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Unusual time histories of galactic and anomalous cosmic rays at 1 AU over the deep solar minimum of cycle 23/24

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[1] The unusually quiet Sun of the cycle 23/24 solar minimum (that ended in December, 2009) has resulted in lower values of the interplanetary magnetic field and a slower approach of the tilt angle of the heliospheric current sheet toward the solar equator than has been observed for recent solar minima. As a result of these changes, the time-histories of galactic and anomalous cosmic rays over this period are very different from those of recent minima at the same phase of the heliomagnetic cycle. Since ~2005.6 there has been an on-going increase in cosmic-ray intensity (except for one brief transient decrease) that lasted for 4.4 years. The relative rigidity dependences of these increases compared to previous cycles are complex and should provide insight into the role of various solar and interplanetary phenomena in the modulation process. The largest increase occurs in the nominal "cross-over energy" region (where the modulation is essentially the same for each minimum of the two past 22 year heliomagnetic cycles) which extends from ~200 MeV/n to >500 MeV/n. **Citation:** McDonald, F. B., W. R. Webber, and D. V. Reames (2010), Unusual time histories of galactic and anomalous cosmic rays at 1 AU over the deep solar minimum of cycle 23/24, *Geophys. Res. Lett.*, *37*, L18101, doi:10.1029/2010GL044218.

1. Introduction

[2] Our heliosphere is a giant asymmetric bubble, carved out of the interstellar medium by the outward flowing solar wind. Galactic and anomalous cosmic rays probe the structure and dynamics of this vast region. On finite time scales (i.e., *millennia*) the Sun is the dominant variable force controlling this structure and the modulation of cosmic rays through the level of solar activity (coronal mass ejections), the tilt angle of the heliospheric neutral current sheet, the velocity as well as density of the solar wind and the strength and turbulence of the interplanetary magnetic field.

[3] At 1 AU studies of the galactic cosmic rays (GCR) temporal variations over the "Modern Era" (which began with the introduction of the neutron monitor in 1951 [*Simpson*, 2000]) established the existence of a 22-year cosmic ray modulation cycle that is dominated by the 11-year solar activity cycle but which is significantly influenced by gradient and curvature drifts in the interplanetary magnetic field (IPB) in association with changes in the tilt of the heliospheric neutral current sheet (HNCS) over the 22-year heliomagnetic cycle. The discovery of anomalous cosmic rays (ACRs) in the early 1970s provided a new, predominantly singly charged, high rigidity, low energy component that is especially sensitive to changes in modulation conditions in the interplanetary medium.

[4] The transition from the solar minimum of cycle 23 to the onset of cycle 24 was different from that of any other solar minimum over the past 100 years. It has been marked by a prolonged and continuing period of very low solar activity that began in 2006. In January 2008, the first sunspots of cycle 24 appeared but vanished after a few days. Since that time there have been several periods of moderate activity which did not persist for more than a single solar rotation until mid-December 2009. This continuation of the Quiet Sun is the basis for the designation: the cycle 23/24 minimum. The polar magnetic fields of the Sun are about half that of recent solar minima and through ~2009.2 [cf. *Wang et al.*, 2009], the average tilt angle of the heliospheric current sheet remained above 10°, appreciably higher than observed by the Wilcox Observatory over the previous 3 solar minima. The interplanetary magnetic field is ~28% lower than during the previous 4 solar minima when such data became available [*Smith and Balogh*, 2008]. *McComas et al.* [2008], using Ulysses data, have reported an ~20% decrease in the solar wind pressure compared to the cycle 22 minimum, which will have an effect on the size and structure of our heliosphere.

[5] In December, 2009 there was an increase in the sunspot number, 10.7 cm radio emission, and tilt angle of the current sheet that has continued through 2010.35. These interplanetary conditions produce modulation conditions that are unlike those encountered previously during the Modern Era. They result in time histories and particle intensities that differ from those of the past 5 minima, and provide an opportunity to more accurately define the effects of the weaker IPB, of changing the tilt angle and of altering the structure of the outer heliosphere. This minimum should also provide insight into the conditions that prevailed during previous "Grand Minima" such as the Dalton (1810), Maunder (1645–1715), Spoerer (1420–1540) and Oort (1050 AD). [cf. *Beer et al.*, 1991].

2. Observations

2.1. Modern Era, 1951–2006.5

[6] The remarkable repetitive nature of the 11 year and 22 year cosmic ray modulation and their inverse relation with solar activity from 1951–2006 are seen in the plots of the monthly averages of the Climax neutron monitor counting rate and the sunspot number over the 1951–2006.5 time period (Figures 1b and 1c) (sunspot numbers are used as a convenient proxy for solar activity [*Webb and Howard*,

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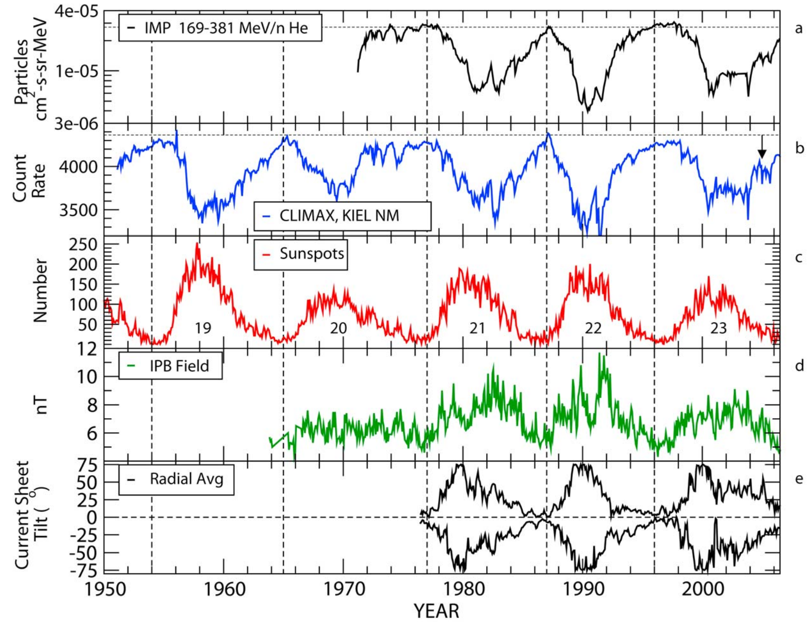

Figure 1. Comparison of (a) IMP 8 GCR He, (b) climax neutron monitor rates, (c) monthly sunspot number (SIDC), (d) interplanetary magnetic field (NSSDC) and (e) current sheet tilt (Wilcox Solar Observatory).

1994]). Other data such as the interplanetary magnetic field, the IMP8 flux of 150–380 MeV/n GCR He and the tilt angle of the HCS are included as they became available on a systematic basis (Figures 1a, 1d, and 1e).

[7] The 22 year heliomagnetic modulation cycle is more complex [*Jokipii and Thomas*, 1981; *Kota and Jokipii*, 1983]. In qA < 0 epochs (when the magnetic field at the north solar pole is directed into the Sun and positive ions flow in along the neutral sheet and out over the solar poles), the solar minimum cosmic-ray time history for ions peaks over a periods of several months (1965, 1987), in contrast to the 3–4 year quasi plateau periods for qA > 0 minimum when the flow pattern is reversed.

[8] At high energies the peak intensity at the Climax neutron monitor is ~3% higher for the solar minima of cycles 19 and 21 (1965, 1987) (qA < 0) than for cycles 18, 20 and 22, (1954, 1977, 1997) (Figure 2b). For lower energy 265 MeV/n GCR He the intensities are essentially the same for the solar minima of cycles 20, 21, and 22. It has been shown previously [*Webber and Lockwood*, 2001; *McDonald*, 1998] that the energy spectra for He (20–450 MeV/n) and H (20–350 MeV) are identical for cycles 20 and 22 minima while the spectra of cycles 19 and 21 are also similar to each other. The qA < 0 spectra show a decrease with respect to those of the even cycles at energies below 200 MeV/n. There is a cross-over region that extends from ~200 MeV to energies above 500 MeV where the intensities are essentially the same for the minima of cycles 19–22.

[9] Over the previous four solar minima the IPB has approached the same level of ~5nT (Figure 1d) [*Svalgaard and Cliver*, 2007]. The variation of the current sheet resembles that of the monthly sunspot number (Figures 1c and 1e), reaching a minimum annual tilt of ~3°~4° since observations began at the Wilcox Solar Observatory. Except for 1954, the sunspot number over the previous minima of the "Modern Era" has been on the order of 10.

2.2. Ongoing Cycle 23/24 Solar Minimum

[10] Figure 2 covers the period from 1997.0–2010.3 and is similar to Figure 1 except for the addition of 8–18 MeV/n anomalous cosmic ray oxygen and 8–18 MeV/n C (which is predominantly of galactic origin) from the WIND Spacecraft. The interplanetary magnetic field reaches a minimum value of 3.6 nT after 2009.5, 28% below its minimum value of ~5nT over the minimum of cycles 20, 21 and 22 (Figure 2d). The current-sheet tilt decreased to a value of 11° in 2006.9, then increased to ~20° before beginning a steady decrease over much of 2008 reaching a value of 4.5° in 2009.94. The tilt angle using the LOS method showed a similar pattern but displace by ~15°. The sunspot number has remained at very low level from 2007.5 to 2009.83 (Figure 2f) and the total number of spotless days over that time is at its highest levels over the last 96 years.

[11] The three cosmic ray intensities in Figure 2 increase rapidly after the "Halloween Events" in late 2003 which marked the end of the solar maximum of cycle 23. This initial increase is followed by an ~1.5 year plateau region centered about 2004.7. Since that time, the GCR and ACR intensities increased continuously over the following 3 years (except for a brief decrease associated with a small transient increase of 5.5° in the tilt angle) reaching a broad minimum between 2009.5 and 2009.85 followed by a sharp decrease beginning in ~2009.9. The relative changes compared to cycle 21 can be seen more clearly in Figure 3 where the cycle 21 data has been shifted forward 20 years.

[12] The relative intensity comparisons between the cycle 21 and 22 and the 23/24 solar minima particle intensities of Figure 2 along with the Ulysses KET 2.5 GV electron data [*Heber et al.*, 2009]; the 200 MeV/n GCR Fe intensity from ACE [*Mewaldt et al.*, 2009]; the >100 MeV intensities at the Pfotzer maximum from daily balloon flights at Murmansk, Russia, and 10–21 MeV/n ACR He are tabulated in Table 1.

[13] The transient increase of ~5° in the tilt angle of the HNCS from 2007.9–2008.14 provides a unique opportunity

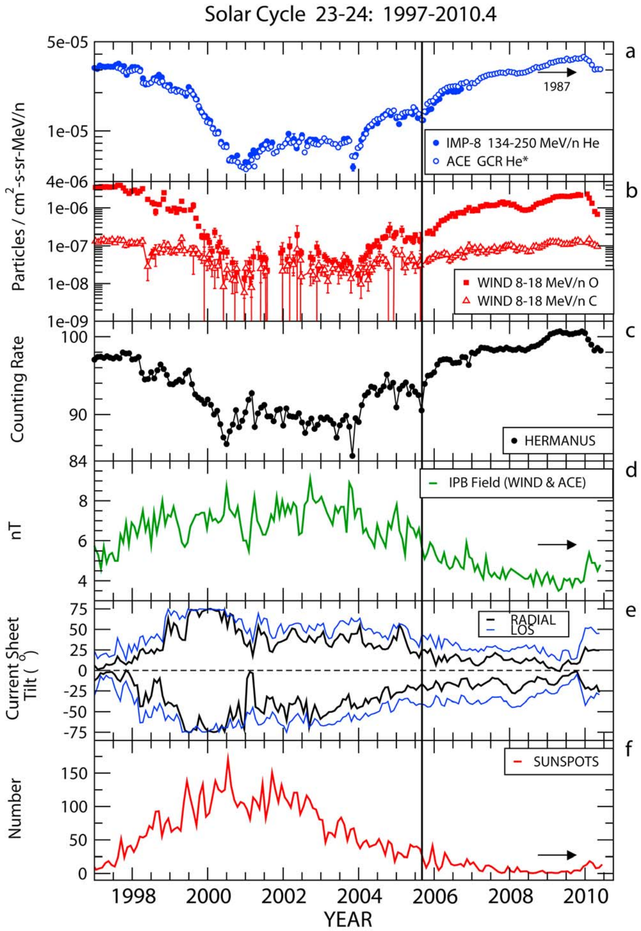

Figure 2. (a) The GCR He* data is both from IMP 8 until it ceased operation in 9/2009 and from ACE 134–250 MeV/n GCR Oxygen which has been normalized to the IMP 8 data from 1997.75–2006.6 and is identified as GCR He. There is a very close agreement between the two data sets over the period of over-lap. The Hermanus neutron monitor data replaces that of Climax. (b–f) The other data sets are from the same source as those of Figure 1.

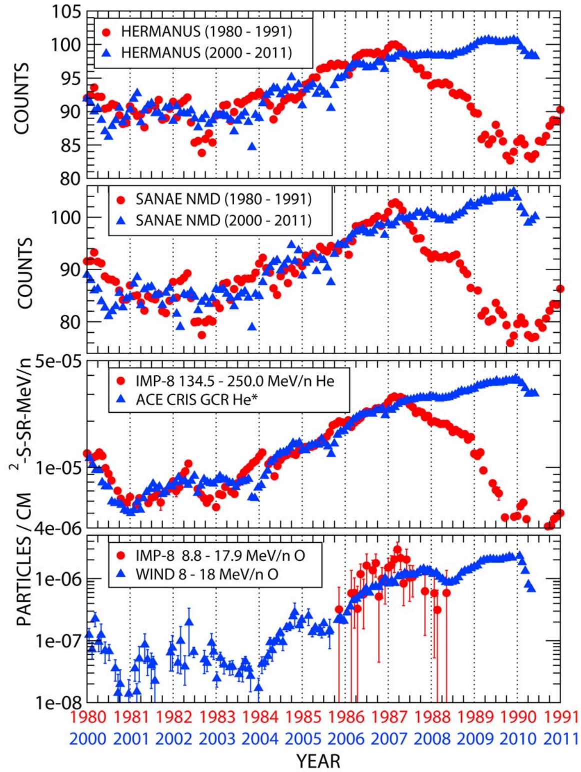

Figure 3. A comparison of the recovery and solar minimum of cycle 21 with that of cycle 23/24 for the Hermanus and Sanae neutron monitor data, GCR He and 8–18 MeV/n ACR 0 and GCR C. The cycle 21 data has been time shifted by 20 years.

to measure the effect of a change in the tilt on the cosmic ray intensity (Figure 4) near solar minimum, producing a 0.45% decrease in the SANAE NM data, 3.5% in 196 MeV/n He and 40% in 8–18 MeV/n ACR O. There is a delay of some 4 solar rotations between the changes in the tilt angle and the onset of the cosmic ray decreases, consistent with the 3 solar rotations found by *Cane et al.* [1999]. The magnitude of this increase was essentially the same for the LOS and radial methods of estimating the tilt angle.

3. Discussion

[14] The extended solar minimum of cycle 23/24 created interplanetary conditions that were very different from those present over previous minima in the “modern era”. There appear to be two major effects that produce the unusual time histories and different relative energy dependence compared to those of cycles 19 and 21:

[15] 1. The weaker interplanetary magnetic field that reached a value some 28% lower than that of the minima of cycles 19–22 [1965–1997].

[16] 2. The slower approach and higher value of the tilt angle at the end of the 23/24 minimum compared to cycles 20–22.

[17] *Wang et al.* [2009] have pointed out that these effects appear to be related–the weaker polar fields result in the apparent refusal of the heliospheric current sheet to flatten closer to the equator.

[18] Charge-dependent modulation provides important diagnostic tool for understanding modulation processes. Through the end of 2008.0, the Ulysses 2.5 GV electron intensity increased by ~30% over the 1997 value while 2.5 GV protons did not show any increase [*Heber et al.*,

Table 1. Comparison of Cycle 21 and 22 With 23/24[a]

	Cycle 23/24	
	Cycle 21 $\frac{J(2009.92)}{J(1987.14)}$	Cycle 22 $\frac{J(2009.92)}{J(1997.5)}$
Hermanus N.M (R_c = 4.9 GV)	0.55%	2.8%
SANAE NM Rate (R_c = 0.8 GV)	0.83%	3.2%
200 MeV/n Fe		21.8
196 MeV/n GCR He	27 ± 2%	14 ± 1.5%
10–18 MeV/n ACR 0	−10 ± 3%	−40 ± 3%
10–18 MeV/n GCR C		−4 ± 6%
Ulysses KET 2.5 GV electrons	—	~30
Russian Murmansk Balloon Flights (R_c = 0.6 GV)	15%	13%

[a]The 23/24 Solar minimum intensities were from the end of 2009 except Ulysses KET (end of 2008), the Murmansk Balloon Flights (April 2009) and ACE Iron (2009.3).

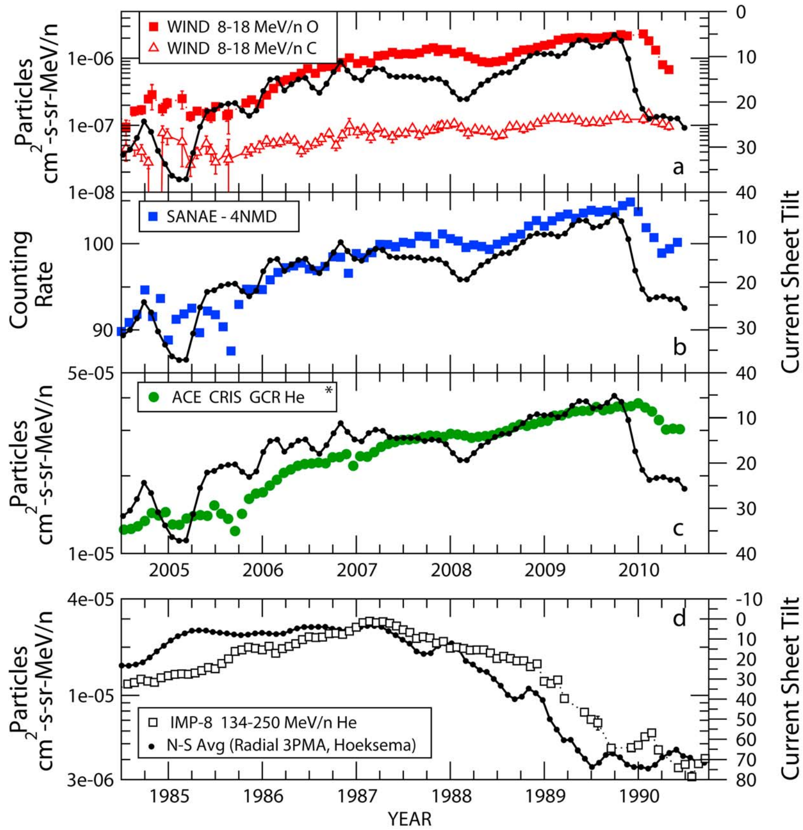

Figure 4. Cosmic ray intensity and tilt angle for cycles 21 and 23/24. The tilt angle values are three solar rotation running averages that are plotted at the center of the three month period. We have used the Wilcox Solar Observatory tilt angle data from their radial model.

2009]. For tilt angles < 30°, these high energy electrons are not sensitive to the tilt angle inclination [*Ferreira and Potgieter*, 2004] so the electron increase must reflect the larger diffusion coefficient associated with the weaker interplanetary magnetic field [*Ferreira and Potgieter*, 2004; *Heber et al.*, 2009].

[19] For GCR ions the largest increase in intensity for the 23/24 minimum compared to cycle 21 occurs around the nominal cross-over region from ~200 MeV/n to >500 MeV/n. This would appear to be mainly related to the decrease in the interplanetary field strength. The decrease in the plasma velocity has varied between 5 and 10% and should have a smaller effect.

[20] The more sharply peaked time history of all cosmic ray ions over the solar minimum of cycles 19 and 21 show the important role of drift effects in qA < 0 epochs. While the 2008.7 transient decreased in tilt angle produces a larger percentage change at low energies, it should be noted that the relative change from the onset of cycle 23 in 1997 to the 2001.5 maximum is much larger at lower energies. The ratio of the 5° change in tilt angle to the % change from solar minimum to solar maximum (1997.7–2001.5) is 3% of the SANAE solar cycle decrease, 0.7% for 200 MeV/n GCR He and 0.2% for 8–18 MeV/n 0, indicating that the tilt angle plays a significant role at the higher energies.

[21] Lower energy ACR and GCR ions are constrained to follow the field lines while high energy particles at NM energies will travel a more direct route. *Reinecke et al.* [1997] using a two-dimensional steady state model showed the suppression of low energy GCR ions in qA < 0 minima and the higher intensity at neutron monitor energies. The difference between 8–18 MeVn GCR C and ACR O is most probable related to the difference in spectral slope with GCR C having a Compton-Getting factor approaching zero compared to a value of ~2 for ACR oxygen. Over the last 1000 years there have been previous epochs of low solar activity that have resulted in significant increases in the GCR intensity [*Bard et al.*, 1997; *Beer et al.*, 1991; *McCracken et al.*, 2004] as measured by archival data from ^{10}Be in polar ice cores and ^{14}C in tree rings. The response function for ^{10}Be peak at lower energy (0.8–1.5 GeV) than that of mid-latitude neutron monitors [*Webber and Higbie*, 2003; *McCracken and Beer*, 2007]. To better understand the past it is important that contemporaneous measurements be made of ^{10}Be over this unusual period.

[22] *Caballero Lopez et al.* [2004] and *McCracken* [2007] modeled the cosmic ray intensity variations from 850–2000 AD by varying the strength of the heliospheric magnetic field. At the Maunder Minimum a value as low as 2nT was required for certain periods. *Usoskin et al.* [2002] calculated the cosmic ray intensity since 1610 using *Solanki et al.* [2000] estimate of the suns magnetic field. Reductions in the solar wind speed, density and the IPB could lead to larger values of the diffusion coefficient and in the structure of the heliosphere.

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