IMPLICATIONS OF TIME VARIATIONS FOR THE ORIGIN OF LOW ENERGY COSMIC RAY NITROGEN AND OXYGEN NUCLEI

R. A. Mewaldt, E. C. Stone and R. E. Vogt

California Institute of Technology
Pasadena, California 91125

We report observations of time variations in the quiet time intensity of 5-27 MeV/nuc nitrogen and oxygen and 13-25 MeV/nuc helium nuclei, obtained with the Caltech Electron/Isotope Spectrometers on IMP 7 and 8. We find no significant correlation of the O variations with variations in the low intensity fluxes of 1-2 MeV solar protons. However, we do find the O intensity to be well correlated with the modulation of galactic cosmic rays as measured by neutron monitors. When compared with the neutron monitor, the factor of ~ 3 change in the O intensity during 1972 through 1974 is consistent with the factor of ~ 30 increase observed since 1969. These observations imply that the enhanced low energy N and O fluxes are not of solar origin, but originate far enough from the sun that they undergo substantial modulation and have significantly increased access to 1 AU at times of minimum solar modulation. It may be possible to determine the charge state of the He and O by comparing their time variations. The He and O variations are strongly correlated, and both exhibit similar hysteresis effects when compared to the neutron monitor.

1. Introduction. Recent observations of low energy cosmic rays have found anomalous features in the energy spectra of helium, nitrogen and oxygen relative to other nuclei such as hydrogen, boron and carbon (Garcia-Munoz et al., 1973; Van Hollebeke et al., 1973; Hovestadt et al., 1973; McDonald et al., 1974). At ~ 10 MeV/nuc the oxygen flux is enhanced by a factor of ~ 30 above an extrapolation of the energy spectra of these elements in the ~ 40-100 MeV/nuc interval. In contrast, no similar enhancements are seen in the low energy spectra of Li, Be, B, C, Mg, or Si (McDonald et al., 1974; Mewaldt et al., 1975a).

The 1972-74 low energy ^{4}He spectrum is also anomalous in that it is relatively flat from ~ 2 to 50 MeV/nuc, in contrast to the ^{1}H spectrum which is approximately proportional to kinetic energy over this interval, giving a $^4He/^1H > 1$ at ~ 15 MeV/nuc.

In this paper we report evidence for significant time variations in the quiet time intensity of < 30 MeV/nuc O and He nuclei and consider the implications of these observations for the origin of the anomalous low energy fluxes.

2. The Instrument. The observations reported here were made with the Caltech Electron/Isotope Spectrometer (EIS), launched on IMP-7 in September 1972. The EIS, which is described in Hurford et al. (1974) and Mewaldt et al. (1975b), consists of a stack of 11 solid state detectors surrounded by an anticoincidence cup. In the analysis mode used for the oxygen observations reported here, the energy loss spectrum of particles that stop in a 1 mm thick solid state detector

is measured. The large geometry factor of this mode (~ 1.8 cm^{2}sr) provides reasonable statistical accuracy on relatively short time scales. Analysis of data from the high resolution mode (Mewaldt et al., 1975a, 1975b) has provided the composition of nuclei measured in the single-parameter analysis mode, where individual charge resolution is not possible, and has confirmed the absolute flux measurements reported here.

3. Observations. The observations reported here were made during selected solar-quiet time intervals during a 2-year period starting October 1, 1972. In order to minimize the possibility of contamination by particles of solar origin we excluded periods during which the flux of 1.3-2.3 MeV/nuc He was $\geqslant 5 \times 10^{-3}$ cm^{-2}sr^{-1}sec^{-1}. In addition we excluded periods within ~ ± 4 days of identified "^{3}He rich flares" because of the enhanced solar emission of heavy nuclei associated with these events (Gloeckler et al., 1975; Hurford et al., 1975). From examination of the 2-30 MeV/nuc CNO and He spectra as a function of the 1.3-2.3 MeV/nuc He count rate, we conclude that solar particles account for less than 5% of the 8-27 MeV/nuc oxygen and 13-25 MeV/nuc He nuclei during the quiet time periods considered here.

In *Figure 1* we show measurements of the energy spectrum of oxygen and

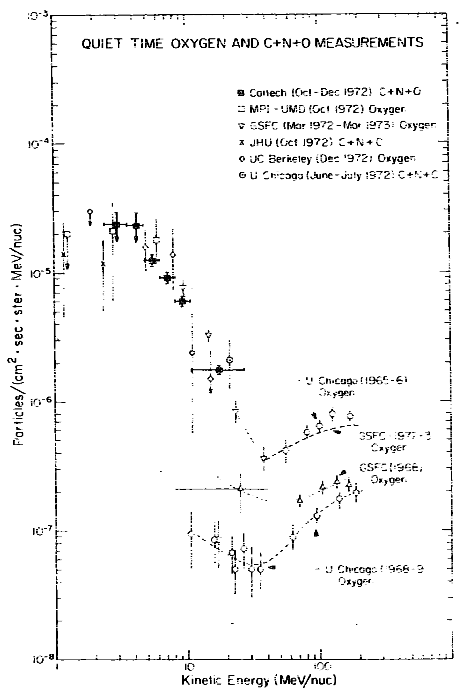

Fig. 1. Comparison of oxygen and C+N+O measurements from 1972 and earlier years.

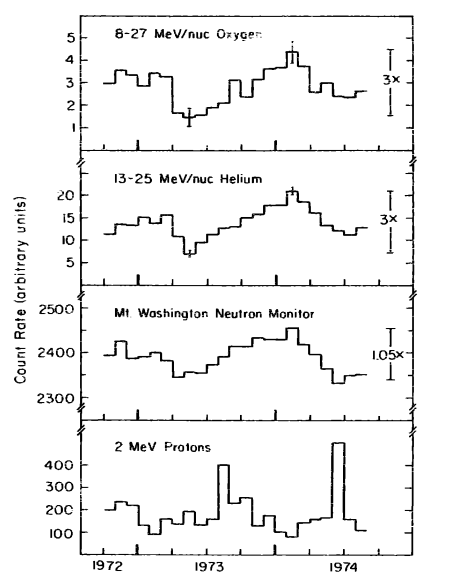

Fig. 2. Monthly average quiet time count rates.

C + N + O nuclei from late 1972 (MPI-UMD, Hovestadt et al., 1973; GSFC, McDonald et al., 1974; JHU, Krimigis et al., 1973; UC Berkeley, Chan and Price, 1974; Chicago, Mogro-Campero et al., 1973) along with measurements from earlier years (Chicago, 1965-6, Fan et al., 1968; GSFC, 1968, Teegarden et al., 1970; Chicago, 1968-9, Mogro-Campero et al., 1973). Note that the 1972 measurements show a sudden turnup below ~ 30 MeV/nuc. Because oxygen comprised ~ 70% of all nuclei with Z > 2 during this time period, the intensity of the CNO group does not differ significantly from that of oxygen alone. The only two measurements from earlier years that extend below 10 MeV/nuc indicate only a slight low energy turn-up in the oxygen spectrum. Note that while the 50-200 MeV/nuc oxygen flux increased by a factor of ~ 5 from 1968-69 to 1972-73, the ~ 8-30 MeV/nuc oxygen flux increased by a factor of ~ 20, implying that the low energy oxygen component is strongly modulated.

We have observed significant variations in the oxygen intensity on shorter time scales, as seen in *Figure 2*, which shows monthly average quiet time count rates of several cosmic ray components, where we have included only those days selected by the quiet-time criteria discussed above. Note the similarity between the O and He intensity variations, both of which varied by a factor of ~ 3 over this 2-year period. There is no significant correlation of the O and He variations with variations in the low intensity fluxes of ~ 1-2 MeV protons, which are likely of solar origin. However, we find both the oxygen and helium intensities to be well correlated with the modulation of galactic cosmic rays, as measured by the Mt. Washington neutron monitor (Lockwood, private communication).

Figure 3 shows a regression plot of the bi-monthly average quiet time flux of 8-27 MeV/nuc oxygen vs. the log of the Mt. Washington neutron monitor, where we have multiplied the C + N + O fluxes by a factor of 0.7 to obtain the flux of O alone. Ignoring the GSFC point, which was obtained at 1-4 AU on Pioneer-10, it can be seen that an extrapolation of the 1972-4 dependence of the oxygen intensity on the neutron monitor to much lower neutron monitor counting rates is roughly consistent with the much lower oxygen intensities measured in 1968 and 1969. *Figure 4B* shows the 1972-4 oxygen regression curve in more detail, as well as a similar regression plot for He nuclei (*Figure 4A*) Both the O and He exhibit a sizeable hysteresis with respect to the neutron monitor. The correlation between the O and He modulation is further demonstrated in *Figure 5*.

4. Discussion. The temporal behavior summarized in *Figures 2-5* shows that the low energy O and He intensity variations are in general anticorrelated with solar activity. This anticorrelation provides additional evidence against a solar origin for the enhanced N, O, and He fluxes, thereby supporting the conclusions of others which were based on the anomalously low C/O ratio in the ~ 3-30 MeV/nuc interval and the positive radial gradient in the oxygen intensity (McDonald et al., 1974).

The correlation of the low energy O and He with the neutron monitor is suggestive of particles of galactic origin. Galactic objects which might provide the anomalous elemental composition have been proposed (e.g. Hoyle and Clayton, 1974). However, the observed energy spectra of O, N, and ^{4}He in the 3-30 MeV/nuc interval do not exhibit a $j \propto T$ dependence, suggesting that these particles have not been affected to a great extent by adiabatic deceleration in the

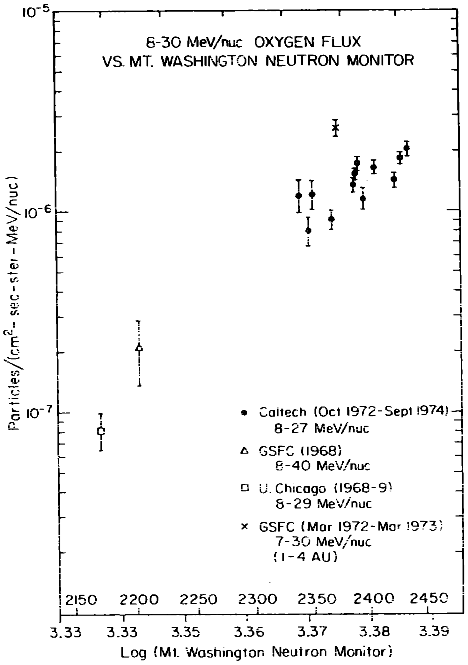

Fig. 3. *Regression plot of monthly averages of the 8-30 MeV/nuc oxygen flux vs. the log of the Mt. Washington neutron monitor (10/72-9/74).*

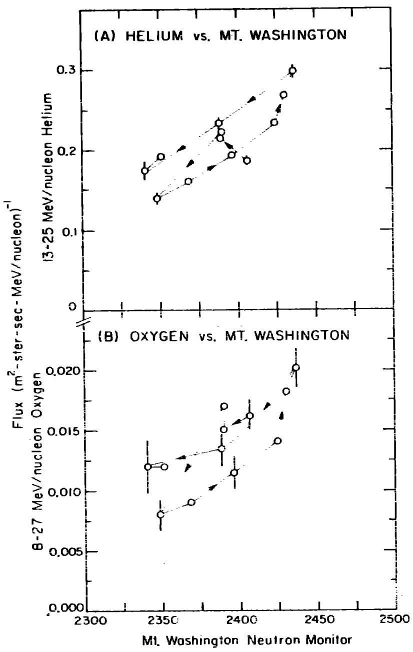

Fig. 4. *Helium and oxygen regression plots (bi-monthly averages) showing the hysteresis effects (10/72-9/74).*

heliosphere, as would be expected from present theories of solar modulation (see e.g. Goldstein et al., 1970).

Fisk et al. (1974) have suggested that this anomalous low energy component originates from neutral interstellar particles that penetrate the heliosphere, are singly ionized, and are then accelerated to several MeV/nuc. If this is so, then the present observations imply that the acceleration mechanism required by this local origin model must be located far enough from the sun that the singly charged ions, once accelerated, undergo substantial modulation in penetrating to 1 AU.

The time variation of the He and O fluxes may provide information on the charge state of these nuclei, which should be either singly or fully ionized depending on whether they are of local or galactic origin. O'Gallagher (1975) has found that hysteresis effects arise directly from differences in the time required for particles with different rigidities and velocities to propagate in to 1 AU. The similarity of the hysteresis of O and He when compared to the neutron monitor (*Figure 4*) and the corresponding lack of significant hysteresis effects between O and He (*Figure* 5) suggests one of following possibilities: 1) the rigidities of He and O are similar (i.e., O and He are fully ionized); 2) the diffusion coefficients for He^{II} (R ~ 0.6 to 0.9 GV) and O^{II} (R ~ 2.0 to 3.6 GV) are similar; or 3) the diffusion coefficients for He^{II} and O^{II} are small enough that the propagation time is convection limited and thus independent of particle velocity and rigidity. Based on O'Gallagher's (1975) numerical work, the second and third possibilities may not be consistent with proton hysteresis effects. However, more detailed comparison of observation and theory is required in order to quantitatively assess the uncertainties in the charge state of He and O which result from the analysis of the observed hysteresis effects.

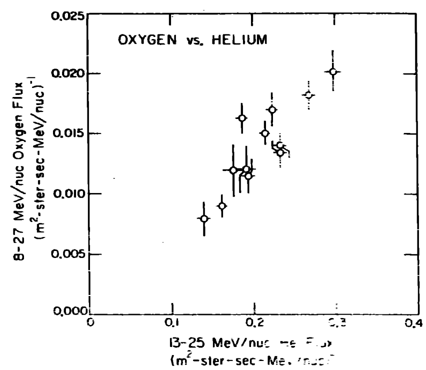

Fig. 5. *Plot of oxygen vs. helium (bi-monthly averages, 10/72-9/74).*

5. Acknowledgements. This work was supported in part by the National Aeronautics and Space Administration under Contract NAS5-11066 and Grant NGR 05-002-160.

6. References.

Chan, J. H., P. B. Price, Astrophys. J., 190, L39, 1974.

Fan, C. Y., G. Gloeckler, and J. A. Simpson, Canad. J. Phys., 46, S548, 1968.

Fisk, L., B. Kozlovsky, R. Ramaty, Astrophys. J., 190, L35, 1974.

Garcia-Munoz, M., G. M. Mason, J. A. Simpson, Astrophys. J., 182, L81, 1973.

Gloeckler, G., D. Hovestadt, and C. Y. Fan, "Iron Nuclei Emission from the Sun", University of Maryland Preprint, 1975.

Goldstein, M. L., R. Ramaty, L. A. Fisk, Phys. Rev. Lett., 25, 832, 1970.

Hovestadt, D., O. Vollmer, G. Gloeckler, C. Y. Fan, Phys. Rev. Lett., 31, 650, 1973.

Hoyle, F., D. D. Clayton, Astrophys. J., 191, 705, 1974.

Hurford, G. J., R. A. Mewaldt, E. C. Stone, R. E. Vogt, Astrophys. J., 192, 541, 1974.

Hurford, G. J., R. A. Mewaldt, E. C. Stone, R. E. Vogt, "Enrichment of Heavy Nuclei in ^{3}He-rich Flares", SRL 75-11, to be published, 1975.

Krimigis, S. M., T. P. Armstrong, J. W. Kohl, 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 2, 1656, 1973.

McDonald, F. B., B. J. Teegarden, J. H. Trainor, W. R. Webber, Astrophys. J., 187, L105, 1974.

Mewaldt, R. A., E. C. Stone, S. B. Vidor, R. E. Vogt, "The Elemental Composition of 3-30 MeV/nuc Cosmic Ray Nuclei with $1 \leq Z \leq 8$", Proceedings of the 14th Int. Cosmic Ray Conf., Munich, 1975a.

Mewaldt, R. A., E. C. Stone, S. B. Vidor, R. E. Vogt, Proceedings of the 14th Int. Cosmic Ray Conf., Munich, Paper OG 7-10, 1975b.

Mogro-Campero, A., N. Schofield, J. A. Simpson, 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 1, 140, 1973.

O'Gallagher, J. J., University of Maryland Technical Report #75-079, 1975.

Teegarden, B. J., F. B. McDonald, V. K. Balasubrahmanyan, Acta. Phys. Acad. Sci. Hungaricae, 29, Suppl. 1, 345, 1970.

Van Hollebeke, M. A. I., J. R. Wang, F. B. McDonald, 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 2, 1298, 1973.