# THE INTERSTELLAR GAS EXPERIMENT: ANALYSIS IN PROGRESS

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## SUMMARY

The interstellar gas experiment (IGE) exposed thin metallic foils aboard the LDEF spacecraft in low earth orbit in order to collect neutral interstellar particles which penetrate the solar system due to their motion relative to the sun. By mechanical penetration these atoms were imbedded in the collecting foils along with precipitating magnetospheric ions and, possibly, with ambient atmospheric atoms. During the entire LDEF mission, seven of these foils collected particles arriving from seven different directions as seen from the spacecraft. After the foils were returned to earth, a mass spectrometric analysis of the noble gas component of the trapped particles was begun. The isotopes of $^{3}He$, $^{4}He$, $^{20}Ne$ and $^{22}Ne$ have been detected. We have given a first account of the experiment in ref. 1.

In order to infer the isotopic ratios in the interstellar medium from the concentrations found in the foils, several lines of investigation had to be initiated. The flux of ambient atmospheric noble gas atoms moving toward the foils due to the orbital motion of LDEF was estimated by detailed calculations. Any of these particles which evaded the baffles in the IGE collector could be entrapped in the foils as a background flux. However, the calculations have shown that this flux is negligible, which was the intent of the experiment hardware design. This conclusion is supported by the measurements.

However, both the concentration of trapped helium and its impact energy indicate that the flux of magnetospheric ions which was captured was larger than had been expected. In fact, it appears that the magnetospheric particles constitute the largest fraction of the particles in the foils. Since little is known about this particle flux, their presence in the IGE foils appears fortunate. The analysis of these particles provides information about their isotopic composition and average flux.

Foil and machine backgrounds for the four measured isotopes had to be assessed individually. While this was easy for $^{4}He$, spurious foil background of $^{3}He$ had to be monitored carefully by systematically analyzing unflown foil pieces. Concentrations of trapped neon are not far above background even for the larger pieces.

During the flight, the foil trays did not sequentially expose several foils as designed, because of a stuck electrical relay. Therefore, we could not use the seasonal variation of the angular distribution of the incoming interstellar atoms to distinguish them from the magnetospheric component of the trapped particles. However,

the interstellar helium impacts the foils at much lower energies than most of the magnetospheric helium. Thus we could use the method of stepwise heating to extract from the foils the interstellar component at lower temperatures than are used to release the bulk of the magnetospheric component. However, the high voltage for the shielding grids was not commanded to switch on; thus, separation of the two sources was more difficult because the energies of magnetospheric ions and interstellar atoms overlapped.

The analysis of entrapped gases in the IGE foils is still proceeding. Thus far, we have concluded that we are able to give a reliable figure for the $^4He/^3He$ ratio of the more energetic magnetospheric component of the trapped flux.

## INTRODUCTION

The isotopic composition of the present-day interstellar gas of our galaxy is not well known. Spectroscopic methods are limited, practically, to determinations of elemental frequencies. Space-borne mass spectrometers of the AMPTE and Ulysses missions did observe interstellar $^4He^+$ ionized near the Sun and carried away with the solar wind, but they are not sufficiently sensitive for $^3He^+$, and they are not detecting neutral species. Our knowledge of the local interstellar neutrals is derived mainly from systematic observation of the scattering, by $^4He$ atoms, of the Sun's He I 58.4-nm resonance line (refs. 2, 3, 4).

Isotopic abundances of helium and neon in the interstellar gas are highly significant: both elements, being noble gases, are completely contained in the gas phase. Isotopic ratios do not suffer from fractionation, nor does any gas chemistry alter them. The isotopes of helium were produced in the Big Bang. Fusion in stars has produced $^3He$ ever since. Whenever stars explode, they enrich the interstellar gas by $^3He$. The $^3He/^4He$ ratio of the presolar material is known from meteoritic and solar wind data. Today, we expect a higher $^3He/^4He$ ratio in the interstellar medium than when the Sun formed 4.6 billion years ago.

The differences in the $^{20}Ne/^{22}Ne$ ratios found in different sources (meteorites, solar flares, solar wind, cosmic rays) are as yet unexplained. A known ratio in the interstellar medium would serve as a baseline datum.

Finally, a direct measurement of the interstellar $^3He$ influx into the atmosphere would shed light on the old problem of the mass balance of $^3He$ in the atmosphere. One other important source of the atmospheric $^3He$ is the precipitation from the magnetosphere of solar wind $^3He$ that previously penetrated through the magnetopause.

In-situ collection of neutral atoms from the local interstellar medium opens a new source of material from outside the solar system. Sufficient concentrations of trapped noble gases are building up

during few months in the metal foils to allow mass-spectrometric measurement of $^{3}He$, $^{4}He$, $^{20}Ne$, and $^{22}Ne$ in returned foil samples.

The technique of using foils to entrap particles for later laboratory mass spectrometric analysis was first developed for the Apollo missions to the moon by the Bern group. In this application, noble gas isotopes were measured in the solar wind (refs. 5, 6). Later, on the Skylab missions, this technique was used to analyze the isotopes of precipitating magnetospheric particles (ref. 7). This same procedure has been utilized on a sounding rocket to investigate auroral particles (refs. 8, 9). Although it is a relatively new experimental technique, considerable experience has been accumulated in this method of collecting samples of extraterrestrial particles.

For the interstellar gas experiment, the collecting foils consisted of 15 μm thick beryllium-copper (2% Be by weight). On the surface of these foils a thin Be oxide layer was formed in a procedure especially adapted for large foils. The foils were positioned at the bottom of seven rectangular IGE collectors (shown in Figure 1) which were mounted on four trays at different LDEF locations. The open end of each box-like collector established the field of view from which particles could reach the foils. The center line of the collector, standing orthogonally on the center of the foil, defined the orientation of the field of view relative to LDEF and, ultimately, to the celestial sphere.

Each collector contained six foils mounted on separate plates. It was planned to expose the foils to the particle flux in sequence for periods of roughly two months. The varying concentrations in the sequence of foils should reflect the seasonal variation of the flux of the interstellar neutrals in the vicinity of the sun. However, because of a stuck relay in the initiation circuit, the foil trays were not repositioned as intended. Thus the entire particle flux was directed to a single foil in each collector for the entire 69 months of the LDEF mission. During each orbit of LDEF, the center line of any collector was scanning along a parallel of latitude of the celestial sphere. Particles coming into its sweeping field of view were trapped by the exposed foil.

One axis of LDEF pointed radially outward from the earth and one axis pointed forward along the velocity vector. The collectors were oriented so as to optimize the collection of interstellar particles and to reduce the collection of particles from other sources. They were positioned roughly perpendicular to the direction of orbital motion. This was because the LDEF velocity would have been sufficient to ram ambient atmospheric atoms into the foils as a background flux, if they could reach the foils. The orientation of the collectors prevented that. In addition, a series of knife-edge baffles near the opening of the collectors, and serrations along the inner walls of the collectors prevented atmospheric particles from striking the walls and from reaching the foils in a single bounce. The view directions of the five collectors oriented orthogonal to the velocity vector were designated by the angle which their center line makes with the LDEF radial vector, i.e., 24°N, 24°S, 70°N, 70°S, and 110°N. The 110°N

collector looked 20° below the horizon with the intention of measuring only background particles. In the event that, after deployment, LDEF had stabilized with the space and earth-pointing ends reversed, it could have performed a minimal experiment by itself. The center lines of the two remaining collectors, designated "0° forward" and "0° backward", lay in the orbital plane and were tilted 24° forward or backward of the radial vector. The collector tipped forward into the flux of ambient atmospheric particles was to check the effectiveness of the system of baffles described above. The one tipped backward was shielded further from this possible atmospheric particle flux. Fig. 1 in reference 1 shows the fields of view for the seven foil cassettes.

A model calculation, starting from a set of fairly well known parameters for the interstellar $^4$He far from the Sun, predicts different concentrations in each IGE foil. These parameters are (ref. 1): velocity 24 km/s, temperature 12'000 K, density 0.0124/cm$^3$, right ascension 252°, declination -17.5°, ionization rate at 1 a.u. $1/1.5 \cdot 10^7$s. As the neutral interstellar particles enter the heliosphere and approach the sun, their velocity distribution is significantly altered by the gravitational focussing of the sun. Thus, during the spring and summer months when the earth is in the upwind portion of interstellar flux, the angular distribution of interstellar particles approaching the earth, and hence approaching LDEF and the IGE foils, is radically different from the angular distribution observed in the wintertime (see details in ref. 1, figure 3).

The seasonal rate of particle entrapment is complicated further as the trapping efficiency changes by more than an order of magnitude as the earth moves upstream, then across the stream, and finally downstream in the interstellar particle flow. As the earth moves upstream, the orbital velocity of the earth adds to the on-coming interstellar particle velocity, increasing the impact velocities of the particles as they strike the foil, thus increasing the trapping probability (ref. 10). The opposite, reduction in trapping probability, occurs on the downstream side of the orbit as the earth moves away from the overtaking interstellar particles. A full calculation was performed (ref. 1) to determine how many helium atoms were entrapped in each foil as each collector swept a precessing path across this seasonally changing angular distribution on the celestial sphere, with the seasonally varying trapping probability, for the length of the entire LDEF mission. The result is shown in Figure 2. The model, of course, predicts equal concentrations of particles in both 0° collectors, and no particles being captured in the +110° collector (not shown). For a collector which points in a direction where, throughout the entire earth orbit, particles arrive predominantly from an off-axis part of this particular field of view, a collector wall partially shadows one side of the foil and there is a pronounced north-south gradient in the predicted interstellar particle concentration across the foil. It is remarkable that even though the IGE foils contain the particles accumulated in almost six years, it is expected that a characteristic pattern of concentrations is still recognizable.

## PARTICLE SOURCES

As we analyze the recovered IGE foils in a mass spectrometer, we would expect to find noble gas atoms from several different sources.

1. The interstellar atoms which originate in the local interstellar medium and travel as neutrals into the inner solar system should be distributed among the various foils as we have outlined above. It is a goal of IGE to infer, from the measurements of the particle concentration in the foils, the helium and neon isotopic ratios in the local interstellar medium.

2. Magnetospheric ions which come from the trapped particle region around the earth and precipitate at low latitudes down to the LDEF altitude should also appear in the IGE foils. We assume that these particles reach the lower altitudes through a double charge-exchange process. They are originally geomagnetically trapped in the ring current as ions. Then they loose their charge by charge exchange and escape to lower altitudes. As neutrals they can cross the earth's magnetic field lines. The flux of these particles would be insignificant if a fraction of them did not undergo a second charge exchange, regaining their charge, and again become trapped by the geomagnetic field at the LDEF orbital altitude. To accumulate a significant flux at this low altitude, they must remain trapped for a relatively long time. Ions with a low pitch-angle are quickly lost; therefore, large pitch-angles are expected to dominate. The gyroradius (in the order of 1 km) is small compared to a reasonable scale height for these magnetospheric particles. We expect a rather isotropic distribution in the east/west - up/down plane and a marked decrease in the north/south direction. Relatively little is known about the flux and composition of magnetospheric precipitation at these low latitudes, so another goal of IGE is to attempt to separate and analyze this particle component trapped in the foils.

3. Neutral ambient atmospheric atoms do not appear to give a significant contribution to the entrapped foil particles. As indicated earlier, the sidewalls of the IGE collectors and the baffling system eliminate the vast majority of these potential background particles. The measurements support this conclusion.

4. He and Ne either already present in the untreated metal foils or introduced as contamination during foil preparation constitute foil background and must be accounted for in our data analysis. This is accomplished by analyzing portions of prepared foil material which was not flown on IGE.

5. Similarly, the He and Ne background of the gas extraction system and of the mass spectrometer has to be subtracted.

## SEPARATION OF PARTICLE SOURCES

The flux of interstellar particles integrated over the extended LDEF mission should show the characteristic pattern indicated in Figure 2. This is one characteristic which we can use to separate these particles from the other significant foil particle component - the magnetospheric ions. However, there is a second characteristic which should also be useful in separating these two major particle sources. That is the impact energy of the arriving particles. As previously mentioned, the energy of the interstellar particles varies according to the position of the earth in its orbit. In the spring time this energy reaches almost 120 eV for $^4$He. By summer it drops to about 70 eV and in the fall it drops to around 10 eV. In contrast, most of the magnetospheric particles have higher energies, up to 50 keV. This difference in energy has the consequence that the magnetospheric particles are much more firmly imbedded in the collecting foils. By using the technique of stepwise heating, we can extract most of the interstellar atoms at lower temperatures than are used to liberate the more tightly bound magnetospheric particles. Calibrations on pretreated foils (ref. 11) showed how two particle populations with significantly different impact energies are released from foils in a series of different heating steps. The squares and fine curves in Figures 3 and 4, starting at a temperature of 210°C, show the integrated fraction of gas released in the calibrations.

## MASS-SPECTROMETRIC ANALYSIS

Concentrations of the helium and neon isotopes were measured in 20 rectangular pieces cut from the seven foils which had been exposed in space. Each foil piece is identified by a label (first column in the tables). Its history including formation process, location during exposure, and analysis can be traced throughout the documentation by means of this label. Its position on the backing plate during exposure was mapped. The coordinates of its four corners were determined taking as a reference the coordinate system defined during the survey for impacts by the M&D SIG inspectors (ref. 12). After cutting, the pieces were weighed (absolute error < 0.1 mg) and their length and width measured to ± 0.2 mm. The area was calculated by using the calibration factor between foil mass and area of 12.0 mg/cm$^2$ (±3%). The result was checked for gross errors by comparison with the area calculated from length and width. Because the calibration error was small and constant for all pieces, it was not included in the errors given in the tables.

After weighing, the foil pieces were rinsed with clean ethanole, then rolled and filled into a cup made of 15 µm thick Al foil. The cup made it possible to handle the CuBe foil pieces and to insert them into the noble gas extraction system of the mass spectrometer. The small amount (33 mg) of Al foil did not contain measurable quantities of neon or helium. However, when pieces of unexposed foil are analyzed, the neon background is perceptively higher than when the extraction procedure is run without foils. The difference, called "foil blank" here, is not proportional to the area. Therefore, care was taken to make the unexposed foil pieces of comparable size with

the exposed ones. A total of 17 unexposed pieces with a total area of 310 $cm^2$ was analyzed, compared to the 20 exposed pieces analyzed which had a total area of 550 $cm^2$. (The total exposed area is approximately 7 x 22 x 21 $cm^2$ or 3200 $cm^2$.)

Analysis was performed routinely in a mass spectrometer dedicated to helium and neon measurements. The spectrometer is connected directly to the extraction system. After considerable conditioning of the extraction line and doing frequent machine blank checks, samples were dropped into a molybdenum crucible and heated in steps by HF induction. The crucible reached a specified temperature (between 150 and 1800°C) after 10 to 20 minutes and was kept at this temperature for 12 minutes. After each step, released gases were cleaned from reactive components by titanium getters and active charcoal cooled with liquid nitrogen, then pumped into the mass spectrometer. Five spectra were sequentially measured by peak-jumping. The error of their average intensities was calculated from the variation of the individual mass peaks. Interferences and background were subtracted. Background and its reproducibility were carefully assessed, separately for each temperature step.

The "foil blank", estimated from measurements of unexposed foil pieces, was negligible for $^4He$. For neon, however, it was of the same order of magnitude as the released amount of trapped gas, especially for the high-temperature steps. For a few unexposed foil pieces, the $^3He$ released in the 450°C and 600°C steps was of the same order of magnitude as for the exposed pieces. For the foils in the cassettes with almost vertical view directions (24°N to 24°S), the $^3He$ foil blank never amounted to more than 15 percent of the trapped $^3He$, while for the cassettes with almost horizontal view directions (110°N, 70°N, and 70°S) the foil blank renders the $^3He/^4He$ ratio more unreliable, possibly up to ±50%. The uncertainty of the blank estimates is reflected in the errors given.

## RESULTS

The results are presented in Tables 1 and 2. In order to get a first estimate of the concentrations, five small pieces (4 to 10 $cm^2$), one each for the view directions 110°N (view below the horizon), 70°N, 24°N, 24°S, and 70°S, were heated to 1400°C for total extraction. These measurements are marked [1] in Table 1. Obviously, even these small pieces allowed good helium measurements, while larger areas are needed for more precise neon measurements. Concentrations were higher by a factor of about three than expected from the model of Fig. 2. The average ratio of the concentrations for $^4He$ and $^3He$ was 7400. With the correction for different trapping probabilities for $^4He$ and $^3He$ (Fig. 2), this ratio would reflect a $^4He/^3He$ ratio in the flux of approximately 4500. Of course, no interstellar particles at all should have hit L249-2-1 which was exposed on the cassette pointing 20° below the horizon.

With these results, it seemed possible that a fraction of the $^4He$ could be atmospheric atoms that had hit the foil directly or after collisions with the inner walls of the collectors. Their energies

would be of the order of 30% of $^1/_2mv^2$ (m = atomic mass of $^4He$, v = satellite orbital velocity), i.e., 0.4 eV. The trapping probability was never measured for atoms with such a low energy. On the other hand, only an extremely low fraction (approx. 1 ppm) of the flux n.v (n = atmospheric $^4He$ density at spacecraft altitude) hits the foils directly, and the baffles and serrations on the inner walls practically prevent any atom to hit the foil after only one collision.

We assumed that, if atmospheric $^4He$ atoms are trapped in the foils, heating to 150°C should at least release part of them, while calibration experiments done by Michel in the Bern laboratory (ref. 11) showed that only approximately 15 percent of 75 eV $^4He$ (the incidence energy of interstellar particles) were released at 210°C (see Fig. 3). Four pieces from the two collectors with 0° view angle were heated to 150°C, then to 450°C, finally to 1400°C, in order to check for the presence of trapped atmospheric atoms (see pieces marked with $^{2)}$ in Tables 1 and 2). The fraction of $^4He$ released at 150°C was 3% of the amount released at 450°C for L290-2-1 on the 0° collector tilted backward. For L296-1-1 to -3 (on the 0° collectors tilted forward) which could be expected to see more incoming atmospherics, the fractions were between 1.2 and 2.2% only. At 150°C $^3He$ and the neon isotopes could not be detected on any of the pieces. Atmospheric particles, therefore, certainly contribute unimportant quantities to the 450°C releases as given in Table 2. This conclusion is strengthened by the arguments that the ratios $^4He/^3He$ found on the two 0° collectors are not different from each other (both are about 6000) while one would expect a higher ratio for the forward-looking ones (L296-1-..) as the atmospheric $^4He/^3He$ ratio is very high, approximately 100'000, at 300 km.

The atmospheric particles thus excluded from being responsible for the deviation of the measurements from the model calculations, we had to take into account a possible contribution of magnetospheric precipitation. As the magnetic field is approximately horizontal and south-north at low latitudes, we expect the 0° view collectors to see the highest fluxes of particles gyrating about these field lines, the 24°N and 24°S collectors slightly smaller fluxes, and the 110°N, 70°N, and 70°S much smaller fluxes because of the loss cone. The $^4He$ concentrations in Table 1 do show this tendency which is, unfortunately, similar to the signature of interstellar particles in Fig. 2. Finer models of the expected distribution have not been worked out yet. The magnetospheric particles are assumed to cover a wide energy spectrum, with a considerable part of the flux down to energies characteristic for interstellar particles. Note that the experiment was designed to protect the foils from the infall of ions with energies below 1 keV. One of the three grids in Fig. 1, at +1200 V relative to the spacecraft, should have rejected low-energy magnetospheric ions, while neutral interstellar particles (energies for $^4He$ below 140 eV, for $^{20}Ne$ below 700 eV) would not have been affected. Because, as mentioned above, a system relay malfunctioned, the grids never were connected to a high potential; thus, the spectra of the two particle populations were superposed. Still, we hoped that a difference between low-temperature and high-temperature releases could be seen in the isotopic ratios. We did not, however, do the fine-step release

from 210° to 450° of Michel's calibrations, because of the small amounts expected to be released in each step. Instead, we chose steps 450, 600 and 800°C in the hope to sufficiently separate low energies from high energies. An additional step at 1700°C made sure that the 1400°C step had extracted the trapped gases completely. The results of the stepwise extractions are given in Figures 3 and 4. For both $^{4}He$ and $^{20}Ne$, the release patterns were very similar to each other for 7 pieces (the darker shaded region contains all their release curves) and only two pieces showed greater, irregular deviations (brighter region).

Losses by thermal diffusion are much more dependent on temperature than on time. Therefore, comparison with the calibration experiments indicates that a large part of the trapped particles impacted the foil with high (magnetospheric) energies, but that a considerable part of the 450°C release are interstellar particles which arrive with low energies. It could, however, be argued that the influence of the diffusion time can not be neglected, and that the comparison gives an impression of too high energies for the trapped particles in the exposed foils. Fine-resolution heating steps and more direct calibrations, including $^{3}He$, will be necessary to resolve the question.

The stepwise heating method should not only give clues as to the energies with which particles have hit the foil. Its potential to separate low-energy from high-energy components also allows to determine, independently, isotopic and elemental ratios for low-energy and for high-energy populations. We have to take into account, however, that even if helium has hit the foils with the same energy as neon, it is released at lower temperatures, owing to its higher mobility. The effect can give the illusion of a difference in elemental ratios for low- and for high-energy components; thus, careful calibration is necessary. The effect gets worse if energies are proportional to mass, such as for interstellars which impact with equal velocities. Even for isotopic ratios, it may not be neglected.

From Table 2, the isotopic and elemental ratios can be calculated for the trapped gas components which are released at 450°C.

Their weighted averages are:

$$^{4}He/^{3}He = 6300\pm300$$
$$^{20}Ne/^{22}Ne = 14.4\pm1.4$$
$$^{4}He/^{20}Ne = 10'600\pm1'000$$

The errors (one sigma) of the averages are estimated from the variation of the 15 measurements. They are only little higher than expected from the errors given for the individual measurements of the isotopic ratios. They are three times as large, however, for $^{4}He/^{20}Ne$, reflecting a poorer reproducibility for the elemental ratio than for the isotopic ratios.

Isotopic and elemental ratios for trapped gases released in four temperature steps and for the total release (all steps summed) are in the following ranges for over half the number of the measured pieces:

| Temperature | Pieces | $^4He/^3He$ | $^{20}Ne/^{22}Ne$ | $^4He/^{20}Ne$ |
|---|---|---|---|---|
| 450°C | 15 | 5500-7300 | 11-22 | 7800-17000 |
| 600°C | 11 | 5000-7500 | 13-56 | 7100-12000 |
| 800°C | 11 | 6200-7500 | 14-18 | 2300-3600 |
| 1400°C | 11 | 6300-10500 | 15-18 | 340-670 |
| total | 20 | 6000-7100 | 13.9-17.5 | 2300-4200 |

$^4He/^3He$ ratios do not differ from step to step. Actually, if we assume that most of the 450°C step is of interstellar and the bulk of the other steps of magnetospheric origin, the average ratio for the trapped magnetospheric helium, 6600, is not far from the ratio 6300 for the trapped interstellar particles.

$^{20}Ne/^{22}Ne$ is 14.4 for the 450°C step, 15.5 for the total release. Even though the range of measured ratios is large, these numbers are definitely above 9.8, the terrestrial ratio, and are also above 13.7, the value in the solar wind. If the magnetosphere is mainly supplied by atoms escaping from the atmosphere, a ratio higher by up to a factor of 2 than the terrestrial value may be expected, because the two neon isotopes have different scale heights in the exosphere, and the lighter isotope is enriched.

The $^4He/^{20}Ne$ ratio, finally, clearly shifts from high to low values with higher temperature. This trend merely reflects the fact that helium of any energy is released at lower temperatures than neon of the same energy (compare Fig. 3 with Fig. 4). The average $^4He/^{20}Ne$ ratio for the total release is 3000, and 10 out of the 20 pieces show ratios between 2300 and 4200. This is much higher than expected for interstellar particles, but may be explained for magnetospheric ions.

## DISCUSSION

The results show that atmospheric contamination of the trapped helium and neon is negligible.

The bulk of the particles is magnetospheric, while an appreciable part of the 450°C release is probably of interstellar origin. If release curves from Michel's calibrations (ref. 11) are taken at face value, postulating complete independence of diffusion times, it may be that 30 percent of the trapped $^4He$ are interstellar atoms (energies around 100 eV), 40 percent are 3 keV and 30 percent are 30 keV magnetospheric particles. This estimate is very crude, and different combinations of percentages and energies are possible, considering the limited applicability of the available calibrations. It is clear from the difficulties with the analysis of the components that methods like high-voltage protection grids and protection of the foils from particle infall when the collector is not directed toward the arrival direction of interstellar particles would be highly useful for separating particle sources.

Taking as an example L199-2-2 (from the collector looking 24°N), with $133 \cdot 10^9$ $^4He$ atoms trapped per $cm^2$, the suggested 30 percent

interstellar particles would almost exactly correspond to the concentration proposed by the calculations (Fig. 2) where we assumed an interstellar $^4He$ density far from the sun of $0.0124/cm^3$.

The average $^4He/^3He$ ratio of the 450°C release is 6300, not far from the average for the total trapped helium of 6500. After correction for the lower trapping probability of $^3He$ compared to $^4He$ (approximately 60 percent according to Fig. 2), an estimate of the interstellar $^4He/^3He$ density ratio of 3800 would result. This value falls in the range of possible values for the present interstellar medium. It is too early to speculate, however, whether it is different from the value at the time of formation of the solar system.

For the magnetospheric contribution to the $^4He$ trapped in L199-2-2, a concentration of $0.7 \cdot 133 \cdot 10^9/cm^2$, after an approximate correction for the trapping probability, results in a fluence of about $1.5 \cdot 10^{11}$ atoms/$cm^2$. Other foils contain 30-50 percent more or less particles, thus a crude average over the 69 months of exposure would be 800 $^4He/s\ cm^2$, arriving from 0.34 sterad (the solid angle of directions seen by a foil piece through the open end of the collector box). The resulting figure for the average magnetospheric flux along the LDEF orbit, for approximately vertical infall, is a rather brave guess. It suffers from the fact that the energy spectrum is not known and, therefore, the trapping probabilities must be guessed. Moreover, no detailed model of the flux was worked out. Also, the concentrations on different pieces seem not to follow an obvious pattern as yet.

The magnetospheric $^4He/^3He$ flux ratio is 6600 and corresponds, practically, to the ratio of concentrations for the total trapped helium. This ratio is clearly much higher than the solar-wind ratio of 2350 (ref. 6), but very much lower from the atmospheric ratio at high altitudes which is near 100'000. The ratio of 6600 would clearly indicate a mixture of particles in the magnetospheric regions from which they originate. Similar contributions from escaped atmospheric atoms and from solar-wind ions which have penetrated the magnetosphere can be assumed. A foil experiment flown in 1973 on Skylab (ref. 7) collected precipitating particles. Because of varying contamination by ambient atmospheric atoms, the $^4He/^3He$ ratios fluctuated widely, from <3'000 to >50'000. It was not sure whether the low values found were representative of the low-latitude magnetospheric precipitation. The Skylab orbital inclination was 50° (for LDEF, 18.5°), thus Skylab eventually approached auroral latitudes. In another foil experiment, Bühler et al. (ref. 9) had found that auroras can contain almost pure solar-wind helium ($^4He/^3He$ = 3'000). Thus the low-latitude magnetospheric trapped component on the Skylab foils could have been contaminated by direct auroral precipitation.

For neon, assessing fluxes from the stepwise releases is more difficult than for helium, as the calibration curves contradict each other for 3 keV and for 30 keV (see Fig. 4). Moreover, interstellar neon has a five times higher energy than $^4He$, i.e., about 500 eV, and its release pattern is similar above 600°C to that of neon of higher energies. It is difficult, even based on the low-temperature steps alone, to suggest that more than ten percent of the trapped neon could

be interstellar. Because the averaged $^{20}Ne/^{4}He$ ratio for the trapped gases is 1/3000 in the foils analyzed so far, this would mean that neon is much rarer in the interstellar medium than predicted by models (e.g., ref. 13).

Even for the magnetospheric neon, the measured ratio is lower than expected when compared to ratios estimated for the upper atmosphere, or if a considerable admixture of solar-wind neon is assumed as in the case of helium. Certainly, measurements of neon are less conclusive than those of helium because they depend more critically on assumptions on foil blanks and trapping probabilities. For interstellar particles ionization losses near one astronomical unit may have been underestimated; moreover, losses for neon are higher than those for helium.

## CONCLUSIONS

About a third of the helium trapped in our foils seems to be of interstellar origin, two thirds being precipitated magnetospheric particles. This agrees with our model calculations and is consistent with our preliminary calibrations of the release curves for stepwise heating. The $^{4}He/^{3}He$ density ratio of the interstellar medium is tentatively estimated as 3800, with wide error limits. The $^{4}He/^{3}He$ ratio for the flux of magnetospheric ions must be around 6600. The averaged flux of magnetospheric $^{4}He$ ions is, for large pitch angles, of the order of 2000/s $cm^2$ sterad.

We expect that the reliability of the interstellar $^{4}He/^{3}He$ ratio can be improved by more detailed calibrations.

To estimate the interstellar and magnetospheric contributions to the trapped neon is more difficult. We found about 3000 times less trapped neon than trapped helium in the exposed foils. This low Ne concentration is difficult to understand. We hope to improve the measurements of neon by performing heating steps at lower temperatures, with lower background, and with calibrations in parallel.

The method of collecting interstellar and magnetospheric helium and neon has proved to be successful, even though the reliability of the results suffered from the superposition of trapped particles from the two sources. Superposition of interstellar atoms and magnetospheric ions can be prevented successfully on future missions. Based on our experience with IGE, we propose: 1) to shield off magnetospheric ions of low energies with high-voltage grids, 2) to open a cover on top of each collector only at times when the arrival direction of the interstellar particles is in the field of view, and, most effectively, 3) to fly an inertially stabilized platform with collectors continuously pointed at the direction of the most intense interstellar flux.

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Table 1: Concentrations [in $10^6$ atoms/cm$^2$] of trapped gases in exposed foils: total amount of gases released in all heating steps up to 1400°C. Corrections were applied for foil and machine blanks.

| Foil piece | Area [cm$^2$] | $^3$He | $^4$He | $^{20}$Ne | $^{22}$Ne |
|---|---|---|---|---|---|
| Cassette 9, 110°N | | | | | |
| L249-2-1[1] | 9.6 | 2.34 ±0.36 | 17300 ± 400 | 6.2 ± 2.7 | 0.35 ±0.35 |
| L249-2-2 | 56.9 | 3.36 ±0.86 | 18600 ± 300 | 6.0 ± 0.6 | 0.35 ±0.13 |
| Cassette 8, 70°N | | | | | |
| L275-1-1[1] | 9.6 | 3.79 ±0.47 | 27400 ± 700 | 15.3 ± 2.8 | 1.42 ±0.27 |
| L275-1-2 | 57.7 | 3.28 ±0.30 | 26000 ± 400 | 6.6 ± 0.5 | 0.36 ±0.06 |
| Cassette 5, 24°N | | | | | |
| L199-2-1[1] | 3.8 | 18.08 ±0.64 | 135000 ±3400 | 76.8 ±10.7 | 6.53 ±0.67 |
| L199-2-2 | 38.4 | 21.33 ±0.73 | 133300 ±1900 | 34.4 ± 1.2 | 2.26 ±0.24 |
| L199-2-3 | 9.7 | 17.17 ±1.27 | 98600 ±1300 | 32.3 ± 2.7 | 1.99 ±0.38 |
| L199-2-4 | 9.7 | 19.08 ±1.09 | 110600 ±1300 | 37.5 ± 1.7 | 2.18 ±0.39 |
| L199-2-5 | 49.0 | 11.96 ±0.46 | 74800 ±1100 | 13.7 ± 0.8 | 0.78 ±0.14 |
| Cassette 4, 0° bwd. | | | | | |
| L290-2-1[2] | 19.9 | 12.63 ±0.43 | 85300 ±1700 | 48.4 ± 2.4 | 3.47 ±0.39 |
| L290-2-2 | 57.8 | 14.29 ±0.63 | 89100 ±1400 | 40.1 ± 1.2 | 2.71 ±0.16 |
| L290-2-3 | 49.3 | 16.60 ±0.51 | 98500 ±1400 | 34.9 ± 0.8 | 2.28 ±0.18 |
| Cassette 3, 0° fwd. | | | | | |
| L296-1-1[2] | 19.0 | 30.23 ±0.76 | 197600 ±3100 | 69.0 ± 2.3 | 4.38 ±0.23 |
| L296-1-2[2] | 3.8 | 30.12 ±1.61 | 190000 ±3100 | 72.5 ±10.6 | 4.94 ±1.47 |
| L296-1-3[2] | 3.7 | 30.01 ±1.90 | 186100 ±3000 | 87.9 ± 8.2 | 5.29 ±1.03 |
| L296-1-4 | 38.2 | 32.16 ±0.92 | 199000 ±2700 | 63.4 ± 1.4 | 3.25 ±0.37 |
| Cassette 6, 24°S | | | | | |
| L273-1-1[1] | 3.9 | 12.68 ±0.64 | 92400 ±1900 | 69.6 ± 8.1 | 6.37 ±1.34 |
| L273-1-3 | 44.6 | 14.45 ±0.91 | 98800 ±1400 | 45.0 ± 0.9 | 3.12 ±0.28 |
| Cassette 7, 70°S | | | | | |
| L255-1-1[1] | 9.4 | 3.92 ±0.40 | 30600 ± 800 | 20.7 ± 4.0 | 1.85 ±0.40 |
| L255-1-2 | 56.8 | 5.86 ±0.86 | 35000 ±1000 | 21.2 ± 0.9 | 1.48 ±0.24 |

[1] Total extraction at 1400°C.
[2] Heating step sequence was 150°, 450°, 1400°C.
All others: heating step sequence was 450°, 600°, 800°, 1400°C.

Table 2: Amount [in $10^6$ atoms/cm$^2$] of trapped gases released at 450°C. Corrections were applied for foil blank and machine background.

| Foil piece | Area [cm$^2$] | $^3$He | $^4$He | $^{20}$Ne | $^{22}$Ne |
|---|---|---|---|---|---|
| Cassette 9, 110°N | | | | | |
| L249-2-2 | 56.9 | <0.4 | 8500 ± 300 | 0.6 ±0.3 | <0.07 |
| Cassette 8, 70°N | | | | | |
| L275-1-2 | 57.7 | 1.8 ±0.2 | 9200 ± 200 | 1.5 ±0.1 | 0.15 ±0.04 |
| Cassette 5, 24°N | | | | | |
| L199-2-2 | 38.4 | 6.7 ±0.4 | 40900 ±1100 | 3.4 ±0.4 | 0.27 ±0.09 |
| L199-2-3 | 9.7 | 3.5 ±0.4 | 22000 ± 500 | 3.0 ±1.3 | 0.13 ±0.11 |
| L199-2-4 | 9.7 | 6.0 ±0.5 | 33100 ± 700 | 4.2 ±1.3 | 0.19 ±0.08 |
| L199-2-5 | 49.0 | 4.4 ±0.2 | 25600 ± 700 | 1.5 ±0.2 | <0.12 |
| Cassette 4, 0°, backward | | | | | |
| L290-2-1[2)] | 19.9 | 2.6 ±0.3 | 20100 ± 500 | 5.6 ±1.7 | 0.43 ±0.17 |
| L290-2-2 | 57.8 | 3.2 ±0.2 | 18000 ± 500 | 1.6 ±0.3 | 0.16 ±0.03 |
| L290-2-3 | 49.3 | 4.5 ±0.3 | 27200 ± 700 | 2.9 ±0.3 | 0.24 ±0.08 |
| Cassette 3, 0°, forward | | | | | |
| L296-1-1[2)] | 19.0 | 7.2 ±0.4 | 48200 ± 900 | 6.1 ±0.4 | 0.30 ±0.15 |
| L296-1-2[2)] | 3.8 | 7.9 ±1.1 | 54900 ±1600 | <7.0 | <0.6 |
| L296-1-3[2)] | 3.7 | 9.8 ±1.0 | 51900 ±1300 | 8.3 ±1.4 | <0.4 |
| L296-1-4 | 38.2 | 8.1 ±0.5 | 52100 ±1300 | 4.3 ±0.3 | <0.3 |
| Cassette 6, 24°S | | | | | |
| L273-1-3 | 44.6 | 4.0 ±0.8 | 24800 ± 500 | 2.4 ±0.3 | 0.16 ±0.05 |
| Cassette 7, 70°S | | | | | |
| L255-1-2 | 56.8 | 2.3 ±0.8 | 9200 ± 900 | 7.3 ±0.8 | 0.62 ±0.16 |

[2)] Heating step sequence was 150°, 450°, 1400°C.
All others: heating step sequence was 450°, 600°, 800°, 1400°C.

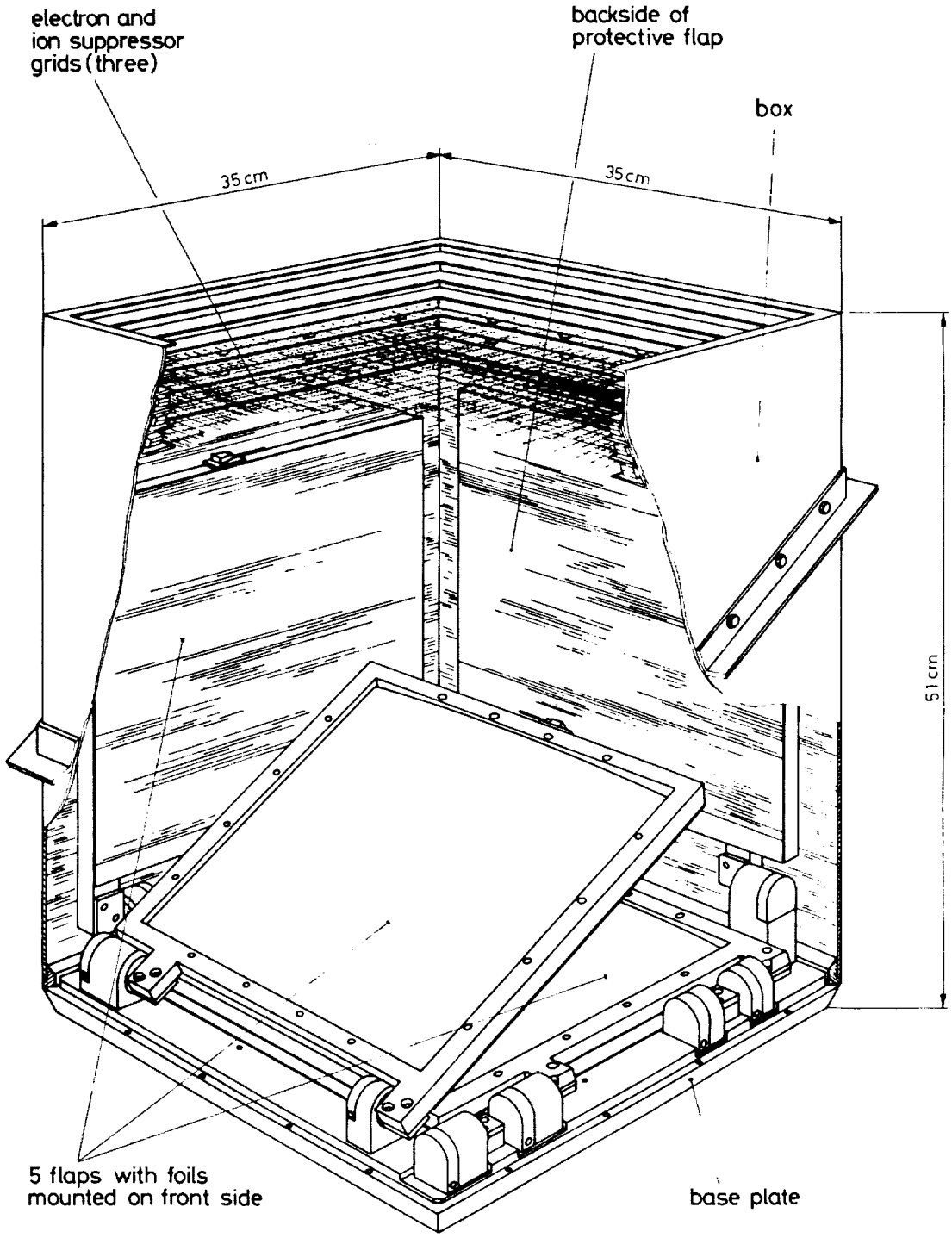


Fig. 1 One of seven collectors, containing a cassette with six plates (5 moveable, one fixed) holding one foil each. The third plate is shown turning up to expose the fourth foil.

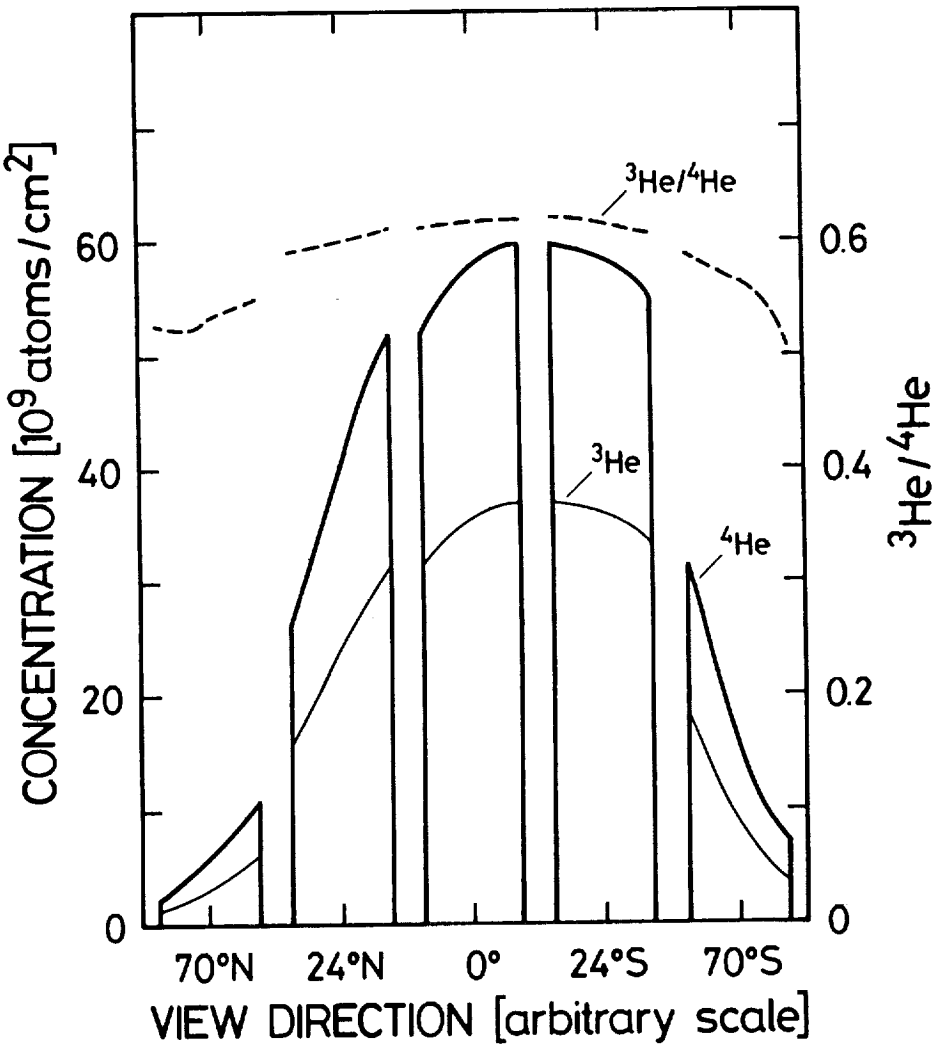


Fig. 2 Model calculation for interstellar neutral helium trapped in the IGE foils of different collectors (see ref. 1).

Interstellar $^4$He density was assumed for both isotopes in order to show the discrimination of $^3$He by its lower trapping probability.

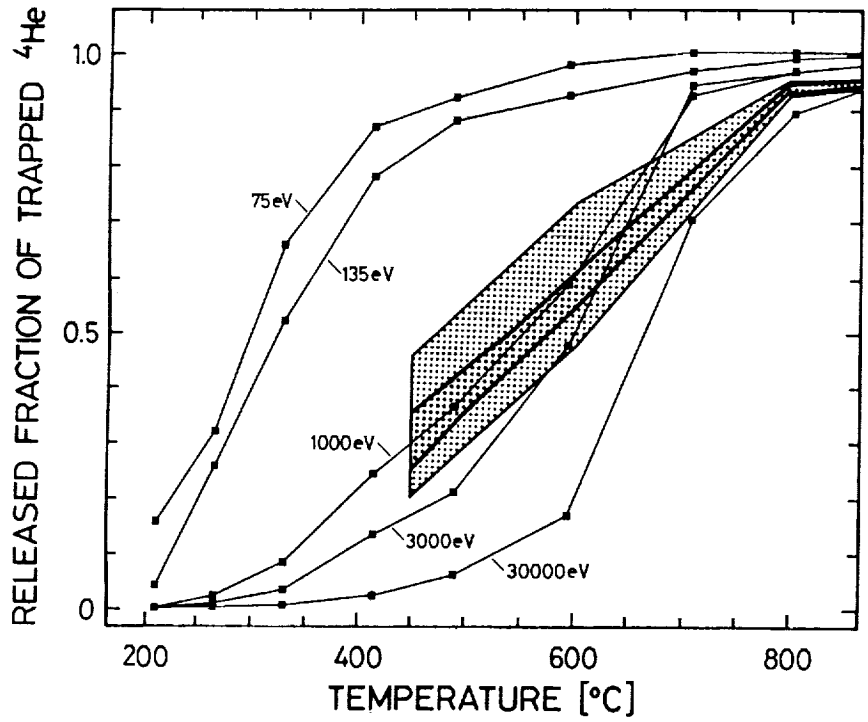


Fig. 3 $^{4}He$ released from IGE foils by stepwise heating. Squares connected by thin lines are from calibrations (ref. 11). Heating steps for exposed pieces were 450°, 600°, 800° and 1400°C, and release curves (not drawn) are within shaded regions.

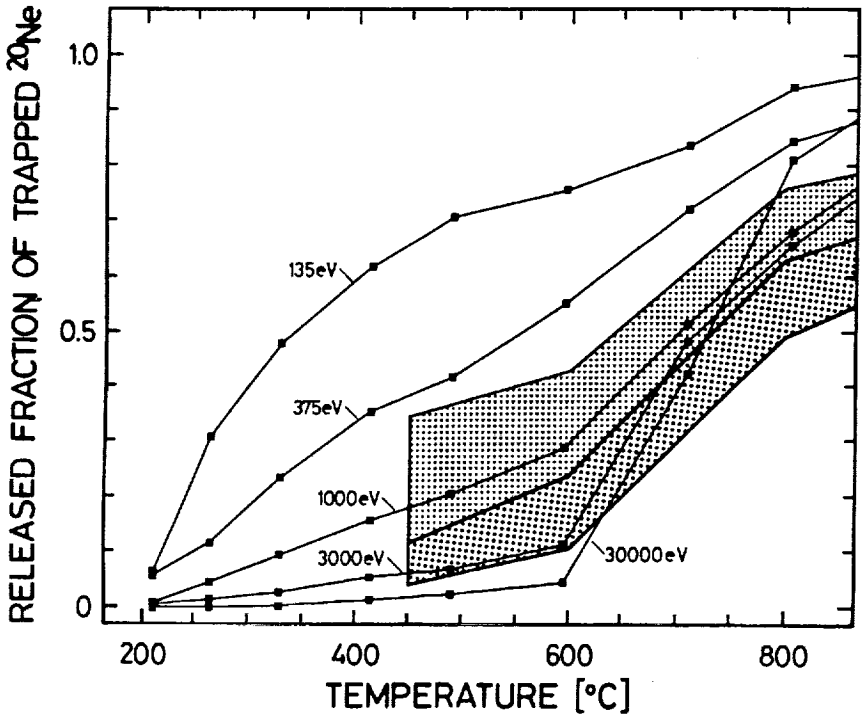


Fig. 4 $^{20}Ne$ released from IGE foils in calibrations (ref. 11) and from exposed pieces (shaded regions).

# SPACE ENVIRONMENTS

## *MICROGRAVITY*

L-84-4337