THE ASTROPHYSICAL JOURNAL, 312:178–182, 1987 January 1

A REEXAMINATION OF THE COSMIC-RAY HELIUM SPECTRUM AND THE ^{3}He/^{4}He RATIO AT HIGH ENERGIES

W. R. WEBBER
Space Science Center, University of New Hampshire
R. L. GOLDEN
Electrical and Computer Engineering Department, New Mexico State University
AND
R. A. MEWALDT
Downs Laboratory of Physics, California Institute of Technology
Received 1986 March 18; accepted 1986 June 10

ABSTRACT

We have reexamined the implications of a recent measurement of cosmic-ray ^{3}He at ~6 GeV per nucleon which reported an unexpectedly high abundance of this rare isotope. The implied ^{3}He/^{4}He ratio from this high-energy measurement depends critically on the assumed rigidity spectrum of helium nuclei between ~10 and 20 GV. A careful analysis of published measurements of the helium spectrum, along with new data obtained using a magnetic spectrometer, show that the appropriate spectral index (γ) to be used to interpret this measurement has a value of less than 2.55, for a differential rigidity spectrum $dJ/dR \propto R^{-\gamma}$. Since this index is lower than originally used, the ^{3}He/^{4}He ratio of less than 0.17 that we derive (evaluated at constant energy per nucleon), is significantly lower than the original quoted value of 0.24 ± 0.05. The cosmic-ray escape pathlength in g cm^{-2} of interstellar material deduced from this revised ratio and from ^{3}He/^{4}He measurements at low energies is now found to be consistent with that deduced from studies of heavier nuclei. The body of ^{3}He/^{4}He measurements now available thus severely restricts the types of models that might be invoked to explain the high intensity of cosmic-ray antiprotons that has been reported.

Subject heading: cosmic rays: abundances

I. INTRODUCTION

A recent observation of the isotopic composition of helium at energies of ~6 GeV per nucleon (Jordan and Meyer 1984; Jordan 1985) has been interpreted to suggest that, as a result of the large inferred abundance of secondary ^{3}He, primary ^{4}He must have traversed considerably more matter than heavier cosmic-ray nuclei with the same energy per nucleon. Interpreted in terms of the standard "leaky box" model for cosmic-ray propagation, the resulting mean interstellar pathlength for escape from the galaxy that Jordan and Meyer deduced for high-energy ^{4}He was ~15 g cm^{-2} from this measurement. This escape length is considerably greater than the value ~8 g cm^{-2} determined from studies of heavier elements such as carbon or iron and their secondaries at lower energies (≤2 GeV per nucleon)—and it is similarly greater than the value implied by ^{3}He/^{4}He observations at energies of a few hundred MeV per nucleon or less. This discrepancy is even greater when one recognizes that the cosmic-ray escape length is found to be energy-dependent for heavier cosmic-ray nuclei, leading to a value of ~5–6 g cm^{-2} at an energy of ~6 GeV per nucleon corresponding to the new ^{3}He measurement. Propagation models more complex than the standard simple leaky box model, including possibly different origins and/or propagation histories for helium nuclei and heavier nuclei, would be required to understand a ratio as high as this new high-energy ^{3}He/^{4}He ratio in the context of previous data. This possibility assumes increased significance in the light of recent antiproton measurements which also seem to require an increased escape length or matter traversal for cosmic-ray protons.

The Jordan and Meyer ^{3}He/^{4}He ratio was determined by the adaptation of the "geomagnetic method," in which a gas Cerenkov counter was used to measure the velocity spectrum of He nuclei with rigidities greater than the local geomagnetic cutoff. The method relies on the fact that at a given rigidity the velocity of ^{4}He is less than that of ^{3}He, because of its smaller charge-to-mass ratio. In deconvolving their measured velocity spectrum, Jordan and Meyer found that the resulting ^{3}He/^{4}He ratio depended sensitively on the assumed differential spectrum of ^{4}He nuclei, especially in the rigidity interval of their measurement (~10–15 GV). Based on a survey of reported measurements, these authors took this helium spectrum to be $dJ/dR \propto R^{-\gamma}$, with $\gamma = 2.65 \pm 0.05$, a spectrum that also provided a reasonable fit to their data.

In this paper we examine published helium spectral data and present new helium data, which determine that the helium spectral index at Earth in this rigidity range at the time of the above ^{3}He measurement can definitely be specified to have a value of ≤2.55, thus leading to a significantly smaller ^{3}He/^{4}He ratio at 6 GeV per nucleon than was deduced by the above authors. This leads to a smaller escape length—one that is consistent with the value and energy dependence of the escape length determined from observations of heavier cosmic-ray elements.

II. HELIUM SPECTRAL DATA

A composite helium rigidity spectrum obtained using previously reported data is shown in Figure 1. In each case we have gone back to the original data and converted to differential rigidity spectral points where necessary. A few remarks are necessary with regard to each data set. The most comprehensive spectrum that covers the rigidity range of interest

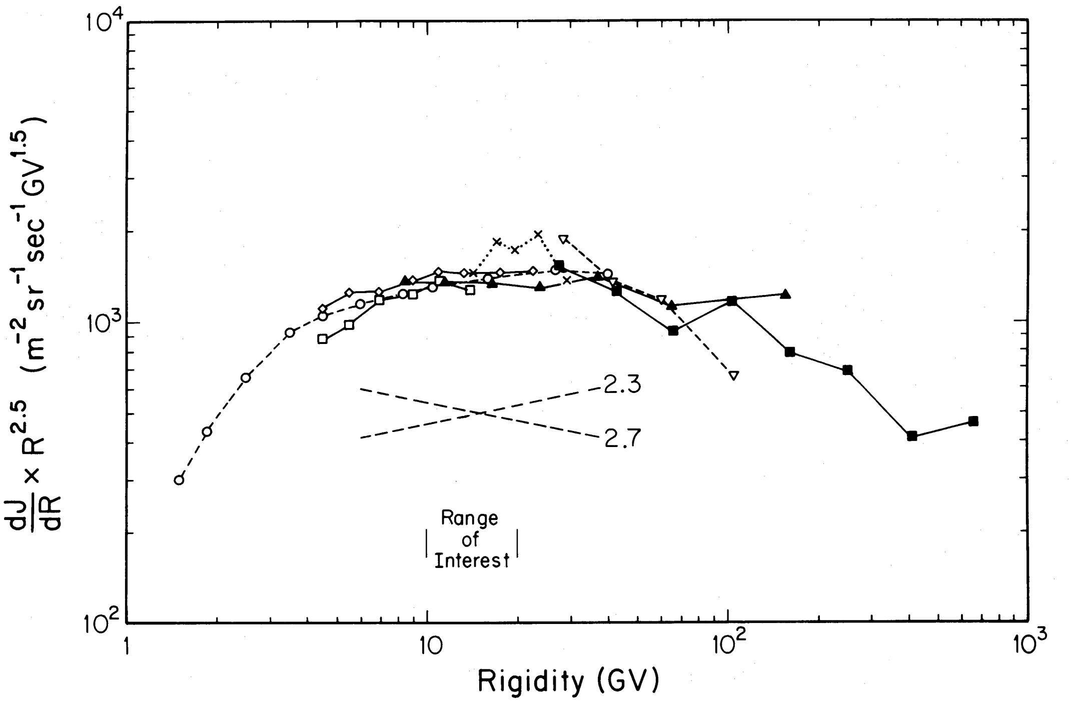

FIG. 1.—Summary of measurements of the differential rigidity spectrum of helium nuclei. All data are multiplied by $R^{2.5}$ to show more clearly features of the spectrum. Dashed lines indicate spectra proportional to $R^{-2.3}$ and $R^{-2.7}$. Data points are as follows: *diamond*, Badhwar *et al.* (1971); *solid triangle*, Smith *et al.* (1973); *downward triangle*, Verma *et al.* (1972); *solid square*, Ryan *et al.* (1972); *cross*, Anand *et al.* (1968); *open circle*, von Rosenvinge *et al.* (1969) and Webber and Lezniak (1974); *open square*, Brown, Stone, and Vogt (1973). Measurement uncertainties on the individual data points (apart form overall normalization uncertainties) can be characterized as follows: Uncertainties in the data of Smith *et al.* are typically ~5% for $R < 30$ GV, ranging up to ~15% at 150 GV. For the Ryan *et al.* data they are less than ~10% for $P < 100$ GV, ranging up to ~40% at ~600 GV. Uncertainties in the data of Verma *et al.* range from ~15% to ~50%, while those for the Anand *et al.* points are typically ~35%. In the case of the latitude survey data (von Rosenvinge *et al.* and Lezniak and Webber; Badhwar *et al.*; Brown, Stone, and Vogt) the uncertainties are estimated to be ~10% to 20%.

was derived by Smith *et al.* (1973), over the range 8–160 GV using a magnetic spectrometer. The work of Verma *et al.* (1972) is also based on magnetic spectrometer measurements at rigidities >22 GV. Ryan, Ormes, and Balasubrahmanyan (1972) used a calorimeter to derive the helium spectrum above 12.5 GeV per nucleon (~27 GV). The energy spectrum derived by these latter authors was converted to a rigidity spectrum by us.

Anand *et al.* (1968) used an oriented emulsion and the east-west geomagnetic cutoff effect to derive the helium spectrum between 12 and 30 GV. Only integral intensities above certain rigidities were reported in their original paper—we obtained a differential spectrum by taking differences between integral intensities. Note that this spectrum agrees less well with the other data, and indeed we believe this spectrum to be considerably less accurate than other published data due at least in part to its relatively large statistical uncertainties.

The other data sets in Figure 1 utilized the geomagnetic field as a magnetic analyzer. This is potentially a very accurate approach free of systematic errors. The work of von Rosenvinge, Webber, and Ormes (1969) and Webber and Lezniak (1974), supplemented by more recent data points, is based on integral helium intensities measured at several latitudes with cutoffs between ~1.5 and 17 GV, along with integral intensities measured using gas Cerenkov detectors to construct a spectrum between 1.5 and 50 GV. A smooth curve was drawn through this integral spectrum, and the differential of this curve gives the spectrum shown in Figure 1. This procedure is described in more detail in Webber and Lezniak (1974). This same procedure was used to present the data from a latitude survey using the *OSO 3* satellite reported by Badhwar, Kaplan, and Valentine (1971). These authors quoted an integral rigidity spectrum exponent of 1.47 ± 0.05 between 8 and 30 GV. A similar helium spectrum, which was found to approach an integral index ~1.6 above 8 GV, was obtained by Brown, Stone, and Vogt (1973) from a latitude survey covering 2–15 GV with a cosmic-ray counter on the *OGO 6* satellite. Measurement uncertainties for the various observations included in Figure 1 are discussed in the figure legend. Perhaps the best overall indication of the uncertainty in the spectral shape is given by the level of consistency between the various measurements.

The same general data set (minus the spectrometer data of Verma *et al.* and the latitude survey data of Badhwar *et al.* and of Brown, Stone, and Vogt), was used by Jordan (1985) to determine an appropriate spectral index to use for helium. In addition, Jordan considered a measurement at extremely high energies which found $\gamma = 2.83 \pm 0.20$ at >2000 GV (Burnett *et al.* 1983), and a preliminary report at the spectral index determined over the interval 8–100 GV (Badhwar *et al.* 1979) based on the magnetic spectrometer data to be discussed below (Golden *et al.* 1985). In the report by Badhwar *et al.* (1979) the value of $\gamma = 2.73$ that is quoted refers to the interstellar spectrum, after solar modulation corrections have been applied (Golden 1986). For comparison with measurements made at Earth the appropriate value of γ from this measurement is in the range from 2.55 to 2.60, as discussed below.

In addition to the spectral measurements discussed above, Golden *et al.* (1985) have recently reported a new analysis of magnetic spectrometer measurements of the differential rigid-

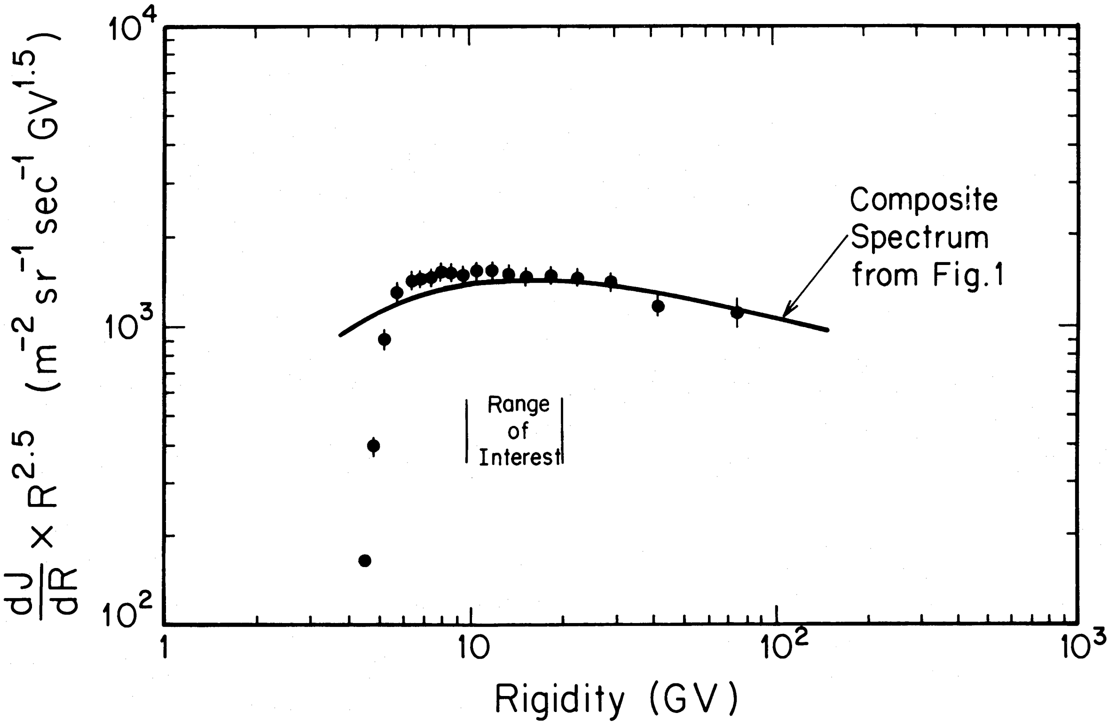

FIG. 2.—Helium spectrum (multiplied by $R^{2.5}$) derived from the data of Golden *et al.* (1985). Also shown is a smooth curve drawn to fit the composite data set shown in Fig. 1. The sharp drop in the spectrum below ~6 GV is due to the effect of the local geomagnetic cutoff.

ity spectra of protons and helium nuclei made during solar minimum conditions in 1976. Golden *et al.* reported only a simple spectral index of 2.71 ± 0.05 for the rigidity interval 10–25 GV, where again this value refers to the derived interstellar spectrum, taking into account the effects of solar modulation. In this paper we carry this analysis further and show in Figure 2 the differential spectral intensities directly measured at Earth, as deconvolved from the measured deflection spectrum shown in Figure 1 of the above paper, using the resolution function of the instrument. A complete description of this analysis will be published separately. There are some small differences between this spectrum and the average of the data shown in Figure 1; however, the spectral index of the Golden *et al.* data between 10 and 25 GV is in the range 2.55–2.60. This spectrum is consistent with that obtained from the other high-resolution magnetic spectrometer experiment, which found $\gamma = 2.47 \pm 0.05$ (Smith *et al.* 1973), when differences in the level of solar modulation at the times of the measurements are taken into account.

III. THE HELIUM SPECTRUM AND THE $^3He/^4He$ RATIO

We see from Figures 1 and 2 that the helium rigidity spectrum *at Earth* cannot be described by a single spectral index. The flatter spectrum that is observed below ~40 GV is likely due in large part to the effects of solar modulation, which need to be considered when comparing measurements below ~20 GV. Since the Jordan and Meyer measurement was made in 1981 at a time of extreme solar modulation, this will lead to a flatter spectrum at Earth than in interstellar space, even at rigidities of ~10–20 GV. For the purposes of comparison here this modulation can be described by the force field parameter φ expressed in rigidity units of GV. The larger the value of φ the greater the degree of solar modulation. Since the amount of modulation is roughly proportional to $(\text{rigidity})^{-1}$, a greater modulation will affect low-rigidity particles more, thus tending to flatten the apparent spectrum at Earth. With this background the following can be observed from Figures 1 and 2. Above ~40 GV where modulation effects are relatively less important, the spectrum is clearly steeper than $R^{-2.5}$ and probably approaches its high-rigidity value of $R^{-2.75\pm0.05}$ (e.g., Ryan, Ormes, and Balasubrahmanyan 1972; see also Burnett *et al.* 1983). Between 10 and 40 GV the spectrum is flatter, and although strongly influenced by modulation effects at the low end, it is best described by an average exponent of ~2.5. Below 10 GV the spectrum is flatter still as a rsult of the dominant influence of solar modulation. Overall, when one recognizes the rigidity dependence of the spectral index, it can be seen that there is excellent agreement between almost all of the measurements shown in Figures 1 and 2.

The Jordan and Meyer experiment is most sensitive to the helium spectrum in the rigidity range ~10–20 GV. Their measurement was made in 1981 April, near the time of the most extreme modulation in the current solar cycle, with $\varphi \approx 1.2$ GV or greater (at minimum modulation φ is believed to be ~0.4 GV). The 10–20 GV data in Figures 1 and 2 were obtained when φ is estimated to have ranged from ~0.4 to 1.0 GV. Based on standard numerical solutions of the Fokker-Planck equation describing the effects of solar modulation (e.g., Fisk 1971), we estimate that with $\varphi = 1.2$ GV, the spectral index of ~12 GV helium observed at 1 AU will be flatter by $\Delta\gamma \approx 0.25$ than the corresponding index measured when $\varphi = 0.4$ GV. Considering the time of the Jordan and Meyer measurement, we believe that the appropriate helium spectral index to use to interpret their ^{3}He data is certainly not greater than 2.55 and is most likely considerably lower. Figure 6 in the paper by Jordan (1985) shows how the ratio Γ_r, defined to be the ^{3}He/^{4}He ratio measured at the same rigidity, depends on the assumed spectral index for helium. A spectral index $\gamma \leq 2.55$ leads to an inferred value of $\Gamma_r \leq 0.10$ instead of the value of 0.15 ± 0.03 obtained for their assumed specral index of $\gamma = 2.65 \pm 0.05$. Because of the uncertainty in the relatively large correction for solar modulation that would be required, we do not feel confident in deriving a particular value for Γ_r. To estimate the escape length, it is necessary to consider the ^{3}He/^{4}He ratio at the same energy/nucleon. This Γ_r to Γ_E conversion, using the formula given by Jordan (1985), leads to a value of $\Gamma_E \leq 0.15$ if ^{3}He and ^{4}He are assumed to have the same spectral index, and a value of $\Gamma_E \leq 0.17$ if we allow for the expected difference of $\Delta\gamma \approx 0.2$ between the high-energy ^{3}He and ^{4}He spectra that is predicted by standard energy-dependent propagation models (see § IV below). For comparison, the value quoted by Jordan and Meyer (assuming equal spectral indices for ^{3}He and ^{4}He) was $\Gamma_E = 0.24 \pm 0.05$. We believe that it is this upper limit of $\Gamma_E \leq 0.17$ that should be used to interpret the escape pathlength traversed by high-energy ^{4}He producing ^{3}He.

IV. INTERPRETATION OF ^{3}He/^{4}He DATA IN TERMS OF A COSMIC-RAY ESCAPE LENGTH

To interpret available ^{3}He/^{4}He data at both high and low energies we make use of recent calculations presented in Mewaldt (1986) that are based on the propagation calculations by J. P. Meyer (1974). J. P. Meyer's calculated interstellar spectra were used to obtain ^{3}He and ^{4}He spectra appropriate to an rigidity-dependent pathlength of the form required by studies of heavier nuclei. The effects of solar modulation on these spectra were then calculated using numerical solutions of the Fokker-Planck equation including the effects of diffusion, convection, and adiabatic deceleration (Fisk 1971). For the escape length (in g cm^{-2}) we have taken $\lambda_e = 28.5\beta R^{-0.6}$ for $R > 5.5$ GV and $\lambda_e = 10.2\beta$ for $R \leq 5.5$ GV, where R is rigidity in GV, β is the particle velocity in units of the speed of light, and where we assume an interstellar medium that is 10% helium by number. This rigidity-dependent escape length is equivalent to that derived by Soutoul *et al.* (1985; who assumed a pure H medium) to fit the observed secondary fragmentation of heavier nuclei including C and Fe. This escape length reaches a maximum of ~9 g cm^{-2} at ~2 GeV per nucleon, falling off at both lower and higher energies as required by the observations.

Figure 3 shows the calculated ^{3}He/^{4}He ratio for an assumed spectrum with $dJ/dE \propto (E + E_0)^{-2.6}$, where E is kinetic energy per nucleon and $E_0 = 500$ MeV per nucleon, a form typical of recent estimates of the interstellar spectrum (e.g., Webber and Yushak 1983). The observations shown at lower energies are all from the recent sunspot minimum period and have been corrected for the presence of "anomalous" ^{4}He in the case of the spacecraft data (<100 MeV per nucleon) and for atmospheric secondary ^{3}He in the case of the balloon data, as discussed in Mewaldt (1986). The level of solar modulation assumed for the calculated spectrum corresponds to solar minimum conditions with $\varphi \approx 0.4$ GV—however, it has been shown by Webber and Yushak (1983) that the ^{3}He/^{4}He ratio itself changes only slightly as φ is varied from 0 to 1 GV (see also Beatty 1986).

It is seen that the measured ^{3}He/^{4}He ratios at all energies, including the revised measurement at high energy, are consistent with the escape length variation with energy deduced from measurements of heavier cosmic-ray nuclei.

Recent observations of a relatively high intensity of anti-

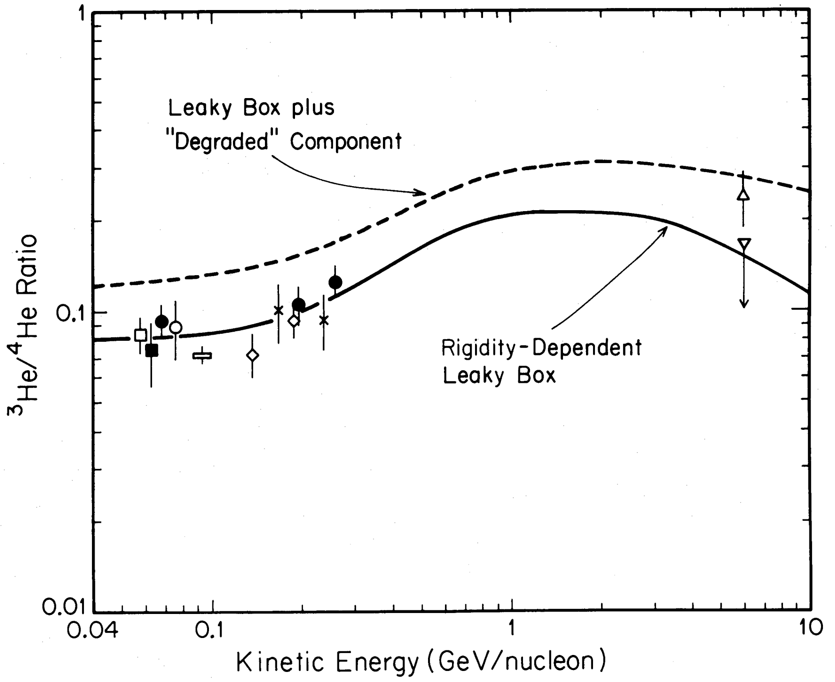

FIG. 3.—Measured and calculated ^{3}He/^{4}He ratios. The solid curve is for the rigidity-dependent escape length described in the text with an input helium spectrum characterized by $E_0 = 500$ MeV per nucleon. The dashed curve is for the model of Cowsik and Gaisser (1981; see also Mewaldt 1986) and assumes that 30% of cosmic rays come from "thick" sources surrounded by 50 g cm^{-2} of material. Data points are as follows: *upward triangle*, Jordan and Meyer (1984), Jordan (1985); *downward triange*, Jordan and Meyer measurement as revised in this paper; *solid circle*, Webber and Yusak (1983); *cross*, Leech and O'Gallagher (1978); *diamond*, Webber and Schofield (1975); *open square*, Teegarden *et al.* (1975); *sold square*, Mewaldt (1986); *rectangle*, Evenson *et al.* (1985); *open circle*, Garcia Munoz, Mason, and Simpson (1975).

protons (e.g., Golden *et al.* 1979; Bogomolov *et al.* 1979; Buffington, Schindler, and Pennypacker 1981) have led to several new cosmic-ray origin and/or propagation models in which some nuclei have traversed a great deal of material. Most such models produce an excess of ^{2}H and ^{3}He in addition to antiprotons (see, e.g., Stephens, 1981; Legage and Cesarsky 1985; Morfill, Meyer, and Lust 1985). As an example, Figure 3 includes the predicted ^{3}He/^{4}He ratio for the model of Cowsik and Gaisser (1981), in which a "degraded" component of cosmic rays originates in "thick" sources surrounded by ~ 50 g cm^{-2} of material. While this model is consistent with Jordan and Meyer's original interpretation of their observation, it is clearly inconsistent with the revised interpretation presented here as well as with all of the lower energy ^{3}He/^{4}He measurements in Figure 3 (see also Mewaldt 1986). The body of ^{3}He/^{4}He measurements now available therefore severely restricts the types of models that can be invoked to explain the overabundance of antiprotons that is observed.

This work was supported by the National Aeronautics and Space Administration under grant NGR 30-002-052 at the University of New Hampshire, NAGW-110 at New Mexico State University, and grants NGR 05-002-160, NAG-722, and NAG5-727 at Caltech.

REFERENCES

Anand, K. C., Daniel, R. R., Stephens, S. A., Bhowmik, B., Krishna, C. S., Aditya, P. K., and Puri, R. K. 1968, *Canadian J. Phys.*, **46**, S652.

Badhwar, G. D., Golden, R. L., Lacy, J. L., Stephans, S. A., and Daniel, R. R. 1979. *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 345.

Badhwar, G. D., Kaplon, M. F., and Valentine, D. A. 1971, *J. Geophys. Res.*, **76**, 4224.

Beatty, J. J. 1986, *Ap. J.*, **311**, 425.

Bogomolov, E. A. Lubyanaya, N. D., Romanov, V. A., Stepanov, S. V., and Shulakova, M. S. 1979, *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 330.

Brown, J. W., Stone, E. C., and Vogt, R. E. 1973, *Proc. 13th Internat. Cosmic Ray Conf.* (Denver), **1**, 556.

Buffington, A., Schindler, S. M., and Pennypacker, C. R. 1981, *Ap. J.*, **248**, 1179.

Burnett, T. H. *et al.*, 1983, *Phys. Rev. Letters*, **51**, 1010.

Cowsik, R., and Gaisser, T. K. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **2**, 218.

Evenson, P., Kroger, R., Meyer, P., and Muller, D. 1985, *Proc. 19th Internat. Cosmic Ray Conf.* (La Jolla) (NASA CP-2376), **2**, 60.

Fisk, L. A. 1971. *J. Geophys. Res.*, **76**, 221.

Garcia-Munoz, M., Mason, G. M., and Simpson, J. A. 1975, *Ap. J.*, **202**, 265.

Golden, R. L. 1986, private communication.

Golden, R. L., Horan, S., Kimball, B., Badhwar, G. D., Lacy, J. L., Zipse, J. E., Daniel, R. R., and Stephens, S. A. 1985, *Proc. 19th Internat. Cosmic Ray Conf.* (La Jolla) (NASA CP-2376), **2**, 1.

Golden, R. L., Horan, S., Mauger, B. G., Badhwar, G. D., Lacy, J. L., Stephens, S. A., Daniel, R. R., and Zipse, J. E. 1979, *Phys. Rev. Letters*, **43**, 1196.

Jordan, S. P. 1985, *Ap. J.*, **291**, 207.

Jordan, S. P., and Meyer, P. 1984, *Phys. Rev. Letters*, **53**, 505.

Leech, H. W., and O'Gallagher, J. J. 1978, *Ap. J.*, **221**, 1110.

Legage, P. O., and Cesarsky, C. J. 1985, *Astr. Ap.*, **147**, 127.

Mewaldt, R. A. 1986, *Ap. J.*, **311**, 979.

Meyer, J. P. 1974, Ph.D. Thesis, Université d'Paris.

Morfill, G. E., Meyer, P., and Lust, R. 1985, *Ap. J.*, **296**, 670.

Ryan, M. J., Ormes, J. F., and Balasubrahmanyan, V. K. 1972, *Phys. Rev. Letters*, **28**, 985.

Smith, L. H., Buffington, A., Smoot, G. F., Alvarez, I. W., and Wahlig, W. A. 1973, *Ap. J.*, **180**, 987.

Soutoul, A., Englemann, J. J., Ferrando, P., Koch-Miramond, L., Masse, P., and Webber, W. R. 1985, *Proc. 19th Internat. Cosmic Ray Conf.* (La Jolla) (NASA CP-2376), **2**, 8.

Stephens, S. A. 1981, *Nature*, **289**, 267.

Teegarden, B. J., von Rosenvinge, T. T., McDonald, F. B., Trainor, J. H., and Webber, W. R. 1975, *Ap. J.*, **202**, 815.

Verma, R. P., Rengarajan, T. N., Tandon, S. N., Damle, S. V., and Pal, Y. 1972, *Nature Phys. Sci.*, **240**, 135.

von Rosenvinge, T. T., Webber, W. R., and Ormes, J. F. 1969, *Ap. Space Sci.*, **5**, 342.

Webber, W. R., and Lezniak, L. 1974, *Ap. Space Sci.*, **30**, 361.

Webber, W. R., and Schofield, N. J. 1975, *Proc. 14th Internat. Cosmic Ray Conf.* (Munich), **1**, 312.

Webber, W. R., and Yushak, S. M. 1983, *Ap. J.*, **275**, 391.

R. L. Golden: Electrical and Computer Engineering Department, New Mexico State University, Las Cruces, NM 88003

R. A. Mewaldt: 220–47 Downs Laboratory of Physics, California Institute of Technology, Pasadena, CA 91125

W. R. Webber: Space Science Center, University of New Hampshire, Durham, NH 03824