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Solar modulation of low energy galactic cosmic rays in the near-earth space environment

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Abstract

This is an overview of the solar modulation of galactic cosmic rays as seen from the Earth and spacecrafts closeby, where we have put the contributions of Latin-American researchers in the global context in the last five to ten years. It is a broad topic with numerous intriguing aspects so that a research framework has to be chosen to concentrate on, therefore we have put our emphasis on measurements of the cosmic ray flux, without attempting to review all details or every contribution made in this field of research. In consequence, after establishing the basic characteristics of the cosmic radiation such as composition and energy spectrum, we focus on a few selected subjects, almost all within the framework of solar modulation of galactic cosmic rays such as Forbush decreases, periodic variations, space and atmospheric weather cosmic ray relationships, to which we add a general description of ground level enhancement observations. Controversial aspects are discussed where the appropriate results are presented, some of the challenges and prospects of key issues are also pointed out. At the end of the paper, a brief summary of the last decade Latin-American contributions to the subjects treated is given.
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Keywords: Cosmic rays; Solar modulation

1. Introduction

Galactic cosmic rays (GCRs) are ionized nuclei with energies above ~100 MeV/nucl. Very few of them can have energies up to 10^{20} eV, corresponding to about 20 J (that is the kinetic energy of a tennis ball moving at the speed of 160 km/h). GCRs hit the Earth at a rate of about 1000/(m^2 s), their source is outside the solar system but within the galaxy, probably it is shock acceleration at supernova remnants. Only the very highest energies might originate in extragalactic sources.

The GCR incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer. The basic constituents of galactic cosmic radiation are protons and α-particles, and around 1% of electrons. Heavier ions, such as C, and Fe can be observed in much smaller numbers. The incoming charged particles are "modulated" by the solar wind, the expanding magnetized plasma generated by the Sun, which decelerates and partially excludes the lower energy galactic cosmic rays from the inner solar system. There is a significant anticorrelation between solar activity (which has an alternating eleven-year cycle) and the intensity of the cosmic rays with energies below about 10 GeV, in this paper these will be denominated as "low energy galactic cosmic rays".

In addition, the lower-energy GCRs are affected by the geomagnetic field, which they must penetrate to reach the top of the atmosphere. Thus the intensity of any component of the cosmic radiation in the GeV range depends both on the location and time of the observer.

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The longest time records of GCRs are from neutron monitors. They provide integral measurements above their respective cut-off rigidity ranging from a few GV to 17 GV with cut-off rigidities being lower at high geomagnetic latitudes and at higher altitudes. The lowest energies can be measured only either from balloons or at the outer space.

The observable quantities therefore are time sequences at fixed positions in space and spatial gradients in GCR intensities between observers at different positions. In addition, an easy access of GCRs over the poles of the Sun was expected, as observed: in the plane of the ecliptic, the magnetic field line is tightly wound to an Archimedean spiral while it is much less wound up above the poles. Thus it was observed that in the inner heliosphere GCR intensities are higher over the poles than in the plane of the ecliptic.

The main questions regarding GCRs are: 'Where do they come from? How are they accelerated to such high energies?', and 'How do they propagate through the interstellar and interplanetary medium toward the inner heliosphere?

This paper deals with the low energetic part of GCRs, namely the energy range from some tens of MeV to some tens of GeV. Thus we are mainly concerned with the interaction between particles and the background heliospheric plasma. The way these interactions develop and the influence they will have on the galactic cosmic ray flux will largely depend on the state of the heliosphere, which in turn will be determined by the solar activity. Therefore studying solar modulation, we are at the same time increasing our knowledge about the Sun and its sphere of influence: the heliosphere.

We make a brief review of the main aspects of solar modulation that involve results from measurements of the GCR intensity at the Earth or its near space environment. The contributions done by the Latin American researchers in these fields are referred in the proper places in the text; a brief summary of what we consider to be the main results is given at the end of the manuscript.

In addition, we have included a section where solar flare particles were observed with detectors located at the Earth´s surface, the so called Ground Level Enhancements (GLEs, see Section 6), since most of these events have been detected with the same instruments that operate for GCRs, they represent an extreme phenomenon of solar activity, the phenomenology of GLEs is strongly related with GCR, they play a significant role in space weather studies and there are relevant contributions of Latin American researchers in the field.

The plan of the paper is as follows: we start with a brief historical description of some of the discoveries that allowed the advancement in the knowledge of the subject (Section 2); Section 3 deals with the main characteristics of the galactic cosmic radiation, namely their spectra and composition. In Section 4 we review what we consider to be the main aspects of GCR modulation by solar activity, apart from the most important phenomenon of Forbush decreases, which we discuss separately in Section 5. Research done on periodic variations is presented in Section 6; from which we continue to describe and discuss recent findings in the subject of GLEs. A discussion of the relationships found between GCRs, space and terrestrial weather is left until Section 8, since there are many interrelated issues and there are still many controversies around the results found by different groups. In Section 9 we summarize the already referenced main contributions done by the Latin American research groups to the subjects presented and point to some of the unresolved questions.

For a recent review on the work done in this region of the world concerning the highest energy part of the cosmic ray spectrum see Sidelink (2014).

2. The early years

The first observations of the energetic particle component which later was to become the galactic cosmic radiation date back to 1912, when Victor Hess flew an ion chamber on a manned balloon up to an altitude of 5 km. The radiation increased with height, in contrast to what was expected from its supposed terrestrial origin. Since Hess found no difference between day and night side, he ruled out the Sun as the cause for the increased ionization. Instead, he suggested a penetrating radiation from the outside which he called 'Hohenstrahlung' in a very general denomination as the nature of the radiation was still unknown. In 1927 Clay was the first to report a latitudinal effect: close to the equator, the radiation was lower than at higher latitudes. When Stormer's calculations of particle trajectories in the geomagnetic field became available in 1930, the latitudinal effect could be understood as due to shielding by the geomagnetic field. One of the pioneers to calculate particle trajectories at cosmic ray energies in the geomagnetic field was M. Sandoval- Vallarta from México, together with the Belgian G. Lemaitre. The next corner stone in cosmic ray research was the discovery of a maximum in cosmic ray intensity at an altitude of about 15 km by Pfotzer (1936). This Pfotzer maximum results from the interaction between GCRs and the atmosphere. In 1937 Forbush observed a world-wide decrease in GCRs during a strong magnetic storm (Forbush decrease), giving the first evidence for a relation between solar activity and GCRs. Subsequently, GCR energy spectra, composition and temporal variations have been studied; the most important results of the portion of the spectrum affected by solar activity and their interpretation will be described below. Today, there are basically two means to register cosmic rays: ground-based observations by a world-wide net of neutron monitors and muon telescopes, and satellite observations. It is important to note that ground based observations register generally one or the other components of the secondary cosmic radiation that is developed in the Earth´s atmosphere as the primary cosmic rays interact with the atmospheric nuclei. The secondary cosmic radiation was discovered in experiments done in the French Alps by Pierre Auger and his students (Auger et al., 1939).

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An extensive network of neutron monitors was installed over the Earth in 1957, on the occasion of the International Geophysical Year; they were selected as they provide information at rather high energies above their cut-off rigidity of some GV, at one position in space with an angular resolution (anisotropy) derived from the combination of neutron monitors from different places (see Sections 4–8).

Spacecraft, on the other hand, give measurements from different positions in space, including the outer heliosphere and higher heliographic latitudes. Spacecraft measurements can be made in rather small, well defined energy or rigidity bands well below neutron monitor energies, as well as in integral channels above a certain threshold. For limited small time intervals, measurements are also made from balloons.

3. Energy spectra and composition of GCR

Fig. 1 shows a composite of measurements giving the energy spectra for four different particle species: hydrogen (H), helium (He), carbon (C), and iron (Fe) reported by Simpson (1983). As the state of the heliosphere changes from solar minimum to solar maximum, therefore the spectra of the different species are not always identical. In Fig. 1, the spectra of H, He and Fe have two noticeable different sets of measurements at the lowest energies due to solar maximum/minimum conditions.

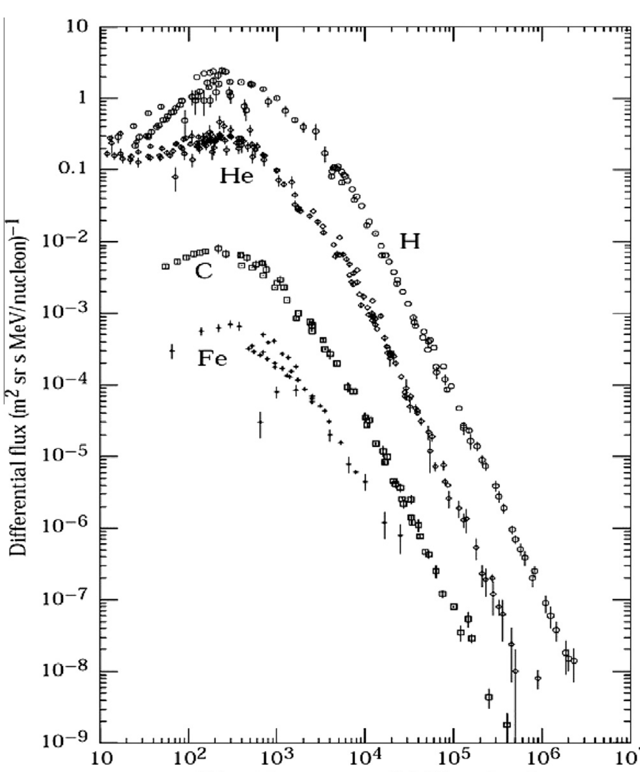

Fig. 1. Cosmic ray energy spectra for the elements H, He, C, and Fe, (from: Simpson, 1983).

Energetically, the galactic cosmic radiation starts at energies of some 100 MeV/nucl. At lower energies, the spectrum is dominated by particles accelerated on the Sun or locally at raveling interplanetary shocks or corotating interaction regions. At energies above some ten MeV/nucl, the spectrum has a positive slope, i.e. the intensity increases with increasing energy. A positive slope can be observed up to some hundred MeV/nucl, it then turns over to a power-law $E\gamma$ with a slope $\gamma = -2.5$ (see also, e.g., Swordy, 2001).

4. Solar modulation of GCRs

At energies below a few GeV/nucl, GCRs show a strong dependence on solar activity with maximum intensities during solar minimum, cf. Fig. 1. With increasing solar activity, the maximum of the energy spectrum shifts toward higher energies. At proton energies of about 100 MeV/nucl the modulation is maximal, while at energies of about 4 GeV/nucl the modulation only is 15–20%. The energy/rigidity dependence may also be seen in the comparison of neutron monitors with different cut-off rigidities. Up to about 10 GeV galactic electrons show a spectrum similar to that of the protons, modulation of galactic electrons is observed between 0.1 and 1 GeV (see, e.g. Strauss et al., 2011).

From Fig. 2 it is obvious that GCRs are modulated by an 11-year cycle with intensity maxima during solar minimum (e.g. in 1964, 1976, 1986, 1996, 2009) and vice versa (as in 1969, 1980, 1990, 2000). In addition, the shapes of successive maxima alternate between peaked and flat (or mesa-like): the maximum of cycle 20 (1972–1978.0) is a broad plateau upon which several large decreases are superimposed while in cycles 19 (1965) and 21 (1987) the peaked maximum lasts only a little longer than a single solar rotation.

The theory of GCR transport was first formulated by Parker (1965). Due to the irregularities of the large scale interplanetary magnetic field IMF, energetic particles in the interplanetary space walk randomly as the irregularities are moving with the solar wind velocity. A Fokker Planck equation describes the time evolution of the probability density function of position and momentum of the particles. In addition to convection due to the constant expansion of the solar wind and diffusion due to magnetic irregularities, GCRs experience two additional effects. One of them is the acceleration or deceleration. The solar wind plasma expands in free space and is compressed at the shocks near the planets or in the interplanetary space. The inhomogeneities with different IMF become mutually more distant or closer to each other. This leads to adiabatic cooling or heating due to multiple interactions of GCRs with inhomogeneities. Modulation of GCRs in the inner heliosphere is controlled by convection in the solar wind, diffusion, particle drifts and adiabatic energy losses. An excellent review of the current understanding of the modulation is given by (Potgieter, 2013).

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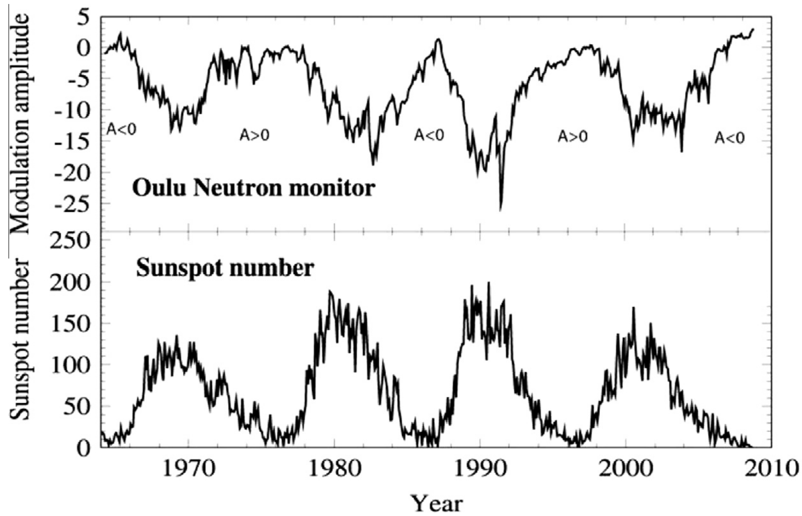

Fig. 2. Anti-correlation between cosmic ray intensity, measured by Oulu neutron monitor, and the sunspot number (from: Heber et al., 2009).

In addition, the curvature and gradB drifts in the IMF play a role in the modulation. The gyration of particles around the field line is faster than scattering. Thus particles are subject to drift due to the large scale spatial structure of the IMF.

For the solution of the transport equation the determination of the coefficients deduced from the measurements at various positions and energies is important. Reviews of transport coefficients for GCRs can be found in e.g. Palmer (1982), Valdés-Galicia (1993), Usoskin et al. (2005) provide a long series of a parameter allowing for a quantitative estimate of the average monthly differential energy spectrum of GCR near the Earth for a long time interval.

Galactic cosmic rays, measured directly by their secondaries at Earth over more than half a century reveal a complicated structure in its temporal behavior. The nucleonic component of primary CR is appropriate to study solar modulation from ground based measurements. GCR modulation as observed from the Earth was reviewed e.g. by (Belov, 2000). Single point measurements are influenced by the large scale structure of the IMF over the heliosphere. Long term modulation is observed as a series of steplike decreases. Outward propagating diffusion barriers were identified as merged interaction regions, MIRs (Burlaga et al., 1985).

Strauss et al. (2012) reviewed some of the most prominent GCR observations made near Earth, and indicate how these observations can be modeled and what main insights are gained from the modeling approach. Also, discussion on drifts as one of the main modulation processes, is given as well as how drift effects manifest in near Earth observations. A discussion trying to explain the observations during the past unusual solar minimum is included.

Siluszyk et al. (2011) developed a two-dimensional (2-D) time dependent model of the long period variation of GCR intensity, they included the slope of the power spectrum density of IMF fluctuations, the magnitude of B, the tilt angle of heliocentric current sheet and the alternating effect of particle drift of the IMF.

The recent solar minimum was unusually long and deep, the modulation of GCRs was the smallest we have had for more than 70-years of continuous records (see e.g. Badruddin, 2011; Bazilevskaya et al., 2011). In 2009 the highest GCR fluxes were recorded (particles with energy > 0.2 GeV) in the history of the GCR measurements in the stratosphere (Stozhkov et al., 2011). An increase of the flux on NMs during that minimum was also reported (e.g. Moraal and Stoker, 2010). GCR modulation for solar cycle 24 began at the Earth's orbit in January 2010 (Ahluwalia and Ygbuhay, 2011). That paper reports long-term drifts of unknown origin in some NMs. Such effects have to be examined in detail to reconcile the understanding of the long term GCR variations from measurements with the predictions of the models. Sources of multiple NM measurements have become available recently for the use of the community, e.g. NMDB data base at http://nmdb.eu.

Modulation of the low energy component of GCRs inside the heliosphere provides useful tools to determine the relevance of solar phenomena that influence the structure and evolution of the heliosphere. Reviews of the advancement in the understanding of the transport of CRs in the heliosphere may be found e.g. in (Valdés-Galicia, 2005; Chowdhury et al., 2011; Potgieter, 2013). GCR time profiles observed at a single detector (say, a NM or a muon Telescope) on the ground are the result of the superposition of many transitional effects due to the changing structures of IMF irregularities inside the heliosphere, the rotation of the detector with the Earth, the effects of the magnetosphere and by the variable state of the atmosphere.

5. Forbush decreases

Forbush decreases (FDs) are perhaps the most impressive phenomenon of GCRs caused by solar activity. The

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cosmic ray intensity may have a drastic decrease (which could be up to 20%) in a few hours, with a slow recovery, lasting typically around a week. It is one of the extreme manifestations of transient modulation of GCRs, therefore it is an interesting subject of study to elucidate the mechanisms of solar activity and its influence in the interplanetary medium. FDs are generally correlated with co-rotating interaction regions (CIRs), interplanetary shocks or interplanetary coronal mass ejections (ICMEs) originated at the Sun (e.g. Prasad Subramanian, 2009; Richardson and Cane, 2011; Musalem, 2013). One of the first papers suggesting that the solar cycle dependent modulation of GCRs can be explained by ICMEs and IMF inhomogeneities in the heliosphere was that of (Newkirk et al., 1981). Correlation of CR intensity and ICME occurrence at a single NM with high geomagnetic cut-off is reported e.g. by Mishra et al. (2011) for different solar magnetic field polarities.

Recently (Dumbovic et al., 2011; Musalem et al., 2015) performed statistical studies of the relationship between characteristics of solar wind disturbances, ICMEs, CIRs and shocks, with properties of FDs. It was found that not only the increase in magnetic field strength and fluctuations define the amplitudes of the GCR decrease, but it is also important the length of time the Earth stays inside the solar wind disturbed region; the recovery phase depends on the magnetic field strength and size of the disturbance. Distinct relations of FDs and geomagnetic activity measured by the Dst geomagnetic index in different events was reported by Kudela and Brenkus (2004), Kane (2010). Richardson and Cane (2011) analyzed a large number of ICMEs and their associated shocks passing through the Earth during 1995–2009. The deepest FDs are always found to be associated with ICMEs accompanied by a magnetic cloud. Examining simultaneous observations of FD events by different GCR stations remains a subject of interest. Variability in the manifestations of FDs demonstrates that there are still open questions in this field (e.g. Okike and Collier, 2011; Pintér et al., 2011).

FDs are observed not only by NMs but also at higher energies of primary GCRs by muon telescopes or other types of detectors (e.g., Braun et al., 2009; Abbrescia et al., 2011; Bertou, 2011; Augusto et al., 2012; Dasso and Asorey, 2012; Deggeroni et al., 2013).

6. Ground level enhancements

The Sun emits many types of radiation during solar flares (from radio to gamma rays) as well as energetic particles that may be observed in the interplanetary medium or at Earth depending on the energy released by the explosive phenomenon whose main phase can last up to some 20 min. The most energetic of these flares may be able to accelerate particles to GeV levels. In this case particles can be observed at the Earth´s surface, since they are able to penetrate the geomagnetic field, energies of about 1 GeV penetrate only the polar regions (beyond 55° latitude), but progressively lower latitudes are penetrated as energies increase; in this case the event is denominated as a ground level enhancement (GLE).

Solar flares are still commonly assumed as the source of SEPs; however, since the mid 80's CMEs are also recognized to be associated with the release of solar particles into the interplanetary medium (see e.g., Kahler et al., 1984). During a solar flare, electromagnetic radiation (from radio to, in the most intense events, gamma rays) is generated by the hot plasma interactions with the local magnetic fields. The onset of an increase in, say, X-ray emission detected at Earth-orbiting spacecrafts is approximately simultaneous with the visible range observations of a solar flare. Unlike electromagnetic radiation, both the onset time and maximum intensity of the SEP flux at an observation point in space depends on the energy of the particle, the heliolongitude location of the flare with respect to the observation point and the particular state of the solar wind plasma (quiet or perturbed); in particular, a CME may contribute to the acceleration process and modify the time profile of the solar particles.

Since the 1980s (e.g. Lin, 1987), two types of SEP events have been recognized: impulsive and gradual. Miroshnichenko (2001) reviewed the results of SEP investigations since 1942, including a large amount of data, obtained during a long time, readers are referred to that extraordinary monograph for details on historical evolution of SEP observations and a thorough discussion of the main physical phenomena associated. Recently Hudson (2011) reviewed the knowledge of solar flares putting emphasis on their general properties. Flare radiation and CME kinetic energy may have both magnitudes, of around 10^{25} J each for an X-class event, with most of the radiant energy in the visible and UV. According to the analysis done, the impulsive phase of the flare dominates the energetics of the process; energy and momentum of this phase reside mainly in the electromagnetic field, not in the plasma. Barnard and Lockwood (2011) constructed a database of gradual SEP events for 1976–2006 using mainly data of protons with $E > 60$ MeV. The events during solar minimum are observed with higher fluence, although the number of events decreases when solar activity is low. Thus, at lower solar activity very strong flares may be more probable.

GLEs are observed by NMs when the energy of accelerated particles in the flare or in interplanetary space exceeds the atmospheric threshold and the geomagnetic cut-off rigidity. Gopalswamy et al., 2010 and Andriopoulou et al. (2011) summarized and discussed the main characteristics of GLEs for the past solar cycles. Moraal and McCracken (2011) analyzed all the cycle 23 GLEs. A double pulse is observed in three of the 16 GLEs; this could probably indicate a two stage acceleration process in the Sun, but also the observed two peak profiles if the particles followed two different paths through the IMF changing conditions (see, e.g. Flückiger, 2009). The associated flares have good magnetic connection to the Earth. A fast

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anisotropic first pulse is always followed by a smaller, gradual, less anisotropic second pulse. Vashenyuk et al. (2011) present a GLE modeling technique applied for 35 large GLEs for the period 1956–2006 and obtained features of prompt and delayed components of relativistic solar particles. Kurt et al. (2011) studied signatures of protons with energy above several hundred MeV associated with major solar flares and observed by NMs during GLEs. The authors revealed that the delay of the earliest arrival time of high-energy protons at 1 AU with respect to the observed peak time of the solar bursts did not exceed 8 min in 28 events. This indicates that an efficient acceleration mechanism of protons responsible for the GLE onset must be operating near the time of the main flare energy release. In contrast with these are the results of Reames (2009), who found that the initial solar proton release times occur after the onset of type II emission, suggesting a coronal acceleration mechanism around 2 solar radii for 30 GLEs between 1973 and 2006. For GLE observations, high altitude NMs are important due to their high count rate and high statistics. A list of GLEs observed at one high mountain NM can be found in (Kudela and Langer, 2008). Evidence exists that GLEs may reach low latitude, mountain altitude NMs, that lead to estimates that 10 GeV protons were produced in the source flare (Vargas Cárdenas and Valdés-Galicia, 2012).

Miroshnichenko et al. (2012) found some peculiar time variations in the GCR flux and other solar and interplanetary phenomena that seem to indicate precursors of GLEs; this could be an indication that solar particle generation may be synchronized with periodic processes in the solar dynamo and solar atmosphere. In a study that uses wavelet spectral analysis combined with fuzzy logic tools, Pérez-Peraza and Juárez (2015) were able to reproduce previous known GLEs and make a prognosis of future events, predicting that the next GLE should occur in the first semester of 2016.

Some space weather events might be predicted based on GLE detection (see Section 9).

An important source of information about protons accelerated near the Sun and about their interactions with residual solar atmosphere are solar gamma-rays and neutrons. Their observation near Earth is not affected by magnetic fields as it is in the case of protons. Production of γ-rays and neutrons results from nuclear interactions of ions in the solar atmosphere.

Vilmer et al. (2011) reviewed the γ-ray and neutron observations, putting emphasis on the RHESSI measurements that provide high spectral resolution to reveal line shapes and fluences, and provide a gamma-ray imaging technique. The authors point out that the study of high energy neutral emissions from the Sun still has many open questions.

Biermann et al. (1951) visualized a long time ago that high energy neutrons created by nuclear interactions of protons in the atmosphere of the Sun may be observed on the Earth's orbit, the first direct indication of solar neutrons on the ground was reported from high mountain NMs Jungfraujoch and Lomnický štít after the flare of June 3, 1982 (Debrunner et al., 1983; Efimov et al., 1983). Following that event, the interest to detect solar neutrons with ground based equipment increased. Several NMs started to measure with better temporal resolution, and new experimental devices for detection of gamma rays and neutrons both on the ground as well as on satellites were constructed. High energy gamma rays and neutrons during several solar flares have been observed in the past decade also e.g. on low altitude polar orbiting satellite Coronas-F (Kuznetsov et al., 2006, 2011; Kurt et al., 2010) and on special purpose detectors located on top of high mountains (Muraki et al., 2008; Valdés-Galicia et al., 2009; González et al., 2010). Recently, the Large Area Telescope on board of Fermi has also detected gamma ray emissions from the Sun (Abdo et al., 2011).

7. Periodic variations

As previously stated, the GCR intensity is most frequently measured by ground-based neutron monitors (NMs) which are sensitive to GCR with energy of a few tens of GeV. The worldwide network of NMs has been regularly measuring the CR intensity during the last five decades. The flux rate of GCR incident on the Earth's upper atmosphere is modulated by solar activity, giving as a result a first order anticorrelation between them which is the origin of the well-known 11y cycle. However, the power spectrum of GCR exhibits periodicities from minutes to decades; some of the important periodicities detected are 27, 38, 66, 150, 170 days, 1.3 y, 1.68 y (see e.g.: Attolini et al., 1975; Xanthakis et al., 1989; Kudela et al., 1991, 2002; Kudela, 2009; Valdés-Galicia et al., 1996; Mavromichalaki et al., 2003a; Alania and Wawrzynczak, 2008; Minarovjech et al., 2008). Most of those observed periodicities are correlated with solar phenomena. The transport of CR from the edges of the heliosphere to the Earth or spacecrafts nearby depends on the structure of the IMF status, which in term is determined by the different manifestations of solar activity. So, the study of GCR variations provides keys to derive the configuration of the IMF in the heliosphere. Therefore, time-series analysis of GCRs and specially their periodic behavior would enable us to investigate both the large and small scale fluctuations of magnetic fields in the heliosphere.

El-Borie and Al-Thoyaib (2002) calculated the Power Spectral Density to the daily data of cosmic rays registered by eight different NM stations and detected the 28 and 50–54 days periods in Climax NM during the solar minimum of cycles 21 and 22. They also found the 45–48 days and $\sim$66 days peaks around the maximum phase of cycle 20 and 21. Periods of $\sim$40 days, $\sim$55 days and $\sim$78 days were detected in GCR time-series of Haleakala and Climax stations in different time phase during the declining phase of cycle 22 (Caballero and Valdés-Galicia, 2001). In the same paper these authors investigated the periodic nature of CR

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intensity in the Huancayo-Haleakala neutron monitors for the period 1990–1999 and found significant peaks at 30, 38 and 115 days. Mavromichalaki et al. (1990) detected prominent peaks at 81 days and 111 days in GCR data during cycle 21. In another paper Mavromichalaki et al. (2003b) studied the periodic fluctuation of GCRs data obtained from Climax NM for the time interval from 1953 to 1996 and noted significant peaks at 2.3, 2.8, 5.1, 6.6, 8.7 and 12.4 months. A period of ~170 days was noted by Joshi (1999) in climax NM data for the period 1989–1991 which corresponds to the maxima of cycle 22.

Parallel investigations have revealed similarities between the periodicities of cosmic ray intensity and different solar activity indices in different solar cycles (e.g.: Rybák et al., 2001; Mavromichalaki et al., 2003a; Chowdhury et al., 2010; Bai, 2003; Joshi and Joshi, 2005). An important quasi-periodicity observed in GCR is that of ~1.7 year (Valdés-Galicia et al., 1996; Kudela et al., 2002). It was found also in the outer heliosphere in Voyager data (Kato et al., 2003). Okhlopkov (2011) reports that the length of the quasi-2 year periodicity in even and odd numbered cycles may differ by as long as ~2 months. Mendoza et al. (2006) and Valdés-Galicia and Velasco (2008) examined solar magnetic fluxes during the period 1971–1998 and found that the ~1.7 year is the dominant fluctuation for all the types of magnetic fluxes analyzed and that it has a strong tendency to appear during the descending phase of solar activity. Quasi-periodicities of ~1.3 year (observed in the solar wind too) and ~1.7 years were seen neither often nor prominently in several solar activity indices (Kane, 2005). Rouillard and Lockwood (2004) relate a strong 1.68-year oscillation in GCR fluxes to a corresponding oscillation in the open solar magnetic flux and infer CR propagation paths confirming the predictions of theories in which drift is important in modulating GCR flux. Kane et al. (1949) reported that starting with Alfven's original suggestion, it is possible to develop a quantitative equilibrium theory for the trapping of CR in the magnetic field of the Sun, where in addition to the effect of scattering in the geomagnetic field, the direct absorption of GCR by five heavenly bodies Mars, Venus, the Earth, the Sun, and the Moon is also taken into account. This may be one of candidates for finding the link between the work of Chárvatová (2007), who suggested that the motion of the inner planets and the ~1.7 year quasi-periodicity observed in GCR may have some relationship.

At longer time scales McCracken et al. (2002) identified quasi-5 year variability in GCRs when solar activity is low. It is desirable to investigate whether a correlated 5-year signal exists in other geophysical and biological records, and if so, it could provide an additional source of data on the characteristics of the Sun at times of low solar activity. Using IMP-8 data, Laurenza et al. (2009) studied solar proton flux between 190 to 440 MeV and found 9.8, 3.8, and 1.7–2.2 year periods as the most significant. The coronal emission line of Fe XIV at 530.3 nm measurements by the worldwide network of coronal stations (Rybanský, 1975) was used by Mavromichalaki et al. (2005) to find a ~2.3 year's periodicity in the coronal index. A summary of all GCR quasi-periodicities obtained with NM measurements is presented in Fig. 3.

A power spectrum analysis at various cut-offs for NM and using also muon detector data that are sensitive to higher energies would be suitable to find out whether that quasi- periodicity has a cut-off energy in the region where these detectors operate.

8. Cosmic rays, space and terrestrial weather

Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space borne and ground based technological systems and affect

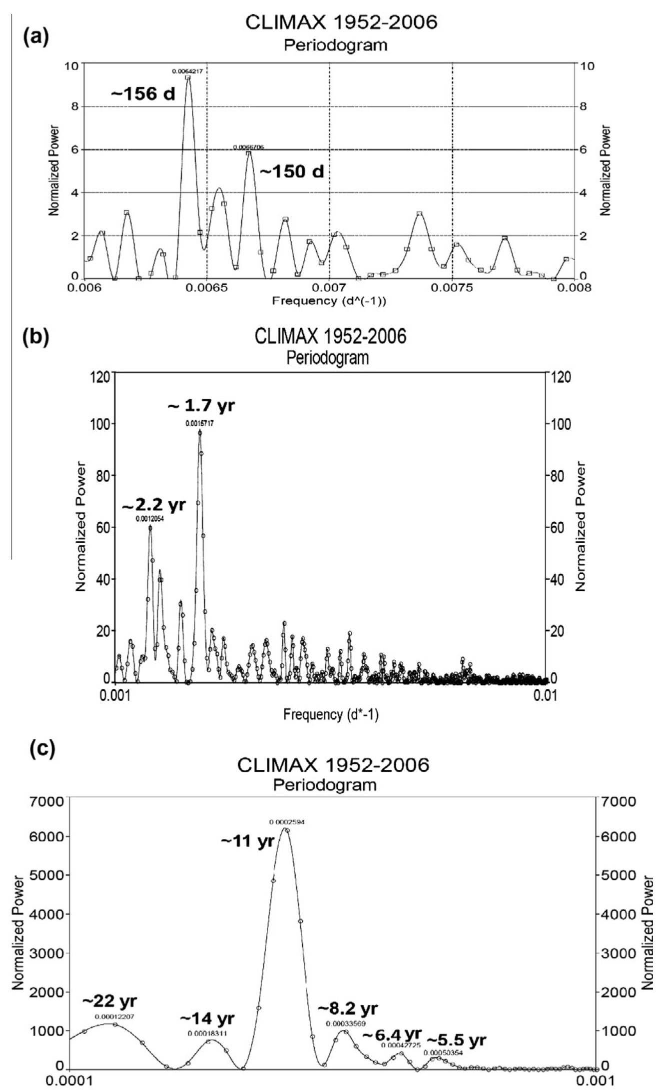

Fig. 3. Periodograms of the Climax neutron monitor counting rates from 1952 to 2006. (a) Shows the two peaks above 0.95 of significance level, ~150 d and ~156 d. (b) shows the most important peaks for ~2.2 yr. and ~1.7 yr. (c) Periodogram with several quasi-periodicities at low frequency, (from: Kudela, 2012).

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human life and health (NSWP, 1995). Space Weather has recently emerged as a scientific field of study, GCRs may play a role in this field either through the consequences in materials irradiated in space, atmosphere and on the ground, where they might be affecting technological systems in use and the biota. On the other hand the flux of GCRs may develop anisotropies as a consequence of an ICME or shock approaching the Earth and could therefore be used as precursor signals of geomagnetic storms. GLEs might also provide precursory information for some space weather manifestations. There are several books and reviews on space weather, its possible forecasting and its relationships with CR (see e.g. Kamide and Chian, 2007; Kudela, 2009; Flückiger, 2009; Dorman, 2010).

Strong solar storms produce manifold radiation that might have hazardous effects to satellites, communications and biota (Azcárate et al., 2012). Ions with energies from tens to hundreds of MeV are amongst these. A good network of NM producing data in real time with good statistical resolution might produce alerts to solar storms several tens of minutes in advance, this is an essential point to use ground based measurements.

Eight high and medium latitude NMs have been integrated into a network that detects count rate increases recorded in real time and triggers an alarm when a GLE is detected (Kuwabara et al., 2006). The authors claim that this GLE alert precedes the earliest indication from GOES (100 MeV or 10 MeV protons) by around 10–30 min.

Another system using NMs is described by Mavromichalaki et al. (2006). At higher energies the Global Muon Detector Network is important source of the precursory information for geomagnetic storms (e.g., Rockenbach et al., 2001) and for sounding of CME geometry before its arrival to Earth (Kuwabara et al., 2004). Precursor signatures of relatively small geomagnetic storms were observed by Braga et al. (2011). Recently (Agarwal et al., 2011) stressed the importance of the change of geomagnetic cutoff rigidity to understand the physical mechanism responsible for Forbush decrease and geomagnetic storms.

Galactic cosmic rays and solar energetic particles interact with the material of spacecrafts, airplanes and atmosphere, and may cause failures or particular effects on some of these systems. There is a variety of effects with potential consequences on the reliability of the electronic elements. The energy deposition in materials resulting in permanent damage in silicon semiconductor devices due to individual events caused by the interaction of particles inside the active volume of silicon devices, along with the review of processes of electromagnetic interaction, nuclear interaction with matter is described in detail, e.g., in the book by Leroy and Pier-Giorgio (2009). Miroshnichenko (2003) provides a phenomenological picture of the radiation environment of the Earth, summarizes observational data and theoretical findings related to the main sources of energetic particles in space; the author also surveys the methods of prediction of radiation risk on spacecraft.

Augusto et al. (2012) point out that ICMEs and CIRs may cause disturbances in cosmic rays that are not necessarily Forbush decreases. Making use of the muon telescope installed in the middle of the South Atlantic Anomaly they found anomalies in the cosmic ray data well correlated with interplanetary disturbances. These are relevant for space weather predictions.

The influence of ionizing radiation, including CR, on the emergence and persistence of life is reviewed by Dartnell (2011). Consequences of the impact of ionizing radiation on organisms and the complex molecules of life are discussed; the author also points out that ionizing radiation may perform crucial functions in the origin of life and the generation of habitable planetary environments. The continuous measurement of CR with good temporal resolution by many ground based detectors is important for monitoring radiation and its temporal and spatial variability, and has a potential to be one of the elements for schemes of space weather effects prediction (Schrijver et al., 2015). The study of the possible effect of solar variability on living organisms is one of the most controversial issues of present day science. A research conducted by Mendoza and Sánchez de la Peña, 2010, showed that at middle geomagnetic latitudes there are biological consequences of the solar/geomagnetic activity, pointing out that there is a tendency for myocardial infarctions (death or occurrence) to increase one day after a geomagnetic Ap index large value or during the day of the associated Forbush decrease.

Studies on the possible relation of GCRs to the atmospheric processes started probably with Svensmark and Friis-Christensen (1997). Nowadays long term series of data from NM and muon detectors are available to characterize CR variability in detail; those, together with recent experimental results giving a primary role to cosmic rays in aerosol formation (Kirkby et al., 2011), may shed some light on the matter. Harrison et al. (2011) report base height distributions for low clouds (<800 m) measured at the Lerwick Observatory, Shetland, UK, they found variations commensurable with those present in GCR: 27 day and 1.68 year periodicities might be identified in the cloud base height data of stratiform clouds, when those are also observed in GCRs series. Other papers (Sloan and Wolfendale, 2008; Erlykin et al., 2009a,b) show that a large portion of the clouds is not related to GCRs. Forbush decreases seem to be unrelated to global cloud cover at any altitude nor latitude (Calogovic et al., 2010). The mechanisms of solar forcing of the climate and long term climate change is summarized, and the role of energetic charged particles (including GCRs) on cloud formation and their effect on climate is discussed in (Siingh and Singh, 2010). Fichtner et al. (2006) point out that the presence of a 22-year periodicity must be expected if GCRs play some role in driving climate. The test of whether 22-year periodicities in climate indicators are present or

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not could be a promising tool to bring the intense debate present currently in the scientific literature to a conclusion satisfying the community.

Cosmic ray characteristics along with the geomagnetic and solar activity are discussed also in connection with hurricanes (e.g. Kavlakov et al., 2008; Mendoza and Pazos, 2009; Pérez-Peraza et al., 2008; Kane, 2006; Mendoza, 2011).

During the last decade the relations of GCRs to the atmospheric electricity has been studied extensively. Intensity variations of secondary GCRs during thunderstorms (Lidvansky, 2003; Lidvansky and Khaerdinov, 2011) studied with the Carpet shower array of the Baksan Neutrino Observatory were found to have, in addition to regular variations correlating with the near-ground electric field, considerable transient changes of the intensity. Chilingarian et al. (2010) presented the energy spectra of electrons and gamma rays from the particle avalanches produced in the thunderstorm atmosphere, reaching the Earth's surface. Ermakov et al. (2009) show that the main parameters of atmospheric electricity are related to GCR. Álvarez-Castillo and Valdés-Galicia (2009, 2010) and DeMendoça et al. (2011) reported on short term periodicities in the CR flux that are present only during times of thunderstorms. Results of a spectral analysis of surface atmospheric electricity data (42 years of Potential Gradient, PG at Nagycenk, Hungary) showed a 1.7 year quasi-periodicity (Harrison and Märcz, 2007) that is present during 1978–1990, but not during 1963–1977. The occurrence of that quasiperiodicity typical of GCRs in the data of atmospheric electricity in several places around the world and time periods after 1990 could provide evidence to support or disregard CR influence in atmospheric phenomena.

Singh et al. (2011b) and Siingh et al. (2011a) reviewed CR effects on terrestrial processes such as electrical phenomena; lightning discharges, temperature variation, space weather phenomena, Earth's climate and the effects of GCRs on human health. The paper includes the new results and the authors point out many basic phenomena which require further study as well as new and long data sets.

9. Brief summary of contributions done by researchers in LA

We have done a review of the solar modulation of GCRs as seen from the Earth and spacecrafts closeby, where we have put the contributions of Latin-American researchers in the global context. The topic treated is wide and has many unresolved issues so that we have chosen a few subjects to concentrate on, our emphasis was put on measurements of the cosmic ray flux at the Earth´s surface, without attempting to review all details or every contribution made in this field of research. Therefore, we chose Forbush decreases, periodic variations, space and atmospheric weather cosmic ray relationships, to which we added a general discussion of GLE observations, as these are closely related to solar modulation and their occurrence is relevant for space weather.

Certainly the first and very important contribution of a scientist in Latin America for low energy cosmic ray research was that of Sandoval Vallarta with his detailed calculations of asymptotic directions of approach. Lines of research that were continued successfully by Ruth Gall and co-workers (see, e.g., Gall, 1964) In the last decade, mainly the groups in Argentina, Brazil and Mexico have maintained research lines in the fields covered by this paper. It is not surprising that is in these countries where detectors of one kind or the other have been operating for long periods of time.

One of us has done reviews to join the effort to try to understand different aspects of solar modulation (Valdés-Galicia, 1993, 2005). Within the limits of the scope adopted by this paper, measurements of the cosmic ray flux at the Earth´s surface will continue to be important to fully understand the role of the different physical processes involved in modulation of GCRs.

Several researchers have used the scientific infrastructure installed in the region to study Forbush decreases and its relationship to solar phenomena (Bertou, 2011; Augusto et al., 2012; Dasso and Asorey, 2012; Deggeroni et al., 2013; Musalem, 2013; Musalem et al., 2015). Being an extreme phenomenon introducing drastic changes in the GCR flux in a short time, their connection to solar activity and the dynamics accompanying them are relevant subjects still lacking a full comprehension. Studies involving characteristics of solar and solar wind phenomena connected to FDs should continue.

Solar particles have attracted some attention in the area too, from theoretical studies of the acceleration of particles at the Sun (Miroshnichenko, 2001; Miroshnichenko et al., 2009), to relevant characteristics of GLEs (Vargas Cárdenas and Valdés-Galicia, 2012; Pérez-Peraza and Juárez, 2015). In that category falls also the effort done to install detectors and join the effort to understand solar neutrons (Muraki et al., 2008; Valdés-Galicia et al., 2009; González et al., 2010). The research on GLEs should now include, whenever available, the detection of solar neutrons and gamma rays from the parent flares.

Cosmic ray periodic variations have produced a large amount of papers in recent times. The contributions of Latin-American researchers here is mainly the discovery of the GCR 1.7y variation by Valdés-Galicia et al. (1996) that is present in many solar, interplanetary and atmospheric phenomena (Kane, 2005; Mendoza et al., 2006; Valdés-Galicia and Velasco, 2008) and seems to play a role in the generation of the solar magnetic field and the interplanetary medium dynamics. Periodic variations are a field of research that is giving us tools to deepen our knowledge on many of the solar manifestations that give origin to them. These studies should be continued to observe their time evolution both in GCR and solar phenomena.

The relationships of GCRs with space and atmospheric weather are a subject of much debate nowadays, especially the latter. Here we have some contributions of importance by scientists of the subcontinent. Mendoza and Sánchez de la Peña (2010) and Mendoza (2011) reviewed some aspects of these relationships, including effects in the biota. Rockenbach et al. (2001) found precursors of geomagnetic storms in GCR signals. Augusto et al. (2012) studied peculiar GCR variations found in the South Atlantic Anomaly region in connection with ICMEs and CIRs. The connection of cosmic rays with hurricanes has been also the subject of some published research (Kavlakov et al., 2008; Mendoza and Pazos, 2009 Pérez-Peraza et al., 2008; Kane, 2006; Mendoza, 2011). A couple of papers were devoted to disentangle the possible consequences of thunderstorms in the CR flux (Álvarez-Castillo and Valdés-Galicia, 2009, 2010; DeMendoça et al., 2011). Given the many controversial issues that are now discussed around the space weather and the effect of the Sun on the terrestrial weather, it is difficult to try to single out any particular line of research as more relevant than the others; but it is certain that we are still lacking models that might explain the relationships found. All in all we believe that the contributions of the Latin-American groups in the fields reviewed in this paper have shed different degrees of light into them. Some made the first and most important contribution, some other redirected the attention of the community, some confirmed results previously found.

What is undoubtedly true is that, besides the research done by the native groups, the infrastructure maintained in the region is doing a paramount contribution to cosmic ray science.

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