A Review of Cosmic-Ray Albedo Studies: 1949-1970

Allan J. Tylka
Code 7652, Naval Research Laboratory, Washington DC
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Abstract

I review experimental results on cosmic-ray albedo from balloon and sounding rocket experiments in the 1950s and 1960s. I show how the normalizations and spectral shapes of these early measurements, as well as theoretical albedo estimates from that era, are in good agreement with recent comprehensive proton-albedo measurements from the Shuttle-borne Alpha Magnetic Spectrometer (AMS). These comparisons confirm that the AMS results can provide a reliable starting point for GLAST background studies. The early experiments also reveal two other potentially important features of the albedo which were missed by AMS: the ~60% increase in albedo flux at zenith angles near ~90^o and the electron albedo flux, which exceeds the proton flux at ~100-1000 MeV by roughly an order of magnitude. Finally, I also compare the AMS data with the recently suggested GLASTSIM proton albedo parameterization. At larger magnetic latitudes, where GLAST will spend a significant fraction of its time, this parameterization significantly overestimates the proton albedo above 200 MeV.

Introduction

The term "cosmic-ray albedo" denotes secondary particles produced by interactions of cosmic rays in Earth's atmosphere. The cosmic-ray albedo was discovered in 1949, when Van Allen, Singer, and co-workers used sounding rockets to show that the average omnidirectional particle flux exceeded the average vertical flux, contrary to expectations if all observed particles were primary cosmic rays, incident upon Earth from interplanetary space. The interpretation of the excess particles as interaction products was bolstered by observations showing a larger intensity at zenith angles near 90^o. Cosmic-ray albedo was widely studied in the 1950s and 1960s, as researchers sorted out these backgrounds while using balloon and sounding-rocket measurements to uncover the spectrum of the primary cosmic radiation. It was recognized that albedo particles played a key role in generating the high-energy protons trapped in Earth's magnetic field, through the mechanism of cosmic-ray albedo neutron decay (CRAND).

In the cosmic-ray literature, two kinds of albedo are distinguished, based upon direction motion near the top of the atmosphere: (1) ***splash albedo***, which refers to upward moving particles emerging from the atmosphere, and (2) ***re-entrant albedo***, which denotes downward moving particles whose rigidities are below the local geomagnetic cutoff for particles arriving directly from interplanetary space. S.B. Treiman first enumerated these two classes in a seminal paper in 1953. In that paper, Treiman also explained the close relationship between these two particle populations: the re-entrant albedo are simply splash albedo particles which leave the production site along forbidden Stoermer trajectories[1]. As a result, these particles return to Earth very close to the same geomagnetic latitude from which they left Earth, i.e. to the conjugate mirror point in the opposite

[1] Forbidden trajectories are those for which a particle cannot reach Earth from infinity. Conversely, these same directions are those for which splash albedo particles cannot escape to infinity and hence must be channeled back to Earth.

geomagnetic hemisphere[2]. Moreover, Treiman invoked Liouville's theorem to argue that re-entrant albedo particles should be more or less isotropic.

Comparison of Balloon-Borne and AMS Proton Albedo Measurements

In ~1950-1970, there were numerous balloon- and sounding-rocket measurements of cosmic-ray proton albedo, and I have made no attempt to make an exhaustive survey of all of them. For this review, I have used only those results which appeared in easily-accessible, peer-reviewed English-language literature. I have also neglected reports of a single measurement, averaged over a broad energy band, without spectral information (e.g., McDonald 1958; Hasegawa et al. 1965; Ormes & Webber 1964). The authors which are quoted here have demonstrated that these earlier results are consistent with their later, more detailed spectral measurements.

Splash (Upward-Moving) Proton Albedo

Figures 1 and 2 show measurements of splash (i.e, upward-moving) proton albedo at two different geomagnetic latitudes.

Figure 1 compares balloon measurements [Verma 1967; Wenzel et al. 1975; Pennypacker et al. 1973] at Palestine, Texas ($\theta_M \sim 41^o$). Alcaraz et al. [2000] neglected to include comparisons between their recent results and these previously-published measurements. Figure 1 therefore also shows the tabularized AMS results [Alcaraz et al. 2000] for the latitude bin at $40.1^o \leq \theta_M < 45.9^o$. Of particular note are the Verma (1967) results[3], which were obtained in May 1965, almost exactly 33 years before the AMS measurements and hence at nearly the same point in the Solar Cycle. All of the measurements above ~100 MeV are in remarkably good agreement[4]. This good agreement suggests that the AMS albedo results provide a reliable starting point for GLAST background estimates.

Figure 2 compares splash proton albedo measurements at somewhat higher geomagnetic latitude. The balloon results were all taken at Fort Churchill, Canada. The AMS results in this Figure are the tabulated results in their highest reported latitude bin, at $51.5^o \leq \theta_M < 57.3^o$. Again, the results are in reasonably good quantitative agreement, except for the July 1969 results, which are somewhat lower, perhaps because of solar-cycle modulation of the cosmic-ray intensity.

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[2] The recent AMS albedo measurements [Alcaraz et al. 2000] appear to be in a good position to test this ~50-year-old prediction. The AMS report shows maps of the "geographical origin" of albedo particles, determined by using modern computer power and precise momentum-vector measurements to follow albedo proton trajectories backwards through the Earth's magnetic field. These origin points appear to be arranged symmetrically about the geomagnetic equator, just as one would expect from Treiman's argument about conjugate geomagnetic latitudes. However, the AMS collaborators are apparently unaware of Treiman's 1953 paper, and they do not discuss their "origin maps" in terms of conjugate mirror points.

[3] The Verma (1967) study is also noteworthy for its methodology. A first balloon flight was performed on 20-21 May 1965, with the instrument oriented toward zenith to observe only re-entrant albdeo particles. (The geomagnetic cutoff at Palestine, Texas excluded primary cosmic rays within the instrument's energy range.) The same balloon payload was flown again on 29-30 May 1965, but with the apparatus inverted and oriented vertically toward earth, so as to observe splash albedo. This exact same methodology was employed by AMS in 1998, which compared data taken with the Shuttle bay oriented either toward zenith or toward nadir.

[4] Wenzel et al. (1975) comment that the discrepancies below ~100 MeV are too large to be due to solar cycle effects and suggest that they may be due to the poorer energy resolution and higher backgrounds at low energies in the Verma (1967) instrument.

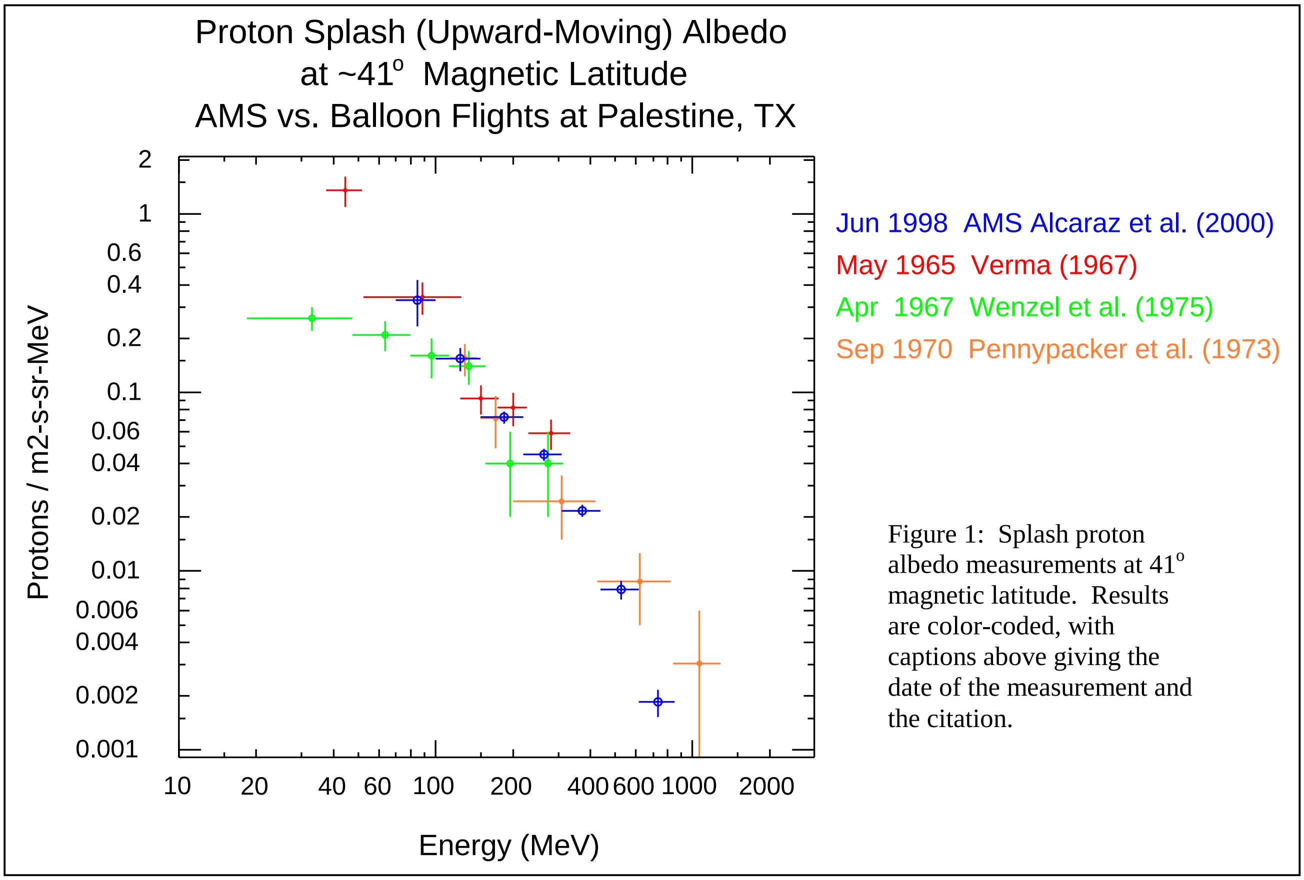

Figure 1: Splash proton albedo measurements at 41° magnetic latitude. Results are color-coded, with captions above giving the date of the measurement and the citation.

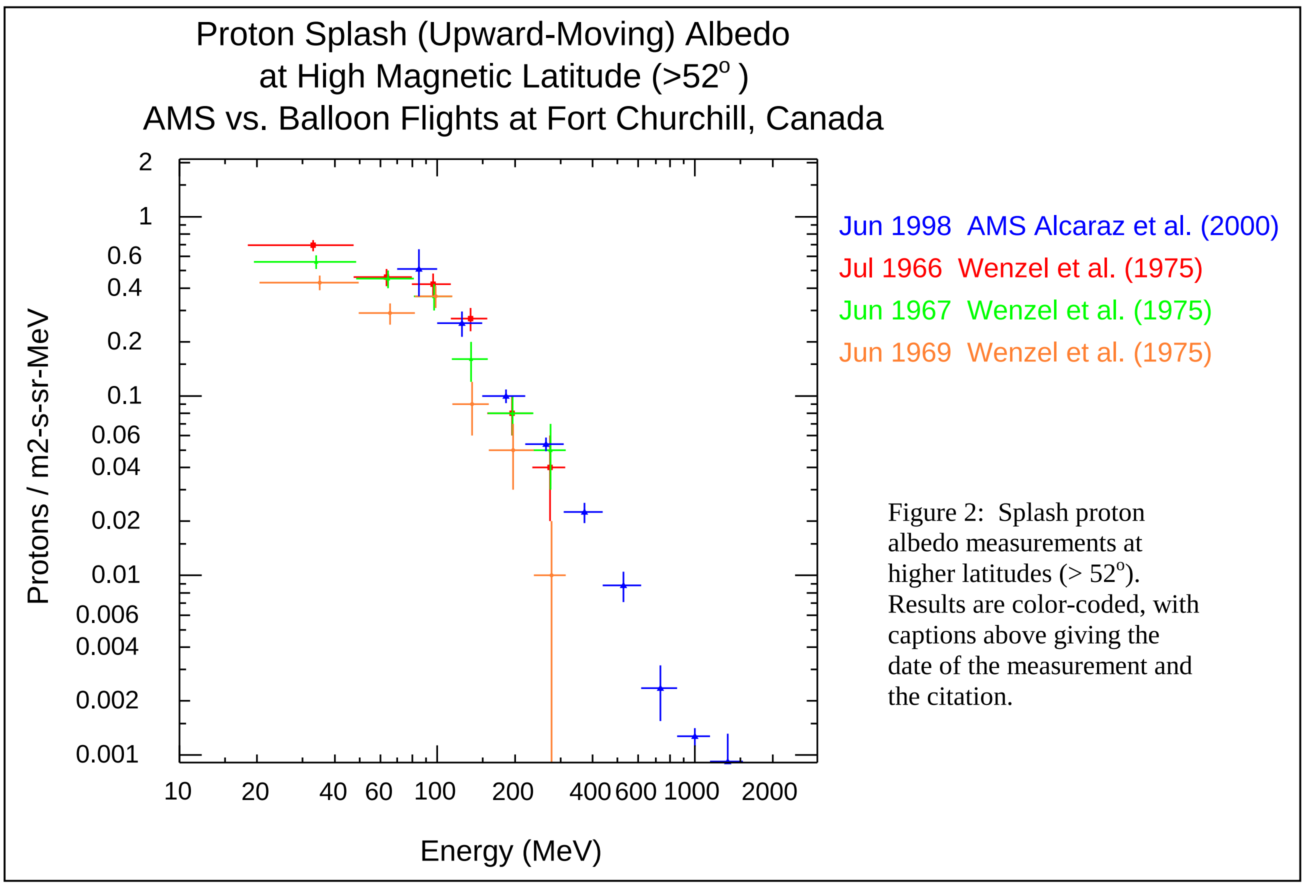

Figure 2: Splash proton albedo measurements at higher latitudes (> 52°). Results are color-coded, with captions above giving the date of the measurement and the citation.

Re-Entrant (Downward-Moving) Proton Albedo

Figure 3 compares two balloon measurements of the re-entrant (i.e., downward-moving) protons at Palestine, Texas [Verma 1967; Pennypacker et al. 1973]. As noted by these authors, to within measurement errors, the downward-moving re-entrant albedo protons have the same spectrum and intensity as the upward-moving splash albedo.

Also shown in Figure 3 is a theoretical calculation of the re-entrant proton albedo at Palestine, as given by Pennypacker et al. [1973] and based on the work of Ray [1962; 1967]. It should be noted that this is an absolute prediction, which has *not* been normalized to the data. The agreement with Ray's calculations is good, and this comparison illustrates the quantitative understanding[5] of cosmic-ray albedo which was achieved in the 1960s.

Before comparing to space-based re-entrant albedo measurements, the balloon results must be corrected "to the top of the atmosphere", by accounting for energy loss in the residual atmosphere (typically a few g/cm^2) above the balloon[6]. Only Verma [1967] explicitly carried out such corrections, and his corrected re-entrant albedo proton results are compared to the AMS data in Figure 4. Again, the agreement appears to be quite reasonable.

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[5] See also the discussion in Verma [1967]. Wenzel et al. [1975] subsequently made refinements upon Ray's techniques and calculated spectra which exceeded their re-entrant albedo measurements by factors of ~2 to 4. Wenzel et al. suggest that these discrepancies were due to uncertainties in the emulsion "star-production" data which Ray employed in his calculations. Any attempt to refine Ray's calculations for application to the AMS data should avail itself of better nuclear interaction data, which are presumably now available.

[6] Such a correction is not important for the splash albedo, since the residual atmosphere above the balloon is small compared to the atmospheric grammage between the balloon and the production altitude.

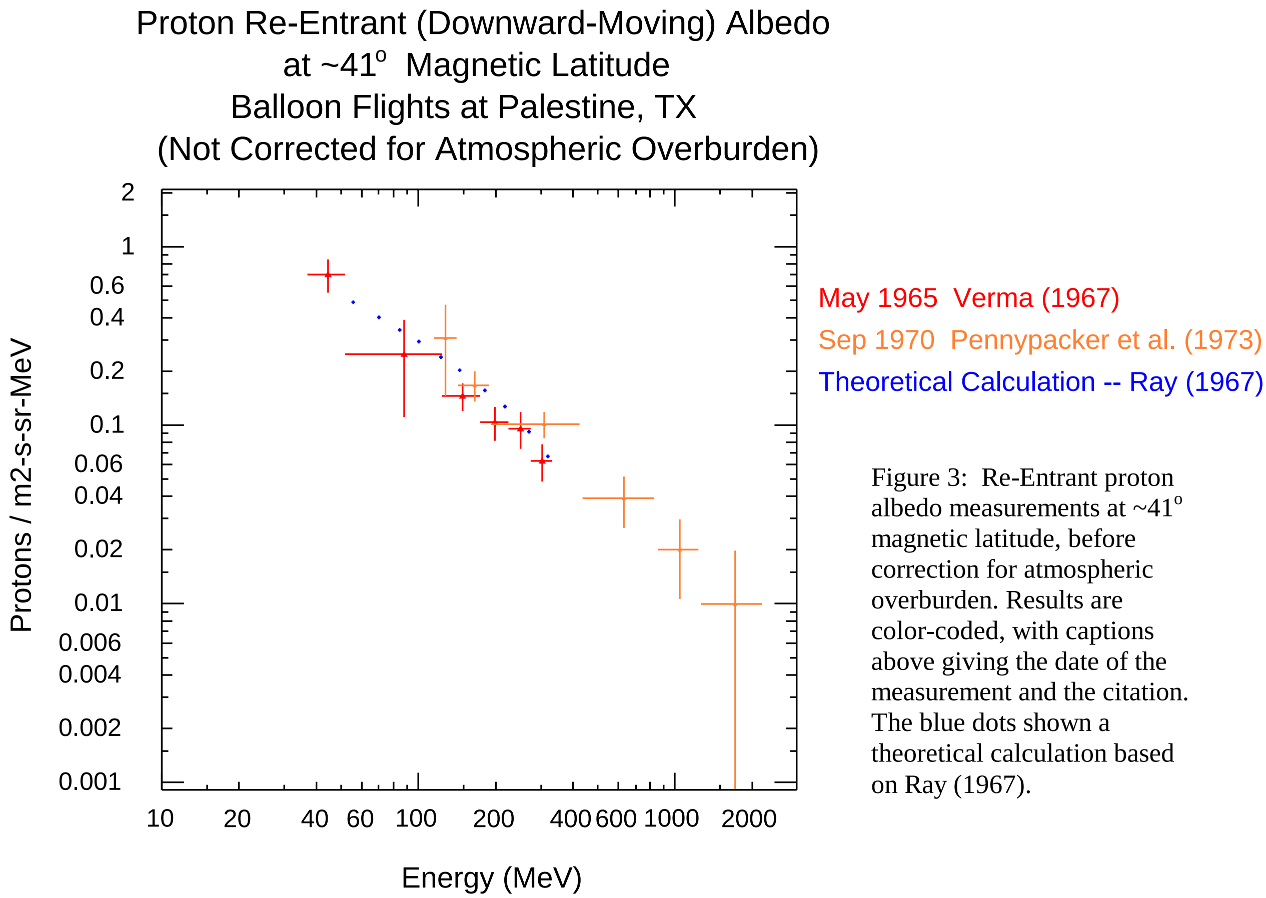

Figure 3: Re-Entrant proton albedo measurements at ~41° magnetic latitude, before correction for atmospheric overburden. Results are color-coded, with captions above giving the date of the measurement and the citation. The blue dots shown a theoretical calculation based on Ray (1967).

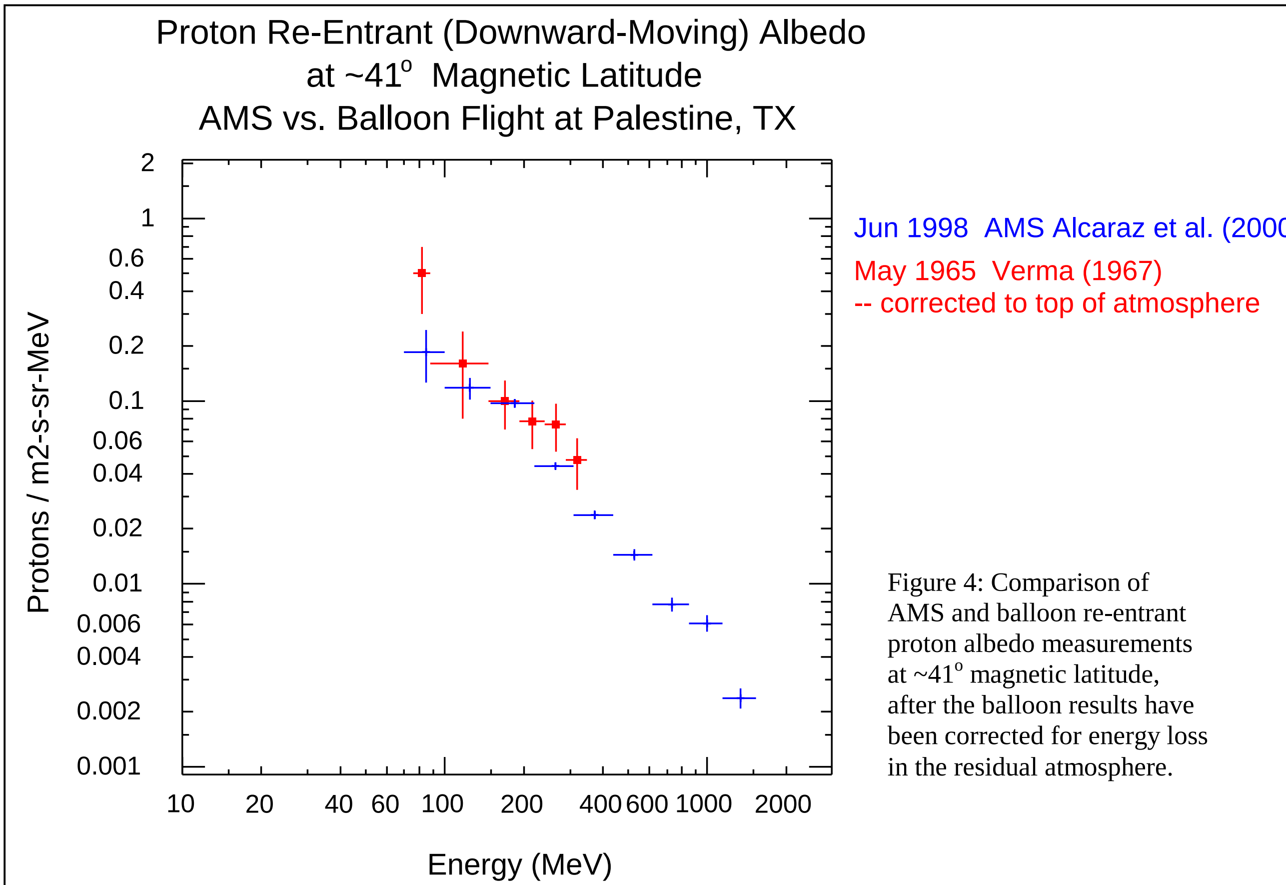

Figure 4: Comparison of AMS and balloon re-entrant proton albedo measurements at ~41° magnetic latitude, after the balloon results have been corrected for energy loss in the residual atmosphere.

Albedo Zenith Distribution

The recent AMS albedo measurements were restricted to $\pm 32^o$ of zenith or nadir. Within this restricted angular acceptance, the intensity is nearly isotropic, as predicted by Treiman (1953) and as previously reported by Pennypacker et al. [1973]. However, in 1949 Van Allen and Ganges used arrays of Geiger-Mueller tubes flown aboard sounding rockets to ~100 km to measure the azimuth-averaged zenith-angle distribution. They reported an increase in the intensity near zenith angles of 90^o, which could be described by the relationship:

$$J(\theta) \sim 1 + 0.6 \sin \theta$$

where θ is the zenith angle and $J(\theta)$ is the particle intensity per cm^2-sr. The same result was found for sounding rockets launched at the geomagnetic equator [Van Allen & Ganges 1950a] and at $\theta_M = 41^o$ [Ganges, Jenkins, and Van Allen 1949] and was also confirmed by Singer [1950a;b]. Recent albedo observations by *SAMPEX* at ~600 km are also consistent with such a distribution (R.A. Mewaldt, private communication to J.E. Grove).

The effect of this additional intensity at zenith angles near 90^o is to increase the total rate of albedo protons incident upon GLAST by ~50% over that which would be produced from a purely isotropic distribution.

Albedo Electrons

Thus far, all discussion has been limited to proton albedo. However, it is perhaps worth noting that a large intensity of electron albedo will also be present in the GLAST orbit. Figure 5 compares the splash electron and proton albedo measurements at $\theta_M = 41^o$. The albedo electron fluence at ~100-1000 MeV is roughly an order of magnitude larger than the albedo protons in this energy range.

Figure 6 compares splash albedo electrons (as compiled by Verma [1967]), re-entrant albedo electrons [Verma 1967; Barwick et al. 1998], and the primary cosmic-ray electron intensity at solar minimum [Evenson 1995]. To within a factor of two or so, the re-entrant and splash albedo electron are equal. At ~1 GeV, the albedo electron intensity is roughly comparable to the primary cosmic-ray electron intensity.

Only cosmic-ray electrons above ~3 GeV can penetrate to a 28.5^o orbit, and it has been reported that primary cosmic-ray electrons are a negligible concern for GLAST. However, Figure 6 suggests that it may also be important to also assess the potential impact of albedo electrons below 3 GeV.

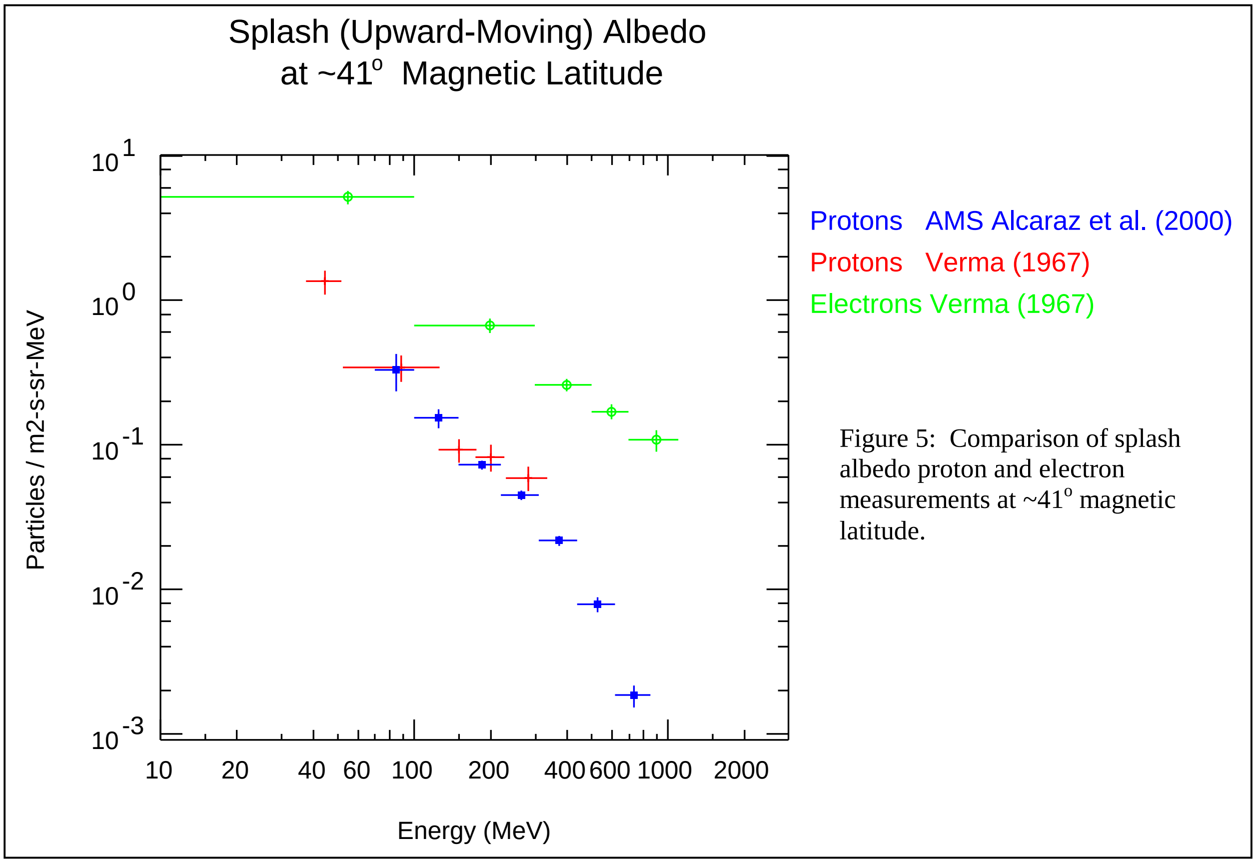

Figure 5: Comparison of splash albedo proton and electron measurements at ~41° magnetic latitude.

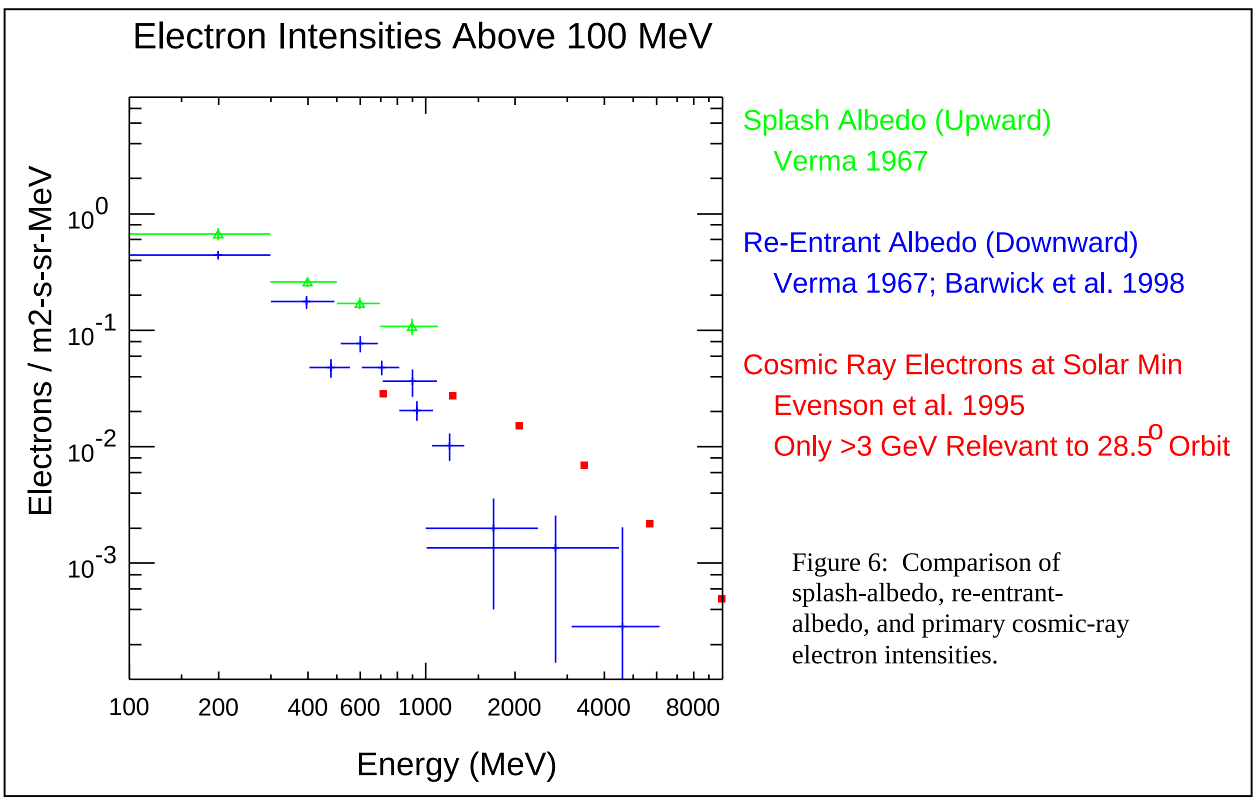

Figure 6: Comparison of splash-albedo, re-entrant-albedo, and primary cosmic-ray electron intensities.

Comparison between AMS Results and Proposed GLASTSIM Proton Albedo

P. Nolan (e-mail message dated 4/25/00) proposed a simple formula for describing the proton albedo above ~70 MeV in the GLAST orbit:

$$\mathbf{F(E,\theta_M) = 1736\, g(\theta_M) \times \{\ 0.015\, exp(-E/w)\ +\ 0.12\, exp(-2E/w)\ \}}$$

where:

- $\mathbf{F(E,\theta_M)}$ is the proton intensity in $(m^2\text{-s-sr-GeV})^{-1}$
- $\mathbf{g(\theta_M)}$ describes the magnetic-latitude dependence, at least at low latitudes, and for $\boldsymbol{\theta_M}$ in radians is given by

$$\mathbf{g(\theta_M) = exp(-h(\theta_M)/0.245)} \quad \text{where } \mathbf{h(\theta_M) = min(\theta_M, 0.38)}$$

- **w = 1.03 GeV.**

This functional form assumes that the spectral shape is the same at all magnetic latitudes.

Figure 7 compares this formula with the AMS splash albedo measurements given by Alcaraz et al [2000]. The panels in Figure 7 illustrate magnetic latitudes which are actually encountered during the nominal 28.5^o x 450 km GLAST orbit. Noted on each panel is an estimate of GLAST's relative dwell time in this magnetic latitude bin.

The normalization and functional form were clearly chosen to give an accurate description in the lowest latitude bin. There are significant discrepancies at higher magnetic latitudes, where GLAST will spend proportionately more time. Below ~200 MeV, the formula generally underestimates the albedo, but these lower energies may be irrelevant for GLAST. However, the overestimate above 200 MeV is large and potentially important. For example, in the bin at $28^o < \theta_M < 34^o$, the proposed formula exceeds the measured >200 MeV albedo fluence by ~85%. A more careful treatment of latitude-dependence spectral shapes appears to be warranted.

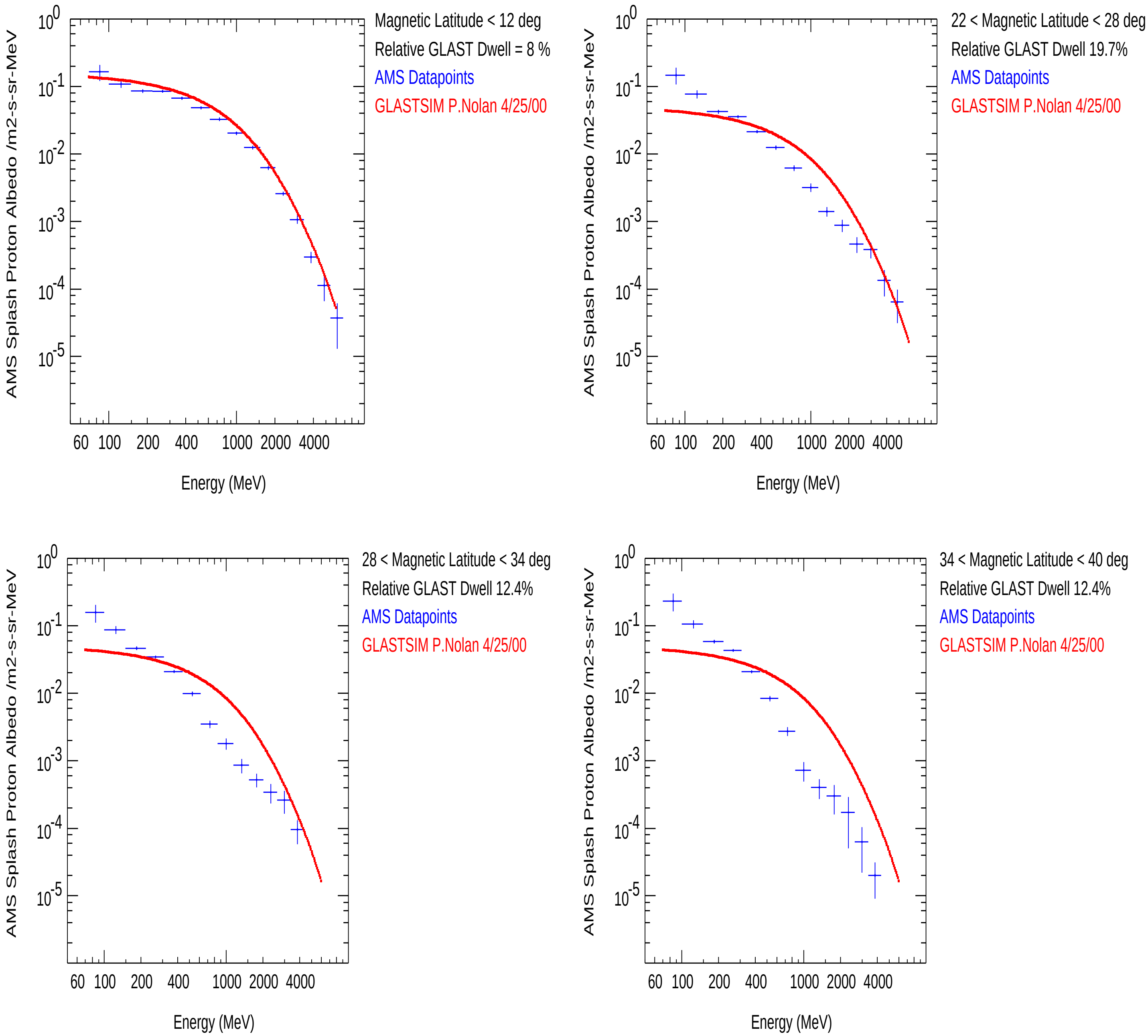

Figure 7: Comparison of AMS splash albedo measurements (blue) and proposed GLASTSIM proton albedo function (red) for four magnetic latitude intervals. Also noted in each panel is an estimate of GLAST's relative dwell time in that latitude interval.

SUMMARY:

The recent AMS proton albedo results are in remarkably good quantitative agreement with balloon measurements from 30-40 years ago. The comprehensive AMS albedo measurements therefore appear to offer a reliable starting point for GLAST background studies, provided that care is taken to extract a reliable parameterization for the AMS data. In addition, the GLAST background studies should also consider the enhanced albedo intensity at zenith angles near 90^0 and the potential contribution of albedo electrons.

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