Geofísica Internacional (2000), Vol. 39, Num. 1, pp. 87-92

Solar-terrestrial response to large extension or long-duration solar gamma ray events

R. Pérez Enríquez[1], L. Miroshnichenko[1], R. E. Rodríguez Taboada[2] and A. Méndez Berhondo[2]
[1] *National University of Mexico, UNAM, UNICIT, Juriquilla, Querétaro, Mexico.*
[2] *Instituto de Geofísica y Astronomía, Depto. de Astronomía, CITMA, La Habana, Cuba.*

Received: November 6, 1998; accepted: May 6, 1999.

RESUMEN

Durante el gran evento de rayos gamma del 29 de septiembre de 1989 se observaron líneas de rayos gamma de una región alrededor de 25 grados del sitio de la ráfaga. El mecanismo que parece más plausible para explicar la aceleración de partículas responsables de los rayos gamma es un choque producido por una eyección de masa coronal (EMC). Sin embargo, no existe a la fecha una explicación de aceptación general. Por otro lado, en junio de 1991, se observaron por lo menos tres eventos de rayos gamma de larga duración. De igual manera, ninguno de los modelos que se han propuesto para explicar estos eventos es convincente. En este trabajo analizamos los datos de plasma y partículas a la órbita de la Tierra para estos dos tipos de eventos y discutimos la posibilidad de que algunas de las perturbaciones en el medio interplanetario se originaron en la cromosfera fuera de regiones activas.

PALABRAS CLAVE: Medio interplanetario, regiones interactivas, ciclo solar.

ABSTRACT

Gamma ray lines (GRL) from the large event of 29 September 1989 were observed from a site about 25 degrees from the flare site. In June 1991, at least three long-duration GRL events were observed by several spacecraft. None of the models put forward to explain these events are convincing. We discuss the plasma and particle data at Earth´s orbit for these two types of events and we propose that some perturbations in interplanetary space may originate in the solar chromosphere *outside* active regions.

KEY WORDS: Interplanetary medium, interactions regions, solar cycle.

INTRODUCTION

Solar gamma-ray (GR) emission is produced by accelerated electrons and ions interacting with the ambient solar atmosphere, whose main components are electron bremsstrahlung at energies of the photons less or order of 1 MeV, and at energies of ~ 10-50 MeV; nuclear gamma ray line (GRL) emission of ~ 1-10 MeV, and pion decay emission (>50 MeV) (*e.g.*, Ramaty and Mandzhavidze, 1994). Gamma rays provide important information on a fundamental problem of particle acceleration in solar flares. Thus a 2.22 MeV-to-4.44 MeV line fluence ratio can be used to determine the spectrum of accelerated particles in the energy range of 1-100 MeV/nucl. However, due to uncertainties in alpha/proton ratio, ambient and accelerated particle compositions, and flare geometry, the uncertainty in the power-law spectral indexes may be as large as 1.5 (Ramaty *et al*., 1996).

The advent of new and better instruments in space has resulted in a considerable increase in the number of solar GR events detected. However, the number of these events is still rather low compared, for instance, to the number of observed X-ray bursts or SPEs. In recent years a new type of GR flares has been discovered: some GRL events come from a very extended region like those associated with the 29 September, 1989 flare (Cliver *et al*., 1993), and some have a duration of several hours as in June 1991 (*e.g.,* Hudson and Ryan, 1995).

Gamma ray lines from the large event of 29 September 1989, were observed originated from a site about 25 degrees from the flare site. A CME shock was proposed as the most plausible mechanism to account for the accelerated particles responsible for the gamma rays, but no generally accepted explanation exists at present. On the other hand, in June 1991, at least three long duration GRL events were observed at several spacecraft. Likewise, none of the models put forward to explain these events were convincing.

We discuss the plasma and particle data at Earth's orbit for these two types of events and propose that some perturbations in interplanetary space may originate in the solar chromosphere *outside* active regions. In the next section, we review the observations evidences concerning the 29 September, 1989 GR event. In Section 3, we discuss the observations of the long duration GR events in June 1991. In Section 4, we propose a possible mechanism to explain the observations.

2. THE LARGE EXTENSION GR EVENT OF 29 SEPTEMBER 1989

As reported by Vestrand and Forrest (1993), a large flare behind the south-west limb of the Sun on 29 September 1989 was associated with detectable GR emission. SMM gamma ray spectrometer observations of this event began when the SMM satellite emerged from a South Atlantic Anomaly pass at 1133 UT, coincident with the maximum of a X9.8 soft X-ray burst, but presumably after the peak of the impulsive phase of the GR emission (see Bhatnagar *et al.*, 1996).

The GR featured a high (~ 0.2) ratio of the 2.2 MeV to 4-7 MeV emission. As Vestrand and Forrest (1993) point out, because of attenuation of the 2.2 MeV neutron capture line near the limb, a significant fraction of the GR emission may have originated at longitudes on the visible disk as far as 25° from the flare centroid (Cliver *et al*., 1993). They conclude that this flare provides the first evidence of a spatially extended component of GR emission from solar flares.

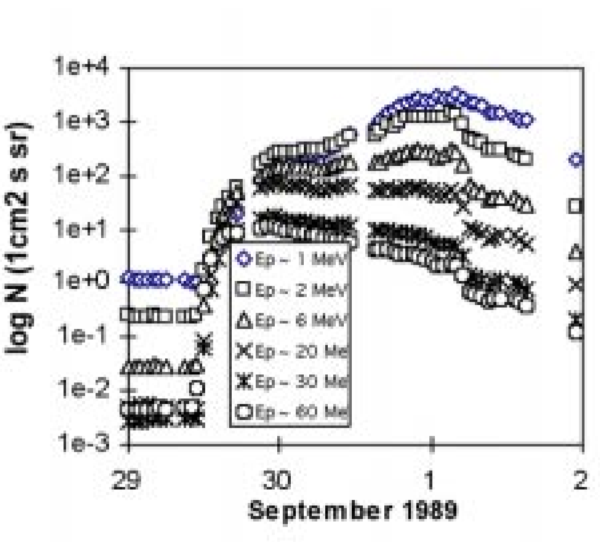
For SEPs, such rapid transport from the flare region is generally attributed to widespread acceleration on open field lines by a coronal/interplanetary shock (Lin and Hudson, 1976). Cliver (1982) presented observations supporting a coronal shock as the fast propagation mechanism for the behind-the-limb GLE-flare (~ W120°) of 1 September 1971, and Debrunner *et al.* (1988) made a similar suggestion for the GLE-flare (~W130°) of 16 February, 1984. According to Kahler *et al.* (1984), such shocks may be driven by fast CMEs.

The event at the solar disk occurred closed to the limb, yet energetic particles were observed in interplanetary space (Figure 1). The SPE profile is shown in Figure 1a. Notice that initially the energy spectrum was extremely hard, but became softer with time (Figure 1b). Unfortunately, no interplanetary data was available during the event, but the Dst index of geomagnetic activity showed some response as late as October.

3. THE LONG DURATION GR EVENTS IN JUNE 1991

Most gamma ray events are impulsive, with duration as short as a few seconds (Chupp, 1987). Mandzhavidze and Ramaty (1993) point out, however that extended gamma ray emission lasting about an hour are observed from some solar flares, *e.g*., 27 April 1981, 7 December 1982, 16 December 1988, and 6 March 1989). Of particular interest are the long duration GR events of June 1991 (for a review see Mandzhavidze, 1994; Hudson and Ryan, 1995). Nuclear line emission was observed from the 4 June flare for about 2 from the 11 June flare for about 4 hours (Ryan *et al*., 1993; Murphy *et al*., 1993), and from the 15 June flare for over an hour (Ryan *et al*., 1993).

Gamma rays with energies above 2 GeV were detected during at least 8 hours after the impulsive phase of the 11 June flare (Kanbach *et al*., 1993; Mandzhavidze and Ramaty, 1996). Gamma rays of up to 3 GeV were seen for about 2 hours after the 15 June flare (Akimov *et al*., 1991). According to Mandzhavidze and Ramaty (1993), protons of up to 5 GeV are required to explain the energy spectrum of gamma-ray emission in the 11 June event. In fact, both 11 and 15 June



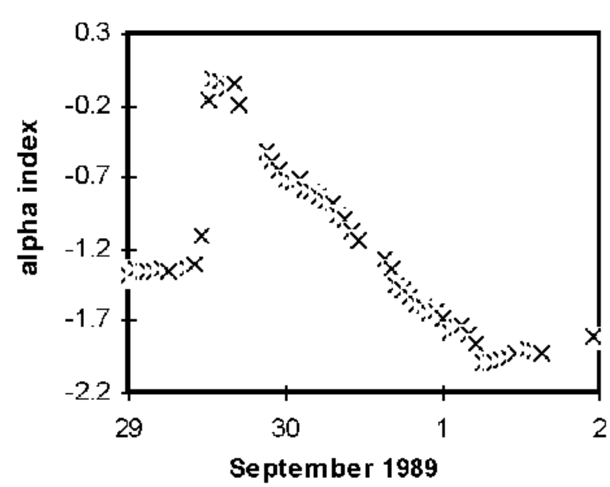


Fig. 1. a) NSSDC OMNIWeb data on the energetic particle profile in interplanetary space during the event of 29 September, 1989, for the energy channels: 1, 2, 4, 10, 30 and 60 MeV; b) Approximate spectral index evolution for the event 29 September, 1989.

events may be interpreted as pion decay emission produced by trapped protons (Kocharov *et al*., 1994; Ramaty *et al*., 1996).

A possible shock wave acceleration would be too high up in the corona at the time of occurrence of the GR component which occurs during the post flare episode (Kahler, 1984; Mandzhavidze and Ramaty, 1992; Akimov *et al*., 1994; Somov, 1996).

Energetic particle data were available for the GRL events of 4 and 15 June. In Figure 2a, the SPE profile of the 4 June shows an impulsive phase, followed by a gradual phase. The energy spectrum, being quite soft at the beginning of the event, became harder and remained so until 6 June (Figure 2b).

The event of 15 June seems to be more gradual as shown in Figure 3a. Here, the energy spectrum starts being hard and becomes softer towards the end of 16 June (Figure 3b).

Interplanetary data are scarce; yet strong activity can be observed (Figures 4a and 4b). This activity is apparent in the Dst index (Figure 5), where we can see at least five geomagnetic storms occurring within a month.

4. DISCUSSION AND CONCLUSIONS

For the 29 September 1989 event, Vestrand and Forrest (1993) suggest that the spatially extended component is powered by particles that diffuse from the flare loops, or by particles precipitating from the coronal shock. Cliver *et al.* (1993) favour the latter suggestion. The solar energetic particles (SEPs) were rapidly injected onto interplanetary field lines rooted in the corona far from the flare site, a similar transport problem as for the GR-producing protons in this event, assuming that the flare region was the source of both.

Akimov *et al*. (1994) discussed the 15 June 1991 long duration GR event taking into consideration optical, X-ray, microwave and solar cosmic rays observations. They conclude that prolonged particle acceleration during the late phase of the flare, rather than long-term trapping of particles from the impulsive phase is necessary to explain this particular event. The most likely source of the acceleration is a current sheet that appears as the CME moves outward and the magnetic field is restored. Akimov *et al.* (1994) argue that rapid expansion of coronal loops in other cases would lead to a similar result.

In looking at the microwave data for these event we notice the oscillating character of the emission. Energetic particle data for this event, as for the 29 September 1989 and the 4 June 1991 events, a similar oscillating character is found (see Akimov *et al*., 1994). In conclusion, Akimov et al.'s model can explain many peculiar features of this kind of events, especially the microwave emission except for the fact that this emission, at least in the case of the 15 June event, is *oscillating.*

We suggest that a prolonged acceleration may involve precipitation of the particles in a loss cone configuration. Rather than being accelerated in an electric field, the particles might be accelerated continuously while trapped in a magnetic field loop. This suggests stochastic acceleration by hydromagnetic turbulence in the magnetic field during its post-flare restoration. This idea implies:

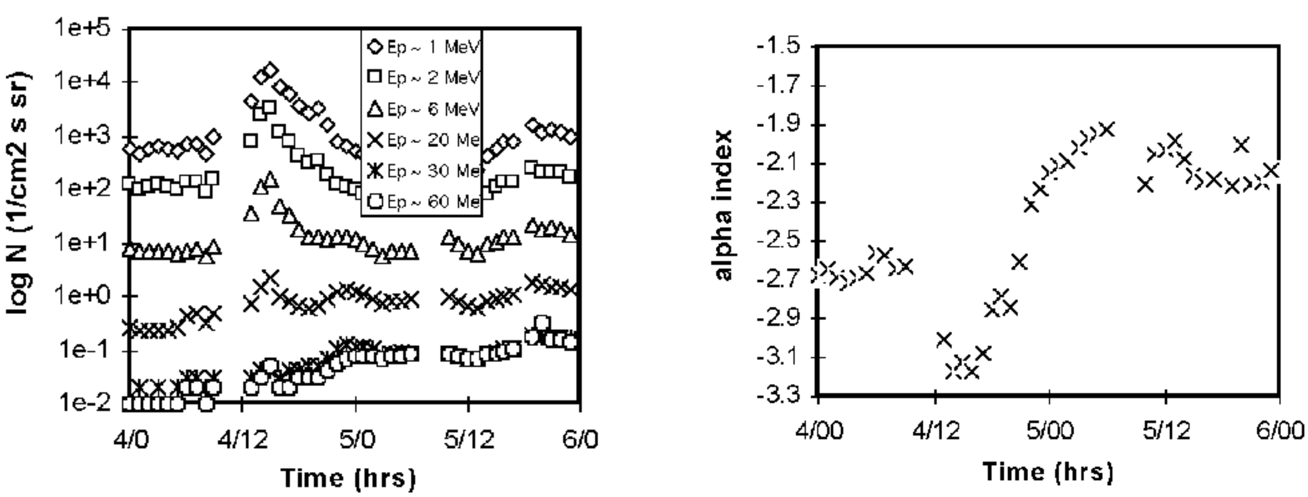


Figure 2. a) NSSDC OMNIWeb data on the energetic particle profile in interplanetary space during the event of 4 June 1991, for the energy channels: 1, 2, 4, 10, 30 and 60 MeV; b) Approximate spectral index evolution for the event 4 June 1991.

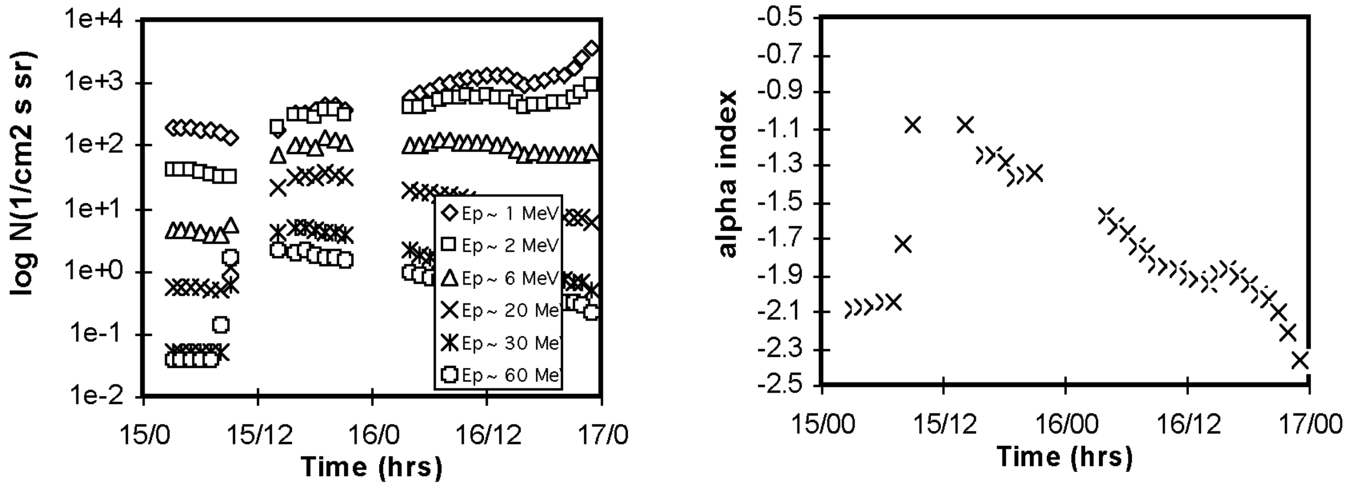


Fig. 3. a) NSSDC OMNIWeb data on the energetic particle profile in interplanetary space during the event of 15 June, 1991, for the energy channels: 1, 2, 4, 10, 30 and 60 MeV; b) Approximate spectral index evolution for the event 15 June, 1991.

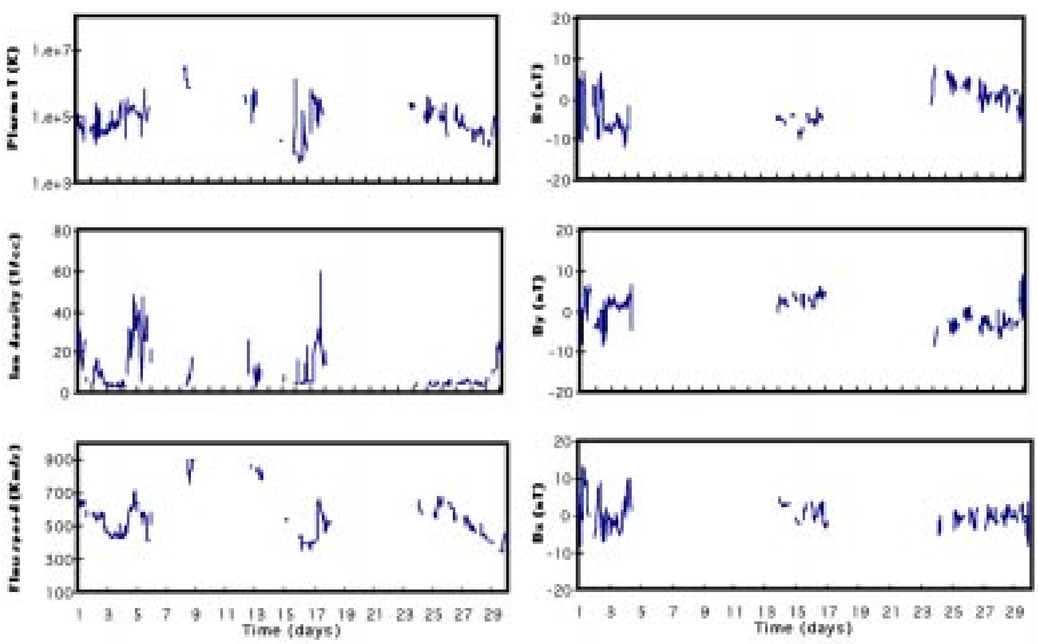


Fig. 4. Interplanetary a) plasma and b) Magnetic field during June 1991 (from OMNIWeb Data Explorer Results, 1998).

1. The acceleration process takes place at coronal levels and not in the chromosphere.

2. The oscillatory behaviour of the microwave and energetic particle profiles observed during these events is an important clue.

3. Due to the high energies of the gamma rays, alternative particle acceleration should be considered.

4. The heating of chromospheric plasma due to dumping of energetic particles should be considered. This may account for the oscillatory behaviour observed in the microwaves and energetic particles during large extension and long duration GR events.

The model involves a concept of evolving magnetic structures (EMSs), as introduced by Feynman and Hundhausen (1994). Such structures may represent a kind of canopy of hot plasma in a magnetic loop heated from below by hydromagnetic waves, in such a way that the initially Maxwellian distribution of the particles builds up a suprathermal tail. The particles remain trapped in the magnetic field as long as it is sufficiently strong and stable. However, the rearrangement of the magnetic field proper destabilises the loop. The particles start to precipitate into the atmosphere as they find themselves into the loss cone of the magnetic field, like water drops in a rain storm in the Earth's atmosphere. Dumping of energetic particles into the solar atmosphere and the resulting gamma ray emission could

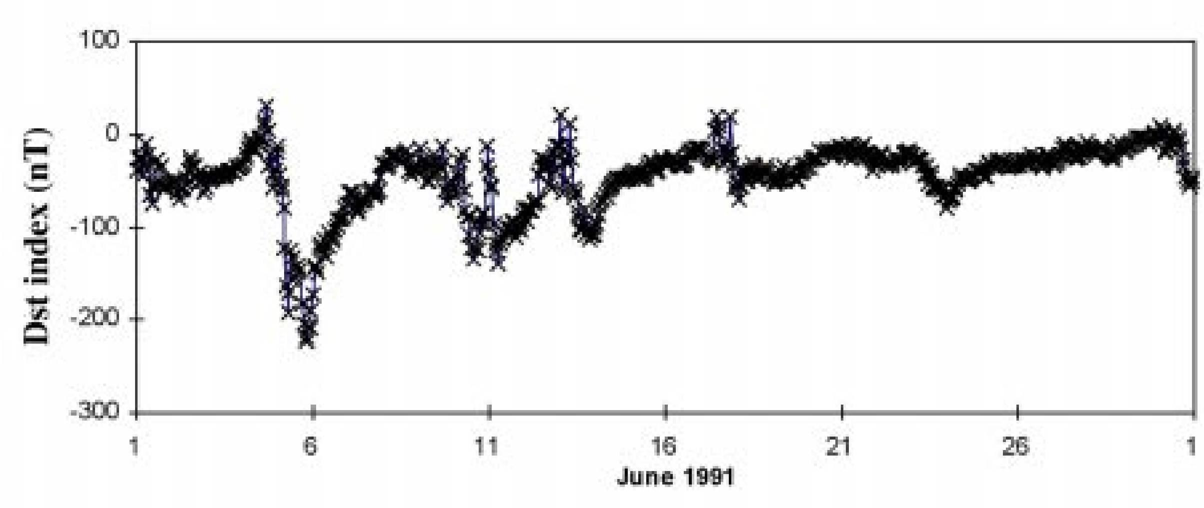


Fig. 5. Hourly data of the Dst index of geomagnetic activity for June 1991 (from OMNIWeb Data Explorer Results, 1998).

thus take place during long periods of time and in an extended area. As a result of the collapse, a CME is produced in the corona, and a fraction of the accelerated particle population might penetrate into the chromosphere. The interaction of these particles with the chromospheric material *outside* an active region would produce long duration SEP in space and a GRL event from an extended region and for a long time.

ACKNOWLEDGEMENTS.

This work was partially supported by CONACyT (Mexico). One of us (L.M.) acknowledges support from the State Scientific and Technical Program of Russia “Astronomy” and Russian Foundation of Fundamental Research (project 96-02-16827a).

BIBLIOGRAPHY

AKIMOV, V. V., V. G. AFANASSYEV, A. S. BELOUSOV and I. D. BLOKHINTSEV, 1991. Observations of high energy gamma-rays from the sun with Gamma-1 telescope (E > 30 Mev). Proc. 22nd Int. Cosmic Ray Conf. Dublin 3, 73-76.

AKIMOV, V. V., N. G. LEIKOV, A. V. BELOV, I. M. CHERTOK, V. G. KURT, A. MAGUN and V. F. MELNIKOV, 1994. Gamma-ray flare of June 15, 1991. *In:* J.M. Ryan and W.T. Vestrand (eds.), AIP Conf. Proc.. No.294, High Energy Solar Phenomena: A New Era of Spacecraft Measurements, AIP, New York 294, 106-111.

BHATNAGAR, A., R. M. JAIN, J. T. BURKEPILE, I. M. CHERTOK, A. MAGUN, H. URBARZ and P. ZLOBEC, 1996. Transient Phenomena in the Energetic Behind-the-Limb Solar Flare of September 29, 1989, *Astrophys. and Space Sci. 243*, 209-213.

CHUPP, E. L., 1987. High-Energy Particle Production in Solar Flares (SEP, Gamma-Ray and Neutron Emissions), *Physica Scripta* T18, 5-19.

CLIVER, E.W., 1982. Prompt Injection of Relativistic Protons from the September 1, 1971 Solar Flare. *Solar Phys*. 75, 341-345.

CLIVER, E. W., 1996. Solar flare gamma-ray emission and energetic particles in space. *In:* R. Ramaty, N. Mandzhavidze and X.-M. Xua (eds.). High Energy Solar Physics Workshop Proc. AIP, New York 374, 45-60.

CLIVER, E.W., S.W. KAHLER and W.T. VESTRAND, 1993. On the Origin of Gamma-Ray Emission From the Behind-the-Limb Flare on 29 September 1989. *In:* Proc. 23rd Int. Cosmic Ray Conf. 3, 91-94.

CROSBY, N. B., M. J. ASCHWANDEN and B. R. DENNIS, 1993, Frequency distributions and correlations of solar X-ray flare parameters, *Solar Phys.* 143, 275-299.

DEBRUNNER, H., E. FLUCKIGER, H. GRADEL, J. A. LOCKWOOD and R. E. MCGUIRE, 1988. Observations Related to the Acceleration, Injection, and Interplanetary Propagation of Energetic Protons during the Solar Cosmic Ray Event of February 16, 1984, *J. Geophys. Res*., 93, 7206-7216.

FEYNMAN, J. and A. J. HUNDHAUSEN, 1994, Coronal mass ejections and major solar flares: The great active center of March 1989. *J. Geophys. Res.* 99, 8451-8464.

HUDSON, H. and J. RYAN, 1995. High-energy particles in solar flares. *Ann. Rev. Astron. Astrophys.*, 33, 239-282.

KAHLER, S. W., 1984. Gradual hard X-ray events and second phase particle acceleration. *Solar Phys*. 90, 133-138.

KAHLER, S. W., N. R. SHEELY, R. A. HOWARD, M. J. KOOMEN, D. J. MICHELS, R. E. MCGUIRE, T. T. VON ROSENVINGE and D. V. REAMES, 1984. Associations between coronal mass ejections and solar energetic proton events. *J. Geophys. Res*., 89, 9683.

KANBACH, G. O., L. BERTSCH, L., C. E. FICHTEL, R. C. HARTMAN, S. D. HUNTER, D. A. KNIFFEL, P. W. KNOW and Y. C. LIN, 1993. Detection of a long duration solar gamma-ray flare on June 11, 1991 with EGRET on COMPTON-GRO. *Astron. Astrophys, Suppl. Ser.* 97, 349-353.

KOCHAROV, L. G., G. A. KOVALTSOV, G. E. KOCHAROV, E. I. CHUIKIN, I. G. USOKIN, M. A. SHEA, D. F. SMART, V. F. MELNIKOV, T. S. PODSTRIGACH, T. P. ARMSTRONG and H. ZIRIN, 1994. Electromagnetic and corpuscular emission from the solar flare of 1991 June 15: Continuous acceleration of relativistic particles. *Solar Phys.* 150, 267-283.

LIN, R. P. and H. S. HUDSON, 1976. Non-Thermal Processes in Large Solar Flares, *Solar Phys.* 50, 153-178.

MANDZHAVIDZE, N., 1994. Solar particles and processes. *In:* Proc. 23rd Int. Cosmic Ray Conf.: Invited, Rapporteur, and Highlight Papers, eds. D.A. Leahy, R.B. Hicks and D. Venkatesan, World Scientific Publ. Co. Pte Ltd, Singapore, p. 157-167.

MANDZHAVIDZE, N. and R. RAMATY, 1992. High-energy gamma-ray emission from pion decay in a solar flare magnetic loop. *Astrophys. J.* 389, 739-755.

MANDZHAVIDZE, N. and R. RAMATY, 1992. Gamma Rays from Pion Decay: Evidence for Long-Term Trapping of Particles in Solar Flares. *Astrophys. J. Lett.* 396, L111-L114.

MANDZHAVIDZE, N. and R. RAMATY, 1993. Particle acceleration in solar flares. *Nucl. Phys. B, Proc. Suppl.* 33AB, 141-160.

MANDZHAVIDZE, N. and R. RAMATY, 1996. Implications of solar flare charged particles, gamma ray and neutron observations. *In:* R. Ramaty, N. Mandzhavidze and X.-M. Xua (eds.). High Energy Solar Physics Workshop Proc. AIP, New York 374, 533-543.

MANDZHAVIDZE, N., R. RAMATY, V. V. AKIMOV and N. G. LEIKOV, 1993. Pion decay and nuclear line emission from 1991, June 15 flare. Proc. 23rd Int. Cosmic Ray Conf. 3, 19-122.

MURPHY, R .J., G. H. SHARE, D. J. FORREST, D. A. GRABELSKY, J. E. GROTH, C. M. JENSEN, W. N. JOHNSON, G. B. JUNG, R. L. KINZER, R. A. KROEGER, J. D. KURSEFF, S. M. MATZ, W. R. PURCELL, M.S. STRICKMAN, M.P. ULMER and W. T. VESTRAND, 1993. OSSE Observations of the 4 June 1991 solar flare. Proc. 23rd Int. Cosmic Ray Conf. 3, 99-102.

RAMATY, R. and N. MANDZHAVIDZE, 1994. On the origin of long lasting gamma ray emission from solar flares. Proc. of Kofu Symp., NRO Report No. 360, pp. 275-278.

RAMATY, R., N. MANDZHAVIDZE and B. KOZLOVSKY, 1996. Solar atmospheric abundances from gamma ray spectroscopy. *In:* R. Ramaty, N. Mandzhavidze and X.-M. Xua (eds.). High Energy Solar Physics Workshop Proceedings, AIP, New York 374, 172.

RYAN, J. M., D. FORREST, J. LOCKWOOD, M. LOOMIS, M. MCCONNELL, D. MORRIS, W. WEBBER, K. BENNET, L. HANLON, C. WINKLER, H. DEBRUNNER, G. RANK, V. SCHÖNFELDER and B. N. SWANENBURG, 1993. Neutron and gamma-ray measurements of the flare of 1991 June 11. *In:* M. Friedlander, N. Gehrels and D. J. Macomb (eds.). *AIP* Conf. Proc. No. 280, Compton Gamma Ray Observatory, AIP, New York 280, 631-636.

SOMOV, B.V., 1996. Reconnection and acceleration to high energies in flares. *In:* R. Ramaty, N. Mandzhavidze and X.-M. Xua (eds.). High Energy Solar Physics Workshop Proceedings, AIP, New York 374, 493-497.

VESTRAND, W. T. and D. J. FORREST, 1993. Evidence for a spatially extended component of gamma rays from solar flares. *Astrophys. J. Lett.* 409, L69-L72.

R. Pérez Enríquez[1], L. Miroshnichenko[1], R. E. Rodríguez Taboada[2] and A. Méndez Berhondo[2]

[1] National University of Mexico (UNAM), UNICIT, Juriquilla, Querétaro, Mexico. Email: roman@conin.unicit.unam.mx.

[2] Instituto de Geofísica y Astronomía, Depto. de Astronomía, CITMA, La Habana, Cuba.