Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 171–174

Characteristics of cumulative particle fluences at different heliospheric radii

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Abstract: In the inner heliosphere, cumulative energetic particle fluence plots show that individual flux enhancements contribute substantially to the total fluence collected during an extended time period (e.g. in a year or even in a solar cycle). Fluxes of solar and inner heliospheric origin are thus quite intermittent, and one useful measure of that intermittency or variability is the K (Kolmogorov) parameter introduced by us some time ago. Its dependence on energy and on the phase of the solar cycle have been discussed in earlier contributions, and now some further examples will be given for spacecraft at different heliocentric radii. The importance of another measure of intermittent flux enhancements (day-to-day variability) in the distant heliosphere will also be emphasized.

Introduction

Energetic particle flux increases in the inner heliosphere are more or less directly connected with solar effects (flares, CME's, fast SW streams, CIR's), although small enhancements can rarely be traced back to their sources. Galactic CRs contribute little to the total fluence during a solar activity cycle below some tens of MeV, while above 100 MeV their contribution becomes dominant. Near solar minimum, however, GCRs contribute appreciably to quiet-time fluxes (but not to yearly fluences) above several MeV.

The contribution of a small number of individual events is mostly comparable to the total fluence in an extended time period. The ratio of highest and lowest fluxes at around 1 MeV can be as large as 10^7, i.e. the largest events contribute more in a few seconds than quiet-time fluxes do during several months. Cumulative fluence plots are thus characterized by a number of steps of various heights.

Some measure of the deviation of such a step-like fluence plot from a straight diagonal line (corresponding to a constant average flux) can thus be used to characterize the actual temporal variability of the flux. Mewaldt et al. [1] considered the number of dominant step-like increases as a relevant parameter, and concluded that it increased with decreasing energy. In subsequent work [2,3] we introduced the maximum vertical distance between the normalized fluence plot and the (0,0) – (1,1) diagonal line as a measure of deviation, and called it K parameter because of its similarity to the measure used in Kolmogorov's statistical test [4]. Figure 1 shows a normalized cumulative fluence plot and the definition of K.

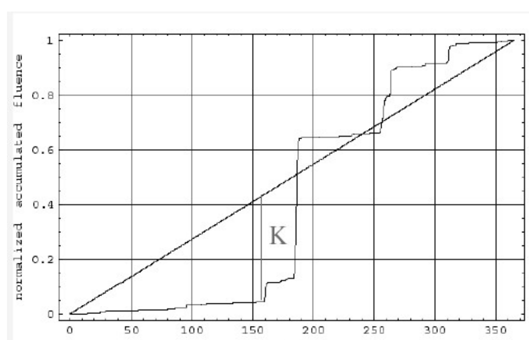

Figure 1: Normalized cumulative fluence plot of 0.29–0.5 MeV ion data of IMP8 CPME, and the definition of the K parameter as the maximum vertical distance between the two lines (here the maximum is reached on day 160, and K= 0.393)

Other distance measures, e.g. root mean square (rms) deviation, may be equally acceptable.

Energy dependence at 1 AU

The dependence of the K parameter on particle energy was discussed for some 1 AU missions in [3]. The IMP8 Charged Particle Measurement Experiment (CPME) had a very long data set of low-energy ion measurements from its launch (1973) to the formal termination of the mission (2001); in fact, measurements were later continued as a support for outer heliospheric missions up to the recent loss of the spacecraft. Although the loss of the anticoincidence scintillation detector in 1989 increased the background, it did not appreciably affect cumulative fluences. K parameters for the three lowest energy ion channels (0.29 to 2 MeV) and for each of the 28 years were calculated.
As one sees in Figure 1, the value of K for fixed energy should depend strongly on the relative strengths of individual events, and, as expected, the frequency of events also changes with the phase of the solar cycle. However, the ordering of K values with respect to energy is less random. In fact, K was increasing with energy in more than 95% of the 28 years. Averaging the K values for each energy over 28 years, one finds a nearly linear change with log energy in the given energy range (Figure 2). A similar linear dependence is obtained when rms deviation (or standard deviation, SD) is used instead of K.

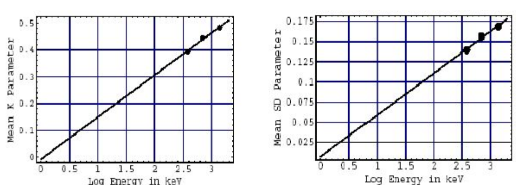

Figure 2: Mean K parameter (left) and standard deviation (right) as a function of $\log_{10}(E)$. Linear extrapolation suggests that fluctuations are small at around 1 keV, i.e. not far from SW energies.

IMP8 spent about half of the time in the magnetosheath of Earth or in the vicinity of the bow shock, therefore it may be questioned how representative are the data for energetic particles in the undisturbed SW. Actually, the data were cleaned for shock spikes, and typical magnetospheric and upstream particle energies are also somewhat smaller than the energies measured by IMP8 CPME. Thus the results may be more reliable than appears at first sight.
More reliable is to check the energy dependence of K for spacecraft in the vicinity of L1. The first spacecraft that spent an extended time period near L1 (between 1978 and 1982) was ISEE-3. The DFH/EPAS detector measured ion fluxes in 8 nearly equal logarithmic energy bins between 35 and 1600 keV. K parameters were calculated for 9 semiannual periods for each of the 8 energies, and K was averaged for those 9 periods. The dependence of the mean K on log energy is shown in figure 3.

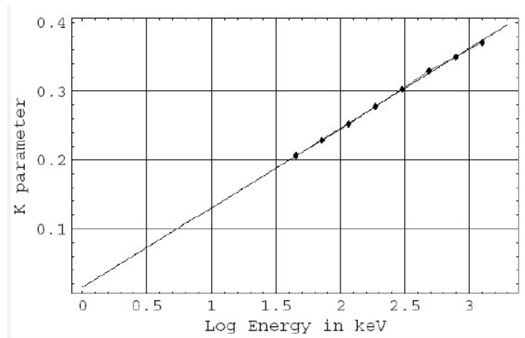

Figure 3: Energy dependence of the mean K parameters for ion fluxes measured by ISEE-3 DFH/EPAS at L1 between 1978 and 1982.

K parameters can of course not continue to grow linearly with log energy up to much higher energies. As shown in [3], IMP8 CPME results suggest a Gaussian shape for higher energies. One should not forget, however, that at several tens or even hundreds of MeV, smooth CR contributions become more and more important, and it becomes increasingly difficult to separate out the solar-heliospheric component.
SOHO LION data are also in an energy range comparable to ISEE-3, and SOHO is also near L1. Figure 4 shows the energy dependence of the mean K values for some LION data. K is again increasing with log energy, although the dependence is somewhat farther from linear than for ISEE-3. Background effects are not negligible for most instruments, and a smooth background contribution always reduces the apparent level of fluctuations.

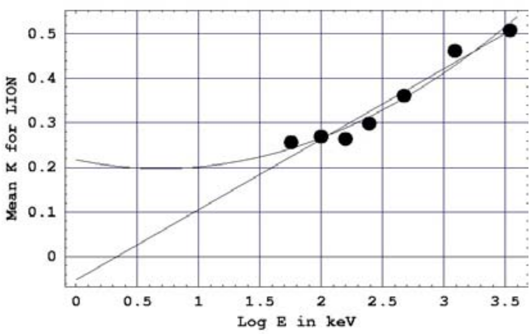

Figure 4: Mean K parameters for SOHO/LION as a function of $\log_{10}(E)$. Accumulated annual fluence plots of telescope 2 of detector 1 from 1999 to 2005 were used, measuring ions between 40 keV to 6 MeV in 7 logarithmic channels. Both linear and quadratic fits are given.

As an illustrative example we show the cumulative fluence plots for 1999 and for the 6 lower energies, where it can be seen how the importance of large events increases with energy (Figure 5).

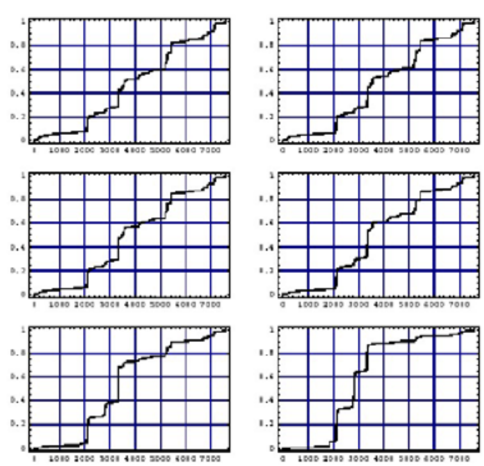

Figure 5: SOHO/LION cumulative fluence plots for 1999 from 40 keV to 2 MeV. Energy increases from left to right and top to bottom.

Fluence plots also showed qualitatively similar features at smaller heliospheric radii (Helios 1 and 2), although data on small (suprathermal) energies were not available there.

Voyagers and the distant heliosphere

The fluctuation characteristics of energetic particles change as heliospheric radius increases. The relative importance of flare particles decreases while corotating interaction region (CIR) and global merged interaction region (GMIR) contributions increase. The time scale of variations also increases, and annual K values typically decrease. A new regime starts when short-term fluctuations increase again in the foreshock region of the heliospheric termination shock (TS). Such intermittent low-energy flux enhancements first appeared in May 2002 at Voyager 1 and in May 2005 at Voyager 2. While Voyager 2 is still in the foreshock region at the time of writing (although the increasing flux enhancements may signal an imminent shock crossing), Voyager 1 crossed the TS on 16 December 2004 and has been in the subsonic heliosheath ever since. Figure 6 shows the pre-shock mean values of K for both Voyagers.

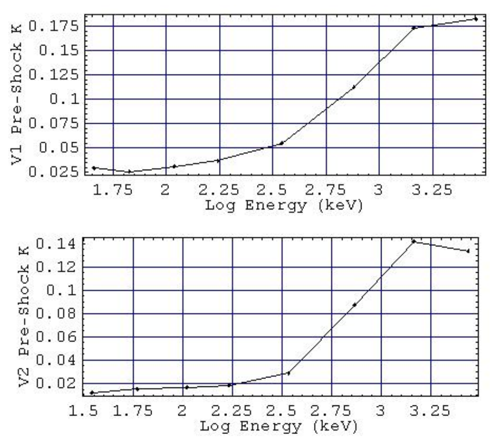

Figure 6: Mean K values for Voyager 1 (top) and Voyager 2 (bottom) as functions of $\log_{10}(E)$. K values were averaged for 2002 to 2004 for V1 and for 2005 to 2007 (up to May 2007) for V2.

The energy dependence for both pre-shock regions appears quite similar, although V2 has not yet reached the termination shock. But both functions are quite different from the nearly linear dependence on log energy that was observed at 1 AU in a comparable energy range. Admittedly, no background correction was applied to the Voyager fluxes, and a proper correction may somewhat change the shape of the curves.

The energy dependence of the average yearly post-shock values of K for V1 (2005 to 2007) is also of interest. Figure 7 shows the results.

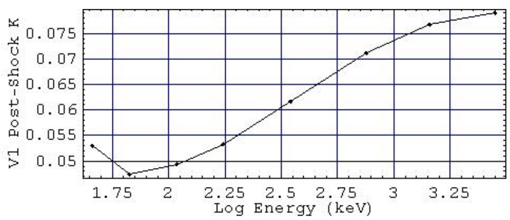

Figure 7: Post-shock mean values of K for V1.

Again a smooth curve is obtained, but K values are much smaller than in the pre-shock regions.

Does the K parameter provide relevant information on the distant heliospheric Voyager data, or is some other measure of fluctuations preferable? The similarity and smoothness of the above curves suggest that important information about the fluctuations on relatively long temporal scales is obtained, but from the point of view of the shock transition the short-term fluctuations are more relevant. The day-to day variability also used in [5] separates pre- and post-shock regions much better, as shown if Figure 8.

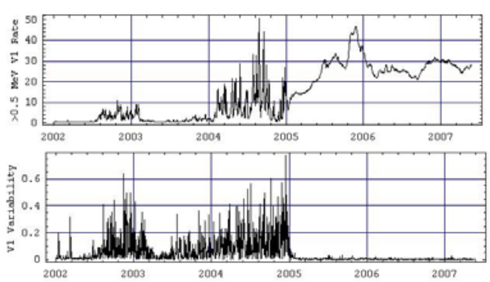

Figure 8: V1 count rates above 0.5 MeV (above) and their "day-to-day variability" (below). The latter represents the absolute values of base 10 logs of count rate ratios for consecutive days.

Conclusions

The K parameter, a measure of suprathermal and energetic particle flux variability based on cumulative fluence plots, is often useful for characterizing the importance of large solar particle releases in the inner heliosphere. Up to several MeV it is an increasing and nearly linear function of log energy. Extrapolations towards small energies show that it becomes small at about 1 to several keV, i.e. at SW or mildly suprathermal energies. Recent Voyager results in the foreshock region of the heliospheric termination shock and beyond, in the heliosheath, show that the variation of the K parameter with energy has also some relevance in those regions, although other fluctuation measures may play a more important role near the shock.

Acknowledgement

This work was supported in part by the International Space Science Institute (ISSI) in Bern, Switzerland, in the framework of the International Working Group Number 70. Hungarian research grant OTKA-K 62617 is also acknowledged for financial support. The IMP8 CPME, ISEE-3 DFH/EPAS, SOHO LION, Voyager LECP and CRS teams are acknowledged for providing data.

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