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AN INTERPRETATION OF THE OBSERVED OXYGEN AND NITROGEN ENHANCEMENTS IN LOW ENERGY COSMIC RAYS

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ABSTRACT

It is proposed that the enhancements of cosmic-ray oxygen and nitrogen observed at $\sim$ 10 MeV/nucleon could result from neutral interstellar particles which are swept into the solar cavity by the motion of the Sun through the interstellar medium, and are subsequently ionized and accelerated.

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Recently, McDonald _et al_. (1974) have reported that the intensity spectra of cosmic-ray oxygen and nitrogen show a significant turnup in the energy range from about 5 to 30 MeV/nucleon. Only these two elements are clearly observed to be enhanced. Thus, at low energies the abundances of oxygen and nitrogen relative to carbon and helium differ greatly from either solar abundances or cosmic-ray abundances at higher energies. The O/C ratio becomes as large as 20, and the He/O ratio approaches unity. Based on this anomalous composition, as well as on the observation that the oxygen intensity increases with increasing heliocentric distance, McDonald _et al_. (1974) conclude that these nitrogen and oxygen particles do not originate on the Sun.

In this letter we propose that the oxygen and nitrogen enhancements could result from neutral interstellar particles which are swept into the solar cavity by the motion of the sun through the interstellar medium, and are subsequently ionized and accelerated. We demonstrate that this mechanism imposes no severe requirements either on the number of particles that have to be accelerated, or on the energy that has to be removed from the solar wind to perform this acceleration.

The outward flow of the solar wind excludes from the solar cavity any thermal interstellar particles that are ionized, and permits only the neutral particles to enter. The penetrating atoms should include mainly H, He, N, O, and Ne. Neutral hydrogen has, in fact, been detected in the solar system by observations of Ly α emission (Bertaux and Blamont 1972). The first ionization potentials of He, N, O, and Ne are greater than that of H; in fact, substantial neutral components of N and O have been detected in the interstellar medium

(Rogerson et al. 1973). Other elements such as C, Mg, Si, and Fe should not penetrate into the solar cavity in significant numbers, because with their relatively low first ionization potentials these particles are mainly ionized in the interstellar medium. For example, Weisheit (1973) has recently calculated the states of ionization of interstellar C, N, and O for various ionization models, and finds in all cases that the ratios [CI/C]/[OI/O] and [CI/C]/[NI/N] are less than a few times 10^{-3}.

Once inside the solar cavity, some of the penetrating neutral atoms will be ionized by photo-ionization from solar UV or by charge-exchange with solar wind particles (Axford 1972). The number of interstellar atoms of a given species that are ionized per unit time, Q_i, is approximately

$$Q_i \simeq \pi r_o^2 V n, \tag{1}$$

where n is the number density of neutral interstellar atoms of this species, and $V \simeq 20$ km/sec is the speed of the Sun through the interstellar medium. The distance r_o is the mean distance from the Sun that is reached by neutral atoms prior to their ionization. In Table 1, we have listed values of r_o as were determined by Axford (1972). We note that r_o for H, N, and O is roughly the same, but for He and Ne, r_o is smaller.

After being ionized, the interstellar particles should be forced to co-move with the solar wind, particularly if the interplanetary magnetic field is inclined in the azimuthal direction about the Sun. The interstellar particles, then, should be immediately accelerated to energies of about 1 keV/nucleon. These particles, however, will differ from solar wind particles in that their energy in the frame of the wind is also 1 keV/nucleon, which is considerably higher than solar wind thermal energies. Further, the interstellar particles are expected to be only singly ionized, while solar wind particles are predominately in higher states of ionization (e.g. Bame et al. 1968). Thus, for N, O, and Ne, and to a lesser extent for H and He, the gyro-radii of the interstellar particles are much larger than the gyro-radii of solar wind particles. It is conceivable therefore that an acceleration mechanism operating somewhere in the solar cavity could preferentially accelerate interstellar particles, particularly N, O, and Ne. We suppose that this mechanism is capable of raising the average energies of these particles to $\sim$ 10 MeV/nucleon.

At $\sim$ 10 MeV/nucleon, the accelerated interstellar particles are subject to the effects of solar modulation, which tends to exclude the particles from the inner solar system. The modulation of N, O, and Ne, however, is expected to be small. Because we do not expect that further electron stripping occurs during the acceleration process, the rigidity of these accelerated particles is several GV. Thus, even when we take into account the low velocities of the N, O, and Ne, the modulation of these particles should be comparable to the modulation of cosmic-ray protons with energies of several hundred MeV/nucleon. The accelerated H, on the other hand, should be excluded from the inner solar system as are comparable energy cosmic-ray protons (Goldstein, Fisk, and Ramaty 1970; Gleeson and Urch, 1971). The modulation of the accelerated He is intermediate between that of H and that of N, O, and Ne.

Considering all of these processes together, we see that the proposed mechanism could enhance N and O at $\sim$ 10 MeV/nucleon over other elements, in agreement with the observations (McDonald *et al*. 1974). The N and O are among only five elements (H, He, N, O, Ne) that can easily penetrate into the solar cavity as neutral interstellar atoms. The N and O are also among the most easily ionized of the five elements once in the solar cavity (see Table 1); they may be preferentially accelerated; and they should experience little solar modulation. This mechanism should also accelerate Ne, although the Ne enhancement will be less than that of the N and O because Ne is not as easily ionized. In fact, a Ne enhancement may occur, but the observations are not conclusive (B. J. Teegarten, private communication, 1973). A He enhancement could also occur, although such an enhancement should be rather small because these particles are not easily ionized, and they may be modulated. Our mechanism nonetheless could account for part of the flattening of the He spectrum that is observed below $\sim$ 80 MeV/nucleon (Garcia-Munoz, Mason, and Simpson 1973). On the other hand, no significant enhancement of low-energy protons, resulting from accelerated interstellar H, should be seen. These particles may not be easily accelerated, and they should be strongly modulated. There is in fact no conclusive evidence for a significant non-solar proton component below about 20 MeV; i.e. the majority of the observed protons in this energy range could originate on the Sun.

Finally we demonstrate that the proposed mechanism does not place severe requirements either on the number of interstellar particles that must be accelerated, or on the energy needed to perform this acceleration. We consider the case for O, and solve for f, the fraction of interstellar O, which after ionization in the solar cavity is accelerated to energies $\sim$ 10 MeV/nucleon. In a steady-state, the rate at which O is ionized and accelerated should roughly equal the rate at which these particles leak out of the solar cavity. Using equation 1, we have that

$$f \pi r_o^2 V n \simeq (4/3) \pi R^3 \bar{n}/\tau \qquad . \tag{2}$$

Here, $R \simeq 50$ AU is the dimension of the solar cavity, which we assume has a spherical shape; $\bar{n}$ and τ are, respectively, the mean number density and mean dwell time of 10 MeV/nucleon O in the solar cavity. For the number density of neutral interstellar O, we take $n=10^{-4}cm^{-3}$, and from Table 1, $r_o = 3$ AU. Since the accelerated O is not expected to experience much modulation, $\bar{n}$ should roughly equal the number density of 10 MeV/nucleon O observed near earth, i.e. $\bar{n} \simeq 3\cdot 10^{-13}cm^{-3}$ (McDonald et al. 1974). Similarly, with little modulation τ is not expected to be long. However, a reasonable lower limit for the dwell time is $\tau \simeq 2\times 10^6$ sec, which is an order of magnitude larger than the linear transit time of 10 MeV/nucleon particles across the dimension of the solar cavity. For the above values we find that f is only $\sim 10^{-4}$. Of course, smaller values for R or longer dwell times τ will lead to smaller results for f. In any event, an acceleration of only 0.01% of the ambient matter to energies ~10 MeV/nucleon is not unreasonable, nor is it uncommon in nature, e.g. such acceleration appears to occur in solar flares. Similarly, the power required to produce the observed O enhancement will not drain much energy from the solar wind. With the above values for R, τ, and $\bar{n}$, the required power is only $\sim 3\times 10^{22}$ergs sec^{-1}, a value small in comparison with the total solar wind power $\sim 10^{27}$ ergs sec^{-1}.

In conclusion, the anomalous composition of N and O observed at $\sim$ 10 MeV/nucleon can be understood if neutral interstellar particles that penetrate into the solar cavity are ionized and accelerated. This mechanism should enhance only N, O, and to some extent Ne and He. Thus, a test of the model will be to determine conclusively that other elements such as Mg, Si, and Fe are not enhanced. Another test, which, however, is beyond current experimented capabilities, will be to determine the charge state of the particles which are enhanced. In the present model, these particles should be mainly singly ionized.

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Table 1

Mean distances from the Sun reached by penetrating neutral atoms prior to ionization (Axford 1972)

element	H	He	N	O	Ne
r_o (in AU)	4	0.5	4	3	1.6