Space Weather of the Heliosphere: Processes and Forecasts
Proceedings IAU Symposium No. 335, 2017
C. Foullon & O.E. Malandraki, eds.

doi:10.1017/S1743921318000066

Effects of ICMEs on High Energetic Particles as Observed by the Global Muon Detector Network (GMDN)

A. Dal Lago[1], **C. R. Braga**[1], **R. R. S. de Mendonca**[1], **M. Rockenbach**[1], **E. Echer**[1], **N. J. Schuch**[2], **K. Munakata**[3], **C. Kato**[3], **T. Kuwabara**[4], **M. Kozai**[5], **H. K. Al Jassar**[6], **M. M. Sharma**[6], **M. Tokumaru**[7], **M. Duldig**[8], **J. Humble**[8], **P. Evenson**[9] **and I. Sabbah**[10]

[1]National Institute for Space Research (INPE), Avenida dos Astronautas-12227-010, São José dos Campos-SP, Brazil
email: `alisson.dallago@inpe.br`

[2]Southern Regional Space Research Center - CRS/INPE, Santa Maria, Brazil

[3]Shinshu University, Matsumoto, Japan

[4]Chiba University, Chiba City, Chiba, Japan

[5]Japan Aerospace Exploration Agency - JAXA, Sagamihara, Kanagawa, Japan

[6]Kuwait University, Kuwait City, Kuwait

[7]Institute for Space-Earth Environmental Research, Nagoya University, Japan

[8]University of Tasmania, Hobart, Tasmania, Australia

[9]Bartol Research Institute, University of Delaware, Newark, USA

[10]Department of Natural Sciences, College of Health Sciences, Public Authority for Applied Education and Training, Kuwait City, Kuwait

Abstract. The Global Muon Detector Network (GMDN) is composed by four ground cosmic ray detectors distributed around the Earth: Nagoya (Japan), Hobart (Australia), Sao Martinho da Serra (Brazil) and Kuwait city (Kuwait). The network has operated since March 2006. It has been upgraded a few times, increasing its detection area. Each detector is sensitive to muons produced by the interactions of ~50 GeV Galactic Cosmic Rays (GCR) with the Earth′s atmosphere. At these energies, GCR are known to be affected by interplanetary disturbances in the vicinity of the earth. Of special interest are the interplanetary counterparts of coronal mass ejections (ICMEs) and their driven shocks because they are known to be the main origins of geomagnetic storms. It has been observed that these ICMEs produce changes in the cosmic ray gradient, which can be measured by GMDN observations. In terms of applications for space weather, some attempts have been made to use GMDN for forecasting ICME arrival at the earth with lead times of the order of few hours. Scientific space weather studies benefit the most from the GMDN network. As an example, studies have been able to determine ICME orientation at the earth using cosmic ray gradient. Such determinations are of crucial importance for southward interplanetary magnetic field estimates, as well as ICME rotation.

Keywords. interplanetary medium, cosmic rays, coronal mass ejections (CMEs)

1. Introduction

Ground-based detectors are optimal for detecting secondary particles resulting from the interaction of Galactic Cosmic Rays (GCR) with energies from tens to several hundreds of GeV with the Earth's atmosphere (Duldig 2000; McDonald 2000). At this energy interval, GCR are modulated by the solar activity and corresponding interplanetary magnetic field

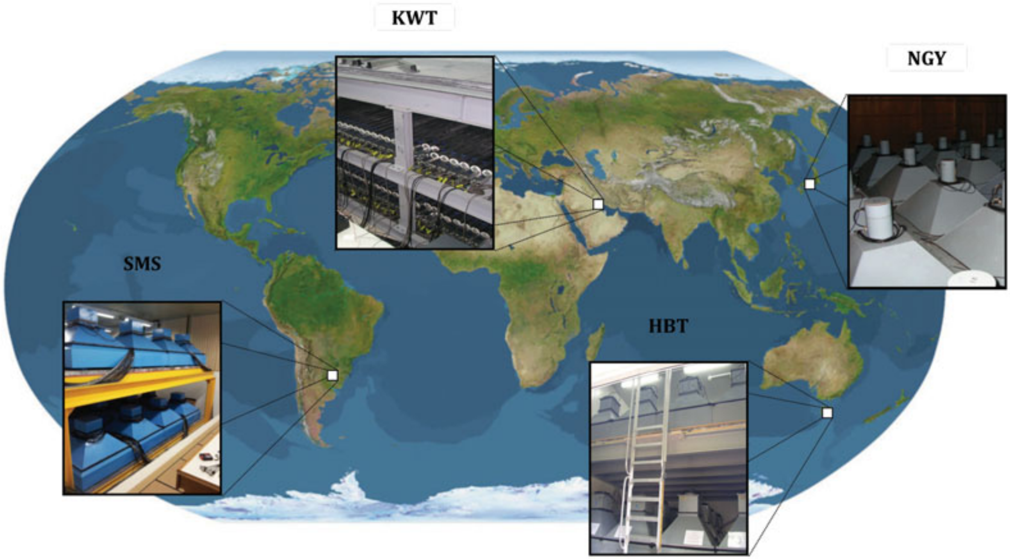

Figure 1. Current configuration of the Global Muon Detector Network (GMDN). From right to left, the detectors are: Nagoya, Japan (NGY), Hobart, Australia (HBT), Kuwait City, Kuwait (KWT) and Sao Martinho da Serra, Brazil (SMS).

(IMF) perturbations (Kuwabara *et al.* 2009). Among the main disturbances that drive geomagnetic activity at the Earth are the interplanetary counterparts of coronal mass ejections (ICMEs) (Gosling *et al.* 1991). They are the traveling disturbances originated at solar mass ejections, also referred to as coronal mass ejections (CMEs), as they are widely known because they are observed in the solar corona using coronagraphs (Schwenn 1996; Schwenn *et al.* 2005). ICMEs are the main drivers of geomagnetic storms for two main reasons, the first being the fact that their flux rope structures carry out-of-the ecliptic IMF for substantial amounts of time, sometimes up to ten hours or more. The second reason is the fact that they often drive interplanetary shocks, whose sheath compressed magnetic fields were found to be the most frequent sources of intense and very intense geomagnetic storms (Gonzalez *et al.* 2011; Szajko *et al.* 2013). In this paper, we shall present a brief description of some of the most important modulations produced by ICMEs on ground cosmic rays observed by the Global Muon Detector Network.

2. The Global Muon Detector Network (GMDN)

Since 2006, four muon detectors are in operation around the earth: Nagoya (Japan), Hobart (Australia), Sao Martinho da Serra (Brazil) and Kuwait city (Kuwait). Their locations were chosen to be as homogeneously distributed as possible. Since 1992, however, the Nagoya and Hobart detectors were already in operation as a two-hemisphere network. In 2001, a 4 m^2 prototype was installed in Sao Martinho da Serra in order to improve the coverage over the Atlantic. It was later upgraded to a 28m^2 detector. In 2006, a detector was installed in Kuwait city, after which all 4 instruments together were named the “Global Muon Detector Network (GMDN)”. Since then, three detectors have had their detection area increased: Kuwait was upgraded to 25m^2, Hobart was upgraded to 16m^2 and Sao Martinho da Serra was upgraded to 32m^2. Nagoya detection area is 36m^2. Figure 1 shows the current distribution of GMDN detectors around the Earth.

https://doi.org/10.1017/S1743921318000066 Published online by Cambridge University Press

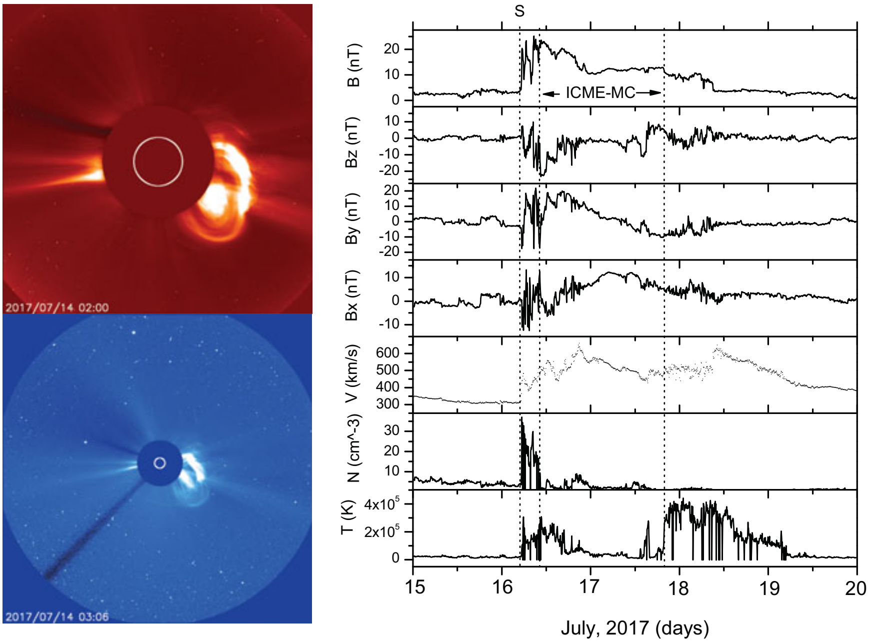

Figure 2. (left) Coronal mass ejection occurred on 14 July 2017, observed by the LASCO instrument aboard the SOHO space observatory. (right) From top to bottom, magnetic field intensity, its z, y and x components, solar wind speed, number density and temperature observed by ACE on the period from 15-19 July 2017. An interplanetary shock is observed in the first dotted line (from left to right), marked as "S". The ICME-magnetic cloud is located inside the second and third vertical lines. A magnetic field rotation can be identified in the "y" component of the magnetic field (By). One can see the abrupt changes in all parameters across the shock. A sheath compressed magnetic field is clearly seen between the shock and the ejecta (ICME). The ICME has a magnetic field which is few times stronger than the normal solar wind value. The only data available from ACE was level 1, which we used because our purpose was only to characterize the macroscopic features of the event. No quantitative calculations were made, which would require level 2 data.

3. Interplanetary coronal mass ejections

Coronal mass ejections (CMEs) are one of the most important solar energetic transients that drive Space Weather (Schwenn *et al.* 2005). They consist of large expulsions of solar material observed by coronagraphs. Figure 2 (left) shows a CME observed on 14 July 2017 by the Large Angle and Spectroscopic Coronagraph (LASCO), which is one instrument aboard the Solar and Heliospheric Observatory (SOHO). When pointed along the Sun-Earth line, they appear as "halos" in Earth-orbiting or L1 coronagraphs (Howard *et al.* 1982). Such CMEs can either be traveling away or towards the Earth. In the latter case, they are very likely to produce an interplanetary disturbance that has the potential to impact our planet. Such disturbances are the interplanetary counterparts of the CMEs, the so-called ICMEs. Some of them are ejecta-like structures, possessing a organized magnetic structure, called a magnetic clouds (MC) (Burlaga *et al.* 1981). Because of their high speeds, they often drive shocks in front of them. A sheath compressed magnetic field is produced in between the shock and the ICME ejecta. Figure 2 (right) shows an example of an ICME-MC observed on 15-19 July 2017 by the Advanced Composition Explorer (ACE). It is presented from top to bottom the magnetic field intensity, its z, y and x components, solar wind speed, number density and temperature.

https://doi.org/10.1017/S1743921318000066 Published online by Cambridge University Press

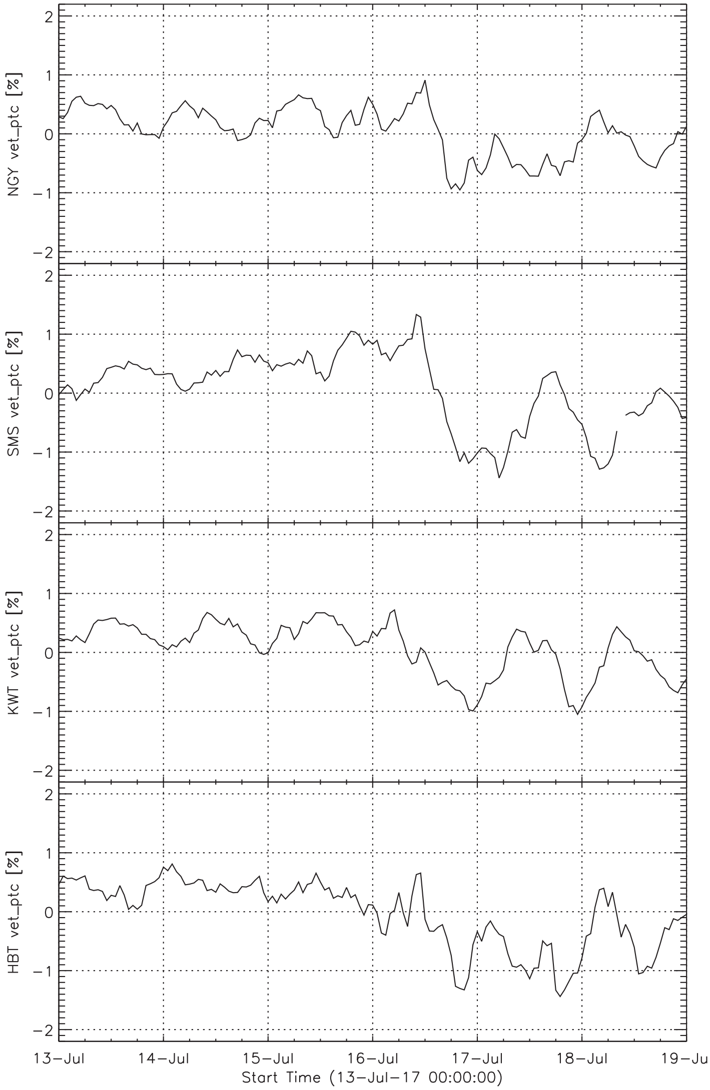

Figure 3. Pressure and temperature corrected vertical channels of all GMDN detectors, NGY (Japan), SMS (Brazil), KWT (Kuwait) and HBT (Hobart) during the passage of the ICME on 16 July 2017, related to the CME observed at the Sun on 14 July 2017. Clear Forbush decreases are observed on 16 July in all detectors.

4. Modulation

Before comparing ground cosmic ray intensity modulation due to extraterrestrial phenomena, it is necessary to take into account atmospheric effects, such as pressure and temperature. They produce a seasonal variation on the cosmic ray intensity observed by muon detectors. We recommend a careful reading of De Mendonca *et al.* (2016) for details on corrections of GMDN observations for atmospheric effects. Perhaps the most well known modulation that ICMEs impose in ground cosmic rays is the Forbush decrease (Forbush 1937; Simpson 1954). It consists of a global decrease of cosmic ray intensity observed during the passage of the Earth through interplanetary disturbances. Figure 3 shows the Forbush decrease observed by all four GMDN detectors, NGY (Japan),

https://doi.org/10.1017/S1743921318000066 Published online by Cambridge University Press

SMS (Brazil), KWT (Kuwait) and HBT (Hobart) during the passage of the ICME on 16 July 2017, related to the CME observed at the Sun on 14 July 2017. Another type of modulation imposed by approaching ICMEs at Earth is the loss cone effect, which produces a precursory anisotropy. This effect occurs before the arrival of the ICME at the Earth, thus attracting attention to possible Space Weather applications towards forecasting arrival of interplanetary disturbances. Very good descriptions of this anisotropic modulation can be found in Nagashima *et al.* (1992), Munakata *et al.* (2000), Kuwabara *et al.* (2006), Fushishita *et al.* (2010), Rockenbach *et al.* (2011) and Braga *et al.* (2011). Munakata *et al.* (2000) reported many such loss cone precursors using observations from two muon detectors (Nagoya and Hobart). His overall conclusion was that such precursors could be detected up to 8 hours before the arrival of the ICME at Earth. Later work from Rockenbach *et al.* (2011) found similar results. As already mentioned in Figure 2 description, ICMEs often drive interplanetary shocks. As these shocks propagate, they sweep out galactic cosmic rays forming a depleted region behind them. Kozai *et al.* (2016) studied the cosmic ray density and gradient derived by GMDN observations during Forbush decreases of a number of CME-ICME shock events, originating in several positions at the solar disk. These authors found a distinct modulation of galactic cosmic rays, one related to the shock-sheath region and another due to the ICME flux rope.

5. Orientation of ICME flux ropes

It has been shown to be possible to determine the flux rope orientation of ICMEs using cosmic ray directional anisotropies observed by ground-based muons detectors. Remarkable results were reported by Kuwabara *et al.* (2009), where excellent agreement of ICME inclination was found when comparing a cosmic ray derivation and a more widely used Minimum Variance Analysis method, which is based on the Interplanetary Magnetic Field.

6. Summary

In this paper we presented a brief description of the Global Muon Detector Network (GMDN) and of some of the most important modulations produced by interplanetary counterparts of coronal mass ejections (ICMEs) on ground cosmic rays observed by the GMDN. In particular, we described the Forbush decrease occurred in 11-16 July 2017 observed by the detectors of the GMDN. Following on, we make reference to many previous studies related to the loss cone effect produced by ICMEs approaching the Earth. This particular effect has potential for Space Weather applications. We also pointed out some important results related to the estimate of the orientation of ICME-magnetic clouds using cosmic ray observations from GMDN.

7. Acknowledgements

A.D.L., E.E. and R.R.S.M thank CNPq for grants 304209/2014-7, 302583/2015-7 and 152050/2016-7. C.R.B. thanks FAPESP 2014/24711-6. We thank the SOHO/LASCO and ACE teams for the data used in this work. SOHO is a joint collaboration between ESA and NASA.

References

Braga *et al.* 2011, *32nd International Cosmic Ray Conference*, 10, 286, ISBN: 978-1-63439-138-2

Burlaga, L. F., E. Sittler, F. Mariani & R. Schwenn 1981, *J. Geophys. Res.*, 86, 6673
De Mendonca *et al.* 2016, *ApJ*, 830, 88
Duldig, M. 2000, *Space Science Review*, 93, 207
Forbush, S. E. 1937, *Physical Review*, 51, 12, 1108
Fushishita, A., *et al.* 2010, *ApJ*, 715, 2, 12391247
Gosling, J. T., McComas, D. J., Phillips, J. L. & Bame, S. J. 1991, *J. Geophys. Res.*, 96, A5, 7831
Gonzalez, W. D., Echer, E., Tsurutani, B. T., Clua de Gonzalez, A. L. & Dal Lago, A. 2011, *SSR*, 158, 69
Howard, R. A., *et al.* 1982, *ApJ*, 263, 2L, 101
Kozai, M., Munakata, K., Kato, C., Kuwabara, T., Rockenbach, M., Lago, A. Dal, Schuch, N. J., Braga, C. R., Mendonça, R. R. S., Jassar, H. K. Al, Sharma, M. M., Duldig, M. L., Humble, J. E., Evenson, P., Sabbah, I. & Tokumaru, M. 2016, *ApJ*, 825, 100
Kuwabara, T., *et al.* 2006, *Space Weather*, 4, 8, S08001
Kuwabara, T., *et al.* 2009, *JGR*, 114, A05109
McDonald, F. B. 2000, *Space Science Reviews*, 93, 263
Munakata, K., *et al.* 2000, *JGR*, 27457
Nagashima, K., *et al.* 1992, *Planetary and Space Science*, 40, 8, 1109
Rockenbach, M., *et al.* 2011, *GRL*, 38, L16108
Schwenn, R. 1996, *Astrophys. Space Sci.*, 243, 1, 187
Schwenn, R., Dal Lago, A., Huttunen, E. & Gonzalez, W. D . 2005, *Ann. Geophys.*, 23, AG/2004180, 1033
Simpson, J. A. 1954, *Physical Review*, 94, 2, 426
Szajko, N. S., Cristiani, G., Mandrini, C. H. & Dal Lago, A. 2013, *ASR*, 51, 10, 1842