'Universal Heliophysical Processes'
Proceedings IAU Symposium No. 257, 2008
A.C. Editor, B.D. Editor & C.E. Editor, eds.
© 2008 International Astronomical Union
DOI: 00.0000/X000000000000000X

Forbush effects and their connection with solar, interplanetary and geomagnetic phenomena

A.V. Belov

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation
Russian Academy of Sciences (IZMIRAN),
142190 Troitsk, Moscow region, Russia
email: abelov@izmiran.ru

Abstract. Forbush decrease (or, in a broader sense, Forbush effect) - is a storm in cosmic rays, which is a part of heliospheric storm and very often observed simultaneously with a geomagnetic storm. Disturbances in the solar wind, magnetosphere and cosmic rays are closely interrelated and caused by the same active processes on the Sun. Thus, it is natural and useful to investigate them together. Such an investigation in the present work is based on the characteristics of cosmic rays with rigidity of 10 GV. The results are derived using data from the world wide neutron monitor network and are combined with relevant information into a data base on Forbush effects and large interplanetary disturbances.

Keywords. elementary particles, Sun: activity, interplanetary medium, solar-terrestrial relations, coronal mass ejections (CMEs), shock waves.

---

1. Introduction

A special kind of cosmic ray (CR) variation which we name Forbush decrease (FD) or Forbush effect (FE) was discovered by S. Forbush in 1937 (Forbush 1937, Forbush 1938). Since then hundreds of such events have been observed and discussed, and a large number of papers have been devoted to their study. The present work is not a traditional review of the published literature, such as the fundamental reviews J. Lockwood (Lockwood 1971), and H. Cane (Cane 2000). Much information on the FEs can be found in Dorman's books (eg. Dorman 1963, Dorman 1974) and in other works (eg. Iucci et al. 1979, Iucci et al. 1986, Cane 1993, Richardson & Cane 2005). The present work should best be considered as a review of FEs observed on Earth during the last five solar activity cycles.

FEs were discovered in ground level measurements of CRs and the data from ground level detectors remain as the main source of the information on these phenomena. This paper is based on the data from the world wide neutron monitor network and contains a discussion of the following themes: FE definition; variety of FEs; time and size distribution of FEs; interrelation of different characteristics of FEs; behavior of the CR anisotropy in the FE; relation of the FE to characteristics of the interplanetary disturbances; relation of FE to geomagnetic activity; dependence of FEs on the solar source characteristics; precursors of FEs.

Since the first years of the space era FEs have been recorded not only on Earth but in space as well - onboard of satellites (Fan et al. 1960) and on the remote spacecraft (eg., Lockwood & Webber 1987). These measurements are worth discussing separately. Another theme which is becoming more and more popular although not being discussed here is the influence of Forbush-effects on atmospheric processes and on the climate. It also deserves a separate talk and consideration.

2. Data base on Forbush effects and interplanetary disturbances

Almost all results presented here are obtained by means of databases created in IZMIRAN during the last 12 years. The first database contains calculations of CR density and anisotropy performed by the global survey method for each hour over 50 years since 1957 (Krymsky et al. 1981, Belov et al. 2007a). Results for 10 GV rigidity CRs (http://cr20.izmiran.rssi.ru/AnisotropyCR) are combined with the solar wind parameters and geomagnetic activity indexes from OMNI database (http://omniweb.gsfc.nasa.gov). Another database includes information on the interplanetary disturbances and Forbush effects. Selecting events for this database we tried to include all FEs in their broad definition and find a connection with each of them corresponding to a large scale interplanetary disturbance. Into this database are entered: 1. all events followed by the shock, even in the cases when no clear effect in the CR density was observed; 2. all big enough variations in CR density independent of the interplanetary conditions; 3. small events (as a rule, 0.5-1.0 %) - if the significant solar wind disturbances were observed at that time. Such a catalogue has some obvious advantages. 1. It is based on physical characteristics (density and anisotropy) of CRs of definite rigidity (10 GV) but not on the data of separate CR detectors. 2. Quantitative characteristics of separate events in this case are much more accurate than in the catalogues constructed on the data from separate stations. 3. the catalogue covers all the events observed in the defined period. Also included are events of small magnitude which may be a consequence of large interplanetary disturbances. 4. Each event (FE) in CRs is associated with certain interplanetary disturbance and possibly with its solar source. Thus, this is a catalogue not only for the FEs but also for the interplanetary disturbances.

At present our database includes about 5900 events covering the period from July 1957 to December 2006 - practically the whole time the world wide neutron monitor network has been operating. Each event is characterized by of the tens of various parameters on the CR variations and relevant phenomena. For the CRs these are the characteristics of charged particles with a rigidity of 10 GV. The main parameter is the FE magnitude A_F which is the maximum variation of CR density during the event.

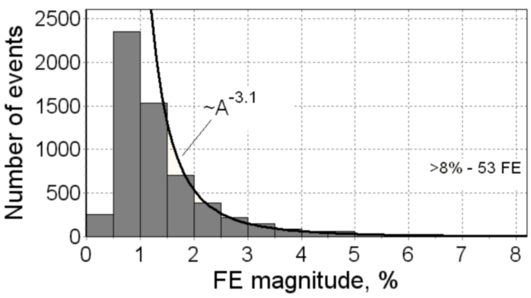

Figure 1. Size distribution of Forbush effect magnitudes.

In Fig. 1 a distribution of the FEs by their magnitude A_F is presented. The maximum of the distribution is located near 1 %. The location of maximum is explained by methodological reasons related to the difficulties of selection of the FEs of small magnitude. However, there are probably also physical reasons connected with the characteristic size and other parameters of interplanetary disturbances, first of all, ICMEs. If we ignore the range of small FEs, then, for A_F>1.5 % the considered distribution is well described by a power law with an index 3.1±0.1. This index is larger than for other solar parameters. For example, the distribution of soft X-ray flare power has an index of 2.19 (Hudson 2007, Belov et al. 2007). Once having the full FE distribution by magnitude it is possible to answer the question, which FEs should be considered as large? Comparing the frequency distribution of the FEs with those for geomagnetic storms of different classes (http://www.swpc.noaa.gov/NOAAscales), one can see that FEs with magnitude of >3 % correspond to strong geomagnetic storms (with maximum Kp-index $\geqslant 7$) and such events occur once per 36 days on average. FEs of >12.5 % correspond to extreme magnetic storms which occur on average once per three years.

3. What is the Forbush effect?

Forbush effect definition. It is surprising that after a 70-year intensive investigations Forbush effect is not defined conventionally. It is clear that original definition of FE as the CR variation during a geomagnetic storm, found in the old books (e.g., Dorman, 1963), is now out of date. FEs have been already observed many times far from the Earth and other planetary magnetospheres. And even on Earth FE does not always accompany a magnetic storm. And what do we have now apart from the old definition? If we look up the Glossary of solar-terrestrial terms NOAA (http://www.ngdc.noaa.gov), we will read: "Forbush decrease - an abrupt decrease, of at least 10 %, of the background galactic cosmic ray intensity as observed by neutron monitors". Unfortunately, this definition is erroneous in almost each word. FD is not necessarily abrupt, very often it occurs gradually. Only very rare FEs reach 10 %, the majority of them are much less. FE may be observed not only by neutron monitors but by many other detectors: in the ionization chambers by which they were discovered, in the ground and underground muon telescopes, on various detectors used in space exploration of CRs. It is more often observed in galactic CRs but the FE may be recorded (and is really often observed) in solar CR variations as well. The same concerns the anomalous CR. There is no doubt that this definition does not suit us.

So, what is the FE? FE is often said to be a storm in CRs and this is correct. During the FE we see mostly disturbed galactic CRs (Belov et al., 1997). During the FE the CR often happen to be most modulated, and the magnitude of the largest FEs is higher than 11-year CR variation. It is shown in Fig. 2, where CR variation during the FE and long term CR modulation during the solar cycle for rigidity of 10 GV are plotted on the same magnitude scale but on two different time scales. CR variations in solar cycle 23 did not exceed 19 %, whereas in one FE at the end of October 2003 they made about 28 %. And finally, during the FE galactic CR flux may be the most anisotropic. FE is a storm in CRs and a manifestation of heliospheric storm. Perhaps, it is reasonable to give the definition of the FE basing on its origin. It may look as follows: "Forbush effect is a result of the influence of coronal mass ejections (CMEs and ICMEs) and/or high speed streams of the solar wind from the coronal holes on the background cosmic rays". Thus, interplanetary disturbances that created the FEs are both of sporadic and recurrent nature. It would be desirable to leave only one class of sources and not consider recurrent phenomena as the FEs. But this is practically impossible because the solar wind disturbance is often a result of interaction of different factors (Crooker & Cliver 1994, Ivanov 1997), both of sporadic (flares, filament disappearances, coronal ejections) and recurrent (coronal holes, streamer structure) origin.

Forbush effect variety. FEs are rather diverse. Among them are large and small, short and long lasting, with fast and gradual fall, with full recovery and without it at all, two-step or not, with simple and complicated time profile, and so on. One reason for such a variety is a diversity of solar sources and their combinations. A second reason is

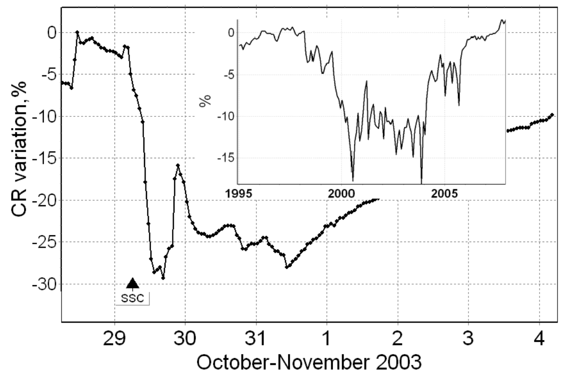

Figure 2. 10 GV cosmic ray variations during the giant Forbush effect in October 2003 (hourly data) and in 23th solar cycle (monthly data).

the variety of interplanetary situations arising before and during the event. Therefore we observe peculiarities in developing of a solar wind disturbance and its interaction with other heliospheric structures. A third and most important reason is the nature of the FE observation. FE is usually recorded at one point, mostly on Earth, and such observation cannot be complete. We should remember that FE occurs within a large volume occupying a significant part of heliosphere, and the same event at another point may look quite different, e.g. a considerable decrease of CR density may change into an increase (Belov et al. 1999).

Sporadic and recurrent FEs. The majority of FEs are of sporadic character and caused by ICMEs. In this case CR decrease is created by expansion of a disturbed solar wind region that is partly screened from outside by strong and/or transverse magnetic fields. The earliest phase of FE is observed prior to arrival of the interplanetary disturbance at Earth as a pre-increase of CR intensity caused by the acceleration of high energy charged particles on the outer boundary of an ICME, and a pre-decrease due to magnetic connection between the Earth and the region of FD inside of ICME. When the shock created by ICME movement, and/or solar ejecta itself arrives at Earth, the main phase of FE begins (Forbush decrease), when the CR behavior reflects directly magnetic structure of the propagating disturbance. Finally, at the last stage when a ICME propagates beyond the Earth orbit we see the phase of FE recovery, showing that an expanded disturbed region continues to modulate CRs. Solar wind recurrent high speed streams may be the main reason of many FEs, but these effects are never too large. It seems the limiting value of FE caused by coronal holes does not exceed 5 %. Herewith in the large recurrent FEs it is also possible to find the effect of CME. We may certainly state that all FEs of large magnitude and the majority of FEs of middle and small magnitude are caused by CMEs. However, in the periods when large and effective CMEs are rare the FEs, caused by coronal holes, dominate. A striking examples of such quiescent periods are the years of 1995-1996 or 2007-2008 when we did not practically see the sporadic FEs.

4. When do Forbush effects occur?

Fig. 3 demonstrates quasi 11-year cycles in the behavior of the FE magnitude averaged monthly and yearly. 11-year periodicity appears also in the variations of numbers of different magnitude FEs (Fig. 4). Since all sufficiently large FEs (e.g., >5 %) are connected with CMEs, by studying the variations in the number of large FEs we can get information about CMEs during those time periods when there were no CME observations.

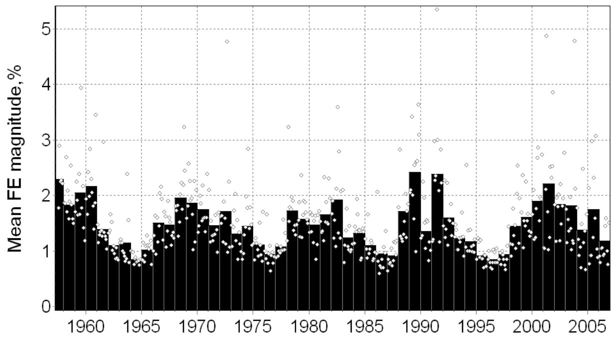

Figure 3. Monthly (points) and yearly (columns) mean FE magnitudes over 1957-2006.

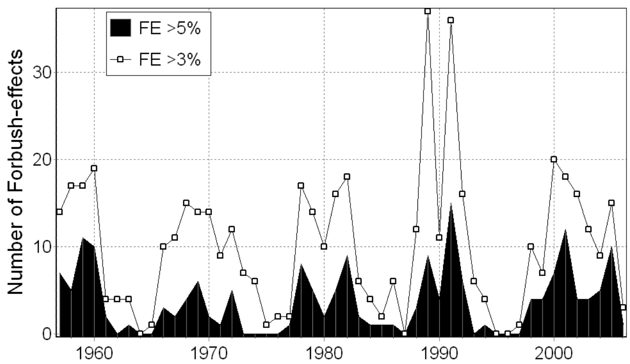

Figure 4. Annual numbers of Forbush effects with magnitudes >3 % and >5 % in 1957-2006.

If we compare the number of different magnitude FEs within different solar cycles, then some unexpected distinctions appear. The maximum sunspot number in cycle 23 is very similar to that in cycle 20. But this similarity goes away if we compare the numbers of FEs in these cycles. In cycle 20 the FEs of >5 % magnitude registered was 23, whereas in cycle 23 it was 50. Large FEs appear in cycle 23 more often compared with any other cycle, starting from cycle 19. FEs very often appear in series and each series is usually connected with a burst of solar activity. This peculiarity allows the rate and magnitude of FE to be used for special index calculation (Belov et al. 2005) for quantitatively describing the rate of bursts of solar activity and forecasting their probability.

5. Cosmic ray anisotropy in Forbush Effects.

If we look at the long term behavior of the first harmonic of the anisotropy in Fig. 5 where all results obtained so far by IZMIRAN group are combined, an opinion may be formed about slow, regular and well ordered variations of anisotropy. Note, that one of the most active researchers of long term variations of anisotropy and their connection with the solar magnetic cycle (which is evident from Fig.5) was the same Scott Forbush (e.g., Forbush 1973). However, if we blow up any part of this curve one can see that the anisotropy is extremely variable, especially during large FDs.

It is during the FEs that the biggest anisotropy of the galactic CRs is observed. For example, on February 15, 1978 in one of the largest FE both the first and the second

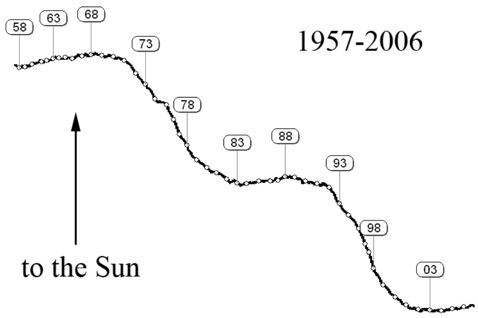

Figure 5. Behavior of the equatorial component of CR (10 GV) anisotropy in 1957-2006.

harmonics of CR anisotropy reached about 10 % (Belov et al. 1979) that is 1-2 orders higher than usual values.

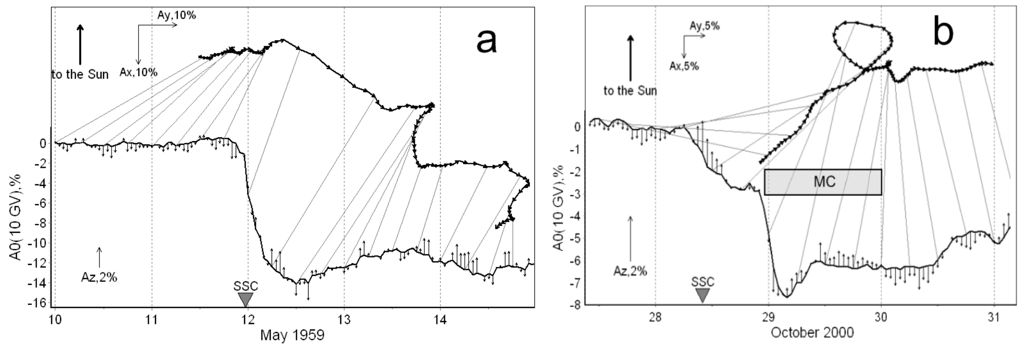

Figure 6. Behavior of the density, north-south and equatorial component of CR (10 GV) anisotropy in two Forbush effects.

Although the anisotropy of CRs changes in magnitude and direction during the whole FE, the fastest and essential variations usually occur near the interplanetary shock (SSC) and close to minimum CR density in the FD. That is clearly seen in the large FE recorded in May 1959 (Fig. 6). The CR anisotropy reflects a more detailed structure of interplanetary disturbance than CR density variations. In particular, the boundaries of magnetic cloud are normally clearly seen in the behavior of anisotropy. The magnetic cloud as a specific part of interplanetary disturbance is a cause for a second step in the two-step FD structure (Barnden 1973, Cane 1993, Wibberenz et al. 1997). In the event recorded at the end of October 2000 (Fig. 6) the first decrease of CR density started with the shock arrival near the SSC, another (much deeper) decrease is connected with a magnetic cloud that was passing the Earth from 23UT on October 28 to 00UT on October 30 (http://lepmfi.gsfc.nasa.gov/). In this case during the passage of the cloud the CR anisotropy vector rotated almost a full circle. We should remember also that magnetic clouds can influence the second harmonic of CR anisotropy even more strongly than the first harmonic (Richardson et al. 2000).

6. Some relations of Forbush effect characteristics

The FE is one part in a complex of sporadic phenomena characterizing a solar-heliospheric storm (eg. Belov et al. 2007c). It is natural to expect at least statistical relations between the parameters of FEs and other phenomena, from solar flares to

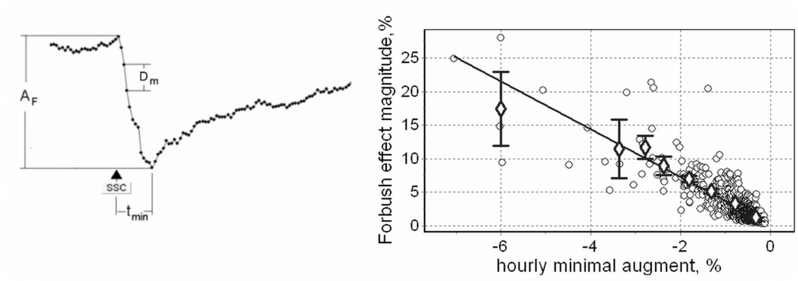

Figure 7. Typical Forbush effect time profile (left part) and relation of FE magnitudes A_F and maximal hourly decrements D_m (right part).

geomagnetic disturbances. Here we start from the inner interrelations among different characteristics of the FE itself.

Inner interrelations. The interrelations exist between parameters of either FE. Thus, maximum CR anisotropy in the FE well correlates with its magnitude A_F. In the right half of Fig. 7 we consider a relation of FE magnitude A_F to the maximum decrement D_m, i.e., minimal hourly augment of CR density variation. One can see that D_m and A_F (depicted in left half of the figure for typical FE time profile) are rather closely related (correlation coefficient is -0.87). It means that a reasonable forecast of maximum depth of FE can be made on the basis of FE evolving in a decrease phase.

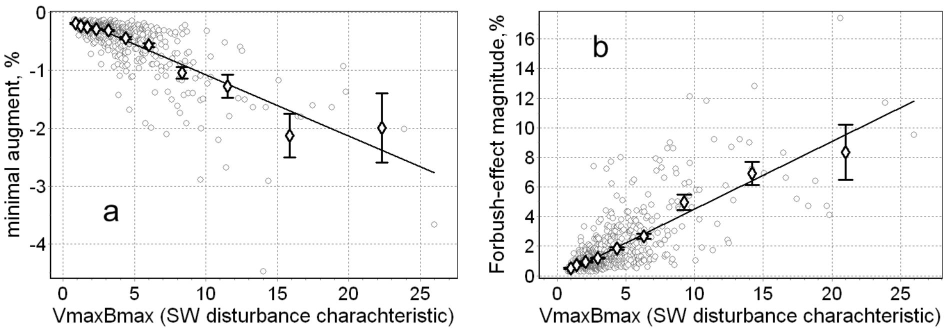

Figure 8. Dependence of Forbush effect maximal hourly decrements D_m (a) and magnitudes A_F (b) on product of maximum solar wind speed and IMF intensity in inteplanetary disturbances.

Relations to characteristic of solar wind disturbances. It is clear that the faster the propagation of interplanetary disturbance and the stronger its magnetic field, the faster will be the decrease of CR density during the main phase of FE. It may be assumed that the rate of a decrease for CR of certain rigidity R will vary in inverse proportion to the time t_r, which is necessary for a disturbance to go a distance equal to gyroradius of the same rigidity particle. Then D_m is proportional to VB, if V and B are solar wind velocity and interplanetary magnetic field (IMF) intensity within the most disturbed part of interplanetary disturbance. The parameter VB has been calculated in our data base for each event as VmaxBmax - the product of maximum values of solar wind velocity and IMF intensity in this disturbance, normalized to 400 km/s and 4 nT respectively. Using this parameter we can verify the above relation. A statistical relation between min and D_m and VmaxBmax in Fig. 8 is evident enough and close to the linear dependence. The magnitude A_F of FE is also related statistically to the same characteristic VmaxBmax, as obtained by (Belov et al. 2001) from the 1977-1998 data. To plot Fig. 8 the results calculated over the period 1964-2006 have been used. A relation of FD depth with the product VB is evident in some theoretical models (e.g., Parker 1963, Krymsky et al. 1981, Wibberenz et al. 1998).

Relations to geomagnetic activity. Belov et al. (2005) calculated mean values of FEs connected with different levels of geomagnetic activity, starting from very low (Kp-index <2-) and up to extreme magnetic storm (Kp=9) using the data through 1977-1999. In the present work these calculations are made for a longer period (1957-2006) and presented in Fig. 9.

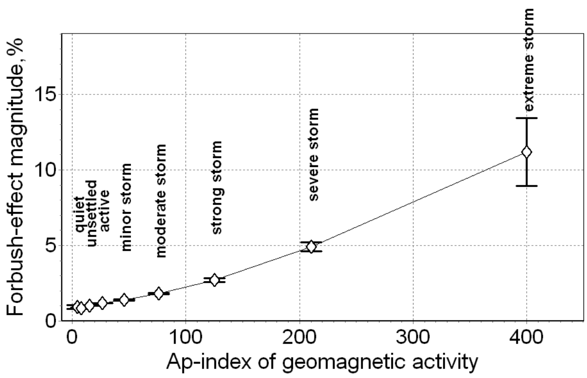

Figure 9. Dependence of mean Forbush effect magnitude on Ap-index of associated geomagnetic acivity.

We see a statistical relation between the FE magnitude and the geomagnetic activity level. Small values of FE (<1 %) usually correspond to quiet and unsettled geomagnetic conditions. On the contrary, extremely large magnetic storms are usually followed by giant FEs, for example, the events in August 1972, July 1982 and October 2003. Of 16 magnetic storms with maximum Kp=9, 13 were followed by the FEs >5 %. On the other hand, half of the 10 biggest FEs during 50 years were followed by extreme geomagnetic storms, and in other cases there were severe or strong storms.

However, a relation between FEs and magnetic storms is statistical and is often violated. Two such exceptions are shown in Fig. 10, where the situation of 8 days in November 2002 is presented during which two FEs were recorded. The first one started on November 17, reached very large magnitude (7.4 %), but was not followed by a magnetic storm (maximum Kp=4). The next one, the onset of which is marked by SSC on November 20, was almost unnoticed (its magnitude was 0.8 %), but it occurred on the background of a strong magnetic storm (maximum Kp=7-). Both FEs and geomagnetic storms are created by the same disturbances of the solar wind, but in different ways. In a magnetic storm the key role may be played by a sign of the Bz component of the IMF, which generally doesn't affect the FD magnitude. The same may be said about the density of solar wind plasma. Geomagnetic disturbances are determined by the local characteristics of solar wind flowing around the Earth magnetosphere, whereas CR modulation is a result of the influence of the whole large scale interplanetary disturbance.

7. Forbush effect connection with solar flares and precursors of FEs.

Forbush effects and solar flares. In Fig. 11 the series of three large FEs occurred in July 1959 is presented.

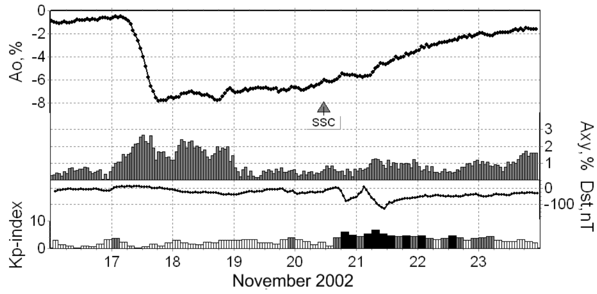

Figure 10. Density variation A0 and equatorial component of anisotropy Axy for 10 GV cosmic rays together with Kp- and Dst- indicies of geomagnetic activity during November 16-23, 2002.

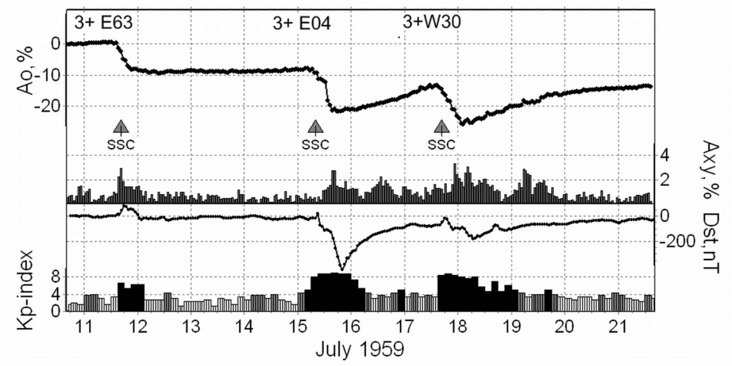

Figure 11. Variations of density and equatorial component of anisotropy Axy for 10 GV cosmic rays together with Kp- and Dst- indexes of geomagnetic activity during July 10-21, 1959. In the upper part optical importances and heliolongitudes are indicated for solar flares associated with the shocks that caused SSCs.

During one week, on July 11, 15 and 17 1959 three powerful shocks arrived at Earth after which strong geomagnetic storms and very deep FDs with magnitudes 10.1, 14.8 and 14.4 % occurred. Each of these three events turned out to be associated with a powerful solar flare with optical importance 3+ (Dorman 1963) recorded on July 10, 14 and 16 correspondingly. All three flares generated in one active region at heliolatitudes N15-N26 and are distinguished mainly by heliolongitudes: E64 for the first flare, E04 and W30 - for the second and third. As we understand now, in all three cases large interplanetary disturbances came to Earth with high solar wind velocity, caused by powerful and fast CMEs, whose centers were near the mentioned flares (Yashiro et al. 2008). Those three CR events (together with the associated magnetic storms) were connected with the eastern, central and western CMEs, and it is the difference in the relative position of these ejections and Earth that explains the distinctions between those events. The first FE started on July 11, had a prolonged profile and it hardly recovered by the time of the onset of the next FE. It was followed by a short and moderate magnetic storm (maximum Kp=7-, Dst-index is only -36 nT). The second FE was the biggest in this series. It was characterized by a fast two-step decrease and relatively quick recovery. The geomagnetic storm in that event was not only the biggest of these three but was one of the largest over the history of Dst index observations which fell down to -429 nT on July 15 (Kp index herewith went to a upper limit value 9). The third FE looked similar to the first one in the rate of decrease but had the fastest recovery. It was followed by a severe storm (Kp=9-, minimum Dst was at -183 nT). In the first case Earth entered a remote western periphery of the eastern ejection and then gradually approached its central part. In the second case it is natural to think that Earth passed through the central part of disturbance including a magnetic cloud. Finally, in the third case the main part of disturbance passed to the west of the Earth and Earth rapidly left the main region of FD.

The dependence of FE characteristics on heliolongitude of solar sources was found long ago and had numerous discussions (eg. Sinno 1961, Iucci et al. 1986, Cane 2000). Recentlty higher efficiency of central CME in the FE creation and east-west asymmetry of such efficiency was demonstated on large experimental material (Belov et al. 2007c). The majority of ejections associated with far from the central meridian flares normally don't create the FE near Earth, but if they do these FEs are very small. However, there are exceptions from this rule, and they are not so rare (eg. Belov et al. 2003a). Usually they are associated with anomalously large and essentially powerful CMEs. Observing CR variations near Earth in these cases we get information about larger variations at the great distances [to the east or west of Earth].

Precursors of Forbush effects. In a similar way we obtain the information from CR variations about remote heliospheric events by observing the precursors of FEs. It was discovered long ago (eg. Fenton et al. 1959, Bloch et al. 1959), that sometimes the changes in CR behavior begin well before the arrival of the interplanetary shock or solar wind disturbance at Earth. Now we know that the effect of approaching shock (precursor) is a complicated combination of pre-increase and pre-decrease in CR variations and assumes specific angle distribution of CR intensity which is difficult to describe by the sum of the first spherical harmonics. However, this effect should result in CR density variations and in the behavior of the first spherical harmonic of CR anisotropy.

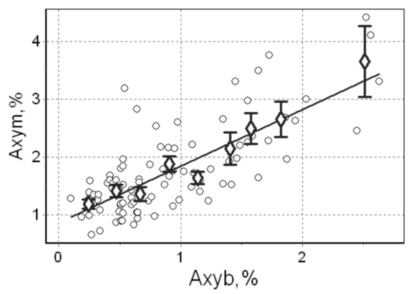

Figure 12. Maximum amplitude Axym of the equatorial component of CR anisotropy during the Forbush decrease versus amplitude Axyb of the same component just before the shock arrival.

Fig. 12 is obtained for all the FEs over 1964-2006 that occurred on the quiet background. Presented results indicate a connection (correlation coefficient is 0.74) between CR anisotropy measured at the last hour before the shock and CR anisotropy inside the FE and far behind the shock. More detailed analysis shows that in some groups of events (especially with western solar sources) the precursors are sufficiently large and become noticeable more than a day before the shock arrives at Earth. This should not be surprising if we remember that the FE is a heliospheric phenomenon which starts well before the interplanetary disturbance arrives at Earth, when the disturbance is being formed near the Sun.

8. Conclusion.

After 70 years of study FEs continue to be a hot topic. An array of problems connected with FE await to be solved. A complete FEs theory doesn't exist yet although both interesting and useful attempts of theoretical description have been made (eg. Parker 1963, Krymsky et al. 1981). Still there is no clear understanding of FE contribution in the full heliospheric CR modulation and long term CR variations. For a long time we have been aware of the benefit of FE observation for space weather tasks, but effective tools for practical use of FE information are not developed so far. FEs originate in the largest area of short term solar activity manifestations observed on Earth and nearby, which distinguishes FEs from geomagnetic and ionospheric disturbances and even proton events. That is why the connection of FE characteristics with the parameters of interplanetary disturbances or with geomagnetic activity indices exists but is not very close. Deflections from the average dependencies are informative, they are affected by specific features of the given interplanetary disturbance and its solar sources and provide information on heliospheric processes in interplanetary space remote from the Earth. The ability to reflect large scale processes, that are very often quite remote from the observation point make CR variations a unique tool for the study of solar activity and heliospheric processes. Without FE observation the picture of solar and heliospheric storms would not be complete and clear. Still more unique is the information on the old FEs (eg. 19 solar cycle events) when CMEs were not known, solar wind parameters were not measured and there was not even a tenth part of a customary now solar and heliospheric information. The study of old FEs (complete data of them have existed since 1957) is the most natural and straightforward method to investigate CME and other solar activity manifestations in long time period. Thus, FE data provide information on previous and coming storms. Being very complicated phenomena FEs need a complex approach and accumulation a great amount of various information. Our epoch of large data bases and Internet technologies should make such exploration both easier and more effective.

Acknowledgments. I am thankful to all teams providing continued ground level CR monitoring (http://cr0.izmiran.rssi.ru/ThankYou/). Special gratitude to International Astronomical Union and IAUS257 Organizing Committee for initiating and support this work.

References

Barnden L.R. 1973, *Proc. 13th Internat. Cosmic Ray Conf.*, 2, 1277

Barouch, E., & Burlaga, L.F. 1975, *J. Geophys. Res.*, 80, 449

Belov, A.V., Blokh, Ya.L., Dorman, L.I., Eroshenko, E.A., Guschchina, R.T., Kaminer, N.S., & Libin, I.Ya. 1979, *Proc. 16th Internat. Cosmic Ray Conf.*, 3, 449

Belov, A.V., Dorman, L.I., Eroshenko, E.A., Iucci, N., Villoresi, G., & Yanke, V.G. 1995, *Proc. 24th Internat. Cosmic Ray Conf.*, 4, 912

Belov, A.V., Eroshenko, E.A., & Yanke, V.G. 1997, *Correlated Phenomena at the Sun, in the Helosphere and in Geospace*, 463

Belov, A.V., Eroshenko, E.A., & Yanke, V.G. 1999, *Proc. 25th Internat. Cosmic Ray Conf.*, 6, 431

Belov, A.V., Eroshenko, E.A., Struminsky, A.B., & Yanke, V.G. 2001, *Adv. Space Res.*, 27, 625

Belov, A.V., Buetikofer, R., Eroshenko, E.A., Flueckiger, E.O., Oleneva, V.A., & Yanke V.G. 2003, *Proc. 28th Internat. Cosmic Ray Conf.*, 6, 3581

Belov, A., Bieber, J., Eroshenko, E.A., Evenson, P., Pyle, R. & Yanke, V.G. 2003, *Adv. Space Res.*, 31, 919

Belov, A.V., Buetikofer, R., Eroshenko, E.A., Flueckiger, E.O., Gushchina, R.T., Oleneva, V.A., & Yanke V.G. 2005, *Proc. 29th Internat. Cosmic Ray Conf.*, 1, 375

Belov, A.V., Baisultanova L., Eroshenko E., Mavromichalaki H., Yanke V., Pchelkin V., Plainaki C., & Mariatos G. 2007, *J. Geophys. Res.*, 110, A09S20
Belov, A., Kurt, V., Mavromichalaki, H., & Gerontidou, M. 2007, *Solar Phys.*, 246, 457
Belov, A.V., Eroshenko E., Oleneva V., & Yanke V. 2007, *J. of Atmospheric and Solar-Terrestrial Physics*, doi:10.1016/j.jastp.2007.08.021
Bloch, Ya.L., Dorman, L.I., & Kaminer, N.S. 1959, *Proc. 6th Internat. Cosmic Ray Conf.*, 4, 77
Cane, H.V. 1993, *J. Geophys. Res.*, 98, 3509
Cane, H.V. 2000, *ISSI Space Science Series, 10, "Cosmic Rays and Earth"*, 41
Crooker, N.U., & Cliver, E.W. 1994, *J. Geophys. Res.*, 99, 23383
Dorman, L.I. 1963, *Cosmic Ray Variations and Space Research*, oscow, N USSR, p.1027
Dorman, L.I. 1974, *Cosmic Ray Variations and Space Explorations*, North-Holland Publ. Co., p. 460
Fan, C.Y., Meyer, P., & Simpson, J.A. 1960, *Phys. Rev. Letters*, 4, 421
Fenton, A.G., McCracken, R.G., Rose, D.C. & Wilson, B.G. 1959, *Can. J. Phys.*, 37, 970
Forbush, S.E. 1937, *Phys. Rev.*, 51, 1108
Forbush, S.E. 1938, *Phys. Rev.*, 54, 975
Forbush, S.E. 1973, *J. Geophys. Res.*, 78, 7933
Hudson, H. S. 2007, *ApJ.*, 663, 45
Iucci, N., Parisi M., Storini M. & Villoresi G. 1979, *Nuovo Cimento*, 2C, 1
Iucci, N., Pinter, S., Parisi M., Storini M. & Villoresi G. 1986, *Nuovo Cimento*, 9C, 39
Krymsky G.F. et al. 1981, *Cosmic Rays and Solar Wind, Nauka, Novosibirsk*, p. 224
Lockwood, J.A. 1971, *Space Sci. Rev.*, 12, 658
Lockwood, J.A., & Webber, W.R. 1987, *Proc. 26th Int. Cosmic Ray Conf.*, 4, 87
Lockwood, J.A., Webber, W.R., & Debrunner,H. 1991, *J. Geophys. Res.*, 96, 11587
Parker E.N. 1963, *Interplanetary dynamical Processes, John Wiley and Sons, London*
Richardson, I.G., Dvornikov, V.M, Sdobnov, V.E. & Cane, H.V. 2005, *J. Geophys. Res.*, 105, 12579
Richardson, I.G., & Cane, H.V. 2005, *Proc. Solar Wind 11*, 755
Sinno, K. 1961, *Ionosphere a. Space Res. Japan*, 15, 276
Wibberenz, G., Cane, H.V., & Richardson, I.G. 1997, *Proc. 25th Int. Cosmic Ray Conf.*, 1, 397
Wibberenz, G., Le Roux J.A., Potgieter M.S., & Bieber J.W. 1998, *Space Sci. Rev.*, 83, 309
Yashiro, S., Michalek, G., Akiyama, S., Gopalswamy, N., & Howard, R.A. 2008, *ApJ*, 673, 1174

Discussion