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Comment on 'Scaling factors for production rates of in situ produced cosmogenic nuclides: a critical reevaluation' by Tibor J. Dunai

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1. Introduction

In a recent paper, Dunai [1] discusses several problems with the altitude and latitude scaling of production rates given by [2–4]. Dunai describes three major flaws in Lal's scaling: (1) cosmic-ray measurements are ordered according to geomagnetic latitude calculated from an axial dipole representation of the geomagnetic field; (2) the high-altitude (atmospheric depth 580–770 g cm^{-2}) attenuation length at 41°N geomagnetic latitude is assumed to be constant down to sea level; and (3) the scaling expression is given in terms of elevation rather than atmospheric depth. In an attempt to improve on Lal's scaling, Dunai derives a new scaling model following a procedure similar to that of [4], but incorporating some neutron monitor, nuclear emulsion and cloud chamber data unavailable to [4]. In this comment we show that Dunai's scaling model is based on several false assumptions. Due to the significance of these false assumptions, we find no evidence that Dunai's scaling model represents an improvement over Lal's scaling model. We also point out that geological factors affecting production of cosmogenic nuclides can be difficult to evaluate, and suggest that the ^{3}He data [5] used to confirm the Dunai [1] scaling may underestimate production rates.

2. Neutron monitor data

The neutron monitor data now available far exceed those available to Lal [4], but unfortunately Dunai limits his analysis to data collected in the 1950s. Since the 1950s, numerous latitude and altitude surveys of nucleon intensity have been conducted with neutron monitors (e.g., [6–13]), of which Dunai appears unaware. These surveys adequately characterize the nucleon attenuation length (λ_N) as a function of atmospheric depth and cut-off rigidity, and therefore the procedure described by Dunai of linking latitude curves is unnecessary (by using a constant λ_N at one latitude to link latitude curves at different altitudes, a constant λ_N at all latitudes can be calculated). By linking latitude curves, Dunai assumes that the attenuation length is constant between sea level and 4000 m. This is a poor assumption, since the neutron monitor attenuation

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length varies with altitude by about 8 g cm^{-2} between sea level and 4000 m at low latitudes [7].

3. Instrumental biases

The neutron monitor data cited in section 2 provides a fairly detailed picture of how the neutron monitor counting rate varies with latitude, altitude and solar activity. These data, however, should not be used without first correcting the neutron monitor counting rate for instrumental biases. For example, correcting the high-latitude, sea-level neutron monitor attenuation length (Λ_{NM}) for the effects of muons and constant background contributions decreases Λ_{NM} by about 10 g cm^{-2} [7]. The size of this correction should increase towards lower latitudes and decrease towards higher elevations.

A correction is also needed to account for the energy bias of the neutron monitor response. This correction is important because the nucleon attenuation length decreases with increasing median nucleon energy [14,15]. The neutron monitor response is biased towards the high end of the nucleon energy spectrum because relatively high-energy nucleons ($E > 400$ MeV) are counted by the neutron monitor more times than lower-energy nucleons ($E < 400$ MeV) [14,15]. The size of this correction should increase with both decreasing latitude and increasing altitude.

The cloud chamber and emulsion data cited by Dunai ([16–18]) are also biased towards the higher end of the nucleon energy spectrum. The cloud chamber experiment by Brown [16], for example, undercounted one- and two-prong stars (low energy disintegrations) while Dixit [17] and Roederer [18] neglected these altogether. In the silver bromide emulsions used by [17] and [18], one- and two-star prongs correspond to energies of about 41 MeV and 90 MeV, respectively [16]. Again, the effect here is to underestimate the nucleon attenuation length. We corrected the data of [16] for this effect using the procedure outlined by Lal ([4], p. 67) and have obtained a value of 137 ± 5 g cm^{-2} for the flux-weighted attenuation length of nucleons with $E > 40$ MeV. This compares to a value of 132 ± 4 g cm^{-2} given by [16] (and cited by Dunai) for the uncorrected nucleon attenuation length between 700 and 1032 g cm^{-2}.

4. Inclination versus effective cutoff rigidity for ordering neutron monitor data

A unique feature of Dunai's work is his use of geomagnetic inclination for ordering neutron monitor data. Since the late 1960s, most neutron monitor measurements have been ordered in terms of effective vertical cutoff rigidity (P_C) [19–21]. The reliability of P_C has been confirmed by numerous sea-level latitude surveys that show a smooth and consistent relationship between cutoff rigidity and nucleon intensity [11–13,19].

In contrast, the relationship between inclination and the neutron intensity given by Dunai ([1], Fig. 3a) is rough and non-unique. Dunai observes a

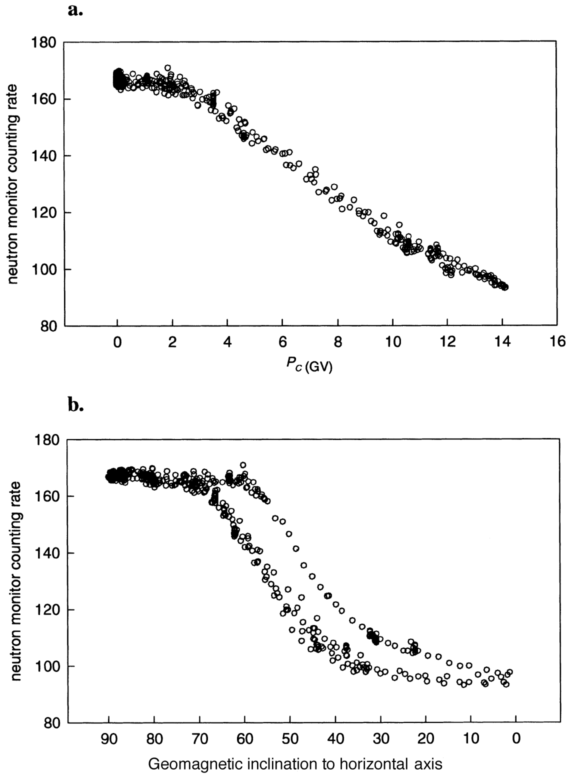

Fig. 1. Sea-level neutron monitor data from Rose et al. [8] ordered according to (a) effective vertical cutoff rigidity (P^C) and (b) geomagnetic inclination.

large discrepancy between neutron monitor data collected by Rose et al. [22] in the South Atlantic, Antarctic Sea and elsewhere ([1], p. 164). Although Dunai attributes the discrepancy to a highly anomalous field in this area ([1], p. 164), the inconsistencies between latitude survey data clearly indicate the inadequacy of using inclination for ordering neutron intensity data. In Fig. 1, we show that trajectory-derived cutoffs effectively order the data of [22] and eliminate the anomalies seen in Dunai's figure 3. Contrary to Dunai's statement that the dipolar equation (Dunai's equation 1) is essentially the same as 'trajectory tracing' of cosmic-ray particles ([1], p. 158), the two types of cutoffs differ considerably in both how they are derived and how they order neutron monitor data. The dipolar equation is an analytical solution to the equations of charged particle motion in a dipole field [23], whereas the trajectory tracing is a numerical method of calculating cutoffs in an empirically derived model of the real geomagnetic field. Dunai's equation 2 is nothing more than a modified version of the dipolar equation that still does not adequately account for the effects of the real geomagnetic field.

The main problem with ordering neutron monitor data according to geomagnetic inclination is that the effects of the eccentric dipole field are inadequately characterized. The method described by Dunai of linking latitude curves is valid only if the two curves cross the geomagnetic equator at nearly the same cutoff rigidity. However, Dunai links the sea-level survey of Rose et al. [22], which crosses the geomagnetic equator at 14 GV, with the airborne survey of Sandström [24], which crosses at 17.4 GV, using a high-latitude attenuation length. This causes the low-latitude counting rate to appear to increase with a greater Λ_N than the true Λ_N.

5. Solar activity and the latitude effect

Dunai incorrectly assumes that the overall shape of the neutron flux versus latitude curves at large atmospheric depth (>600 g cm^{-2}) is not affected by solar modulation of the primary flux ([1], p. 163). He supports this claim by citing the results of Lockwood [25], who observed that fluctuations in the sea-level neutron monitor counting rates at Chicago, Ottawa and Durham, New Hampshire were of the same magnitude from 1954 to 1957 as those observed atop of Mt. Washington, New Hampshire ($\sim$820 g cm^{-2}). However, because all of these monitors were at low cutoffs ($P_C \sim 2$ GV), it is impossible to ascertain the effect of solar activity on the shape of the neutron flux versus latitude curve from [25].

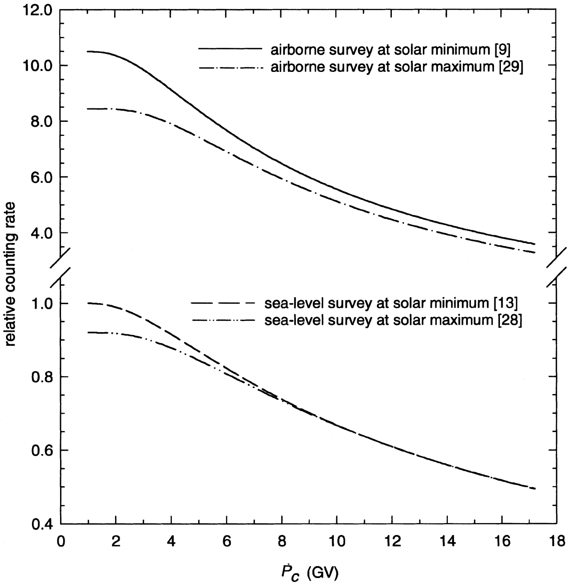

Fig. 2. Latitude surveys of nucleon intensity conducted at solar maximum and solar minimum, normalized at 14 GV. Airborne and sea-level curves correspond to atmospheric depths of 680 g cm^{-2} and 1033 g cm^{-2}, respectively.

Several experiments since [25] have demonstrated that even at depths ranging from 680 to 1033 g cm^{-2} the shape of the latitude curve depends considerably on solar activity (Fig. 2) [26–29]. From solar minimum to solar maximum, the high-latitude sea-level nucleon flux decreases by about 8%, whereas at 680 g cm^{-2} the flux decreases by about 21%. At low latitudes ($\sim$14 GV), solar modulations have a negligible effect on sea-level neutron intensity [26], while at 680 g cm^{-2} the neutron flux varies by only about 5% [30].

6. Measurements of cosmogenic ^{3}He

Geological samples can be used to test scaling models derived from neutron data [31], however, the uncertainty associated with geological samples is typically larger than the uncertainty in measurements of cosmic-ray intensity. This uncertainty is due to geological factors, such as erosion and ash cover, and analytical factors, such as errors in calculation of implanted ^{4}He. Here, we address three potential problems that may have affected the ^{3}He results of Dunai and Wijbrans [5] used to validate the scaling of [1]. First, the erosion depth of 2–4 mm reported in [5] is remarkably low for lava flows in the age range 150–280 ky. If the erosion rates reported in [5] are real, these lava flows could provide the best samples for calibration of other cosmogenic nuclides, such as ^{36}Cl.

Second, Dunai and Wijbrans [5] make no correction for sample thickness (in their case always about 5 cm). They assume that the neutron intensity is constant in the top 10 g cm^{-2} of rock, and, therefore, the production rate of ^{3}He is constant in the top 5 cm. But this constant neutron intensity result was derived using Monte Carlo simulations [32], with resolution insufficient for accurate determination of the shape of the neutron intensity function. The accuracy of these computations has not been confirmed empirically and should be used with caution. Correcting the ^{3}He data of [5] for sample thickness using an exponential model would increase the production rates by approximately 3%.

Third, Dunai and Wijbrans [5] collected a small number of samples from each lava flow, and all samples from the same lava flow were within 10 m of each other. This sampling strategy makes the results vulnerable to effects of shielding by soil or ash, which might have been present at some time. Problems associated with spatially varying ash cover and erosion may be minimized by collecting more samples from a wider area.

In addition to the above potential problems, Ackert et al.'s [33] and Dunai and Wijbrans' [5] ^{3}He data are not directly comparable because of the following considerations. First, the ^{3}He data reported by Dunai and Wijbrans [5] have been corrected for implanted ^{4}He; the data in Ackert et al. [33] have not. If the correction for Ackert et al.'s samples is similar to the corrections in [5], the production rate of Ackert et al. would decrease by approximately 10%. Second, Ackert et al.'s [33] production rates are on clinopyroxene. Although ^{3}He production rates are not strongly composition-dependent, variability of up to 8% is predicted by theory [2,32]. Third, Ackert et al. [33] corrected for sample thickness using the attenuation length of 160 g cm^{-2}; Dunai and Wijbrans [5] made no such corrections. Fourth, and most important, the production rate reported by Ackert et al. [33] was preliminary. It has been revised due to new ^{40}Ar/^{39}Ar and K–Ar ages obtained from new samples, which were better suited to the technique (R. Ackert, personal communication, October 2000), and ^{3}He measurements in olivine. The new production rate is 25% higher than that reported by [33]. It cannot be reconciled with the production rate of [5] using the scaling formulation proposed by Dunai [1], and neither can the two production rates be reconciled using Lal's [2] scaling.

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