The Positron Annihilation Line at 511 keV in the Upper Atmosphere

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We present the results of a series of balloon flights made at two latitudes over Aire sur l'Adour, France (4.5 GV), and Sao José dos Campos, Brazil (12.5 GV). We used two types of omnidirectionnal detectors: a 4.5 × 5.1 cm NaI crystal and a 23 cm³ Ge-Li high-energy resolution detector. The two were surrounded by a 0.8-cm thick plastic anticoincidence. These measurements allowed us to determine precisely the characteristics of the 0.511-MeV line versus altitude and latitude. We have also determined from the analysis of the growth curves at the two latitudes an extraterrestrial component value of $(4.3 \pm 1.5) \times 10^{-2}$ photons/cm² s and an upper limit of 4×10^{-3} photons/cm² s for the flux from the galactic center region.

INTRODUCTION

The 511-keV line results from a single well-defined phenomenon, i.e., the annihilation of positive electrons via the two-photon process. As this phenomenon occurs frequently and universally, this line must have the highest detection probability. In addition, the study of line structure, which can lead to information on the physics of the emitting region is now possible with the development of high-resolution solid state detectors. For this reason, such a study is a particularly interesting part of cosmic gamma ray physics.

The presence of this line in atmospheric gamma radiation and the explanation of its origin as annihilation of positive electrons have been known for many years [*Peterson*, 1963; *Rocchia et al.*, 1966; *Chupp et al.*, 1967]. In diffuse extraterrestrial or point source gamma radiation this line has been predicted, but to date, experimental data, including upper limits, are very limited: *Metzger et al.* [1964], *Ling et al.* [1977], and *Trombka et al.* [1973] for diffuse background; and *Haymes et al.* [1975c, *Johnson and Haymes* [1973], *Leventhal et al* [1978], and *Albernhe et al.* [1978] for the region of the galactic center.

Because of its theoretical implications, the determination of a 511-keV photon flux is very important in the diffuse background and possibly from specific celestial objects. An accurate measurement of the atmospheric flux is the first step in finding the cosmic flux in a balloon or even a low-orbit satellite experiment; however, in spite of the fact that many measurements have been made, and apparently due to differing experimental conditions (resolution, β^+ radiation interference produced within the experiment, differences in detector designs), there is rather substantial disparity in the results.

INSTRUMENTATION AND FLIGHTS

For the present study, flights at two different latitudes with different types of detectors were made: a traditional combination of sodium iodide scintillator and photomultiplier, and a high-energy resolution system with a germanium-lithium detector. Both detectors were omnidirectional.

The NaI detector used a 4.5 × 5.1 cm crystal, which, along with its associated photomultiplier, was surrounded by a 0.8-cm thick, 20-cm long anticoincidence plastic scintillator used to eliminate the charged particle contribution. Information was coded into 128 channels in two energy ranges: 0.4–0.8 and 1–10 MeV. The energy range 0.4–0.8 MeV was specially designed to cover the 511-keV line.

The system was calibrated on the ground using calibrated radioactive sources; the in-flight resolution was about 8% at 511 keV (Figure 1). The flux in the peak was found by subtraction of the background, which had been calculated by curve fitting, using parts of the spectrum located above and below the peak.

The high-resolution experiment was composed of a 25-cm³ germanium-lithium detector surrounded by a 0.8-cm thick plastic scintillator placed in anticoincidence. The associated electronics included a 4096-channel pulse height analyzer with a channel width of 2 keV. Continuous calibration was performed during the flight using an Yttrium 88 source giving two lines at 898 and 1836 keV; this permanent, very accurate energy calibration allowed compensation for possible drifts in the system. The results were analyzed at 10-min intervals during which no appreciable drift disturbing the resolution of the system was observed.

With these detectors we performed a series of flights at two different latitudes: (1) at Aire sur l'Adour, France (cut-off rigidity 4.5 GV), one flight with the NaI detector in April 1972 and one with the high-resolution detector in November 1973 and (2) at Sao José dos Campos, Brazil (cut-off rigidity 12.5 GV), three flights in February 1973 with the NaI detector.

The position of Sao José dos Campos (23°S geographical latitude) is very favorable to a study of the region of the galactic center, which crosses the sky near the zenith. The Brazil flights were carried out so as to have the ceiling altitude reached at times either as near as possible the passage of the galactic center region at the zenith or as far as possible from this passage. Thus it may be possible to determine by comparison the contribution from the galactic center region.

All the flights, the two in France and the three in Brazil, operated correctly after reaching ceiling altitudes between 3.2 and 4 mbar. Because of the good resolution and the number of these experiments, we were able to define the 511-keV photon flux as a function of the altitude for both latitudes.

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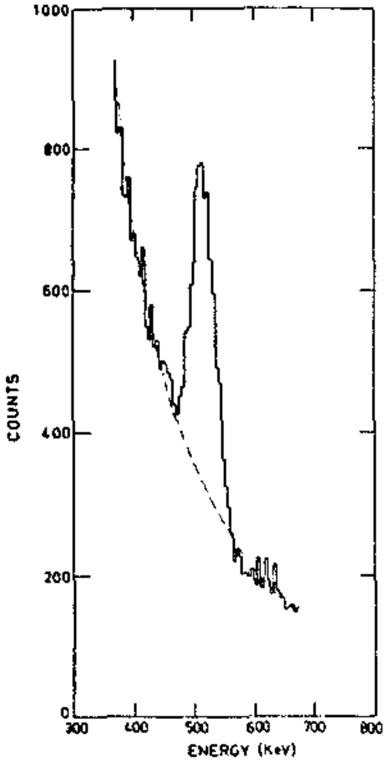

Fig. 1. Ninety-minute spectrum at ceiling at 10°S. The overprint curve is used to calculate the flux in the peak.

RESULTS

The growth curves of the 511-keV line for both latitudes are given in Figure 2. It can be noted on these curves that, as for the gamma ray continuum at similar energies, the Pfotzer maximum is located deeper in the atmosphere at low latitude (120 mbar at 10°S) than at mid-latitude (90 mbar at 45°N); furthermore, this maximum is much flatter at low latitude. The attenuation lengths below the Pfotzer maximum are 190 cm^2/g at 4.5-GV geomagnetic cut-off and 215 cm^2/g at 12.5 GV, respectively. These values are near those found by other authors: 190 cm^2/g at 16.9 GV [*Kasturirangan et al.*, 1972] and 170 cm^2/g at 4.5 GV [*Rocchia et al.*, 1965].

The fluxes measured at 4 mbar in our case 0.118 ± 0.0025 photons/cm^2 at 45°N and 0.075 ± 0.002 photons/cm^2 s at 10°S. In Figure 3 these values are plotted with the measurements obtained by other experimenters at different latitudes. To facilitate comparison they are normalized to a pressure of 4 mbar using our growth curves. For this comparison we have used the recent experiments of the same type as ours, i.e., made with an omnidirectional detector surrounded by a plastic scintillator anticoincidence; in addition, we have included the measurement at 27°N [*Nagakawa et al.*, 1971], which is the only one made at an intermediate latitude and whose energy resolution is very good. The straight line drawn on this figure was plotted by the maximum likelihood method with the set of points. The graph shows that the agreement between these different measurements is quite good, with the exception of those of *Chupp et al.* [1970], which is much higher.

The much greater values found during other experiments may be explained by experimental conditions: poor resolution bringing about a high error factor during evaluation of the peak, and especially creation of β^+ particles near the detector, mainly in the case of directional detectors with heavy collimation systems. In our case it seems that the local production may be of little significance because of the light weight of the NaI detector gondola (21 kg). In addition, we find results in perfect agreement for the two detectors (Ge(Li) and NaI), although the detectors and their environment are quite different.

The fluxes measured at Pfotzer maximum (0.36 ± 0.03 photons/cm^2 s at 45°N and 0.25 ± 0.02 photons/cm^2 s at 10°S) and at ceiling determine the general shape of the growth curve in the upper part of the atmosphere. To characterize this, we calculated the ratio (Pfotzer maximum flux)/(ceiling flux). We find ratios of 3.15 and 3.33, respectively, in good agreement with the value of 3.03 for the same ratio measured by *Kasturirangan et al.* [1972] at low latitude (7.6°N). We have compared these values with the results of the semi-empirical model developed by *Ling* [1974] for the continuum and for the 511-keV line [*Ling et al.*, 1977]. This model gives a (Pfotzer maximum flux)/(ceiling flux) ratio of 9 for the 511-keV line, which is much greater than what we find. This difference seems to stem from the points between 25 and 600 g/cm^2 [*Boclet et al.*, 1963] used in this mode and which give significantly higher flux values than those we have measured.

We have made the same comparison for the gamma ray continuum which is mainly responsible for the creation of 511-keV photons via the pair production process. Due to the spectral shape of atmospheric gamma rays and to the energy dependence of the cross section for pair production, photons contributing to this production are essentially those with energies between 1.5 and 10 MeV. We find for this energy band a (Pfotzer maximum flux)/(ceiling flux) ratio of 3.65 using the data from the semi-empirical model [*Ling*, 1974]. This value is in agreement with our value for 511-keV photon flux and with those found during previous experiments: 2.5, 3.4, and 2.6 for gamma rays between 0.7 and 4.5 MeV for 10°N, 46°N, and 62°N, and 3.15 for gamma rays between 0.9 and 18 MeV at 10°N [*Martin et al.*, 1971, 1975]. It therefore seems that if the 511-keV atmospheric photons are indeed mainly due to the disintegration of e^+ created via pair production by gamma continuum photons, the ratio (Pfotzer maximum flux)/(4-mbar flux) given by *Ling et al.* [1977] may be too high, and consequently, the growth curve of 511-keV photons between Pfotzer maximum and ceiling seems too steep.

Another comparison may be made with neutron fluxes which are responsible for part of the 511-keV photon flux by nuclear reaction and β^+ emissions. We have found [*Martin et al.*, 1971] for the same ratio 3.8, 2.8, and 2.44 for latitudes of 10°N, 46°N, and 62°N. These values are also in agreement with our results for the 511-keV photons.

Owing to its good energy resolution, the measurement with the germanium detector has also allowed a determination of the characteristics of the 511-keV line. The measured energy defined from the two lines at 898.2 and 1836.2 keV from the in-flight calibration source of Yttrium 88 is 510.3 ± 1 keV. This value therefore corresponds very well to the annihilation energy of the positive electron: 511.00 keV [*Lederer et al.*, 1967]. We did not observe broadening of the 511-keV line, but the resolution of our detector and the channel width used for coding enable us to give only an upper limit of 2 keV for the width of this line.

The terrestrial albedo is determined from extrapolation of the growth curves given in Figure 4 above the Pfotzer maximum. The extrapolated values we found are (1.07 ± 0.1) × 10^{-1} photons/cm^2/s. at 10°S and (1.56 ± 0.15) × 10^{-1} pho-

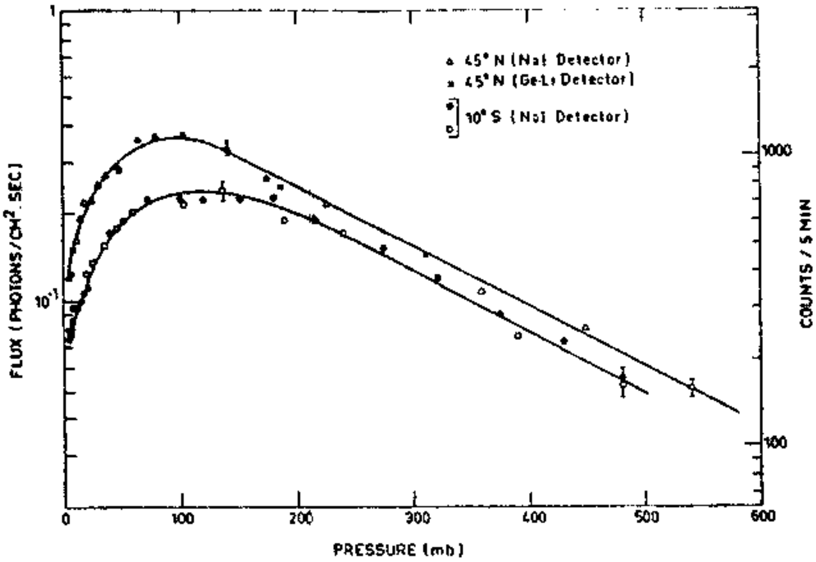

Fig. 2. Growth curves for 511-keV photons for the latitudes 10°S and 45°N. The points obtained with the Ge(Li) detector at 45°N have been multiplied by a factor corresponding to the ratio of the effective area of the two detectors (respectively, 10.5 and 2.1 cm² for the NaI and Ge(Li) detectors). The points for the third flight at low latitude, in good agreement with those of the other flights, are not shown for reasons of clarity in the figure, but they appear in Figure 4 between 4 and 70 mbar.

tons/cm² s at 45°N. This was done without subtracting the extraterrestrial contribution. These values, along with others which are comparable, are plotted against geomagnetic latitude in Figure 5. We have also plotted on this figure the values we obtained after subtraction of the extraterrestrial component as deduced from our measurements. All these values were obtained by very different methods: either using balloons with omnidirectional detectors (our values and those at the equator by *Kasturirangan et al.* [1972] or by satellite, with an omnidirectional detector [*Mazets et al.*, 1975] which therefore simultaneously measures the extraterrestrial component and the albedo, or with a passive collimator detector [*Nakano et al.*, 1974] for which the extraterrestrial component is much smaller. A rather good agreement can be noted between these values in spite of the different techniques used and although the extraterrestrial component, which remains high particularly at low latitude, is taken into account in different ways.

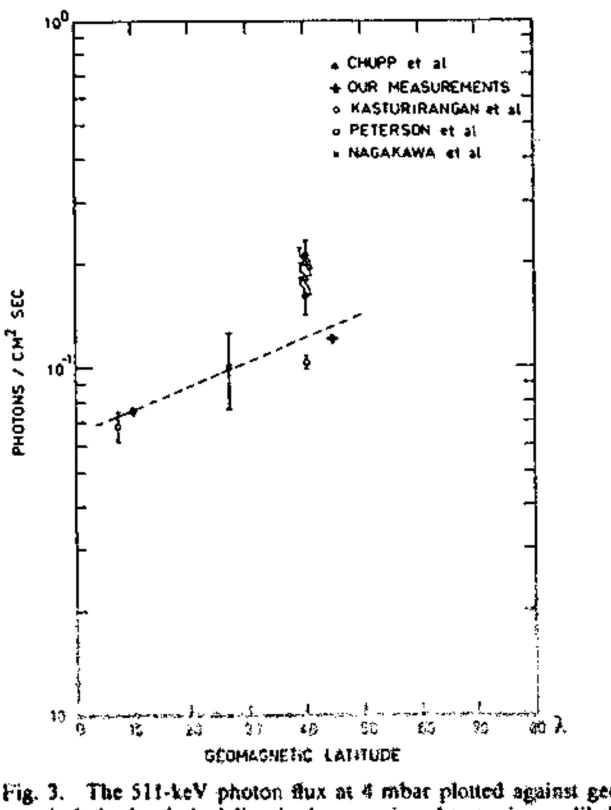

Fig. 3. The 511-keV photon flux at 4 mbar plotted against geomagnetic latitude; dashed line is drawn using the maximum likelihood method with different measurements.

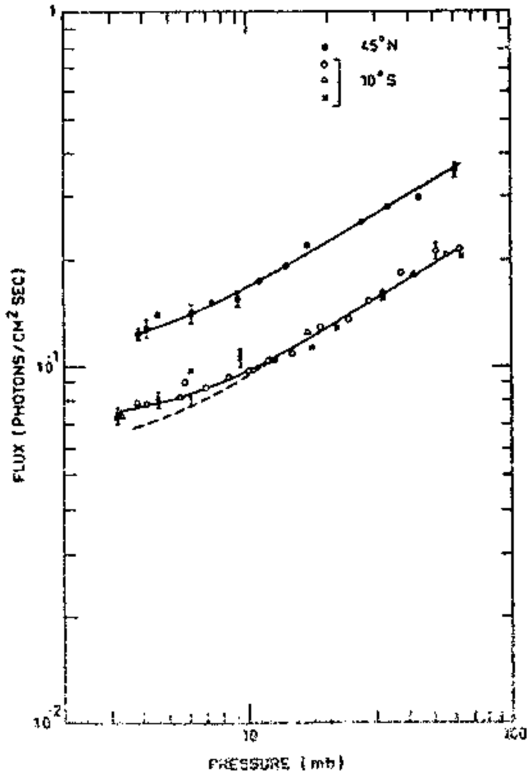

Fig. 4. Intensity of 511-keV line plotted against atmospheric depth between ceiling and 70 g/cm² for the two latitudes with the NaI detector. The dashed curve represents the atmospheric flux extimated at 10°S.

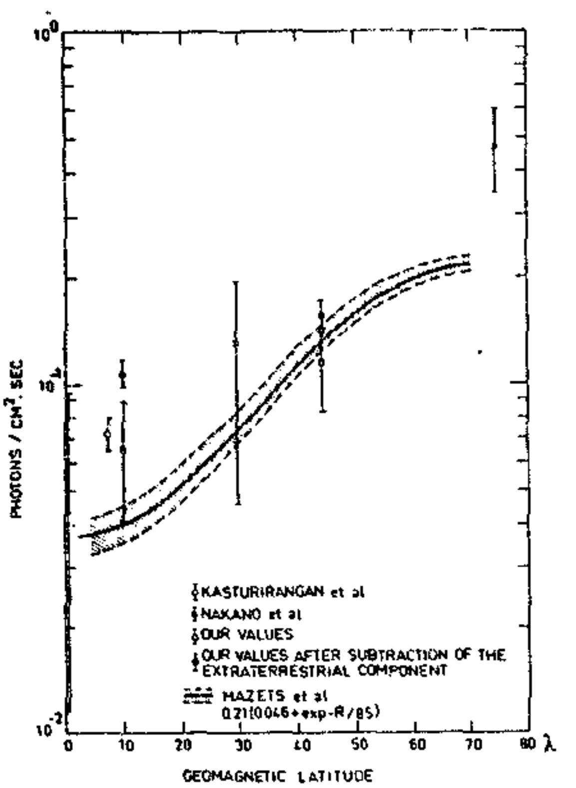

Fig. 5. The 511-keV terrestrial albedo values plotted against geomagnetic latitude. Our values are deduced from the growth curves and are presented with and without subtraction of the extraterrestrial component.

The evaluation of the extraterrestrial contribution can be made by analyzing the growth curves (Figure 4). Between 70 and 15 g/cm² these are linear and parallel, then curve in and rise less sharply for low-latitude observations than for mid-latitude observations. This can be attributed in part to the effect of an extraterrestrial component, which is proportionally greater at low latitude and will therefore have a stronger influence.

This flattening at low latitude does not seem to be attributable to an excess in local production due to neutrons; indeed, their flux with respect to that of the gamma photons is about twice as low at low latitudes as at mid-latitudes [*Vedrenne et al.*, 1971]. In addition, the ratios of neutron fluxes (Pfotzer maximum/4 mbar) of 3.8 at 10°N and 2.8 at 45°N. can only emphasize the flattening of the rise curve at mid-latitude and not at low latitude.

In order to evaluate this excess we have assumed that at mid-latitude (45°N) the contribution of the extraterrestrial component is small and, within the margins of uncertainty, does not modify the growth curve; in addition, since the growth curves in the purely atmospheric radiation zone between 15 and 70 g/cm² are identical for both latitudes, we have accepted that this is still true for pressures below 15 g/cm², for the atmospheric component. We have therefore taken a curve parallel to the mid-latitude rise curve as a low-latitude atmospheric reference.

With this hypothesis, i.e., that the atmospheric 511-keV photon fluxes have the same altitude dependence at different latitudes, we find for the extraterrestrial component a value of $(4.3 \pm 1.5) \times 10^{-2}$ photons/cm² s after correction for atmospheric absorption. It can be seen that this flux is low enough to affect only slightly the growth curve at 45°N and enters within the error limits of the points of this curve, which justifies the hypothesis to define the atmospheric component dependence versus pressure by using the growth curve at mid-latitude.

The cosmic 511-keV photon flux values which were already determined are an upper limit of 1.4×10^{-2} photons/cm² s by *Metzger* [1964] aboard the Ranger 3 satellite, an upper limit of $(2.4_{-3.5}^{+5.8}) \times 10^{-2}$ photons/cm² s by *Ling et al* [1977], and a value of $(3 \pm 1.5) \times 10^{-2}$ photons/cm² s aboard Apollo 15. [*Trombka et al.*, 1973]. Our measurement confirm this last value.

The three flights made in Brazil allowed observations to be made on and away from the galactic center. These observations were compared for two 90-min periods, one centered on $\alpha = 19$ hours (the galactic center being near zenith) and the other centered on $\alpha = 24$ hours (the declination remaining near 23°). After correction for the difference in altitude of the two measurements, we have detected no significant flux variation, and we can only give an 1σ upper limit to the flux from the galactic center region of 4.5×10^{-3} photons/cm² s to be compared with the different measurements already known: $(1.8 \pm 0.5) \times 10^{-3}$ and $(8.0 \pm 2.3) \times 10^{-4}$ photons/cm² s [*Johnson and Haymes*, 1973; *Haymes et al.*, 1975] $(1.21 \pm 0.22) \times 10^{-3}$ photons/cm² s [*Leventhal et al.*, 1978], and the upper limit of 2.3×10^{-3} photons/cm² s [*Albernhe et al.*, 1978]. These last two measurements were made with high-resolution detectors. If this flux is coming from a nonextended source in the direction of the Galactic Center, there is good agreement with these different measurements. If this flux is emitted by a line source along the galactic disc, our upper limit (restricted by the atmosphere to an opening angle of 120°) becomes 2.3×10^{-3} photons/cm² s rad. This is still compatible with the other measurements even assuming that the emission extends up to ±60° around the galactic center direction, i.e., similar to that reported by *Fichtel* [1977] at higher energies.

CONCLUSION

Despite the relatively large flux, measurements of the extraterrestrial annihilation line are difficult due to the need to separate it from the background sources of 511-keV photons, both atmospheric radiation and local contribution created around the detector. In our experiment, local production of 511-keV photons was minimized by choosing a light detector, and the altitude and latitude dependence of the atmospheric component was used to determine the cosmic 511-keV line. The flux which we found is $(4.3 \pm 1.5) \times 10^{-2}$ photons/cm² s, in agreement with Apollo 15 results [*Trombka et al.*, 1973]. In this last case the atmospheric or lunar components were negligible and the measurement of the flux created by local interaction thanks to successive measurements made at different distances from the spacecraft, was used to find the cosmic annihilation line. Moreover, measurements with and without the galactic center region above our detector were used to find an upper limit of 4×10^{-3} photons/cm² s for this region.

The methods chosen for these measurements are complex (balloon flights at several latitudes, measurements far from the earth with a detector at the end of an extensible boom), and they give only fluxes integrated over the whole sky. In the future it therefore seems that the most favorable method of studying the diffuse 511-keV line may be to use a detector collimated by a large active anticoincidence system and to subtract all the background contribution by occulting the field of view, without varying the amount of matter in front of the detector. For this, a more elaborate system than the blocking crystal must be used.

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