THE RETURN OF THE ANOMALOUS COSMIC RAYS TO 1 AU IN 1992

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Abstract. New observations of low energy (~1 to 200 MeV/nuc) cosmic rays measured by three newly launched experiments on SAMPEX during 1992 and 1993 show the strong presence of anomalous cosmic ray (ACR) nitrogen and oxygen, well before the approaching solar minimum. When compared with ACR temporal variations over the past two solar cycles we find that the 1992-1993 fluxes are ~5 to 10 times their level at corresponding neutron monitor counting rates in 1969-1970 and 1985.

Introduction

It is now twenty years since the discovery of anomalous flux increases in the low energy (< 50 MeV/nuc) spectra of helium and oxygen led to the identification of a new component of cosmic rays (McDonald et al. 1974, Garcia-Munoz, Mason, and Simpson 1973, Hovestadt et al. 1973). This "anomalous" cosmic ray (ACR) component is now thought to represent interstellar neutral particles that have drifted into the heliosphere, been singly-ionized by solar UV or by charge exchange with the solar wind, convected into the outer heliosphere, and then accelerated to energies of 10 to 100 MeV/nuc (Fisk, Kozlovsky, and Ramaty 1974), probably at the solar wind termination shock (Pesses, Jokipii, and Eichler 1981). The ACR component is especially sensitive to solar modulation, varying over the solar cycle by a factor of > 100, and observable at 1 AU only at solar minimum. The elements whose energy spectra in the outer heliosphere exhibit anomalous increases in flux above the low energy galactic cosmic ray (GCR) spectrum include He, C, N, O, Ne, Ar, and possibly H (see, e.g., Cummings and Stone 1988; Christian, Cummings, and Stone 1989), although only He, N, O, and Ne are clearly identifiable at 1 AU.

In this paper we present observations of C, N, and O covering nearly three decades in energy/nuc from the newly-launched Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX). These observations indicate that during the current recovery to solar minimum the ACR component returned to 1 AU (became observable) in mid-1992, well before it might have been expected to on the basis of its behavior during previous solar cycles, and that it is already approaching flux levels observed during previous solar minima. A preliminary report of some of the data reported here appears in Mewaldt et al. (1993).

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spectrum. At the lowest energies (<5 MeV/nuc) there is
evidence for a solar/interplanetary component.

Figure 2 shows that there is also an enhancement in the N
spectrum below ~35 MeV/nuc; a similar turn-up is observed
for Ne at this time (Mewaldt et al. 1993). The Mg, Si, and Fe
spectra show no significant enhancements in the ~10 to 40
MeV/nuc energy range. The observed features in the N and
O spectra are the classic signatures of anomalous cosmicrays, although it had not been generally expected that ACRs
would be evident at 1 AU this long before solar minimum.

Both HILT and MAST observe a small C enhancement at
~10 to 15 MeV/nuc. Quiet time measurements at 1 AU
during previous solar cycles have sometimes observed small
enhancements in the C spectrum at ~10 MeV/nuc (e.g.,
Webber et al. 1977), usually interpreted as due to small solar
or interplanetary events that were not eliminated by the quiet-
time selection criteria. The only clear evidence for ACR
carbon comes from Voyager observations in the outer
heliosphere, where solar contributions are much less
significant (Cummings and Stone 1988). The Voyager 10 to
20 MeV/nuc C/O ratio is ~0.01, whereas the ratio in Figure 1
is closer to ~0.1. While it is therefore possible that some of
the "bump" in the 10 to 20 MeV/nuc C spectrum is due to
ACR carbon, there is more likely a significant solar
contribution, and this region of the spectrum will require
additional study as more SAMPEX data are obtained.

To relate the 1992-93 observations to those from earlier
years Figure 3 shows the 8 to 27 MeV/nuc oxygen flux over
two solar cycles, based mainly on 1972 to 1992 data from the
Caltech experiments on IMP-7&8 (Mewaldt et al. 1976)
supplemented by OGO-5 and IMP-6 data from earlier years,
and extended with new data from SAMPEX. It has
previously been shown that the ACR intensity is well-
correlated with neutron monitor measurements of the flux of
high-energy cosmic rays (Mewaldt, Stone, and Vogt 1975;
von Rosenvinge and McDonald 1975; Klecker et al. 1980), and
Figure 3 includes the Mt. Washington neutron monitor
counting rate, taken to the 30th power and normalized to the

Discussion

While the scaling of the neutron monitor rates in Figure 3
provides a reasonable representation of the ACR temporal
variations at 1 AU over two solar cycles, the correlation is
not perfect. Note that the 1987 solar minimum fluxes never
quite reached their 1976-77 levels, even though the 1987
neutron monitor exceeded its 1976-77 level. It is possible
that this is a result of the differing effects of gradient and
curvature drifts (e.g., Pesses, Jokipii, and Eichler, 1981) in
the two orientations of the solar magnetic field, or it may be
an example of "hysteresis" between low-energy and higher
energy particles, in which the 1987 ACR fluxes at 1 AU
never recovered to an equilibrium level before the onset of
increased solar modulation in mid-1987.

A much greater difference between the ACR fluxes and
scaled neutron monitor rate is evident in 1992, when the O
flux is at least 5 times greater than would be predicted by the
correlation extrapolated from earlier years. We might expect
the 1992-1993 recovery to mimic its behavior 22 years earlier
more closely than ~11 years earlier (e.g., Jokipii and Thomas
1981), since the solar magnetic field orientations are the same
in these two cases. To examine the onset of these three
successive solar minima in more detail, we show in Figure 4
regression plots between the ACR oxygen flux and the
neutron monitor for the periods 1968 to 1972, 1985 to 1987,
and 1992 to 1993. When compared at corresponding neutron
monitor levels we see that the ACR oxygen flux at the
beginning of 1993 is ~5 times greater than in 1968-72. A
similar low-energy increase is seen in the N (Figure 2) and
Ne spectra (Mewaldt et al. 1993).

The origin of the rapid recovery of ACR N and O in 1992
is presently unknown, but it may be related to a decrease in
the tilt of the heliospheric current sheet (Cummings, Stone,
and Webber 1990), which decreased from >50° in late 1991
to ~30° in mid-1992 (Hoeksema, private communication).
Corresponding current sheet data from 1969 to 1970 are not
available, but the tilt in 1971-72 was already <30° in early
Fig. 3: The 8 to 27 MeV/nuc oxygen flux from 1968 to early 1993, based mainly on 1972 to mid-1992 data from the Caltech experiments on IMP-7&8. The 1968 (Teegarden et al. 1969) and 1968-69 (Mogro-Campero et al. 1973) points are from OGO-5, while the 1971 point is from IMP-6 (von Rosenvinge and McDonald 1975). The last four (open) points in 1992-1993 are from the HILT sensor on SAMPEX. Also shown is the Mt. Washington neutron monitor rate (MtW; Labonte and Lockwood, private communication), scaled using the equation $J = 2.1 \times 10^{-6} (\text{MtW}/2440)^{0.5}$.

Fig. 4: Regression plots of the 8 to 27 MeV/nuc oxygen flux vs. the Mt. Washington neutron monitor counting rate for the three recovery periods in Figure 3.

1971 (Saito and Swinson, 1986). The lack of current sheet (and detailed ACR) measurements from 1969-70 prevent us from exploring this possibility further.

It is also possible that the increased ACR flux at 1 AU in 1992-1993 results in part from a closer approach of the solar wind termination shock than its corresponding distance in the early 1970’s. We might expect the termination shock distance at any given time to reflect the solar wind pressure at 1 AU ~1 year earlier. This possibility is under investigation, but it does not appear likely that a closer approach of the termination shock would affect the intensity at 1 AU by as much as a factor of ~5, given the generally small intensity gradients measured in the outer heliosphere (Cummings and Stone 1988, Cummings, Stone, and Webber 1990).

It is also possible that the apparently different modulation of low and high energy cosmic rays in 1992 and the early 1970’s reflects a property of the solar wind and interplanetary magnetic field that determines the interplanetary diffusion coefficients of these two components, which depend on the power spectrum of magnetic field fluctuations in the interplanetary medium. In addition, a change in the diffusion coefficient in the vicinity of the termination shock might alter the ACR "source" strength.

Irrespective of its origin, the sudden return of the ACR fluxes to 1 AU in 1992 provides a fortunate opportunity for the new instrumentation on SAMPEX to make improved measurements of its elemental and isotopic composition, charge states, temporal behavior, and its trapping in the Earth’s magnetosphere (Cummings et al. 1993).

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