pioneer Venus Multiprobe Bus Mass Spectrometer, from [1].

The most precise N_2 measurements come from the Pioneer Venus Large Probe Gas Chromatograph (labeled 1 in Figure 3) and the MESSENGER NS. Ignoring for the moment the possibility that differences arise from the temporal variability in atmospheric composition, these data support the existence of a discontinuity in N_2 concentrations at an altitude of ~45 km (Venus' lower cloud deck), as noted previously [1]. This conclusion is inconsistent with the expectation that Venus should have a well-mixed atmosphere.

Alternatively, N_2 concentrations in the upper atmosphere may vary with time and thus the difference between our value (5.38 v%; 60-70 km altitude) and the next-closest value (4.6 v%; 52 km altitude) could be attributed to the 29-year gap between measurements. For example, *Marcq et al.* [7] proposed "long period oscillations of the general atmospheric circulation" as a means of explaining large (factor of ~8) variations in SO_2 concentrations in Venus' upper atmosphere. While this possibility cannot be ruled out, we note that the December 1978 measurement alone supported the presence of an N_2 discontinuity at ~45 km.

References: [1] von Zahn et al. (1983) in *Venus*, Univ. Az. Press. *pp. 299-430.* [2] Lingenfelter, Hess, and Canfield (1962), J. Atmosphere. Sci. 19, 274-276. [3] Prettyman et al. (2004), *JGR 109, E05001*. [4] Lawrence et al. (2010), *Icarus 209, 195-209.* [5] Seiff et al. (1986), *Adv. Space Res. 5, 3-32.* [6] Weider et al. (2015) *EPSL 416*, 109-120. [7] Marcq et al. (2012), *Nat. Geosci. 6, 25-28.*