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SOLAR CYCLE VARIATIONS OF ANOMALOUS ^{4}HE AS DEDUCED BY STUDIES OF COSMIC RAY ^{3}HE

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Abstract. Voyager 1 and 2 observations have been used to derive the energy spectrum of 'anomalous' cosmic ray (ACR) helium using a technique based on the separation of the isotopes of He. Previously reported observations show that the ACR oxygen spectrum underwent a change in shape following the solar magnetic field reversal in 1980; in this paper we present evidence for a corresponding change in the ACR helium spectrum. We find that the energy spectra of ACR helium and oxygen and galactic cosmic ray (GCR) ^{4}He and ^{3}He can be reproduced both before and after the field reversal using a simple solar modulation model in which the effects of curvature and gradient drifts are arbitrarily neglected.

Introduction

During the 1972 - 1978 solar minimum period, observations of low-energy cosmic rays below ~50 MeV/nucleon revealed anomalous enhancements in the energy spectra of the elements He, N, O, and Ne relative to other elements such as B and C [Garcia-Munoz et al., 1973; Hovestadt et al., 1973; McDonald et al., 1974]. The particles of this so-called 'anomalous component' are now thought to originate from interstellar neutrals which drift into the heliosphere, become singly-ionized, and are then accelerated to the energies of observation [Fisk et al., 1974], possibly at the solar wind termination shock [Pesses et al., 1981]. With their large geometry factors, excellent resolution, and broad dynamic range, the Low Energy and High Energy Telescopes (LETs and HETs) of the Cosmic Ray Subsystem (CRS) on the Voyager 1 (V1) and 2 (V2) spacecraft [Stone et al., 1977] have been used extensively to study the composition, energy spectra, and the temporal and spatial variations of the anomalous component over the almost nine years since their launch.

Cummings et al. [1986] have recently reported observations of changes in the energy spectrum of ACR oxygen over the current solar cycle. They found that after the solar magnetic field reversal the energy at which the intensity maximum occurs shifted from ~5 up to ~10 MeV/nuc, a change that has persisted for ~4 years. In this Letter, we extend these observations to ACR He by carefully isolating the ACR component using GCR ^{3}He as a 'tracer' of the GCR ^{4}He contribution. We find that the ACR He spectrum exhibits a change in shape similar to that observed for ACR O, and that these changes can be modeled using conventional solar modulation theory. We can not yet verify or disprove a recent model for the acceleration and propagation of the ACR component [Jokipii, 1986], but a test of this model may well be possible when full recovery to solar minimum fluxes is complete.

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Observations

The two time periods selected for this study are indicated in Figure 1, which shows the counting rate of penetrating particles (mainly protons with ≥70 MeV) from a V2 HET telescope. In period I we have used data from both V1 and V2 which were spatially close together in the ecliptic plane at an average heliocentric radius of 1.8 AU. In period II we used data from V2 which was in the ecliptic plane at an average radial position of 14.9 AU. The two time periods were chosen to be before and after the reversal of the solar magnetic field to provide information on the importance of field-polarity dependent terms in the modulation process, such as curvature and gradient drifts, which have been predicted to be significant for the anomalous component [Pesses et al., 1981; Jokipii, 1986].

In order to determine accurately the energy spectrum of ACR He, a precise subtraction of the GCR He contribution to the observed spectrum is required. Cummings et al. [1984] derived the ACR He spectrum for period I by estimating the GCR He from their observed carbon spectrum. Such a technique is reasonable for period I but for the low ACR He fluxes observed in

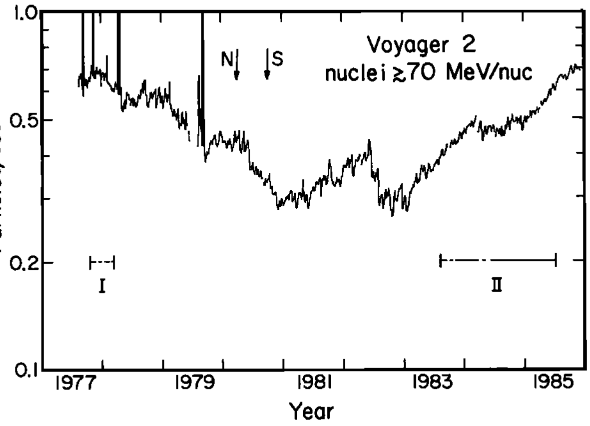

Fig. 1. Three-day average counting rate of penetrating particles observed on Voyager 2. The horizontal bars labeled I and II indicate the time intervals selected for analysis. The vertical arrows indicate approximate times of the solar magnetic field reversal at latitudes > 70° in the north (N) and south (S) [Webb et. al, 1984].

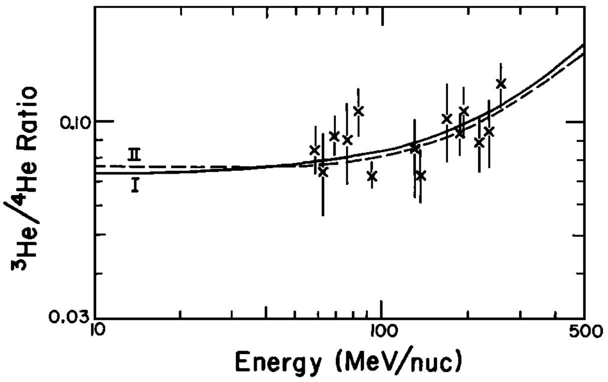

Fig. 2. Measured and calculated GCR $^3He/^4He$ ratios. The observations are from selected spacecraft and balloon-borne experiments compiled by Mewaldt [1986]. The curves show the predicted ratio for periods I and II at 1.8 AU and 14.9 AU, respectively. The calculated curve for 1 AU is essentially identical to curve I.

period II a more accurate subtraction is necessary. The ^3He method described here eliminates several possible sources of systematic error by measuring the ^3He and ^4He spectra simultaneously with the same telescopes.

The ^3He method assumes that all the observed ^3He is of secondary origin produced by interactions of heavier galactic cosmic rays with interstellar material. This assumption is consistent with the ACR He being essentially pure ^4He (see, e.g., Mewaldt et al. [1984]), as would be expected for an interstellar neutral origin. By dividing our observed ^3He by a fit to the GCR $^3He/^4He$ ratio observed at slightly higher energies, we obtain the GCR ^4He energy spectrum. This estimated GCR spectrum is then subtracted from the observed spectrum to obtain the ACR He energy spectrum.

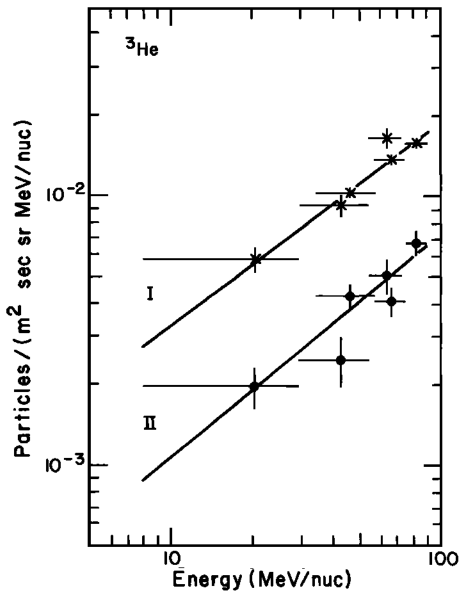

Fig. 3. Energy spectra of ^3He for periods I and II. The lines are least-squares fits to the data.

Figure 2 shows low-energy observations of the GCR $^3He/^4He$ ratio as compiled and corrected by Mewaldt [1986] along with predictions for the $^3He/^4He$ ratio during periods I and II based on interstellar propagation and solar modulation calculations [Meyer, 1974; Mewaldt, 1986]. The propagation calculations assume energy spectra of the form $dJ/dT \propto (T + 500)^{-2.6}$, where T is the kinetic energy in MeV/nuc, and an energy dependent escape length from the galaxy of the form $\lambda = \beta\lambda_o$ for rigidities <5.5 GV [Soutoul et al., 1985], where β is the particle velocity in units of the speed of light. The solar modulation calculations are based on a model discussed below. The curves I and II

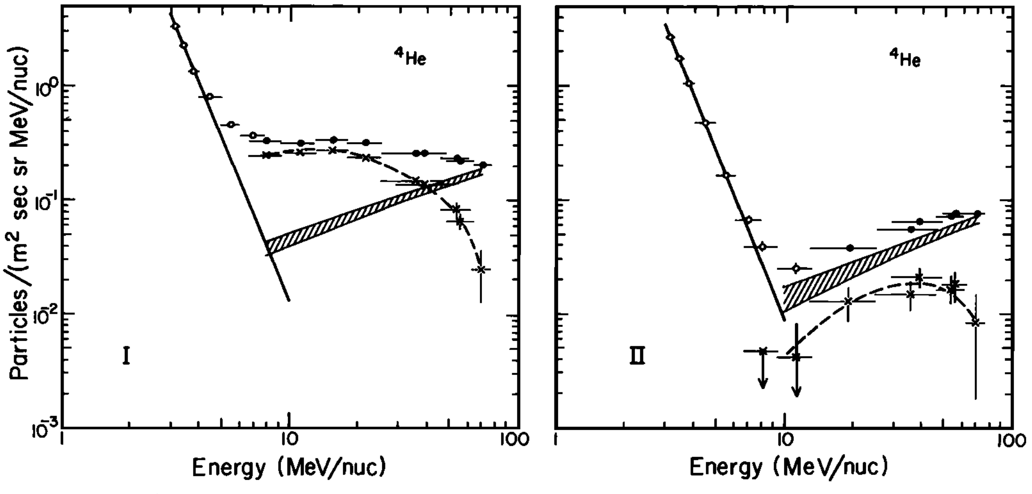

Fig. 4. Energy spectra of ^4He for period I (left) and II (right). The low-energy data (o) are from the LET telescopes and are assumed to have negligible contamination from ^3He. The higher energy observations (●) are from the HET telescopes. The cross-hatched bands are the estimated spectra and associated uncertainty of GCR ^4He as described in the text. The solid line is a least-squares fit to the three lowest energy LET points. The spectra of ACR He are shown by the points (×) connected by dashed lines.

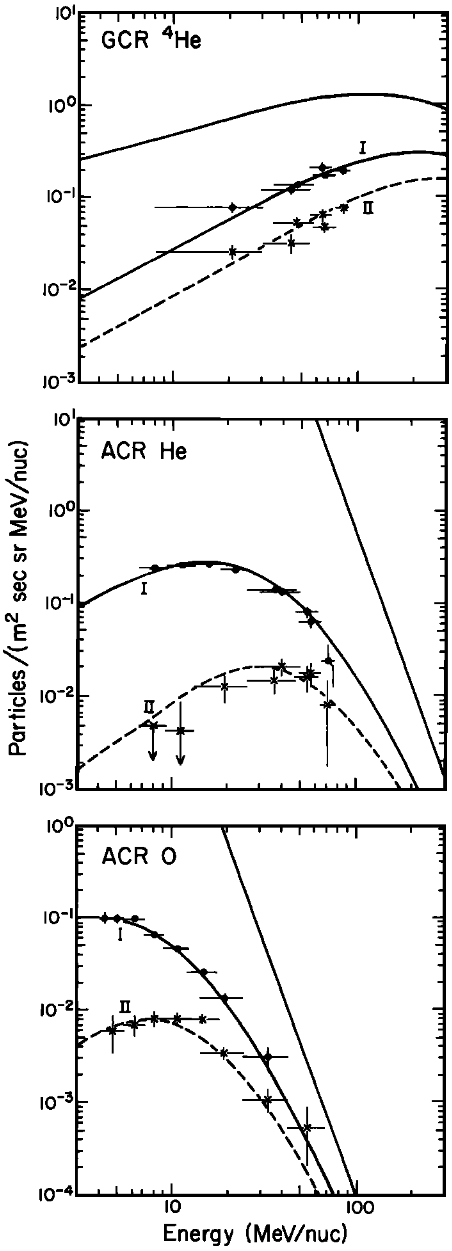

Fig. 5. Comparisons of calculated and observed spectra of GCR ^{4}He, ACR He, and ACR O for periods I and II using parameters described in the text. The observed GCR ^{4}He spectra are from the spectra in Figure 3 divided by the calculated ^{3}He/^{4}He ratio. The observed ACR O spectra are described in more detail in Cummings et al. [1986]. The assumed interstellar spectra are also shown.

are calculated for the particular radial positions of the spacecraft appropriate for the two periods. Note that the small difference between curves I and II indicates that the GCR ^{3}He/^{4}He ratio is relatively insensitive to solar modulation and that below ~100 MeV/nuc the ratio is essentially independent of energy, as expected for solar modulation models that include adiabatic energy losses. By fitting a similar curve calculated for 1 AU to the data in Figure 2, we find $\lambda = 9.4$ g/cm^{2} (for an interstellar medium that is 10% ^{4}He by number), consistent with that derived to fit observations of cosmic-ray nuclei with $3 \leq Z \leq 26$ [Soutoul et al., 1985]. Although the individual observations are uncertain by typically 10 to 20%, by fitting the entire set of observations we obtain an uncertainty of ± 6% in our normalization of the calculated curves.

The observed ^{3}He energy spectra are shown in Figure 3 for the two time periods, along with power-law fits to the data. These power-law fits have been divided by the appropriate ^{3}He/^{4}He ratios of Figure 2 to derive the estimates of the GCR ^{4}He spectra shown as the cross-hatched bands in Figure 4. The width of the bands includes both the uncertainty in the spectral fits in Figure 3 and the uncertainty in the fit to the ^{3}He/^{4}He observations in Figure 2. Also shown in Figure 4 are the ^{4}He observations and a fit to the low-energy solar or interplanetary component. The ACR He spectra are obtained by subtracting the GCR ^{4}He and low-energy components from the ^{4}He observations.

We have considered whether rigidity-dependent 'hysteresis' effects could significantly alter the ACR He flux that we derive for period II as a result of the different charge-to-mass ratios of ^{3}He and ^{4}He. For the ^{1}H/^{4}He ratio at ~60 MeV/nuc, hysteresis effects of ~20% can be deduced from observations made during the recovery from the 1969 solar maximum [Van Hollebeke et al., 1972]. However, our calculations show that the low-energy ^{3}He/^{4}He ratio is much less sensitive to solar modulation effects because the rigidity difference between ^{3}He and ^{4}He is compensated for by spectral differences. As a result, we estimate that the effect on our derived ACR He flux would be at most a few per cent, significantly less than the uncertainties shown in Figure 4.

Discussion

The energy dependence of the ACR He spectra in the two periods is quite different, with the peak energy shifting from ~ 10-20 MeV/nuc in period I to ~ 40 MeV/nuc in period II. We note that a similar shift is evident in the energy spectra of helium observed on Pioneer 10 (see Figure 3 in McDonald et al. [1986]). This shift by a factor of ~ 2 in energy is essentially the same as that observed for ACR O for similar time periods [Cummings et al., 1986]. This change of spectral shape before and after the solar field reversal can come about in two ways: either the source spectrum or the propagation of the ACR component can change. The source spectrum is predicted to change with field polarity in a theory of the acceleration and propagation of the ACR component by Jokipii [1986] that predicts an energy shift in the spectra of about the magnitude we observe.

However, we have also found that for these two time periods we can calculate reasonable fits to the spectra, without altering the source spectra, using spherically symmetric solar modulation theory including the effects of diffusion, convection, and adiabatic deceleration, but arbitrarily neglecting the effects of drifts. In Figure 5, we compare observed and calculated spectra (based on the method of Fisk [1971]) of GCR ^{4}He, ACR He, and ACR O for periods I and II, using a very simple model in which the ACR particles are singly ionized (as expected for the model of Fisk et al. [1974]), the diffusion coefficient is independent of radius and proportional to βR (R=rigidity), and the ACR spectra at the boundary of the solar modulation region are proportional to $T^{-5.5}$ The only difference in the period I and II fits is that the boundary distance has been moved from 50 to 95 AU in going from period I to II. Such a boundary shift is consistent with that derived by other investigations [Webber et al., 1985; Randall and Van Allen, 1986]. We also note that the parameters chosen lead to radial gradients for ~10MeV/nuc ACR O of ~14%/AU and ~9%/AU for periods I and II, respectively, in agreement with observations [Webber et al., 1985].

As the fluxes of ACR He and O continue to increase during the current recovery phase of solar cycle 21 it appears that a key observation will be the location of the peak in the spectrum. A persistent upward shift in the peak energy with the return to solar minimum conditions would be consistent with the predictions of Jokipii [1986]. It would also explain why the ACR He component was not observed during the 1965 solar minimum, since a higher energy peak is more easily masked by the GCR component (see, e.g., Figure 4). A decrease in the peak energy to the value observed during the last solar minimum would be inconsistent with Jokipii's model.

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