The Unusual Time History of Galactic and Anomalous Cosmic Rays at 1 AU over the Solar Minimum of Cycle 23

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***Abstract*. The continuing unusually Quiet Sun of the cycle 23 solar minimum has resulted in time-histories of galactic and anomalous cosmic rays at 1 AU that are very different from those of recent solar minima at the same phase of the 22 year heliomagnetic cycle. Instead of a peaked structure, the time-history of both galactic and anomalous cosmic rays display a broad plateau that is followed by an ongoing increase that as of 2009.2 has lasted for 1 year. 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.**

***Keywords*: Cosmic Ray Modulation**

I. Introduction

Galactic and anomalous cosmic rays probe the large scale structure and dynamics of our heliosphere, monitoring the interaction of the heliosphere with the Sun and with the interstellar medium. On finite time scales (i.e. millennia) the Sun is the dominant variable force through the level of solar activity (coronal mass ejections), the tilt angle of the heliospheric neutral current sheet, the velocity and density of the solar wind and the strength of the interplanetary magnetic field.

II. Cosmic Ray Observation: 1951-2006.5

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) established the existence of a 22-year cosmic ray modulation cycle. This cycle 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 over the heliomagnetic cycle. In qA$<$0 epochs (when positive ions flow in along the neutral sheet and out over the solar poles), the solar minimum cosmic rays intensity is peaked over a period of several months (1965, 1987) in contrast to the 3-4 year plateau periods for qA$>$0 minimum when the flow pattern is reversed. (Fig. 1a,b)The peak intensity at neutron monitor energies is $\sim$3% higher for the solar minimum of cycles 21 and 23 (qA$<$0) than for cycles 18, 20 and 22 (Fig. 1b). For 315 MeV/n GCR He the intensities are essentially the same for the solar minima of cycles 20, 21 and 22. The energy spectra for He (20-450 MeV/n He and H 20-350 MeV) are identical for cycles 20 and 22 minima while the similar spectra of cycles 19 and 21 show a steady decrease with respect to those of the even cycles [1], [2] at rigidities below 1GV. This suppression becomes large at lower rigidities.

Sunspots serve as a proxy for solar activity [3]. For the previous solar minima, the sunspot number has been on the order of 10 while the peak sunspot number at solar maximum in the modern era have been among the highest over the previous 22 cycles, leading to a cosmic ray intensity level that is estimated to be the lowest over the last thousand years.

The IPB and the solar wind velocity play an important role in the modulation process [4], [5]. The IPB has approached the same level of $\sim$5nT over the three previous solar minima (observations were not made prior to 1963.9). This recurring level over three solar minima had led to the concept that there was a floor on the minimum value of the IPB field [6].

The variation of the current sheet tilt resembles that of the monthly sunspot number, reaching an average tilt of $\sim 10^\circ$ over the three solar minima since observations began at the Wilcox Solar Observatory.

III. The Cycle 23/24 Solar Minimum

The data over the Modern Era through 2006.7 established a remarkable repetitive 22 year pattern that clearly showed the dominance of the Sun in controlling the level of solar modulation. This dominance is maintained over the progression from the cycle 23 solar minimum toward cycle 24 but the solar orchestration is very different from the previous 5 minima. Figure 2 covers the period from 1997.0-2009.2 and is similar to that of 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 and the substitution of 192 MeV/n GCR He from IMP-8 and ACE. The 192 MeV/n He intensity is 13% higher than over the 1997 solar minimum and 25% above its 1987 value.

In early 2009 the 13.5 MeV/n ACR oxygen (Fig. 2b) is a factor of 2.5 below its 1997 peak value which was also very close to the 1987 solar minimum peak intensity. The 13.5 MeV GCR C is only $\sim$25% below the 1997 intensity - a factor of $\sim$10 smaller decrease

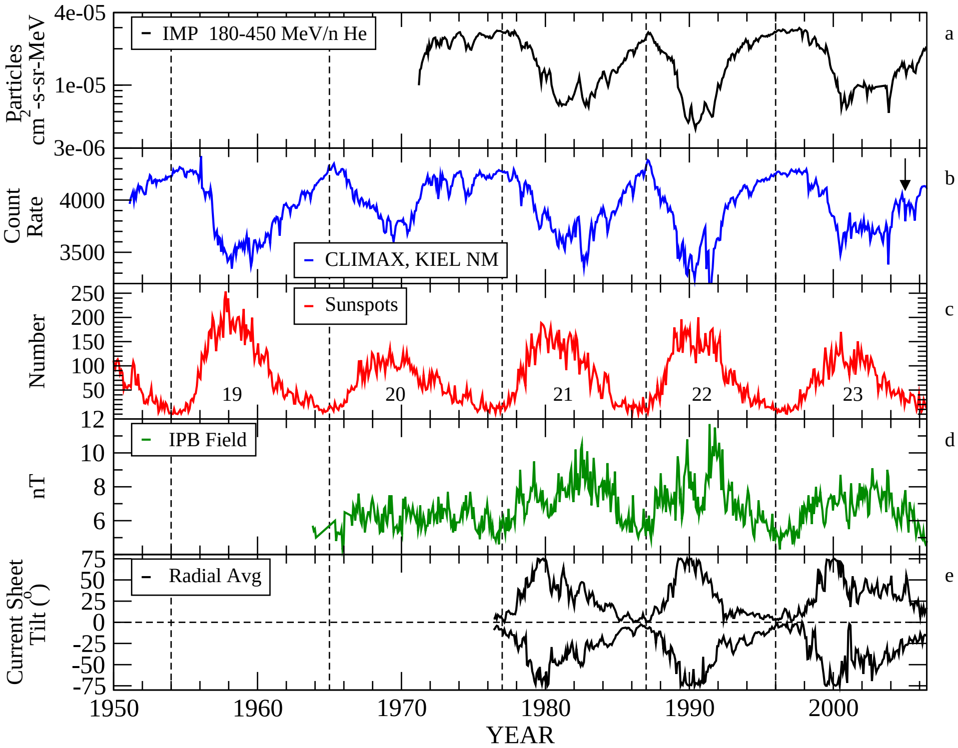

Fig. 1: Comparison of IMP-8 GCR He, CLIMAX and normalized Kiel Neutron Monitor rates, Monthly Sunspot Number (SIDC), Interplanetary Magnetic Field (NSSDC) and Current Sheet Tilt (WSO).

than that of ACR O. The Kiel neutron monitor is 2.4% higher in 2009.1 than in 1997 but is at the same intensity as its 1987 peak value. These comparisons of course will change if the 1 AU intensities continue to increase.

The interplanetary magnetic field is at an average level of 3.9nT in early 2009 - 22% below its value of 5nT over the minimum of cycles 20, 21 and 22. The current sheet tilt reached a minimum value of 10° in 2006.5, then move up to ∼25° then started a steady decrease over much of 2008 before leveling off over the last solar rotation of 2008 and through at least the first four solar rotations of 2009.

The sunspot number has remained at a very low level since 2007.5 and the number of spotless days is at its highest level over the last 96 years.

A more detailed comparison between the cycle 21 recovery and minimum and that of cycle 23 can be obtained by time-shifting the cycle 21 196 MeV/n He by 20 years on a plot of the cycle 23 data (Fig. 3). The recovery of the 2 cycles from solar maximum conditions is very similar but the cycle 23 intensity has a much broader quasi-plateau region that reaches a maximum at 2008.0 that is very close in intensity to that of the cycle 21 solar minimum period. After a very small decrease there has been a continuous, ongoing, increase over the past year to a level 25% above that of 1987.

The increase that began in 2008.25 appears to be related in-part to changes in the calculated tilt of the heliospheric current sheet that began to increase in late 2008 and then decreased to its lowest value over cycle 23 but as of April 28, 2009 has remained constant over the last 5 solar rotations. The influence of this change is clearly seen at all energies from low-energy anomalous cosmic rays to neutron monitor energies. However the decrease in early 2008 is larger for ACR 0 than the GCR He or the Kiel neutron monitor.

Using Ulysses solar wind data McComas *et. al.* [7] found that the fast solar wind through early 2008 was slightly slower and significantly less dense than at the previous minimum. This lower momentum of the solar wind would reduce the heliocentric distance to the termination shock and heliopause which will have an additional effect on the modulation of GCRs and ACRs. Smith and Balogh [8] using Ulysses magnetic field measurements showed that the low values of the IPB field are also present at high heliolatitudes.

IV. Discussion

The ongoing period of very low solar activity has a multi-faceted effect on the modulation process.

a. The tilt angle changes of the current sheet (Fig. 2,4) play a major role, especially for ACR 0 and perhaps for NMs but less for 135-250 MeV/n GCR He. This is probably because the GCR He is closer to the cross-over rigidity that defines the different

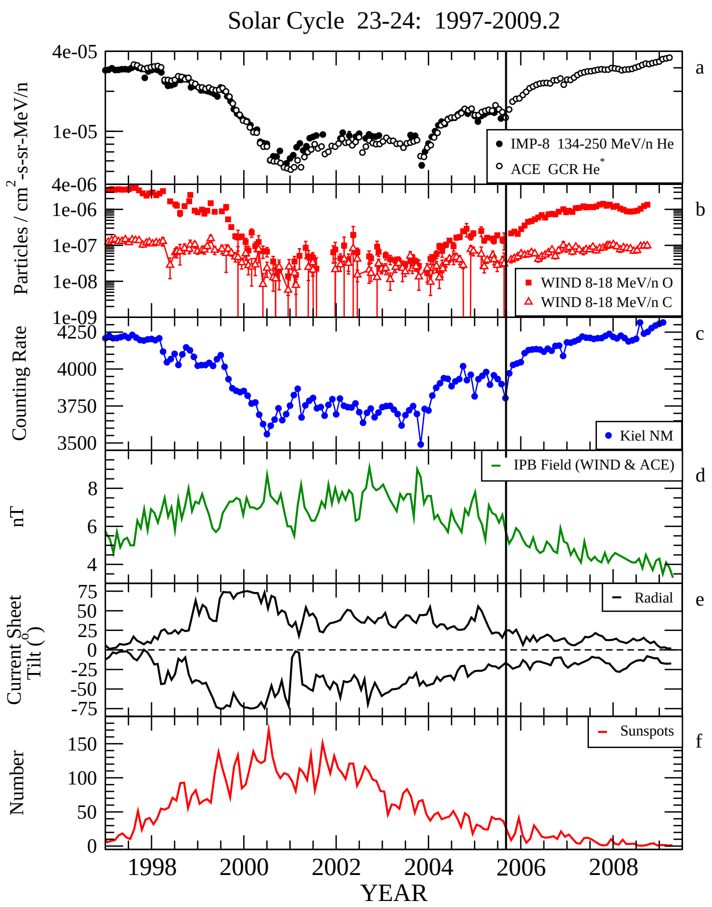

Fig. 2: The GCR He data of panel A is both from IMP-8 until it ceased operation in September 2006 and from ACE 134-250 MeV/n GCR oxygen which has been normalized to the IMP-8 data from 1997.75-2006.6. There is remarkable close agreement between the two data sets over the period of over-lap. The normalized ACE data is identified as GCR He*.

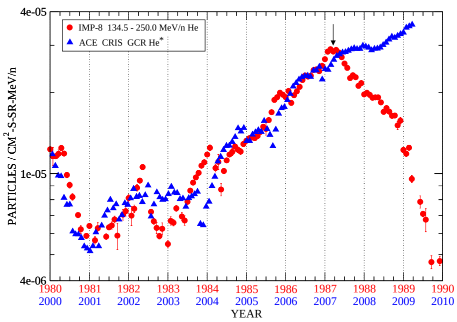

Fig. 3: Comparisons of recovery and solar minimum cycle 21 with that of cycle 23 GCR He*. The cycle 21 data has been time shifted by +20 years.

behavior for low rigidity and high rigidity particles in different phases of the heliomagnetic cycle [9], [10].

b. The lower IPB field will have a significant effect. At the Voyagers in the heliosheath there is an on-going increase of 265 MeV/n He (7.4%/year) and H (15.5%/year) that is temporal and not spatial in nature. Since drift effects are not expected to be important in the heliosheath, this increase is probably related to the lower B field. This decrease in B will take years to reach the flanks and tail region of the heliosheath. The lower momentum of the solar wind will produce a somewhat smaller heliosphere which will further reduce the cosmic ray modulation.

The pronounced difference between the 8-18 MeV/n ACR 0 and GCR C is probably due to the fact that the Compton-Getting factor for C is expected to be zero in this energy interval based on measurements over the previous solar minimum [15].

Over the last 1000 years there have been previous epochs of low solar activity that have resulted in significant increases in the GCR intensity [11], [12], [13]. As measured by archival data from ^{10}Be in polar

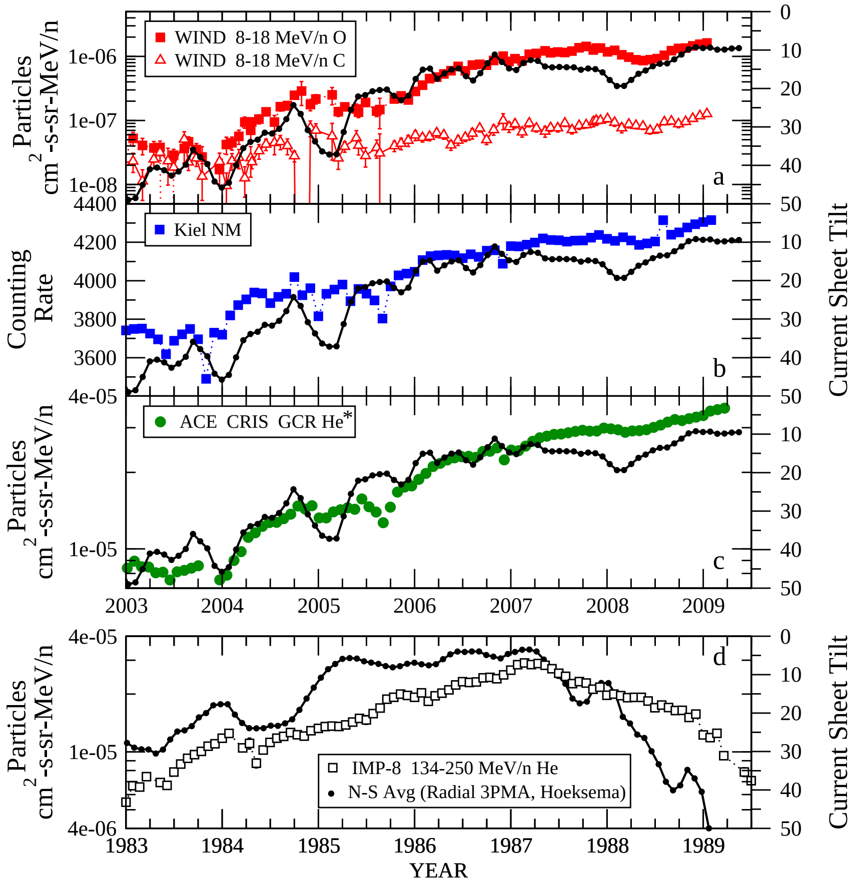

Fig. 4: Cosmic ray intensity and tilt angle. The tilt angle values are 3 solar rotation running averages that are plotted at the center of the 3 month period.

ice cores and ^{10}C in tree rings. Caballero-Lopez *et. al.* [14] 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. Reductions in the solar wind speed and density could lead to a larger values of IPB. The current Quiet Sun period should provide insight into the changes that occurred on the Sun and in the IP medium over those very unusual earlier periods.

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