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The scaler mode in the Pierre Auger Observatory to study heliospheric modulation of cosmic rays

S. Dasso^{a,1}, H. Asorey^{b,2}, For The Pierre Auger Collaboration^{c,*}

^a *Departamento de Física (FCEN-UBA) and Instituto de Astronomía y Física del Espacio (FCEN-UBA, CONICET), Buenos Aires, Argentina*

^b *Centro Atómico Bariloche (CNEA), U. N. de Cuyo and U. N. de Río Negro, Bariloche, Río Negro, Argentina*

^c *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*

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Abstract

The impact of the solar activity on the heliosphere has a strong influence on the modulation of the flux of low energy galactic cosmic rays arriving at Earth. Different instruments, such as neutron monitors or muon detectors, have been recording the variability of the cosmic ray flux at ground level for several decades. Although the Pierre Auger Observatory was designed to observe cosmic rays at the highest energies, it also records the count rates of low energy secondary particles (the scaler mode) for the self-calibration of its surface detector array. From observations using the scaler mode at the Pierre Auger Observatory, modulation of galactic cosmic rays due to solar transient activity has been observed (e.g., Forbush decreases). Due to the high total count rate coming from the combined area of its detectors, the Pierre Auger Observatory (its detectors have a total area greater than 16,000 m²) detects a flux of secondary particles of the order of $\sim 10^8$ counts per minute. Time variations of the cosmic ray flux related to the activity of the heliosphere can be determined with high accuracy. In this paper we briefly describe the scaler mode and analyze a Forbush decrease together with the interplanetary coronal mass ejection that originated it. The Auger scaler data are now publicly available.

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1. Introduction

Transport of galactic cosmic rays (CRs) in the heliosphere is one of the topics of major interest in space physics and presents several unsolved questions. Transport of CRs is modulated by different physical mechanisms, which can be divided into large scale processes (related to the large scale heliospheric magnetic field) and transient phenomena, such as those produced by transient solar ejecta or interplanetary shocks.

As the flux of CRs decreases for higher energies, a large collecting surface is required when detecting high energy CRs, so ground-based instruments have to be used to study these elusive particles. For several decades, neutron monitors and muon detectors have been the detectors of secondary particles commonly used to determine fluxes of primary CRs with energies larger than ~ 1 GeV.

The time variability of the cosmic ray flux has been systematically recorded since the 1950s by neutron monitors. They have been crucial for understanding different mechanisms of solar modulation of cosmic rays, such as the anti-correlation between the sunspot number and cosmic rays intensity (Meyer and Simpson, 1955), the 27 days recurring intensity variations associated with the impact of the solar rotation combined with coronal holes on the interplanetary magnetic field (see e.g., Simpson, 1998), and Forbush decreases (Fd) (Forbush, 1937). Forbush decreases are significant depressions observed in CR flux at Earth, which

* Corresponding author.

E-mail addresses: dasso@df.uba.ar (S. Dasso), asoreyh@cab.cnea.gov.ar (H. Asorey), auger_spokesperson@fnal.gov (The Pierre Auger Collaboration).

URL: http://www.auger.org/archive/authors_2011_05.html (The Pierre Auger Collaboration).

¹ Tel.: +54 11 4781 6755x128; fax: +54 11 4786 8114.

² Tel.: +54 2944 44 5151x38; fax: +54 2944 44 5126.

are generally observed in association with the arrival to the Earth's environment of interplanetary shocks driven by huge transient magnetic structures of solar origin, the so called Interplanetary Coronal Mass Ejections (ICMEs) (e.g., Cane, 2000). Forbush decreases can be also produced by ICMEs without shocks, and the structure of the time profile of CR intensity is significantly different in cases with the presence of a shock when compared to cases of ICMEs without a driven shock wave (e.g., Wibberenz et al., 1998). Despite several properties of the structure of a Fd being relatively well understood, their recovery times are still not well known (e.g., Usoskin et al., 2008).

The heliosphere presents a variety of dynamical structures, which are not yet satisfactorily understood. In the last decades solar wind observations made from spacecraft have helped to significantly improve our knowledge of these structures. Remote observations of the solar wind have serious limitations to competently determine spatial magnetic distributions in the heliosphere. Instead, 'in situ' solar wind observations can provide direct magnetic field observations, but they have some difficulties in measuring global magnetic structures because they can

only observe local quantities (one point – multi times) along the linear (one dimensional) trajectory of the probe in the solar wind, and then they can combine spatial shapes and time evolution during the observation period.

Alternatively, ground observations of cosmic rays of low energies can provide precious information to complement 'in situ' information about the interplanetary magnetic field. The combination of observations from both cosmic ray ground observations and solar wind observations from space provides a good opportunity to make detailed studies of interplanetary structures and their effects on propagation of particles.

The $1660 \times 10 \text{ m}^2$ detectors of the Pierre Auger Observatory measure the flux of low energy cosmic rays arriving at Earth with a huge total collecting area, more than 16000 m^2 . This provides a cosmic ray detector of high accuracy, recording of the order of $\sim 10^8$ counts per minute, with a consequent very high statistical significance.

In Section 2 we briefly describe the Pierre Auger Observatory. Section 3 presents its scaler mode for observing low energy particle fluxes. A comparison of Auger scalers and neutron monitor observations is given in Section 4. In

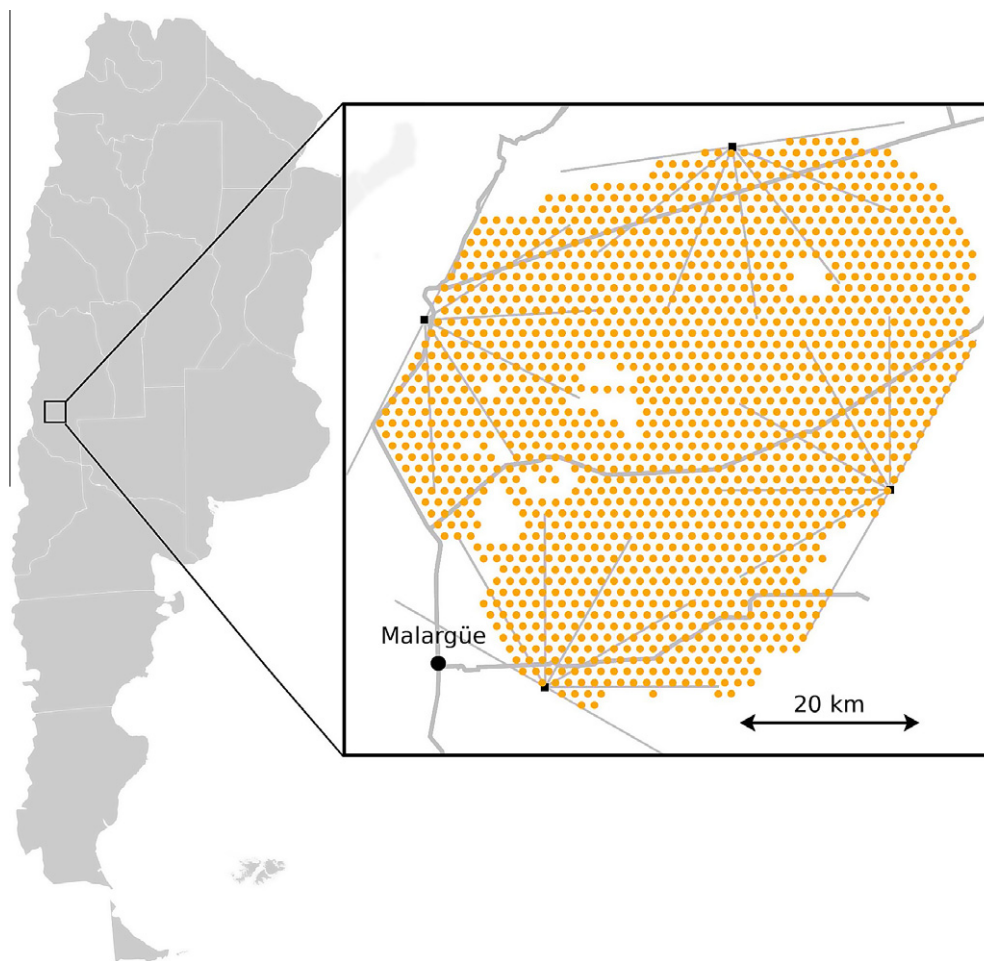


Fig. 1. Geographical location of the SD array of the Pierre Auger Observatory, Malargüe, Argentina. The position of the four fluorescence telescope buildings surrounding the SD array are indicated by the black squares, with gray lines indicating the field of view of the six telescopes at each building. The positions of 1660 water-Cherenkov detectors (in the year 2009) are marked with small dots.

Section 5 we present an analysis of the interplanetary perturbation producing a Forbush decrease observed at Auger. Finally, in Section 6 we present a summary and the conclusions of the paper.

2. The Pierre Auger Observatory

The Pierre Auger Observatory (Pierre Auger Collaboration, 2004) was designed to study the physics of cosmic rays at the highest energies. It is located in the west of Argentina (Malargüe, 69.3° W, 35.3° S, 1400 m a.s.l.) and it combines two techniques: (a) the observation of the fluorescence light produced by secondary particles as they propagate through the atmosphere, and (b) the direct measurement of particles reaching ground level. The layout of the Pierre Auger Observatory is shown in Fig. 1.

The interaction of a high-energy particle with the atmosphere produces a shower formed by a huge number of secondary particles, called an Extensive Atmospheric Shower (EAS). The development of the EAS can be tracked by the Fluorescence Detector (Pierre Auger Collaboration, 2010), which consists of 24 telescopes grouped in modules of six telescopes at four different locations (Los Leones, Coihueco, Loma Amarilla and Los Morados).

The ground level observations are based on measurements coming from an array of Surface Detectors (SD), which covers a surface of 3000 km² where 1660 water-Cherenkov detectors are placed in a triangular grid with a spacing of 1500 m. Each water-Cherenkov detector consists of a polyethylene tank (10 m² area) containing 12 m³ of high-purity water in a highly-reflective Tyvek[®] liner bag (Allekotte et al., 2008). Cherenkov radiation produced by the charged particles passing through the water volume in each detector is measured by three photomultiplier tubes (PMTs) and the signals from the PMTs are processed with a sampling rate of 40 MHz by six 10-bit flash analog-to-digital converters (FADC), and sent by a radio link to the central data acquisition system (CDAS) in Malargüe city, Argentina. A GPS system is used for timing and synchronization.

Particles interact with the water producing pulses of different size (with the area of the pulse related to the energy deposited by the particle in the detector), which are recorded to construct histograms. Scalers record the total count of signals above a low threshold (see next section). More details about SD detectors can be found in Allekotte et al. (2008) and about scalers in Pierre Auger Collaboration (2011).

3. Pierre Auger Observatory and galactic cosmic rays counting

In March 2005, a “single particle technique” mode was implemented for the full array of SD detectors at the Pierre Auger Observatory. It consists in recording the rate of signals associated with the energy deposited by secondary particles, the scaler mode (Pierre Auger Collaboration, 2011),

and it measures low energy radiation which is mainly useful for monitoring the long-term stability of the detector, for searching transient events (such as gamma ray bursts or Forbush decreases), and for studying long-term trends in the heliospheric modulation of cosmic rays during the solar cycle.

Two different scaler modes have been implemented at Auger. In the first one (period I: from March 1, 2005 to September 20, 2005) it counted the total number of signals per second in each detector above a threshold that corresponds to secondary particles with deposited energies (E_d) larger than ~ 15 MeV. In Period II (from September 30, 2005 to present) an upper bound was introduced to reduce the influence of muons, and the deposited energies considered correspond to $15 \text{ MeV} \lesssim E_d \lesssim 100 \text{ MeV}$ (see Fig. 1 of Asorey (2011)). The full SD array was completed in 2008, with a collecting area of more than 16,000 m² and a scaler counting rate of $\sim 2 \times 10^8$ counts min⁻¹. More details about scaler modes can be found in Asorey (2009), Pierre Auger Collaboration (2011) and Asorey (2011).

The response of the detector is shown in Fig. 2. It was computed from a set of low energy shower simulations using CORSIKA 6.980 (Heck et al., 1998) with the QGSJET-II model for high energy hadronic interactions and GHEISHA low energy interaction routines. The flux of primary particles at the top of the atmosphere (100 km of altitude) was simulated as a power law in primary energy (E_p) with exponents obtained from the measured spectra in the range $10 \times Z_p < (E_p/\text{GeV}) < 10^6$, and for $0^\circ \leq \theta_p \leq 88^\circ$ in zenith angle (Grieder, 2001), for all nuclei in the range $1 \leq Z_p \leq 26$ ($1 \leq A_p \leq 56$). The detector response to the secondary particles was simulated using a simple simulator developed within the Auger data analysis framework. The detectors are sensitive to charged particles from the shower

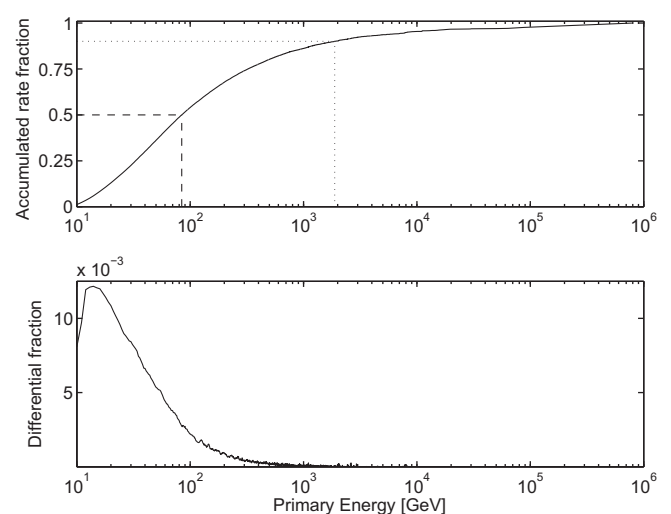


Fig. 2. Upper panel: accumulated scaler counts in Period I as a function of the energy of the primary cosmic ray assuming a stationary mean flux (see main text). Dashed and dotted lines show the 50% and 90% of counts, respectively. Lower panel: differential response (derivative of the function shown in the upper panel), obtained considering $dE = 1$ GeV (see main text).

of secondary particles at ground level. This shower is essentially dominated by μ^\pm and e^\pm , as well as to high energy photons that can be converted in e^+e^- pairs before being detected.

The simulated fraction of total counting rate produced by primaries with kinetic energies lower than a specific energy (in the range 10 GeV–1 PeV) is shown in the upper panel of Fig. 2. The dashed lines shows 50% of the counts, which corresponds to a median of ~ 90 GeV. It also shows that primary particles from ~ 10 GeV (the geomagnetic rigidity cut off at Malargüe is 9.5 GV, see Pierre Auger Collaboration, 2011) up to ~ 2 TeV produce 90% of the counts in the detector for Period I (dotted lines). No significant differences in the detector response have been observed for Period II.

The lower panel of Fig. 2 shows the detected count rate fraction per unit of flux energy (i.e., the derivative of the curve shown in the upper panel, which is frequently referred to the differential response function), where a numerical derivative was computed using an increment of $dE = 1$ GeV. It shows that the largest sensitivity (per unit of log energy) of the instrument corresponds to primary particles in the range 10–100 GeV.

4. Comparison with neutron monitor observations

Neutron monitors (NMs) are standard detectors of cosmic rays at ground level. In particular, the understanding of the modulation of CRs with energies larger than ~ 1 GeV arriving at Earth was significantly improved from observations given by NMs (see e.g., the review by Cane (2000) and references therein). A sudden decrease of CRs observed at ground level (Forbush decrease, Fd), with a gradual recovery lasting approximately one or two weeks, occurs generally in coincidence with the passage of an interplanetary shock or/and an ICME.

The amplitude of the daily variation of CRs observed by NMs generally increases during the recovery phase of a Fd due to the presence of the anisotropy caused by the transient interplanetary structure propagating beyond the Earth's orbit, which produces a decrease of the cosmic ray flux arriving from that direction (e.g., Lockwood, 1971 and references therein).

We present here the period after the Fd of May 2005 to make a comparison between the daily variation observed with the scaler counter at the Auger Observatory and a neutron monitor station. In particular we chose the recovery phase from May 16 to 19, 2005 (see Fig. 3).

The flux of secondary particles at ground level is significantly modulated by the atmospheric pressure. The scaler counts used and shown in this work are pressure-corrected, as explained in Pierre Auger Collaboration (2011).

In order to compare with observations at a similar location we chose neutron monitor observations from Los Cerrillos Observatory 6NM64 (Chile), which is located at 33.3°S and 70.4°W (Cordaro and Olivares, 2005), only ~ 250 km westward from the Auger Observatory.

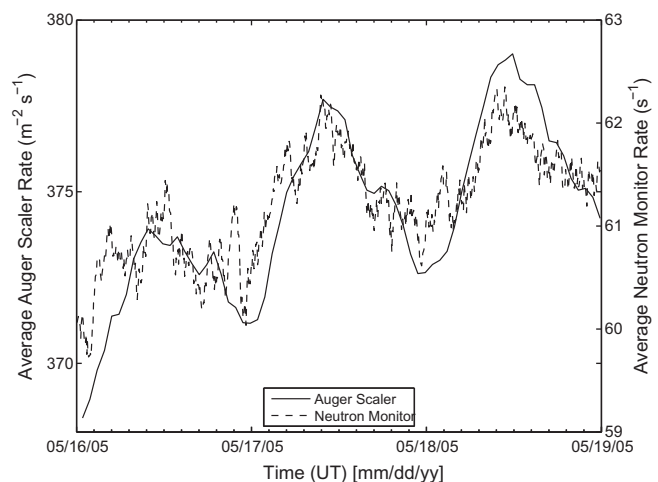


Fig. 3. Comparison of Auger scalers (solid line) with a neutron monitor station (dashed line) for a period when the daily modulation is enhanced.

The enhanced daily variation during the recovery phase of the analyzed Fd is compared in Fig. 3 (for a comparison of the full time range of this Fd, see Pierre Auger Collaboration, 2011), where a solid line represents the average hourly Auger scaler counts, and the dashed line shows the counts (hourly moving average over 5 min data points) observed at the NM in Los Cerrillos Observatory. An excellent agreement can be observed on the daily variation.

We emphasize that the scalers from the Auger Observatory provide an absolute flux of secondary particles with the high level of statistics provided by the huge area of collection of particles.

5. Interplanetary cause of a Forbush decrease observed at the Auger Observatory

In this section we briefly analyze the transient interplanetary structure that caused the Fd of May 2005 observed with the Auger scalers.

Fig. 4 shows ‘in situ’ observations of the interplanetary medium obtained from the spacecraft ACE, which is located at the Lagrangian point L1 in the solar wind near Earth, combined (lowest panel) with the Auger scaler rate for the time range around the Forbush event of 15 May 2005.

The solar wind data were obtained from the Magnetic Fields Experiment (MAG) (Smith et al., 1998) and the plasma data from the Solar Wind Electron Proton Alpha Monitor (SWEPAM) (McComas et al., 1998). In the upper panels the figure shows the modulus (B) and orientation (latitude θ_B and longitude ϕ_B) of the interplanetary magnetic field (IMF), with its direction in the Geocentric Solar Ecliptic system, GSE. Then, it shows plasma conditions of the interplanetary medium (bulk velocity V and proton temperature T_p), and the scaler count data.

Data in Fig. 4 clearly show the presence of an interplanetary mass ejection between May 15 and 17. Inside this time range a large scale smoothly varying magnetic field

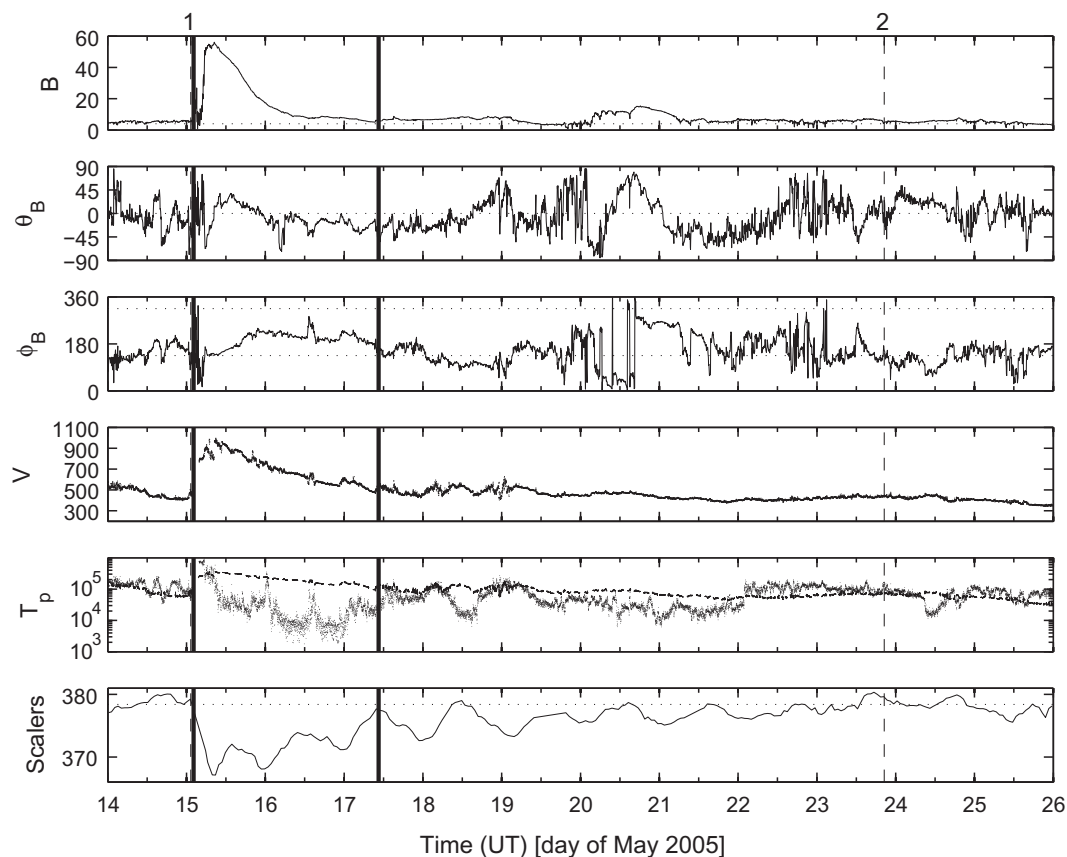


Fig. 4. From the upper panel: modulus [nT] of the IMF, latitude and longitude of the IMF direction, bulk velocity [km/sec], and proton temperature [K] (observed temperature marked with dots and expected temperature, T_{ex} , marked with dashed line). Lowest panel: Auger scaler counts per square meter per second (time average of 1 h).

orientation of high intensity can be observed, typical of a subset of ICMEs called magnetic clouds (Burlaga et al., 1981). The bulk velocity for this ICME is in agreement with an expanding ICME, traveling faster in the front than in the back, presenting an almost linear bulk velocity profile, as expected for typical ICMEs (Demoulin et al., 2008). The observed proton temperature is lower than the expected temperature (T_{ex}) for a typical solar wind at a given observed bulk velocity (Lopez, 1987; Demoulin, 2009), in agreement with typical observations of an ICME (Richardson and Cane, 1995).

The arrival of the ICME was previously identified at 02:11 UT on 15 May (Dasso et al., 2009). The temporal length of this ICME corresponds to a very extended region, ~ 0.93 AU, one of the largest ICMEs ever observed. The magnetic field in this ICME is huge, reaching almost 60 nT, one of the largest values observed in the interplanetary medium at 1 AU. At 10:30 UT of 17 May, the magnetic field recovers its background value of ~ 5 nT and typical solar wind conditions. Thick vertical solid lines in Fig. 4 show the boundaries of this huge ICME, which was formed by two flux ropes (Dasso et al., 2009) and their strongly perturbed environment.

Some simple models for describing arrival of CRs at Earth are based on diffusive obstacles (or barriers Wibberenz and Cane, 2000) that obstruct the transport of low

energy cosmic rays. These barriers result from perturbed solar wind associated with ICMEs, and they have a diffusion coefficient depending on the interplanetary magnetic field intensity. It has been proposed that these diffusive barriers are the main origin of the weakened flux of CRs observed at Earth during a Fd (e.g., Cane, 2000 and references therein).

Scaler counts (last panel of Fig. 4) show the structure of this Fd, which starts at 01:18 UT on 15 May 2005 and ends at 20:30 UT on 23 May 2005, as has been reported in Pierre Auger Collaboration (2011). Start and end times of the Fd are marked with ticks '1' and '2' and also as vertical dashed lines in Fig. 4. The start time (1) is in agreement with the arrival of the interplanetary shock driven by this huge ICME.

The magnetic field (B) in ICMEs plays an important role in the transport of CRs. Its typical decay for solar distances (D) between 0.3 AU and 5 AU has been quantified as $B(D) \sim B_0(D/D_0)^{-1.5}$ (Wang et al., 2005), with B_0 the reference magnetic field at a reference distance D_0 . This decay is a direct consequence of the increase of the ICME size with D and the conservation of the magnetic flux across a material surface. The increase of the ICME size in the direction perpendicular to its main axis is mainly driven by the decrease of the environment solar wind pressure (Demoulin and Dasso, 2009; Gulisano et al., 2010). Its typical size (S)

along the radial direction from the Sun evolves as $S(D) \sim S_0(D/D_0)^{0.6}$ (Wang et al., 2005).

The ICME observed during May 15–18, traveled with a mean bulk speed of ~ 700 km/sec. According to the scalers (shown in the last panel at the bottom of Fig. 4) the Forbush decrease finished around 23–24 May (see also Pierre Auger Collaboration, 2011). Thus, assuming that the ICME shown in Fig. 4 will evolve as a typical one, at the moment of the end of the decay phase of the Fd (when it finished its effect on the weakening of CRs flux at Earth), it could have been at a distance $D \sim 4.2$ AU from the Sun, with a radial size of $S \sim 2.2$ AU, and a maximum magnetic field of the order of $B \sim 7$ nT, while a typical solar wind magnetic field at this solar distances is lower than 1 nT.

6. Summary and conclusions

The heliosphere provides a natural laboratory where it is possible to study a huge number of physical processes, with the help of fleets of spacecraft (which can observe remote and 'in situ' properties of the plasma in the interplanetary medium) and with the increasing number of new observatories at ground level (which can observe electromagnetic radiation from the local cosmos and cosmic ray fluxes). The combination of results from these new generation observatories of increasing quality will allow us to improve our heliospheric models and achieve significant progress in our understanding of space physics during the next years.

The Pierre Auger Observatory provides scaler data, which measure the flux of low energy cosmic rays with a very high statistical significance from its huge total collecting area of more than 16,000 m², which provides a consequent $\sim 10^8$ counts per minute and a statistical accuracy well below 1% with the scalers (Pierre Auger Collaboration, 2011).

These observations correspond to a wide primary energy range of three order of magnitudes, from ~ 10 GeV to ~ 10 TeV (see Fig. 2). Primary particles in the range of ~ 10 GeV and ~ 1 TeV give the maximal ($\sim 90\%$ of the scaler rate fraction) contribution to the signal, with a median primary energy of ~ 90 GeV.

Thus, scalers provide data-sets complementary to networks of neutron monitors (which have lower effective/median energy) and nearer to networks of muon detectors (effective/median energy > 50 GeV), with scalers having a significantly higher statistical accuracy.

From a detailed comparison of the Auger scalers with a neutron monitor station near Malargüe, during a period when the daily modulation is enhanced at the decay phase of a Forbush decrease, we observe an excellent agreement on the phase of this modulation.

The combination of ground and space observations has allowed us to analyze some properties of the ICME and the interplanetary shock that caused one of the Forbush decreases observed at Auger. It was a very large ICME at distances of 1 AU from the Sun (almost ~ 1 AU of size

in the Sun–Earth direction) with one of the highest magnetic fields ever observed.

The 15 min time averaged Auger scalers, averaged over the whole surface detector array, are publicly available and can be downloaded from the Pierre Auger Observatory Public Event Display site [<http://www.auger.org>]. This web interface permits visualization and downloading of the data.

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