29th International Cosmic Ray Conference Pune (2005) **1**, 303-306

Rigidity dependence of galactic cosmic ray modulation: 1. Eleven year modulation

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Modulations of galactic cosmic ray (GCR) intensity, on all time scales, contain a wealth of information regarding their mode of transport in the heliosphere. To extract crucial information from the data one studies the rigidity dependence of modulations. We use data obtained with a variety of detectors on ground, at mountain altitudes, on balloons, satellites and space probes. For such studies to be meaningful, it is important to have an understanding of the response characteristics of detectors. There is a great deal of confusion on this topic in the literature. For example, the median rigidity of response (Rm) to GCR spectrum, for Mt. Washington neutron monitor is listed in the range: 5.4 GV to 14 GV, by the same authors, at different times. We define Rm as the GCR rigidity below which lies 50 % of detector counting rate. It is easily calculated from the latitude survey data. We compare Rm values computed by us with those given by others for some observing sites of the global network,

1. Introduction

A phenomenological understanding of the observed modulation of galactic cosmic ray (GCR) intensity, over a range of time scales and rigidities (R), has been arrived at by using data from a global network of ion chambers (IC), muon telescopes, and neutron monitors (NMs) over the last seven decades; global NM network has operated stably for more than a half century. These data contain a wealth of information pertaining to parameters of GCR transport in the turbulent interplanetary magnetic field (B). Recently, we argued that a large part of 11-year modulation is accounted for in terms of the convection and diffusion processes in the solar wind (speed = V); convection is initiated by the solar wind electric field **E** (= **V x B**) which drives an electric drift (**E x B**) for charged particles away from the sun, setting up a radial density gradient in the heliosphere [1]; GCRs from the local interstellar medium diffuse inward to minimize the gradient. The inward flow nearly cancels the outward flow; a small imbalance between them leads to a diurnal variation observed by detectors situated on the spinning earth [2]. Convection is a local effect, depending upon the value of **B** and **V** at the point of observation; thereby it controls the onset phase of modulation, often leading to the Stoker- Carmichael steps in the descending phase of a cycle at earth's orbit [3] and in the outer heliosphere [4]. At higher GCR rigidities ($R > 10$ GV) the neutral current sheet drifts (outward for $A > 0$ and inward for $A < 0$) play a secondary role, such as shifting the diurnal phase from east-west to radial direction (sunward) during solar minima in $A > 0$ epoch. Moreover, charged particle drifts contribute little to the latitudinal gradients at high and low rigidities near solar maxima [5,6].

The rigidity dependence of modulation arises from the local and global GCR contributions. To explore this dependence, we use data obtained with a variety of detectors at sea level, at mountain sites, on balloons, satellites, and space probes. For such studies to be meaningful, it is important to have a clear understanding of the response characteristics of the detectors involved. We characterize them in terms of their median rigidity of response (Rm) to GCR spectrum; below it is 50 % of a detector counting rate [7]. It is easily computed from the detector response function, derived from the latitude survey data at sea level and mountain altitudes. Data are available from several surveys undertaken by different research groups over several decades. Most of the surveys are carried out near solar minima for an understandable reason that minima are free of the transient events (solar cosmic rays, Forbush decreases, etc); also the intensity of lower rigidity GCRs is largest then. Other colleagues define effective rigidity of modulation for NMs in an ad hoc manner [8,9]; we present our calculated Rm values for several global sites.

2. Response Functions

Latitude surveys are carried out with shipborne neutron monitors [10,11,12,13], and overland [14,15,16]; airborne surveys have been made also [17,18]. Inter-comparison of surveys made at different times became possible with the availability of the vertical trajectory based cut-offs [19]. However, vertical cut-off rigidity (Ro) undergoes time variations at several sites [20]. Coupling constants may be derived from the slope of the latitude curve ($100/N\partial N/\partial R$, %/GV), see eq (1) in [13]. NM response functions have been provided by Webber and Quenby [21], Lockwood and Webber [22], Bachelet et. al [23], Nagashima et. al [24] and Dorman et. al [25]. We used the differential response curves of Lockwood and Webber [22] and Bachelet et. al [23] to compute Rm values for several NMs at sea level and mountain sites; they are listed elsewhere [26].

Table 1. Particulars of Detector Sites

Station	Latitude degree	Longitude degree	Altitude meters	Depth g/cm^2	Ro GV
Alma Ata	43.25	76.92	806	939	6.61
Climax	39.37	-106.18	3400	680	2.97
Deep River	46.10	-77.50	145	1030	1.10
Hermanus	-34.42	19.23	26	1030	4.56
Hobart	-42.88	147.33	0	1030	1.80
Haleakala	20.72	-156.27	3030	715	13.30
Huacayo	-12.03	-75.33	3400	680	13.0
Kiel	54.30	10.10	54	1030	2.30
Moscow	55.47	37.32	200	939	2.39
Mt Norikura	36.11	137.55	2770	733	11.36
Rome	41.90	12.50	60	1030	6.30
Tokyo	35.75	139.72	20	1030	11.50

3. Additional computed Rm Values

The latitudes, longitudes, altitudes, depth in the atmosphere, and the vertical cut-off rigidities of detectors at some sites are listed in Table 1. Rm values computed by us and others for NMs as well as other detectors are listed in Table 2; last column gives observed amplitude of modulation (%) for four years during each of the two adjacent solar cycles (21, 22) as given in [8].

4. Rigidity Dependence of Modulation

Lockwood and Webber [8] studied the rigidity dependence of modulation for cycles 21 and 22 using data listed in the last column of Table 2. The Rm values computed by them are based on two assumptions. First, modulation ceases above 100 GV. Second, Rm value depends upon the modulation function assumed by them (see their Fig. 2). We know that the limiting GCR rigidity

Table 2. Comparison of Rm Values for Detectors with References

Rm (GV) / Detector Site	LW, [8]	LW, [28]	LWD, [29]	AUMK [9]	Present Work	% CR Decrease 1977-81/1987-90
IMP 8	1.25/1.05	1.8	1.3			69.7 / 77.0
Balloons					1.3	
VELA					~ 3	
Mt. Wash/NM	5.4 / 7.0	10	14		10	17.0 / 24.5
Climax/NM	6.4 / 7.3		12.5	~ 6.5	11	15.6 / 23.9
Deep River/NM	5.6 / 7.5				16	13.2 / 20.6
Durham/NM	5.6 / 7.5				16	13.7 / 20.8
Kiel/NM	6.3 / 8.0		18		17	11.9 / 20.5
Alma Ata/NM	10.0/10.3				21	12.2 / 13.9
Rome/NM				~ 9	23	
Mt.Norikura/NM					28	
Tokyo/NM	17 / 19				39	4.25 / 9.3
Huancayo/NM	18.5/21.5		30	~ 17	33	3.45 / 8.2
Haleakala/NM	18.5/21.5		30		33	
Yakutsk/IC					67	1.47 / 2.64

(Rc) for modulation is not invariant, its value undergoes a significant change over a solar cycle [27]. Our values are computed in a straightforward manner; in particular, no assumption is made about the form of

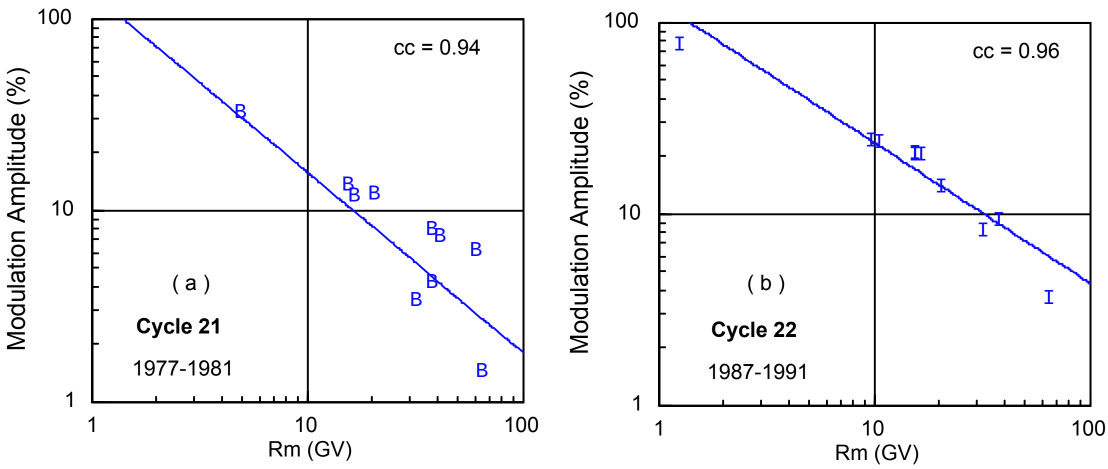

Figure 1 a,b. Amplitude (%) of modulation versus Rm (GV) for the detectors are plotted on a log-log scale. The diagonal lines represent power law fits to the data for two adjacent solar cycles (21, 22).

modulation function or Rc values, thereby neglecting solar cycle variations in Rm values. For cycles 21/ 22, L & W values Rm = 5.4 / 7.0 GV for Mt. Washington NM may be compared to our value of 10 GV. Later, Lockwood and Webber [28] give Rm = 10 GV for Mt. Washington NM, in agreement with our value. Later still Lockwood, et. al [29] give Rm = 14 GV for Mt Washington NM which exceeds our value. Similarly, there is a disagreement between their Rm values and ours for NMs at Alma Ata, Tokyo, Huancayo, Haleakala, Climax, Deep River and Kiel. We have similar dis agreements with Rm values computed by Alanko et. al [9].

Figure 1 a,b depict a log-log plot of data from the last column of Table 2 versus the applicable Rm values from column labeled ‘present work’ in Table 2. It is interesting to note that inspite of such a wide disparity between Rm values computed by us and those in [8], we still get an inverse R dependence of modulation amplitudes for cycles 21 and 22 just like L&W; they used Rm values listed in column ‘LW’ in Table 2 The reader may compare our plots with those in Figures 6 and 7 in [8]; our plots extend to a higher rigidity. IC data are not included in L&W plots; if it were, the datum point will lie well outside the fit provided by L&W. We get arigidity exponent of - 0. 94 for cycle 21 and - 0. 73 for cycle 22 respectively. Details will be reported elsewhere.

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