VOL. 80, NO. 25 JOURNAL OF GEOPHYSICAL RESEARCH SEPTEMBER 1, 1975

Splash Albedo Protons Between 4 and 315 MeV at High and Low Geomagnetic Latitudes

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The differential energy spectrum of splash albedo protons has been measured at high geomagnetic latitude near Fort Churchill, Manitoba, at three periods of the solar cycle in 1966, 1967, and 1969 and at low latitude near Palestine, Texas, in 1967 by using a balloon-borne solid state detector telescope. We observed splash albedo proton fluxes between 4 and 315 MeV of 81 ± 11, 70 ± 11, and 48 ± 8 protons/(m² s sr) at high latitude in 1966, 1967, and 1969 and of 37 ± 9 protons/(m² s sr) at low latitude in 1967. The decreases from 1966 to 1969 are due to solar modulation of the cosmic ray parent nuclei. The albedo spectrum shows a similar shape for both latitudes. The difference in intensity can be explained by different local geomagnetic cutoffs; i.e., a significant contribution to the splash albedo flux arises from primary particles with rigidity below 4.5 GV. The splash albedo flux near Fort Churchill is consistent with corresponding fluxes previously reported near 53°–55°N. The flux below 100 MeV near Palestine is significantly lower than that reported by Verma (1967).

INTRODUCTION

Primary cosmic ray nuclei entering the earth's atmosphere interact with air nuclei and produce secondary particles. Some of these secondaries move upward and emerge from the atmosphere as 'splash albedo.' The charged splash albedo particles with rigidities below the local geomagnetic cutoff cannot escape from the earth. They spiral along magnetic field lines and reenter the atmosphere in the opposite hemisphere. These particles constitute the 'reentrant albedo.' The albedo proton spectrum is related to albedo neutrons which may be a source of protons trapped in the inner radiation belt (see the recent review by *White* [1973]).

No comprehensive measurements of the spectrum of splash albedo protons exist. Most observers quote only flux values over broad energy intervals rather than detailed energy spectra. *McDonald and Webber* [1959] determined the sum of splash plus reentrant proton albedo in the 100- to 350-MeV energy region at geomagnetic latitudes of 4°, 53°, and 55°N without being able to distinguish between the two. Estimates of the reentrant proton albedo [*Ormes and Webber*, 1964; *Bingham et al.*, 1968; *Teegarden*, 1967] and of the splash proton albedo [*McDonald*, 1958; *Hasegawa et al.*, 1965; *Webber*, 1967] are discussed for latitudes mostly about 53°–55°N and energies above 70 MeV. *Ormes and Webber* [1968] observed reentrant albedo protons between 90 and 600 MeV with a Cherenkov scintillation counter telescope near Ely, Minnesota, and Fayetteville, Arkansas. *Verma* [1967] observed the vertical splash and reentrant proton albedo spectra between 37 and 334 MeV near Palestine, Texas, with a ΔE range detector telescope. *Pennypacker et al.* [1973] measured the splash albedo proton spectrum between about 110 and 1200 MeV with a magnetic spectrometer near Palestine. The only calculation of the intensity of albedo protons has been published by *Ray* [1962, 1967]. No previous measurements of splash albedo protons near Fort Churchill have been reported.

As part of a program to study low-energy cosmic ray protons and α particles with a balloon-borne directional ΔE range detector telescope we have measured the differential energy spectrum of splash albedo protons between 4 and 315 MeV. We report the results of measurements near Fort Churchill, Manitoba, in 1966, 1967, and 1969 and near Palestine, Texas, in 1967.

INSTRUMENT

The observations were made with a directional energy loss range solid state detector telescope which is physically similar to one of the California Institute of Technology Ogo 6 detector systems. The balloon-borne and Ogo 6 instruments have previously been described [*Althouse et al.*, 1968; *Wenzel*, 1968, 1970; *Garrard*, 1972]. A cross section of the ΔE range telescope is shown in Figure 1. The energy loss ΔE is measured in each of the solid state detectors D1, D2, and D3 by using 256-channel pulse height analyzers. The range of an incident particle is determined by the number of detectors D4–D7 which are penetrated by the particle. The absorbers A2–A6 are sandwiched between detectors D2–D7. The entire detector-absorber stack is surrounded, except for the entrance and exit apertures, by a plastic scintillator anticoincidence cup D8. D1 is a totally depleted 100-μm-thick surface barrier detector, and D2–D7 are lithium-drifted detectors with depletion depths of ~1000 μm.

The discriminators on range detectors D4–D7 have a low and a high threshold. The discrimination thresholds are set so that the low discriminators will trigger on any charged particle which penetrates the detector, while the high discriminators will trigger only on protons which have an energy of less than ~300 MeV at the top of the detector stack (or on any particle with $Z > 1$). This feature aids in distinguishing electrons, muons, and interacting protons. A second, higher-energy detector system measuring the energy loss of a particle in solid state detectors and its velocity in a Cherenkov radiator was flown in the same instrument, but its results will not be discussed in this paper.

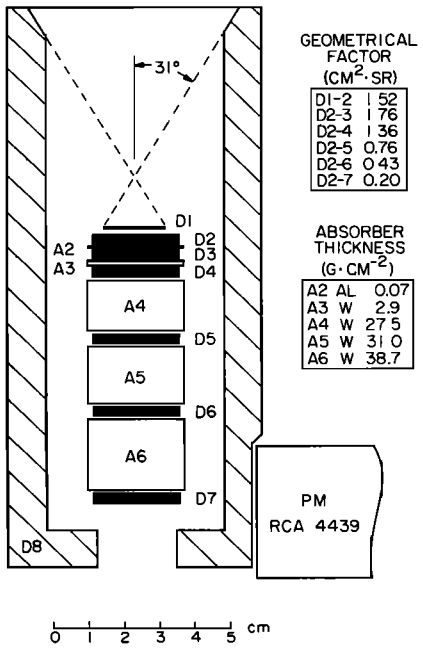

Fig. 1. Schematic cross section of the detector system.

BALLOON FLIGHTS

We report results from four series of balloon flights launched from Fort Churchill, Manitoba, in July 1966, June 1967, and June 1969 and from Palestine, Texas, in April 1967. In all of these flights the same instrument was used, and the detector system was pointed toward the antizenith. A summary of the pertinent flight data is presented in Table 1. The Mount Washington neutron monitor rates (J. A. Lockwood, private communication, 1969) are the averaged hourly values for the time periods when the balloons were at floating altitudes.

DATA ANALYSIS

A valid particle event is described by two pulse heights (either D1 and D2 or D2 and D3), a range parameter, and discriminator parameters. These data are converted into energy spectra by using a telescope response matrix based on proton calibrations obtained at the Space Radiation Effects Laboratory as described in detail by *Garrard* [1972]. The calibrations, which were performed at seven energies from 114 to 569 MeV and at seven angles of incidence, provided accurate estimates of the effects of nuclear interaction processes on the telescope detection efficiency. For example, the observed range was correct for 97 ± 1%, 86 ± 1%, 65 ± 1%, and 52 ± 1% of the protons which should have had nominal R4, R5, R6, or R7 signatures, respectively.

The signatures of the interacting events were also determined. In the case of the nominal R7 events, 25% triggered the anticoincidence D8, and 1, 5, 8, and 9% had range signatures of R3, R4, R5, or R6, respectively. These interacting events, which contribute to the background, were further suppressed in the flight data by requiring that the appropriate high-level discriminators on D3–D7 be triggered and by requiring that the energy losses measured in D2 and D3 be consistent with the observed range. By means of these techniques the average interaction background subtraction was ~15% for the splash albedo flight data.

In order to obtain more spectral information we subdivided the R4 interval, which corresponds to the relatively wide energy interval of 48–157 MeV, into three intervals (R4A, R4B, and R4C) as indicated in Table 2. This subdivision was based on the measured energy loss in D2 and D3, which was ~2.6 MeV in each for 48-MeV protons, decreasing to ~1 MeV for 157-MeV protons.

Details of the data analysis procedure have been described by *Wenzel* [1968, 1970] and *Garrard* [1972].

RESULTS

The proton splash albedo intensity shows no significant variations with altitude above ~50 g/cm². As an example the 4- to 315-MeV proton ascent data of two flights at Palestine, Texas, which were combined in order to obtain better statistical accuracy, are shown in Figure 2, broken into discrete altitude intervals. The absence of intensity variations above 50 g/cm² is as was expected, since the splash albedo flux consists of particles produced in a large thickness of atmosphere below the instrument. We shall therefore assume for all flights that the energy spectrum of the splash albedo observed at float altitudes also represents its spectrum at the top of the atmosphere.

In Table 2 we summarize the results of the splash albedo flights from Fort Churchill in 1966, 1967, and 1969 and from Palestine in 1967. Since the Mount Washington neutron monitor rates (which reflect the parent nuclei intensity) during the two Fort Churchill flights in 1966 were nearly identical, we averaged the results of both flights. Similarly, the two Palestine flights were summed. The total number of protons observed at floating altitude in each range bin is listed. We also present the observed number of protons that penetrated the complete detector-absorber stack ($E > 315$ MeV). Most of these are downward moving primary protons. In the lower part of Table 2 we list the integral proton and alpha flux above 315 MeV/nucleon derived from flights during the same observation periods with the detector system pointing upward. These primary fluxes are a measure of the level of solar modulation of the primary cosmic ray spectrum responsible for the albedo production.

TABLE 1. Balloon Flights

Launch Site	Launch Date	Mount Washington Neutron Monitor Counting Rate	Average Floating Altitude, g/cm²	Floating Time, hours
Fort Churchill	July 3, 1966	2365	2.2	7.5
Fort Churchill	July 26, 1966	2364	2.1	10.5
Palestine	April 8, 1967	2262	4.5	3.0
Palestine	April 17, 1967	2307	4.1	9.7
Fort Churchill	June 25, 1967	2292	1.7	13.8
Fort Churchill	June 25, 1969	2120	3.7	14.2

TABLE 2. Splash Albedo Proton Flux as a Function of Energy for Three Flight Periods in Fort Churchill in 1966, 1967, and 1969 and in Palestine in 1967

		Fort Churchill							
		1966		1967		1969		Palestine, 1967	
Range	Energy at Detector, MeV	No. of Protons	Splash Albedo Proton Flux, protons/m² s sr MeV	No. of Protons	Splash Albedo Proton Flux, protons/m² s sr MeV	No. of Protons	Splash Albedo Proton Flux, protons/m² s sr MeV	No. of Protons	Splash Albedo Proton Flux, protons/m² s sr MeV
R2	3.8–18.5	92	0.76 ± 0.08	68	0.69 ± 0.08	40	0.39 ± 0.06	32	0.34 ± 0.06
R3	18.5–47.5	195	0.69 ± 0.05	128	0.56 ± 0.05	103	0.43 ± 0.04	57	0.26 ± 0.04
R4A	47.5–80	98	0.46 ± 0.05	77	0.45 ± 0.05	54	0.29 ± 0.04	34	0.21 ± 0.04
R4B	80–113	90	0.42 ± 0.06	61	0.36 ± 0.06	61	0.36 ± 0.05	27	0.16 ± 0.04
R4C	113–156.5	76	0.27 ± 0.04	39	0.16 ± 0.04	28	0.09 ± 0.03	28	0.14 ± 0.03
R5	156.5–235	19	0.08 ± 0.02	15	0.08 ± 0.02	10	0.05 ± 0.02	8	0.04 ± 0.02
R6	235–315	4	0.04 ± 0.02	4	0.05 ± 0.02	1	0.01 ± 0.01	3	0.04 ± 0.02
R7	>315	1029		781		598		321	
Primary protons	>315		2562 ± 62		2046 ± 84		1406 ± 48		642 ± 48
Primary alpha particles	>(315 MeV)/n		200 ± 15		202 ± 17		129 ± 11		105 ± 21

The table includes for comparison the integral fluxes of primary protons and alpha particles (in units of particles/m² s sr) above 315 MeV/nucleon for the same flight periods.

We observed splash albedo proton fluxes between 4 and 315 MeV of 81 ± 11, 70 ± 11, and 48 ± 8 protons/(m² s sr) at Fort Churchill for 1966, 1967, and 1969. The flux near Palestine in 1967 was 37 ± 9 protons/(m² s sr).

DISCUSSION

The splash albedo proton spectra measured near Fort Churchill are compared in Figure 3. The shapes of the spectra in all 3 years of observation are very similar. The percentage change in the albedo is compared in Table 3 with changes in other cosmic ray fluxes. As is indicated in this table, the changes in the splash albedo intensity are comparable to changes in the >320-MeV proton fluxes due to solar modulation. Primaries between 0.3 and 2 GeV seem to make significant contributions to the albedo production.

The splash albedo spectra near Fort Churchill, Manitoba, and Palestine, Texas, are compared in Figure 4. The spectra at the two latitudes are very similar in shape. They are essentially flat at low energies (about 10–40 MeV) and can be described by a power law $E^{-\gamma}$ with $\gamma \simeq 2$ above about 100 MeV. There is, however, a difference in intensity at lower energies of about a factor of 2 between the two latitudes. Above ~100 MeV the difference is less obvious. It can be assumed that the splash albedo particles of higher energy are mainly produced by primaries of energies above the cutoff at Palestine (~4.5 GV) and that therefore the albedo intensity would become less latitude dependent toward higher energies. The higher intensity at Fort Churchill indicates that primary cosmic rays below the 4.5-GV cutoff at Palestine contribute significantly to the production of splash albedo protons. A similar conclusion was reached by *Israel* [1969] for splash albedo electrons.

No previous measurements of splash albedo protons at latitudes above ~60° have been reported. But several observations at geomagnetic latitudes of about 53°–55°N exist. Since primaries below a few hundred MeV do not contribute significantly to the albedo production, as can be seen from Table 3, albedo observations at latitudes below a cutoff rigidity of about 1 GV (450-MeV protons) should be essentially latitude independent. Thus observations at geomagnetic latitudes above about 55° should be comparable to our high-latitude data (Figure 5*a*).

Hasegawa et al. [1965] measured the integral splash albedo proton flux in 1959 near Sioux Falls (λ_m = 53.5°N), using emulsions. Their flux of 0.15 ± 0.01 proton/(m² s sr MeV) between 66 and 300 MeV is an upper limit, since their data are not corrected for sideward particles produced in the atmosphere and packing materials during ascent. It is in agreement with our average flux for the 70- to 315-MeV interval

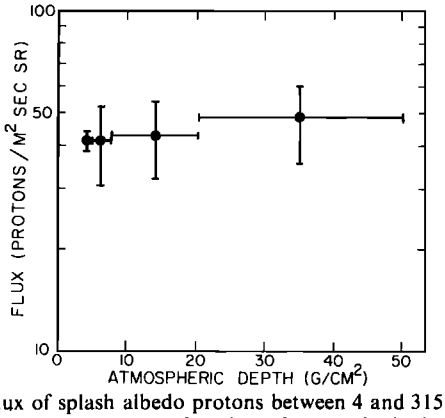

Fig. 2. Flux of splash albedo protons between 4 and 315 MeV near Palestine, Texas, as a function of atmospheric depth.

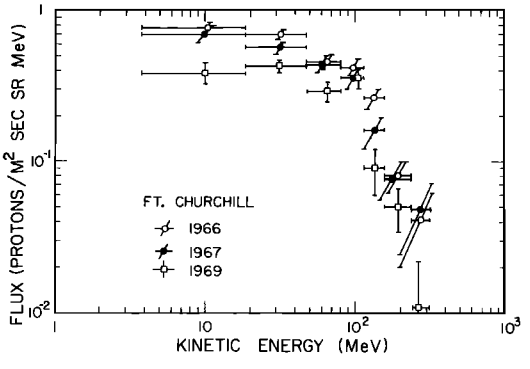

Fig. 3. Differential energy spectra of splash albedo protons near Fort Churchill, Manitoba, in 1966, 1967, and 1969.

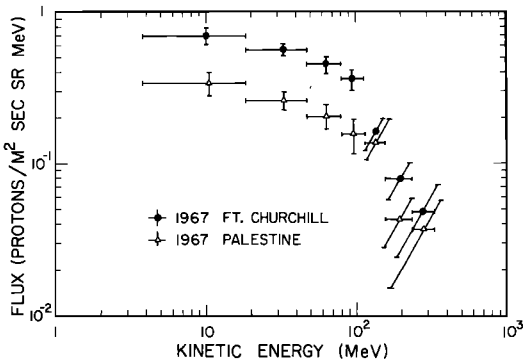

Fig. 4. Differential energy spectra of splash albedo protons near Fort Churchill and Palestine in 1967.

(Figure 5*a*). *Ormes and Webber* [1964] measured the spectrum of splash plus reentrant albedo and the spectrum of reentrant albedo in Minneapolis (cutoff 1.3 GV) in 1963. By subtraction we deduced a splash albedo flux of 0.17 proton/(m² s sr MeV) between 100 and 150 MeV from their data. *Webber* [1967] derived a splash albedo proton spectrum between 80 and 300 MeV at 5-g/cm² atmospheric depth near Minneapolis from measurements of different investigators. Since extrapolation to the top of the atmosphere does not produce any significant change, this spectrum may be compared directly with our spectrum at Fort Churchill. Both spectra agree relatively well, at least below 150 MeV.

In Figure 5*b* we compare our splash albedo spectrum measured near Palestine, Texas, in April 1967 with that of Verma [1967] measured in May 1965 and that of *Pennypacker et al.* [1973] measured in 1970–1971. All spectra agree above about 100 MeV within the experimental errors. Below 100 MeV, however, Verma's spectrum continues to rise, while our spectrum flattens. The 2-year time difference between the two flights cannot be responsible for the discrepancy in the spectral shape. Differences in instrumental resolution and background may be important; the present instrument was specifically designed for high-resolution, low-background measurements below ~45 MeV.

TABLE 3. Comparison of Intensity Changes in the Albedo and Primary Fluxes

Component	Energy	Intensity Changes, %	
		1966–1967	1966–1969
Splash albedo	4–315 MeV	−14	−41
Primary protons	70–320 MeV*	−48	−81
	>320 MeV*	−20	−46
	>2 GeV†	−8	−28

**Garrard* [1972]; see also *Garrard et al.* [1973].
†Based on changes in the Mount Washington neutron monitor rate and the regression curves by *Ormes and Webber* [1968].

CALCULATION OF ALBEDO SPECTRUM

The intensity of secondary protons created in nuclear interactions of primary cosmic ray particles (protons and α particles with air nuclei) and subsequently traveling through the atmosphere gyrating about magnetic field lines and losing energy by ionization in air was calculated by *Ray* [1962, 1967], including the effects of nuclear interactions.

We have made a number of improvements in the approximations and functional relationships used by Ray and have numerically integrated the resulting equation [cf. *Ray*, 1967, equation (4)]. The calculated albedo spectra were, however, a factor of 2 (at $E < 100$ MeV) to 4 ($E > 100$ MeV) higher than the observed spectra. This discrepancy is most likely due to uncertainties in using the Bristol data [*Camerini et al.*, 1950, 1951; *Powell et al.*, 1959] to describe the angular distribution and number of secondary protons produced by a nuclear interaction.

We believe that the measurements present the correct spectrum and that improved calculations of the albedo proton spectrum should be based on a Monte Carlo technique using detailed nuclear cross-section data for protons in air.

Acknowledgments. We thank T. L. Garrard for his assistance, especially during the data analysis. We are very grateful to W. E. Althouse for the design of the electronics and his support during measurements. J. A. Lockwood kindly supplied the Mount Washington neutron monitor data. Most of this work was performed

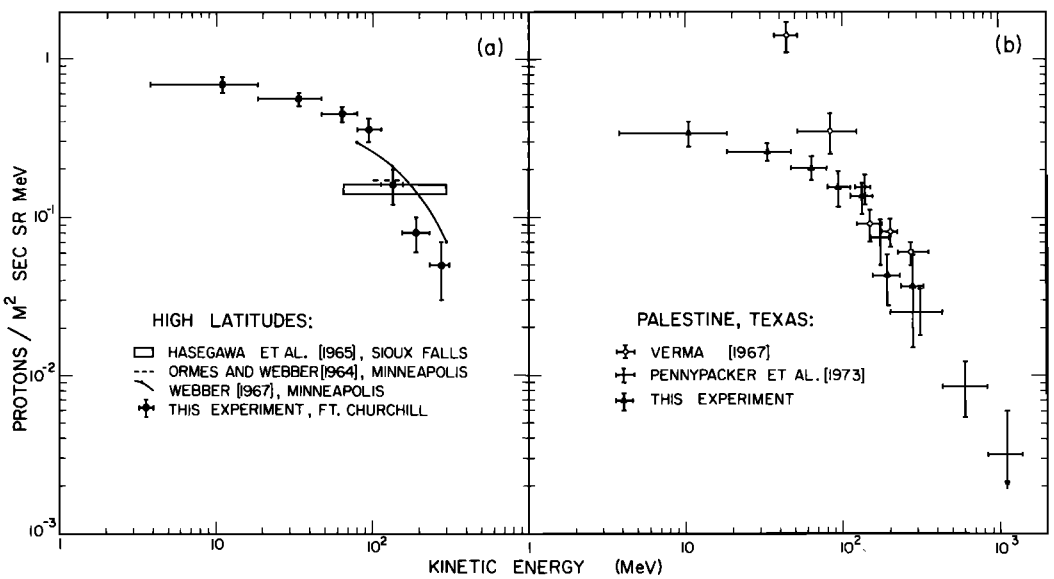

Fig. 5. Differential energy spectra of splash albedo protons (*a*) at high latitudes and (*b*) near Palestine.

during a stay of one of the authors (K.P.W.) at the California Institute of Technology, supported by a NASA International Fellowship. It was completed as part of a Ph.D. thesis at the University of Heidelberg in Germany. This research was supported in part by the National Aeronautics and Space Administration under grant NGR-05-002-160.

The Editor thanks W. R. Webber and R. S. White for their assistance in evaluating this paper.

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(Received October 1, 1974;
revised February 14, 1975;
accepted March 6, 1975.)