The Unusual Behavior of Anomalous and Galactic Cosmic Ray Intensities at 1 AU During the Present Solar Minimum

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***Abstract*. Since the early 1970's, anomalous cosmic ray (ACR) intensities at 1 AU at solar minimum have generally tracked the galactic cosmic ray (GCR) intensities as measured by neutron monitors. Throughout the current A<0 cycle, however, the ACR intensities are a factor of 3–4 lower than expected from scaling neutron monitor rates; a similar discrepancy seems to have been present during the last A<0 period in the mid-1980's. Also, although there have been no major solar particle events for over 2 years, and sunspot numbers have been at minimum levels for at least a year, the ACR intensities are at present a factor of ∼2 lower than their maximum values during each of the last 3 solar minima, suggesting that heliospheric conditions are not yet at minimum modulation levels. This is probably associated with the fact that ACRs drift inward along the heliospheric current sheet (HCS) during A<0 cycles, and the tilt of the current sheet is still relatively high (∼23°) for solar minimum. However, while ACR intensities are low, GCR intensities are at a record high, and compared with the last A<0 cycle, we find that *both* ACR and GCR intensities are actually much higher now for a given HCS tilt angle than they were in the mid-1980's.**

***Keywords*: cosmic ray modulation, heliospheric current sheet tilt angle, 27-day variations**

I. Introduction

Measurements of anomalous cosmic ray (ACR) and galactic cosmic ray (GCR) intensities over the past decades have been used to investigate the role of drifts, convection, and diffusion in heliospheric cosmic ray transport throughout the solar cycle. Differences have long been observed in intensity versus time profiles for positively-charged particles between solar minima of opposite polarity cycles, and have been attributed to drifts inward along the heliospheric current sheet (HCS) when the Sun's magnetic field direction is inward in the northern hemisphere (A<0) and drifts down from the polar regions and outward along the HCS when the polarity is reversed (A>0) [1]. Correlations between ACR and GCR (neutron monitor) intensities, and hysteresis effects between the two, have been reported for quite some time (e.g., [2]), and these correlations have often been consistent across multiple solar cycles [3].

The Solar Isotope Spectrometer (SIS) and Cosmic Ray Isotope Spectrometer (CRIS) onboard the Advanced Composition Explorer (ACE) spacecraft have been measuring ACRs and GCRs, respectively, since ACE was launched in August 1997. These instruments provide a continuous, high-precision data set spanning the end of the last A>0 solar minimum, through solar maximum, and into the present A<0 solar minimum, allowing detailed comparisons of modulation effects throughout the solar cycle. As we show in this report, ACR and GCR intensities show dramatic differences in their correlations with each other and with the HCS tilt angle during the present solar minimum compared with previously observed solar minima.

II. Observations

Fig. 1 shows examples of ACR oxygen and GCR iron intensities measured at 1 AU throughout the ACE mission to date. After dropping by 2 orders of magnitude from the last solar minimum through solar maximum, ACR oxygen intensities at 7-29 MeV/nucleon have recovered significantly, but are still a factor of ∼2 below their 1997 levels. However, GCR intensities as reported by both the Newark neutron monitor (scaled for comparison with the ACRs in Fig. 1 as in [3]) and as measured on ACE/CRIS now significantly exceed the levels reached in the last solar minimum. Also, as we have pointed out in previous reports [4], the excellent agreement between the scaled neutron monitor rate and ACR intensities, which persisted during the approach to solar maximum while ACR intensities declined by nearly two orders of magnitude, has changed since about late 2000, or about when the solar magnetic polarity reversed. This change is not primarily due to a time lag between the ACRs and GCRs, but rather is in the overall intensity scale factor; the ACRs and scaled GCRs in the top panel of Fig. 1 can be brought into agreement after 2000 by raising the ACR intensities a factor of ∼3–4.

The power-law index of the neutron monitor scaling has not changed between the decline from the last solar minimum and the rise of the present minimum (Fig. 2). The recovery from solar maximum to 2009 has the same

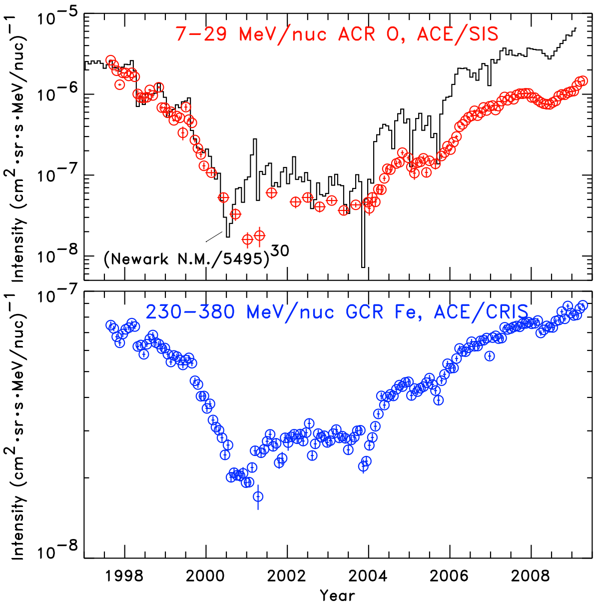

Fig. 1. Bartels rotation averages of quiet-time 7-29 MeV/nucleon oxygen (mostly ACRs) from ACE/SIS (*top panel*) and 230-380 MeV/nucleon iron (GCRs) from ACE/CRIS (*bottom panel*). Also shown in the *top panel* is the Newark neutron monitor rate, scaled as indicated.

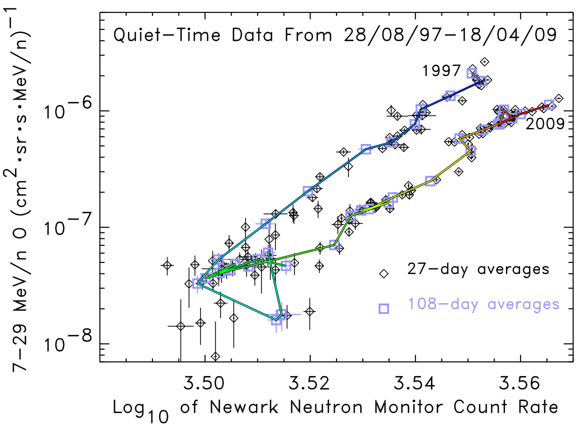

Fig. 2. ACE/SIS quiet-time 7-29 MeV/nucleon oxygen plotted versus the Newark neutron monitor count rate, using both 27-day (*diamonds*) and 108-day (*squares*) averages.

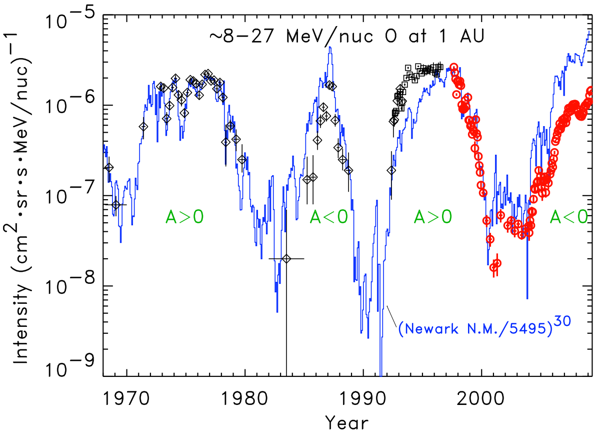

Fig. 3. Quiet time intensities of ∼8-27 MeV/nucleon ACR oxygen at 1 AU over the past 40 years (*data points*), compared with the Bartels rotation averaged count rate of the Newark neutron monitor scaled as indicated (*blue curve*). Data from ACE/SIS are shown as *red circles*; older measurements are from SAMPEX, OGO-5, and IMP-6,-7, and -8 (see [3] for data references).

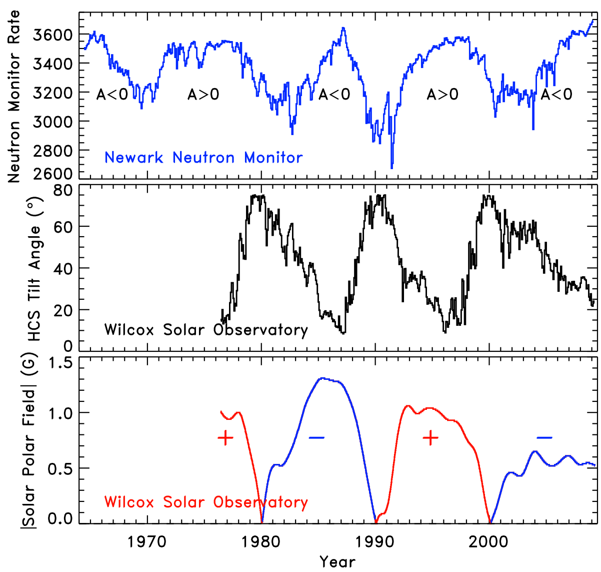

Fig. 4. Newark neutron monitor rate (*top panel*), heliospheric current sheet tilt angle (*middle panel*), and absolute value of the solar polar magnetic field (*bottom panel*) over the last several solar cycles. Data in the bottom 2 panels are from the Wilcox Solar Observatory [7]; the tilt angle shown here (and in Fig. 5) is their average "classic" line-of-sight value. The polarity of the polar field in the *bottom panel* for each cycle is indicated with "+" or "−".

slope as the decline from 1997 to solar max, with the ACR oxygen intensity scaling as the neutron monitor rate to the ∼30th power, but with a large offset between the decline and recovery tracks. This "hysteresis curve" between GCRs and ACRs shows no sign of closing yet, unlike those between GCRs at different energies which have already closed at ACE/CRIS energies [5]. This behavior also differs from that reported in the outer heliosphere [6], in which no hysteresis is apparent between ACR He (at 30-56 MeV/nucleon) and GCR He (at 300-450 MeV/nucleon), and the hysteresis between ACR He at two different energies shows a change in the power law index between the decline and recovery.

To put the present observations into perspective, Fig. 3 compares ACR and neutron monitor observations over the past 40 years. Note that the same scaling between ACRs and the neutron monitor that applies during the decline from 1997 to 2000 also holds throughout the last A>0 cycle in the 1970s, while the deficit of ACRs relative to the neutron monitor in the present cycle seems to have been present at a similar magnitude during the approach to the last A<0 solar minimum [3]. The 2009 ACR intensities are still significantly lower than the peak values observed at any of the last 3 solar minima, suggesting that either we are experiencing an unusually weak ACR recovery, or the heliosphere is not yet at minimum modulation conditions. Simultaneously,

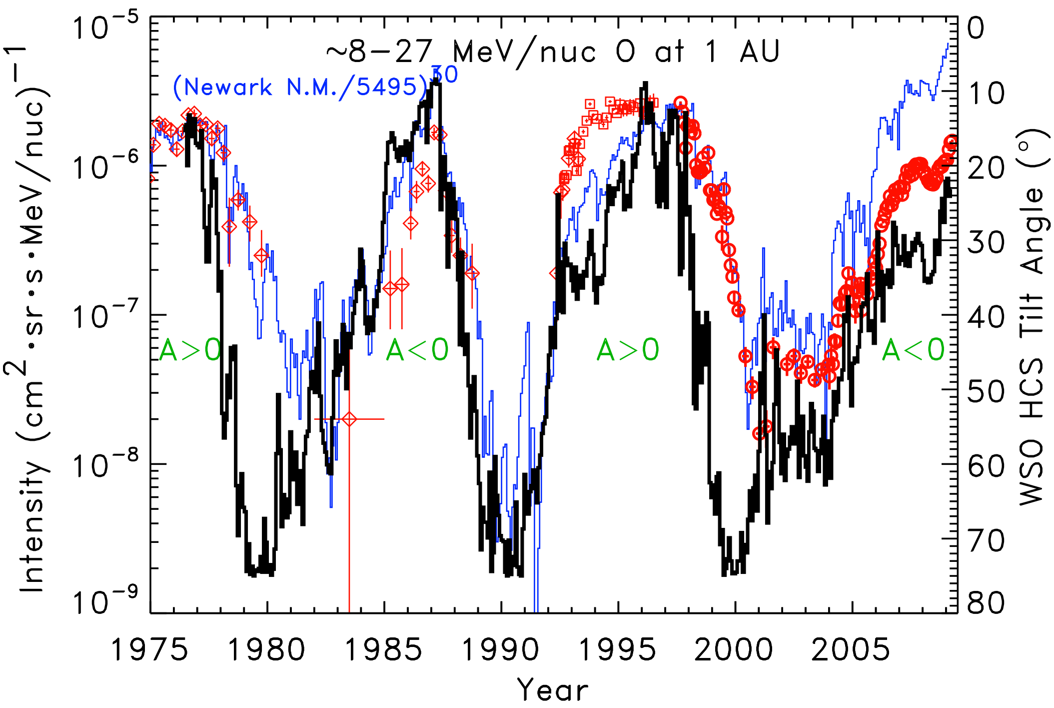

Fig. 5. Comparison of the ACR intensity (*red data points*) and the Newark neutron monitor count rate (*blue curve; left axis*), scaled as indicated, with the tilt angle of the heliospheric current sheet from the Wilcox Solar Observatory [7] (*thick black curve; right axis* – note inverted scale) over the past several solar cycles.

the Newark neutron monitor rate is at its highest level ever recorded, dating back to 1964. (Stations such as McMurdo with ∼0 cutoff rigidity are also experiencing record high count rates, so this can not be solely due to cutoff changes from reduction of the geomagnetic field).

III. Discussion

The unusually low ACR intensities are most likely associated with the fact that ACRs drift inward along the HCS during A<0 cycles [1]. The tilt of the current sheet is still relatively high (∼23°) [7], as illustrated in Fig. 4, and has been decreasing much more slowly this cycle than in the previous two, so the integrated pathlength along the sheet to the heliopause is probably different now than for the same tilt angle in the last A<0 solar minimum [8]. Also, the strength of the solar polar magnetic field is lower than the maximum values reached during the last 3 solar cycles and is only about half its peak value during the last A<0 cycle.

A phenomenological model [9] relating the tilt of the HCS to ACR gradients successfully accounts for the differences in ACR intensities between A>0 and A<0 and between the inner and outer heliosphere. The transport of GCRs within the heliosphere is expected to be similar to that of ACRs, and neutron monitor rates during A<0 have been shown to be well-correlated with the HCS tilt angle [10].

In Fig. 5 we compare both the ACR and GCR neutron monitor rates with the HCS tilt angle. The correlation between the neutron monitor and tilt angle is striking throughout the last A<0 cycle of the 1980s and even into the onset of the following A>0 cycle in the early 1990s. Prior to 2000, the major, prolonged deviations between the two curves occur during the approach to solar maximum from the two A>0 minima, when the neutron monitor rates declined only slowly as the tilt angle rapidly increased. Since particles are drifting in from the polar regions of the heliosphere during A>0 periods, it is not surprising that they are virtually unaffected by changes in the largely near-equatorial HCS, at least until the HCS reaches high latitudes.

After the last field reversal in 2000, the neutron monitor rate and HCS tilt angle no longer scale as they did for the previous three solar minima. For a given tilt angle, the GCR (neutron monitor) intensity is much higher now than it was during the last A<0 cycle. As displayed in this figure, the ACRs fall somewhat below the HCS tilt angle curve at the last A<0 solar minimum, while they fall significantly above it during the present A<0 period. That is, although ACR intensities are currently low compared to those at previous solar minima or compared to expectations from scaling the neutron monitor, for a given tilt angle they are actually much *higher* than during the last A<0 epoch.

IV. Conclusions

Although the correlation between HCS tilt angle and the neutron monitor rates during the 1980s is not surprising, the promptness of the neutron monitor response to a change in the tilt angle may

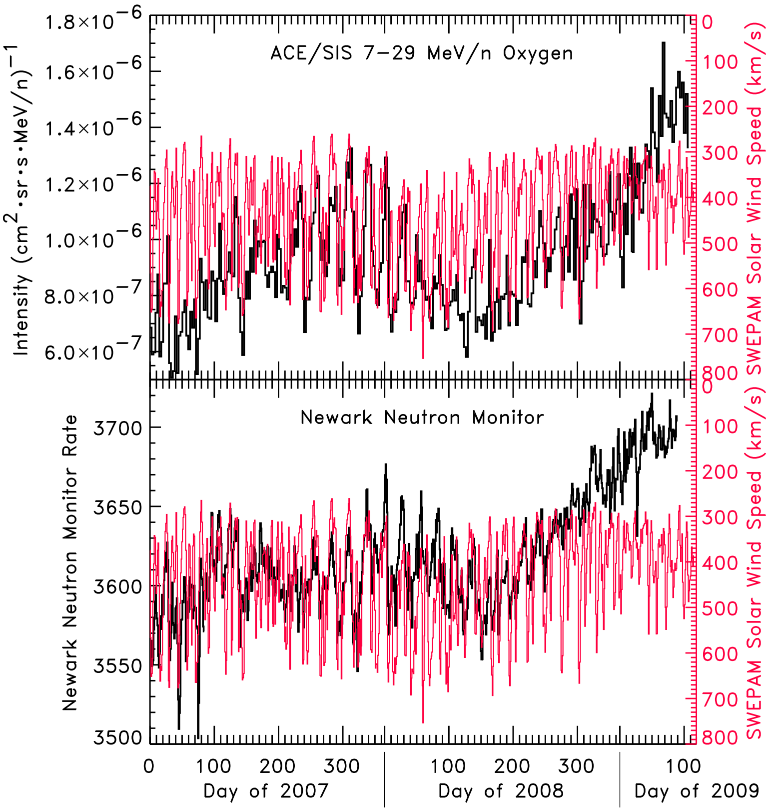

Fig. 6. Comparison of 3-day averaged 7-29 MeV/nucleon ACR oxygen from ACE/SIS (*top panel, left axis*) or daily-averaged Newark neutron monitor counts (*bottom panel, left axis*) with daily-averaged solar wind speeds from ACE/SWEPAM (*red, right axes* – note inverted scale) during the present solar minimum.

be unexpected, as models predict smoother proton intensities in response to the average tilt angle during this period [8]. Some local modulation effects may be responsible for at least part of the correlation. Certainly local modulation on short time scales exists, as shown by the "27-day" variations in ACR and GCR rates in Fig. 6 and their strong correlation with solar wind speed. As the tilt angle increases, high-speed wind from polar coronal holes is more likely to have access to an observer in the ecliptic, which could lower the rotation-averaged cosmic ray counting rates.

The present behavior of the ACR and GCR intensities is unusual, and illustrates that not only are there differences between A>0 and A<0 cycles [10], but also that there can be considerable variability between different A<0 cycles. Observations from Ulysses show that the average solar wind dynamic pressure has had a significant long-term decline [11], and that the heliospheric magnetic flux has decreased [12], as is also indicated by the Wilcox Solar Observatory measurements (Fig. 4). Such global heliospheric changes would be expected to affect turbulence levels and drift velocities, possibly altering the relative importance of diffusion versus drift effects between the different solar cycles. Further observations as the solar cycle progresses, including consideration of the energy-dependence of the particle intensity changes reported here, along with detailed modeling of the heliosphere under the present unusual solar minimum conditions, may yield a better understanding of solar modulation and cosmic ray transport in the heliosphere.

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