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Experimental Technique to Investigate the Interstellar Gas: Preliminary Analysis

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The Interstellar Gas Experiment (IGE) exposed thin metallic foils to collect neutral interstellar gas particles. These particles penetrate the solar system due to their motion relative to the sun. Thus, it was possible to entrap them in the collecting foils along with precipitating magnetospheric and perhaps some ambient atmospheric particles. For the entire duration of the Long Duration Exposure Facility (LDEF) mission, seven of these foils collected particles arriving from seven different directions as seen from the spacecraft. In the mass spectrometric analysis of the noble gas component of these particles, we have detected the isotopes of ^{3}He, ^{4}He, ^{20}Ne, and ^{22}Ne. In the foil analyses carried out so far, we find a distribution of particle arrival directions which shows that a significant part of the trapped particles are indeed interstellar atoms. The analysis needed to subtract the competing fluxes of magnetospheric and atmospheric particles is still in progress. The hope of this experiment is to investigate the noble gas isotopic ratios of this interstellar sample of matter which originated outside the solar system.

Introduction

WHEN the Long Duration Exposure Facility (LDEF) mission was announced, an opportunity became available to collect particles in the vicinity of the Earth and to later return them to Earth for laboratory analysis. The Interstellar Gas Experiment (IGE) was designed with precisely this goal in mind, based on a suggestion by J. Geiss[1] in 1971. Therefore, IGE was proposed for flight on LDEF and was eventually selected as part of the experiment compliment for that spacecraft. LDEF with IGE aboard was in low Earth orbit from April 1984 until January 1990.

The purpose of the experiment was to detect and, if possible, to isotopically analyze the noble gas component of the local interstellar medium. These particles which originate outside the solar system would, for the first time, be subject to direct laboratory analysis. This analysis could provide important data on the synthesis of light nuclei in the early universe (the Big Bang) and the continuing processes of nucleosynthesis and galactic evolution.

In the vicinity of the solar system, the particles of the local interstellar medium are mostly individual neutral atoms. Because of their motion relative to the sun, a portion of this flux can penetrate into the solar system as far as the region of the inner planets. The presence of these particles near the Earth was first confirmed[2] by the OGO-5 spacecraft in 1969, and they have provided us with considerable insight[3] as to the nature of the nearby interstellar medium.

The thin-foil detection technique for these interstellar particles which we proposed for the IGE was first employed on the Apollo missions to the moon to measure the isotopic ratios of the solar wind.[4,5] Later, on the Skylab mission this same technique was used to measure the isotopes of precipitating magnetospheric particles.[6] The technique has also been utilized on a sounding rocket to analyze auroral particles.[7,8] Thus, considerable experience has been accumulated in this method of collecting extraterrestrial particle samples.

The detection technique consists of exposing very thin metallic foils to the particle flux. For the IGE application, we used 15-μm-thick beryllium-copper foils with a beryllium-oxide surface layer. The impact velocities of the particles are sufficient to imbed them into the surface of the collecting foils. When the experiment is returned to Earth, the entrapped particles are liberated by heating the foils. The released gases are then analyzed in a mass spectrometer. Since the collected particle sample is extremely minute, special mass spectrometer techniques are required for their measurement. The gases are passed through a chemical getter. This removes all chemical elements except the noble gases.

In the analysis of these particles, not only can the amounts of the various noble gas isotopes be measured, but additional information can be obtained by heating the collecting foils in increments. At the first relatively low temperature (450°C), the least tightly bound particles are released. At higher temperature steps, the particles which had penetrated farther into the foil are released. Thus, we can determine a rough approximation of the impact velocity for the various portions of the collected sample.

In IGE, the foils are located at the bottom of a collector—a rectangular box which establishes the field of view for the foil and the orientation of this field of view on the celestial sphere. IGE consisted of seven such collectors, each viewing a different direction relative to the LDEF spacecraft. Figure 1 shows the orientation of these fields of view for the various collectors. In the figure, the directions of viewing are designated by the angle from the outward radius vector through LDEF to the centerline of the collector in the plane perpendicular to the velocity vector. Positive angles are to the north of the LDEF ground track. The +110 deg viewing direction points below the horizon where interstellar gas particles are shielded from LDEF by the Earth. This collector was intended to entrap only background particles. In the event that after deployment LDEF had stabilized in the inverted position, this collector could have performed a minimal experiment on its own. The remaining six collectors point above the horizon in five specific directions: +70, +24, 0, −24 and −70 deg. These angles would be unaffected if LDEF had stabilized in an orientation with leading and trailing sides reversed. As LDEF moves in its orbit, these collectors sweep out five separate swaths on the celestial sphere. As shown in the figure, two collectors point in the 0 deg direction, but view the same part of the sky, one several minutes later than the other. The purpose of tilting

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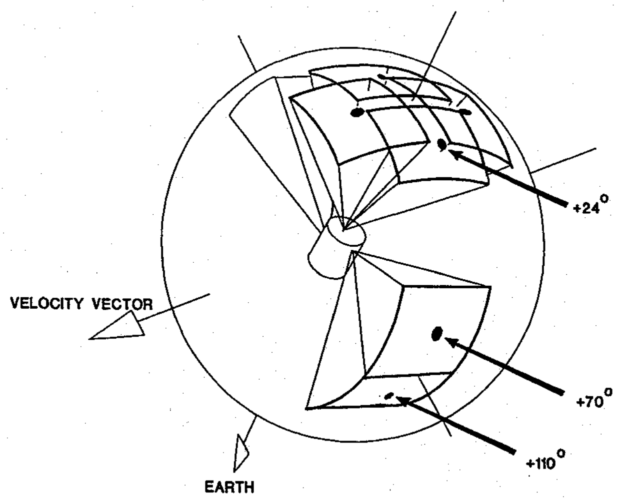

Fig. 1. The orientation of the fields of view of the seven IGE collectors relative to LDEF.

these collectors slightly forward and backward in the direction of orbital motion is to measure the background flux of ambient atmospheric particles. At the LDEF altitude, an extremely dilute portion of the Earth's atmosphere remains. Although the collectors are normally pointed perpendicular to the direction of orbital motion, a small fraction of the atmospheric particles that form the high-temperature end of the velocity distribution could have enough lateral velocity to enter the collectors as a background flux. By intentionally tipping one collector toward this flux and one collector away from it, we could measure and later subtract out these atmospheric particles.

Provisions were made to reject as many background particles as possible. Along the inner surfaces of the collectors, knife-edge baffles and serrations prevented a particle from reaching the collecting foils in a single bounce off the collector walls. This significantly reduced the number of background atmospheric particles which could be entrapped in the foils. An additional source of background particles is the flux of charged particles precipitating from the magnetosphere, particularly from the double charge-exchange reactions. IGE was designed to reject a significant fraction of these particles with a high-voltage grid (+1250 V) across the entrance of the collector.

LDEF was gravity-gradient stabilized about the roll and pitch axes. Asymmetric moments of inertia coupled to the orbital angular momentum provided a weaker stabilizing torque about the yaw axis. The deviation of the final orientation of LDEF from the predicted orientation was 0 deg (roll—the most critical axis for IGE); 0.8 deg (pitch), and 8.1 deg (yaw—the least critical axis). Thus, for IGE the LDEF orientation was entirely satisfactory.

Interstellar Particle Estimates

To estimate how the interstellar particles would be distributed among our collectors as they entrap particles approaching from different regions of the sky, and also to understand how the particle's angular distribution varies in different seasons of the year, we developed a computer model of the interstellar particle angular distribution as a function of location along the Earth's orbit. The appropriate portions of these distributions were then summed as the collector's fields of view were swept across the celestial sphere by LDEF orbital motion. For the changing angular distribution calculation, we followed the program developed by R.R. Meier at the Naval Research Laboratory.[9,10]

We, in effect, calculate the trajectories of individual interstellar gas particles from the time they cross the heliopause until they reach the orbit of the Earth. The mean distance between collisions for these particles is so great that each individual particle follows a separate keplerian trajectory past the sun.[11,12] The gravitational attraction of the sun concentrates the particles beyond the sun (gravitational focusing) and significantly alters their original angular distribution. Figure 2 shows the trajectories of particles as they approach and pass the sun. Only neutral particles can move upstream against the solar wind plasma as it flows outward from the sun. Therefore, we must estimate the rate at which these neutral particles are ionized by solar radiation. If a particle is ionized, it is swept away from the sun by the solar wind and is dropped from the calculation. The photoionization rate at 1 AU determines the ionization at all locations in our calculation.

The initial state of the interstellar gas as it penetrates the heliopause can be characterized by the following parameters: the particle velocity relative to the sun, temperature, particle density by species, and the initial direction of approach toward the solar system. The apparent direction of approach of the interstellar gas is determined by the vector sum of the velocity of the sun (toward the solar apex) and the proper motion of the interstellar gas itself. This proper motion is from a galactically southern direction. We used for our model calculations the best estimates for these parameters given at the workshop, "Interstellar Gas in Interstellar Space," held at the Max Planck Institut für Aeronomie in Lindau, Germany June 18–20, 1980.[13] The values of the parameters in our calculations were as follows:

Velocity	24 km/s
Temperature	12,000 K
Helium density	0.0124 cm^{-3}
Right ascension	252 deg
Declination	−17.5 deg
Photoionization rate	0.68×10^{-7} s^{-1}

Since the efficiency of the trapping of the interstellar gas particles by the collecting foils varies considerably as a function of impact velocity, we calculated the velocity of each arriving particle as a function of approach direction toward the Earth and multiplied the flux from that direction by the laboratory measured trapping efficiency for that velocity. This gave us a map across the sky of the flux of particles which would be energetic enough to be entrapped in the IGE foils. Figure 3 shows four examples of these all-sky maps. In our

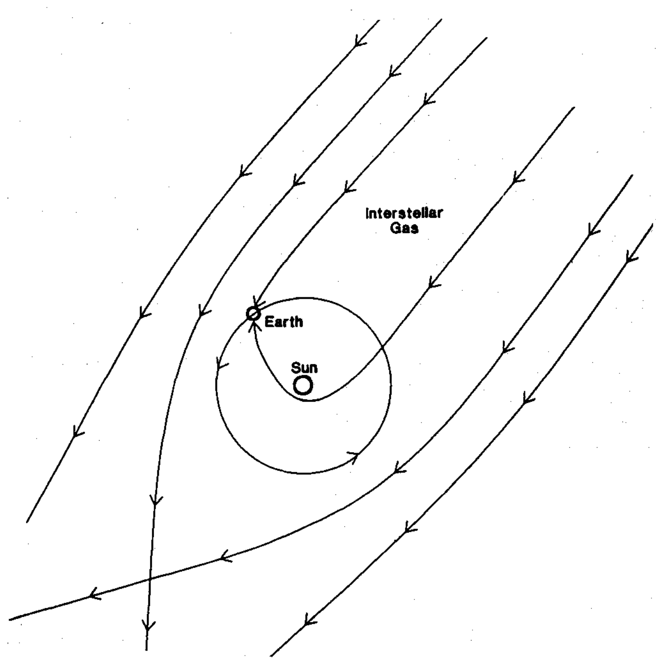

Fig. 2 Interstellar gas particle trajectories in the vicinity of the Earth.

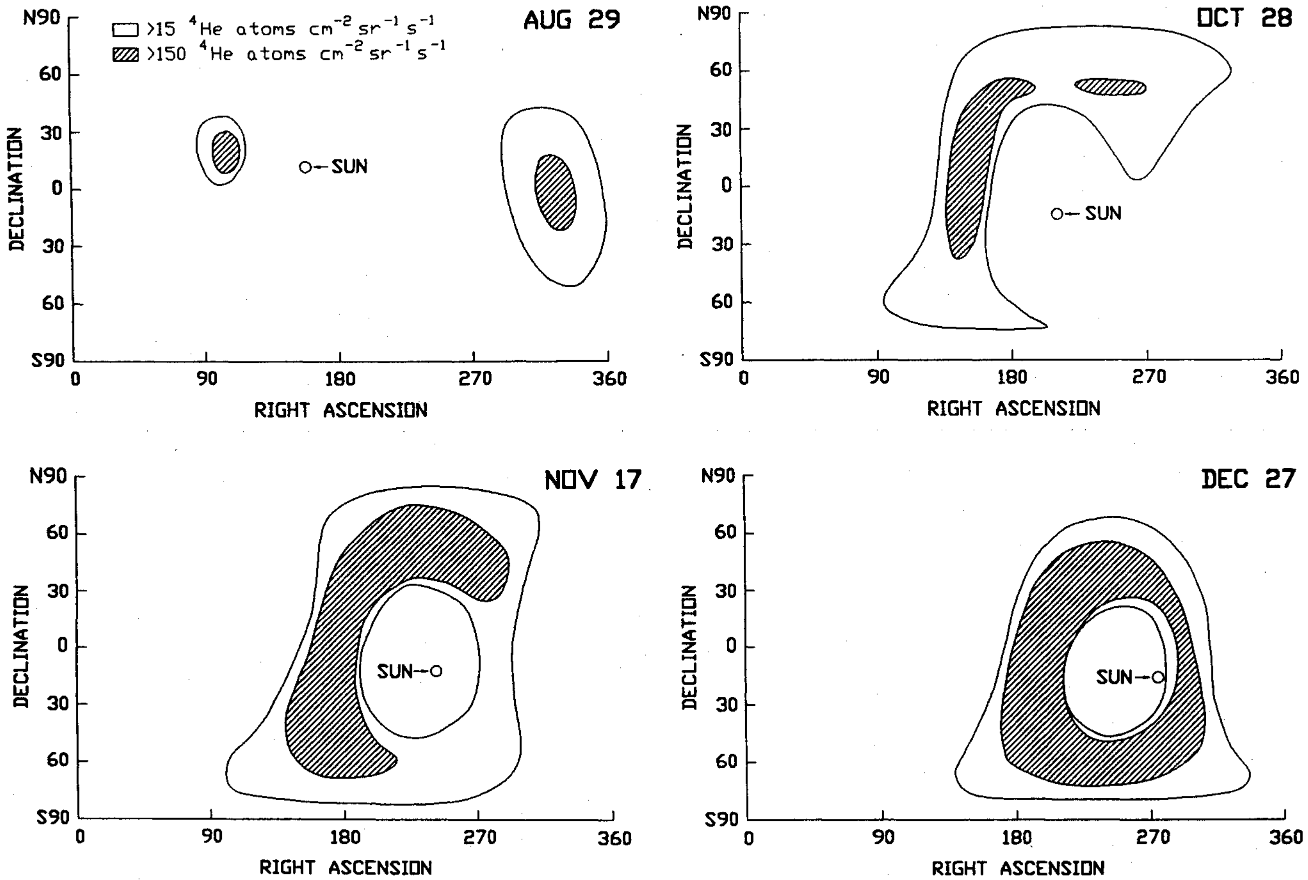

Fig. 3 All-sky maps of the flux of interstellar helium with sufficient energy to be entrapped in the IGE collecting foils.

model, a calculation of this kind was made for each day of the year, that is, entirely around the orbit of the Earth. Each map is a contour plot of the particle flux over the entire celestial sphere. Only two contours are shown for clarity. In Fig. 3, the Aug. 29 map shows the situation when the Earth is in the upstream portion of its orbit when particles are approaching the Earth and LDEF from two widely separated directions. This situation corresponds to the two particle trajectories in Fig. 2 which arrive at the Earth. On this map, particles approaching from the direction on the right are only slightly deviated from the original direction from which the interstellar gas approaches the solar system. However, the particles arriving on the left have passed very close to the sun and have been significantly deviated in direction. They appear to be coming from a direction very different from the original direction of the interstellar wind. Also since they have traveled for a longer time in a region of high photoionization, their flux intensity has been reduced more than the particles arriving on the right. The relative intensity and location of these two flux populations varies considerably throughout the year.

In the winter portion of the Earth's orbit, where the downstream interstellar gas flux is located, a unique geometric singularity occurs. The initial direction of the interstellar wind and the positions of the sun and the Earth are almost in a straight line. This geometry allows particles to pass both over and under the sun and then to to be deflected toward the Earth. This is not geometrically possible at other seasons of the year. This condition radically alters the angular distribution of the arriving interstellar particles. As shown in the remaining three maps in Fig. 3, the flux gradually shifts into a configuration where particles are approaching LDEF from an annular region encircling the sun.

On these maps, the LDEF orbit traces out a single sinusoidal curve across the sky. As the orbit precesses, this curve moves slowly to the left, crossing the entire map once every 53 days. As a result of this motion, the five swaths which the fields of view of the IGE collectors sweep out, likewise move in a corresponding pattern across the map of the sky. By integrating the particle flux within these moving fields of view, with proper account being taken of the shadowing effects of the collector walls, we could predict how many particles each foil would collect for any proposed exposure period. In this manner, we preprogrammed the IGE exposure sequences to optimize the recognition of the seasonally changing particle angular distribution pattern.

IGE Space Operations

Each of the seven IGE collectors contains six foils which were intended to be mechanically moved in sequence into the exposure position. However, due to as yet unexplained problems, this did not occur as programmed. After the flight, all of the electronic and pyrotechnic components of the system separately operated properly and the analysis of why the composite system failed to initiate the deployment of most of the foils is still in progress.

As a result of this situation, in each collector a single foil collected particles for the entire LDEF mission time. This has had both a positive and a negative effect on our data. The total flux collected was almost six times more than we had planned for the original 1-yr LDEF mission. However, the time history of the changing particle angular distribution was lost when the particle collection was integrated over all seasons onto one set of seven foils.

Data Adequacy

The question which had to be answered because of this malfunction was whether or not we would still be able to identify interstellar gas particles in our data. To address this question, we calculated with our model the integrated interstellar particle flux which each exposed IGE foil should expect to collect during the mission using the actual LDEF orbit as it had been tracked by the NORAD radar system. The results of this calculation are shown in Fig. 4. The five swaths on the celestial sphere swept out by the IGE collectors still showed the clearly recognizable interstellar gas pattern, even when integrated over the entire exposure period. These five predicted values represent all seven IGE collectors. Two collectors looked in the 0 deg direction and the 110 deg collector, which was to measure only background, had a predicted flux, of course, of zero. The predicted range of interstellar particle densities is more than an order of magnitude between the various foils. It appeared that the collected data would still be adequate to identify interstellar gas particles among the background particles which would also be in the foils.

We pursued this question one step further. One edge of every foil (either the northern or the southern edge) looks out of the opening of the collector to view a slightly different area of the sky than that seen by the opposite edge. If either a more or less intense flux consistently arrives from this part of the sky, there will be a gradient in the numbers of particle entrapped in the foil in the north-south direction. To check on this effect, we divided each foil into seven strips and calculated from our model how many particles would be entrapped in each portion of each foil. The results are presented in Fig. 5. The calculation indicated that an interstellar particle density gradient should be present in each foil. In the 24 and −70-deg foils, the particle density should differ by a factor of 2 and 5, respectively, from one side of the foil to the other. These gradients in the particle concentration are another feature which can identify interstellar gas particles and differentiate them from background particles.

Background Calculations

We are presently in the process of estimating the flux of background particles which we expect in the collecting foils. Currently at Utah State University we are modeling the temperature and density profiles of the atmosphere at the LDEF altitudes, accounting for the effects of the solar cycle, to calculate how many ambient atmospheric particles were able to bypass the baffle system and enter the different regions of each IGE foil. In parallel, the magnetospheric background particles are being estimated at the University of Bern. We have measured the current drain though each of the sets of collector electronics and have calculated how long each battery survived during the extended LDEF mission. Thus, we can infer how long the high-voltage grid on each collector functioned in suppressing charged particles. This will effect our estimates of the magnetospheric particle fluxes.

Mass Spectrometric Measurements

The initial set of measurements of the entrapped isotopes in small samples from each of the IGE foils have been completed

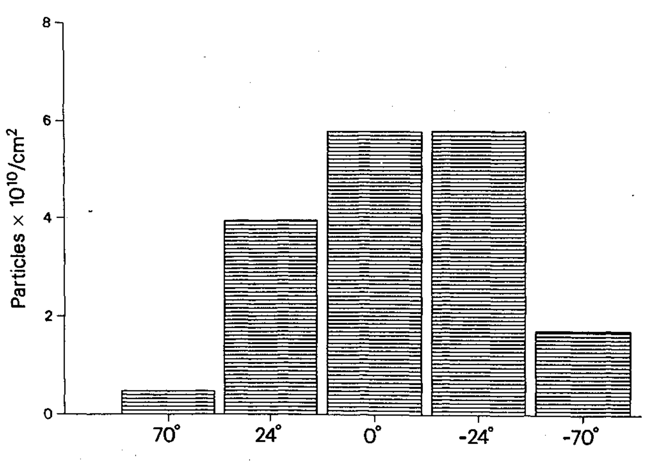

Fig. 4 The predicted concentration of entrapped interstellar^4 He atoms in the IGE collectors.

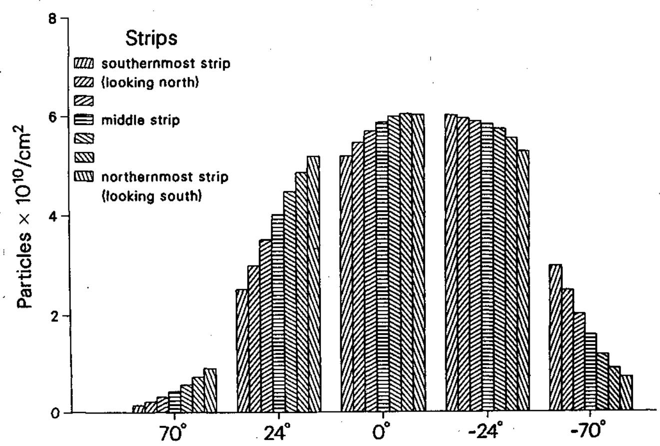

Fig. 5 The predicted concentration of entrapped interstellar^4 He particles across each IGE collecting foil.

at the University of Bern. The isotopes of ^{3}He, ^{4}He, ^{20}Ne, and ^{22}Ne have so far been measured.

The analysis of these measurements is currently at a preliminary stage. The isotopes measured so far appear to be occurring in approximately the expected relative amounts, assuming that in the present interstellar medium the values are not totally different from those inferred for the protosolar gas.[14] Also, the particle concentration pattern between collectors follows generally the predicted pattern for interstellar gas particles. The measured fluxes are between 1.3 and 3.6 times larger than the predicted interstellar particle fluxes which we interpret to mean that the competing background fluxes together are of nearly the same order of magnitude as the interstellar fluxes. If this is the case, we can probably do the background subtractions quite confidently. Also the forward-tipped collector sees a higher flux than the backward-tipped collector which looks at the same part of the sky. This appears to result from the increased flux of atmospheric background particles, as expected. However, the depth of penetration as indicated by the heating steps and the ^{3}He/^{4}He ratio for this component is not understood yet. Finally, in the two foils where we have attempted to measure an intensity gradient so far, a gradient does exist which is of the correct magnitude and is in the correct direction.

Conclusions

Based on the preliminary analysis of our initial mass spectrometric measurements, we have drawn the following conclusions.

1) IGE was successful in collecting and returning to Earth for analysis a sample of neutral interstellar gas. Since this sample of matter originates outside the solar system, it is of intrinsic interest. If we are successful in determining the ratios of the helium and neon isotopes, they should contain significant information relative to the predictions of Big Bang and stellar nucleosynthesis.

2) Despite the loss of the time history of the changing angular distribution of the interstellar gas particles due to the failure of the collecting foils to sequence properly, we still have enough information to verify that a major fraction of the collected sample is from the interstellar gas. It appears possible that we will be able to approximately separate the three components of the trapped particles, i.e., interstellar, magnetospheric, and ambient atmosphere.

3) IGE has verified the usefulness of our thin foil collection technique in the investigation of the interstellar gas. Based on our experience with IGE, we can establish reasonable guidelines for future investigations of the interstellar gas. It would be most effective to mount foil collectors on an inertially stabilized platform in low Earth orbit. The collector could be continuously pointed to the calculated direction of the most

intense interstellar gas flux. This would significantly increase the ratio of collected interstellar particles to background particles. Thus, with the techniques developed for IGE, the local interstellar medium is now accessible for laboratory investigation and analysis.

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