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LOG Id: LOG_0113
LOG Titel: Cosmic ray electrons in the atmosphere
LOG Typ: article

Übergeordnetes Werk

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J. Geophys. 40, 751—759, 1974

Cosmic Ray Electrons in the Atmosphere *,**

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Received August 5, 1974

Abstract. We have measured the energy spectrum of atmospheric secondary electrons at various depths in the atmosphere. The results are compared with calculations by Daniel and Stephens (1974) and good agreement between the shapes of calculated and measured spectra are found. The measured intensity of secondary electrons undergoes larger time variations than predicted from the calculations.

Key words: Cosmic Rays — Atmospheric Secondary Electrons.

1. Introduction

In 1936 Pfotzer (1936a, 1936b) published two fundamental papers which for the first time demonstrated the interplay between the primary and the atmospheric secondary components of the cosmic radiation. Using a balloon-borne Geiger-counter telescope Pfotzer was able to show that the intensity of charged particles with near vertical incidence exhibits a broad maximum at around 100 g/cm² of residual atmosphere, and he correctly interpreted this phenomenon as a superposition of an attenuated primary component and the build-up and subsequent attenuation of secondary particles produced in the atmosphere.

Since the time of this early work the nature of both the primary and secondary particles has become well understood. The interaction mechanisms that lead to the variety of secondaries have been investigated in detail and it has become possible to quantitatively describe the build-up and the decay of the various components.

Over the past years we have conducted a series of experiments to investigate the energy spectrum of the primary cosmic ray electron component and its variations with time. This work was carried out with balloon-borne instruments and hence under a layer of 2 to 3 g/cm² of residual atmosphere.

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* Work supported in part by the National Science Foundation under grant GA 41692X.

** To Prof. G. Pfotzer in honor of his 65th birthday.

In order to properly extrapolate to the top of the atmosphere and to arrive at the primary flux one must fully understand the contributions of secondary atmospheric electrons. The accuracy of such extrapolations can be tested experimentally through a study of the secondary electron flux as a function of atmospheric depth from the smallest depths attainable in a balloon flight down to sea level.

The data gathered during the ascent of 18 balloon flights which were carried out over the past seven years from Ft. Churchill, Manitoba, Canada have provided extensive information on the development of the secondary electron component as a function of atmospheric depth. In this paper we wish to present some of this experimental evidence and to compare it with recent calculations of the development of the electron-photon component in the atmosphere (Beuermann, 1971; Daniel and Stephens, 1974).

2. *Experiment*

In 1968 we designed and built an instrument capable of measuring the energy spectrum of electrons from 20 MeV to 20 GeV for the purpose of studying the long term changes of the electron spectrum under the influence of solar modulation. A cross section of this instrument is shown in Fig. 1. We shall not here dwell on the capabilities of this counter telescope but refer the reader to the details which have been published elsewhere (Hovestadt *et al.*, 1970). Suffice it to say that, due to the properties of the gas Cerenkov counter, T2, and the CsI and lead glass shower detectors, T4 and T5, a unique discrimination between electrons and the nuclear as well as meson components is possible over the entire energy range. The instrument however, makes no distinction between positive and negative electrons. The energy resolution is 20% FWHM at 1 GeV and better than 40% FWHM at other energies. The various properties of the instrument have been verified during several accelerator calibrations.

Every summer since 1968 this instrument has been flown on two or three balloon flights launched from Ft. Churchill, Manitoba. Most ascents were made during the night hours when the geomagnetic cut-off at Ft. Churchill drops to 10 MV or less (Jokipii *et al.*, 1967; Hovestadt and Meyer, 1970). The rate of rise of the balloon instruments was less than 5 m/sec allowing the collection of data with good statistics during the ascent.

3. *Results*

The electron component in the atmosphere includes both primaries originating beyond the atmosphere and secondaries created within the atmosphere mainly by the interaction of high energy cosmic ray nuclei with air molecules. The immediate problem is to distinguish between the two components so that they can be investigated separately.

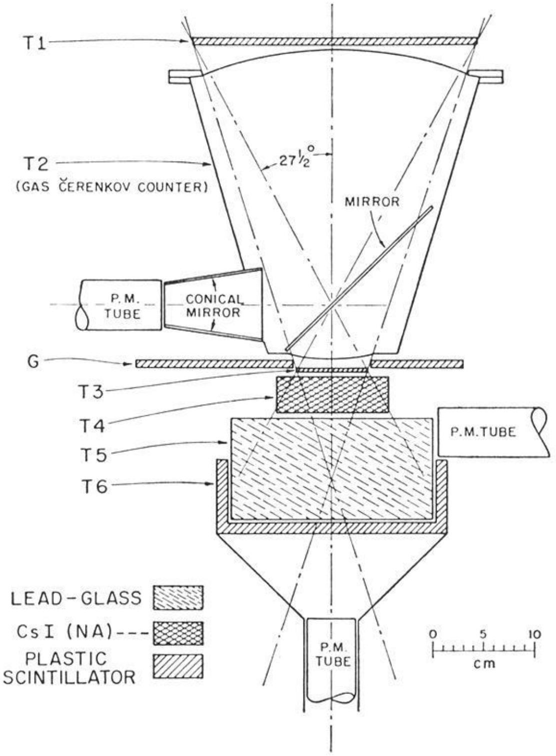

Fig. 1. Schematic cross section of the instrument

In certain cases the observations include only secondary electrons. At large atmospheric depths, past the Pfotzer maximum, the primary component is severely attenuated so that for practical purposes only secondaries are left. Fig. 2 shows examples of this situation at two atmospheric depths. Theoretical calculations of the secondary electron energy spectrum at these two depths from Daniel and Stephens (1974) are included for comparison. (We have added the negatron and positron curves that they give for a geomagnetic latitude corresponding to Ft. Churchill, Manitoba and interpolated as necessary to obtain these curves as well as others used in this paper.) Except for normalization the Daniel and Stephens curves fit our observations rather well.

"Growth curves" of the measured flux versus depth for particular energies also, in special cases, include secondary electrons only. Fig. 3 shows a 1970 growth curve for electrons from 35.6 MeV to 54.0 MeV with three calculated secondary curves superimposed for comparison. This particular measurement was chosen because it extends an earlier comparison by Schmidt (1972) and because the primary electron flux at this energy

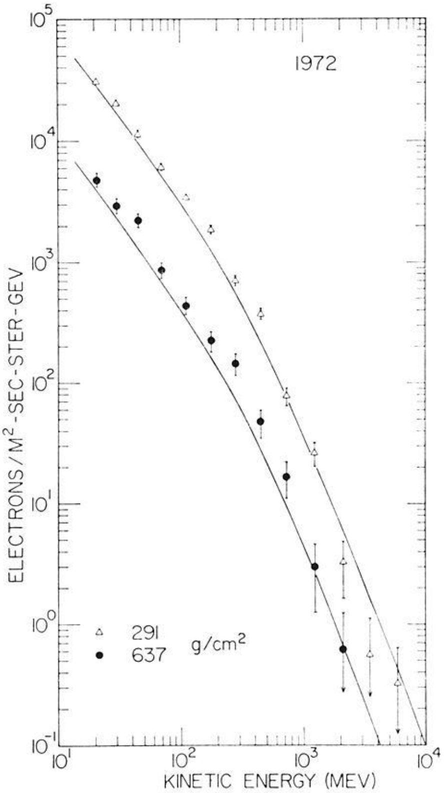

Fig. 2. Electron energy spectra at two large depths in the atmosphere. The data points come from this experiment, flight 72L2, and the curves for the same depths from calculations of Daniel and Stephens (1974)

in 1970 was so small that it could not be observed. All depths have been increased by 4% from the measured values to account for the fact that the average particle arrives at a slight angle to the vertical. As noted by Schmidt (1972), the straight line fits the data below 50 g/cm² considerably better than does the curve calculated by Beuermann (1971) and normalized to the intensity maximum. The best fit is provided by the calculations of Daniel and Stephens (1974) normalized to the data points by a least-squares method. This fit is excellent from the top of the atmosphere down to the Pfotzer maximum, becoming a poorer match at larger depths. In other instances the Daniel and Stephens curves match the data at least as well as in Fig. 3 and often much better at larger depths, and we therefore use them exclusively throughout the following discussion.

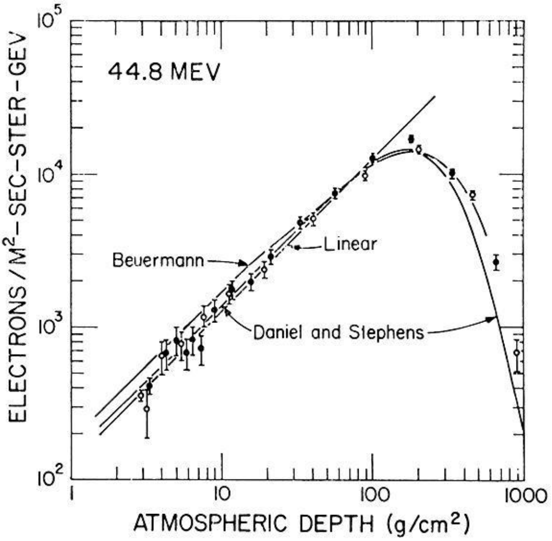

Fig. 3. 1970 growth curve for the energy interval 35.6 MeV to 54.0 MeV. The data points represent measurements from this experiment and the curves are calculated results

Most growth curves include a mixture of primary and secondary electrons whose sum must be fit to the data. The attenuation of primary electrons in the atmosphere is relatively easy to calculate because the energy loss processes are well known. To do this we guess the primary electron spectrum at the top of the atmosphere and propagate downward for each energy bin. The first guess for the primary electron spectrum is then used to separate primaries from secondaries at balloon float altitude and to arrive at a new primary electron spectrum extrapolated to the top of the atmosphere. This new primary spectrum can be run through the computations for a second or third time until a self-consistent primary spectrum is obtained. This usually requires one or two iterations. The propagation of the primaries through the atmosphere is accomplished assuming a continuous slowing down process given empirically by the electron energy loss tables of Berger and Seltzer (1964) with extrapolations beyond 1 GeV. The assumption of a continuous energy loss is valid through approximately the first two radiation lengths of the atmosphere (1 radiation length = 38 g/cm^2), becoming poorer beyond. For each depth, in steps of 1 g/cm^2, we determine the energies that an electron at the top of the atmosphere must have to hit the upper and lower edge of the energy interval under consideration. Then the primary electron flux at the particular depth is the flux at the top of the atmosphere multiplied by the ratio of the energy interval at the top of the

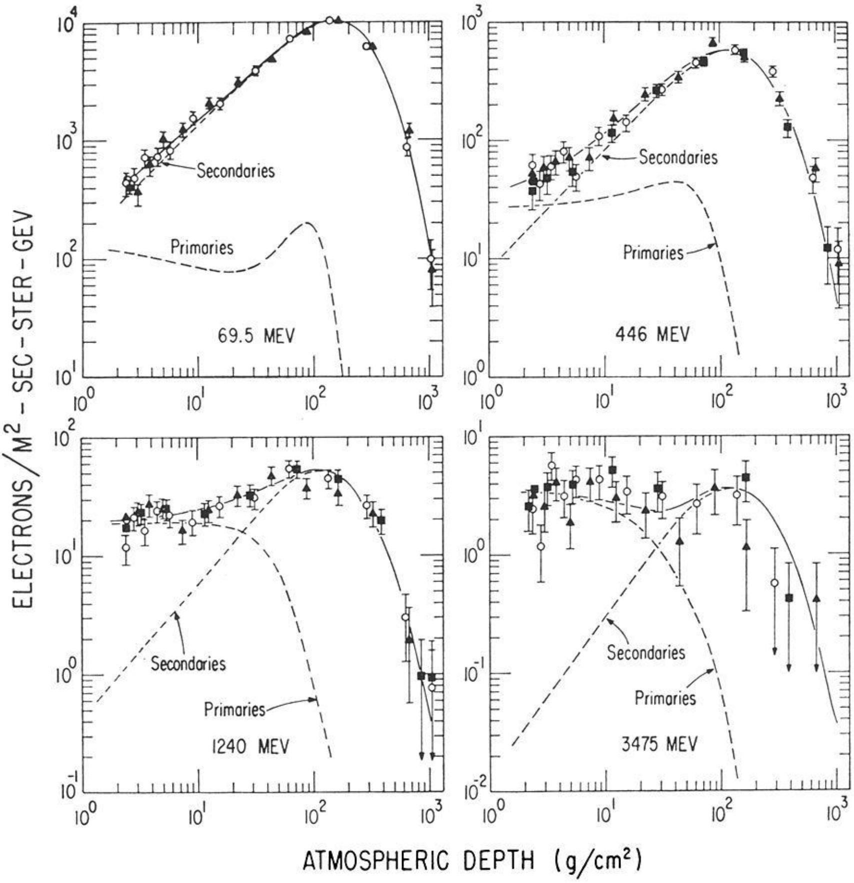

Fig. 4. Electron intensity versus residual atmosphere for four energy intervals in 1972. (These are 54–85 MeV, 340–552 MeV, 910–1570 MeV, and 2650–4300 MeV.) The points come from measurements taken during three ascents, 72L1 (triangles), 72L2 (circles), and 72L3 (squares). The secondary curves come from calculations of Daniel and Stephens (1974) and the primary curves from calculations described in the text. Both curves have been normalized so that their sum (solid line) provides the best fit to the data points

atmosphere to the corresponding energy interval at altitude. At energies where bremsstrahlung is important, the energy interval at the top of the atmosphere increases in percentage terms as fast as the average energy. When the average energy is located in a flat portion of the primary spectrum, this increasing width causes an increase in the flux of primaries with increasing atmospheric depth as shown in the two low energy growth curves of Fig. 4.

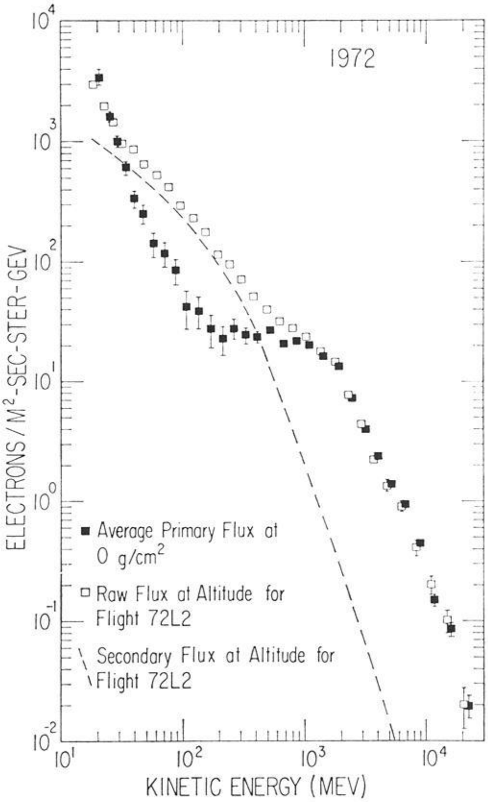

Fig. 5. Open squares show the differential electron energy spectrum from this experiment for flight 72L2 at balloon altitude and the dashed line shows the derived secondary component for the same flight. The solid squares show the primary electron spectrum extrapolated to the top of the atmosphere and averaged over three balloon flights made during the same week

Once the primary attenuation curves have been calculated we use a generalized least-squares computer routine developed by Bevington (1969) to adjust both our primary curves and the Daniel and Stephens secondary curves such that their sum matches the measurements. The need for normalization of the Daniel and Stephens secondaries has been shown in Fig. 2. Such normalization for a given year varies from a few percent to as much as 50% depending on the energy. Furthermore this normalization at a given energy shows as much as a 20% variation over the years considered. These variations are correlated with the counting rate of the Climax neutron monitor. In general we see more of a time variation in the secondary electrons than Daniel and Stephens predict.

Fig. 4 shows several examples of growth curves in 1972 ranging from low energies where the primaries are difficult to extract to high energies where they are much more obvious. The data are well fit by the superposition of the computed primary and secondary fluxes.

The principal interest of our investigations has been the primary electron spectrum. This spectrum is obtained by fitting a smooth curve to the derived secondary spectrum at float altitude and subtracting it from the raw flux points. Extrapolation to the top of the atmosphere is accomplished by correcting for energy losses from bremsstrahlung and ionization. The same electron energy loss tables used to obtain the primary component as a function of depth are used to propagate the average energy and energy interval. Fig. 5 shows the raw flux at float altitude (2.4 g/cm^2) for the same flight in 1972 as used for Fig. 2. In addition the derived secondary spectrum for that flight and the resulting primary spectrum extrapolated to the top of the atmosphere (averaged over three flights) are shown. Details of the changes of the primary electron spectrum from 1968 through 1972 are contained in the thesis of G. Fulks (to be published).

4. Conclusions

Since the pioneering work of Pfotzer the propagation of primary and secondary cosmic ray particles in the atmosphere has become well understood. Separation of primary and secondary electrons can be achieved with a high degree of accuracy. We have compared the measured flux and energy spectrum of secondary electrons with recent calculations of Daniel and Stephens (1974). After normalization we find quite good agreement between the measured and calculated spectra. There are, however, some discrepancies. We observe considerably larger time variations in the flux of secondary electrons than predicted by Daniel and Stephens, and hence have to change the normalization to match with the experimental data. Our observations also suggest that the shape of the growth curves undergoes larger changes over the solar cycle than indicated by Daniel and Stephens.

Acknowledgements. Our thanks go to Messrs. H. Boersma and H. Reisch for their assistance with the operation of the instrument and the execution of the balloon flights. We are grateful to the ONR Skyhook balloon program for providing the large number of successful balloon flights.

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