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Solar and heliospheric sources of suprathermal and energetic particle populations

P. Király[a], W.I. Axford[b], E.I. Daibog[c], B. Heber[d], R. Kallenbach[e], K. Kecskeméty[a], G.M. Mason[f], Yu.I. Logachev[c], R.A. Mewaldt[g], A. Posner[h], J. Rodríguez-Pacheco[i], R. Treumann[j] and M.A. Zeldovich[c]

(a) KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest P.O.B. 49, Hungary
(b) University of Alabama in Huntsville, USA, and MPI in Lindau, Germany
(c) Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992 Moscow, Russia
(d) 1. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart, Germany
(e) International Space Science Institute (ISSI), Hallerstr. 6, CH-3012 Bern, Switzerland
(f) Dept. of Physics, University of Maryland, College Park, MD 20742, USA;
now at Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723,USA
(g) Space Rad. Lab, California Inst. of Technology, Pasadena, CA 91125, USA
(h) Southwest Research Institute, San Antonio, TX 78238-5166, USA
(i) Space Research Group,Dept. de Física, Univ. Alcalá, 28871 Alcalá de Henares, Spain
(j) Centre for Interdisciplinary Plasma Science, and MPI, Garching bei München, D-85741 Germany
Presenter: P. Király (pkiraly@sunserv.kfki.hu), hun-kiraly-P-abs1-sh12-poster

Objectives and some preliminary findings of an ongoing international team project carried out at ISSI, Bern will be presented. Suprathermal and energetic particles in interplanetary space have a multitude of origins, i.e. acceleration and propagation histories. Solar flares, coronal mass ejections (CMEs), co-rotating interaction regions (CIRs), the heliospheric termination shock, planetary bow shocks and magnetospheres have all been recognized as energetic particle sources. Less energetic (suprathermal) particles of solar origin and pick-up ions have also a vital role both in their own right and as seeds of energetic particles accelerated in interplanetary disturbances. The relative contributions of various particle populations vary with energy and with the phase of the solar cycle. Particular attention will be given in our project to quiet periods and to large events. While quiet-time fluxes are expected to shed light on some base-line features of coronal and interplanetary acceleration processes, relatively large events dominate both the long-term fluence levels and the statistical properties of cumulative fluence plots. The importance of energetic and suprathermal particles that mostly cannot escape into interplanetary space, but contribute to coronal heating and possibly also to solar wind composition, will also be discussed.

1. Introduction

Solar–heliospheric suprathermal and energetic particles provide an important tool for the quasi–"*in situ*" study of astrophysical acceleration processes. The same particles – in association with electromagnetic and plasma signatures – also carry "remote sensing" information on solar chromospheric and coronal processes. A better understanding of the origin and statistical properties of energetic particle populations is also important for space weather issues, in particular for risk assessment of space missions where either human life or sensitive electronics are involved.

Although suprathermal and energetic particle measurement techniques have much improved during the past decades, progress in identifying their sources and propagation processes has been slower than expected. Several basic questions are still unanswered. A new effort has now been initiated in the framework of the international team projects of the International Space Science Institute (ISSI, Bern) in order to achieve further progress in that field. Those participating in the project have all worked on several facets of those problems before, both in experimental and theoretical fields, and it is now timely to pool efforts. A first discussion meeting aimed at reviewing the present situation and setting up research schedules was held in Bern in April 2005, and two more meetings are planned: the first for discussing progress and preparing the second, extended one (a mini-symposium with invited guests) for conclusions and for defining further tasks. In this report we present a brief description of the background science and of the main objectives, with only hints on preliminary progress. Four more contributions to the SH sessions of the 29th ICRC will be presented on results in specific fields (two by P. Király *et al.*, two by K. Kecskeméty *et al.*). A more comprehensive discussion and conclusions will be presented at the 30th ICRC, after terminating the project.

2. Solar flares, SW composition, flare energetic particles, and coronal heating

Solar energetic particles escaping from solar flares were likened by E.L. Fireman *et al.* (1975)[5] to sparks of nuclear fires, whose ashes were expected to be gradually transported out by the SW. They hoped those (partly radioactive) ashes would be identified by elemental and isotopic composition measurements in the SW itself, or even more efficiently, on surfaces exposed to it. In spite of much effort and progress, the relationship between flares, acceleration of particles, and coronal heating is still poorly understood. It is not known how much nuclear ashes flare particles produce. Electromagnetic signals provide useful but somewhat indirect evidence (Reames, 2000)[16]. The occurrence frequency of energy releases is also poorly known for very small flares (nanoflares, picoflares), where the bulk of the power input for heating is expected (Benz and Krucker, 2002[3], Benz, 2004[4]). The relationship between locally generated energetic particles and those escaping is also uncertain (Reames, 2000)[16]. Evidence for huge ^{3}He enhancements without appreciable ^{2}H and ^{3}H increases has shown that wave processes are more important for fractionation than nuclear ones. Isotopic fractionation due to nuclear processes should, however, not be discounted. Axford and McKenzie (2002)[1] and recently Axford (2004)[2] have emphasized the role of small-scale flares in heating the corona both in open and closed-field regions. Fast wind emerging from open-field regions may well hold measurable remnants of nuclear ashes created in the very small (pico-) flares that may give rise to the complex particle and wave processes heating the corona. Most of the energetic particles in those sources may not easily escape, or are adiabatically decelerated in rapidly diverging fields, thus it is hard to tell in what proportion should they contribute to the SW and to suprathermal fluxes. Both old records and modern ACE/ULEIS results, RHESSI data on electromagnetic signatures, and possibly also GENESIS solar wind sample-return composition data should be checked for positive indications or for new upper limits.

3. Heliospheric suprathermal and energetic ions and their energy spectra

Suprathermal and energetic ions of solar-heliospheric origin are always present in interplanetary space, up to at least several MeV/amu. Their intensity levels depend on past solar activity, on radial distance, and also on heliographic latitude. During extended periods of low solar activity that population is often referred to as ‘quiet-time’ or ‘baseline’ population. Its origin is poorly understood, and even its definition is somewhat vague. Instruments often have poorly known background count rates that may mask quiet-time intensity levels. Counting statistics is another limiting factor at MeV energies, hiding fast fluctuations. However, there is a widely held belief that a genuine energy dependent minimum flux exists in local interplanetary space, and the identification of its source(s) may hold vital information about quiet-time acceleration processes.

Intensities in the suprathermal domain are much higher than at 1 MeV, and counting statistics as well as cosmic ray related background are less of a problem. Power-law tails of Maxwellian solar wind ion distributions are always found when the detector is sensitive enough. Recent theoretical advances in non-equilibrium statistical mechanics yield hope for a better understanding (Treumann, 2001)[18]. Suprathermal tails are of course not restricted to periods of low solar activity. The shapes of spectra are much more variable under disturbed conditions. No spectral minimum is then seen in the combined spectra of solar-heliospheric particles and adiabatically decelerated cosmic rays, while at quiet times a distinct minimum at several MeV/n is observed. The quiet-time spectrum is fairly well described in terms of a superposition of two power laws (Logachev et al., 2002)[11]. The spectral exponent of the decreasing low-energy, solar-heliospheric component is usually between –3 and –2, while the high-energy component of decelerated CR origin increases with energy. Quiet-time spectra also depend on distance from the Sun, but the dependence is weak. Based on Helios data, the lowest intensities at the spectral minimum were found at about 0.6 AU (Kecskeméty et al., 2001)[7].

Spectral features of fluences (time-integrated intensities) of He, O, Fe, and some other nuclei accumulated over 33 months by ACE instruments were discussed by Mewaldt et al. (2001), and a decomposition into components originating from different sources was attempted. In the spectral behaviour of the total fluence a surprisingly smooth power-law behaviour was found over a wide energy range, with a spectral exponent –2. Because of the highly fluctuating nature of intensities, fluences at several MeV/nuc are dominated by a few large events, while around 100 keV/nuc many small events were found to dominate. The long-term average ^{3}He/^{4}He ratio at those low energies is about 0.01 to 0.02, and ^{3}He is present even at quiet times (Mason et al. 1999[12], Slocum et al. 2002[17]), suggesting a possible connection to microflares and nanoflares. Power-law spectra are frequent both at quiet and at active periods. The longer the period of integration, the higher the upper energy limit of the validity of the power-law behaviour. Even the poorly understood 'SEP' component in lunar soil was suggested to result from solar events summed over very long time scales.

4. Intensity distributions, anisotropies, temporal and spatial variations

Distributions of omnidirectional intensities and anisotropies are also key characteristics of the fluctuating suprathermal and energetic particle populations. Usually hourly or daily mean intensities are binned. Because of the huge range of variations (6 to 7 orders of magnitude for 1 MeV protons), distributions of logarithmic fluxes are more conveniently represented, in either differential or integral form.

During and after our 1997 ISSI quiet time project, intensity distributions of several IMP-8 data sets were analysed. Distributions at solar maxima and minima proved very different at MeV energies (Király and Kecskeméty, 1998)[8]. Also, data of the low-energy DFH/EPAS ion instrument aboard ISEE-3 that spent more than 4 years (1978 to 1982) near the L1 Lagrangian point were analysed (P. Király and J. Rodríguez-Pacheco, 1999)[9]. It is remarkable how smooth and regular the integral distributions were found, although the Sun was active in that period. At low energies, differential distributions had a sharp cutoff on the low-flux side. Spacecraft-frame anisotropies, however, were found to go to zero at low flux levels, indicating some spacecraft-related background (possibly due to CR interaction). Comparison with ACE and IMP-8 data is planned. Low-flux anisotropy may provide a sensitive check on background.

The spatial variation of suprathermal and energetic ion populations is poorly understood. Mainly Helios, Ulysses, and Voyager data are planned to be used for the analysis far from Earth. Intensity distributions and anisotropies will be compared. Attempts will be made to check and use Helios data for inner heliospheric comparisons. The possible extension of the Ulysses mission beyond the next solar activity minimum may provide a good opportunity to study radial and latitudinal variation under different solar polarity conditions. Although originally not a primary objective, the properties of the puzzling suprathermal and energetic particle populations detected by Voyager-1 well before and also after the termination shock crossing in mid-December 2004 will also be examined for any analogies with inner heliospheric processes.

5. A short list of objectives, and some preliminary results

1) Better understanding of the correlation between solar flare total energy release, and the flux levels, spectra, and composition of escaping energetic particles (particularly for small flares); 2) Seeking indications

for products of nuclear processes in large and small flares in electromagnetic radiation, as well as in SW and energetic particle composition; 3) Role of adiabatic deceleration and of various in-flight acceleration processes in connecting particle energies at the source and at the point of observation; 4) Better understanding of power law–type flux distributions, using up-to-date theoretical approaches; 5) Spatial and temporal variation of energetic particle flux distributions in the heliosphere, also including the large-flux side, consequences for dosimetry and long-term effects; 6) Spatial and temporal variation of quiet-time flux levels at various energies, with particular emphasis on high-latitude observations at solar minima by Ulysses; 7) Extension of earlier research on quiet-time H and He fluxes to electrons and to heavier ions, providing new clues to their origin; 8) Better understanding of solar and interplanetary conditions necessary for the occurrence of quiet-time fluxes; 9) Anisotropy as a function of flux levels; 10) To compare recent Voyager-1 results to inner heliospheric flux variations, and to discuss similarities and novel features.

Some of the preliminary results are to be reported on during this ICRC: the characterization of time-histories of cumulative fluences (Király *et al*, see also Király, 2005[10]); pointing out some interesting features of recent Voyager-1 data (Király); characterization of quiet-time fluxes and their gradients between 0.3 and 84 AU (Kecskeméty *et al.*)[7], and a discussion of how the decline rates of SEP events depend on parameters of the interplanetary medium (Kecskeméty *et al.*)[7].

During our April meeting in Bern several topics were discussed, both on the observational and theoretical sides. Several important new data sets and their implications were revealed (see e.g. Posner et al., 2004[15]), and theoretical understanding of wave effects (Kallenbach, see e.g. Kallenbach et al., 2005)[6] was described. A general theoretical approach to our field, illustrated by many simulation results, was presented by Treumann.

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