MeV states in B^{10}. The independence of the spectroscopic factors on T_z permits their extraction for the unresolved 1.74- and 5.16-MeV states in B^{10} from the data on the isolated ground and 3.37-MeV states in Be^{10}, respectively. The experimental parentage is given in Table II. The calculated values are derived, as above, from the Kurath wave functions.

The present measurements indicate that there are no large isospin impurities in the heavy-ion transfer reactions investigated and illustrate the utility of these reactions in spectroscopic tests of wave functions for light nuclei. Extensions of this work with higher resolution, variable-energy heavy-ion beams will be of considerable interest.

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LOW-ENERGY COSMIC-RAY MODULATION RELATED TO OBSERVED INTERPLANETARY MAGNETIC FIELD IRREGULARITIES*

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The diffusion coefficient describing the motion of cosmic-ray particles in the interplanetary magnetic field is determined from the power spectrum of magnetic irregularities observed on space probes, and is found to be proportional to $R\beta$ (R = particle magnetic rigidity, β = particle velocity). Near minimum solar activity, only this dependence of the diffusion coefficient on R and β can account for the observed long-term intensity variations of cosmic-ray protons and helium nuclei down to 10 MeV per nucleon in energy. Thus, the motion of cosmic rays in interplanetary space may be quantitatively related to the observed magnetic field.

Parker[1] has described the motion of cosmic rays through interplanetary space in terms of diffusion through magnetic field irregularities which are carried by the solar wind. Although cosmic-ray observations have shown that this picture reasonably accounts for the 11-yr modulation of galactic cosmic radiation,[2-7] the diffusion coefficient κ has remained essentially a free parameter and was not quantitatively related to the observed interplanetary magnetic field. Recently, Jokipii has related κ directly to the Fourier spectrum of the magnetic field irregularities,[8] measurements of which have now been reported.[9,10] In this Letter we analyze magnetic field and cosmic-ray proton and helium observations obtained near solar minimum in the vicinity of the orbit of Earth. We find that (1) the measured interplanetary magnetic field irregularities require κ to be proportional to $R\beta$ for particles with magnetic rigidity R and velocity $c\beta$; (2) it is precisely this dependence of κ on $R\beta$ which is required if Parker's model is to explain the observed variation of both protons and helium down to 10 MeV per nucleon kinetic energy.

Measurements of the low-energy proton and helium fluxes and spectra have been made in interplanetary space by Fan, Gloeckler, and Simpson[11,12] on the satellites IMP-I, -II and -III and cover a two-year period near solar minimum activity (December 1963–September 1965). Figure 1 shows the helium differential

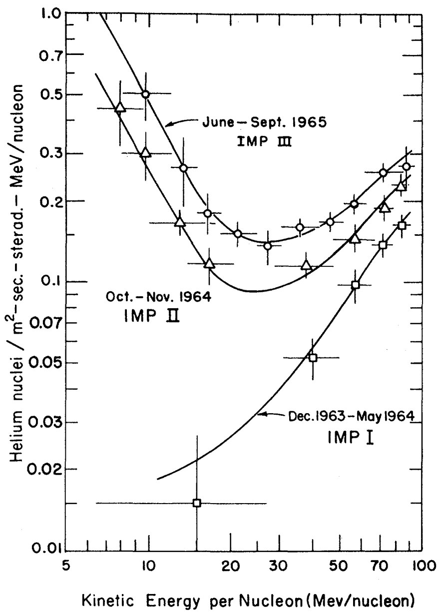

FIG. 1. Differential energy spectra for primary helium during three time intervals near minimum solar activity. These satellite measurements were made in interplanetary space over continuous time intervals and do not include periods when solar-associated particle events are present.

energy spectra for three successive time intervals for which no solar-associated events were present. In addition to the increase in the helium flux above ~30 MeV per nucleon, which was previously reported[5,12] and which is now shown to continue into 1965, there is a factor of ten increase for the flux below ~30 MeV per nucleon. During this two-year period both the Climax neutron monitor intensity[13] and the counting rate of the Geiger-counter array[6] on the IMP satellites were increasing; this indicates a gradual reduction of the modulation of galactic cosmic rays. In this Letter we assume that the observed spectrum above ~10 MeV per nucleon is a modulated galactic spectrum.

Parker's diffusion-convection model for the 11-yr modulation relates $\mu_E(T)$, the cosmic-ray intensity at Earth at a given kinetic energy T, to $\mu_\infty(T)$, the corresponding intensity in the local interstellar region, through

$$\mu_E(T) = \mu_\infty(T) \exp\left[-\int_{1\ \mathrm{A.U.}}^{L} \frac{V_W}{\kappa} dr\right], \qquad (1)$$

where V_W is the wind velocity, κ is the diffusion coefficient, r is the distance from the sun, and L is the dimension of the modulating region. Equation (1) expresses the basic dependence on wind velocity and diffusion coefficient for a spherically symmetric wind. Recently the complicating effects of adiabatic deceleration[14] and anisotropic diffusion have been considered[14-16]; the results suggest that Eq. (1) still expresses the basic physics involved although the integrand may include additional factors independent of particle velocity or magnetic rigidity. Since the diffusion is highly anisotropic, the diffusion coefficient for motion parallel to the average field must be used.

κ can be obtained directly from the magnetic field fluctuations observed at a satellite. Since these fluctuations are due mainly to irregularities carried past the satellite by the solar wind, time variations give the mean-square amplitude and wavelength distributions of these irregularities. The scattering of particles with cyclotron radius r_c in the average magnetic field may be shown to be determined by the power in the fluctuations of the field component transverse to the wind velocity at frequencies near[8] $f_0 = V_W/2\pi r_c$. This states that particles are scattered principally by irregularities with scale $\sim r_c$. Figure 2 gives as a function of fre-

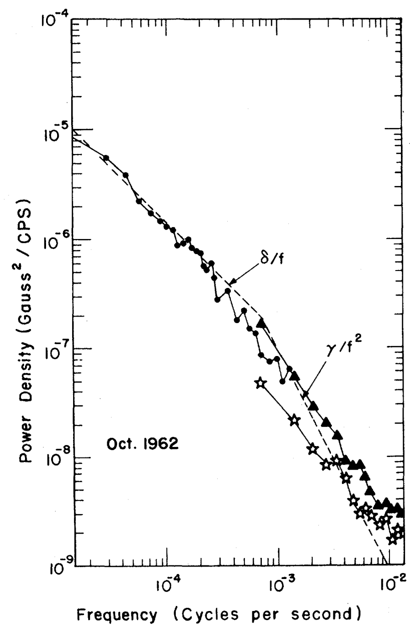

FIG. 2. The power spectrum reported by Coleman (Ref. 9) for B_φ, the component of the interplanetary magnetic field normal to the sun-probe line and in the solar equatorial plane. The data were obtained from Mariner-2 in late 1962. The different symbols refer to differences in time periods and computational techniques which are not relevant here.

quency the quiet-time power spectrum reported by Coleman[9] for a transverse component of the magnetic field measured on Mariner-II in late 1962. The average field intensity is taken to be ~5 γ and $V_W \sim 400$ km/sec. In the frequency range of interest (3×10^{-4} to 3×10^{-5} sec^{-1}, corresponding to the 10- to 100-MeV/nucleon helium and 50-MeV to 3.0-GeV protons considered in this Letter), the spectrum is well represented by $P(f) \sim \delta/f$ ($\delta \sim 1.4\times10^{-10}$ G^2) with a tendency to steepen at $f \gtrsim 5\times10^{-4}$ sec^{-1}. Recently, power spectra have been obtained by Siscoe[10] from Mariner-IV magnetometer data during a typical quiet, two-week period in late 1964. Again the power spectrum of the transverse field is roughly proportional to $1/f$ at low frequencies with a transition to a steeper slope at $f \gtrsim 10^{-4}$ sec^{-1}. This indicates that for the present discussion of the long-term variation $P(f)$ may be taken to be proportional to $1/f$ in the relevant frequency range. The fact that the transition to a steeper spectrum occurs at a lower frequency in 1964 than in 1962 may be significant for the modulation of very-low-energy particles and will be discussed below.

For a magnetic-field power spectrum of the form $P(f) = \delta/f$, Jokipii[8] finds that $\kappa_{\parallel}$, the diffusion coefficient for motion along the field of particles having magnetic rigidity R and velocity $c\beta$ in the average magnetic field B_0, may be written[17]

$$\kappa_{\parallel} \sim \left(\frac{cB_0}{3\pi\delta}\right) R\beta. \qquad (2)$$

It may be shown[8] that the diffusion is highly anisotropic with $\kappa_{\parallel} \gg \kappa_{\perp}$. If we assume that $\kappa_{\parallel}$ remains proportional to $R\beta$ out to the boundary of the modulating region, the cosmic-ray intensity at Earth may be written

$$\mu_E(T) \sim \mu_{\infty}(T) \exp[-\eta/R\beta], \qquad (3)$$

where η is independent of R and β. Dorman,[3] considering various assumptions on the form of the scattering by irregularities, has also suggested that $\kappa \propto R\beta$; however, his discussion does not refer to an observed interplanetary magnetic field.

The observed long-term time variation results from changes with time in η. If μ_2 is the observed flux at time t_2, and μ_1 the corresponding flux at an earlier time t_1, the ratio μ_2/μ_1 is

$$\mu_2/\mu_1 = \exp[(\eta_1 - \eta_2)/R\beta]. \qquad (4)$$

In Fig. 3(a) $\ln(\mu_2/\mu_1)$ is plotted versus $R\beta$ for the two indicated time periods. Below 0.35 GV for $R\beta$ (<90 MeV per nucleon kinetic energy), values of μ_2 and μ_1 were obtained directly from the helium data of Fig. 1. In order to extend the rigidity range and to demonstrate that the modulation of protons is also described by Eq. (4), we have included additional values for $\ln(\mu_2/\mu_1)$ using data from two other detector systems which covered the appropriate time periods. The points at $R\beta = 0.7$ GV represent the variations of the integral proton flux above 50 MeV,[6,18] and those at $R\beta = 3.0$ GV represent changes in the integral proton flux above 3.0 GV deduced from the Climax neutron monitor intensity.[13,19]

Each set of data points in Fig. 3(a), in particular the upper set, is well represented by a line with slope -1 on the log-log plot. This indicates that $\ln(\mu_2/\mu_1) \propto 1/R\beta$, which is in excellent agreement with the dependence predict-

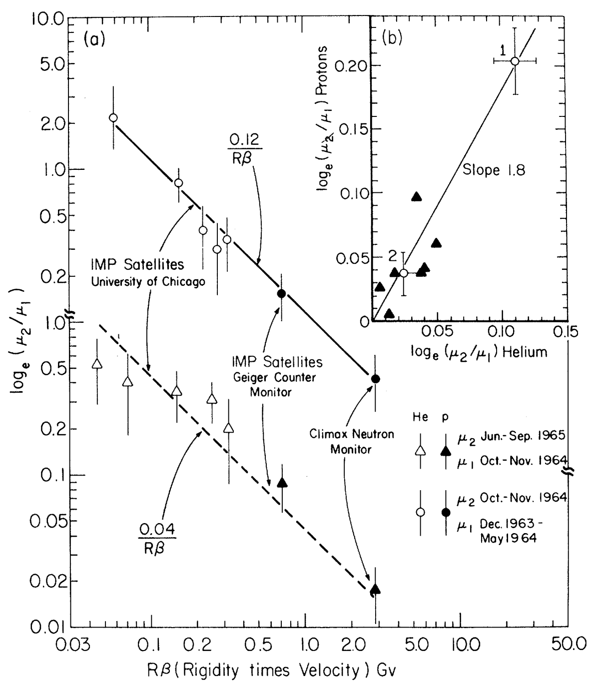

FIG. 3. (a) Fractional change in the observed flux of primary particles as a function of the particle velocity times rigidity ($R\beta$) for two different time periods. Data points below 0.3 GV are taken from Fig. 1. (b) Fractional changes of protons and helium at the same velocity or energy per nucleon in the energy range 50-90 MeV per nucleon, over the same time periods. Point "1" is from IMP-II measurements and point "2" is the average of the variations in 1965, shown by solid triangles, as measured on IMP-III.

ed by the observed magnetic field. Other forms for $\ln(\mu_2/\mu_1)$, such as $1/R$ or $1/\beta$, are clearly ruled out over the energy range covered by the measurements.

We point out that the lower set of points, obtained in 1964-1965, tend to fall below the curve $1/R\beta$ at low energies. This may be related to the observed steepening of the magnetic field power spectrum obtained in late 1964 at frequencies $\gtrsim 10^{-4}$/sec, corresponding to $R\beta \lesssim 0.3$ GV for helium. More extensive measurements of the magnetic-field power spectra are necessary before a quantitative discussion of this point is possible. However, the steepening of the magnetic power spectrum would be expected to produce such an effect.[8] The fact that this divergence from $1/R\beta$ is not present in the earlier data, shown as the upper set of points in Fig. 3(a), is reasonable since the steepening of the power spectrum occurred at a higher frequency in late 1962 than in 1964. Thus only particles with rigidities below those considered here would have been affected. It should also be noted in this regard that divergence from $1/R\beta$ must occur at low energies because otherwise the predicted modulation of low-energy particles would be much too large.

As an independent check on the predicted charge-to-mass ratio dependence, we examine the relative modulation of protons and helium at the same velocity. Since $R = (A/Z)\beta\gamma$, it is expected from Eq. (4) that for a given velocity or energy per nucleon $\ln(\mu_2/\mu_1)_p = 2\ln(\mu_2/\mu_1)_{\text{He}}$. Figure 3(b) shows the relative modulation of protons and helium in the energy range 50-90 MeV per nucleon. To reduce the influence of systematic errors, we have used only data from the same instrument on the same satellite to obtain a given data point. For example, point "1" in Fig. 3(b) represents the relative changes from October-November 1964 to December 1964-January 1965 as measured on the IMP-II satellite, while point "2" is the average of the relative changes recorded on the IMP-III satellite. A line having slope 1.8 ± 0.2 is a reasonable fit to these data; this indicates that protons are modulated about twice as much as helium, as predicted.

The observations which are discussed in this Letter extend the analysis down to energies ~10 MeV per nucleon, where the distinction between the dependence of modulation on $1/R$, $1/R\beta$, and $1/\beta$ can be clearly made. These satellite observations are more appropriate than balloon measurements for a study of the 11-yr variation since they are continuous and insensitive to short-term fluctuations. Silberberg[7] has analyzed the modulation of protons and helium nuclei above 200 MeV per nucleon using results obtained by several investigators. He concludes that a modulation function of the form $\exp[-\eta(t)/R\beta]$ is consistent with the data obtained in 1963 and 1964. Nagashima, Duggal, and Pomerantz[20] and Dorman and Dorman[21] reach similar conclusions. Webber[22] has also reported an analysis of time variations for protons and helium with energies >100 MeV per nucleon using data which he obtained in 1963-1965. He also finds that protons are modulated twice as much as helium at a given velocity. Although he claims that $\exp[-\eta(t)Z/A\beta]$ fits his observations, a careful examination shows that his Fig. 1 is in error and in fact $\exp[-\eta(t)/R\beta]$ is a better fit,[23] in agreement with our conclusions.

We conclude that the cosmic-ray observations show very good agreement with the change in modulation predicted on the basis of reported magnetic-field power spectra. Although the magnetic field data are still fragmentary, and only determine κ near the orbit of Earth, the above considerations verify that modulation is due to magnetic irregularities carried with the solar wind and that particle motion may be quantitatively related to magnetic field observations. Since presently available observations near Earth do not permit a determination of the magnitude of the modulation, but only the dependence of the change in modulation on particle velocity and magnetic rigidity, a determination of radial dependence of cosmic-ray intensity would provide a further test of this model.

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[17]The computation of the diffusion coefficient in Ref. 8 requires that the change in mean field $\boldsymbol{B}_0$ be small over the scattering mean free path $\lambda \sim \kappa_{\|}/c\beta$. For 100-MeV protons, $\lambda \sim 10^{12}$ cm, whereas the scale length of the field beyond 1 A.U. is greater than 1 A.U. $\sim 1.5 \times 10^{13}$ cm so that the assumption is reasonably well satisfied.

[18]We have plotted the data at a weighted median energy $\langle T\rangle = 450$ MeV which is obtained from

$$\int_{50}^{\langle T\rangle} dE\left(\frac{j}{R\beta}\right) = \int_{\langle T\rangle}^{\infty} dE\left(\frac{j}{R\beta}\right).$$

Here j is the differential proton spectrum measured at Earth as given in Ref. 7. The value of $\langle T\rangle$ is not very sensitive to the form of the weighting function. The contribution of helium to the Geiger-Müller rate was neglected since it only amounts to 10-15% of the total.

[19]The fractional change in the Climax neutron monitor intensity is multiplied by 2.0 (private communication from J. A. Simpson) to deduce the primary proton variation. These points are plotted at the detector threshold of 3.0 GV because of the sharply falling spectrum.

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HYDROMAGNETIC WAVES IN THE INTERPLANETARY PLASMA

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This note is a preliminary report concerning a comparison of simultaneous measurements of the plasma velocity and the magnetic field in interplanetary space. The measurements were obtained with the positive-ion spectrometer, incorporating a cylindrical electrostatic analyzer, and the fluxgate magnetometer on board the spacecraft Mariner-II, during the period 29 August through 15 November 1962, while the spacecraft was in transit between the earth and Venus. Our purposes here are, first, to describe the properties of the simultaneous variations in the magnetic field, $\vec{B}$, and the plasma velocity, $|\vec{V}|$, and second, to show that these properties are among those expected if the variations were produced by hydromagnetic waves.

It will be convenient to employ heliocentric, spherical polar coordinates with the polar axis coincident with the sun's axis of rotation, denoted by $\vec{\Omega}_S$. Thus, at a point (r, θ, φ) the positive r direction is radially outward from the sun to the point, the φ direction is the direction of $\vec{\Omega}_S \times \vec{r}$, and the θ direction completes the usual right-handed system. In this system, the variables measured by the magnetometer are B_r, B_θ, and B_φ, and the variable measured by the plasma probe is $V \simeq V_r$.

As the first step in a statistical analysis of the data, amplitude distributions of these variables were examined. It was found that the distributions were roughly Gaussian. Next, using the usual methods applicable to time series that exhibit Gaussian amplitude distributions,