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Mev and Sub-MeV Ion Flux Distributions at 1 AU

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Abstract

MeV and sub-MeV ions (mainly protons) belong to the most variable populations in the inner heliosphere. Distinct events can not be easily defined for low-flux periods, when ‘backgrounds’ of various origin may cover genuine fluctuations. Effects of instrumental noise and particle misidentification and of Poissonian statistics may distort the low-flux side. The fluence distribution of high-flux 'events' appears to be reasonably well approximated by a log-normal model, at least at relatively high energies, while the probability of high daily and hourly mean fluxes decreases faster than predicted by that model. Mainly IMP-8 data are used for the characterization of flux distributions at low and high solar activity periods of the last three solar cycles.

1 Introduction

Energetic particles in local interplanetary space represent a mixture of populations accelerated at the Sun, in various regions of the inner and outer heliosphere, and also contain some decelerated particles originated in galactic sources. Particles accelerated by direct or indirect magnetospheric effects are often also not easily separated from the above components. Ion intensities in the MeV and sub-MeV energy range are very widely distributed, covering about 7 orders of magnitude in flux level. Very low-flux and very high-flux periods are of relevance not only to solar-heliospheric physics, but also to magnetospheric research, providing a relatively 'clean environment' on the low-flux side and exerting substantial influence on magnetospheric and aeronomical processes on the high side. Long-term expectations for high-fluence events and their possible terrestrial effects will be discussed in a separate ICRC contribution (P. Király and A.W. Wolfendale, SH 1.4.26).

The solar-heliospheric environment of Earth either directly or indirectly controls most of the magnetospheric processes, including the formation and decay of energetic particle populations. The relative importance of the various controlling agents and mechanisms is still poorly understood. Magnetospheric energization processes driven by bulk solar wind and interplanetary magnetic field effects are now considered tmore relevant to the key magnetospheric energetic particle populations than the direct access of energetic interplanetary particles, although the latter dominate in certain regions, at particular times, and at high energies.

Interplanetary particle populations extend from sub-keV or keV energies (the convected thermal component of the solar wind) through suprathermal and energetic solar-heliospheric particles to galactic and extragalactic cosmic rays. Quiet periods with low and slowly varying fluxes become shorter and shorter as the energy decreases. At energies above about 10 MeV (the spectral minimum of quiet-time protons under solar minimum conditions) the duration of ‘events’ with enhanced fluxes become shorter and shorter.

The variability of interplanetary fluxes is partly due to reasonably well-known causes, such as coronal mass ejections (CMEs), corotating interaction regions (CIRs), travelling shocks, solar flares, changes of magnetic topology, and can be analysed through case studies of major events, while a probabilistic description is more appropriate for less distinctive events and longer time periods. Both very low and very high flux levels are distorted to some extent by limitations of the detecting techniques. At low flux levels background and small-number statistics, at high levels pile-up and saturation bias the measured results.

High-flux stratospheric and ground-level events, caused by interplanetary flux enhancements extending to energies of several tens or hundreds of MeV, or even into the GeV region, are of particular importance for terrestrial effects.

2 Low-Flux Periods

At 1 AU, anomalous and galactic contributions are predicted to be very low for proton fluxes at 1 MeV and below: at least one order of magnitude lower than the lowest flux values measured so far (for results of recent model calculations, see e.g. Müller-Mellin et al.. (1997). The spectrum is also found to decrease with increasing energy, instead of increasing, as would be expected for a modulated CR or AC component. Also, measured fluxes show positive correlation with solar activity, contrary to the demodulated components. The observed quiet-time protons must then either be accelerated at the Sun or in interplanetary space. Mason et al. (1979) claimed that quiet-time flux levels were too variable to be interpreted in terms of an always-present "background" population of protons, in a sense similar to the CR "background" observed at higher energies. That claim, however, was not universally accepted, and the fluctuation and streaming characteristics at quiet times are still in doubt. Although much has been learnt since, a consensus has not yet been reached.

2.1 Variation with the phase of the solar cycle

When measured by low-background detectors, MeV proton fluxes positively correlate with solar activity as measured e.g. by the sunspot number. The variability of fluxes and the correlation persist over the whole solar cycle. The lower envelope of flux values, however, becomes considerably lower and less variable for 3 to 4 years around solar minima, when quiet periods become longer and more frequent. The envelope can be constructed e.g. by taking the minimum daily mean flux for each Bartels rotation (I_{min} as plotted in Zeldovich et al. (1995) for 1-2 MeV proton fluxes. Those flux minima at solar maximum periods are higher by factors of 20 to 30 than at solar minima; the transition to solar minimum values and back occurs rather abruptly. Similarly, the position of quiet-time spectral minimum energies separating predominantly solar-interplanetary and CR protons changes from about 7 MeV (at solar minima) to more than 20 MeV in more active phases.levels in a year). The change-over is again rather abrupt {Zeldovich et al. 1995).

The number and duration of low-flux periods in each year also provides a good characterization of variation with the solar cycle. We take daily means of 1-2 MeV proton (or, more precisely, ion) fluxes as measured by the Charged Particle Measurement Experiment (CPME) telescope of the Johns Hopkins University Applied Physics Laboratory aboard IMP-8. Consecutive (or quasi-consecutive, as defined more precisely in the caption of Table 1) low-flux periods were those below the limiting flux value of 10^{-2} fdu for at least 5 days, where fdu (flux density unit) is 1 $(cm^2 \text{ s sr MeV})^{-1}$. Table 1, besides showing the marked dependence of the occurrence frequencies of such periods on the phase of the solar cycle, can be directly used for selecting low-flux periods. It is conspicuous that, with our criteria, no low-flux periods have been found outside the most quiet years of the solar cycle.

One difficulty in giving uniform criteria for the selection of low-flux periods on a long time scale is the deterioration of the performance of most low-energy detectors aboard the IMP-8 spacecraft. The measurement of quiet-time fluxes is particularly affected by the increased background due to the failure of anticoincidence cups. Thus the comparison of quiet-time MeV fluxes at widely spaced time periods (e.g. for different solar minima) requires careful consideration. Although the anticoincidence cup of CPME broke down in 1989, the selected limiting flux level of 10^{-2} fdu was above the background noise throughout the whole period of almost 24 years. The increased noise due to galactic cosmic rays, however, prevented a detailed comparison of the lowest fluxes measured during the 1996 minimum with those measured during the 1976 and 1986 minima, when fluxes were often below 10^{-3} fdu.

Criteria for selecting low-flux or quiet-time periods are always arbitrary to some extent. Selections made for different instruments and energies result in somewhat different periods. One has also to keep in mind that data supplied by instruments with small geometric factors have excessive Poissonian noise at low fluxes, thus the lowest 'empirical fluxes' are affected by downward fluctuations. Among the IMP-8 instruments, CPME has the largest geometrical factor in the MeV energy range (1.61 cm^2 st), thus Poissonian noise effects are small below 2 MeV.

TABLE 1. Low-flux periods of 1-2 MeV protons as measured by IMP-8 CPME. All those periods have been included (between day 1 of 1974 and day 266 of 1997), for which the daily mean flux was less than 10^{-2} $(cm^2\ s\ sr\ MeV)^{-1}$ for at least 5 consecutive days. Longer runs interrupted by not more than two consecutive days of higher fluxes have also been included, whenever the number of days with higher fluxes was less than 20% of the total length. Periods of 15 days or longer are emphasized.

Year	Low-flux periods of IMP-8 CPME 1-2 MeV protons (D.o.Y.)
1974	36-40
1975	25-29, 89-97, 118-126, 130-135, **143-161**, 197-205, **243-259**, 271-279, 354-358
1976	5-11, **139-154**, 164-168, 189-201, **214-233**, 240-245, 284-288, 310-314, 319-324
1977	**45-63**, 73-81, 99-106, 113-118, **125-143**
1985	46-50, 55-61, 77-87, 142-150, 163-175, **242-256**, 269-275, 298-304, 321-328
1986	71-75, **80-99**, 110-122, 139-151, 164-177, 198-205, **213-231**, **244-265**, **271-285**, 316-324, 329-340, **348-364**
1987	**7-19**, **26-79**, 83-94, 112-120, 129-139, 164-176, 190-201, 221-226, 356-360
1988	59-63, 72-81
1995	317-326, 350-356
1996	**3-18**, **29-52**, **59-108**, **115-133**, **157-171**, 180-190, **205-220**, 233-238, 295-306, 319-328, 350-355
1997	10-19, 23-27, 31-37, **64-87**, 116-129, 150-159, 163-173, 197-203

3 Flux Distributions

In a first approximation, the set of daily or hourly mean fluxes in an extended period can be thought of as random samples taken from a probability distribution. It is important to keep in mind that the samples are statistically not independent (particularly not for the hourly data), as nearby elements of the time series are correlated. This, however, only influences error bars, not the mean shape. Other factors, like background at small and saturation or pile-up at high fluxes may seriously distort the shape itself, though.

Because of the huge flux range, it is usually convenient either to represent fluxes in logarithmic scales or to study the distribution of the 'log-flux'. An obvious first choice is then the log-normal distribution, or equivalently, a Gaussian for the 'log-flux'. Such a distribution was primarily proposed for the high-flux side, and is used for radiation risk assessment in space (see e.g. in Feynman et al. 1993). As far as we know, no real attempt has been made so far for a close examination of the low-flux part of the distribution.

There are differences between flux distributions at solar minima and maxima, and the shape of distributions also changes with energy. For lower solar activity and also for increasing energy the empirical differential distribution (or histogram) of the 'log-flux' becomes more and more asymmetrical, having a sharp rise at the left-hand side (low fluxes) and then a gradual decrease towards high fluxes. At solar maxima the distributions are more symmetrical and the mean value is shifted towards higher fluxes. Some examples of both differential and integral flux distributions have been given by Király and Kecskeméty (1999), and further ISEE-3 examples are presented in this Conference (Király and Rodríguez-Pacheco, SH-1.4.28).

3.1 Cycle-to-cycle variation

Flux distributions, like other characteristics of general solar activity, change from cycle to cycle. IMP-8 instruments covered three minimum activity periods (1975-77, 1985-87, 1995-97) and two maxima (1979-81, 1989-91). Flux distributions during the first two minima and both maxima can be compared with some confidence, while comparison with the third minimum period is somewhat doubtful because of the deterioration of detector performance (mostly the breakdown of some of the anticoincidence cups, but possibly also shifts in detection thresholds). Roughly speaking, however, minimum fluxes of MeV protons in 1996-97 appear to be between those measured during the previous two solar minima. Medians of the mean daily flux distributions increase by about a factor of 40 to 50 between 1975-77 and 1978-91, and by 80 to 100 between 1985-87 and 1989-91. Factors are even larger when 1-year periods at minimum and maximum are compared.

Around 1 MeV, lowest daily mean fluxes are found to be smaller in the 1985-87 period than in 1975-77. Highest fluxes, on the other hand, are higher for 1989-91. The latter fact is related to the high-fluence events recorded in 1989-91 at higher (>10 MeV, >30 MeV) energies. Causes for lower minimum fluxes around 1986 than in 1976 are not obvious, and need further investigation. Richardson and Paularena (1997) pointed out that the streamer belt at the 1976 and 1996 solar minima was about twice as thick as in 1986-87. The 'pedestal' of MeV ions in the streamer belt (Tappin and Simnett, 1996) may then be expected to have been higher in the 1976 (and 1996) solar minimum periods.

Total fluences in solar cycle 22 were higher than in cycle 21 by a factor of about 2.6 for E>10 MeV and 3.5 for E>30 MeV. Most of the difference comes from the high-fluence events. The only cycle with reasonably well-observed energetic particle fluences that exceeded cycle 21 was cycle 19.

Feynman et al. (1993) analyzed the distribution of events with high fluences and for lower threshold energies of 1 to 60 MeV. For all threshold energies, they find reasonably good fits to log-normal distributions above some limiting fluence values, and parameters of the distributions are determined. They use those parameters for drawing fluence probability curves for 1-7 year exposures in space, in regions where particles above a given threshold energy can penetrate. The question of high-fluence events is discussed in more detail in this conference by P. Király and A.W. Wolfendale (SH 1.4.26).

4. Conclusions

The statistical behaviour of energetic particle fluxes and fluences of solar and heliospheric origin is still poorly understood. On the low-flux side, quiet-time periods can be assigned with some confidence, but the statistics of the lowest fluxes may still be somewhat distorted by instrument and spacecraft-related background effects. High-flux periods have been studied for radiation safety purposes, and a reasonable fit to log-normal distributions was found. Extrapolation of those distributions to higher flux levels is important for very long-term predictions, but requires a deeper theoretical understanding.

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