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Production of 14C from GCR Interactions in Titan's Atmosphere

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The Dragonfly mission will look for signs of prebiotic chemical processes on Titan common to those on Earth. Titan's atmosphere is four times as dense as Earth's atmosphere and is composed primarily of nitrogen (~94%), along with some methane (~5%), hydrogen, and other trace elements. GCR interactions in that atmosphere produce a number of secondary radiations, including neutrons which can then produce ^{14}C via the ^{14}N(n,p)^{14}C reaction. Absorption of ^{14}C into prebiotic chemical processes may serve as a useful tracer to help understand how those processes behave under Titan's environmental conditions. This study uses the transport code PHITS to predict the amount of ^{14}C formed from GCR interactions in Titan's atmosphere, as well as other radioisotopes that may be of interest.

Nomenclature

b = barn (10^{-24} cm^2)
BON2014 = Badhwar-O'Neill 2014 GCR model
ENDF = Evaluated Nuclear Data File
GEM = Generalized Evaporation and Fusion Model
INCL = Liege Intranuclear Cascade model
JAERI = Japan Atomic Energy Research Institute
JQMD = JAERI Quantum Molecular Dynamics
keV = kilo electron volts (10^3 eV)
GCR = Galactic Cosmic Rays
MeV = Mega electron volts (10^6 eV)
mb = millibarn (10^{-27} cm^2)
keV = kilo electron volts (10^3 eV)
PHITS = Particle and Heavy Ion Transport code System

I. Introduction

THE upcoming Dragonfly mission is scheduled to launch in 2026 and land on the surface of Titan in 2034. One of the primary goals of the mission is to investigate signs of prebiotic chemical processes. Along with the chemical processes in Titan's surface, rivers and seas, processes will also occur in the atmosphere. Photochemical interactions, along with interactions from charged particles from galactic cosmic rays (GCR) are some of the interactions that will take place in the atmosphere. The composition of Titan's atmosphere is dominated by nitrogen, and as such interactions between secondary neutrons created by GCR interactions and nitrogen can create ^{14}C via the ^{14}N(n,p)^{14}C reaction. The same process occurs in Earth's atmosphere and is used to date objects that absorbed ^{14}C through biological processes but can no longer absorb the isotope after the process has ended. The half-life of ^{14}C is 5730 years, and as such can date objects over tens of millennia. Because ^{14}C is produced in Titan's atmosphere, the ratio of ^{14}C to ^{12}C in a molecule can provide information on where the molecule was formed in addition to potentially dating any molecular forms where the amount of ^{14}C has been fixed after the chemical process ended. For example, heavy

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carbon-rich compounds formed in the atmosphere settle down to the surface and form the “sand” on the surface. An evaluation of the $^{14}C/^{12}C$ ratio as a function of depth in the surface can provide information on the dynamical processes taking place on and below the surface of Titan.

To provide an estimate of the amount of ^{14}C produced in the atmosphere from GCR and its secondary neutrons, as well as other radioisotopes that may be of interest, PHITS[1] calculations of GCR transport through a simulated Titan atmosphere were performed. Titan’s atmosphere is predominately nitrogen with some methane and heavier carbon-rich molecules. The engineering model used to describe Titan’s atmosphere here was developed by Yelle et al.[2] and is based on data from the Huygens probe. The composition is 95% N_2 and 5% methane. Yelle noted that at the time, no argon had been detected, but was included in his model because it was theoretically possible for Ar to be present and that the difficulty to measure it didn’t rule out its presence. For the calculations performed here, Ar was removed from the Yelle model. Additional details about the atmosphere are described below.

II. PHITS Transport Model

PHITS (Particle and Heavy Ion Transport Code System)[1] is a Monte Carlo simulation code. PHITS utilizes nuclear interaction models and data libraries to calculate particle transport through nuclear and atomic collisions. The JAERI Quantum Molecular Dynamics (JQMD) model calculates the products from heavy ion and nucleon induced interactions. The Liege Intranuclear Cascade (INCL) model calculates proton-ion, pion-ion, and light-ion induced interactions at intermediate energies. Common induced interactions which INCL calculates are deuteron, triton, helium-3, and helium-4 interactions. The Generalized Evaporation and Fission Model (GEM) calculates products from hadron and nucleus induced interactions.

The source term used for the calculations is the Badhwar-O’Neill BON2014[3] GCR solar minimum spectrum and included ions from protons (Z=1) through iron (Z=26). Table 1 shows the abundances of each element in the source term. To simplify the geometry, the Yelle atmospheric model (described below) was carried out to 1000 km using a narrow cyclindrical GCR beam moving through a 100 km (radius) by 1000 km (length) cylinder of Titan’s atmosphere. The atmospheric density as a function of altitude was included into the geometry.

The PHITS tallies T-Yield and T-Cross were used to quantify the yields of radioisotopes produced in the atmosphere and the neutron spectra, respectively. Over 100 million histories were run, with statistical uncertainties less than 10% on all yields.

Table 1. GCR particle flux fractions used for the source term in PHITS calculations.

Element	Fraction of Total Flux	Element	Fraction of Total Flux	Element	Fraction of Total Flux
Z=1	0.898	Z=10	3.71E-04	Z=19	2.01E-05
Z=2	0.0935	Z=11	7.47E-05	Z=20	5.33E-05
Z=3	3.36E-04	Z=12	4.86E-04	Z=21	1.01E-05
Z=4	2.10E-04	Z=13	8.00E-05	Z=22	3.66E-05
Z=5	6.98E-04	Z=14	3.66E-04	Z=23	1.71E-05
Z=6	2.56E-03	Z=15	1.31E-05	Z=24	3.57E-05
Z=7	6.78E-04	Z=16	6.90E-05	Z=25	2.24E-05
Z=8	2.42E-03	Z=17	1.32E-05	Z=26	2.52E-04
Z=9	4.37E-05	Z=18	2.65E-05		

III. Titan Atmosphere

Using a Titan atmosphere composition of 95% N_2 and 5% methane, particle density and areal density profiles were generated as a function of altitude. Table 2 shows the elemental particle density in units of number of particles per barn-cm (10^{-24} cm^3) that were used for the calculations. The atmosphere cylinder was divided into sections, and the altitude of each section is indicated in the first column of Table 2.

Figure 1 shows the atmospheric density as a function of altitude out to 250 km, showing the exponential dependence of density on altitude. At the surface, the density of Titan's atmosphere is 4-5 times Earth's surface atmospheric density. Because of Titan's lower gravity than Earth's, its atmosphere extends out to altitudes much greater than Earth's atmosphere, as well. The simulations represented a static atmosphere. The mixing and circulation of the atmosphere detailed in Ref. 4 is not modeled, thus the transport of any particles after stopping in the atmosphere is not included.

Table 2. Titan's atmosphere density as a function of altitude. One b*cm equals 10^{-24} cm^3.

Titan Atmosphere Altitude (km)	**Titan Atmosphere Density (g/cm^3)**	**Nitrogen (N) Atomic Density (particles/b*cm)**	**Carbon (C) Atomic Density (particles/b*cm)**	**Hydrogen (H) Atomic Density (particles/b*cm)**
0	5.27E-03	2.20E-04	5.79E-06	2.32E-05
1	5.02E-03	2.10E-04	5.52E-06	2.21E-05
2	4.79E-03	2.00E-04	5.27E-06	2.11E-05
3	4.57E-03	1.91E-04	5.02E-06	2.01E-05
4	4.36E-03	1.82E-04	4.79E-06	1.92E-05
5	4.15E-03	1.73E-04	4.57E-06	1.83E-05
6	3.96E-03	1.65E-04	4.36E-06	1.74E-05
7	3.78E-03	1.58E-04	4.15E-06	1.66E-05
8	3.60E-03	1.50E-04	3.96E-06	1.58E-05
9	3.44E-03	1.43E-04	3.78E-06	1.51E-05
10	3.28E-03	1.37E-04	3.60E-06	1.44E-05
20	2.04E-03	8.51E-05	2.24E-06	8.96E-06
30	1.27E-03	5.29E-05	1.39E-06	5.58E-06
40	7.89E-04	3.29E-05	8.67E-07	3.47E-06
50	4.91E-04	2.05E-05	5.39E-07	2.16E-06
60	3.05E-04	1.27E-05	3.36E-07	1.34E-06
70	1.90E-04	7.92E-06	2.09E-07	8.35E-07
80	1.18E-04	4.93E-06	1.30E-07	5.20E-07
90	7.35E-05	3.07E-06	8.08E-08	3.23E-07
100	4.57E-05	1.91E-06	5.03E-08	2.01E-07
200	3.97E-07	1.66E-08	4.36E-10	1.75E-09
300	3.44E-09	1.44E-10	3.79E-12	1.51E-11
400	2.99E-11	1.25E-12	3.29E-14	1.31E-13
500	2.59E-13	1.08E-14	2.85E-16	1.14E-15
600	2.25E-15	9.40E-17	2.48E-18	9.91E-18
700	1.96E-17	8.16E-19	2.15E-20	8.60E-20
800	1.70E-19	7.08E-21	1.87E-22	7.46E-22
900	1.47E-21	6.15E-23	1.62E-24	6.48E-24
1000	1.28E-23	5.34E-25	1.41E-26	5.62E-26

The total areal density of Titan's atmosphere out to 1000 km is approximately 11,300 g/cm^2, about 10 times the areal density of Earth's atmosphere. This areal density represents a substantial amount of shielding for any neutrons created in the upper atmosphere, and as a result most likely means that any neutron-induced radioisotope generation will be limited to the altitudes well above the surface. The $^{14}N(n,p)^{14}C$ cross section is shown in Fig. 2 and comes from the National Nuclear Data Center's ENDF library of cross sections. Most of the secondary neutrons created by GCR interactions will have energies above 1 keV, and the cross sections above 1 keV generally range between 1 mb to 500 mb. As those neutrons penetrate deeper into the atmosphere and moderate, cross sections increase to about 3 or 4 barns at 0.01 eV.

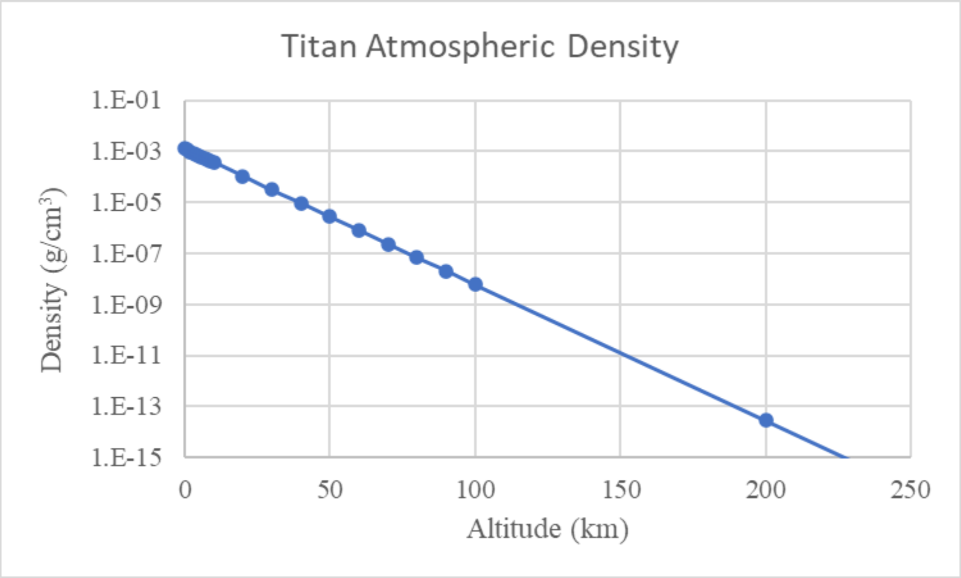

Figure 1. The density of Titan's atmosphere as a function of altitude, using the data from Ref. 2.

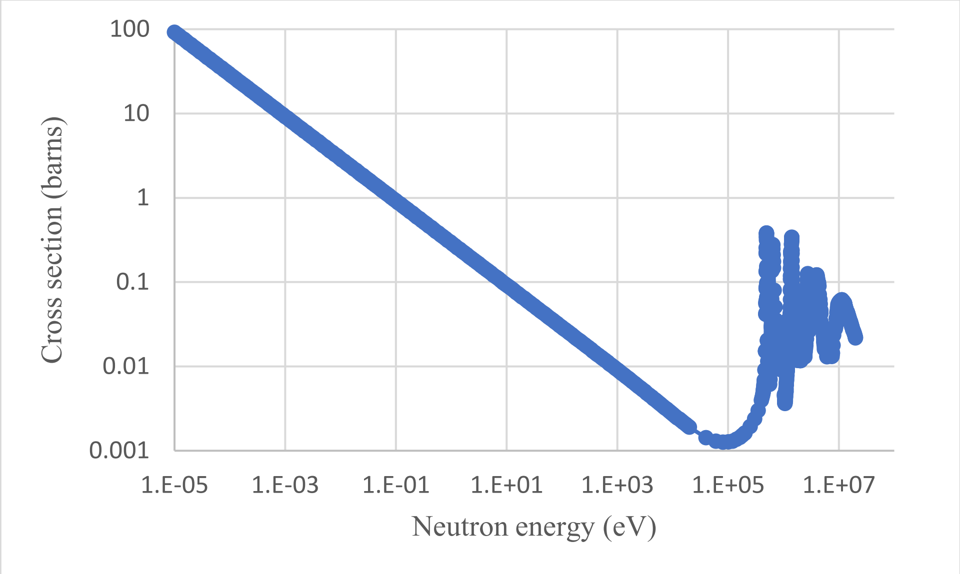

Figure 2. The $^{14}N(n,p)^{14}C$ reaction cross section (barns) as a function of neutron energy (eV).

IV. Results

The secondary neutron production as a function of depth into the atmosphere determined where most of the neutron production takes place Figure 3 shows the neutrons generated per incoming GCR ion (with no distinction on which species of GCR ion created the neutron) as a function of depth into the atmosphere in terms of the areal density. At the top of the atmosphere, the areal density is zero and at the surface the areal density is 11,359 g/cm$^{2.}$. Below the areal density of 1600 g/cm^2, the production of neutrons becomes difficult to determine with satisfactory statistical accuracy. As a result, Fig. 3 shows results down to 1600 g/cm^2, which corresponds to a depth down to an altitude of about 35 km from the surface. Maximum neutron production occurs around an areal density of 150 g/cm^2, or at an altitude of about 90-95 km. In terms of the total number of secondary neutrons produced in Titan's atmosphere, a solar minimum GCR flux yields about 1.2x10^{19} neutrons at 150 g/cm^2.

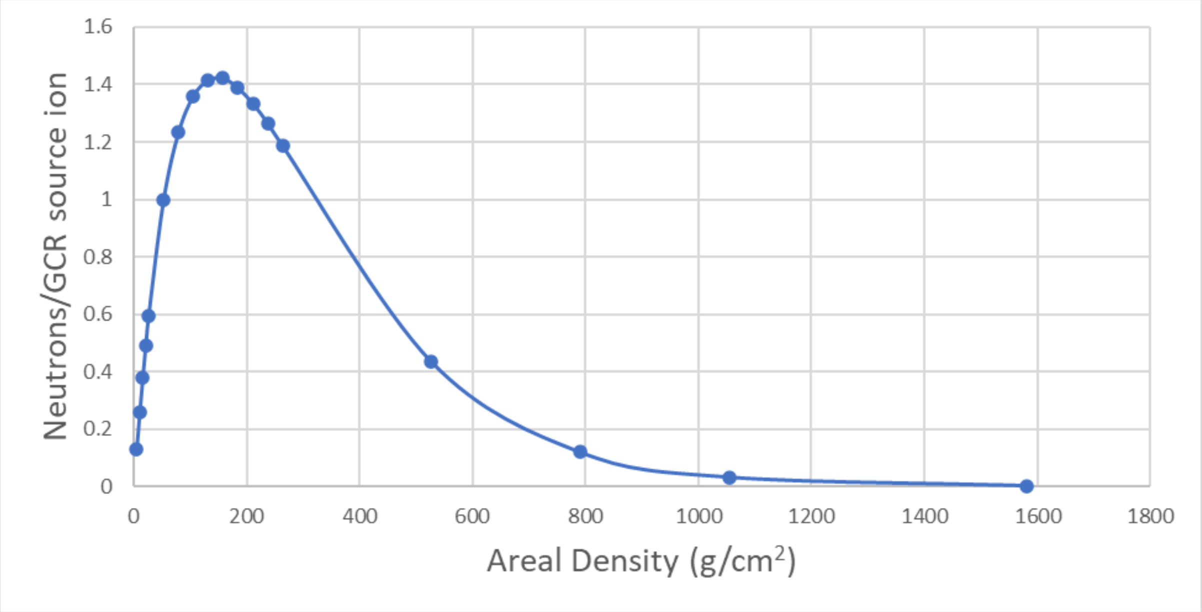

Figure 3. The number of secondary neutrons produed per GCR ion as a function of the depth into the atmosphere in units of g/cm^2. Statistical uncertainties are less than 1% for values below 800 g/cm^2, and increase to 45% at 1600 g/cm^2.

In addition to the total number of neutrons produced per incoming GCR ion, the neutron energy spectra at different depths into the atmosphere were also calculated. Figures 4-7 show the neutron energy spectra as various depths into the atmosphere, starting at very high altitudes (low areal densities) in Fig. 4 down to an altitude of about 40 km (1600 g/cm^2) in Fig. 7. In all cases, the secondary neutron flux peaks around 100 MeV, but as the depth increases the effect of moderation is noticeable in the increase of neutrons with energies below 1 MeV relative to the number of neutrons above 1 MeV.

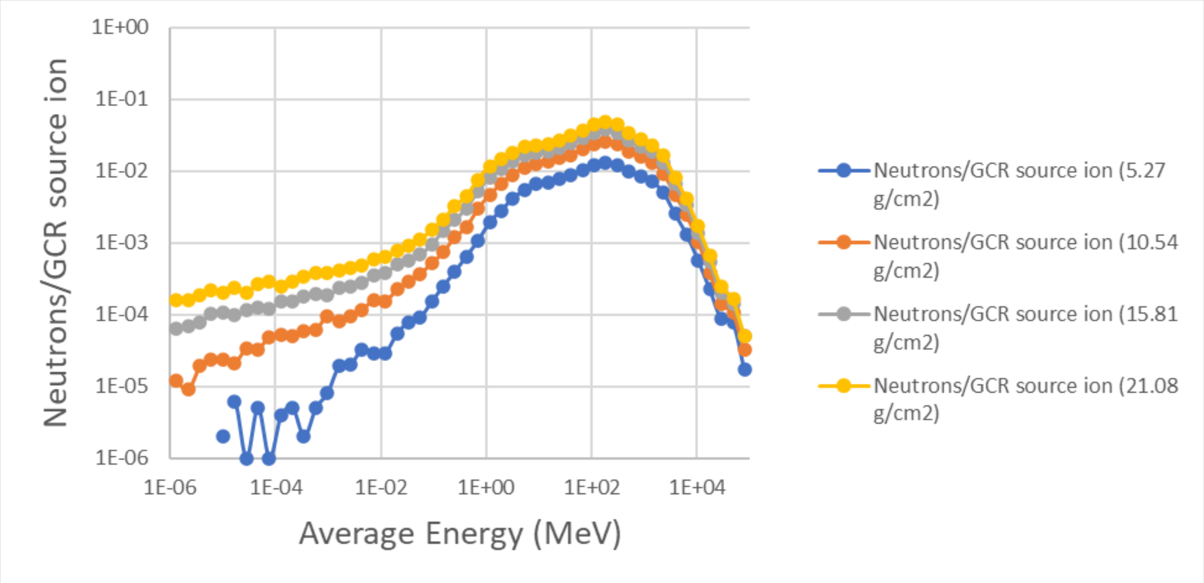

Figure 4. Neutron energy spectra yields at the indicated depths into Titan's atmosphere. The areal densities correspond to altitudes of 97-100 km.

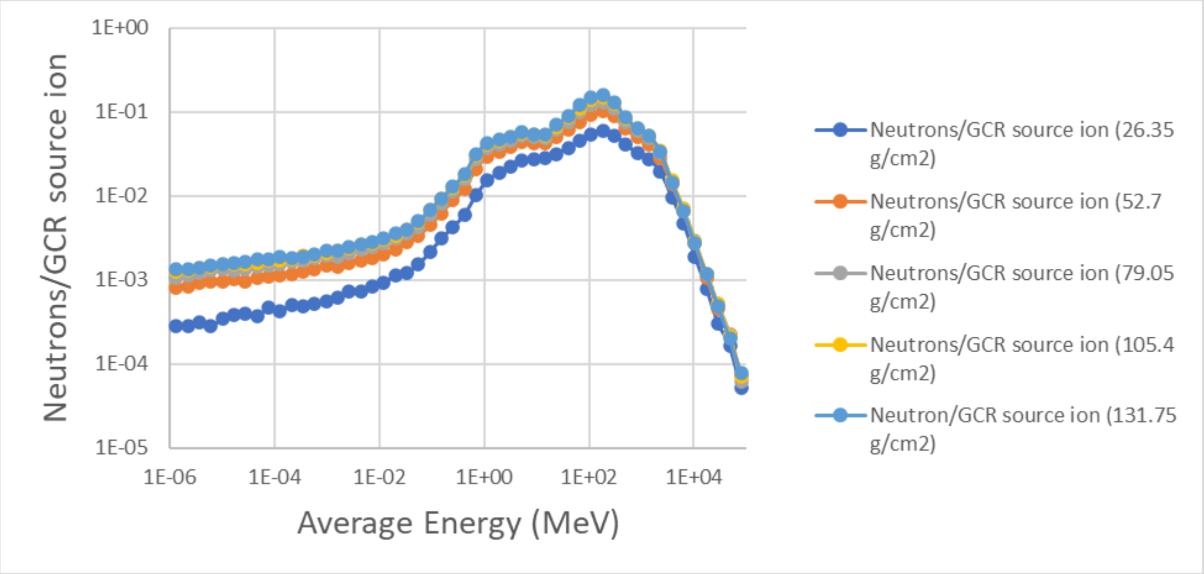

Figure 5. Neutron energy spectra yields at the indicated depths into Titan's atmosphere. The areal densities correspond to altitudes of 94-97 km.

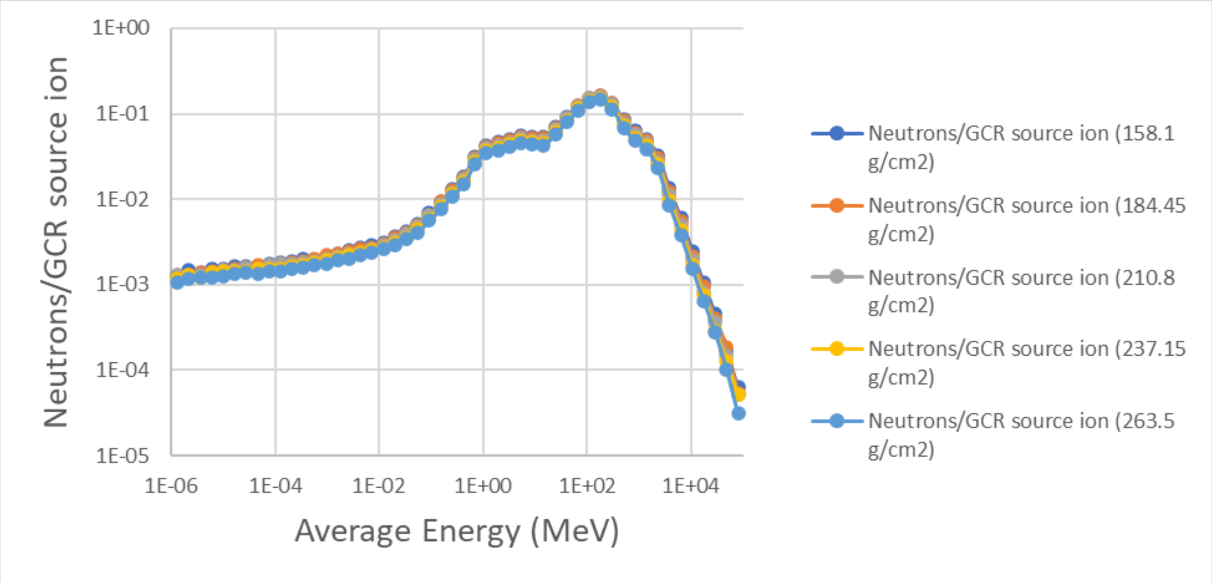

Figure 6. Neutron energy spectra yields at the indicated depths into Titan's atmosphere. The areal densities correspond to altitudes of 94-97 km.

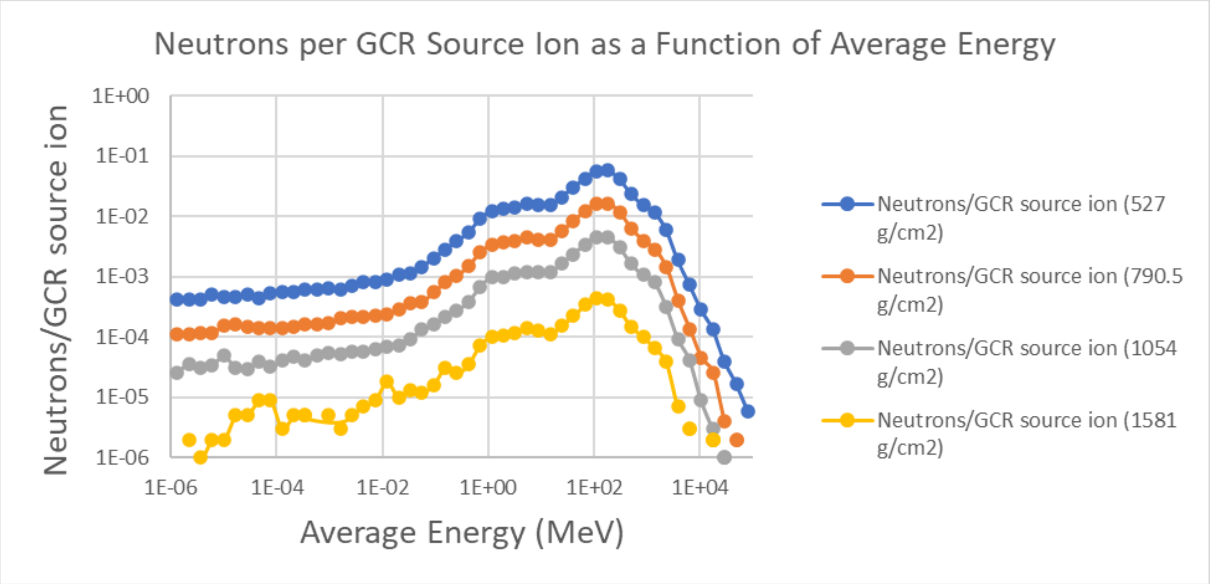

Figure 7. Neutron energy spectra yields at the indicated depths into Titan's atmosphere. The areal densities correspond to altitudes of 35-70 km.

Statistical uncertainties are less than 5% except for energies below 1 keV and for energies below 10 keV at 1581 g/cm^2, where uncertainties vary between 5 and 70 percent. The cross sections for production of ^{14}C above 20 MeV aren't reported, but it is expected that those values will be close to the values around 20 MeV, meaning that the most predominant neutron energies are where the cross section values are on the order of 20-50 mb. PHITS utilizes cross section data libraries for neutron energies below 20 MeV, and uses physics models to calculate the cross sections above 20 MeV. Together with the secondary neutron energy yields, the cross sections are then used to calculate the yields of isotopes such as ^{14}C in the atmosphere.

Table 3 shows the yields of selected isotopes, including ^{14}C, per incoming GCR ion. To get an estimate of the total number of those isotopes produces per second in the atmosphere during solar minimum, multiply the yields by 10^{19}.

Thus, approximately $2.1\text{x}10^{12}$ atoms of ^{14}C are produced per second. Over one half-life of the isotope, 5730 years, that yields about $3.8\text{x}10^{23}$ atoms. The molar quantities produced per second of these isotopes are small, but over the the course of several half lives of ^{14}C, there will be a detectable amount of ^{14}C that could be present in prebiotic molecules. ^{14}C beta decays directly to the ground state of ^{14}N with an average electron energy of 50 keV and endpoint energy of 156 keV. Although the beta energies are low and normally require a scintillation counter, detection is possible, especially if samples are returned to Earth for analysis.

Table 3. Yields of the indicated radioiosotopes per incoming GCR ion, along with their indicated half-lives.

Isotope	Yield (number per GCR ion)	Half-life
^{3}H	2.85e-05 ± 7.9%	12.33 years
^{11}C	7.6e-06 ± 16%	20.39 minutes
^{14}C	2.1e-07 ± 67%	5730 years
^{13}N	8.2e-06 ± 16%	9.965 minutes

V. Conclusion

Results of PHITS model calculations of GCR transport through Titan's atmosphere show that similar to Earth's atmosphere, ^{14}C is produced via the (n,p) reaction on nitrogen. Results were also shown of the resultant neutron spectra as a function of depth into the atmosphere. Maximum neutron production occurs at an altitude of 90-95 km, with most of the ^{14}C production occurring at altitudes above 80 km. Production rates of ^{14}C are on the order of 10^{12} atoms per second at solar minimum, leading to a build of (potentially) detectable yields over several millenia. Additional calculations of radiogenic production of other carbon isotopes (^{12}C, ^{13}C) will need to be performed along with data on the amount of naturally occurring carbon at the surface of Titan will be needed to estimate the fraction of ^{14}C uptake by processes at the surface. In addition, models of atmospheric mixing will be needed to determine what fraction of radiogenic ^{14}C will be available for uptake near the surface. Although instrumentation on the upcoming Dragonfly mission will not be able to detect the decay of ^{14}C, future missions, such as a sample return mission, could enable carbon dating of samples from Titan

References

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