Cosmic Ray Flux in the Presence of a Neutral Background

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Abstract: The study of cosmic rays (CRs) is a very mature subject developed around the concept of radiative particle flux Φ as a mono-variant function of energy E, that is $\Phi = \Phi(E)$. This is based on the notion of the cosmos as being filled with cosmic radiation in the form of a collisionless exosphere of plasma. Neutrals, however, are likewise ubiquitous in space and planetary trapped-radiation belts. In the presence of a neutral background of density ρ, flux Φ is actually bivariant in energy E and ρ, creating a surface $\Phi(E,\rho)$. This is an intrinsic property of charged-particle flux, that flux is not merely a function of E but is dependent upon density ρ when a background of neutrals is present. The effect is produced by multiple scattering of charged particles off neutral and ionized atoms along with ionization loss where charged and neutral populations interact. For the harder portion of CR spectra, flux is mono-variant but at nonrelativistic energies (below ~350 MeV) it becomes sensitive to the presence of neutral backgrounds. The dependence of $\Phi(E,\rho)$ upon background neutrals is helpful in dicussing the anomalous CR (ACR) flux which derives from neutral components of the heliospheric atmosphere.

Introduction

Recent investigations into a possible long-term decrease in the neutral density of the Earth's thermosphere have found a secular decrease in total mass density [1]. This result has been extended to show that a secular decrease in density necessarily produces an increase in the penetration depths of the inner-belt trapped proton flux to lower altitudes [2]. The subject derives partly from improved accuracy in estimating these densitites as inferred from orbital drag measurments on satellites such as CHAMP and GRACE [3].

The method adopted for analyzing the solar-cycle modulation of the inner trapped-belt proton flux is a phenomenological one [2], using a regression algorithm from nuclear physics to determine proton flux from databases available in the original NASA trapped-belt model AP8. An interesting property of the trapped-belt flux becomes apparent, that the flux is bi-variant in energy E and density ρ, as $\Phi(E,\rho)$.

This property of flux in the presence of neutrals will be discussed here.

Thermospheric Flux Analysis

A simple parameterization of the Earth's thermosphere at altitudes $300 < h < 600$ km for mean atmospheric density ρ is [2]

$$\rho = \rho_o \exp\{- (h - 120) / [M(h - 103)^{1/2}]\}, \qquad (1)$$

where the solar-cycle modulation term M is expressed as

$$M = 0.99 + 0.518 \{ (F_{10.7} + F_{bar}) / 110 \}^{1/2} , \qquad (2)$$

and where ρ_o is assumed to be ρ_o = 2.7 x 10^{-11} g/cm^3, h is the altitude in km, $F_{10.7}$ is the instantaneous value of the solar radio flux at 10.7 cm, and F_{bar} is the weighted value of $F_{10.7}$ taken over three previous solar rotations. Since AP8 is the trapped-belt model used, solar cycle 20 is baselined in the analysis. For that cycle, $F_{10.7}$ is 150 for AP8MAX (epoch of 1964) and 70 for AP8MIN (epoch of 1970). Trapped protons have a very slow response time to dynamic changes in atmospheric density $\rho(t)$. Therefore, the values of $F_{10.7}$ and F_{bar} are assumed identical, whereby $F_{10.7}$ + $F_{bar} = 2 F_{10.7}$ in Equation (2).

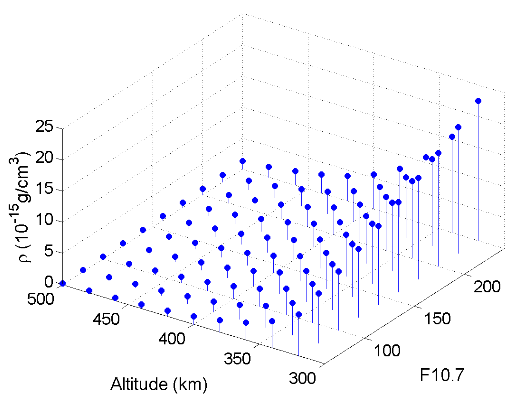

Figure 1: A carpet plot for $\rho = \rho(h, F_{10.7})$ in Equation (1).

Note that the density ρ in Equation (1) is a multivariant function of h and $F_{10.7}$. Similarly the AP8 proton flux Φ is a multi-variant function of h and energy E. Because altitude h is not an intrinsic property of the Earth's atmosphere, the problem at hand is to generate the multi-dimensional surface of Φ as a function of E and ρ, or $\Phi(E, \rho)$. By taking the inverse of Equation (1) for constant surfaces of $F_{10.7}$ and altitude h respectively, altitude $h = f(\rho)$ and solar radio flux $F_{10.7} = g(\rho)$ as a function of atmospheric density ρ in Equation (1) can be obtained from the "carpet plot" in Figure 1.

The Galactic CR (GCR) flux is believed to be the source of the inner trapped-belt particles, creating albedo neutrons when colliding with the Earth's atmosphere which decay into protons spiralling in the inner belts. Due to the geomagnetic cutoff, however, only higher energy GCRs can reach low equatorial latitudes where the inner belt protons are produced. One might conclude that solar modulation (Solar MIN and MAX) does not play a contributing role in inner-belt proton variations. The AP8 model nevertheless shows such a dependence below 350 MeV. For a given altitude, it produces two such curves, $\Phi_{min}(E)$ for Solar MIN and $\Phi_{max}(E)$ for Solar MAX. The task at hand is to produce a functional relationship between $\Phi_{min}(E)$ and $\Phi_{max}(E)$ from AP8 data – and then merge it with $\Phi(\rho)$ using Figure 1.

Under the rough premise that $\Phi(\rho) \sim \rho^{-1}$ in the lower thermosphere, the regression algorithm technique [2] is applied to determine a more accurate functional relationship from AP8. After several trials the best-fitted function thus obtained is given as follows,

$$\Phi_{max}/\Phi_{min} = (a_4 E^4 + a_3 E^3 + a_2 E^2 + a_1 E + a_0)\, \rho^{-2} + (b_3 E^3 + b_2 E^2 + b_1 E + b_0)\, \rho^{-1}$$

$$+ (c_2E^2 + c_1E + c_0), \quad (3)$$

for energies E under consideration (30-300 MeV). Equation (3) is further approximated by writing the coefficients in exponential form,

$$\Phi_{max}/\Phi_{min} = Ae^{\alpha E}\,\rho^{-2} + Be^{\beta E}\,\rho^{-1} + Ce^{\gamma E} \quad . \qquad (4)$$

Specifically, Equation (4) is

$$\Phi_{max}/\Phi_{min} = -0.0241e^{0.0007E}\,\rho^{-2} + 0.1966e^{-0.0007E}\,\rho^{-1} + 0.3208e^{+0.0032E} \quad , \qquad (5)$$

with ρ^{-1} in units of $10^{+15}\ cm^3/g$. This result is illustrated in Figure 2 and Figure 3. To the order of approximation, Equation (3) can be written

$$\Phi(E,\rho) \sim \Phi_o \sum [\, \sum A_{n+2}(E^{n+2})]\,\rho^{-n}, \quad (6)$$

giving the bivariant relationship of $\Phi(E,\rho)$ with respect to any chosen reference flux Φ_o (in this case, Φ_{min}).

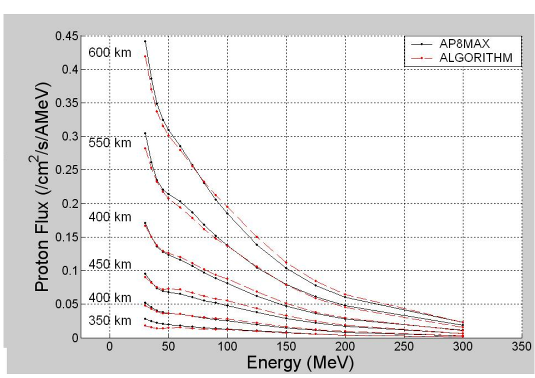

Figure 2: Comparison of the algorithm in Equation (5) with AP8 mono-variant flux $J(E)$ at solar maximum during Cycle 20 for various Shuttle and ISS altitudes h (350, 400, 450, 500, 550, and 600 km) assuming $F_{10.7} = F_{bar} = 110$.

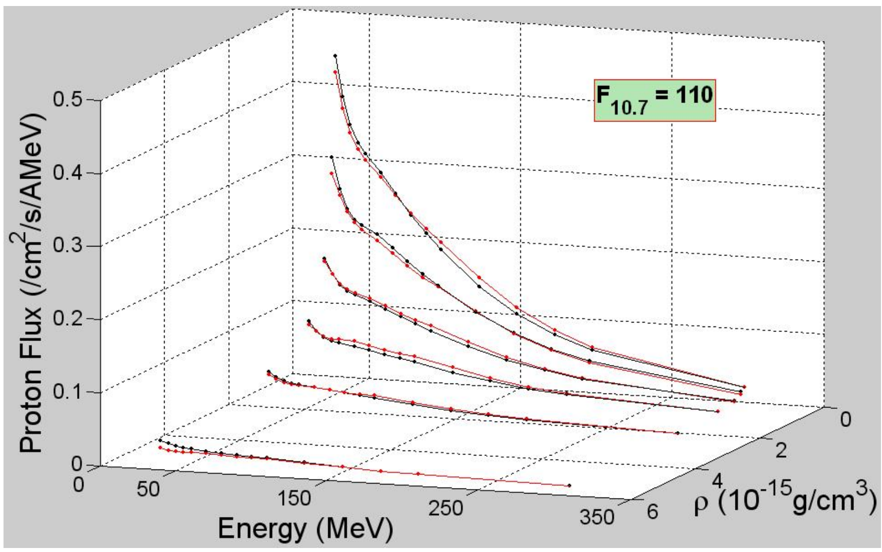

Figure 3: Proton differential flux as a bivariant surface $\Phi(E,\rho)$, demonstrating the three-dimensional nature of flux when neutrals are present.

The dependence of $\Phi(E,\rho)$ in Equation (6) upon background neutrals is helpful in understanding the ACR flux which is made up of components of the heliospheric neutral atmosphere that reach the inner solar system and help populate the Earth's radiation belts [4]. Further, the effect of neutrals can be visualized by conceptually turning off the proton's charge. There must still exist a collisional interaction with the neutral background, related to quantum drag in a planetary or heliospheric exosphere [5].

The proton differential flux in the Earth's inner trapped proton belts has been expressed by a reparameterization of the AP8 model as a bivariant function of energy and density, namely $\Phi(E,\rho) \sim \Phi_o \sum [\sum A_{n+2}(E^{n+2})] \rho^{-n}$. The method provides the potential for evaluating proton intensity as a function of time through the density's dependence on solar $F_{10.7}$ [2].

Conclusions

References

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