Short and Long Term Variations of the Anomalous Component

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We have used data from the cosmic ray experiment (CRS) on Voyagers 1 and 2 to examine anomalous O and He in the time period from launch in 1977 to mid-1982. We find several time periods where large periodic (typically 26 day) temporal variations of O between ~5-15 MeV/nuc are present, with variations in intensity by up to a factor of 10. On the longer term, there is a sharp drop in the anomalous O intensity relative to the galactic cosmic ray components near the middle of 1980. After the decrease we still find evidence at ~10 AU for the presence of anomalous O and He near the time of maximum modulation. Data from a larger fraction of the solar cycle will be required before it can be determined whether the intensity of the anomalous component is lower in the second half of the cycle (after the solar field reversal) than in the first half.

1. Introduction. Approximately a decade ago it was found that quiet-time energy spectra of several elements (e.g. He, N, O, and Ne) showed enhancements below ~50 MeV/nuc relative to other elements such as C. There have been a number of studies of this so-called "anomalous" cosmic ray (ACR) component in an attempt to understand its origin. Most of the studies have have been made using rather long time averages, typically on the order of months. We are reporting a new study of the ACR component in the region from 1 to ~13 AU using the CRS instruments on the two Voyager spacecraft (V1 and V2). The large collecting power of the four CRS telescopes on each spacecraft has allowed us to look at the ACR component on both short and long time scales. This study covers approximately half of solar cycle 21, including data from time periods when the level of solar modulation ranges from minimum to maximum.

2. Short-term Variations. Examples of short-term variations in the counting rate of 4.5-14.7 MeV/nuc O are shown for two time periods (1978 and 1980) in the lower panels of Fig. 1. Earlier studies have noted ~26-day intensity variations by a factor of ~2 for anomalous He and O [*Garcia-Munoz et al.*, 1977; *Webber et al.*, 1979; *Bastian et al.*, 1979; *Von Rosenvinge and Paizis*, 1981]. The variations shown in Fig. 1 are much larger than in these earlier studies, up to a factor of ~10 in both time periods. The upper panels of Fig. 1 show the PEN rate, composed of nuclei with >75 MeV/nuc. It is interesting that this high-energy galactic cosmic ray (GCR) rate shows variations that are correlated with the anomalous O variations, although they are much smaller in amplitude (<15% peak to valley).

We have investigated two possible origins for these variations. The first possibility is that they represent high-energy extensions of low-energy increases associated with corotating interaction regions (CIR's). To investigate this possibility, we have compared our 1978 observations to lower-energy (~1 MeV/nuc) CIR increases reported for the same time period by *Hamilton et al.* [1979]. We find that our measured C/O ratio of <0.05 in the peaks of the variations is much smaller than the ratio of ~0.7 found in their CIR studies. In addition, the maximum intensity of the O variations is out of phase with that of the CIR increases. We estimate, by scaling our own measurements of the He spectrum, that the CIR contribution to our short-term O variations is <1%.

To investigate a second possibility which is that the variations represent an extremely large local modulation effect, we have used V1 and V2 data in 1980 to study the local radial gradients of both the PEN and O rates. We find that the local gradients for the PEN rate (~3-5%/AU) are roughly consistent with the large-scale gradients for these particles from

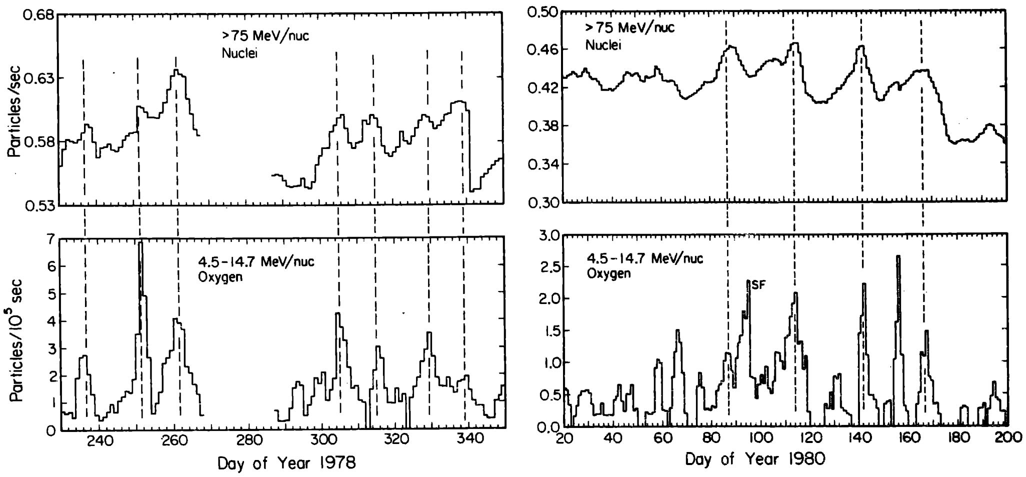

Fig. 1. Voyager 2 three-day moving average counting rate versus time for high-energy nuclei (upper panels) and anomalous O (lower panels) in 1978 (left) and 1980 (right). The dashed lines mark corresponding peaks in the two panels. Two 26-day sequences are indicated in 1978. Only one 26-day sequence is marked for 1980, although it is apparent that a weaker second series is present as well. The peak labeled SF is probably due to a solar flare. Note the offset in the vertical scale of the upper panels.

Pioneer and near-Earth observations [*McKibben et al.*, 1982a], in both the minima and maxima of the variations. It thus appears that for the PEN rate the variations are consistent with a local modulation effect, most likely produced by the large corotating pressure waves seen at the same times in the solar wind and magnetic field data [*Burlaga et al.*, 1983]. On the other hand, the O variations do not seem to fit such a picture. For example, the V1 to V2 ratio of the average peak intensities is $\sim$0.5 rather than 1.20 as expected for a nominal 15%/AU gradient for anomalous O [*Webber et al.*, 1981]. Further discussion of these short-term observations may be found in *Cummings and Webber* [1983].

3. **Long-term Variations.** The long-term behavior of the anomalous O rate may prove crucial to our understanding of its origin as well as providing a test of the relative importance of drifts in cosmic-ray modulation. According to one scenario in which the anomalous component is accelerated at the polar regions of the solar wind termination shock, the intensity after the solar field reversal should be reduced by a factor of $\sim$10 or more because of the drift pattern of these particles [*Pesses et al.*, 1981].

The long-term regression of the anomalous O intensity versus the PEN rate from 1977/250 to 1982/160 is shown in Fig. 2. We have used a strict criterion on the 4.5-7.8 MeV/nuc He rate to select the 18 quiet-time periods shown in the figure. We have corrected the observed O rate for estimated solar contributions (using the measured low-energy He spectra) and for estimated GCR contributions (using the 40-106 MeV/nuc C+O data). These corrections are negligible (<5%) for the first 12 intervals shown, and although larger ($\sim$15-60%) in the later intervals, the basic overall shape of the regression curve is not greatly changed if they are omitted.

During the time period covered in Fig. 2, the Voyager spacecraft were moving radially away from the Sun (e.g. V1 moved from 1 to 13.3 AU). In an attempt to isolate temporal variations from changes due to radial distance, the intensities shown in Fig. 2 have been corrected to a fixed radial distance of 6 AU. We assumed a radial gradient of 15%/AU for the anomalous O [*Webber et al.*, 1981] and a time dependent gradient for the PEN rate (varying from $\sim$1.6 to 3.2%/AU) derived from *McKibben et al.* [1982a].

The regression curve for higher-energy C+O (assuming a gradient twice that used for the PEN rate) is also shown in Fig. 2. Note that these GCR components are well correlated through the solar minimum to solar maximum portion of the cycle (intervals 1-15), although there appears to be a small hysteresis effect at the beginning of the cycle's recovery phase. The O rate, on the other hand, shows a sharp drop relative to the PEN rate between periods 13 and 14. This drop is approximately coincident with the solar field reversal in 1980 [*Howard and LaBonte,* 1981] and coincides with a step-like decrease in the GCR intensity [*McDonald et al.,* 1981], as well as a decrease in the intensity of anomalous He observed on Pioneer 10 [*McKibben et al.,* 1982b]. After the maximum of modulation is reached in period 15 the intensity of anomalous O appears to be recovering along a track similar to that established previously. However, because of large statistical uncertainties when the intensity is low, a larger portion of the solar cycle will have to be analyzed to establish whether the intensity of the anomalous O is different in the two halves of cycle 21, as predicted by the model of *Pesses et al.* [1981].

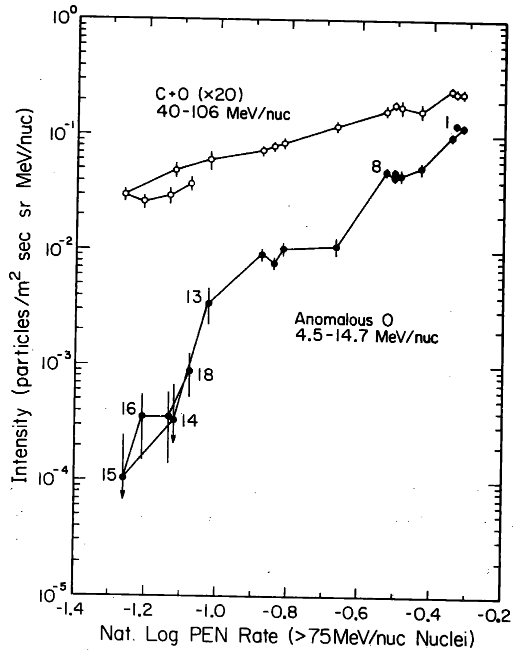

Fig. 2. Intensity of V1+V2 GCR C+O and anomalous O versus the PEN rate for 18 quiet-time intervals. The intensities have been corrected to 6 AU according to discussion in text. The 6 numbered points represent selected quiet times in the following intervals : 1 – 1977/250 - 326; 8 – 1979/1 - 40; 13 – 1980/180 - 202; 14 – 1980/260 - 297; 15 – 1980/350 - 1981/69; 16 – 1981/173 - 266; 18 – 1982/116 - 160.

4. Energy Spectra Near Time of Maximum Modulation. The long-term regression shown in Fig. 2 indicates that the GCR C+O intensity has decreased by a factor of ~ 10 from solar minimum to solar maximum and the PEN rate has varied by a factor of ~ 2.5. The anomalous O intensity has decreased by a much larger factor, ~ 300 or more. In Fig. 3 we show the spectra of O, He, and C for the last 4 intervals (15-18) near the time of maximum modulation. Note that at ~ 10 MeV/nuc O exceeds C by a factor ~ 5. We conclude that at ~ 10 AU the anomalous O is still present at the time of maximum modulation.

In order to examine the anomalous He we have made least-squares fits to the $\geqslant 11$ MeV/nuc He and C data (solid lines in Fig. 3). For He and C of GCR origin we might expect the slopes of the fits to be equal and near unity. The dashed line shows the C fit multiplied by 40 to normalize to the galactic He [see e.g. *Simpson,* 1983]. There is clearly a smaller slope to the He fit (0.44 ± 0.07 for He compared to 0.92 ± 0.17 for C), indicating the presence of anomalous He in the ~ 10-40 MeV/nuc energy range.

5. Conclusions. We have found that large short-term variations in the intensity of anomalous O are present during the first half of solar cycle 21. While the origin of these variations is not clear, they are apparently not related to CIR increases at lower energies and appear to have different characteristics from variations found in the > 75 MeV/nuc nuclei rate. Over the long term, we find a sharp drop in the anomalous O intensity near the middle of 1980. Whether this change is due to the solar field reversal or to increased modulation effects associated with corotating pressure waves in the interplanetary medium is not yet clear. Although the anomalous O intensity undergoes a factor of ~ 300 decrease, both the anomalous O and He are still present near the time of maximum modulation at ~8-13 AU.

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7. References.

Bastian, T. S., R. B. McKibben, and J. A. Simpson, *Proc. 16th Int. Cosmic Ray Conf., Kyoto, 12*, 324, 1979.

Burlaga, L. F., R. Schwenn, and H. Rosenbauer, *Geophys. Res. Lett., 10*, 413, 1983.

Cummings, A. C. and W. R. Webber, to be published in *Proc. Solar Wind 5*, 1983.

Garcia-Munoz, M., G. M. Mason, and J. A. Simpson, *Proc. 15th Int. Cosmic Ray Conf., Plovdiv, 3*, 209, 1977.

Hamilton, D. C., G. Gloeckler, T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, S. M. Krimigis, and L. J. Lanzerotti, *Proc. 16th Int. Cosmic Ray Conf., Kyoto, 5*, 363, 1979.

Howard, R. and B. J. LaBonte, *Solar Phys., 74*, 131, 1981.

McDonald, F. B., J. H. Trainor, and W. R. Webber, *Proc. 17th Int. Cosmic Ray Conf., Paris, 10*, 147, 1981.

McKibben, R. B., K. R. Pyle, and J. A. Simpson, *Ap. J. (Lett.), 254*, L23, 1982a.

McKibben, R. B., K. R. Pyle, and J. A. Simpson, *Ap. J. (Lett.), 257*, L41, 1982b.

Pesses, M. E., J. R. Jokipii, and D. Eichler, *Ap. J. (Lett.), 246*, L85, 1981.

Simpson, J. A., to be published in *Ann. Reviews of Nuclear and Particle Science, 33*, 1983.

Von Rosenvinge, T. T. and C. Paizis, *Proc. 17th Int. Cosmic Ray Conf., Paris, 10*, 69, 1981.

Webber, W. R., E. C. Stone, and R. E. Vogt, *Proc. 16th Int. Cosmic Ray Conf., Kyoto, 5*, 357, 1979.

Webber, W. R., F. B. McDonald, T. T. Von Rosenvinge, and R. A. Mewaldt, *Proc. 17th Int. Cosmic Ray Conf., Paris, 10*, 92, 1981.

Webber, W. R., *Ap. J., 255*, 329, 1982.

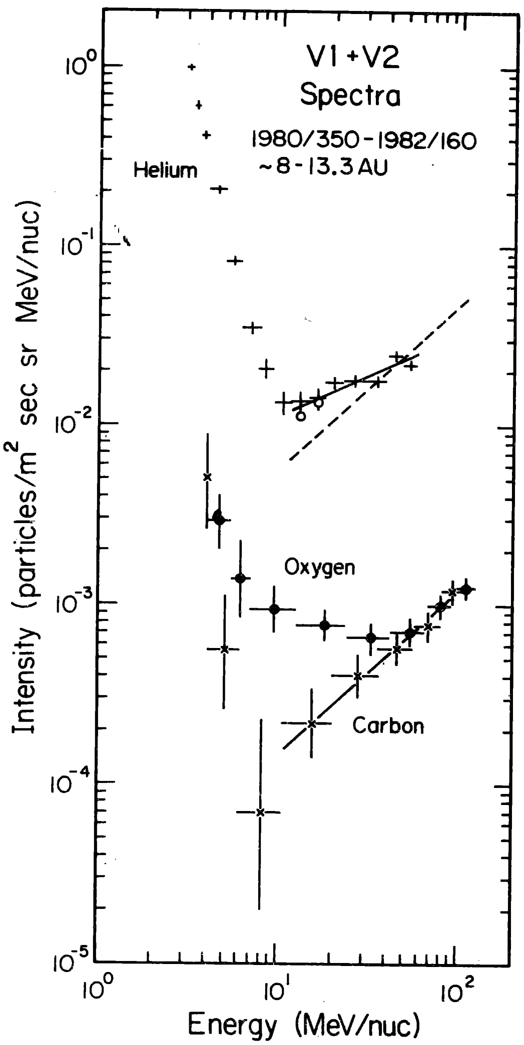

Fig. 3. Spectra of He, O, and C near the time of maximum modulation. The o's represent He data corrected for solar contributions. The solid lines represent fits to the high-energy He and C data. The dashed line is the C fit multiplied by 40. Note that at low energies a solar or interplanetary component is found for all three species.