Some Astrophysical Aspects in the Studies of Solar Cosmic Rays

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Abstract

In this review we discuss very briefly main concepts, available observational data and recent theoretical results related to astrophysical aspects of particle acceleration at/near the Sun. A set of interesting conceptual and physical associations of SCR generation with the high-energy processes at other stars is highlighted.

1. Introduction

Flares on the Sun and other stars are important to astrophysics because they originate in out-of-equilibrium magnetic field-plasma interactions rather than in gravitational, thermonuclear, or radiative processes in near equilibrium. In fact, flaring stars constitute about 10% of the stars in the Galaxy [1]. In spite of its rather modest place in star hierarchy, the Sun is an invaluable proving ground to test predictions of flare theories and to develop analytical techniques for future stellar application. In turn, extreme flare star conditions impose the limits of models. In this context, a flare may be defined as a catastrophic release of magnetic energy leading to particle acceleration and electromagnetic radiation, bearing in mind that the magnetic energy release has never been directly observed.

Since flare-like physical processes occur in diverse astrophysical regimes, the field of solar and stellar flares can serve as an astrophysical "touchstone" [1, 2]. On the other hand, solar flares release a considerable portion of their energy (up to 10%) in the form of solar cosmic rays (SCR), mainly protons with the energy range 1 MeV–10 GeV [3]. These particles are observed near the Earth's orbit as a solar particle event (SPE). Spectral characteristics, elemental abundances and some other features of SCR are quite different from those for galactic cosmic rays (GCR). Nevertheless, in many other respects, SCR are consistent with more extended panorama of astrophysics of cosmic rays [4].

It is widely recognized now that SCR events are time-associated with fast coronal mass ejections (CMEs) that drive shocks and in some cases may be a significant (and perhaps the dominant) source of MeV ions (solar energetic particles, SEPs) [5] observed in the interplanetary space. There are also compelling

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evidences that both flares and CMEs are products of magnetic reconnection process, usually occurring in active regions of great complexity at/near the Sun. In general, the energy release of solar energetic phenomena occurs partly in electromagnetic radiation (*e.g.*, X-rays), partly in kinetic energy of ejecta, and partly in energetic particles. Each form affects the terrestrial environment differently, but in a crude first approximation they can be compared either on the basis of energy fluence in individual events, or in terms of peak fluxes.

From another point of view, it is worth to remind that in space research we deal with the three groups of fundamental factors — physical fields, particles and waves (shocks, MHD waves and plasma turbulence). Heaving been involved in different processes, solar cosmic rays (electrons and ions) bear on and contribute valuable information into all three branches of investigations. For example, they allow probing the magnitude, structure and dynamics of magnetic fields in the Sun's environment. Further, some results of the SCR studies (composition and spectrum of accelerated solar particles, their maximum energy, charge states, *etc.*) may be very helpful for the theory of acceleration and particle astrophysics. Finally, recent findings [3, 5] in the study of particle acceleration by coronal shocks are of common interest for astrophysical plasma physics

2. Solar Cosmic Rays at High Rigidity

Since 1942 more than 60 Ground Level Enhancements (GLE) of SCR have been recorded by the worldwide network of cosmic ray stations at rigidity $R \geq 1$ GV (in particular, the giant GLE of 23 February 1956, outstanding solar event of 29 September 1989, well known Bastille Day Event (BDE) of 14 July 2000 and GLE of 15 April 2001). Solar particles above 1 GV are of special interest to understand the maximum potentialities of solar accelerators. Several large GLEs in 1989–1991 have renewed interest in the effects of those particles. A low-energy threshold of the SCR spectrum seems to be strongly conditioned by intimate micro-processes in solar flare plasma, meanwhile a high-energy one turned out to be determined mainly by the structure of coronal magnetic fields [6, 7] or by the parameters of CME-driven coronal shock [4, 8, 9].

Maximum rigidity, R_m, (or energy E_m) is one of decisive parameters to test different models of particle acceleration at the Sun. Observations by standard surface detectors allowed to estimate the value of R_m up to about 20 GV. The underground Sun-oriented detectors allow to advance into the range of ∼100–200 GeV. On 29 September 1989 a unique increase of 43% was fixed in total counting rate of the BNO "Carpet" detector. The Baksan Underground Scintillation Telescope (BUST) also recorded a burst of muon intensity of 5σ [10]. Several other muon bursts at the BUST proved to be statistically significant and related to certain GLEs ("Baksan effect"). If so, the value of E_m for SCR may be as high as 500 GeV. A question of principal interest that may be addressed here is whether such protons are really accelerated at the Sun, or some specific effect of modulation in the primary flux of galactic cosmic rays (GCR) is observed? Recently, new attempts have been made to observe SCR by non-standard detectors. In particular, an effect of 6.1σ was observed during the GLE of 15 April 2001 by the Project GRAND Array [11]. Also, several muon increases of 4–14σ have been detected at the EAS Array "Andyrchy" during GLEs of the 23rd cycle of solar activity [12]. All those data open a new interesting possibility to study SCR in the energy range from a few tens to a few hundreds GeV.

Several new aspects of the problem under consideration arise due to possible production of medium energy neutrinos (> 1 GeV) by relativistic solar protons *in situ* (immediately in the Sun's atmosphere). Recent calculation [13] showed that these neutrinos can come to the Earth and be detected with neutrino telescopes of a new generation.

3. Implications for Other Astrophysical Problems

Observations from the *Yohkoh, Compton GRO, GRANAT, SOHO*, and reanalysis of older observations from the *SMM*, have led to important new results concerning the location, timing, and efficiency of particle acceleration in flares. In spite of some limitations, these experiments have provided data for fundamental discoveries over the past decades relating to particle acceleration, transport and energetics in flares and to the ambient abundance of the corona and chromosphere [15]. In particular, an intensity of the neutron capture line of 2.223 MeV is a measure of the concentration of ^{3}He in the photosphere (the photospheric ^{3}He abundance can not be determined spectroscopically). Moreover, the time history of this line fluence may be used to determine the altitude profile of plasma density deeply in the photosphere [16]. The density was found to be enhanced in comparison with a standard Sun's atmosphere model for the flares of 16 December 1988, 22 March 1991, and 6 November 1997.

Elemental abundances and charge states of SEPs also are very important sources of astrophysical information. In particular, ^{3}He is thought to be primarily produced by nucleosynthesis in the early Universe, and its abundance is used to place a constraint on cosmological model. A few data of photospheric ^{3}He/H ratio obtained by different research groups from the gamma-ray line spectroscopy have been recently summarized [17]. The ^{3}He/H ratio is related to the ^{4}He/H ratio, which is an important parameter for studies of stellar evolution and solar neutrino production. The gamma-ray studies provide information on the flare accelerated ^{4}He/H and ^{3}He/^{4}He ratios, on the ambient He/H, Mg/O, Si/O and Fe/O in subcoronal regions of the solar atmosphere, and on the photospheric ^{3}He/^{4}He ratio [18]. The data on the 2.223 MeV line from several flares confirm the previous conclusion [18] that the ^{3}He/^{4}He ratio in the photosphere is lower than it is in the corona. These findings have major implications on the understanding of solar atmospheric dynamics, solar wind and solar flare particle acceleration and Galactic chemical evolution.

4. Concluding Remarks

At present, the relative roles of flares and shocks in large SEP events are a matter of intense debate [19]. The final resolution of where and when and at what energies one or the other of these processes dominates (both for electrons and ions) is far from settled. Flares seem to play a more important role either directly or as seed particles than is currently thought.

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5. References

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