Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 807–810

ID 734

2008-09

Changing anomalous cosmic ray oxygen radial intensity gradients between 1 AU and Voyager with the return to solar minimum

R. A. LESKE[1], A. C. CUMMINGS[1], C. M. S. COHEN[1], R. A. MEWALDT[1], E. C. STONE[1], M. E. WIEDENBECK[2], T. T. VON ROSENVINGE[3].
[1]*California Institute of Technology, Mail Code 220-47, Pasadena, CA 91125 USA*
[2]*Jet Propulsion Laboratory, California Institute of Technology, MS 169-327, Pasadena, CA 91109 USA*
[3]*NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771 USA*
ral@srl.caltech.edu

Abstract: Using the Solar Isotope Spectrometer (SIS) on NASA's ACE spacecraft, we have measured the intensities of anomalous cosmic rays (ACRs) near 1 AU down to energies of ∼10 MeV/nucleon since August 1997. As solar minimum modulation conditions return, ACR intensities at 1 AU are recovering, but are significantly lower relative to galactic cosmic rays (GCRs) than they were during the intensity decline following the last solar minimum and are still a factor of ∼4 lower than in 1997. The large-scale radial intensity gradients of ACR oxygen obtained using observations from ACE, Voyagers 1 and 2, and Ulysses are much larger during the present A<0 recovery than they were during the last A>0 solar minimum; in fact beyond ∼50 AU ACR intensities already exceed those at the last A>0 solar minimum. The 1 AU ACR measurements are now being augmented by data from the Low Energy Telescope (LET) on the twin STEREO spacecraft, which will allow us to extend the energy spectra down to ∼3 MeV/nucleon to track the behavior of the peak of the ACR oxygen spectrum and study longitudinal intensity variations.

Introduction

Measurements of anomalous cosmic ray (ACR) and galactic cosmic ray (GCR) intensities throughout the heliosphere during the solar cycle can be used to investigate the role of drifts, convection, and diffusion in cosmic ray transport. Studies have shown that ACR and GCR intensities and their gradients vary with radial distance (e.g., [1]), heliographic latitude [2], phase [3] and polarity [4] of the solar cycle, and with particle rigidity [5]. Most previous ACR gradient studies that used a 1 AU baseline were not done under solar maximum conditions, when ACR intensities at 1 AU are severely reduced and suffer contamination from frequent solar energetic particle (SEP) events. Using data from the Solar Isotope Spectrometer (SIS) on NASA's ACE spacecraft [6], we have previously described a stringent quiet-time cut based on the shape of the 6-30 MeV/nucleon He spectrum that allows us to determine ACR oxygen intensities at 1 AU even at solar maximum [7]. Here we extend these measurements through the recent rise in ACR intensities as solar minimum modulation conditions return.

Observations and Discussion

As shown in Figure 1, the ACR oxygen intensity at 1 AU has increased considerably from its solar maximum level, but it has not yet reached the level observed at the end of the last (A>0) solar minimum. Furthermore, the excellent agreement between GCR intensities (represented by the scaled Climax 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. During solar maximum many days do not satisfy our quiet time criteria and are omitted from our analysis. Forbush decreases often follow SEP events, so many of the active days we exclude have below average neutron monitor rates. When comparing ACR oxygen to neutron monitor rates averaged over only the quiet days (as in Figure 1), it appears the discrepancy between ACR and GCR rates began in late 2000, or about when the solar magnetic polarity switched from A>0 to A<0. A similar deficit of ACRs relative to the neutron monitor seems to have been present throughout the last A<0 period [8].

The hysteresis curve in Figure 1 (lower panel) starts at the upper right during solar minimum, runs to the lower left along the upper trace, and rises back up along the lower trace. The recovery follows the same slope as the last decline, with the ACR oxygen intensity scaling as the neutron monitor rate to the ∼25th power, but with a significant offset between the decline and recovery tracks. This behavior is different from that reported for He in the outer heliosphere [9], 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.

So far the ACR oxygen intensity at 1 AU is less than it was during the A>0 solar minimum, but during the last A<0 cycle its peak intensity in the outer heliosphere (corrected for latitudinal gradients) greatly exceeded that seen during the neighboring A>0 cycles [10]. A phenomenological model [10] relating the tilt of the heliospheric current sheet to ACR gradients successfully accounts for the differences in ACR intensities between A>0 and A<0 and between the inner and outer heliosphere, but the expected behavior of GCRs compared with ACRs was not addressed in this model.

During the period of the ACE measurements at 1 AU, Voyagers 1 and 2 were probing the outer heliosphere at ∼50-100 AU. Figure 2 compares ACR oxygen and GCR carbon time profiles from the CRS instruments on Voyagers 1 and 2 [11] with those from SIS and CRIS on ACE. In general, the large ACR oxygen intensity decrease and recovery seen at 1 AU seem to be followed ∼6 months later by similar but much smaller changes at Voyager 2 and later yet at Voyager 1. Unlike ACR oxygen, at solar minimum GCR carbon intensities at 1 AU are within a factor of ∼1.5 of those in the outer heliosphere; even during solar maximum the rates are only ∼5 times higher at the Voyagers than at ACE. The GCR intensities have begun to recover at both Voyagers, but are still somewhat below their last A>0 solar minimum values.

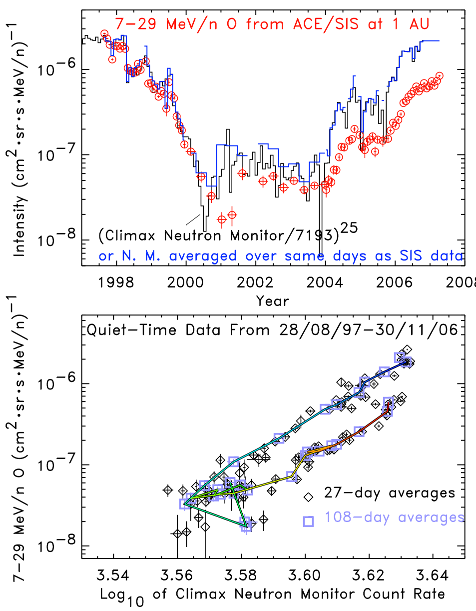

Figure 1: *Top:* Quiet time 7-29 MeV/nucleon oxygen from ACE/SIS (*circles*) compared with the Climax neutron monitor rate (*black histogram*) and the Climax rate during the same quiet days as used for the SIS data (*blue histogram*), both scaled as indicated. *Bottom:* ACE/SIS 7-29 MeV/nucleon oxygen vs. the Climax neutron monitor count rate.

We examine the ACR and GCR intensities as a function of radial distance during the A>0 solar minimum (since the launch of ACE), solar maximum, and the recent recovery during A<0 polarity. Since the actual solar maximum intensities lasted such a brief period with very little quiet time at 1 AU, we also consider a much longer period of somewhat higher intensities labeled "solar maximum equilibrium" in Figure 2. During this longer period the intensities seem to have stabilized throughout the heliosphere, and the inferred ACR mean free paths in the outer heliosphere more nearly resemble earlier solar maximum values than they did during late 2000/early 2001 [12].

Figure 3 shows the quiet-time 1 AU oxygen spectra during the 4 periods of interest. Power law fits to the high energy data indicate the amount of GCR background subtracted to obtain ACR intensities.

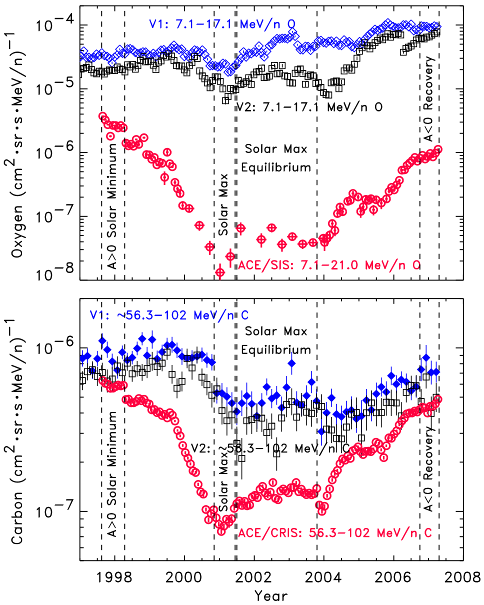

Figure 2: Oxygen intensity (*top*) (mostly ACRs, but with GCR background; see Figure 3) and GCR carbon (*bottom*) vs. time from ACE (*circles*), Voyager 1 (*diamonds*), and Voyager 2 (*squares*). The 4 time periods in which we determine the radial gradient are indicated between vertical dashed lines.

The 1 AU intensities along with those from Voyagers 1 and 2 are shown versus radial distance from the Sun in Figure 4. To span the wide gap between 1 and >50 AU, online rate data from COSPIN/LET on Ulysses were used. Quiet days were selected using COSPIN/LET H and He daily-averaged intensities, and the 7.1-39 MeV/nucleon CNO COSPIN/LET quiet time intensities in our 4 time intervals were calculated. Estimated background due to GCR CNO and ACR N was subtracted (leaving only an upper limit in the case of the solar maximum point), and a correction was applied to account for the different energy intervals in the Ulysses and ACE data. For the A>0 solar minimum all data were corrected for a latitudinal gradient (+ 1.3%/$^\circ$ for ACRs [4], + 0.3%/$^\circ$ for GCRs [13]). A larger negative gradient is expected during A<0, but since the recovery is not yet complete it

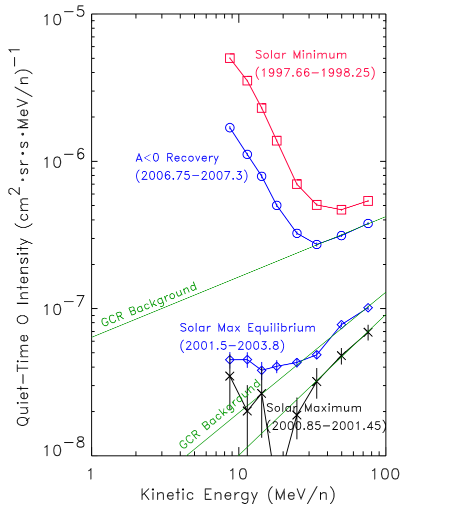

Figure 3: ACE/SIS quiet-time oxygen spectra in the 4 time periods indicated in Figure 2.

is uncertain how large this gradient is at present, so we have not corrected the recent recovery data.

Conclusions

The resulting ACR oxygen gradients are larger throughout A<0, both at solar maximum and during the present recovery, than they were during A>0. Beyond ∼50 AU, ACR intensities are already greater than they were during the A>0 solar minimum, while at 1 AU they are still ∼4 times lower. So far, little or no difference is apparent in the GCR carbon gradients between the present A<0 recovery and the last A>0 solar minimum.

New 1 AU ACR measurements are being made by the Low Energy Telescope (LET) instruments [14] on the two STEREO spacecraft. These measurements extend to lower energies than SIS can reach (Figure 5), which may allow us to monitor the location and intensity of the peak in the 1 AU ACR oxygen spectrum. Also, the increasing angular separation of the two spacecraft will allow us to study ACR longitudinal variations.

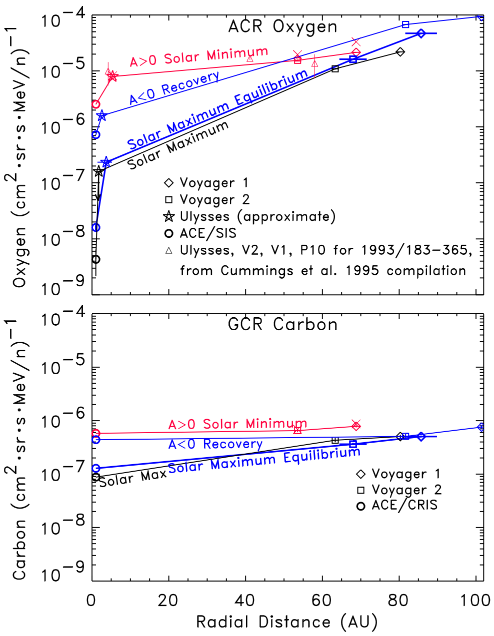

Figure 4: Intensity vs. radial distance for ACR oxygen (*top*) and GCR carbon (*bottom*) from ACE (*circles*), Voyager 1 (*diamonds*), Voyager 2 (*squares*), and Ulysses (*stars*) during the 4 periods of interest. Solar minimum values from an earlier study [4] (*triangles*) and without latitudinal gradient corrections (*crosses*) are also shown.

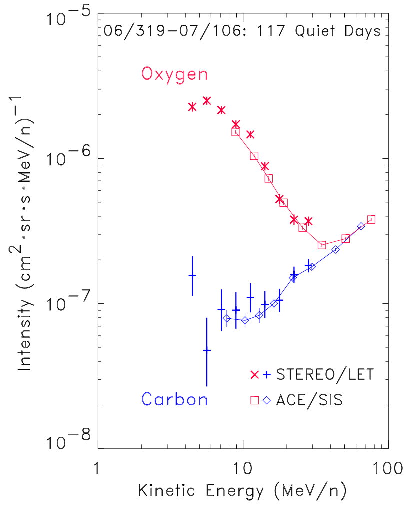

Figure 5: Preliminary oxygen (*crosses*) and carbon (*pluses*) quiet time spectra combining data from the LET instruments on both STEREO spacecraft, compared with oxygen (*squares*) and carbon (*diamonds*) spectra from ACE/SIS.

Acknowledgements

This work was supported by NASA (grants NAG5-12929, NAS5-03131, and contract NAS7-03001). COSPIN/LET data were obtained courtesy of the Ulysses Data System, and we acknowledge the National Science Foundation grant ATM-0339527, which supports the Climax neutron monitor.

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