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OBSERVATIONS OF GALACTIC COSMIC RAY ENERGY SPECTRA BETWEEN 1 and 9 A.U.

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ABSTRACT

The variation of the 5-500 MeV/nuc cosmic ray helium component has been studied between 1 and 9 A.U. using essentially identical detector systems on Pioneer 10 and 11 and Helios I. Between 100 and 200 MeV/nuc a radial gradient of 3.3$\pm$1.3%/A.U. is found. At 15 MeV/nuc this value increases to 20$\pm$4%/A.U. Between 4 and 9 A.U. a well defined intensity maximum is observed at ~17 MeV/nuc. The average adiabatic energy loss between 1 and 9 A.U. is ~4 MeV/nuc/A.U. The observed radial variation between 1 and 9 A.U. is well described by the Gleeson-Axford force field solution of the modulation equations over an energy range extending from 15-500 MeV/nuc and is in good agreement with the results reported by other Pioneer experiments. These values are much smaller than had been theoretically predicted. The data can be interpreted either in terms of large residual modulation with φ (1 AU) $\approx$ 320 mV and with a modulation region extending to 50-100 A.U. or with a significantly reduced modulation parameter of ~150 MV. In the latter case the low energy helium component can originate outside the heliosphere while in the former case an interplanetary origin appears most probable.

Subject headings: cosmic rays: general - interplanetary medium - interstellar: matter

I. Introduction

Galactic cosmic rays with energies less than several hundred MeV/nucleon contain significant information on particle acceleration, injection and interstellar propagation that is not available at higher energies. For example, ionization energy losses in the interstellar medium should produce systematic changes in the low energy spectra of various nuclear species. It is in this energy range that isotopes can be experimentally resolved thus making possible the determination of cosmic ray lifetimes from measurements of isotopes like ^{10}Be and $^{26}A\ell$. The isotopic composition should also provide infomation on nucleosynthesis processes in the source region. An appreciable fraction of the total cosmic ray energy could be contained in the low energy component. These particles could originate in a number of differing energetic particle sources in our galaxy. Within the heliosphere, the sun, the earth and Jovian magnetospheres and the interplanetary medium accelerate large fluxes of MeV particles. The larger and more dynamic stellar plasmas should provide a great variety of low and medium energy cosmic ray sources.

This energy region which contains such a wealth of cosmic ray information is also the region that is most severely affected by solar modulation. As the cosmic rays penetrate into the heliosphere they encounter magnetic irregularities moving outward in the solar wind. The resulting processes of particle diffusion, convection and adiabatic energy loss in the expanding solar wind result in significant modulation of cosmic rays with energies below 500 MeV/nuc. (e.g. Jokipii, 1971, Fisk, 1974).

The cosmic ray modulation displays a striking 11 year variation that is in approximate anti-phase with solar activity. The cosmic ray changes from solar minimum condition to those of solar maximum are reasonably understood and can be explained using conventional modulation theory. However it is difficult to calculate the residual modulation near solar minimum when the observed galactic cosmic ray intensity has its largest value. This difficulty arises since the radial variation of the diffusion coefficient and the physical size of the modulation region are not known. Furthermore, the modulation region may not be spherically symmetric about the sun as has been generally assumed. The amount of residual modulation has been inferred by comparing the measured electron spectrum at 1 A.U. with the interstellar spectrum deduced from observations of the non-thermal galactic radio emission. (Webber, 1968, Goldstein et al., 1970a, Burger, 1971, Cummings et al., 1973) This procedure is a difficult one and is subject to considerable uncertainty. However, when applied to the previous solar minimum cosmic ray electron data in 1965, substantial modulation was inferred at energies below ~500 MeV/nucleon. In fact the calculated interplanetary energy-losses were so large that primary nuclei with energies of several hundred MeV/nuc outside the heliosphere were unlikely to be observed at 1 A.U. (Goldstein et al., 1970(b), Urch and Gleeson, 1972).

The only feasible direct approach to studying low energy cosmic rays is to make measurements at great distances from the sun or perhaps in regions over the solar poles where residual modulation effects might be small. The current Pioneer 10 and 11 and Helios I and II missions provide the first opportunity for such a study. Data is now available from Pioneer 10 out to ~9 A.U. while Pioneer 11 at ~4 A.U. provides an intermediate point and Helios provides a near earth baseline. The Pioneer spacecraft will continue out to much larger radial distances in the future. However, it was felt that 9 A.U. represented a meaningful point at which to summarize the available data. The emphasis in this paper is on precise determination of the helium energy spectra and radial gradient over an extended energy range and on low energy proton studies.

II. Instrumentation and Trajectory

The Goddard-University of New Hampshire cosmic ray experiments on Pioneers 10 and 11 and the Goddard cosmic ray experiment on Helios I and II are essentially identical. A schematic drawing of the detector system is shown in Fig. 1. The "High Energy Telescope" (HET) is used to determine the Helium energy spectrum between 20 and 500 MeV/nuc and the Proton spectrum between 20 and 56 MeV and 120-300 MeV. The particle trajectory for the HET telescope is defined by the A and B detectors. Stopping particles in this telescope are identified by the additional requirement that there is no signal from the C3 detector. This stopping particle mode covers the range from 20-56 MeV/nuc for both protons and alphas. For penetrating α's and protons with energies >56 MeV/nuc, the HET telescope becomes a triple dE/dx device. In this case the energy is determined by the energy-loss measured in the 1 cm C_1+C_2 stack of solid state detectors and the pulse heights measured in B and C_3 are both required to be in an interval that is consistent with a given particle of this energy. This 3-fold multi-parameter analysis reduces the background level of spurious events to a negligible level. It is estimated that the absolute uncertainty in the α flux is ~ 12% at 400 MeV and ~7% at energies below 200 MeV. The operation of the LET I telescope (Fig. 1) is similar to the stopping-particle mode of the HET except that the thin 100μ dE/dx devices (D_1 and D_2, Fig. 1) permit multi-parameter measurements to be made from 3.2-21.6 MeV/nuc for protons and helium nuclei. The multi-parameter measurements used in this study reduces to a negligible amount any corrections due to the presence of large quantities of radioactive material in the Pioneer 10 and 11 power supplies.

The total fluence of energetic electrons and protons incident on the Goddard-University of New Hampshire experiment during the passage of Pioneer 10 through the Jovian magnetosphere was sufficiently high that some 4 electronic failures were induced by radiation damage effects. The most serious of these was the loss of the E detector information from the LET I telescope. It was found that the complete 3-21 MeV/nuc energy range of this detector could be obtained for stopping α's by using a 2 parameter analysis of D_1 vs D_2 with only a small increase in background ($\leq$ 7%). The other failures occurred at several points in the data system but in such a manner that either redundant information is available or in one case a correction factor (which generally was on the order of 3-5%) could be derived from the available data.

The Pioneer 10 and 11 and Helios I trajectories are shown in Fig. 2. Pioneer 10 was at nearly 4 A.U. at the time Pioneer 11 was launched and this combination is intercompared until Helios I was launched in December 1974. At that time Pioneer 11 had just completed its Jovian swing-by at 5 A.U. and was moving toward a new perihelion of some 3.6 A.U. on its way to a Saturn encounter in late 1979. These spacecraft constitute a unique Heliospheric network to study the distribution of galactic cosmic rays in the solar system. The Helios I and II spacecraft move between 0.3 and 1 A.U. In this paper, this data is treated as a 1 A.U. baseline and possible radial variations in the inner solar system will be discussed in a separate paper.

III. Discussion of Results

To examine the long-term temporal and radial variation of the galactic cosmic rays, the data is first divided into broad energy intervals and averaged over 27 day periods. This time averaging should reduce the effects of short term fluctuations and heliolongitudinal variations. The data for seven energy intervals are shown in Fig. 3 and 4 along with the monthly averages of the Deep River Neutron monitor. At the time of the Pioneer 10 launch in March, 1972 the intensity of cosmic ray nuclei was at approximately its 1965 solar minimum value. In the four years since 1972, there have been three significant decreases followed by recoveries to within ~1% of the original neutron monitor level. Essentially this same pattern is observed in the Pioneer 10 and 11 data at low energies. The temporal variations observed on

Pioneer 10 imply that the cosmic ray modulation region at solar minimum extends out to at least 8 A.U. and may be much larger. Comparisons of the Pioneer 10 and 11 and Helios data show a very small intensity difference above ~200 MeV/nuc. However, at lower energies there is a more perceptible difference in intensities observed at the three spacecraft and this difference increases with decreasing energy. The observed spatial variations of the 30-56 MeV proton component are smaller than that displayed by alphas of the same energy/nucleon.

It is also instructive to examine the detailed energy spectra. For this study, the data is averaged over 81 day periods and the width of the energy intervals are decreased. The Pioneer 10 alpha particle energy spectra for 3 periods centered about 1.1, 4.9, and 8.7 A.U. are shown in Fig. 5. During the March-May 1972 period there is a broad maximum between 150 and 250 MeV/nucleon. At lower energies the flux decreases but remains essentially constant below ~60 MeV/nucleon. This data is in excellent agreement with the IMP measurements near earth reported by the Chicago and Goddard group for approximately the same time period (Garcia-Munoz et al., 1973 and Van Hollebeke et al., 1973). At radial distances out to 9 A.U. there is no marked change in the spectral shape above 60 MeV/nuc. The intensity level at ~200 MeV/nuc has increased by ~30% at 4.9 A.U. Comparisons with the Pioneer 11 and Helios data will show that this represents a combination of both temporal changes and a radial gradient. Below 60 MeV/nuc there is a striking change in the spectral shape. By 9 A.U. the flat distribution observed near earth has evolved into a well-defined peaked distribution with an intensity maximum between 15 and 20 MeV/nuc.

After the launch of Pioneer 11 in April 1973 there were two identical experiments with an initial radial separation of ~3 A.U. The first joint observation period occurred during one of the large neutron monitor decreases (Fig. 4). This comparison of Pioneer 10 and 11 spectra (Fig. 6) shows no discernible radial variation above 300 MeV/nuc. However, at 200 MeV/nuc there is an 18% increase at Pioneer 10 which represents a 5.4 $\pm$ 3%/A.U. variation. Below 60 MeV/nuc the Pioneer 11 spectrum near 1 A.U. is remarkably flat, similar to the 1 A.U. spectrum of Pioneer 10. The sharp increase below 10 MeV is due to the large number of low energy co-rotating interplanetary events which have not been removed from this data. In mid-1974 the relative separation between the spacecraft has decreased to 1.3 A.U. and the data above 60 MeV/nuc displays remarkable agreement over the complete range from 60 to 500 MeV/nuc (Fig. 3, 4, 6).

The intercomparison of the detailed energy spectra of Pioneer 10 at 9 A.U., Pioneer 11 at 3.8 A.U. and Helios at 1 A.U. all at essentially the same time clearly shows a small gradient between 140-200 MeV/nuc which decreases as one goes to higher energies. Below 140 MeV/nuc this radial gradient is obvious and becomes large at ~20 MeV/nuc. Note that the intensity maximum observed between 15 and 20 MeV/nuc on Pioneer 10 is also clearly evident in the Pioneer 11 data but with a smaller amplitude.

It is of interest to examine this low energy feature in greater detail. The Pioneer 10 and 11 alpha particle data between 6 and 56 MeV/nuc are plotted for three 81 day intervals (Fig. 8). In all six cases there is a well defined intensity maximum between 13 and 21.6 MeV/nuc which is approximately a factor of 2 larger and some 2 MeV/nuc lower in energy at 8 A.U. than at 4 A.U.

To compare these results with other studies it is useful to determine the radial gradient of the differential intensity which can be defined by

$$(1) \quad G = \frac{1}{J} \frac{dJ(T)}{dr}$$

where J(T) is the differential intensity at a kinetic energy/nuc T.

$$J(r_2, T, t) = J(r_1, T, t) \exp \left[G(r_2-r_1) \right]$$

The values of G(T) obtained from the data of Fig. 6 and 7 are summarized in Table I. As will be discussed in a later section, the values of G at energies greater than 60 MeV/nuc are much smaller than had been theoretically predicted.

Pioneer 10 and 11 represent the only missions that have made cosmic ray measurements beyond 1.5 A.U. The discussion in this section is therefore limited to the results reported by energetic particle experiments on these spacecraft. Between 1 and 5 A.U. the University of Chicago (McKibben et al., 1975) reported a gradient of 4.2 ± 2.6%/A.U. for 29-67 MeV protons and 10.0 ± 4.4%/A.U. for 29-67 MeV/nucleon alphas. At higher energies the University of California (San Diego) has reported a negligible gradient (.15 ± 2.3%) for cosmic rays above 480 MeV and the University of Chicago reported a value of 3.9 ± 0.5%/AU for cosmic rays > 60 MeV/nuc. For cosmic rays greater than 80 MeV, the University of Iowa reported a gradient of 2 ± .5% (Van Allen, 1975) between Pioneer 10 and 11 out to 9 AU. The integral gradients above ~60 or 80 MeV are probably dominated by changes in the proton component between 100 and 400 MeV. The four data sets appear to be in good agreement with each other when their various energy responses are taken into account.

IV. Discussion

The major objective of these studies is to understand the properties of low and medium energy galactic cosmic rays. At 9 A.U., new spectral features are found for helium nuclei below 60 MeV/nuc while at energies above 100 MeV/nuc the radial gradient is much smaller than had been theoretically predicted. It will be seen that conventional modulation theory can be made consistent with these observations by two very different interpretations of the data.

The time independent spatial and energy transport equation used to describe cosmic ray modulation in a spherically symmetric region was first given by Parker (1965). Gleeson and Axford (1968) showed this expression could be expressed in the form of two coupled equations:

$$(2) \quad \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 S) = \frac{V}{3} \frac{\partial^2}{\partial r} \frac{(\alpha T u)}{\partial T}$$

$$(3) \quad S = CVU - \frac{K\partial U}{\partial r}$$

$U(r,t)$ is the cosmic ray density of particles with kinetic energy/nuc = T at a heliocentric distance r. $U(r,T) = \frac{4\pi}{\beta} J(r,T)$ where $J(r,T)$ is the differential flux and β = ratio of particle velocity to the velocity of light. V = solar wind velocity. $S(r,T)$ is the radial current density.

$$C = 1 - \frac{1}{3u}\frac{\partial}{\partial T}(\alpha T u)$$

with $\alpha = \frac{T+2E_o}{T+E_o}$ (E_o = particle rest mass energy)

is the Compton-Getting factor.

One useful approximation occurs when $S \to 0$ and when the diffusion coefficient can be written as a separable function of the radial dependence and the rigidity, R.

i.e.,

(3) $K(r, t, T) = \beta K_1(r,t) K_2(R,t)$

This leads to the force-field solution (Gleeson and Axford, 1968) which is the Liouville relation for an effective potential Φ

(4) $$\frac{j(r,t,T)}{(E^2 - E_o^2)} = \frac{j_o(T + \Phi)}{(E + \Phi)^2 - E_o^2} ,$$

$E = T + E_o$, j_o is the galactic spectrum.

In this case Φ is the mean energy loss in penetrating the interplanetary medium and depends on the particle mass, charge and velocity as well as the form of the diffusion coefficient. It is related to the modulation parameter φ where

(5) $$\varphi = 1/3 \int_r^L \frac{V(x,t)}{K_1(x,t)} dx$$

L is the outer boundary of the modulation region.

For the special case $K_2(R,T) = R$ then

$\Phi(r,t) = |Z|\ e\ \varphi(r,t)$

Equation 4 was originally shown to describe the modulation of 80-600 MeV/nuc protons and alphas by McDonald and Webber (1959) and McDonald (1959). This work was later extended by Freier and Waddington (1965).

Typically, modulation theorists have considered values of φ on the order of 300-350 MV based on the 1965 electron observations. For example, Urch and Gleeson (1972) have calculated the nominal radial variation of the differential intensity using the complete solution of eq. 2 and 3 with

$K = K_1(r)\ R\beta, R > 1$ GV

$K = K_1(r)\ R^{\frac{1}{2}}\ \beta, R < 1$ GV

$K_1(1\ \mathrm{AU}) = 3.0 \times 10^{21}\ \mathrm{cm}^2 - \mathrm{S}^{-1}\ \mathrm{GV}^{-1}$

$\varphi\ (1\mathrm{AU}) = 0.32$ GV

and galactic proton and helium spectra of the form

$U(T)\ \alpha\ (T + E_0/2)^{-5/2}$

$L = 10\mathrm{AU} =$ distance to modulation boundary

Their results for the radial gradient (Fig. 9) are at least an order of magnitude larger than the measured values. Using these same parameters Urch and Gleeson further demonstrated that a spectral turn-up below 200 MeV of the form $T^{-2.5}$ would be almost undetectable in the proton component at 1 AU.

One solution to this large discrepancy between predicted and measured values of the cosmic ray radial gradient is simply to make the modulation region much larger while keeping φ constant. Forman (1975) has shown that a diffusion coefficient of the form

$K = 3.6 \times 10^{22}\ R\beta e^{(r-1)/L}$ with L = 50 AU and φ (1AU) = 350 MV

gives a much smaller gradient in better agreement with the Pioneer 10 and 11 results above 20 MeV/nuc (Fig. 9).

With this nominal value of φ (1AU) $\approx$ 350 MV, and the assumed radial dependence of K_1, the flux increase of alpha particles at low energies that is observed at 5 and 9 AU cannot be produced by a turn-up in the local interstellar spectrum. Fisk et al. (1975) have suggested that the low energy portion of the helium and oxygen spectra could result from the flow of neutral, interstellar atoms into the heliosphere. These particles are ionized by solar UV and charge exchange in the solar wind and it is postulated that a certain fraction will be accelerated by the interplanetary medium. The resulting singly ionized helium nuclei are at twice their normal rigidity and hence can more effectively penetrate back into the inner heliosphere, thus exhibiting less modulation. It has in fact been shown (McDonald et al., 1976) that interplanetary acceleration is an important process in co-rotating regions between 2 and 4 AU with proton energy spectra of the form exp $(-R/R_o)$. Thus presumably an additional acceleration mechanism at larger radial distances would be necessary to explain the observed alpha particle spectrum. Fisk (1976) has proposed particle acceleration by transit-time damping. At this time the possibility of such an acceleration process occurring at large radial distances cannot be ruled out.

The force-field approximation (eq. 4) can be used to determine typical modulation parameters between 1 and 9 AU. An excellent fit to the data in figure 7 is obtained from 15-500 MeV/nuc with $\Delta\Phi = 60 \pm 15$ MV (fig. 10). This value of $\Delta\Phi$ is clear evidence that adiabatic energy losses in the inner solar system are much smaller than had been expected (Goldstein et al. 1970b, Gleeson and Urch 1971). It further suggests that the residual modulation above 100 MeV/nucleon may be much less than the values of ~300-350 MV discussed previously. There are several studies which have reached the conclusion that φ should be significantly smaller. Lezniak and Webber (1971) found their 1965 electron data to be consistent with φ (1AU) = 140 MV. For $K_2 \propto R$ over the complete energy range, Urch and Gleeson (1972) report a value of φ (1AU) = 160 MV for the 1965 period. Comstock et al. (1972) have established a self consistent model based on the interrelation of the measured fluxes of ^1H, ^2H, ^3He and ^4He with a value of φ (1AU) = 150 MV for approximately the same time period. The close correspondence between the 1965 and 1975 alpha spectra (fig. 7) suggest that the modulation conditions during the two periods for the particles in the rigidity range 400-2000 MV are very similar. These three studies are in excellent agreement. For the purposes of discussing the effect of a small modulation parameter, the value of φ (1AU) = 150 MV is adopted. It was shown (Fig. 10) that in late 1975, $\Delta\varphi = 60$ MV (for $K_2 = R$) and hence φ (9AU) = 90 MV. This value of φ(9AU) can be used with the force-field approximation to demodulate the 9 AU data and obtain an estimate of the interstellar alpha spectrum above 100 MeV (Fig. 10). The data below 100 MeV will be discussed separately. This deduced interstellar spectrum is compared with a source spectrum of the form $(T+E_o)^{-2.5}$ which has been propagated through the interstellar medium with an exponential path length distribution of the form $e^{-x/\Lambda}$ (Λ, the mean escape length from galactic confinement is taken as 6gm/cm^2). Above 100 MeV/nuc the agreement is excellent. Note that with this reduced value of the modulation parameter, the observed maximum in the alpha spectrum at ~150 MeV/nuc and the decrease between 120 and 60 MeV/nuc is a combination of both ionization energy loss in the interstellar medium and a modest amount of adiabatic cooling in the interplanetary medium. Lezniak and Webber (1971) have shown that similar modulation parameters and interstellar spectra give good agreement with the 1965 proton observations.

A galactic cosmic ray source spectrum of the form $(T+E_o)^{-2.6}$ should be regarded as an approximation to a relatively flat injection spectrum at energies below ~400 MeV/nuc. This conclusion is strongly dependent on the assumed model of interstellar propagation. It is not clear that the exponential path length distribution is to be preferred over a gaussian distribution or an exponential distribution that is truncated below 1-1.5 g/cm^2. These different forms can have a very large effect on the inferred injection spectrum of low and medium energy nuclei (cf. Daniel and Stephens, 1975).

A reduced value of the modulation parameter permits a different interpretation of the low energy data. With a value of ω (9AU) = 90 mV, direct entry of low energy alphas and heavier nuclei into the inner heliosphere becomes possible. While the force-field solution is at the limits of its validity for this value of φ at energies below ~30 MeV/nuc, it does provide useful physical insight into the expected behavior of the low energy component. For example it predicts that an interstellar spectrum of the form T^{-n} will be observed with an intensity maximum at an energy of $T_M = \Phi/2n$ for multiply charged nuclei. Thus, the local interstellar spectrum should be of the form T^{-3} above 40 MeV/nuc outside the heliosphere. Using the complete solution of eqs. 2 and 3 with $K = \beta R K_1 (r,t)$ good agreement is obtained between the calculated value, and the experimental observations (Fig. 11). There are sufficient adjustable parameters so this agreement is not too surprising. In this view the alpha spectrum in the inner heliosphere is composed of three separate components - galactic cosmic rays, a "local" interstellar component and a very steep interplanetary component below ~5 MeV/nuc. An estimate of the expected interstellar intensities of the galactic and local interstellar components are shown in Fig. 12. As mentioned in the introduction there are many different possible galactic sources and at the present time it is not possible to identify the most probable candidates. The existance of an anomalous helium component was first recognized in the study of low energy helium data at 1 AU (Garcia-Munoz et al. 1973; Van Hollebeke et al. 1973). Studies of low energy ^2H and ^3He also indicated a large local population of ^4He (Teegarden et al. 1975; Mewaldt, Stone and Vogt, 1975). At lower energies other studies have indicated anomalous increases in the spectra of O, N and possibly Ne nuclei (Gloeckler et al. 1973; McDonald et al. 1974).

Fisk (1976b) has stressed the difficulties in explaining the 1 AU observations of low energy oxygen. The energy spectra of this component is very different from that observed for helium. Fisk finds that an unreasonably large intensity of cosmic ray oxygen, by orders of magnitude, would be required in the interstellar medium to account for the observed fluxes. However he discusses time dependent variations of the interplanetary magnetic field that give a diffusion coefficient which is independent of particle speed. Using reasonable interplanetary parameters, a good fit is obtained for the interstellar electron spectrum and the observed anomalous oxygen spectrum can be reproduced with only a reasonable intensity of interstellar oxygen. Studies of the radial dependence of low energy oxygen are now in progress.

An alternate approach to the direct entry of low energy particles has been proposed by Earl (1972). At low energies there should be an attenuated component representing particles diffusing inward from the boundary where the diffusion time is small compared to $r/\theta c$, the time for significant energy loss. The low energy solutions are identical to the original convection-diffusion solutions of Parker (1958). Thus an interstellar energy spectrum of the form T^{-n} could be modulated to obtain the spectra shown in Fig. 7 by suitable choice of $K(R)$ except with T^{-n} spectrum at low energies instead of the observed peak between 15 and 20 MeV/nuc. However, the interstellar intensities would be much higher than required by the two component model discussed above.

It is not possible at this time to make a clear choice between the large and small modulation alternatives, i.e. between $\varphi(1\ \mathrm{AU}) \approx$

320 MV and φ (1 AU) $\approx$ 150 MV. There may also be new processes involved such as the time dependent interplanetary model of Fisk (1976b). This question is important in establishing the low and medium energy interstellar cosmic spectrum and in determining whether the increases in the helium flux below 60 MeV/nuc are produced by interplanetary acceleration processes or represent new low energy sources outside the solar system. Between the two alternatives discussed above, and with the available evidence, the authors have a preference for the small residual modulation view. Between 2 and 4 AU the stream-stream interactions are at a maximum in the solar wind. It is in this region that interplanetary acceleration effects are greatest and where the largest modulation effects have been observed. On the other hand, the turn-up in the oxygen and nitrogen intensity below 15 MeV/nuc appears to represent a significant difficulty for the small modulation case. This question should be resolved by observations at larger radial distances as well as detailed studies of the proton component, ^2H, ^3He and heavier nuclei.

TABLE I

HELIOCENTRIC COSMIC RAY RADIAL GRADIENT

Spacecraft	Radial Distance	α 380-460 MeV/nuc	α 275-380 MeV/nuc	α 2.0-275 MeV/nuc	α 110-210 MeV/nuc	α 66-80 MeV/nuc	α 30-56 MeV/nuc	P 30-56 MeV/nuc	α 10-20 MeV/nuc
P10 P11	4.2 AU 1.25 AU	1.3±5%/AU	2±4%/AU	4.1±3.7%/AU	4.6±3%/AU	3.5±3%/AU	10.4±2.3%/AU	--	13±4%/AU
P10 P11	4.6 AU 1.9 AU	0±5%/AU	2.5±5%/AU	2.7±4%/AU	4.6±3%/AU	2.8±5%/AU	4.9±2%/AU	1±2%/AU	25±6%/AU
P10 P11	8.8 AU 3.85 AU	0±3%/AU	2.2 2.5%/AU	0±2%/AU	2±2%/AU	-1±5%/AU	7±2%/AU	2±1%/AU	9±2%/AU
P10 Helios	8.8 AU 1 AU	1±2%/AU	2.2±1.5%/AU	3.2±1.2%/AU	3.3±1.3%/AU	0±1.4%/AU	10±2%/AU	5±1%/AU	20±4%/AU
P11 Helios	3.85 AU 1 AU	3.8±5%/AU	2.5±4%/AU	0±4%/AU	5.4±3.5%/AU	1±3.5%/AU	13.5±5%/AU	10±3%/AU	4±10%/AU

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FIGURE CAPTIONS

Figure 1 A schematic drawing of the Goddard/University of New Hampshire array of solid state detector telescopes on Pioneer 10 and 11 and the Goddard experiment on Helios I and II. For particles which traverse the "High Energy Telescope" (HET) (coincidence condition A B CIII) the pulse heights of B, CI+CII and CIII are measured separately. For stopping particles the pulse heights in A, B and CI+CII were measured. The complete Pioneer system including electronics weighed less than 3.3kg.

Figure 2 Pioneer 10 and 11 and Helios I trajectories shown in a non-rotating heliocentric coordinate system.

Figure 3 Pioneer 10, 11 and Helios I alpha data between 70 and 480 MeV/nuc. The data has been divided into five energy intervals and averaged over 27 days. Periods where flare associated solar cosmic ray events could be detected have been eliminated from the data. Shown for comparison is the Deep River Neutron Monotor monthly averages.

Figure 4 Pioneer 10, 11 and Helios I and II low energy alpha and proton data between 30 and 56 MeV/nuc averaged over 27 days.

Figure 5 Pioneer 10, Helium energy spectra (81 day averages) measured for three periods between 1 and 9 A.U. when the Deep River Neutron Monitor intensity is at maximum. This data as well as that in Fig. 6 and 7 has been corrected for nuclear interaction in the telescope.

Figure 6 An intercomparison of Pioneer 10 and 11 energy spectra (81 day averages) for three representative periods. The data between 3.3 and 6 MeV/nuc is off scale on the figures. This is due to the large number of co-rotating interplanetary events (McDonald et al., 1975) that have not been removed from the data.

Figure 7 Pioneer 10, 11 and Helios helium energy spectra for the period October, 1975 - December, 1975. Co-rotating interplanetary events have been removed from all 3 data sets. Shown for comparison (dashed line) is a compilation of measurements from the previous solar minimum period in 1965 (Gloeckler and Jokipii, 1967).

Figure 8 Pioneer 10 and 11 low energy alpha spectra for three contiguous 81 day intervals.

Figure 9 The top curve represents the expected radial gradient using nominal values of the diffusion coefficient with φ = 320 MV. The lower curve is obtained by increasing κ and the size of the modulation almost by an order of magnitude with φ = 350 MV. Good agreement with smaller values of φ can be obtained by decreasing the modulation region to ~20 A.U.

Figure 10 The upper dashed line is an estimate of the interstellar spectra using the force-field solution to demodulate the 9 A.U. data with φ (9 AU) = 90 MV. The lower dashed curve represents the modulation of the 9 AU data with $\Delta\varphi$ = 60 MV. The solid line is obtained with a power law in total energy of the form $(T+E_o)^{-2.5}$ which has been propagated through interstellar space with an exponential path length distribution exp - x/Λ with Λ, the mean path for escape from galactic confinement, = 6 g/cm^2.

Figure 11 The upper curve represents a local interstellar spectrum of the form $dJ/dT = T^{-3}$. The middle curve is obtained from the complete solutions of equations 2 and 3 using the diffusion coefficients listed in the caption. The data points are from figure 7 with the galactic cosmic rays subtracted.

Figure 12 An estimate of the expected interstellar helium spectrum just outside the heliosphere for the expected galactic cosmic ray contribution (Fig. 10) and a local interstellar spectrum of the form T^{-3}. Below 50 MeV/nuc, the dashed line represents an extrapolation of the higher energy data.

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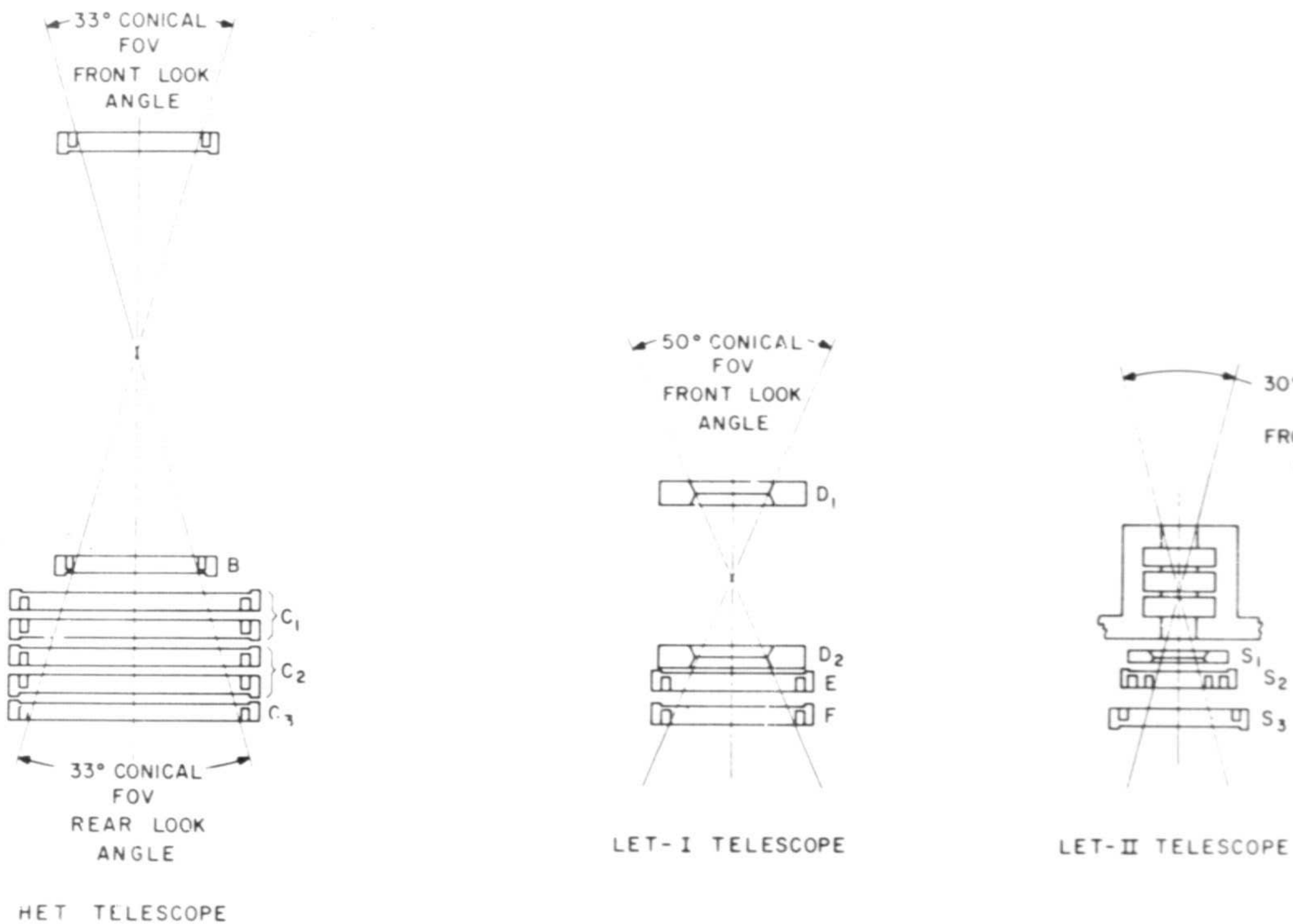

33° CONICAL FOV FRONT LOOK ANGLE
B
C_1
C_2
C_3
33° CONICAL FOV REAR LOOK ANGLE
HET TELESCOPE
50° CONICAL FOV FRONT LOOK ANGLE
D_1
D_2
E
F
LET-I TELESCOPE
30° CONICAL FOV FRONT LOOK ANGLE
S_1
S_2
S_3
LET-II TELESCOPE

Fig. 1

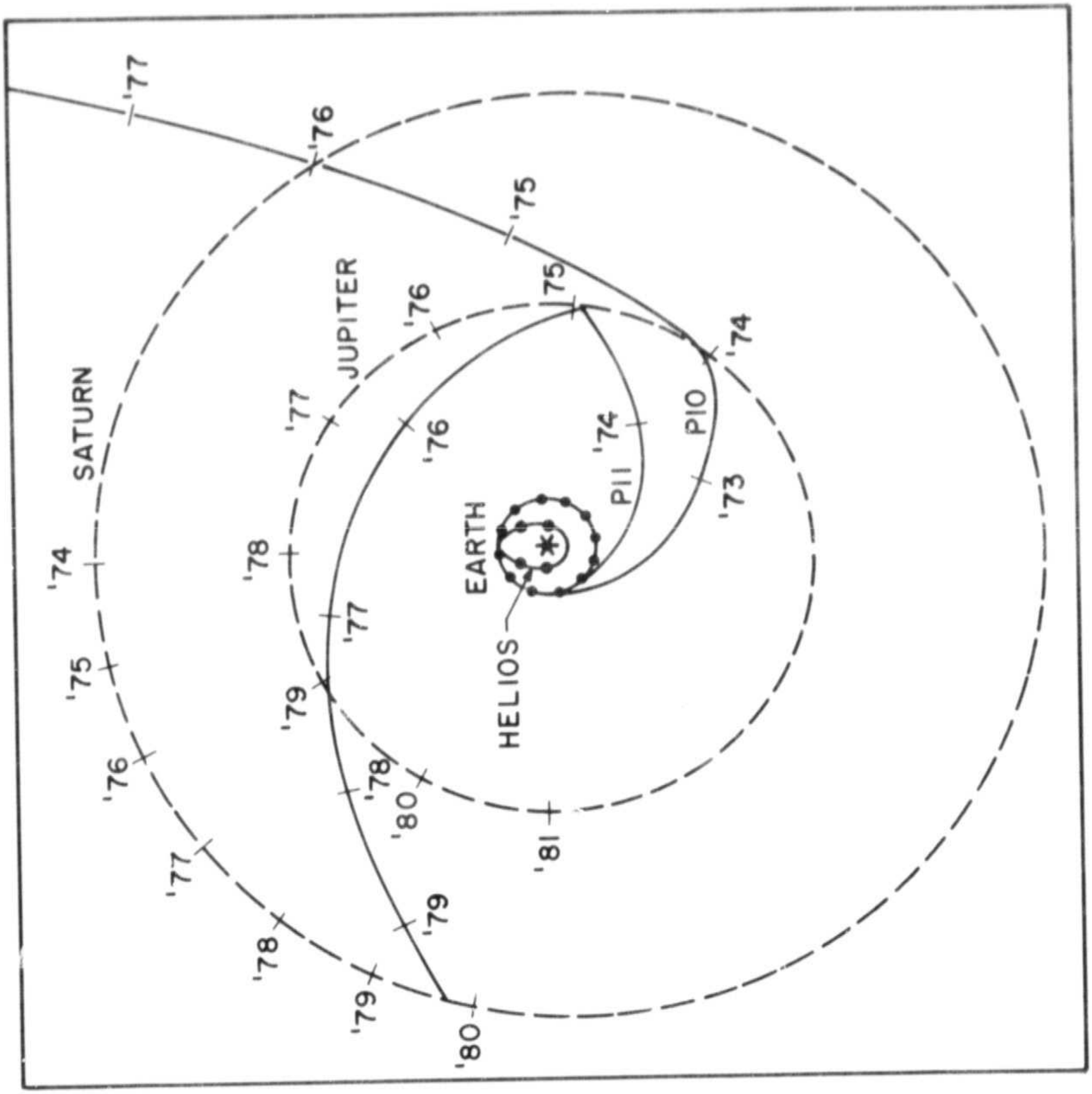


Fig. 2

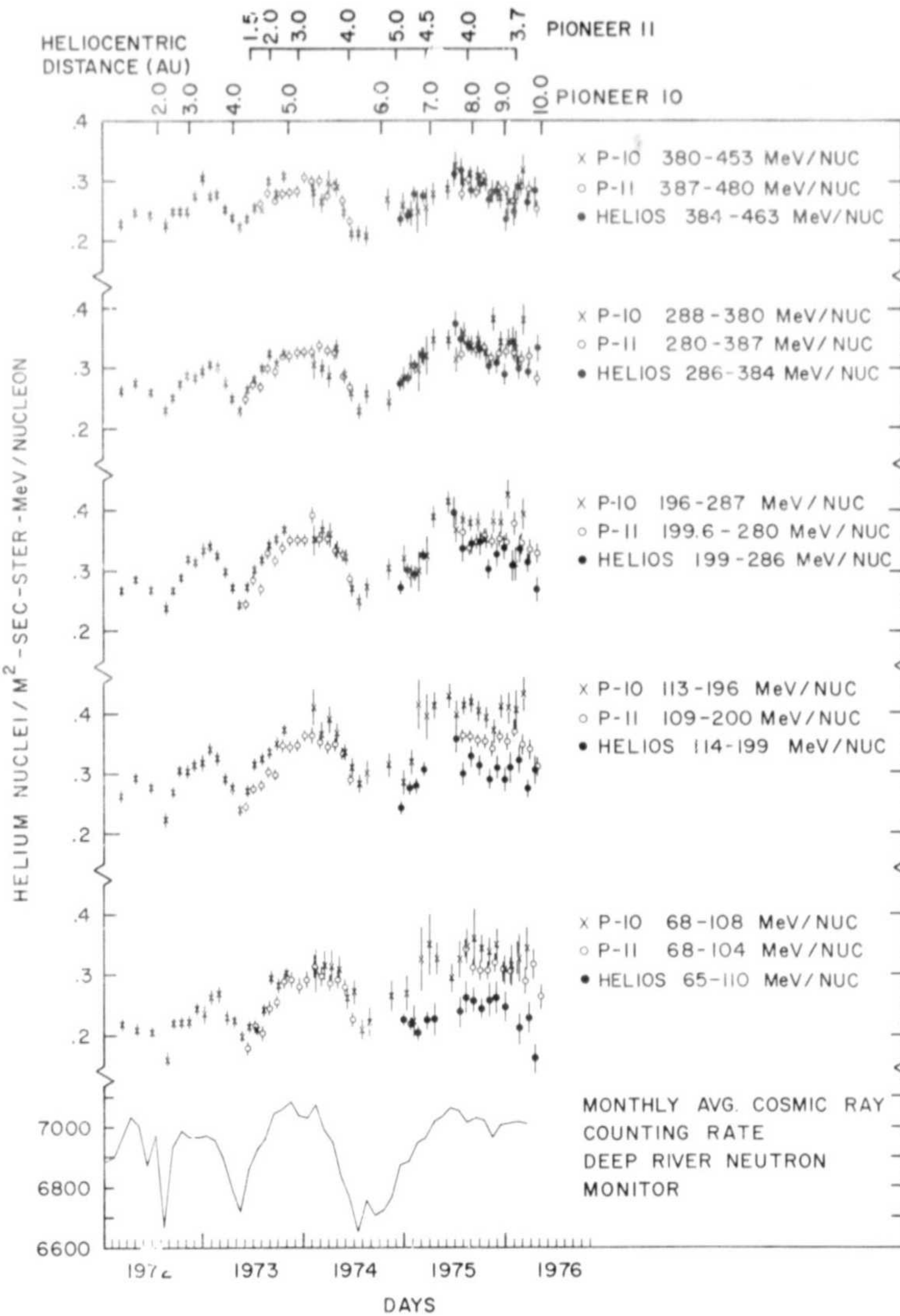

HELIOCENTRIC DISTANCE (AU)
PIONEER II
PIONEER 10
x P-10 380-453 MeV/NUC
o P-11 387-480 MeV/NUC
• HELIOS 384-463 MeV/NUC
x P-10 288-380 MeV/NUC
o P-11 280-387 MeV/NUC
• HELIOS 286-384 MeV/NUC
x P-10 196-287 MeV/NUC
o P-11 199.6-280 MeV/NUC
• HELIOS 199-286 MeV/NUC
x P-10 113-196 MeV/NUC
o P-11 109-200 MeV/NUC
• HELIOS 114-199 MeV/NUC
x P-10 68-108 MeV/NUC
o P-11 68-104 MeV/NUC
• HELIOS 65-110 MeV/NUC
MONTHLY AVG. COSMIC RAY COUNTING RATE DEEP RIVER NEUTRON MONITOR
HELIUM NUCLEI / M² - SEC - STER - MeV / NUCLEON
DAYS

Fig. 3

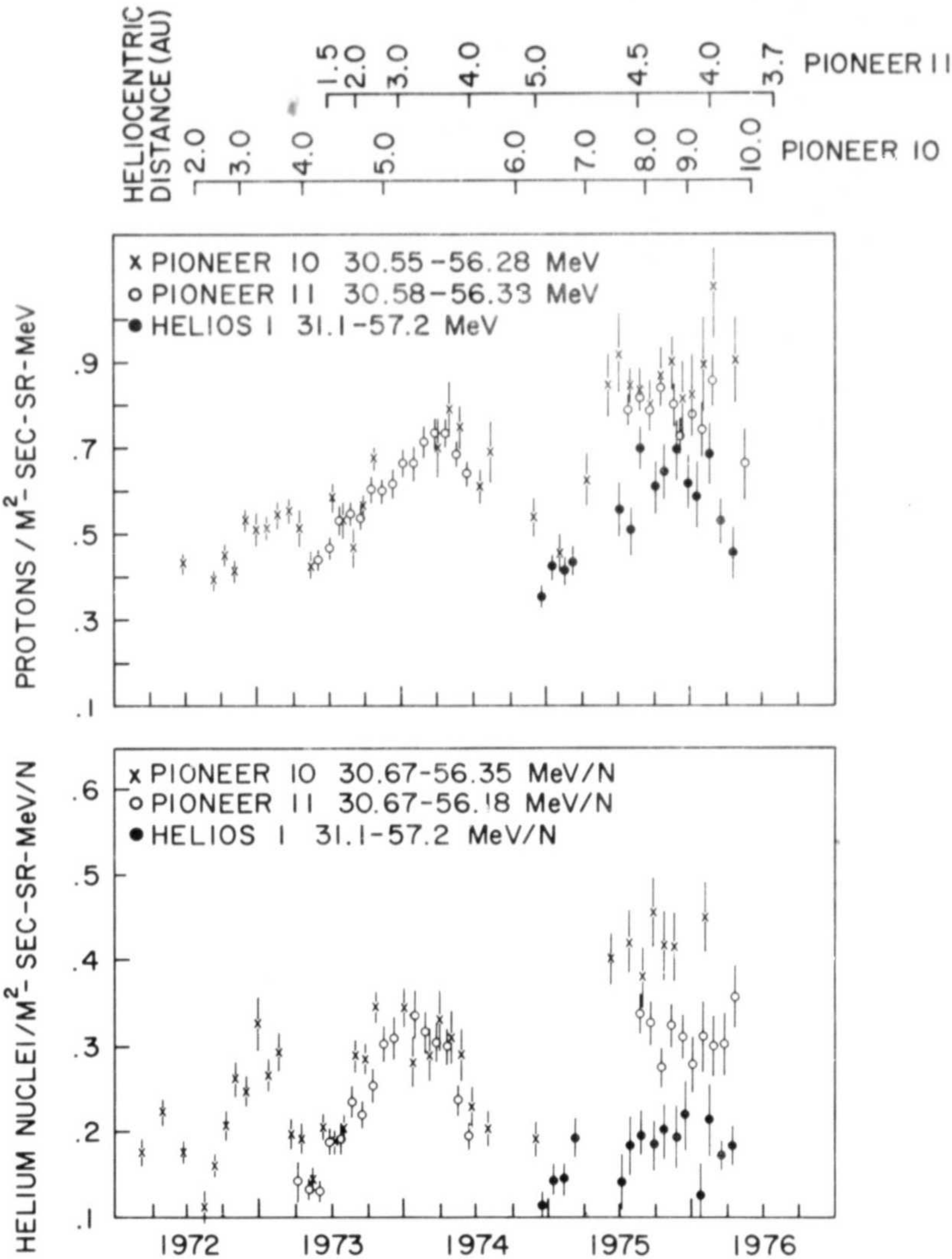

HELIOCENTRIC DISTANCE (AU)
1.5 2.0 3.0 4.0 5.0 4.5 4.0 3.7 PIONEER 11
2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 PIONEER 10
PROTONS / M²- SEC-SR-MeV
x PIONEER 10 30.55-56.28 MeV
o PIONEER 11 30.58-56.33 MeV
● HELIOS 1 31.1-57.2 MeV
HELIUM NUCLEI/M²- SEC-SR-MeV/N
x PIONEER 10 30.67-56.35 MeV/N
o PIONEER 11 30.67-56.18 MeV/N
● HELIOS 1 31.1-57.2 MeV/N
1972
1973
1974
1975
1976

Fig. 4

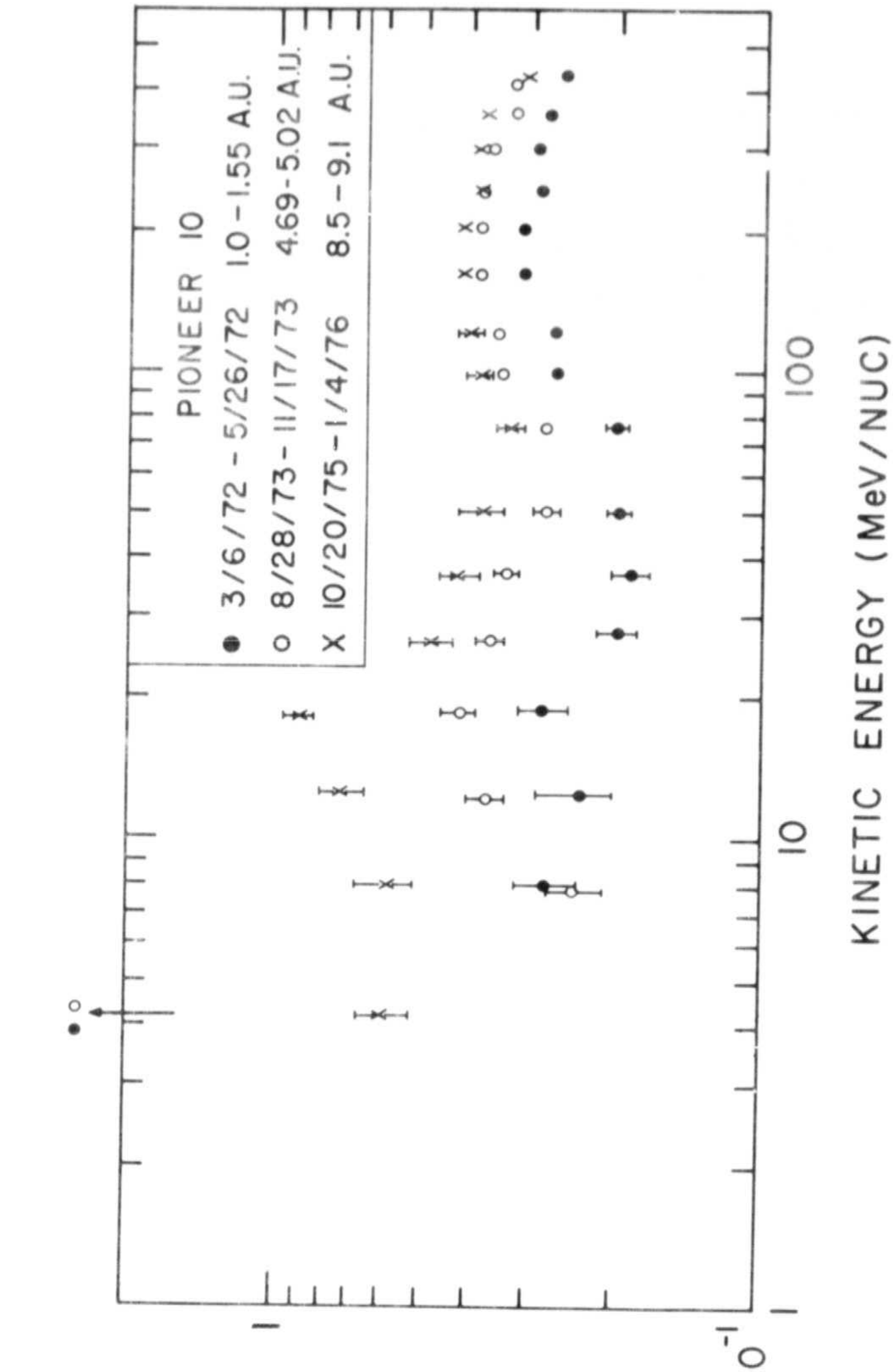
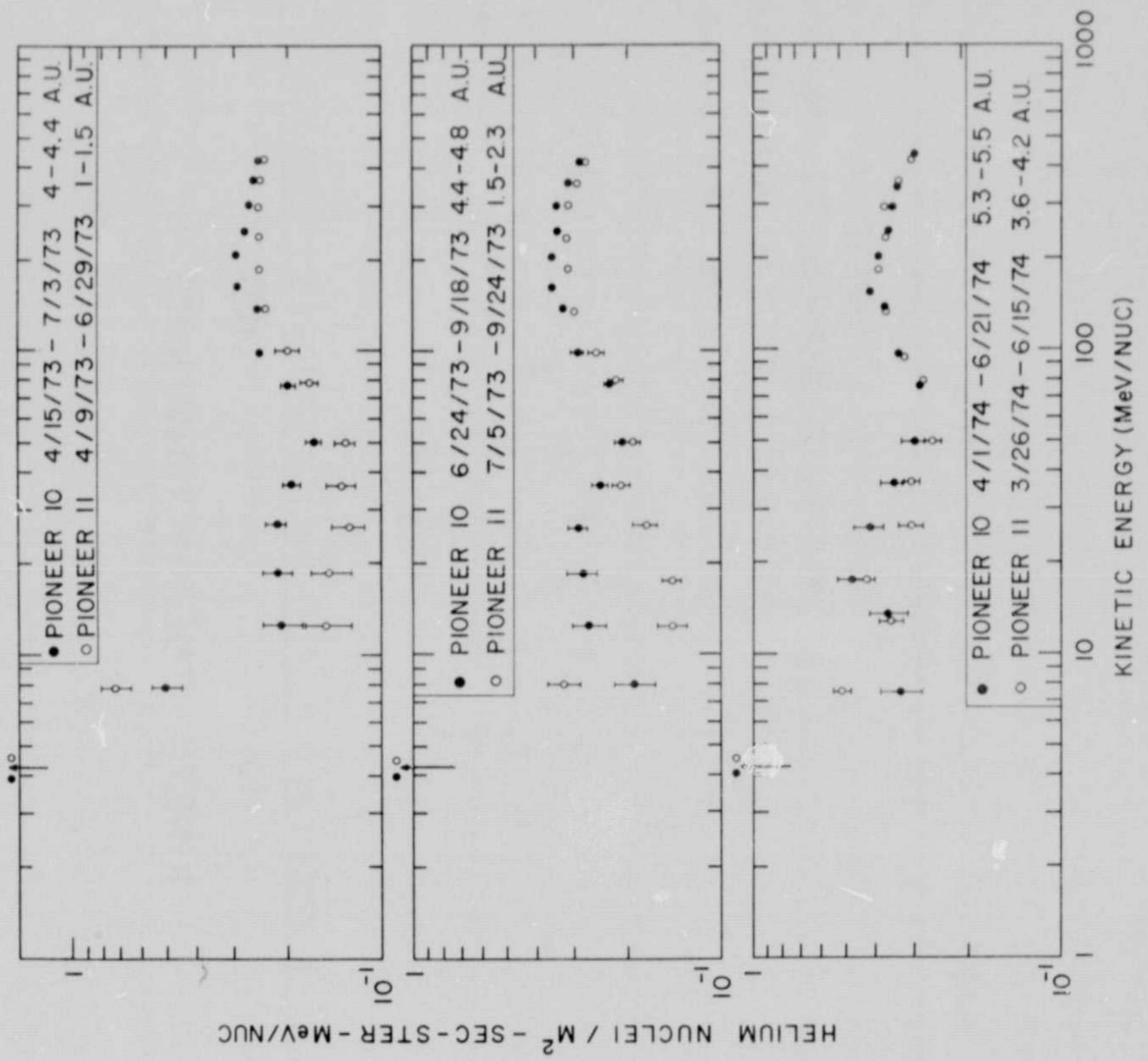
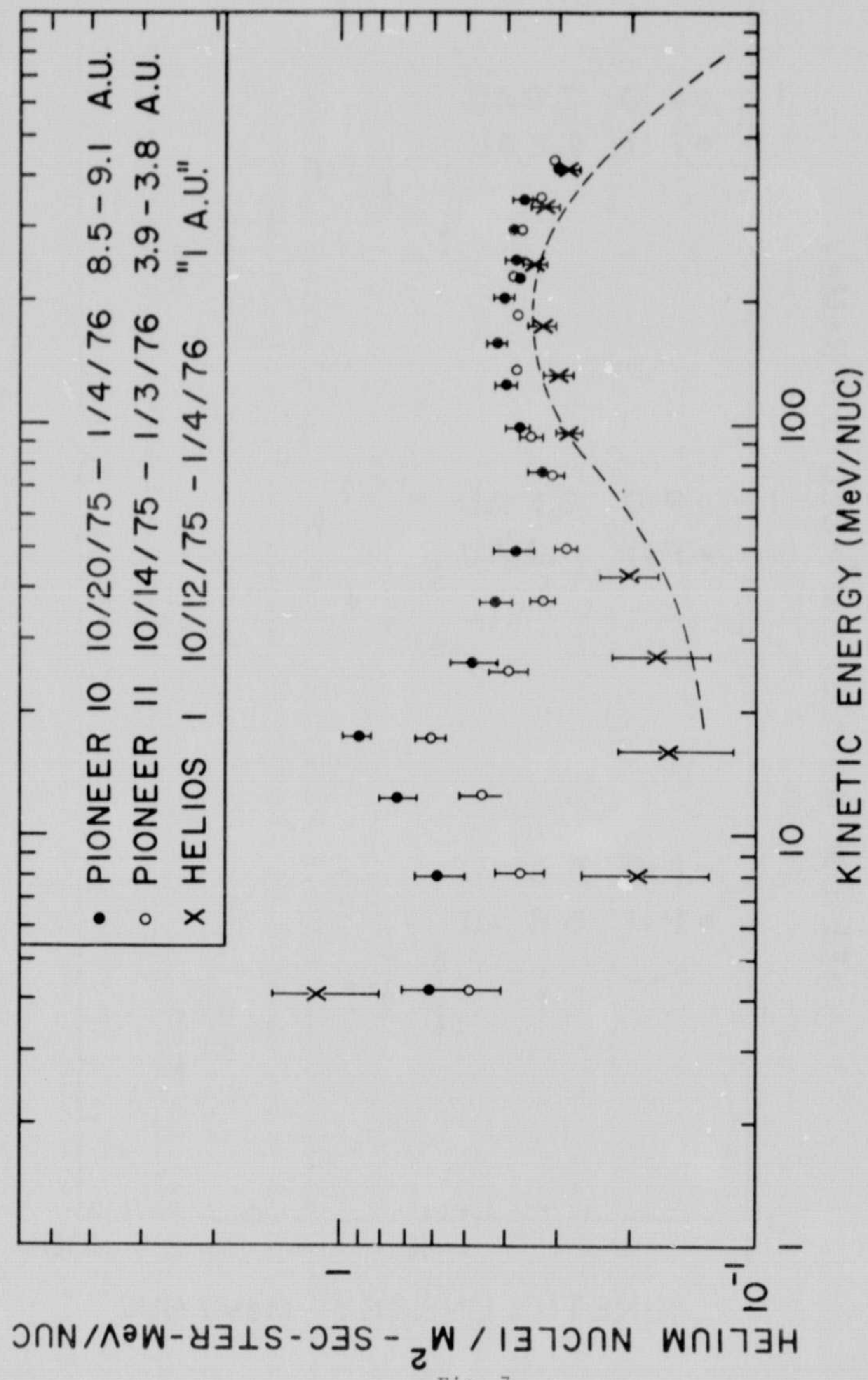

PIONEER 10
● 3/6/72 - 5/26/72 1.0 - 1.55 A.U.
o 8/28/73 - 11/17/73 4.69 - 5.02 A.U.
X 10/20/75 - 1/4/76 8.5 - 9.1 A.U.
1
10^{-1}
10
100
KINETIC ENERGY (MeV/NUC)
HELIUM NUCLEI / M^2 - SEC - STER - MeV/NUC

Fig. 5



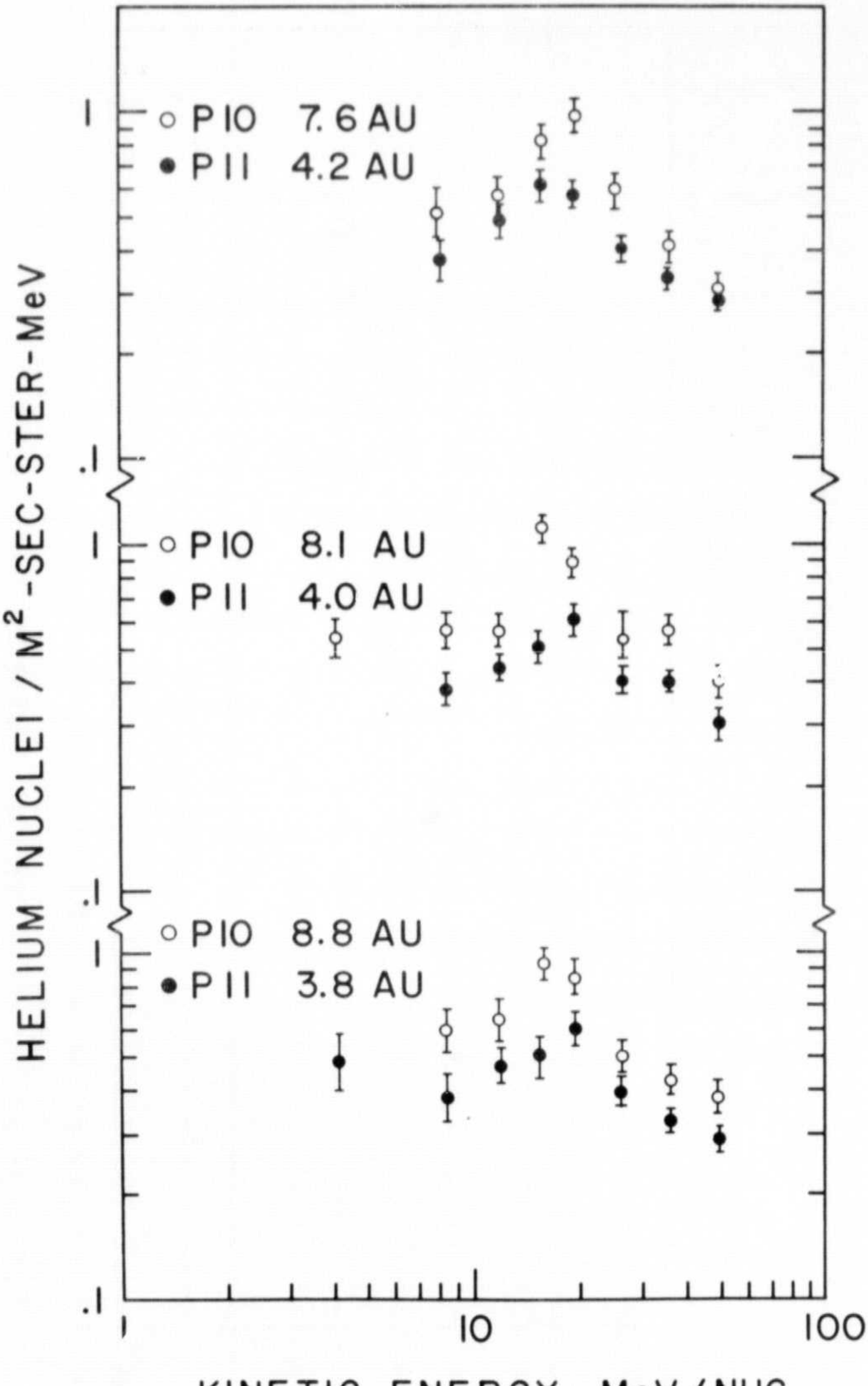
PIONEER 10 4/15/73 - 7/3/73 4-4.4 A.U.
PIONEER 11 4/9/73 - 6/29/73 1-1.5 A.U.
PIONEER 10 6/24/73 - 9/18/73 4.4-4.8 A.U.
PIONEER 11 7/5/73 - 9/24/73 1.5-2.3 A.U.
PIONEER 10 4/1/74 - 6/21/74 5.3-5.5 A.U.
PIONEER 11 3/26/74 - 6/15/74 3.6-4.2 A.U.
1
10
100
1000
KINETIC ENERGY (MeV/NUC)
HELIUM NUCLEI / M² - SEC - STER - MeV/NUC

Fig. 6



• PIONEER 10 10/20/75 - 1/4/76 8.5-9.1 A.U.
○ PIONEER 11 10/14/75 - 1/3/76 3.9-3.8 A.U.
X HELIOS 1 10/12/75 -1/4/76 "1 A.U."
HELIUM NUCLEI / M² - SEC-STER-MeV/NUC
KINETIC ENERGY (MeV/NUC)
10
100
1
10⁻¹

Fig. 7



P10 7.6 AU
P11 4.2 AU
P10 8.1 AU
P11 4.0 AU
P10 8.8 AU
P11 3.8 AU
HELIUM NUCLEI / M^2-SEC-STER-MeV
KINETIC ENERGY MeV/NUC
1
.1
10
100

Fig. 8

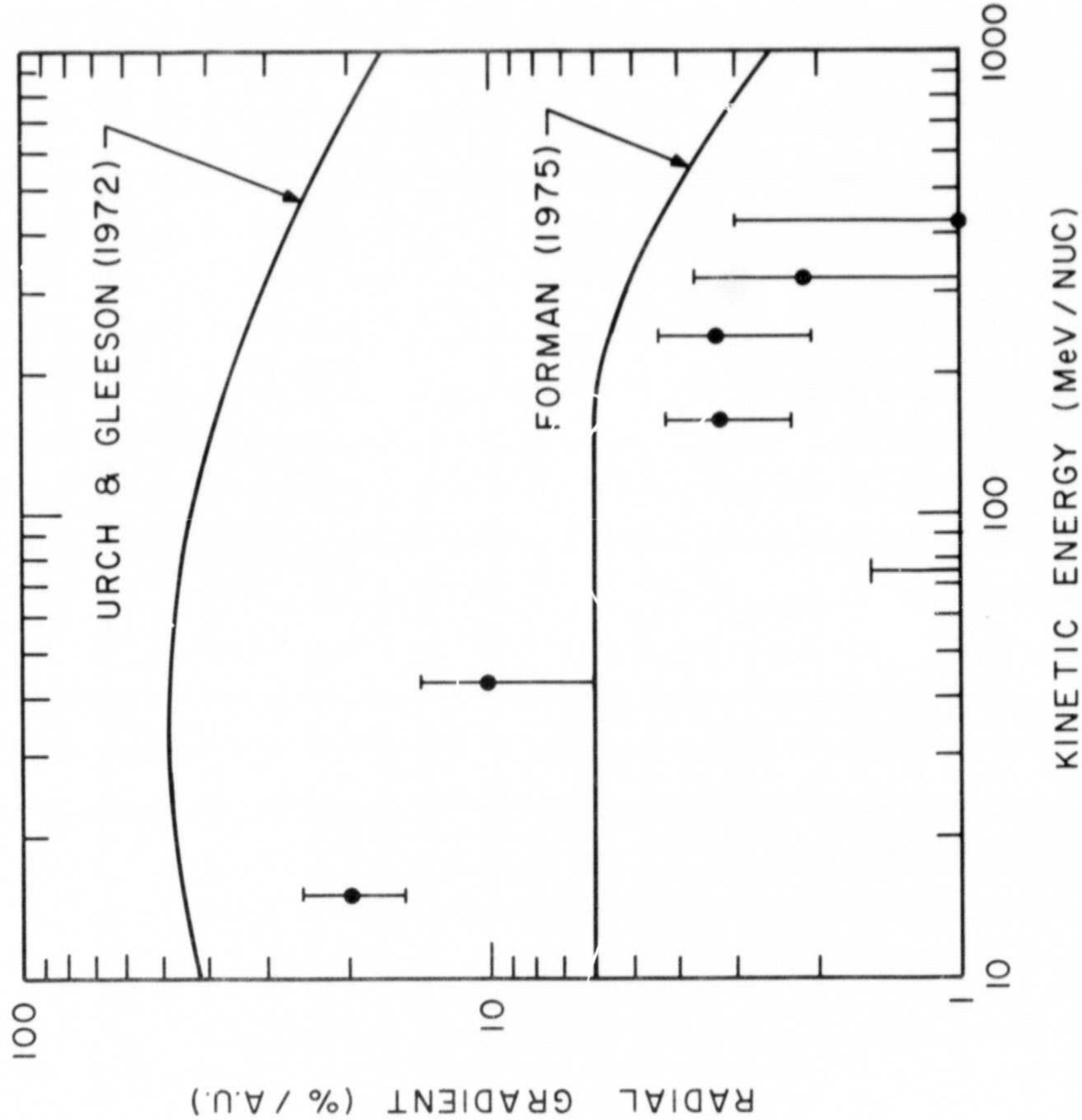
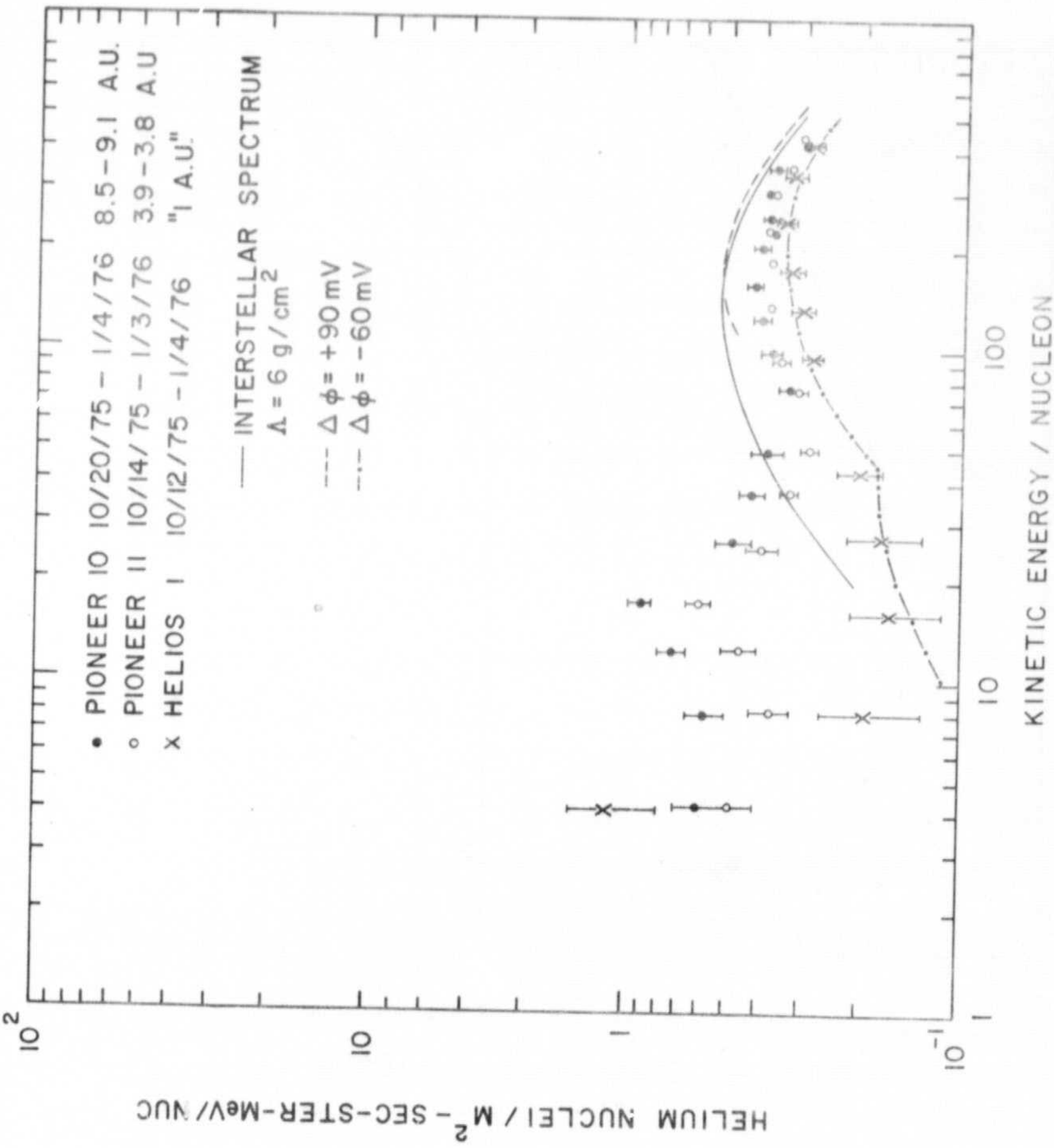
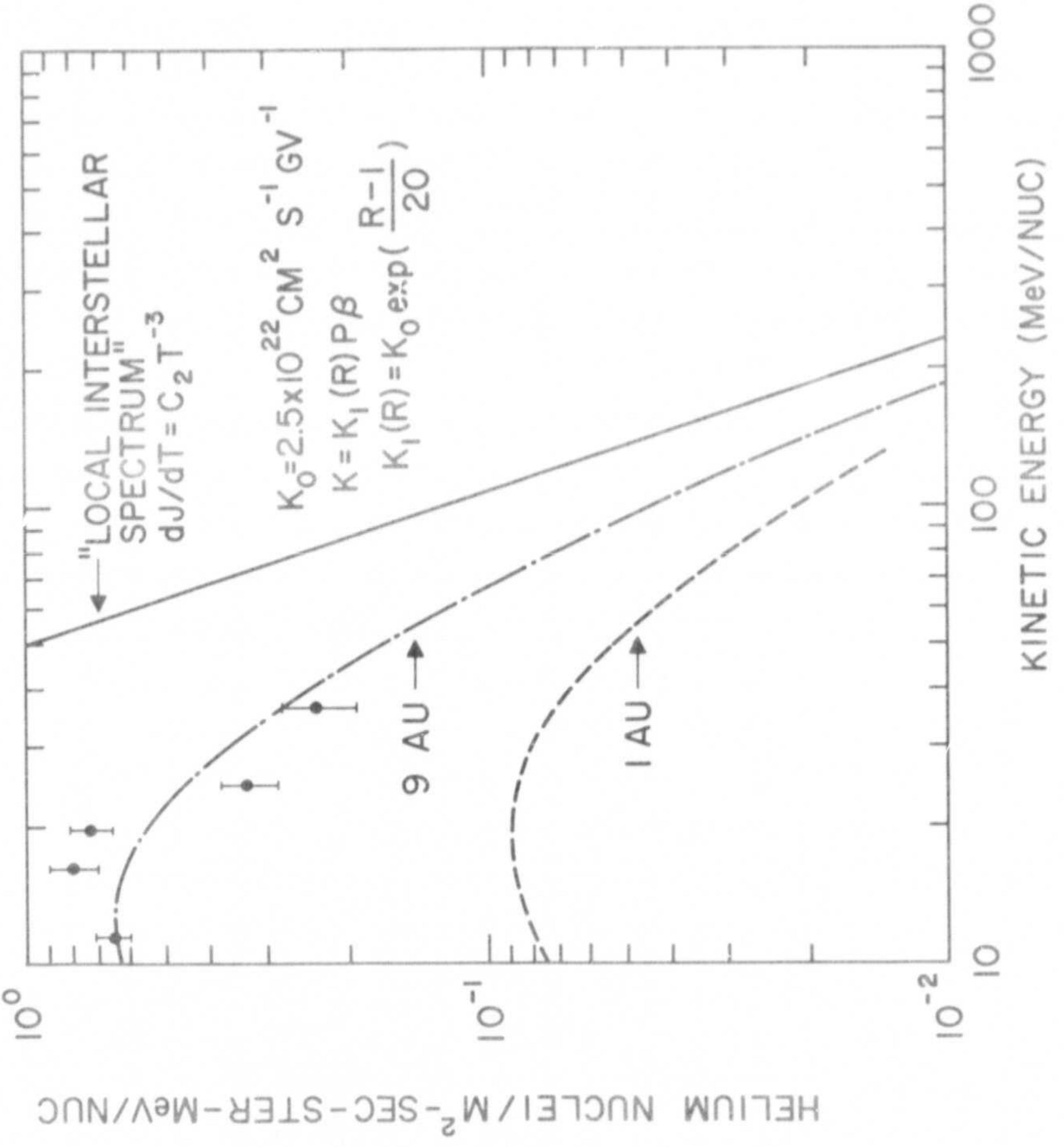

URCH & GLEESON (1972)
FORMAN (1975)
KINETIC ENERGY (MeV/NUC)
RADIAL GRADIENT (%/A.U.)
10
100
1000
1
10
100

Fig. 9



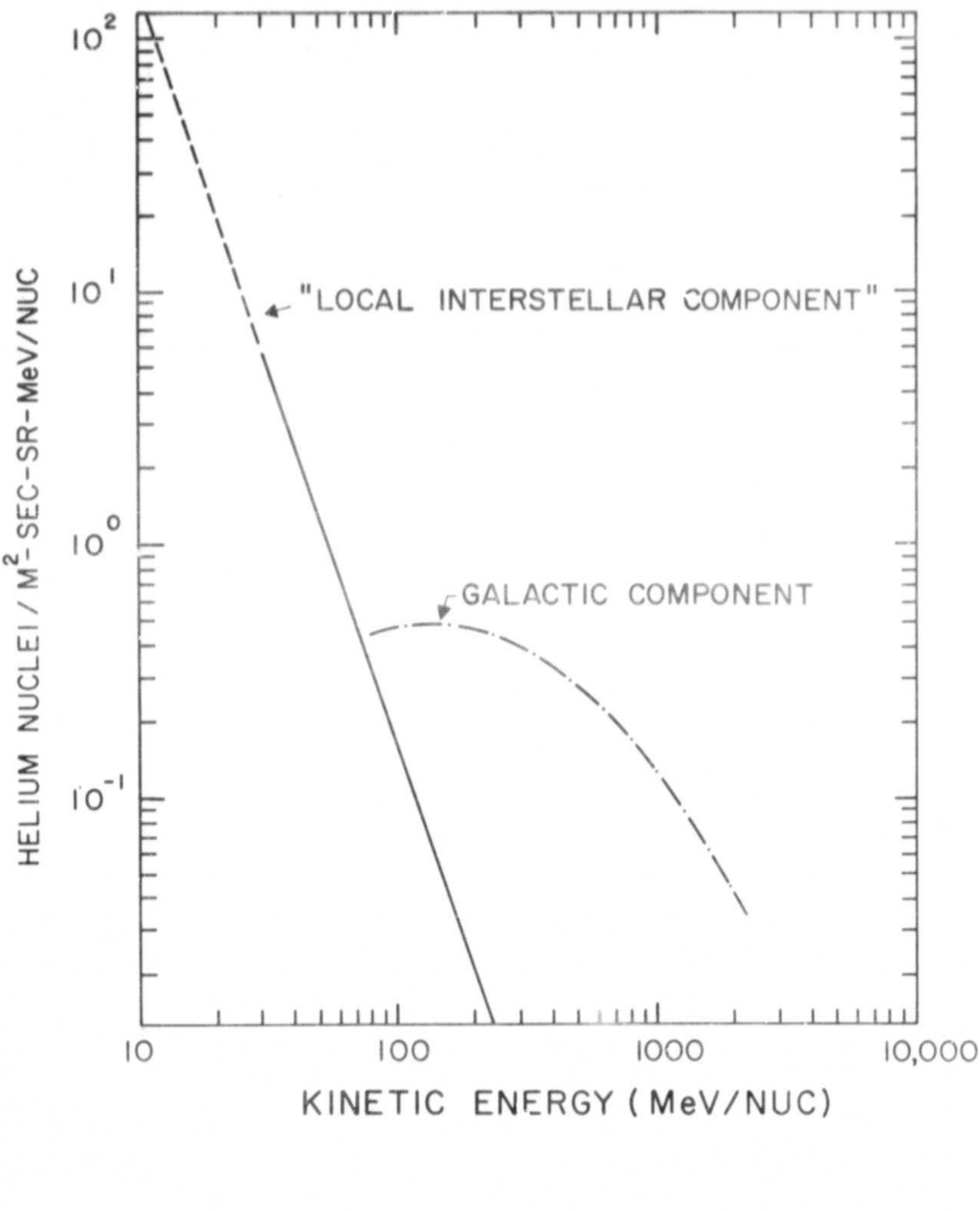
• PIONEER 10 10/20/75 - 1/4/76 8.5-9.1 A.U.
○ PIONEER 11 10/14/75 - 1/3/76 3.9-3.8 A.U
× HELIOS 1 10/12/75 - 1/4/76 "1 A.U."
— INTERSTELLAR SPECTRUM
Λ = 6 g/cm²
--- Δφ = +90 mV
-·- Δφ = -60 mV
HELIUM NUCLEI / M² - SEC-STER-MeV/NUC
KINETIC ENERGY / NUCLEON
10²
10
1
10⁻¹
10
100

Fig. 10



"LOCAL INTERSTELLAR SPECTRUM"
dJ/dT = C2 T-3
K0=2.5x1022 CM2 S-1 GV-1
K = K1(R) P β
K1(R) = K0 exp((R-1)/20)
9 AU
1 AU
HELIUM NUCLEI/M2-SEC-STER-MeV/NUC
KINETIC ENERGY (MeV/NUC)
10
100
1000
100
10-1
10-2

Fig. 11



HELIUM NUCLEI / M^2-SEC-SR-MeV/NUC
10^2
10^1
10^0
10^{-1}
"LOCAL INTERSTELLAR COMPONENT"
GALACTIC COMPONENT
10
100
1000
10,000
KINETIC ENERGY (MeV/NUC)

Fig. 12