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Cosmic ray latitude survey 1996–1997: 2. Apparent cutoff rigidities

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Abstract. In this paper we calculate the apparent cut-off rigidities of the latitude survey from Italy to Antarctica and back. Computations were done for the forward route of the survey, on the basis of results of Danilovà et al. (this issue) on trajectory calculations for inclined cut-off rigidities at eight azimuths (every 45 deg.) and five zeniths angles (every 15 deg.). For calculations of apparent cut-off rigidities we used also the information on integral multiplicities of secondary neutrons detected by neutron monitor in dependence of zenith angle of incoming primary cosmic ray particles. This information is based on the theoretical calculations of meson-nuclear cascades of primary protons with different rigidities arriving to the Earth's atmosphere at zenith angles 0, 15, 30, 45, 60 and 75 degrees (Dorman and Pakhomov, 1979). The results of Dorman and Pakhomov (1979) have been checked and normalized by using the coupling functions obtained by Dorman et al. (2000). We compared the apparent cut-off rigidities with results obtained by Clem et al. (1997) and with apparent cut-off rigidities computed by Dorman et al. (2000) by using dipole approximation for inclined directions.

1 Introduction

During the 1996-1997 solar minimum we conducted a cosmic ray (CR) latitude survey on an Italian Antarctic Research Program ship, measuring the neutron intensity over the ocean using a 3NM-64 neutron monitor (NM) and two bare (BC) BF_3 counters (Villoresi et al., 2000; Iucci et al., 2000; Dorman et al. 2000). In Dorman et al. (2000) we used cutoff rigidities computed for vertical incidence. However, since a neutron monitor is also sensitive to nonvertical incidence primary particles, it is necessary to compute the so-called "apparent" cutoff rigidities (see Clem et al., 1997) by taking into account cutoff rigidities not only for vertically incident particles, but also for nonvertical incidence primary particles with different weights as a function of zenith angle. We will compute the apparent cutoff rigidities on the base of calculations given in Danilova et al. (this issue) and we will compare the results obtained by Clem et al. (1997) for selected locations and Dorman et al (2000) in the dipole approximation of geomagnetic field.

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2 Apparent cutoff rigidities along the ship route

The apparent cutoff rigidities can be computed as

$$R_{cp}^{ap}(R_{cp}) = \int_0^{2\pi} d\varphi \int_0^{\pi/2} R_{cp}(\theta,\varphi) W(R_{cp},\theta,\varphi) d\theta \Big/ \int_0^{2\pi} d\varphi \int_0^{\pi/2} W(R_{cp},\theta,\varphi) d\theta \approx \sum_i \langle R_{cp}(\theta_i - \theta_{i+1})\rangle \langle W(R_{cp},\theta_i - \theta_{i+1})\rangle \quad (1)$$

where $\langle R_{cp}(\theta_i - \theta_{i+1})\rangle$ is the inclined cutoff rigidity averaged over azimuth angle in the zenith zone $\theta_i - \theta_{i+1}$ (see Danilova et al., this issue) and $\langle W(R_{cp},\theta_i - \theta_{i+1})\rangle$ is the normalized relative weight of this zone.

Recently, Clem et al. (1997) and Stoker et al. (1997) discussed the problem of apparent cutoff rigidities. In these papers the authors proposed to perform complete trajectory calculations by taking into account scattering of neutrons in the atmosphere. They showed that for $R_{cp} < 6-7$ GV apparent cutoff rigidities are about the same as vertical ones, but with increasing R_{cp} the difference $R_{cp}^{ap} - R_{cp}$ increases up to $0.7-0.8$ GV at $R_{cp} = 16$ GV.

On the basis of results given by Dorman et al. (2000), in which we determined the normalized zenith angle distribution of neutrons arriving at the NM for an isotropic distribution of CR primary particles over the atmosphere, and by using of results of theoretical calculations of meson-nuclear cascades of primary protons with different rigidities arriving to the Earth's atmosphere at zenith angles 0, 15, 30, 45, 60 and 75 degrees (Dorman and Pakhomov, 1979), we compute the expected weights of six zenith zones to the NM counting rate, as a function of vertical cutoff rigidity R_{cp} :

$$
\begin{aligned}
&W_{0-7.5}(R_{cp}) = 0.084812 - 0.000645 R_{cp},\\
&W_{7.5-22.5}(R_{cp}) = 0.48305 - 0.00240 R_{cp},\\
&W_{22.5-37.5}(R_{cp}) = 0.35829 + 0.001194 R_{cp},\\
&W_{37.5-52.5}(R_{cp}) = 0.071925 + 0.001691 R_{cp},\\
&W_{52.5-67.5}(R_{cp}) = 0.001925 + 0.000161 R_{cp},\\
&W_{67.5-90}(R_{cp}) = 4.789\times10^{-7} + 4.003\times10^{-8} R_{cp}.
\end{aligned} \tag{2}
$$

In Table 1 we give results of computation of the average (over azimuth angle) cutoffs for different zenith angles; in Table 2 we give the computed weights, together with the resulting apparent cutoffs.

In Figure 1 we show the dependences of $R_{cp}^{ap}(\theta,t) - R_{cp}$ versus R_{cp} for the Northern and Southern hemispheres.

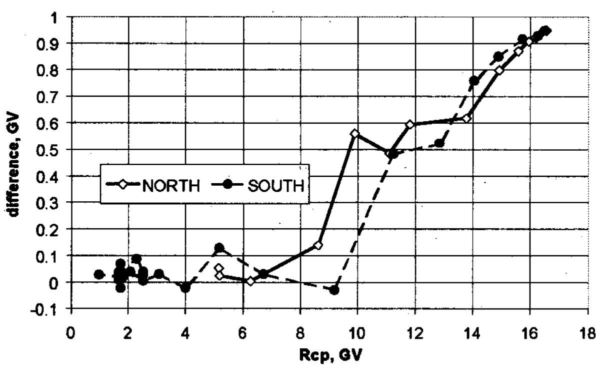

Figure 1. The behavior of $R_{cp}^{ap}(\theta,t) - R_{cp}$ as a function of R_{cp}, computed for the forward part of survey: Southern hemisphere (solid circles), Northern hemisphere (open diamonds).

3 Conclusions

The obtained results (Tables 1 and 2, and Figure 1) show that in the interval of R_{cp} =10-16 GV the difference $R_{cp}^{ap}(\theta,t) - R_{cp}$ is about 1.1-1.3 times bigger than that obtained by Clem et al. (1997); and about 1.6-1.8 in comparison with Dorman et al. (2000).

Results presented in this paper should be considered as preliminary because the trajectory calculations (Danilova et al., this issue) have been done up to now only for the first half of the survey, i.e. from Italy to Antarctica.

As soon as the trajectory calculations for the other part of survey will be completed, we will determine apparent cutoff rigidities for the total survey and compute the coupling functions. These complete results will be published elsewhere.

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Table 1. Cutoff rigidities averaged over azimuth angles are given for different zenith angles of incoming particles, together with vertical cutoffs.

N	Day	Lat.	Lon.	Vertical Cutoff	Average Inclined Cutoff			
				z0	z15	z30	z45	z60
0	355	44.443	12.247	5.15	5.17	5.22	5.37	5.35
1	356	44.402	12.382	5.19	5.18	5.24	5.33	5.38
2	357	41.757	16.556	6.26	6.24	6.28	6.32	6.52
3	358	37.25	21.264	8.61	8.75	8.75	8.86	9.26
4	359	33.857	26.881	9.89	10.2	10.67	11.27	11.7
5	360	31.557	31.921	11.1	11.18	11.82	12.98	13.94
6	361	30.061	32.548	11.82	12.06	12.57	13.93	14.8
7	362	25.651	35.413	13.78	13.95	14.66	15.82	17.82
8	363	20.816	38.544	14.91	15.17	16	17.5	19.89
9	364	16.493	41.145	15.58	15.86	16.76	18.4	21.02
10	365	12.844	44.252	15.95	16.25	17.17	18.87	21.61
11	366	12.239	49.683	16.18	16.48	17.42	19.14	21.92
12	1	9.728	54.71	16.43	16.74	17.7	19.45	22.28
13	2	6.278	59.323	16.56	16.87	17.83	19.6	22.46
14	3	2.82	63.9	16.5	16.81	17.77	19.53	22.37
15	4	-0.64	68.49	16.26	16.56	17.51	19.23	22
16	5	-4.629	73.476	15.74	16.11	16.93	18.57	21.22
17	6	-8.788	78.023	14.9	15.26	16	17.52	19.8
18	7	-12.023	82.657	14.06	14.39	15.05	16.36	18.56
19	8	-15.623	87.286	12.86	13.01	13.57	14.75	15.88
20	9	-18.933	91.709	11.24	11.42	11.99	12.49	13.48
21	10	-22.386	96.41	9.18	9.18	9.12	9.09	9.6
22	11	-25.862	101.473	6.72	6.74	6.75	6.82	7.01
23	12	-29.376	106.587	5.19	5.29	5.36	5.42	5.42
24	13	-32.825	111.807	4	3.97	3.98	3.98	4
25	14	-35.707	118.051	3.08	3.11	3.12	3.11	3.12
26	15	-37.818	125.015	2.52	2.52	2.53	2.55	2.55
27	16	-39.92	132.276	2.08	2.13	2.11	2.12	2.13
28	17	-42.036	139.765	1.76	1.81	1.79	1.8	1.8
29	18	-43.25	146.398	1.72	1.69	1.7	1.69	1.7
30	19	-42.881	147.341	1.73	1.81	1.8	1.79	1.8
31	20	-43.701	150.347	1.66	1.7	1.7	1.7	1.71
32	21	-45.069	158.389	1.67	1.69	1.67	1.67	1.69
33	22	-46.325	166.352	1.7	1.73	1.71	1.73	1.74
34	23	-44.349	172.3	2.29	2.37	2.4	2.41	2.43
35	24	-43.606	172.72	2.53	2.59	2.55	2.58	2.61
36	25	-43.672	172.823	2.53	2.55	2.57	2.58	2.57
37	26	-47.179	174.023	1.83	1.85	1.85	1.87	1.84
38	27	-52.628	175.464	0.98	1.01	1.01	1.02	1.02

Table 2. Weights of 5 zenith zones are given together with $R_{cp}^{ap}(\theta,t)$ and $R_{cp}^{ap}(\theta,t)-R_{cp}$.

N	Day	Weight					Apparent Cutoff	App.Cutoff *minus* Vert.Cutoff
		z0	z15	z30	z45	z60		
0	355	0.08149	0.47069	0.364439	0.080634	0.002754	5.203214	0.053214
1	356	0.081464	0.470594	0.364487	0.080701	0.002761	5.215341	0.025341
2	357	0.080774	0.468026	0.365764	0.082511	0.002933	6.263668	0.003668
3	358	0.079259	0.462386	0.36857	0.086485	0.003311	8.750106	0.140106
4	359	0.078433	0.459314	0.370099	0.088649	0.003517	10.44976	0.55976
5	360	0.077653	0.45641	0.371543	0.090695	0.003712	11.58507	0.485067
6	361	0.077188	0.454682	0.372403	0.091913	0.003828	12.41376	0.593761
7	362	0.075924	0.449978	0.374743	0.095227	0.004144	14.39726	0.617264
8	363	0.075195	0.447266	0.376093	0.097138	0.004326	15.70934	0.799344
9	364	0.074763	0.445658	0.376893	0.098271	0.004433	16.45074	0.870743
10	365	0.074524	0.44477	0.377334	0.098896	0.004493	16.85797	0.90797
11	366	0.074376	0.444218	0.377609	0.099285	0.00453	17.10137	0.921371
12	1	0.074215	0.443618	0.377907	0.099708	0.00457	17.3753	0.945301
13	2	0.074131	0.443306	0.378063	0.099928	0.004591	17.50842	0.948416
14	3	0.07417	0.44345	0.377991	0.099827	0.004582	17.44687	0.946868
15	4	0.074324	0.444026	0.377704	0.099421	0.004543	17.18668	0.926677
16	5	0.07466	0.445274	0.377084	0.098541	0.004459	16.65677	0.916773
17	6	0.075202	0.44729	0.376081	0.097121	0.004324	15.75034	0.850343
18	7	0.075743	0.449306	0.375078	0.0957	0.004189	14.81855	0.758546
19	8	0.076517	0.452186	0.373645	0.093671	0.003995	13.38221	0.522213
20	9	0.077562	0.456074	0.371711	0.090932	0.003735	11.7229	0.4829
21	10	0.078891	0.461018	0.369251	0.087448	0.003403	9.151404	-0.0286
22	11	0.080478	0.466922	0.366314	0.083289	0.003007	6.749528	0.029528
23	12	0.081464	0.470594	0.364487	0.080701	0.002761	5.318217	0.128217
24	13	0.082232	0.47345	0.363066	0.078689	0.002569	3.976962	-0.02304
25	14	0.082825	0.475658	0.361968	0.077133	0.002421	3.111159	0.031159
26	15	0.083187	0.477002	0.361299	0.076186	0.002331	2.525968	0.005968
27	16	0.08347	0.478058	0.360774	0.075442	0.00226	2.117857	0.037857
28	17	0.083677	0.478826	0.360391	0.074901	0.002208	1.797837	0.037837
29	18	0.083703	0.478922	0.360344	0.074834	0.002202	1.696137	-0.02386
30	19	0.083696	0.478898	0.360356	0.07485	0.002204	1.798182	0.068182
31	20	0.083741	0.479066	0.360272	0.074732	0.002192	1.696672	0.036672
32	21	0.083735	0.479042	0.360284	0.074749	0.002194	1.679625	0.009625
33	22	0.083716	0.47897	0.36032	0.0748	0.002199	1.720304	0.020304
34	23	0.083335	0.477554	0.361024	0.075797	0.002294	2.377333	0.087333
35	24	0.08318	0.476978	0.361311	0.076203	0.002332	2.569841	0.039841
36	25	0.08318	0.476978	0.361311	0.076203	0.002332	2.557895	0.027895
37	26	0.083632	0.478658	0.360475	0.07502	0.00222	1.849806	0.019806
38	27	0.08418	0.480698	0.35946	0.073582	0.002083	1.008231	0.028231