29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

Energy dependence of cumulative suprathermal and energetic particle fluence plots

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Suprathermal and energetic particle flux variability can be statistically characterized in a number of ways. As time histories of flux integrals (cumulative fluences) are relevant both for practical reasons (radiation effects) and for a better understanding of the production and propagation processes, simple quantitative methods are of some interest. Previous studies (e.g. Mewaldt *et al.*, 2001) showed that the character of cumulative fluence plots changed substantially with energy. While at several MeV/nuc a few solar particle events predominate, at much lower energies similar contributions from many separate events of various origins were found. We shall now use a simple parametric method for comparisons, and mention some other possibilities. As in the Kolmogorov hypothesis test, the maximum vertical distance of normalized cumulative plots from the straight line valid for a constant flux will be shown to be useful. Small values of that parameter (called K here for Kolmogorov) indicate variation in many small steps, while large K-values correspond to the dominance of a small number of large events. Below a few MeV/nuc K-parameters will be shown to decrease with decreasing energies. Extrapolations to small energies will be mainly discussed.

1. Introduction

Cumulative ion fluence plots for energies around 1 MeV/nuc are dominated by distinct steps, corresponding to coronal mass ejections (CMEs), to some particularly large flares, and sometimes to corotating interaction regions (CIRs). Due to the clustering of flares and CME's to active periods (corresponding to active regions on the Sun), and also to propagation effects, steps are somewhat smoothed out, and also display some substructure. Because of the huge (5 to 7 orders of magnitude) differences between extreme hourly fluxes, quiet time fluxes and instrumental background provide no appreciable contribution to cumulative fluences.

Above several 100 MeV/nuc cumulative fluences are mostly due to galactic CRs, and their rate is much more uniform than for the SH origin. Although Forbush decreases, global merged interaction region effects, and also some relatively fast changes in heliospheric structure show up on the yearly cumulative plots, they are characterized by a steady, almost straight-line increase due to a slowly changing flux.

We shall discuss how cumulative ion fluence plots change with energy around and particularly below 1 MeV, and how those changes vary with the phase of the solar cycle. Apart from some outlook at the end, mainly ISEE-3 DFH-EPAS, and IMP-8 CPME data will be used. For DFH-EPAS hourly mean ion fluxes a relatively short period (1978 to 82) will be used, when ISEE-3 was at L1, and not much affected by the magnetosphere. For IMP-8 data the elimination of magnetospheric effects is harder, particularly at the lowest energy (0.29 to 0.5 MeV). In a preliminary analysis done last year we found that more than 120 hourly flux values (out of about 170 thousand) of the then available data had to be eliminated for fairly obvious magnetospheric interference or for occasional bit errors. Recently cleaned flux data sets put on the web by the CPME team in CVS format appear to have eliminated those problems. We are now using daily mean fluxes from 1973 to 2000, and no data cleaning "by hand" was necessary. For the DFH-EPAS data set (for a more detailed discussion see Király and Rodríguez-Pacheco, 1999), merely 7 hours of data had to be omitted for errors or inconsistencies, out of a grand total of more than 30 thousand.

Although a huge amount of ion flux data obtained by more sophisticated instruments exists now, in this paper we restrict discussion to the above two. On the one hand, IMP-8 CPME data cover an extremely long time period, useful for looking at solar cycle effects (actually we have not yet used data for the last few years, because of yet incomplete cleaning). On the other hand, DFH-EPAS data at L1 appear to have an exceptionally good quality, as proved by the very regular flux distributions shown in our 1999 paper. We plan to return to a more comprehensive discussion of existing data sets at a later stage.

2. Cumulative ion fluences and the K parameter

In order to make cumulative fluence plots for different energies more readily comparable, first we normalize the plots by dividing fluences integrated up to a certain time by the total fluence for the chosen period (e.g. for a year or any pre-defined period). Then we compare a plot with the straight line that would be obtained if the same total fluence was produced in equal steps (corresponding to a constant flux). The plots thus obtained are illustrated on the example of 1978 DoY 228 to 365 ISEE-3 ion data for 8 energy bins (Figure 1).

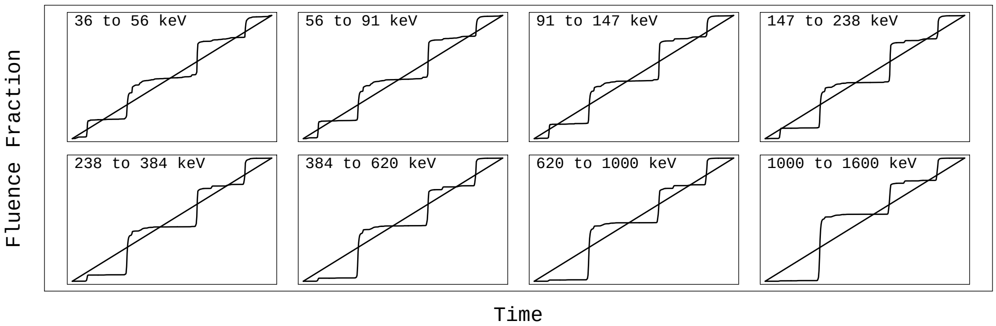

Figure 1. Illustrative example of normalized fluence plots for suprathermal and energetic ions measured by the DFH-EPAS instrument in late 1978, far upstream of the terrestrial magnetosphere. It is clear that for that period maximum vertical distances between the two lines do decrease with decreasing energy, while the number of steps hardly changes.

One measure of the deviation of the two lines is their maximum vertical distance. In fact, Kolmogorov (and Smirnov) used that measure in their famous hypothesis test for integral probability distributions, thus we call that measure "K parameter" (introduced in the present context by Király, 2004). Of course other measures could also be applied, e.g. the area between the two lines, the standard deviation of differences, the sum of maximum vertical distances on the positive and negative sides (for a discussion on the analogous problem in hypothesis tests, see Press et al., 1992). At present we show the usefulness of K, leaving it open whether other methods might prove even more efficient.

3. Energy dependence of K

As qualitatively seen in Figure 1, during that particular period K appears to decrease somewhat with decreasing energy. It is important to check how general that tendency is. The far upstream (mostly near-L1) data of

DFH-EPAS contain 9 similar sets of mean hourly fluxes, for roughly half-year periods between late 1978 and late1882. For each of the 9 periods and 8 energies K has been calculated. Although K values differ considerably for different periods, almost all of the 63 differences of K values for the same period and for subsequent energies are positive, i.e. higher energies were found to correspond to larger K. Averaging the 9 K values for each energy, the plot given in Figure 2 has been obtained. It is remarkable how linearly K appears to depend on log energy in the energy range covered by the DFH-EPAS detectors. That linearity can certainly not extend to a very wide energy range, because the value of K is restricted to the (0,1) interval. It appears still interesting that the linear fit, extrapolated downward in energy, has a zero intersect close to SW energies. Preliminary results for ACE data suggest a similarly monotonous and smooth, but less linear dependence of K on log E. Both the energy dependence and the absolute values of K for given energy, however, may also depend on the phase of the solar cycle, thus further analysis is justified.

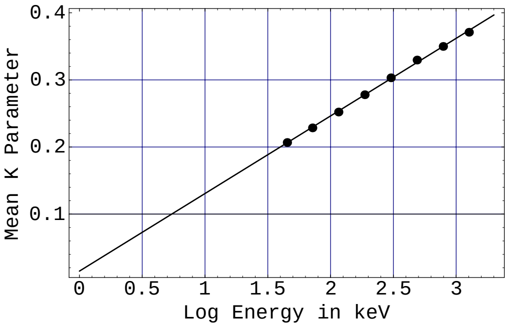

Figure 2. Mean K parameter values for all DFH ion energies

Daily mean ion flux data for the three lowest energies (0.29 to 0.5, 0.5 to 1, and 1 to 2 MeV) of the CPME instrument aboard IMP-8 have also been analyzed for the period 1974 to 2000. With very few exceptions, K parameters were again found to depend monotonously on energy. In addition to the mean K parameter (averaged over 28 years for each energy), also the mean SD parameters have been calculated, representing standard deviations of differences between normalized cumulative fluence plots and the straight lines for steady fluxes (see Figure 1). Both sets of data points and their linear extrapolations are given in Figure 3. It is interesting that downward extrapolations point again towards SW energies.

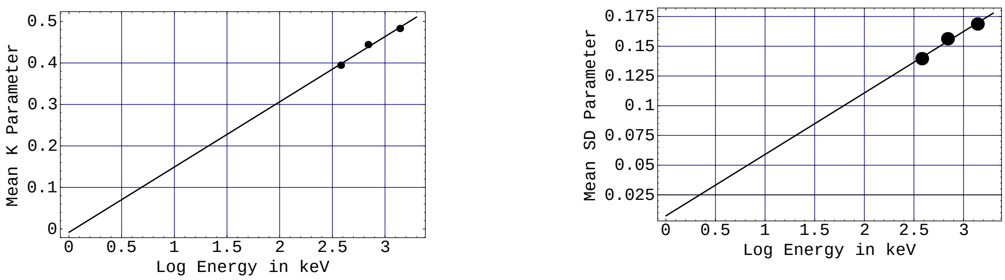

Figure 3. Dots represent mean K parameter values (left) and mean SD parameters (right) for the three lowest IMP-8 CPME ion energies, averaged over 28 years. Linear extrapolations point to vanishing values at about 1 keV

3. Variation over the solar cycle

Because of the long time period covered, IMP-8 CPME data also provide useful information about the solar cycle dependence of both annual fluences and K parameters. Annual fluences were calculated from the normalization constants (the sums of available daily mean fluences multiplied by the seconds in a day), and corrected for the fractional number of available days. Possible instrument saturation effects were not taken into account. K parameters were calculated as described above, without averaging over time. Figure 4 displays the results. It is remarkable that K parameters appear to peak more at solar minima than at maxima.

This can be ascribed to the presence of relatively large numbers of comparable events at solar maxima, while at solar minima contributions from a few rare events may predominate. Some indications for Gnevyshev-type effects for solar maximum periods can also be seen on both plots.

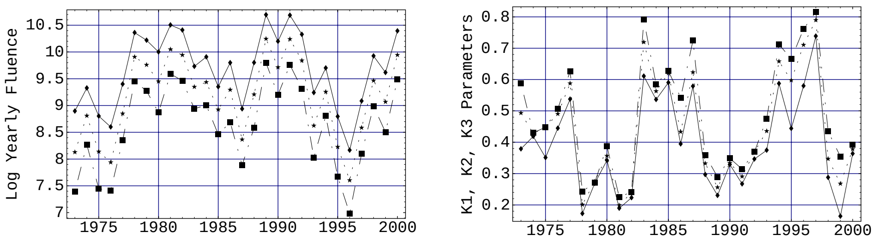

Figure 4. Ion fluences (left) and K parameters (right) for 3 CPME energies (solid: lowest, dash-dotted: highest energy)

5. Further outlook

As stated earlier, the inclusion of further and more sophisticated data sets (particularly of those covering both the suprathermal component and various nuclei for long time periods) is justified. Also, the relative merits of various alternatives to the K parameter should be checked out. The possible relevance of the intriguing downward extrapolations discussed above to suprathermal tail formation should be examined in more detail. As to extrapolations to a wider energy range, linear functions of log E are certainly not applicable. A tentative Gaussian fit to K values derived from 28 years of CPME data for all 10 energies is displayed in Figure 5. At energies much higher than a few MeV, contributions from slowly changing CR fluxes become gradually predominant. In fact, preliminary checks on neutron monitor data yield very small K values, decreasing with energy, in spite of clearly visible modulation effects.

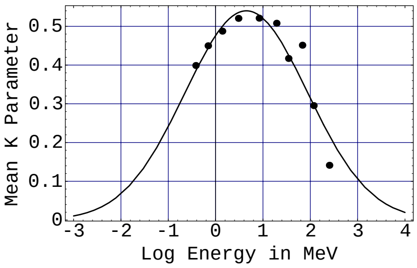

Figure 5. Tentative Gaussian fit to mean K values for 10 CPME energies

On the low-energy side, K values for SW fluences at 1 AU are also well below 0.1 (for Voyager SW fluence data, however, an increase of K values is found with increasing heliocentric distance, due to merged interaction regions, and to the gradual change of the correlation between SW speed and density from negative to positive values). In the eV region of typical solar photon energies, variations of the solar "constant" yield yearly K values as small as 10^{-5} to 10^{-4}.

6. Acknowledgements

Financial and organizational support of the International Space Science Institute (Bern) is gratefully acknowledged. ISEE-3 DFH-EPAS and IMP-8 CPME teams are acknowledged for making data available.

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