A NEW COMPONENT OF COSMIC RAYS OF UNKNOWN

ORIGIN AT A FEW MEV PER NUCLEON

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Technical Report # 74-097

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UNIVERSITY OF MARYLAND
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COLLEGE PARK, MARYLAND

Space Physics Group

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Abstract

Recently discovered anomalies in the abundances and energy spectra of quiet time, extraterrestrial hydrogen, helium, carbon, nitrogen and oxygen require serious revisions of origin theories to account for this new component of cosmic radiation. Abnormally large O/C and N/C ratios, long term intensity variations with time and radial gradient measurements indicate a non-solar origin for these 2 to 30 MeV/nucleon particles. Ideas suggested to explain these measurements range from acceleration of galactic source material having an unusual composition to local acceleration of particles within the solar cavity. Observations are at present insufficient to choose between these alternate origin models.

The galactic origin of cosmic rays is well established for particles with energies exceeding roughly 30 MeV/nucleon. Evidence pointing to this origin has been accumulating over many years, but particular progress was made only during the past decade when experiments carried on satellites and space probes allowed detailed studies below roughly 100 MeV/nucleon. Among the principal findings which argue strongly for the galactic origin are first, a composition rich in elements and isotopes which cannot be readily produced in ordinary stellar processes and, second, a long term variation of intensity with time, the so-called solar modulation, which is anti-correlated with the eleven year solar activity. Related to the eleven year modulation is the observed gradual increase of the cosmic ray intensity with heliocentric radial distance, referred to as the radial gradient. The shapes of the cosmic ray energy spectra observed near earth are determined not only by acceleration and propagation effects in the galaxy but also by actions of magnetic fields in the heliosphere or solar cavity which tend to exclude galactic particles from the inner solar system.

The modulated differential energy spectra of the most abundant elements of galactic cosmic rays are shown in Figure 1. At energies above roughly 30 MeV/nucleon the spectral shapes are similar for all species. The turnover of the spectra between 30 and 300 MeV/nucleon is due to the strong solar modulation which plays a dominant role in determining the spectral shape in this energy region. Modulation theory, describing access of galactic particles to the vicinity of earth, is well understood and is able to reproduce the measured energy spectra above 30 MeV/nucleon remarkably well.

The question of what happens at low energies, that is roughly below about 30 MeV/nucleon, is far from settled. Observations in this energy range are complicated by the frequent presence of energetic particles emitted by the sun. Thus, to see the steady flux of presumably galactic particles one must be careful to exclude time periods of even moderate solar activity when particles of solar origin are present.

Despite these difficulties, measurements of low energy protons and alpha particles have been made during the past decade. Results reported over the years by the University of Chicago group (Fan, et al. 1966, 1968a, 1970) showed a low energy turn up in the spectra of both protons and alpha particles even during the most quiet time periods. Although studies of the long term time variations favored a galactic origin for this component one could not exclude the possibility that the sun was responsible for producing these particles.

Assuming reasonable spectral shapes outside the solar system a straightforward extension of the modulation theory to energies below 30 MeV/nucleon predicts a continued drop in intensity with decreasing energies as shown by the dashed line. If protons and alphas in the turn-up portion of the spectrum are galactic, then major revisions in modulation theories are required. If, on the other hand, these particles are of solar origin, we must learn to understand how the sun can produce a steady stream of energetic particles.

Recently, new features began appearing in the spectra and composition of the low energy, less than 30 MeV/nucleon particles observed during solar quiet times, which are demanding even more serious revisions of our ideas on the origin of these particles. The first evidence came from measurements of the Chicago group (Garcia-Munoz, et al. 1973) which showed a flat helium spectrum between $\sim$10 and 80 MeV/nucleon and no similar anomalies in the proton spectrum. The University of Maryland/Max Planck Institut results on the quiet time oxygen and carbon spectra between 400 keV and 8.5 MeV/nucleon (Hovestadt, et al., 1973) provided the first clear evidence for an unexpected hump in the oxygen spectrum and for an unusually low C/O ratio between 2 and 8 MeV/nucleon. Data from the Goddard/University of New Hampshire experiment on Pioneer 10 above 8 MeV/nucleon (McDonald, et al., 1974a) showed that no only was oxygen considerably overabundant compared to helium but that nitrogen was so also. Taken together these results argued strongly for a non-solar origin of these $\sim$few MeV/nucleon particles. Their source must be rather peculiar in order to produce the anomalous composition.

Before I go into a more detailed discussion of the measurements of this presumably new component of unknown origin let me briefly describe two experimental methods used today to study low energy particles in interplanetary space. The first relies on counters and associated electronic circuitry to process the detector outputs and send data for ground based analysis. The second makes use of stacks of relatively large area plastic sheets which are exposed to the radiation in space and then returned to earth for analysis. Although these plastic, track-registering detectors first developed at GE by Walker, Fleisher and Price have come into use relatively recently, they have already provided an abundance of data on extraterrestrial particles ranging in energy from tens of keV to hundreds of MeV. The technique makes use of the fact that heavily ionizing particles will radiation damage material along the particle track. These tracks become visible after chemical etching. From the size and shape of the cones etched into the material, information on the charge and energy of the particle is obtained. What makes this method especially attractive is its sensitivity to very low particle fluxes by virtue of the large areas one can use for these passive detectors. On the other hand, track detectors must be recovered and to date only data integrated over the entire exposure time (typically days to months) have been obtained.

The counter technique I will describe is the so-called dE/dx vs. E method which was introduced about 10 years ago by the Chicago and Goddard groups to study cosmic rays between 10 and 100 MeV/nucleon. We have extended this technique to energies of a few hundred keV/nucleon by using a thin window proportional counter as the ΔE element. The simplified cross-section of the instrument developed by the Max Planck Institut and flown as part of the Maryland experiment on IMPs 7 and 8 is shown in Figure 2A. The telescope consists of three elements. A 300 $\mu g/cm^2$ proportional counter, a 800μ thick surface barrier solid state detector, and a plastic scintillator anticoincidence detector. Particles which trigger the ΔE and E detectors but not the anticoincidence detector are pulse height analyzed. Figure 2B shows the two dimensional distribution of pulse heights in the ΔE vs. the E detector for a portion of the flight data during a moderately active period. Note the formation of "tracks" corresponding, in this example, to protons and helium nuclei. The tracks are well separated and only negligible background is present. Such analysis allows a unique identification of the particle charge and a measurement of its energy. Unlike the passive plastic detectors, these types of instruments have an excellent time resolution and, of course, need not be recovered.

Let me now describe in some detail what we know about the new and unexpected component of low energy cosmic rays. Figure 3 shows the results of Garcia-Munoz, Mason and Simpson (1973) on the helium anomaly which first appeared in 1972. The helium spectrum is flat from 10 to about 80 MeV/nucleon and at 20 to 30 MeV/nucleon the proton intensity falls below the helium intensity. Adjusting parameters in the modulation theory they could explain either the proton or the alpha spectrum but not both simultaneously. Assuming interstellar spectra to be unusual they could explain their observations.

The oxygen and carbon differential energy spectra of Hovestadt, Vollmer, Gloeckler and Fan (1973) are given in Figure 4. These spectra may be divided into two components. Below roughly one MeV/nucleon the spectra for carbon and oxygen are very steep and carbon is nearly as abundant as oxygen. This component is interpreted to be either of solar or more local origin. Above roughly one MeV/nucleon the oxygen spectrum flattens while carbon seems to continue dropping off. The dashed and dotted lines represent simple connections between our low energy data in Oct. 1972 and the 1965 IMP 3 oxygen and carbon spectra measured by Fan, Gloeckler and Simpson (1968b). Our low energy data provided the first evidence for the anomalous behavior of oxygen and carbon at a few MeV/nucleon.

Figure 5 shows the spectra of protons, helium, oxygen and carbon from $\sim$300 keV to 100 MeV/nucleon using the low energy data of Gloeckler et al. (1974) and Hovestadt et al. (1973), and results of Garcia-Munoz et al. (1973), Simpson and Tuzzolino (1973) and McDonald et al. (1974a) at high energies. Taken together, these combined results reveal the magnitude of the anomaly. Carbon and oxygen, almost neighboring elements with identical charge to mass ratios, have in the limited energy range from 2 to 30 MeV/nucleon drastically different abundances. The helium spectrum is itself peculiar. It has a flat portion from 6 to 60 MeV/nucleon, below 6 the flux increases, reaching another flat portion around 1 MeV/nucleon. Below about 500 keV/nucleon the spectrum has a sharp turnup. The proton spectrum does show a low energy turn up but no obvious anomalous features. However, the low energy local or solar component (below $\sim$700 keV) could be obscuring features in the spectrum similar to the $\sim$1 MeV helium hump.

To exhibit explicitly the anomalous behavior of both oxygen <u>and</u> nitrogen Figure 6, taken from the recent paper by McDonald et al., (1974a) shows the Pioneer 10 oxygen, carbon and nitrogen to helium ratios as a function of energy. The dramatic overabundance of oxygen and nitrogen are obvious. Carbon seems to be underabundant relative to helium.

Other experiments have since confirmed the existence of the anomalous features. Chan and Price (1974) have analyzed track-registering plastic detectors exposed for about 45 hours on the lunar surface in Dec. 1972. They have confirmed both the shape and absolute intensity of the oxygen spectrum over the entire range of the anomaly. These data along with the Maryland/Max Planck data below 8.5 MeV/nucleon and the Goddard-New Hampshire data above that energy are plotted in Figure 7. There is good agreement between all three independent measurements despite the fact that data were taken in different parts of the heliosphere and averaged over different time periods. Below about one MeV/nucleon the data of Chan and Price (1974) show presence of solar oxygen.

Perhaps the first question one may ask concerns the origin of this new component. For example, can the sun produce particles with the anomalous features I described? Not very likely. In the first place, the relative abundance of oxygen and carbon are enormously different compared to photospheric or coronal abundances. Then, the spectral shapes are unlike the characteristically steep spectra of solar energetic particles. Additional evidence for the extrasolar origin was presented at the American Physical Society meeting of April 22, 1974. Mewaldt, et al. (1974) and Von Rosenvinge et al. (1974) studied intensity variations with time of oxygen and helium. The Caltech results (Mewaldt, 1974) for the variations of 8-30 MeV/nucleon oxygen and the 13-25 MeV/nucleon helium in the Oct. 1972 to Nov. 1973 time period show a clear cut correlation with variations in the average monthly rate of a neutron monitor sensitive to cosmic rays of relativistic energies. This indicates that low energy oxygen and helium are modulated just as high energy galactic protons and hence of extrasolar origin.

The Goddard work (Von Rosenvinge et al., 1974) reveals that at equal velocities (8 to 30 MeV/nucleon) oxygen and helium are subjected to the same relative amount of solar modulation.

McDonald et al.(1974b) reported on the radial gradient of oxygen in the 10 to 25 MeV/nucleon energy interval using their Pioneer 10 and IMP 7 data. They concluded that the gradient was positive but small, consistent with the interpretation that these low energy particles are of non-solar origin.

Finally let me discuss measurements of the composition of other elements and of nitrogen and oxygen isotopes. The major difficulty here is due to poor statistics; in many cases no particles of a given type were observed and only upper limits are quoted. Still, it is significant to note that the Apollo 17 results of Chan and Price (1974) show that Mg + Si and iron nuclei are not enhanced in the energy range of the oxygen hump. Similar results emerge from the work of McDonald et al. (1974a) who find that boron, neon, magnesium and silicon are, if anything, underabundant compared to helium. On the other hand, Mogro-Campero and Simpson (1974) conclude from their OGO 5 data taken from 1968 to 1971 that the boron to oxygen and carbon to oxygen ratios at 11-24 MeV/nucleon are normal. They find that spectra of boron, carbon and oxygen show a low energy turn-up.

The only isotopic measurements of the anomalous component were reported by Hurford et al. (1974). They quote $N^{15}/N \lesssim 0.27$, $O^{17}/O \lesssim 0.24$ and $O^{18}/O \lesssim 0.09$ at an 84% confidence level. The most abundant isotopes are therefore ^{14}N and ^{16}O.

Summarizing the experimental results reported so far we have,

(1) Anomalies in spectral shapes and abundances of oxygen and nitrogen between 2 and 30 MeV/nucleon have been observed. At least five independent experiments have confirmed these features.

(2) These anomalous features as well as intensity variations with time and radial gradient measurements rule out a solar origin for this new component.

(3) Aside from He, which also shows peculiar features, elements such as boron, neon, silicon, magnesium and iron have abundances similar to cosmic rays of higher energies. Thus, either the source of this new component is rich in elements such as oxygen, nitrogen and possibly helium, or these elements are preferentially accelerated to energies of several tens of MeV/nucleon.

(4) The major isotopes of oxygen and nitrogen are ^{16}O and ^{14}N.

In attempting to explain what could produce these abnormal cosmic rays of 2 to 30 MeV/nucleon one must, more than anything else, be able to account for the overabundance of oxygen and nitrogen. If these particles are truly galactic one must look for sources with an abnormal composition, since solar modulation alone cannot produce such strong differentiation between species as similar as carbon, nitrogen and oxygen.

Hoyle and Clayton (1974) have proposed novae as a possible source for these particles. They start with the usual nova phenomena in which material of approximately solar composition is transferred from a giant to a white dwarf companion in a binary system, and assume a carbon and oxygen rich white dwarf surface with sufficient surface mixing to produce hydrogen to carbon ratios of order unity. Under these conditions, nuclear burning of carbon and the in-falling hydrogen will produce large amounts of nitrogen relative to carbon. Thus, a composition of carbon, nitrogen and oxygen similar to that observed in the new component may be attained, although an unambiguous prediction is, as these authors are quick to point out, not feasible at the present time. To produce tens of MeV/nucleon particles from this source material it is plausible to consider acceleration either by the shock wave generated in the nova explosion or in turbulent magnetic fields present in the post explosion phase.

One firm prediction of this and other nucleo-synthesis models is the large abundance of such isotopes as C^{13}, N^{15} and O^{17}. The upper limits on isotopes of nitrogen and oxygen reported by the Caltech group (Hurford et al. 1974) already provide considerable constraints on such theories. The limits are not low enough, however, to rule out these processes entirely.

A somewhat more serious objection to the Hoyle-Clayton model comes from considerations of the power requirements necessary to maintain the observed oxygen intensity. First one must estimate the interstellar oxygen spectrum. Ordinary modulation theory is inadequate for this purpose because it leads to interstellar spectra inconsistent with limits placed on ionization of interstellar clouds. Fisk (1974) has shown, on the other hand, that a rather drastic revision of fundamental assumptions upon which current modulation theories are based can lead to reasonable interstellar spectra consistent with a variety of observations.

Figure 8 presents the result of Fisk's calculations. The interstellar and local spectra of oxygen, protons and electrons are shown.

Using the low energy interstellar oxygen spectrum we find an energy density of about 5 x 10^{-3} eV/cm^3. To maintain this density over volume of 10^3 pc^3, requires energies uncomfortably close to 10^{45} ergs released in nova explosions. In this estimate we have taken into account ionization losses of these low energy oxygen nuclei by using a destruction life time of 10^5 years.

A different but perhaps less glamorous approach has been taken by Fisk, Kozlovsky and Ramaty (1974) to explain the anomalies of the new component. They note the correlation between the observed abundance of an element and its first ionization potential. For example, the overabundant elements nitrogen and oxygen also have the highest ionization potentials. They go on and argue that interstellar neutral particles are swept into the solar cavity by the motion of the sun through the interstellar medium. Once inside the cavity these neutral atoms are ionized by solar UV radiation, for example. Carbon, silicon, magnesium and iron atoms are unable to penetrate far because of their low ionization potentials. Hydrogen, helium, nitrogen, oxygen and neon, on the other hand are able to travel to within several astronomical units from the sun before being ionized. This mechanism then provides a source of singly ionized particles having a composition of predominantly nitrogen and oxygen and an energy roughly of order one keV/nucleon in the frame of the solar wind. While these 1 keV/nucleon ions are convected outward by the solar wind, a small fraction is accelerated to energies of tens of MeV/nucleon. The power required for this acceleration is a small fraction of the total solar wind power. The energetic, singly charged ions are, just as galactic cosmic rays, subject to effects of solar modulation. However, unlike the fully stripped low energy galactic cosmic rays, the $\sim$10 MeV/nucleon ions suffer relatively little modulation because of their large rigidities.

Several predictions are made by the local origin theory, the strongest being that oxygen and nitrogen must be singly charged ions. Indirect evidence that this may be the case comes from studies of intensity variations with time (Mewaldt et al. 1974; Von Rosenvinge et al. 1974). More direct evidence comes from the work of Price (private communication). His plastic track detectors were exposed for about 70 days during the last skylab mission. During the exposure, solar activity was sufficiently low so as not to obscure the >10 MeV/nucleon oxygen of non-solar origin he measured. Because of the skylab orbit only particles having relatively high rigidities could reach the detectors. Assuming full stripping one expected to detect only a small percentage of $\gtrsim$10 MeV/nucleon oxygen present outside the earth's magnetic field. It was found, however, that the 10-30 MeV/nucleon oxygen intensity measured was about as high as it is in interplanetary space. Contamination from trapped oxygen was ruled out because the measured spectrum was far less steep than spectra of magnetospheric particles. One plausible explanation of these results is that oxygen between 10 and 30 MeV/nucleon is singly ionized and thus of sufficiently high rigidity to reach the skylab detector.

Let me close by saying that despite the recent discovery of this new component of cosmic rays remarkable progress has been made in identifying its source of origin. Our conclusions today must still be tentative. However, I believe evidence at this time points to an interplanetary or local origin as proposed by Fisk, Kozlovsky and Ramaty (1974). Looking ahead we hope that instruments on spacecraft such as the IMP's, the Pioneers as well as on the upcoming Mariner-Jupiter-Saturn and the Heliocentric missions, will not only measure the isotopic and elemental composition of these low energy cosmic rays more precisely as a function of time and heliocentric radial distance, but also provide direct determination of their charge states.

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Mewaldt, R.A., Stone, E.C., and Vogt, R.E., 1974, Bull. A.P.S., 19, 433.

Mogro-Campero, A., and Simpson, J.A., 1974, Ap. J. (to be published).

Simpson, J.A., and Tuzzolino, A.J., 1973, Ap. J., 185, L149.

Von Rosenvinge, T.T., Teegarden, B.J., and McDonald, F.B., 1974, Bull. A.P.S., 19, 433.

Figure Captions

Figure 1. Differential energy spectra of cosmic rays during solar quiet times in 1965. The abundances at 300 MeV per nucleon relative to oxygen are indicated. Galactic origin for these particles is well established above 30 MeV/nucleon.

Figure 2(A). Simplified cross section of the three element ultra low energy telescope ULET flown on IMP's 7 and 8. The thin window proportional counter ΔE element allows extension of two parameter analysis down to $\sim$100 keV/nucleon.

(B). ΔE vs. E display showing "tracks" of protons and helium nuclei. These flight data were accumulated during a moderately active 20 hour time interval. * indicate $\geq$35 entries in the matrix.

Figure 3. Proton and helium differential spectra measured by the University of Chicago cosmic-ray telescope on the IMP-5 satellite over solar quiet times during May-July 1972. Dashed curves are the 1965 solar minimum proton and helium spectra compiled by Gloeckler and Jokipii (1967). This figure is Fig. 1 of Garcia-Munoz et al. (1973).

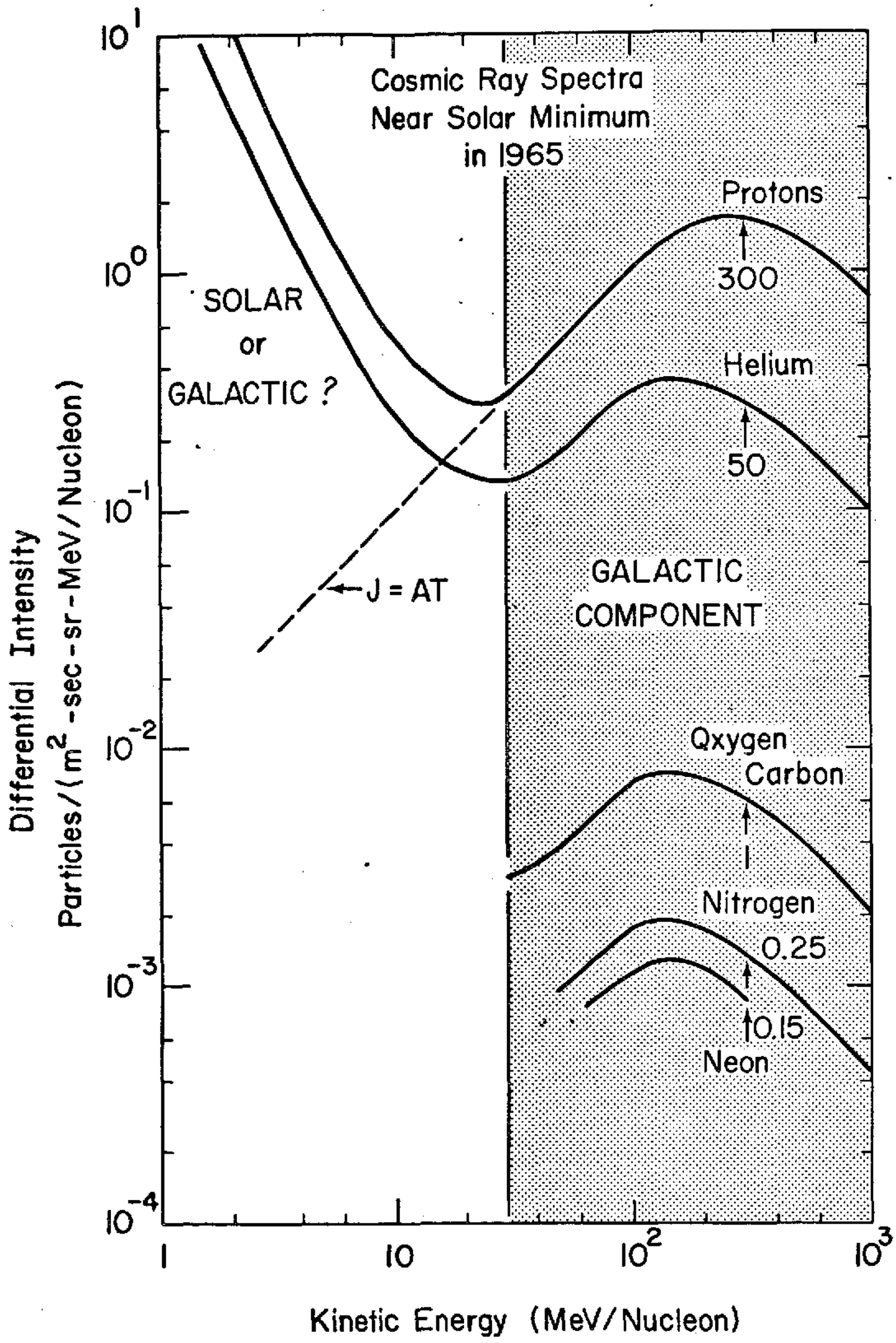
Figure 4. The anomalous oxygen and carbon spectra measured by Hovestadt et al., (1973) during solar quiet times in Oct. 1972. Dashed and dotted curves represent reasonable interpolation between these low energy spectra and the 1965 solar minimum spectra of Fan et al. (1968b).

Figure 5. Differential energy spectra of protons, helium, oxygen and carbon during solar quiet time periods in 1972-1973. Oxygen and helium show anomalous features or "humps" at 2-30 and $\sim$1 MeV/nucleon respectively.

Figure 6. O/He, C/He and N/He ratios as a function of energy per nucleon. These ratios were obtained from the Goddard/University of New Hampshire cosmic ray experiment on Pioneer 10 during solar quiet times from March 1972 to March 1973 and over heliocentric radial distances ranging from 1 to $\gtrsim$4 AU. The cross-hatched areas are representative ratios in galactic cosmic rays above $\sim$30 MeV/nucleon. This figure is Fig. 3 of McDonald et al. (1974).

Figure 7. The differential spectrum of oxygen during solar quiet times. The low energy ($\lesssim$8 MeV/nucleon) portion of the spectrum measured on IMP 7 by Hovestadt et al. (1973) connects well with the $\gtrsim$8 MeV/nucleon data reported by McDonald et al. (1974). Apollo 17 measurements over the entire energy range (Chan and Price, 1974) are in excellent agreement with the IMP 7 and Pioneer 10 results. The Sept.-Dec. 1973 data above $\sim$8 MeV/nucleon were taken by the Goddard Cosmic-ray experiment on IMP 7.

Figure 8. Interstellar and local cosmic ray energy spectra for oxygen, protons and electrons. To obtain the "de-modulated", interstellar oxygen spectrum as shown requires revisions of fundamental assumptions of current modulation theories. The energy density contained in the interstellar oxygen spectrum is about 5 x 10^{-3} eV/cm^3. This figure is taken from the work of Fisk (1974).



Cosmic Ray Spectra
Near Solar Minimum
in 1965
Protons
300
Helium
50
SOLAR
or
GALACTIC ?
J = AT
GALACTIC
COMPONENT
Qxygen
Carbon
Nitrogen
0.25
0.15
Neon
Differential Intensity
Particles/(m2-sec-sr-MeV/Nucleon)
Kinetic Energy (MeV/Nucleon)

Figure 1

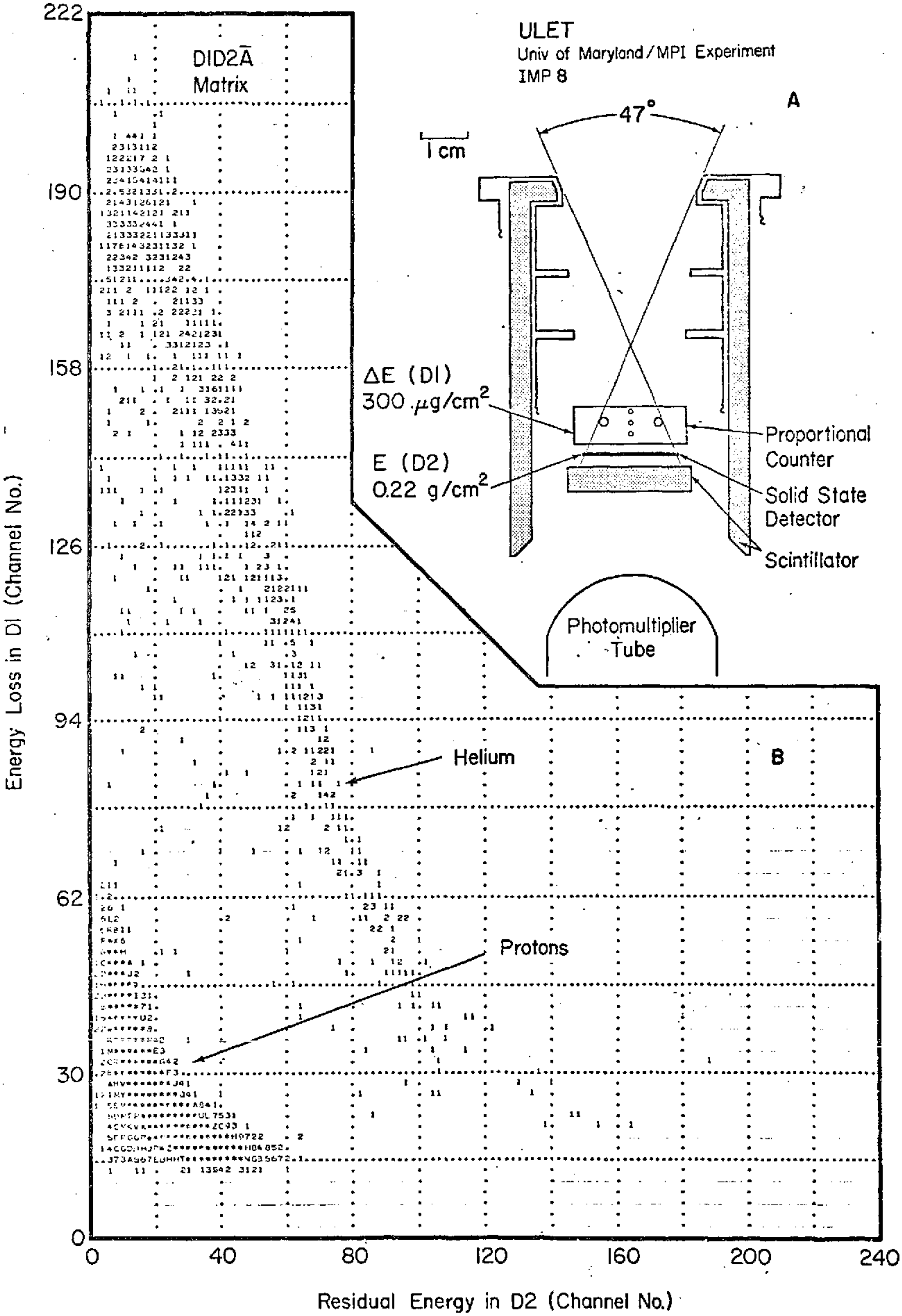

ULET
Univ of Maryland/MPI Experiment
IMP 8
A
47°
1 cm
ΔE (D1)
300 μg/cm²
E (D2)
0.22 g/cm²
Proportional Counter
Solid State Detector
Scintillator
Photomultiplier Tube
D1D2Ā Matrix
Helium
Protons
B
Energy Loss in D1 (Channel No.)
Residual Energy in D2 (Channel No.)
0
30
62
94
126
158
190
222
0
40
80
120
160
200
240

Figure 2

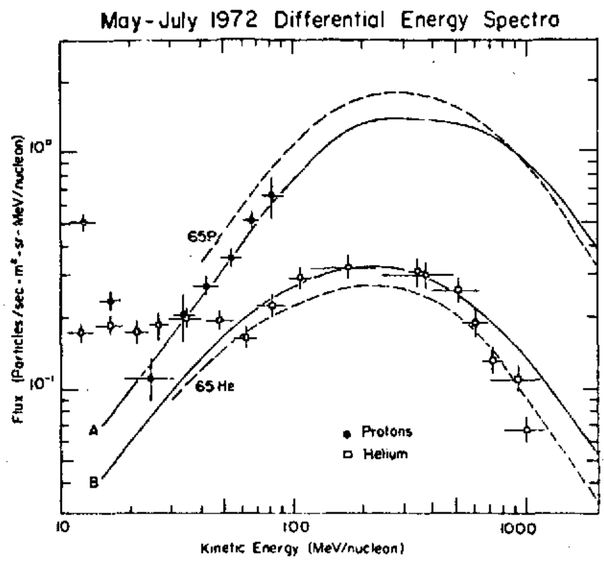
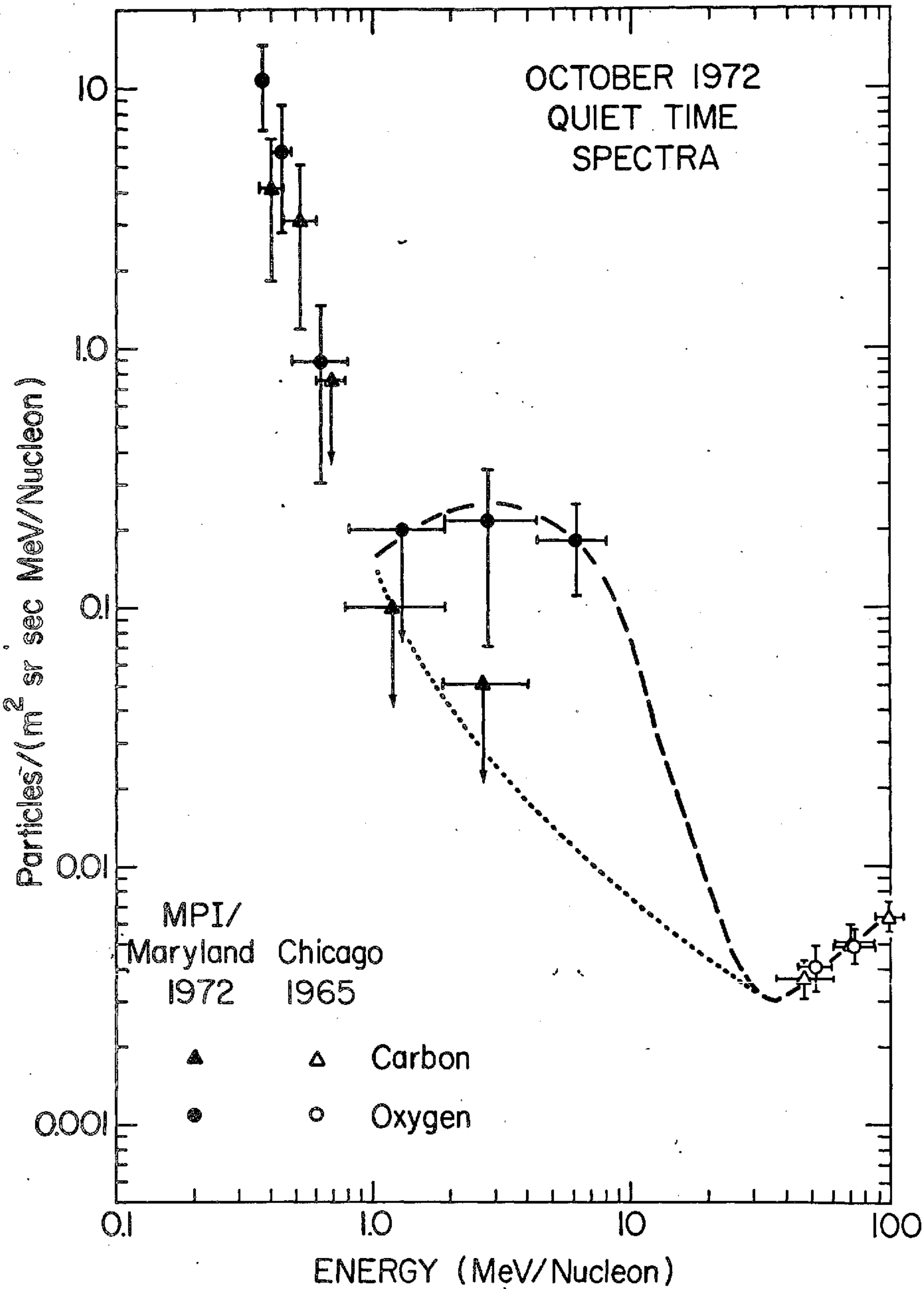
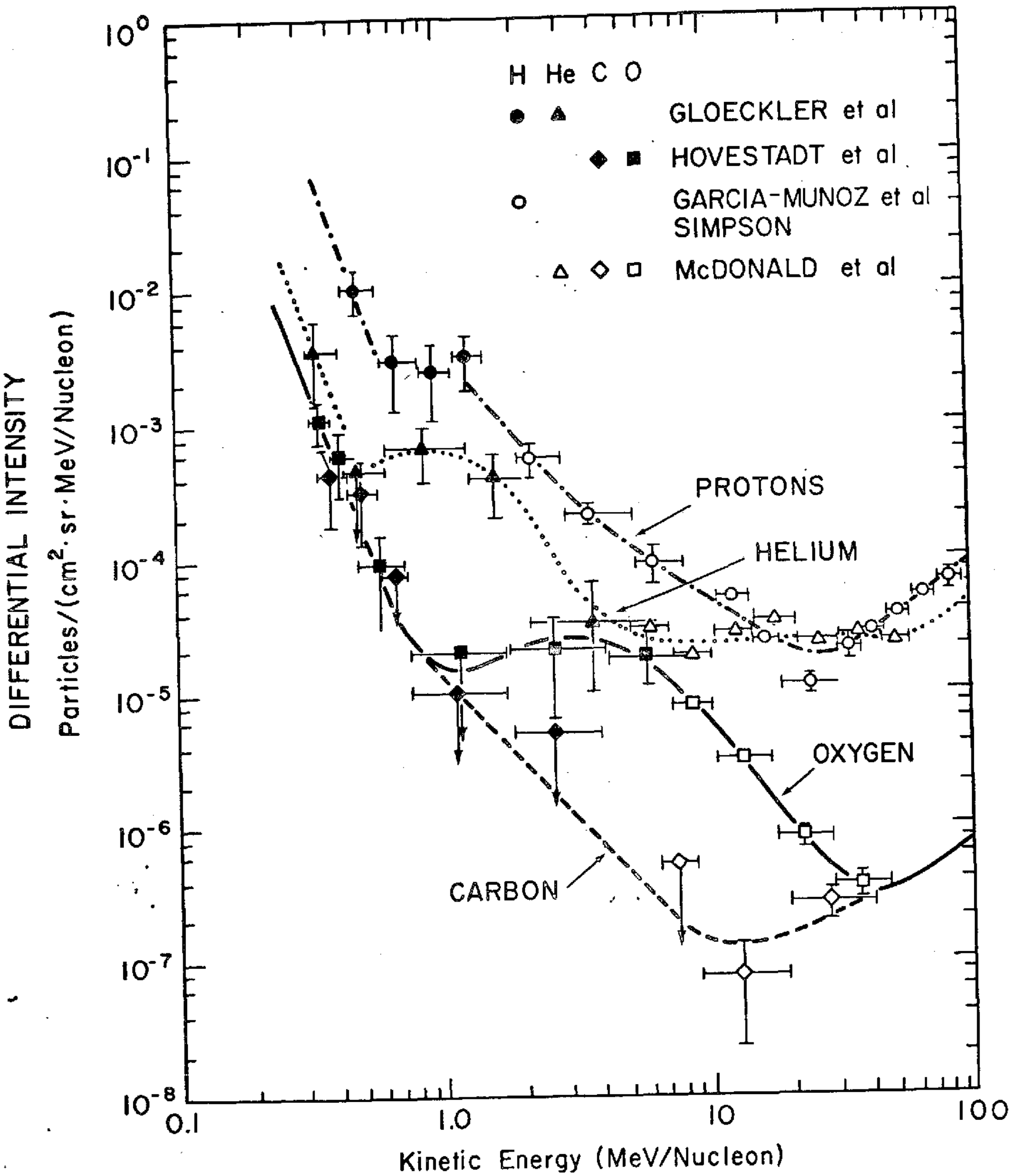

May-July 1972 Differential Energy Spectra
Flux (Particles/sec-m²-sr-MeV/nucleon)
10⁰
10⁻¹
65P
65 He
A
B
Protons
Helium
10
100
1000
Kinetic Energy (MeV/nucleon)

Figure 3


OCTOBER 1972
QUIET TIME
SPECTRA
Particles/(m² sr sec MeV/Nucleon)
10
1.0
0.1
0.01
0.001
MPI/
Maryland
1972
Chicago
1965
Carbon
Oxygen
0.1
1.0
10
100
ENERGY (MeV/Nucleon)



H He C O
GLOECKLER et al
HOVESTADT et al
GARCIA-MUNOZ et al
SIMPSON
McDONALD et al
PROTONS
HELIUM
OXYGEN
CARBON
DIFFERENTIAL INTENSITY
Particles/(cm^2·sr·MeV/Nucleon)
Kinetic Energy (MeV/Nucleon)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.1
1.0
10
100

Figure 5

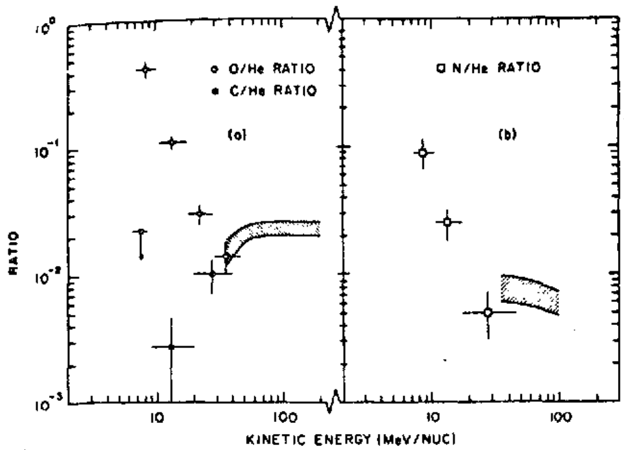

O/He RATIO
C/He RATIO
(a)
N/He RATIO
(b)
RATIO
KINETIC ENERGY (MeV/NUC)
10
100
10
100

Figure 6

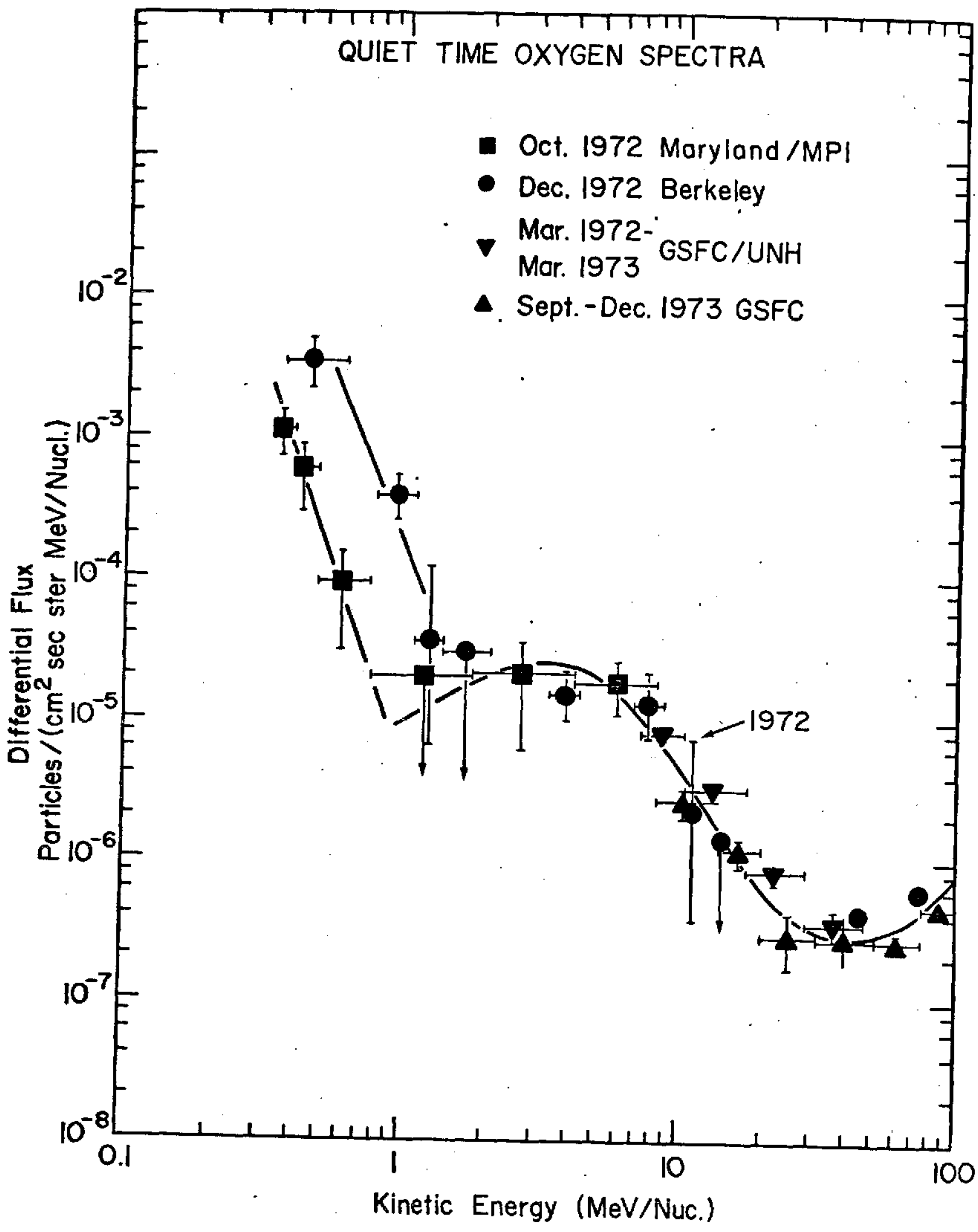
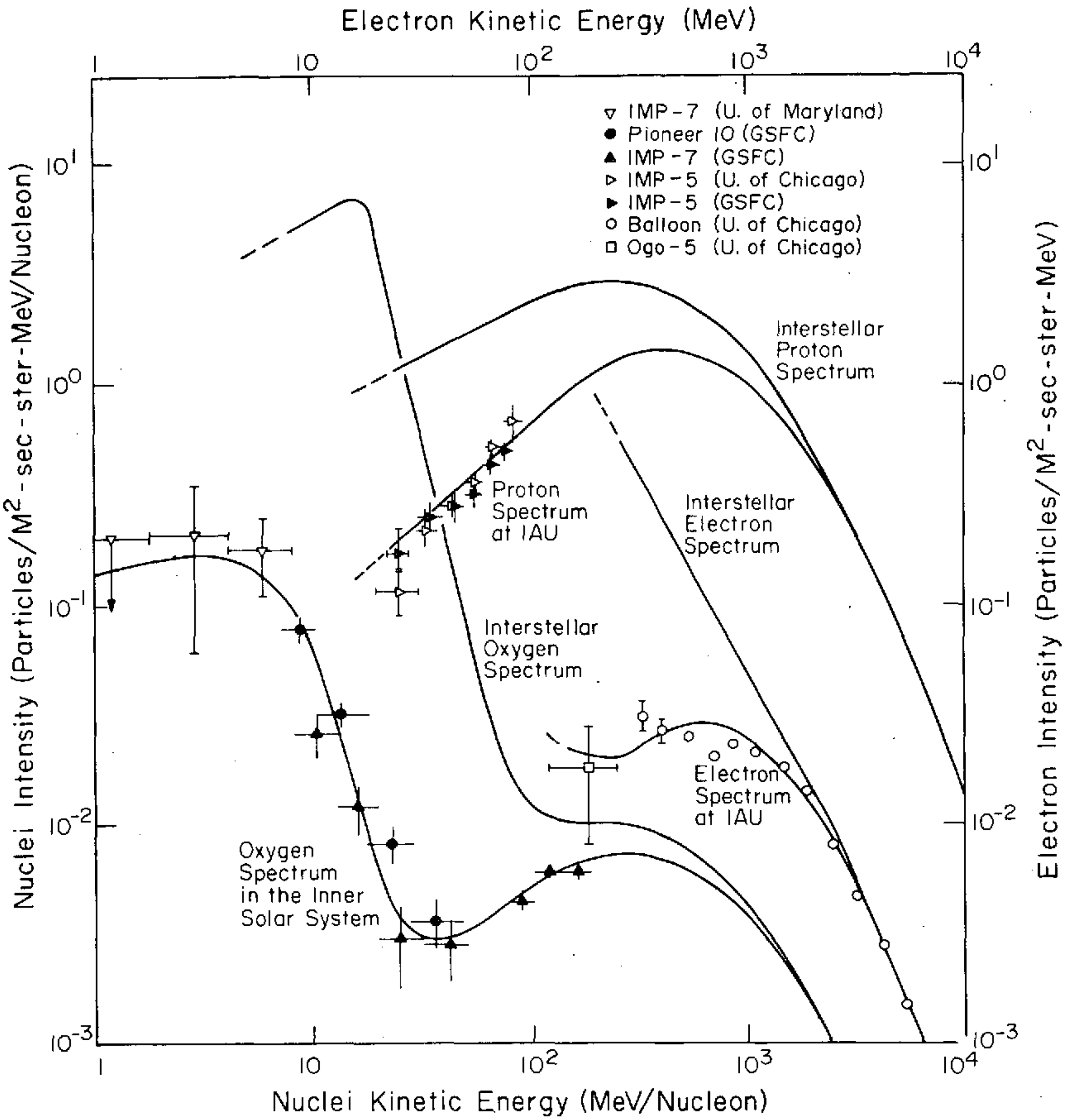

QUIET TIME OXYGEN SPECTRA
Oct. 1972 Maryland/MPI
Dec. 1972 Berkeley
Mar. 1972-
Mar. 1973
GSFC/UNH
Sept.-Dec. 1973 GSFC
1972
Differential Flux
Particles/(cm^2 sec ster MeV/Nucl.)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.1
1
10
100
Kinetic Energy (MeV/Nuc.)

Figure 7



Electron Kinetic Energy (MeV)
IMP-7 (U. of Maryland)
Pioneer 10 (GSFC)
IMP-7 (GSFC)
IMP-5 (U. of Chicago)
IMP-5 (GSFC)
Balloon (U. of Chicago)
Ogo-5 (U. of Chicago)
Interstellar Proton Spectrum
Proton Spectrum at 1AU
Interstellar Electron Spectrum
Interstellar Oxygen Spectrum
Electron Spectrum at 1AU
Oxygen Spectrum in the Inner Solar System
Nuclei Intensity (Particles/M^2-sec-ster-MeV/Nucleon)
Electron Intensity (Particles/M^2-sec-ster-MeV)
Nuclei Kinetic Energy (MeV/Nucleon)

Figure 8