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Effects of increasing solar modulation on anomalous cosmic ray intensities

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Abstract. Anomalous Cosmic Rays (ACRs) are accelerated far out in the heliosphere at the termination shock. As they diffuse back through the solar system to 1 AU, they are modulated in intensity. The intensity of ACRs at 1 AU observed by the Solar Isotope Spectrometer has been decreasing since September 1997 as solar activity has been increasing. Oxygen at 7.1-10 MeV/nuc has decreased by a factor of at least 80. Nitrogen and neon at similar energies have also had similar large decreases. We examine the changing fluxes of various ACR species, and the changing elemental and isotopic composition of ACRs. ACR oxygen, in particular, may no longer be observable in 2001 at 1 AU above the background of solar, interplanetary, and galactic cosmic ray particles. The ^{22}Ne/^{20}Ne ratio at 15 MeV/nuc has also been increasing since September 1997 from a value of about 0.1 to a value more consistent with the GCR ratio of 0.5. This suggests that GCRs now dominate the quiet time flux of Ne at energies of 10 to 30 MeV/nucleon.

1 Introduction

Anomalous Cosmic Rays (ACRs), first discovered in 1972, are today thought to have originated as neutral particles from the local interstellar medium (LISM). As they drift into the Solar System, they are ionized by the Sun or the solar wind and are eventually accelerated by the termination shock far out in the heliosphere. (Fisk et al. 1974; Pesses et al., 1981).

As ACRs drift back to 1 AU, they experience modulation in energy and number density. The degree to which ACRs are modulated by the solar wind changes with the solar cycle (Fisk, 1979). In practice, one sees dramatically different fluxes of ACRs over the course of the solar cycle. For instance, ACR oxygen at about 8 MeV/nuc decreased by a factor of at least 80 between late 1997 and late 2000.

The data and results presented here derive from the Solar Isotope Spectrometer (SIS) aboard the Advanced Composition Explorer (ACE) spacecraft, which is in a halo orbit about the Earth-Sun L1 point, about 1.5 million kilometers upstream of the Earth. SIS is a silicon stack instrument, measuring atomic number and mass using the dE vs. E' technique (Stone et al., 1998). ACE was launched in August 1997. Its position outside the Earth's magnetic field and bow shock allows for a high duty cycle in the detection of ACRs.

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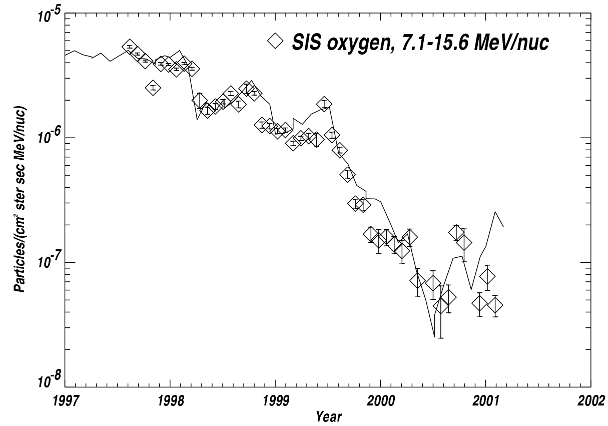

Fig. 1. Comparison of a normalized Climax Neutron Monitor Rate (Climax/3597)^{25} raised to the 25th power with oxygen fluxes recorded by SIS in the energy range of 7.1-15.6 MeV/nuc. The SIS data are 27-day Bartels rotation quiet time averages from the Level 2 data available on the ACE web site. The Climax Neutron Monitor data are Bartels rotation averages from the Space Physics Data System web site at the University of Chicago.

2 Changing Fluxes

Instruments both on the ground and in space have been recording the decreasing fluxes of galactic cosmic rays and anomalous cosmic rays with the progress of the current solar cycle. Figure 1 is a comparision between oxygen at energies between 7.1 and 15.6 MeV/nuc as measured with SIS and nor-

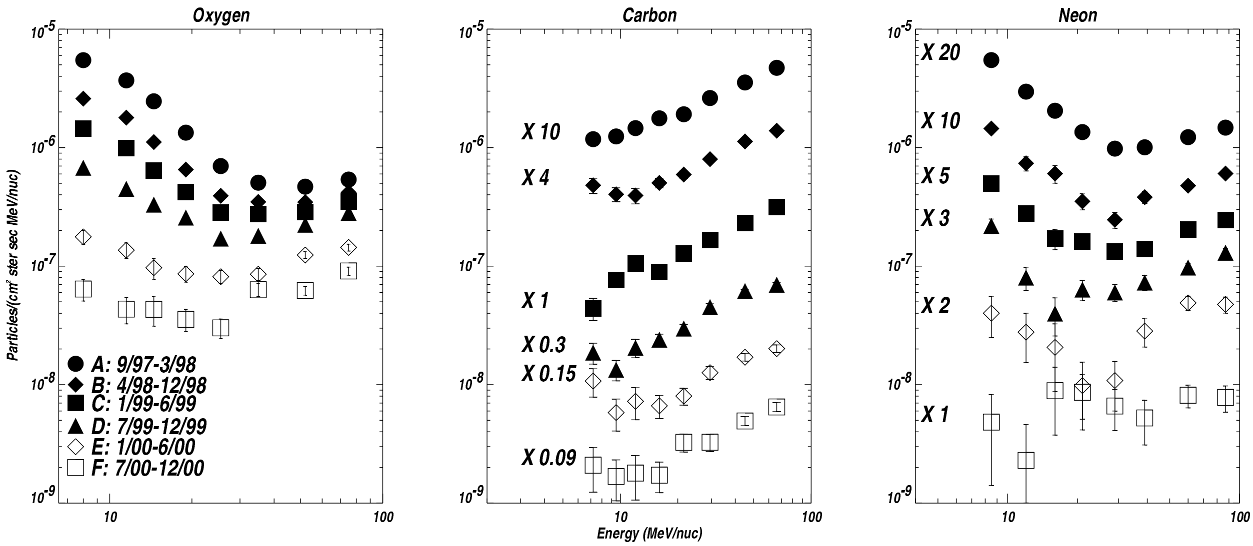

Fig. 2. Element spectra through time for oxygen, carbon, and neon. The carbon and neon spectra have been multiplied by various factors, which are shown, to better separate them from each other and make the trends clearer.

malized fluxes from the Climax Neutron Monitor, raised to the 25th power. The oxygen fluxes seems to track the neutron monitor rates fairly well, as other spacecraft measurements have over the past thirty years. As solar activity increased from 1997 through 2000, the SIS fluxes have been decreasing in a series of steps. The first of these was in early 1998; the second, in late 1998. The third was in the latter part of 1999, and a fourth step down occurred in 2000.

Figure 2 shows changing spectra of oxygen, neon, and carbon as observed with SIS during solar quiet days. In this case, quiet days were determined from the helium flux: for periods in 1997 and 1998, quiet time was taken to be those days in which the helium flux between 3.4 and 7.3 MeV/nuc was under 10^{-4} (particles/cm^2 sec ster MeV/nuc). For periods in 1999 and later, the upper limit on helium flux was reduced to 5×10^{-5} (particles/cm^2 sec ster MeV/nuc). This graduated quiet time criterion was used instead of a flat or constant criterion because the second step in modulation from Figure 1, in late 1998, is also noticeable in helium. A constant quiet time criterion in helium flux, instead of a graduated one, would either allow small solar particle enhancements in the later periods, or would unnecessarily restrict quiet time in the earlier periods. The carbon and neon spectra have been multiplied by various factors to better separate them and demonstrate the trends better.

As can be seen in the figures, the flux of oxygen at about 8 MeV/nuc in the last half of 2000 is smaller than that in the relatively quiet period of September 1997 to March 1998 by about a factor of 80. Low-energy neon has been reduced by about a factor of 56. In contrast, at the higher energies, GCR oxygen, neon and carbon have all decreased by roughly the same factor of 7. The spectral shape of carbon is roughly the same for all the periods, while both oxygen and neon are more stongly modulated at the lower energies in the later periods. In several of the carbon spectra, there may be small enhancements at the lowest energies, which is probably indicative of a solar or interplanetary contribution.

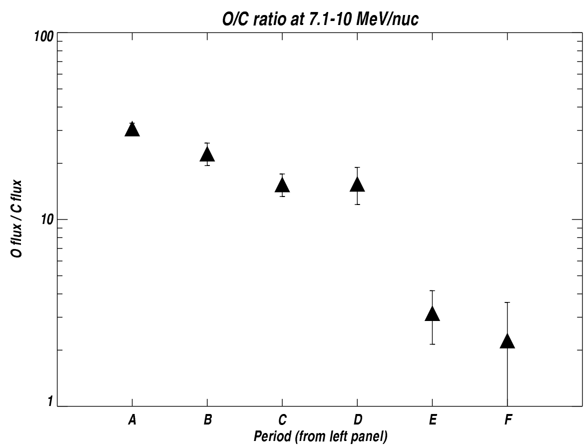

Fig. 3. The changing O/C ratio. The labelled periods are defined in the first panel of Figure 2.

3 Elemental Composition

Figure 3 shows the changing ratio of oxygen to carbon at 7.1-10 MeV/nuc. Each point in this plot represents one of the time periods for which spectra are plotted in Figure 1. The O/C ratio experiences large changes between September 1997 and late 2000. From a value of over 30, which is typical for ACRs (Klecker et al., 1998), the ratio declines to about 2.2 by late 2000, which is more similar to that observed in solar energetic particle events and in corotating interaction regions (CIRs) (Reames, 1996; Richardson et al., 1993). While a purely GCR contribution to carbon would produce a similar trend in the elemental ratio, the existence of the low-energy

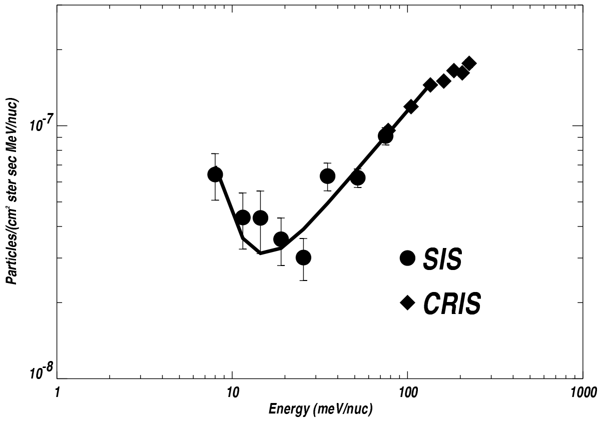

Fig. 4. Oxygen flux in the latter half of 2000. The fit is to a sum of two power laws typical of GCR and solar particles. Data here are from both the SIS and CRIS instruments.

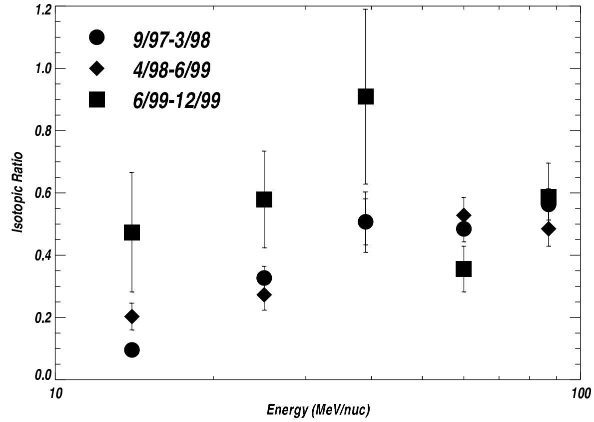

Fig. 5. The changing ^{22}Ne/^{20}Ne ratio. At ACR energies, ^{22}Ne/^{20}Ne evolves from the ACR value in early time periods, to a value closer to GCRs in late 1999.

turn-ups in the carbon spectra indicate that there is a strong contribution from solar material, either from solar energetic particles, from CIRs, or from some other solar source.

The principal feature of note in Figure 3 is the large step between periods D and E. Before period E, which is the first half of 2000, the O/C ratio had fallen by a factor of about two. By period F, the ratio had fallen by a further factor of almost seven from the value in period D. This drop corresponds to the large third step in 1999 from Figure 1 and to the appearance of small low-energy turn-ups in the carbon spectra. That the late period O/C ratio might indicate a solar or CIR origin is further supported by the existence of these small enhancements in the late periods. The lowest energy points in carbon from Figure 2 seem to deviate from the GCR power law index for most of the periods, including periods E and F.

Figure 4 shows once again the spectrum of oxygen in the latter half of 2000, with data from both SIS and the Cosmic Ray Isotope Spectrometer (CRIS), which is also aboard ACE. Here, a GCR power law index of 0.8 was determined by fitting the two highest energy SIS points and the three lowest energy CRIS points. The higher energy CRIS points seem to be deviating from the power law of modulated GCRs, approaching the peak in GCR intensity. A lower energy power law spectral index of -3.4 for oxygen was inferred from a fit to low energy helium. This index is within the range of spectral indices for typical CIR spectra (Richardson et al., 1993). Using these two power law indices, a fit was made to the SIS data and three lower energy CRIS points using a sum of two power laws.

The resulting model spectrum overlays the observed one to within the statistical uncertainties of the experimental spectrum. By the latter part of 2000, the flux of ACR oxygen at 1 AU has dropped to a level below that which SIS can detect above the background of solar, CIR, and GCR particles. At about 15 MeV/nuc, up to 2×10^{-8} particles/(cm^2 sec ster MeV/nuc) could be present in the form of ACRs within our statistical limits. This would then be the upper limit for the flux of ACR oxygen at this energy.

4 Isotopic Composition of Neon

Figure 5 shows changing isotope ratios of neon with energy and time. Since the statistical accuracy of this low-energy isotope ratio is limited, particle counts at 11.1-14.6 and 14.6-17.6 MeV/nuc, and at 17.6-23.6 and 23.6-33.2 MeV/nuc, as well as for periods B and C, have been added together. Periods E and F have been excluded from this plot, owing to their limited statistics. At early times, the ^{22}Ne/^{20}Ne ratio changes with energy, from a value of about 0.1 to 0.2 at 15 MeV/nuc to a value of 0.5 to 0.6 at 100 MeV/nuc. For ACRs at solar minimum, this value is typically 0.1; for GCRs, it is 0.6 (Leske et al., 1999). However, at the later time, the ratio seems to be flat with energy, at values closer to the GCR ratio.

Fluxes in this latter period are relatively low, and statistics limited. One could still be seeing ACR neon in the lowest energy interval. If up to half of the measured flux were due to ACRs, this would still result in a ^{22}Ne/^{20}Ne ratio of about 0.35, which would be consistent with that measured here (within one standard deviation). Note that solar material also cannot be ruled out, since the ^{22}Ne/^{20}Ne ratio of solar material is not dissimilar to that of ACRs (Leske et al, 1999).

5 Discussion and Conclusions

In their multiple-spacecraft study, Lanzerotti and Maclennan (2000) observed the onset of increasing modulation in ACR oxygen at 0.5 to 5 MeV/nuc in 1997 and 1998. The present results from 1 AU extend the study of ACR modulation through solar maximum in 2000. In 2000, the O/C ratio at ACR energies dropped from what was previously an ACR-like value to one that is consistent with solar or CIR material. In that same time, the ^{22}Ne/^{20}Ne ratio at ACR energies increased from an ACR-like value to one more consistent with GCRs.

Having dropped by a factor of 80 at about 8 MeV/nuc, the oxygen flux at this energy might be in large part made up of background solar and CIR material. A fit to two power laws consistent with GCRs and CIRs yields a model spectrum very close to the measured oxygen spectrum. Small low-energy turn-ups in carbon in the later periods lend creedence to the notion that the low-energy turnup in oxygen in the latter half of 2000 might be in large part of solar or CIR origin.

These observations serve to show that by the latter half of 2000, ACR fluxes dropped below the level at which one can meaningfully separate them from the background of GCR, CIR, and solar material.

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