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Galactic cosmic ray intensity variations at a high latitude sea level site 1937-1994

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Abstract. We have created an extended cosmic ray data string (1937 - 1994) by combining data obtained with ion chambers at Cheltenham/Fredericksburg (1937 - 1972) and Yakutsk (1953 - 1994). Both represent high-latitude, sea level sites, with an atmospheric cutoff of about 4 GV. Their common median rigidity of response to galactic cosmic ray spectrum is 67 GV. This data string represents the longest continuous cosmic ray intensity variations record yet. Therefore it is useful for the cosmic ray modulation studies over a longer time period. We show that there is no striking quantitative correspondence between the amplitudes of solar activity cycles and cosmic ray modulation over six cycles. However, an inverse correlation is apparent between the two. Moreover, the results on the durations of the two are ambiguous. Flat-topped recovery pattern predicted for even cycles (A > 0), at lower rigidities, is not observed in the ion chamber data. We speculate that three solar activity cycle quasi-periodicity may be present in the extended data string. Its origin is not identified yet. The quasi-periodicity is shown to exist also in the planetary index Ap data. As such, it may represent a characteristic feature of the solar wind source region on the Sun as yet unexplored. The odd cycles, with a negative polarity in the solar northern hemisphere, yield a better linear correlation between galactic cosmic ray intensity decrease and Ap than even cycles and A > 0 epochs.

1. Introduction

Cosmic ray solar modulation is witnessed in a variety of ways. For example, 11 year and 22 year variations of the annual mean counting rate of diverse detectors [*Ahluwalia,* 1992, 1994a, *Ahluwalia and Wilson,* 1996, and references therein], secular variation in the limiting rigidity of galactic cosmic rays [*Ahluwalia and Riker,* 1987; *Ahluwalia and Sabbah,* 1993a, and references therein], long-term changes in the parameters applicable to the diurnal anisotropy [*Ahluwalia,* 1988; *Ahluwalia and Sabbah,* 1993b] and its higher harmonics [*Ahluwalia and Fikani,* 1996a, b], as well as the observed changes in the transverse gradients [*Ahluwalia and Sabbah,* 1993c; *Ahluwalia,* 1994b, 1996; *Ahluwalia and Dorman,* 1997]. Several creative ideas have been suggested to understand these observations. Even so, a broad consensus still eludes us as to the relative importance of the key concepts and details of their contributions to the transport of charged, energetic particles in the tangled magnetic fields that permeate the heliosphere. This being the case, the studies of the observed variations over a large range of timescales and a broad range of galactic cosmic ray (GCR) rigidities have to be continued into the future.

A worldwide network of four shielded (12 cm Pb) ion chambers (IC) was set up by *Forbush* [1966], at certain strategic locations around the globe, for continuous monitoring of cosmic ray muon intensity. IC at Cheltenham, Maryland, was one of them. It began operation in March 1935, but continuous bihourly observations became available only from March 10, 1937, onward [*Lange and Forbush,* 1948]. It was moved to a new location in Fredericksburg, Virginia, in October 1956 where it operated continuously until it was shut down in 1978. The data for the last 4 years of its operation are not available to the community. Fortunately, a larger IC (type ASK-1, 1 m diameter) has operated continuously at Yakutsk, Russia, from June 14, 1953, onward [*Shafer and Shafer,* 1984, *Krymsky et al.,* 1995]. Both are high-latitude, sea level sites, with an atmospheric cutoff of about 4 GV [*McCracken,* 1962; *Ahluwalia and Ericksen,* 1971] which is greater than the geomagnetic cut offs of 1.7 GV for Yakutsk and 2.2 GV for Cheltenham-Fredericksburg. This means that geomagnetic field admits particles with rigidity < 4 GV at both sites, but they lose energy by ionization and barely make it to the lower stratosphere (Pfotzer maximum) and do not contribute to the counting rate of sea level IC. If the two data streams can be combined into a single string, in a satisfactory manner, one would obtain a credible record of cosmic ray secular variations for the last 6 decades. Our determined attempt to achieve this goal is described in this paper.

We realize that the combined data string may also be useful for the climatological studies. Some time ago, *Ney* [1959] speculated that there might be a connection between ionization produced by galactic cosmic rays (GCR) in the lower stratosphere and a change in the storminess of Earth's weather. For example, a lower conductivity of air (at the maximum of a solar activity cycle) might enhance the buildup of electric fields leading to an increase in thunderstorm activity and to an increased cloud cover which in turn may produce radiation cooling of the Earth at sunspot maximum. One may therefore expect to find an inverse correlation between solar activity cycle and precipitation at high-latitude locations. Recently, measurements in space have indicated

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that solar irradiance decreases in years of declining solar activity. These examples indicate why the subject of Sun-weather connection is so complex [*Reid*, 1995]. No single physical process has been identified whereby small changes in solar output might influence large energy stored in the weather system of the Earth. Because of the inherent nonlinearity of response, one may have to carry out accurate measurements over an extended time period of all solar outputs to Earth's environment. Progress is being made very slowly in understanding correlations of winter cyclone intensity, the storm track latitude shifts, and the long-term changes in GCR flux [*Tinsley and Deen*, 1991; *Tinsley*, 1993, 1994; *Ahluwalia*, 1992, 1994a; *Ahluwalia and Wilson*, 1996]. It is in this context that a reliable index of cosmic ray ionization in Earth's atmosphere, extending over nearly 6 decades, might prove most useful [*Ely et al.*, 1993; *Svensmark and Friis-Christensen*, 1996; and references therein].

2. Ion Chamber Data

The Yakutsk IC data have been normalized to 1000 mbar using a pressure coefficient of -0.11% per mbar [*Shafer and Shafer*, 1984]. The Cheltenham/Fredericksburg IC data have been normalized to the sea level pressure of 760 mm of Hg column (=1013 mbar) using a pressure coefficient of -0.18% per mm of Hg [*Lange and Forbush*, 1948; *Forbush and Venkatesan*, 1960; *Forbush*, 1966]. There are strong seasonal variations in the data of both IC arising from the temperature variations in the upper atmosphere [*Ahluwalia*, 1993]. However, there is no evidence of a systematic long-term seasonal change in IC data [*Dorman*, 1957; *Forbush*, 1958]. Therefore any significant long-term trend in the annual mean muon intensity measured by an IC cannot be ascribed to the meteorological effects. Figure 1 shows a plot of the annual mean muon intensity measured by IC at Cheltenham/Fredericksburg (1937 to 1972) and Yakutsk (1953 to 1994) in units of 0.01%. For Yakutsk IC data, a typical ± 1σ error is ≤ 0.2 %; experimental error bars are not shown to avoid clutter. The uncertainty in the annual mean value at Cheltenham is about the same [*Forbush*, 1958]. Apart from a difference in Dc levels for the two detectors, they seem to track each other quite well where the data sets overlap (1953 to 1972). However, a closer examination reveals a number of difficulties with Yakutsk data points for the 1953 to 1963 period. They are listed below.

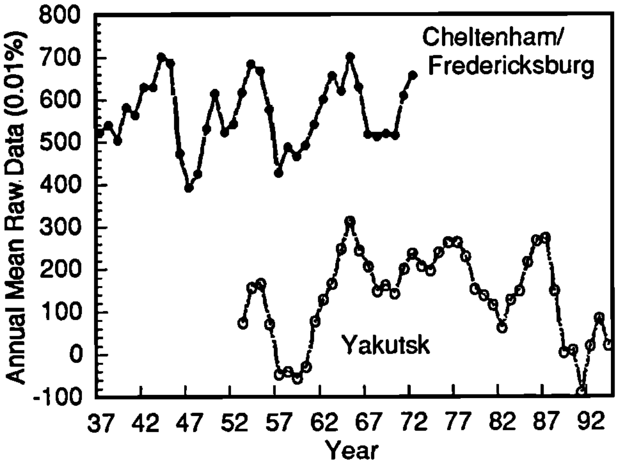

Figure 1. Annual mean hourly values are plotted in units of 0.01% for ion chambers at Cheltenham/Fredericksburg (1937-1972) and Yakutsk (1953-1994).

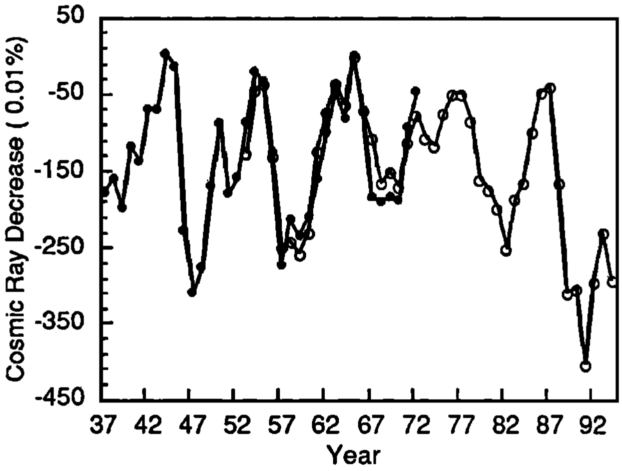

Figure 2. The two data strings are juxtaposed after adding 1.11% to the Yakutsk data points for the 1953 to 1963 time interval, normalizing the two data sets to 100% in 1965 and plotting differences (decreases) from that level for other years. See text for details.

1. The datum point for 1953 is questionable because it is derived from only about six months of continuous operation. It is well known that IC data are notorious for a large seasonal wave arising from a systematic fluctuation in upper atmosphere temperature [*Dorman*, 1957]; in particular they are subject to negative temperature effect [*Ahluwalia*, 1993].

2. The datum point for 1954 is well below (~1.6%) the point for 1965. This is inconsistent with Cheltenham/Fredericksburg IC data as well as NM data at all GCR rigidities which are at about the same level; within ≤ 0.2% [see *Ahluwalia and Wilson*, 1996, Figure 2].

3. The amplitude of cosmic ray modulation for solar activity cycle 19 (1957 to 1965) for Yakutsk IC is much larger (~4%) compared to that for the Cheltenham/Fredericksburg IC (~3%). This is physically impossible because both detectors have the same median primary rigidity of response (67 GV). Therefore they respond to the same range of GCR rigidity spectrum. If we insist that they must be the same, we are compelled to admit that the Dc level in 1957 for Yakutsk IC data is 1.11% below where it should really be. To remove this systematic bias we add 1.11% to all Yakutsk IC data points for the 1953 to 1963 period. Figure 2 shows a replot of the two datasets after applying this Dc shift to Yakutsk IC data. They are plotted with a common scale after normalization to 100% in 1965. It is clear that the overlap between the corresponding data points (excepting 1953), for the common period, has improved significantly. In particular, note that the data points of the reconstituted string for 1957 and 1982 are at about the same level as is also the case for the high-latitude neutron monitor at Climax [*Ahluwalia and*

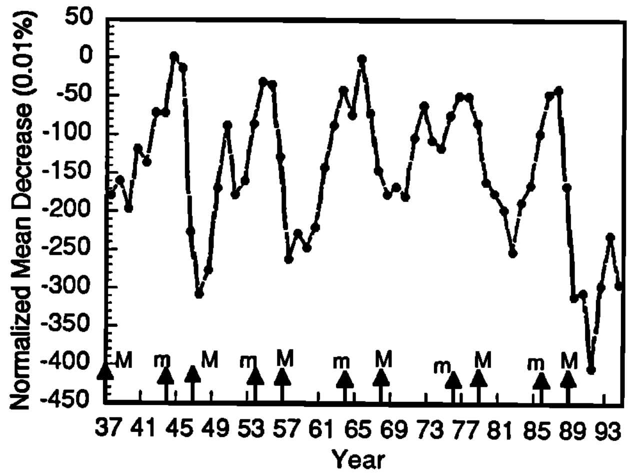

Figure 3. Data points represent our best estimate of cosmic ray modulation observed by a high-latitude ion chamber at a sea level location for the 1937 to 1994 period. See text for details.

Wilson, 1996, Figure 2]. This is indeed very gratifying. The reader should note that the fine structure present in the two data sets is preserved in the reconstituted data string.

3. Data Analysis

Figure 3 represents our best estimate of cosmic ray modulation observed for higher rigidity GCR, for the 1937 to 1994 period, by a high-latitude ion chamber located at sea level. The graph gives a replot of the data in Figure 2 in which the two data strings are joined together after taking an average of the corresponding points for the 1954 to 1972 common interval. The upward pointing arrows on the horizontal scale mark the epochs of solar activity maxima (M) and minima (m). The following features are easily noted in the extended (1937 to 1994) data string.

1. The string extends over four complete solar activity cycles (18, 19, 20, and 21) and includes parts of the other two (17 and 22). The recovery is not complete yet for SAC 22 [*Ahluwalia and Wilson*, 1997].

2. The amplitude of modulation is the largest for cycle 22, while the amplitude for SAC 18 modulation is the second largest. However, the amplitude of SAC in terms of sunspot numbers (SSN) is about the same for the two cycles, but the largest amplitude is observed for SAC 19 which remains the most active cycle ever. So there is no quantitative correspondence between the amplitudes of SAC and cosmic ray decrease. These features are depicted in Table 1. This inference is in accord with that drawn in a previous study [*Ahluwalia*, 1994]. Table 1 also indicates that the durations of solar activity and cosmic ray modulation are the same for SAC 18 and 19. Beginning with SAC 20, however, there appears to be a delay of 2 to 3 years both in the onset and recovery of cosmic ray modulation. The observed delays have not yet been successfully modeled with numerical solutions of the cosmic ray transport equation.

Table 1. Solar Activity Cycles and Observed Cosmic Ray Modulation

	Solar Activity, Sun Spot Numbers			Cosmic Ray Intensity		
Cycle	Minimum	Maximum	Amplitude	Maximum	Minimum	Decrease, %
17	1933	1937		NA	1939	2.0
	(5.7)	(114.4)	108.7			
18	1944	1947		1944	1947	3.0
	(9.6)	(151.6)	142.0			
19	1954	1957		1954	1957	2.3
	(4.4)	(190.2)	185.8			
20	1964	1968		1965	1968-1970	1.4
	(10.2)	(105.9)	95.7			
21	1976	1979		1976-1977	1982	2.1
	(12.6)	(155.4)	142.8			
22	1986	1989		1987	1991	3.6
	(13.4)	(157.6)	144.2			

NA, not available. Parentheses indicate observed sunspot numbers.

3. The recovery for even cycles (18 and 20) is to a level slightly below those for the adjoining odd cycles (17, 19 and 19, 21), although recovery for cycle 21, at higher GCR rigidities is noticeably below that for previous two odd cycles (17 and 19). This is opposite to what is observed for the neutron monitors [*Ahluwalia*, 1994a, *Webber and Lockwood*, 1988]. Also, note that recovery for cycle 20 is to a level distinctly lower than that for SAC 18. There is no explanation for this behavior in terms of currently advocated theoretical ideas if it turns out to be a characteristic feature of modulation at higher GCR rigidities. However, a local cause related to a longer-term change in the thermal structure of the atmosphere and or the barometer coefficient and or an instrumental drift cannot be ruled out yet.

4. The cosmic ray peak intensity for even cycles (18 and 20) can by no means be considered "flat topped" (mesa pattern) but seem to involve two distinct steps which is inconsistent with the *Jokipii and Thomas* [1981] hypothesis involving charged particle drifts in the heliosphere. In fact, the significant temporal intensity variations during all cycles (both even and odd) contain a lot of fine structures (well above the noise level) so that one can hardly see any evidence of alternating sharp (inverted vee-shaped) and flat maximum inferred from the drift hypothesis. However, their simulations involved 2 GV protons and IC responds to higher rigidity GCR. The drift hypothesis [*Kota and Jokipii*, 1983] does not provide any explanation for the observed two-step recovery and other observed fine structures.

5. There may be a suggestion of 3 SAC quasi-periodicity in the cosmic ray data covering nearly 6 decades. The cosmic ray minimum for cycle 17 is distinctly shallower than that for cycles 18 and 19. Similarly, the minimum for cycle 20 is distinctly shallower than that for cycles 21 and 22. It is not clear what the physical cause is. An interesting question arises as to whether the cosmic ray minimum for cycle 23 will be shallower than that for cycles 21 and 22. If the 3 cycle relationship holds, one expects the amplitude of SAC 23 to be smaller than that for cycle 22 with SSN ~ 100 (see Table 1). This remains to be seen. Previously, a similar periodicity has been reported in the solar and geophysical data. For example, a power spectrum analysis of the monthly SSN for 1868 to 1990 indicates the presence of a 33-year peak [*Silverman*, 1992]. It shows up more prominently in the power spectra of monthly auroral occurrence over a longer time period. Silverman also finds that the power in the peak at 33.3 years is comparable to that in the peak for 11.1 years.

4. Galactic Cosmic Rays and the Planetary Index Ap

Forbush [1954] was the first to show that an inverse correlation exists between SSN as well as the H component of the geomagnetic field and the IC data at Huancayo, Peru, on a long-term basis (1937-1953). *Sarabhai et al.* [1954] argued that coronal green line (5303 A) intensity is better correlated with the long term changes in GCR modulation than is the SSN. *Katzman and Rose* [1962] showed that GCR intensity measured with a network of the Canadian detectors (neutron monitors as well as muon telescopes) showed a closer inverse

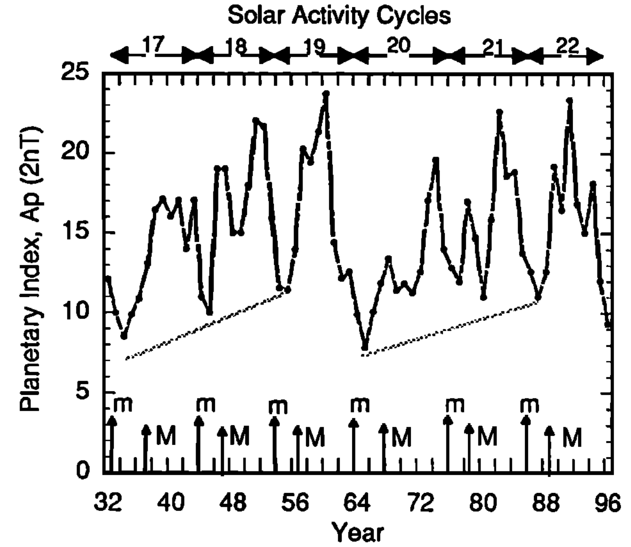

Figure 4. Data for the planetary index Ap are plotted for the 1932 to 1996 period. The three solar activity cycle quasi-periodicity in Ap minima is indicated by shaded lines in the lower half of the figures. See text for details.

correlation to the sum *Kp*. *Snyder et al.* [1963] related the sum *Kp* to the measured bulk velocity of the solar wind. Subsequent work established significant correlations between coronal green line intensity and the index *Ap* [*Gnevyshev*, 1967] and between cosmic ray eleven year modulation and *Ap* [*Balasubrahmanyan*, 1969]. The index *Ap* is the linear equivalent of the sum *Kp* which is measured on a logarithmic scale. It has a range between 0 (quietest day) and 400 (most disturbed day) and has been archived since 1932 [*Bartels*, 1962]. The correlations imply that solar wind velocity plays a significant role in causing cosmic ray modulation, a premise embraced by the diffusion convection model [*Parker*, 1963] of cosmic ray transport in the heliosphere.

Figure 4 is a plot of *Ap* data for the 1932 to 1996 period. The epochs of solar activity maxima (M) and minima (m) are represented by the upward pointing arrows on the horizontal scale. On the top of Figure 4 the durations of SAC are marked by the horizontal arrows. The data span four SAC (18, 19, 20, and 21) and parts of other two (17 and 22). The following features may be noted.

1. There are two maxima per SAC; one near M and other 3 to 5 years before m. In general, the latter peak has a larger amplitude. The separation between the two peaks varies with the SAC; it is appreciable for cycles 18, 20, and 21 and not so for cycles 17, 19, and 22. The first peak is attributed to CME activity, while the second to the high-speed solar wind streams from the coronal holes [*Venkatesan et al.*, 1991].

2. The minimum in *Ap* data always occurs one year after the SSN minimum. On the other hand, minimum cosmic ray modulation sometimes occurs at SSN minimum (cycles 18, 19 in Table 1) and sometimes at *Ap* minimum (cycles 20, 21, 22). Perhaps as a result of this, the length of the modulation cycle does not always equal that of SAC. The physical cause of this observed difference of behavior of cosmic ray modulation remains unidentified at present.

3. During the even cycles (A > 0), subsidiary minima occur in GCR intensity near the second *Ap* peak (1951-1952 and 1973-1974); recovery for cycle 22 is still in progress. No corresponding feature is seen during odd cycles (A < 0). At present the physical cause for this feature is not known.

It is conceivable that the subsidiary minima are the result of the cosmic ray modulation by the corotating interaction regions (CIR) formed further out in the heliosphere as envisaged by *Quenby et al.* [1995]. They postulate that a recurring series of middle-latitude high-speed streams spread out in latitude beyond ~ 4 AU, casting a shadow at the observation locations in the inner heliosphere up to at least ± 70° (to explain the Ulysses near relativistic particle data). They are able to rule out significant contributions from a competing model proposed by *Kota and Jokipii* [1995] involving the tilted heliospheric current sheet with drift and enhanced perpendicular diffusion (from the random walk of the field lines normal to the average magnetic field direction). An analysis of the relativistic protons data obtained on board the Ulysses spacecraft appears to support the inference drawn by them [*Zhang et al.*, 1995]. The ion chambers respond to GCR protons of much higher rigidities. In this respect, it would be interesting to see if the proposed extension of the drift model [*Potgieter et al.*, 1993], by including the effects of the global and transient merged interaction regions, is able to simulate the two step recovery during A > 0 epochs. In particular, one would like to know if the numerical simulations are able to reproduce the correct rigidity dependence of the observed two step increase. We do note, however, that Ulysses data indicate that the observed symmetric gradient (crucial to the validity of the drift model) is significantly smaller [*Simpson et al.*, 1996; *Heber et al.*, 1996] than that predicted by the numerical simulations at high latitudes for the lower rigidity GCR protons and ions even when the strongest possible theoretical modification is made to the IMF to accommodate the enhanced turbulence observed in the solar polar regions and the effect of the GMIR are taken into account [*Haasbroek et al.*, 1995]. In passing, we note the suggestion made by *Fisk* [1996] of a plausible physical scenario in which it is not necessary to invoke an unusual expansion of the CIR in latitude or unusual cross-field diffusion. He shows that if the foot points of interplanetary magnetic field (IMF) lines in the photosphere rotate differentially and if they undergo a nonradial expansion about an axis different from Sun's rotation axis which rotates at a speed other than the differential rotation speed, the natural result is an extensive excursion (≥40° within a radial distance ~ 15 AU) of the IMF line in the heliosphere. This up and down excursion of the field lines in latitude will result in magnetic connections among different latitudes and longitudes in the heliosphere. Not only would this permit high-latitude access to particles modulated by CIR at lower latitudes but also naturally explain why the GCR latitude gradients seen by Ulysses are so small. This attractive idea should appeal to the modelers just enough for them to carry out the numerical simulations to explore aspects of cosmic ray modulation in three dimensions.

4. There is a definite trend in *Ap* minima over three succeeding SAC at a time. This is indicated by the shaded lines in the lower half of Figure 4. It represents a three solar cycle quasi-periodicity. It is not too far fetched to imagine that a new three cycle trend may be starting after 1996. This interesting phenomenon needs to be investigated further. It may be related to as yet undiscovered property of the source region of the solar wind on the Sun.

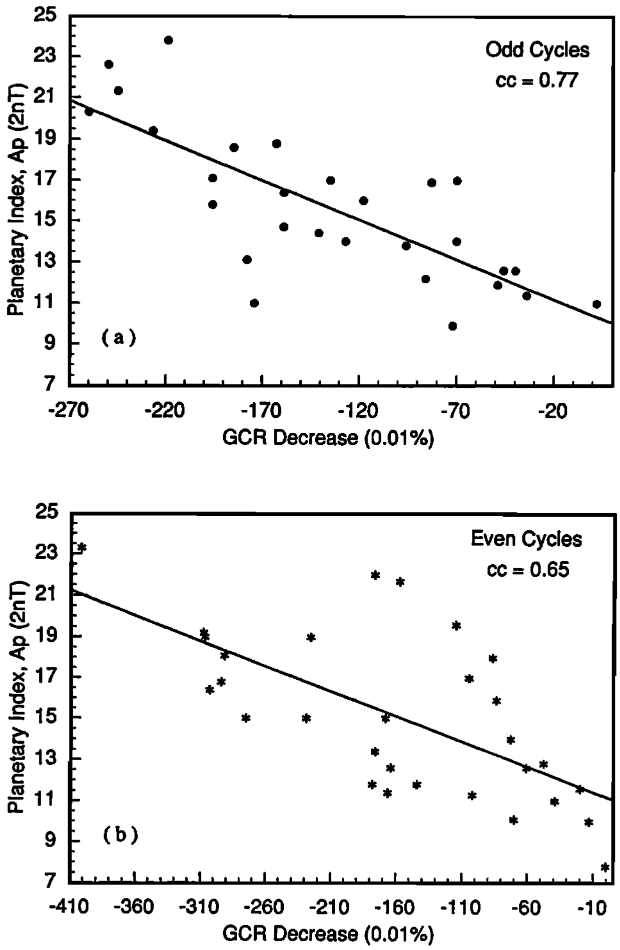

Figure 5. Linear correlations are depicted between GCR decrease and Ap for (a) odd cycles, and (b) even cycles. The correlation coefficient (cc) is higher for the odd cycles.

To further examine the features of relationship between cosmic ray modulation and *Ap* data, we study linear correlations between the two. Figures 5a and 5b represent the correlations between *Ap* and GCR decrease for odd and even cycles; the former seems to be slightly favored than the latter in that the correlation coefficient (cc) is higher (0.77 versus 0.65). While the difference is significant at < 5% level, there is an appreciable scatter of data points (particularly at higher values of *Ap*) which might indicate that the correlations between the two data sets is nonlinear. One encounters a similar situation when one examines the influence of the magnetic polarity in the solar northern hemisphere. The corresponding correlations are depicted in Figures 6a (A < 0) and 6b (A > 0); the negative magnetic polarity is favored with cc of 0.72 versus 0.61 (for A > 0). Our in depth research on the physical significance of these correlations is still in progress and will be reported elsewhere.

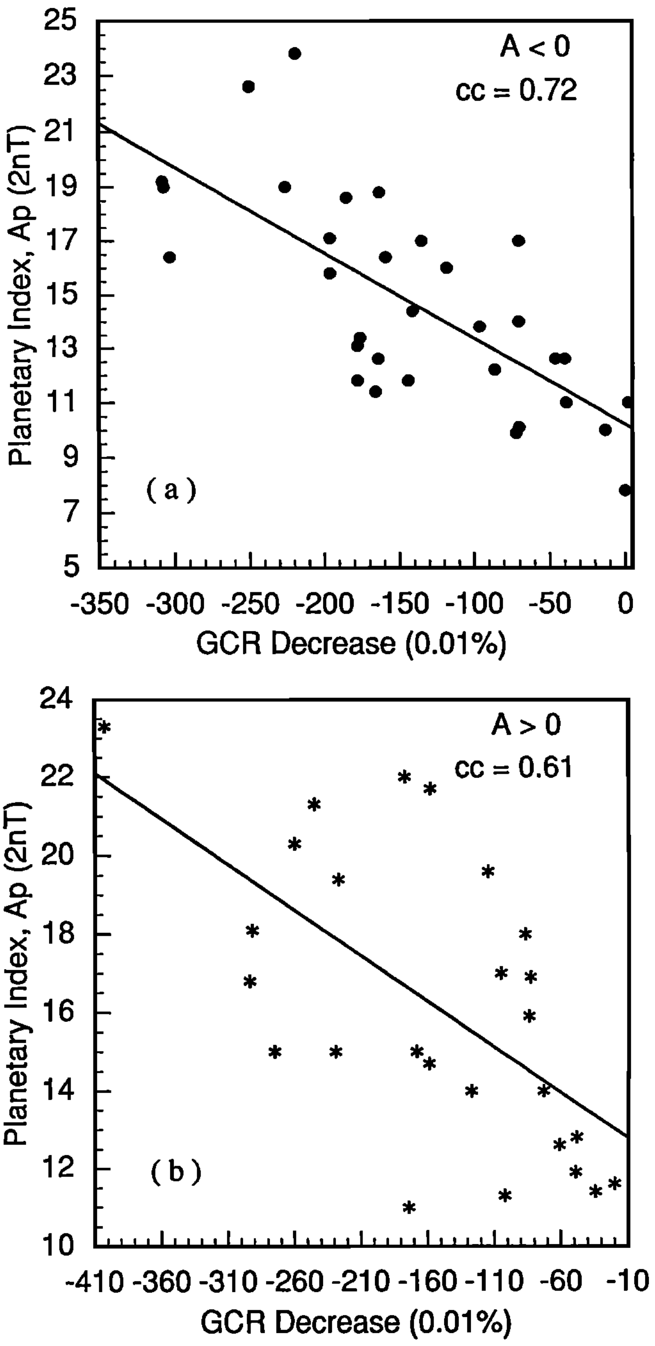

Figure 6. Linear correlation is shown between GCR decrease and Ap for (a) A < 0 and (b) A > 0 epochs. The negative polarity epochs seem to be favored.

5. Summary and Conclusions

We have obtained an extended data string (1937 to 1994) by combining data of ion chambers at Cheltenham/Fredericksburg and Yakutsk. They represent two high-latitude, sea level sites, with an atmospheric cutoff of about 4 GV. The median GCR rigidity of response for both of them is 67 GV. These data can now be used for the study of the characteristics of the long-term changes in cosmic ray modulation extending over six SAC. The data may also be useful for the studies related to the past climatology. The following important conclusions can be drawn from our careful study.

1. There is no striking correspondence between the amplitudes of SAC and cosmic ray modulation. The results on the durations of the two cycles are ambiguous. While they are the same for SAC 18 and 19, they differ for subsequent SAC by 1 to 3 years. So one cannot predict whether or not a delay would occur for SAC 23.

2. The flat-topped cosmic ray peak intensity for even cycles (A > 0), predicted by *Jokipii and Thomas* [1981] at lower rigidities, is not observed in IC extended data. Significant time variations near cosmic ray maxima for both even and odd cycles contain pronounced fine structures so that one does not see the expected alternating sharp and flat maxima near peak cosmic ray intensity. The drift hypothesis has no explanation for the observed fine structures such as the two step recovery which seems to have some relationship to the second *Ap* peak during even cycles (A > 0).

3. A three solar activity cycle quasi-periodicity may be present in the extended data string. However, more work needs to be done to confirm this speculation. A similar periodicity is seen in the solar and geophysical data over an extended time period. The physical cause for this is not known at present. We have shown that this quasi-periodicity also exists in *Ap* data (1932-1996). It may be related to as yet undiscovered property of the source region of the solar wind on the Sun.

4. The odd cycles and A < 0 epochs give a better correlation between GCR intensity decrease and the planetary index *Ap* than even cycles and A > 0 epochs. The physical significance of these correlations is not clear yet.

5. A challenging opportunity is presented to the modelers to perform detailed numerical simulations of the proposed extensions of the drift model (in the literature) to see if the observed fine structures can be reproduced and their rigidity dependence verified.

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References

Ahluwalia, H. S., The regimes of the east-west and the radial anisotropies of cosmic rays in the heliosphere, *Planet Space Sci.*, *36*, 1451-1459, 1988.

Ahluwalia, H. S., Cosmic ray modulation near the onset and maximum phases of solar activity cycle 22, *Planet Space Sci.*, *40*, 1227-1234, 1992.

Ahluwalia, H.S., Hale cycle effects in cosmic ray east-west anisotropy and interplanetary magnetic field, *J. Geophys. Res.*, *98*, 11513-11519, 1993.

Ahluwalia, H.S., Repetitive patterns in the recovery phase of cosmic ray 11-year modulation, *J. Geophys. Res., 99*, 11,561-11,567, 1994a.

Ahluwalia, H.S., Cosmic ray transverse gradient for a Hale cycle, *J. Geophys. Res., 99*, 23515-23521, 1994b.

Ahluwalia, H.S., Measurements of transverse cosmic ray particle density gradient at high rigidities in the Ulysses era, *J. Geophys. Res., 101*, 13,549-13,553, 1996.

Ahluwalia, H.S., and L.I. Dorman, Transverse cosmic ray gradients in the heliosphere and the solar diurnal anisotropy, *J. Geophys. Res., 102*, 17,433-17,443, 1997.

Ahluwalia, H. S., and J. H. Ericksen, Coupling functions applicable to the underground meson telescopes, *J. Geophys. Res., 76*, 6613-6627, 1971.

Ahluwalia, H. S., and M. M. Fikani, Cosmic ray solar semidiurnal anisotropy, 1, Treatment of experimental data, *J. Geophys. Res., 101*, 11,075-11,086, 1996a.

Ahluwalia, H.S., and M. M. Fikani, Cosmic ray solar semidiurnal anisotropy, 2, Heliospheric relationships of anisotropy parameters, *J. Geophys. Res., 101*, 11,087-11,093, 1996b.

Ahluwalia, H. S., and J. F. Riker, Secular changes in the upper cut-off rigidity of the solar diurnal anisotropy of cosmic rays, *Planet Space Sci., 35*, 39-43, 1987.

Ahluwalia, H.S., and I.S. Sabbah, The limiting primary rigidity of cosmic ray diurnal anisotropy, *Planet Space Sci., 41*, 105-112, 1993a.

Ahluwalia, H .S. and I. S. Sabbah, Cosmic ray diurnal anisotropy for a solar magnetic cycle, *Planet Space Sci., 41*, 113-125, 1993b.

Ahluwalia, H.S., and I. S. Sabbah, On cosmic ray asymmetrical latitudinal gradient, *Ann. Geophysicae, 11*, 763-773, 1993c.

Ahluwalia, H.S., and M.D. Wilson, Present status of the recovery phase of cosmic ray 11-year modulation, *J. Geophys. Res., 101*, 4,879-4,883, 1996.

Ahluwalia, H.S., and and M.D. Wilson, Cycle 22 recovery for cosmic ray modulation, *Conf. Paper Int. Cosmic Ray Conf. 25th, 2*, 53-56, 1997.

Balasubhramanyan, V.K., Solar activity and the 11-year modulation of cosmic rays, *Sol. Phys., 7*, 39-45, 1969.

Bartels, J., *Collection of Geomagnetic Planetary Indices K_p and Derived Daily Indices, A_p and C_p for the Years 1932 to 1961, North Holland*, New York, 1962.

Dorman, L.I., Cosmic Ray Variations, State Publishing House for Technical and Theoretical Literature, Moscow, 1957.

Ely, J.T.A., J.J. Lord, and F.D. Lind, Annual modulation of galactic cosmic rays circa 1 GV and relevance to tropospheric processes, *Conf. Pap. Int. Cosmic Ray Conf. 23rd, 3*, 586-589, 1993.

Fisk, L.A., Motion of the footpoints of heliospheric magnetic field lines at the Sun: Implications for recurrent energetic particle events at high heliographic latitudes, *J. Geophys. Res., 101*, 15,547-15,553, 1996.

Forbush, S. E., Worldwide cosmic ray variations, 1937-52, *J. Geophys. Res., 59*, 525-542, 1954.

Forbush, S. E., Cosmic ray intensity variations during two solar cycles, *J. Geophys. Res., 63*, 651-669, 1958.

Forbush, S.E., and D. Venkatesan, Diurnal variation in cosmic ray intensity, 1937-1959, at Cheltenham (Fredericksburg), Huancayo, and Christchurch, *J. Geophys. Res., 65*, 2,213-2,226, 1960.

Forbush, S.E., Time Variations of Cosmic Rays, edited by S. Flugge, Springer-Verlag, New York, 1966.

Gnevyshev, M. N., On the 11-year cycle of solar activity, *Sol. Phys., 1*, 107-120, 1967.

Haasbroek, L.J., M.S. Potgieter, and G. Wibberenz, Long term cosmic ray modulation along the Ulysses trajectory: A numerical simulation, *Conf. Pap. Int., Cosmic Ray Conf. 24th, 3*, 768-771, 1995.

Heber, B., W. Droge, H. Kunow, R. Muller-Mellin, and G. Wibberenz, Spatial distribution of >106 MeV proton fluxes observed during the Ulysses rapid latitude scan: Ulysses COSPIN/KET results, *Geophys. Res. Lett., 23*, 1513-1516, 1996.

Jokipii, J.R., and B. Thomas, Effects of drifts on the transport of cosmic rays, IV. Modulation by a wavy interplanetary current sheet, *Astrophys. J., 243*, 1115-1122, 1981.

Katzman, J., and D. C. Rose, Changes in the intensity level of cosmic rays at four Canadian stations, Can. J. Phys., *40*, 1,319-1,331, 1962.

Kota, J. and J.R. Jokipii, Effects of drifts on the transport of cosmic rays, VI, A three-dimensional model including diffusion, *Astrophys. J., 265*, 573-581, 1983.

Krymsky, G. F., et al., Effects of galactic cosmic ray modulation in the heliosphere, *Conf. Pap. Int. Cosmic Ray Conf. 24th, 3*, 631-634, 1995.

Lange, I., and S.E. Forbush, Peru, June 1936-December, 1946, including Cosmic Ray Results From Huancayo Observatory, summaries from observatories at Cheltenham, Christchurch, and Gadhavn through 1946, in Carnegie Inst. of Washington, *Publ. 175*, Washington, D. C., 1948.

McCracken, K.G., The cosmic ray flare effect, *J. Geophys. Res., 67*, 423-434, 1962.

Ney, E. P., Cosmic radiation and the weather, *Nature, 183*, 451-452, 1959.

Parker, E. N., Interplanetary Dynamical Processes, Interscience, New York, 1963.

Potgieter, M.S., J.A. le Roux, F. B. McDonald, and L. F. Burlaga, The causes of the 11 year and 22 year cycles in cosmic ray modulation, *Conf. Pap. Int., Cosmic Ray Conf. 23rd, 3*, 525-528, 1993.

Quenby, J.J., B. Drolias, E. Keppler, M.K. Reuss, and J.B. Blake, Cosmic ray modulation by expanding high latitude streams, *Geophys. Res. Lett., 22*, 3,345-3,348, 1995.

Reid, G. C., The Sun-climate question : Is there a real connection? *U.S. Nat. Rep., Int. Union Geod Geophys.* 1991-1994, *Rev. Geophys., 33*, 535-538, 1995.

Sarabhai, V., U. D. Desai, and D. Venkatesan, Cycle of worldwide changes in the daily variation of meson intensity, *Phys. Rev., 96*, 469-470, 1954.

Shafer, G.V., and Y.G. Shafer, Precision Measurements of Cosmic Rays at Yakutsk, Nauka, Siberian Div., Novosibirsk, Russia, 1984.

Silverman, S.M., Secular variation in the aurora for the past 500 years, *Rev. Geophys., 30*, 333-351, 1992.

Simpson, J.A., M. Zhang, and S. Bame, A solar north-south asymmetry for cosmic ray propagation in the heliosphere: The Ulysses pole to pole rapid transit, *Astrophys. J., 465*, 69-72, 1996.

Snyder, C. W., M. Neugebauer, and U.R. Rao, The solar wind velocity and its correlation with cosmic ray variations and with solar and geomagnetic activity, *J. Geophys. Res., 68*, 6361-6370, 1963.

Svensmark, H., and E. Friis-Christensen, Variation of cosmic ray flux and global cloud coverage - a missing link in solar-climate relationships, Eos *Trans. AGU Suppl., 77*, Fall Meeting, 1996.

Tinsley, B. A., Reply, *J. Geophys. Res., 98*, 16,889-16,891, 1993.

Tinsley, B., Solar wind modulation of the global electric circuit and apparent effects on cloud microphysics, latent heat release, and tropospheric dynamics, *Proc. 8th Int. Symp. Solar- Terr. Phy., Sendai, 1*, 238-239, 1994.

Tinsley, B. A., and G. W. Deen, Apparent tropospheric response to MeV-GeV particle flux variations: A connection via electrofreezing of supercooled water in high level clouds?, *J. Geophys. Res., 96*, 22,283-22,296, 1991.

Venkatesan, D., A. G. Ananth, H. Graumann, and S. Pillai, Relationship between solar and geomagnetic activity, *J. Geophys. Res., 96*, 9,811-9,813, 1991.

Webber, W.R., and J.A. Lockwood, Characteristics of the 22-year modulation of cosmic rays as seen by neutron monitors, *J. Geophys. Res., 93*, 8,735-8,740, 1988.

Zhang, M., J.A. Simpson, R.B. McKibben, T.S. Johns, E.J. Smith, and J.L. Phillips, Ulysses observations of 26 day intensity variations of cosmic rays and anomalous helium over the south pole, *Conf. Pap. Int. Cosmic Ray Conf. 24th, 3*, 956-959, 1995.

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