Aerogel Captures Cometary and Interstellar Samples via STARDUST

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Abstract

Aerogel is the primary payload on STARDUST, the fourth mission of the National Aeronautics and Space Administration Discovery Program, to be launched in February 1999. Of all aerogel applications, none is more far reaching than launching it into space for explorations. STARDUST is a mission to capture and return to Earth samples from comet Wild-2 and contemporary interstellar samples. Such samples could yield key knowledge for unlocking secrets of the formation of the Solar System and perhaps precursors of life. Aerogel possesses properties that render it very suitable for the intact capture of hypervelocity particles for STARDUST. Several new developments to provide features tailored for STARDUST should advance the state of the art of aerogel and increase the scope of its applications even further.

1. Introduction

Aerogel is being considered for many applications; none reaches further than for space exploration. STARDUST, the fourth mission of the National Aeronautics and Space Administration (NASA) Discovery Program, will loop around the Sun three times to beyond the orbit of Mars to capture extraterrestrial samples and return them to Earth for detailed laboratory analysis. This is a long dream quest realized [1]. Aerogel will be the primary payload of the STARDUST mission to capture and retain samples from a "fresh" comet, Wild-2. On its way to Wild-2, the back side of the sample collector will capture contemporary interstellar samples intercepted by the Solar System from other stars.

Comets are probably the most primitive bodies in the Solar System. They appear to be well preserved frozen relics of the preplanetary material that accreted in the outer fringes of the solar nebula. They also present the most easily obtainable samples of some of the original material from which the Solar System was formed. Thus, the study of comets is important for understanding the processes involved in the formation and subsequent development of our Solar System. Capturing cometary material that accreted in the outer fringes of the solar nebula will provide valuable information about the early solar nebula, planetary formation and possibly life precursors.

The dust detector instrument on Ulysses made a startling discovery [2]: the existence of collimated interstellar material, subsequently confirmed by Galileo [3]. This opens to STARDUST the opportunity in one mission to collect the best preserved remnants of the interstellar material accreted in comets at the formation of the Solar System and "freshly" emitted contemporary interstellar samples. Via STARDUST we now have the unique opportunity to analyze interstellar materials that are intercepted about five and a half billion years apart.

The sample capture medium chosen for STARDUST is inorganic aerogel. This choice was based on extensive laboratory simulation experiments [4] and space validation flights [5]. Aerogel possesses unique properties making it suitable for space applications [6]. With further enhancing developments, aerogel will meet the unique challenges of the STARDUST mission.

This paper presents the goals and background of the STARDUST mission, its exciting science objectives, the unique properties of aerogel that render it suitable for

STARDUST, and a few unique challenges in aerogel enhancing developments to fulfill STARDUST's sample collection goals.

2. STARDUST Mission

NASA's Discovery Program represents a new paradigm for space exploration. This new mantra "faster, better, cheaper" promotes more frequent missions with focused science but with very rigid, much reduced cost caps of $200M. Although STARDUST is the fourth Discovery mission, but the first to be selected by open competition, having been chosen from among 28 proposals submitted.

2.1. Mission strategy

Back in 1982, long before the new NASA mantra was even conceived, it was realized that the feasibility of a comet coma sample return mission depended on being low-cost. This would mean a free-return flyby mission, not a comet rendezvous or lander mission. Furthermore, flyby sample return dictates hypervelocity encounter speeds in the range of 15 to 25 km/s, beyond the speed for intact capture of most solids. Thus, four major thrusts needed to be systematically brought to maturity:

1. Solid proof of intact capture technique at the low hypervelocities (in the range of 10 km/s) in laboratory simulations and space captures,
2. The design of a low-encounter-speed (< 10 km/s) comet free-return sample return trajectory targeted toward a scientifically interesting comet,
3. The search for a simple passive collection medium that could be space qualifiable and suitable for intact capture of hypervelocity particles, and
4. The development of a mandate for a cometary coma sample return mission through recognition in NASA's mission plans by submittal of captivating proposals.

Indeed, STARDUST is the culmination of these and many other efforts in the quest of a cometary coma sample return mission. It took just over a decade and a half for this quest to be granted.

2.2. Mission history

The first major proposal for a cometary mission appeared in 1959 [7]. For the last Halley apparition, the Jet Propulsion Laboratory (JPL) made a series of unsuccessful proposals culminating in the Halley Intercept Mission and the Halley Earth Return (HER) Mission. Later, another major important mission, Comet Rendezvous and Asteroid Flyby, was projectized but was canceled due to lack of funding. Cometary missions have eluded JPL for all these years. JPL did lead a successful International Halley Watch [8]. STARDUST will be the first U.S. and JPL cometary and robotic sample return mission.

HER was the first proposed comet coma sample return mission [9,10]. The first low-cost mission, the Comet Intercept Mission, was proposed to the Planetary Observer Program [11]. Using the European Space Agency's (ESA) spare Giotto spacecraft, a Giotto II was proposed jointly with ESA [12]. Based on Giotto II and JPL studies, an all-European CAESAR proposal was submitted [13]. Later, a Cosmic Dust Intact Capture Explorer was proposed for a NASA Explorer Program [14]. An exobiology Intact Capture Experiment and an Interstellar Dust Intact Capture Experiment were proposed as Space Station attached payload [15]. Since 1987, JPL, jointly with Japan's Institute of Space and Astronautic Sciences, planned for a Sample of Comet Coma Earth Return (SOCCER) mission [16]. Due to these and many other cometary mission endeavors, JPL has attracted a good core of cometary scientists, including M. Hanner, M. Neugebauer, R. Newburn, Z. Sekanina, P. Weissman, and D. Yeomans (four are directly involved with STARDUST).

2.3. *Mission concept*

The Solar System Exploration Committee prepared a Core Program for NASA's Space Exploration in 1983. A "Comet Atomized Sample Return" mission was included as part of the Core Program [17]. By 1986, an Augmented NASA Space Exploration Program stated that "the SSEC considers that the return of a sample from the nucleus of a comet is one of the highest priorities for an augmentation mission" [18]. The NASA strategic plans of 1992 and 1994, Vision 21 and Space Science for the 21st Century, carried a Small Bodies Mission category, which included SOCCER [19]. During the commission of this NASA Small Bodies Science Working Group, the mind-set was transformed from our original proposed "atomized sample return" to our revolutionized "intact sample return", as reflected in their final report [20]. In 1997, NASA published the Space Science Enterprise - Strategic Plan, citing STARDUST as contributing to two of the eleven Science Goals and Objectives [21].

The primary goal of STARDUST is to fly by a "fresh" comet very close to the nucleus, well within the parent molecule region (~100 km), to bring pristine samples back to Earth and to study the comet by in situ chemical analysis and imaging of its nucleus [22]. This will be the first U.S. sample return from a known planetary source since the Apollo lunar sample returns. This mission will improve upon previous missions to the comet Halley and provide the first extraterrestrial samples of known source to scientists all around the world in thirty years.

2.4. *Mission design*

An all-sky search for comet flyby sample return opportunities began in 1984 [23]. This survey has been the guide for our mission proposals [24]. The Discovery Program limited the launch energy to that of a Delta launch vehicle and specified a 1999 launch limit. For good science, the targeted comet has to be interesting and dusty, and the trajectory must permit a low encounter speed to allow adequate intact capture. An ingenious low-energy and free-return trajectory was found to a recently deflected "fresh" comet, Wild-2, at an encounter speed as low as 5.4 km/s. Figure 1 is an artist's concept of this mission, and Figure 2 shows this same trajectory with critical dates denoted. The reduction of the cometary encounter speed was achieved by an Earth gravity assist to speed up the spacecraft to match more closely the speed of the comet [25].

2.5. *Direct Earth reentry*

Due to the need to keep the overall cost down, a less expensive method of Earth return of the captured samples via a direct reentry capsule had to be adapted for STARDUST. In fact, this STARDUST direct reentry capsule is similar to what was proposed for HER, which was the U. S. Air Force's Discoverer capsule [26]. Alternative Earth return options included retrieval by an Orbiting Maneuvering Vehicle to a Space Station or direct retrieval by the Shuttle. This direct reentry capsule option dictates a considerable reduction in the total collection surface area from 8 m^2 on SOCCER to a goal of 1000 cm^2 for STARDUST, and also eliminates the active cooling feature to preserve captured ices [16].

2.6. *Design approach*

For sample return missions, the sample collector should encounter the cometary coma sample first by locating the collector at the foremost of the spacecraft [16]. In this way, no secondary debris will be mixed with the collected samples. In order to best preserve the captured samples, the container that holds the collected samples should be kept in a sealed compartment with a positive purge, as is done for the stratospheric collection of cosmic dust; this will best preserve the samples and prevent contamination from terrestrial sources.

2.7. Complementary instruments

To provide complementary in situ science, an improved time-of-flight spectrometer flown on the Giotto and Vega missions, the Particle Impact Analyzer, is being supplied by the German government. This Cometary and Interstellar Dust Analyzer will provide in situ chemical analysis of dust particles. These data will be used to facilitate post-flight analysis and sample interpretation. To reduce cost further, four engineering subsystems (the navigation camera, the spacecraft's main dust shield, the radio communication subsystem and the attitude control subsystem) are engineered to provide, respectively, in situ cometary imaging, cometary dust flux monitoring, total integrated dust flux and large particle impacts that require spacecraft attitude correction. If the encounter distance turns out to be close enough, tracking by the two-way Doppler from the radio carrier frequencies may provide estimates of the comet's mass.

Although STARDUST is a focused science mission for cometary sample return, it does carry a complementary set of dedicated and shared instruments to provide a well rounded exploration of Wild-2, as well as in situ studying and collection of contemporary samples of interstellar material.

3. Unique Properties of Aerogel

Aerogel possesses a somewhat magical intrigue, which certainly increased STARDUST's appeal as a mission. The suitability of metallic aerogels for cosmic dust collection in space was presented in the preceding Symposium [1]. Some unique properties of aerogel that are specifically applicable to STARDUST are delineated.

3.1. Ultrafine mesostructure

Fine mesostructure will present a more gentle intact capture. Mesostructure refers to the macro shape and arrangement of the material structure. Based on analytical modeling and extensive experimental laboratory simulations at hypervelocities [27], we have shown that the mesostructure of the capture medium has a significant effect on the quality of the intact capture. In fact, within a selected density range, the mesostructure dominates the intact capture process [28]. Aerogel has an ultrafine mesostructure in the nm range, which is finer than that of any polymer foam.

3.2. Coating effect

Cometary particles are expected to be fluffy and loosely connected, with little structural strength. Having very fine microstructure, aerogel is especially effective for capturing these cometary particles. Figure 3 shows that the silica aerogel appears to have coated the frontal portion of the particle; thus, the coating serves as a shield for the particle. This effect is significantly more pronounced for fine-microstructure aerogel as opposed to polymer foams. This coating also serves to further reduce the incoming particle's kinetic energy and thus shorten the total stopping distance. For very fluffy cometary particles, the coating will likely keep fragile composite particles together.

3.3. Ultralow density

Aerogel has been made with lower density than that of air. This property is important for reducing initial shock on capture. It is not possible to fabricate polymer foams or any other solid with lower density than aerogel. Since reducing the aerogel density does not change the mesostructure, but only the scaling, the physics of intact capture is not changed [29].

3.4. Wide density range

The expected size of particles encountered by STARDUST ranges over 3 orders of magnitude, from sub-μm to 100s of μm in diameter, or 9 orders of magnitude in mass. Furthermore, the integrity of the cometary particles will vary from solids such as silicates or ices to very fluffy composite particles. In order to preserve the full range of particle integrity, providing the gentlest possible capture for the fluffy particles while retaining larger solids, the widest possible range of density is needed. No other solid can provide a wider density range than aerogel.

3.5. Transparency

Detecting μm-sized particles on a surface can be challenging and time consuming, as any microscopist would know. Studying the same μm particles within an optically opaque solid medium would be nearly impossible. Optical transparency, along with the particle tracks, makes the task immensely easier. Aerogel, and in particular silica aerogel, can be made very transparent, greater than 80% in the 800-nm range. In silica aerogel, we have been able to detect sub-μm particles routinely under 200X magnification with a microscope. This high transparency also allows a wide range of transmission instruments to be used.

3.6. High internal surface area

Aerogel is known for its high internal surface area. Recently the more spectacular cometary encounters, Halley, Hale-Bopp. and Hyakutake, have shown that comets are rich in organic volatiles. In fact, Halley, studied from the closest distance to date, showed more than 50% of its cometary coma to be organic. Aerogel's very high internal surface area provides ideal physisorptive trapping surfaces as well as the structure for lodging active chemisorption sites to chemically react with specific organic species.

3.7. Immunity to space environmental effects

STARDUST is a seven-year mission. UV radiation is ubiquitous in space. Although some polymeric foams may yield a higher intact recovery ratio than silica aerogel [30], any significant exposure to UV will cause polymeric organic material to undergo significant structural change, i.e., to turn into powder. Inorganic aerogel is immune to UV.

Another significant damaging space condition is caused by free ions. Mylar is quite a strong material, but atomic oxygen is known to etch Mylar very rapidly. Metallic oxide aerogels are not damaged by atomic oxygen. Especially in the case of low-density foams, catastrophic damage can result in a free-ion environment.

In space, the temperature can cycle from very hot to very cold, as the Sun gets in and out of the view. The STARDUST sample tray holding the aerogel cells will be bare aluminum, which can experience very wide temperature swings, e. g., from +100°C to -100°C. Inorganic aerogel withstands such temperature cycling.

For space sample return missions, aerogel is the most nearly ideal capture medium currently available. Since surprises and unexpected discoveries are the rule in space explorations, it is always good planning to include excess capacity or broad flexibility in a space instrument. Aerogel possesses the desired broad flexibility and much excess capacity.

4. The Aerogel Collector

Aerogel has demonstrated a considerable number of properties that render it very suitable for the intact capture of hypervelocity particles in space. For STARDUST, tailored science features and space flight requirements dictate new aerogel developments. For a space flight project, the fabrication and handling of aerogel must be space qualified and under strict contamination control. These new features must be accomplished and flight qualified by June of 1998 and the final delivery made by November 1998 for a launch in February 1999.

4.1. Graded density

It has been shown that hypervelocity particles' initial shock pressure correlates directly with the density of the impinging material for a suitable mesostructure. Consequently, the aerogel capture cell should have the lowest possible density at the surface to minimize the initial shock pressure. This is especially critical for fluffy, weakly held-together STARDUST cometary particles. On the other hand, for a very-low-density monolithic aerogel, the total length of the capture track, i. e., the thickness of the aerogel capture cell, would need to be very long. Since space is limited, the best solution would be to fabricate a graded-density aerogel capture cell so that the surface density is very low and the base density is high. In this way, the total length of the aerogel cell can be much shorter, and it can retain much larger particles. This graded-density aerogel, with a density ratio of around 10:1, needs to be developed.

Based on modeling and experimental data, the following are three targeted graded-density profiles for three general groups of particle integrity, as shown in Figure 4. An interim implementation step to a fully continuous gradient aerogel would be layered monoliths.

4.2. Cast to size

By far the smoothest aerogel surface is a cloven surface, which generates no obscuration. Obscuration is especially important for searching and studying μm-sized or smaller particles. The next best surface would be a cast surface. The least desirable surface is one shaped by either mechanical or thermal means, especially for low-density aerogel. Silica aerogels are quite transparent; even so, the ability to study small features buried within aerogels is limited to a few cm. STARDUST's goal is 1000 cm^2 of aerogel exposed surface area, divided into individual cells to facilitate fabrication, handling and subsequent particle analysis. In order to provide the best cell wall surfaces, the goal is to cast to size. Thus the challenge is to cast aerogel cells into predetermined dimensions and shapes.

4.3. Cell containment

These individual aerogel cells must be constrained in a rigid tray mounted into a mechanized canister, and the entire system must survive launch shock and vibration, motions of tray deployment during collection and retraction, and Earth reentry and surface landing shock. Aerogel is generally perceived as fragile; thus the structure that holds the aerogel cells may need shock absorption, which can be complex and costly. Mass is at a premium for space flights; the simplest and the least massive structure would be desired for STARDUST. Since aerogel is not suitable to be glued, a new method needs to be developed to constrain the cells in such a way as to satisfy all flight qualification requirements, yet with minimum mass.

4.4. Contamination

In order to find out all we can about the comet and interstellar samples, we must be very careful not to mask the sample by terrestrial contamination or inadvertently introduced processes that alter the pristine state of the samples. Contamination cannot be eliminated, but it must be meticulously controlled, for the sources are many and usually have much higher concentrations than the collected samples. The contamination goals set for the STARDUST aerogel are as follows:

Inorganic contaminants ≤ 100 ppm
Organic contaminants ≤ 1000 ppm
Embedded solids ≤ 100 (> 1 μm)/cm^3
Embedded contaminants ≤ 10 /cm^3
Clarity ≥ 90% @ 800 nm

To achieve these goals, the entire aerogel fabrication process must be brought into a clean room with provisions for eliminating both particulate and organic contaminants. Postprocessing of aerogel must be performed under strict controls to avoid contamination from terrestrial sources. A new life-cycle handling and processing technique must also be devised to achieve these contamination goals.

4.5. *Smart aerogel*

The aerogel structure provides passive physisorption of hypervelocity solid particles. In order to retain the abundant organic contents of the cometary samples in the high space vacuum, a process other than physisorption is needed. Furthermore, during Earth reentry the sample will be saturated by reentry and terrestrial environments. If active chemical sites are lodged in the aerogel structure and can react with selected organics to form stable compounds, then the captured organics can be retained against the high space vacuum and contaminating environment. This is another feature that needs development. The introduced "smarts", of course, must not cause cross contamination among cells or with the captured samples.

These developments will add to aerogel's considerable advantages for space exploration and enhance STARDUST goals. The goals set for smart aerogels for STARDUST can only be a beginning effort. The potential for further development and applications is limited only by human imagination.

5. Conclusion

Aerogel is the prime medium selected for STARDUST to collect samples in space that could unlock the secrets of the formation of the solar nebula, the planets and perhaps life precursors. With eager anticipation, scientists will wait for the return of the sample packed aerogel in 2006.

To be sure, there will be many challenges in meeting the specific needs for each unique application of aerogel. To date, JPL has fabricated and flown in space more than 4 m^2 of silica aerogel in Earth orbital missions to collect intercepted cosmic dust. Figure 5 shows the in-flight Mir Sample Return Experiment. JPL has thermally insulated the Pathfinder rover, Sojourner, with aerogel as shown in Figure 6. We have every expectation that aerogel will be in wide usage in space in many more spectacular applications; e.g., a greenhouse on Mars has been proposed to grow food or building material for explorers' habitats in space.

Acknowledgments

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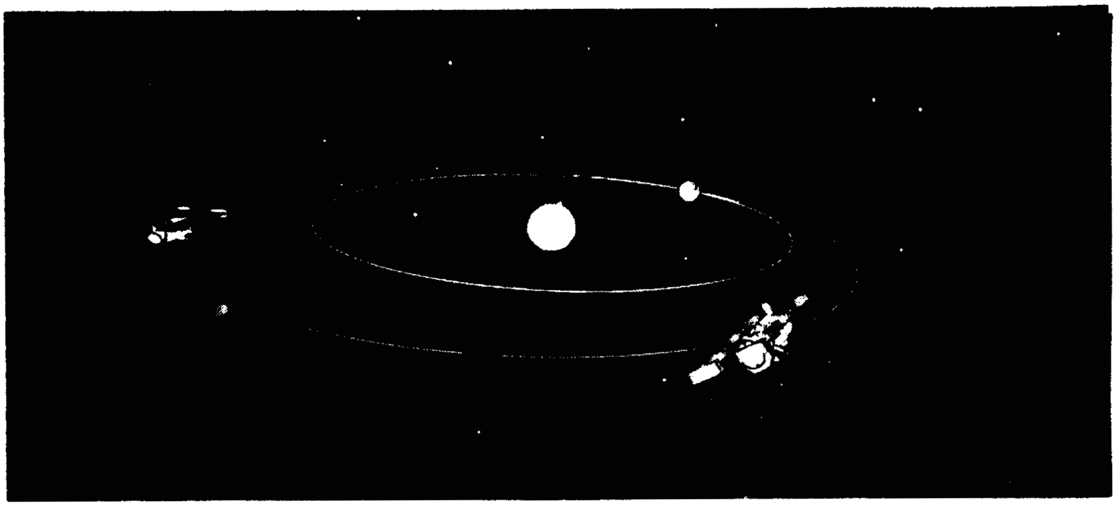
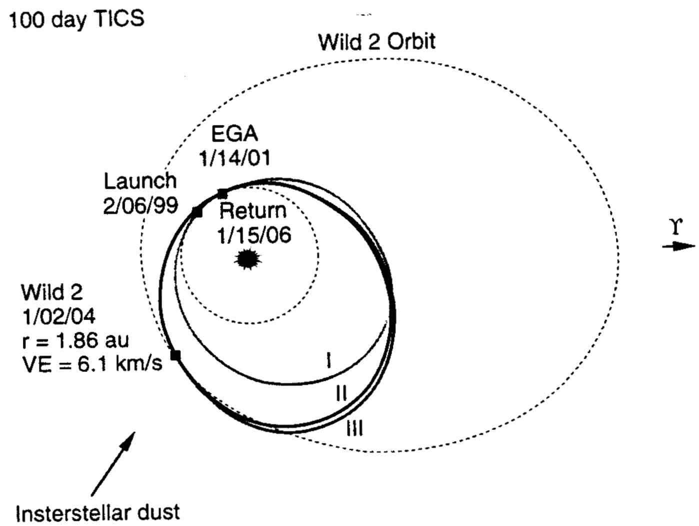


Figure 1. STARDUST Mission



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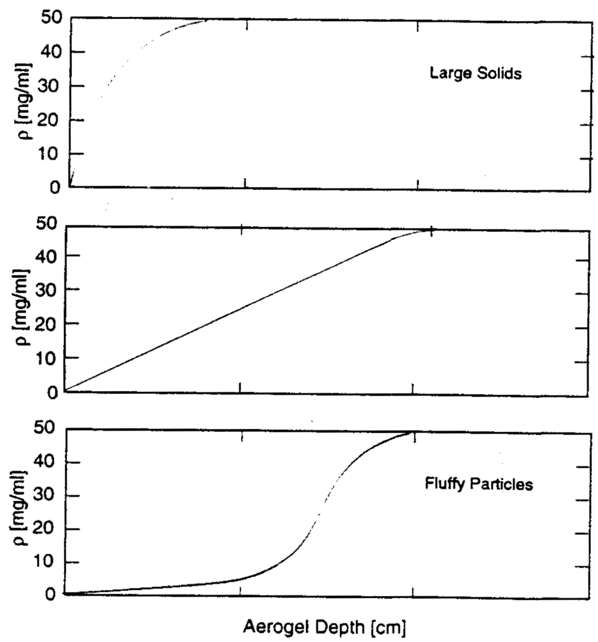

Figure 3. Graded Aerogel Profiles

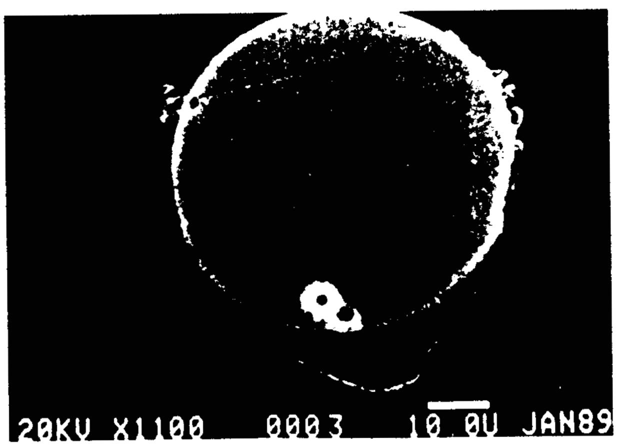

Figure 4. Aerogel Coating Effect

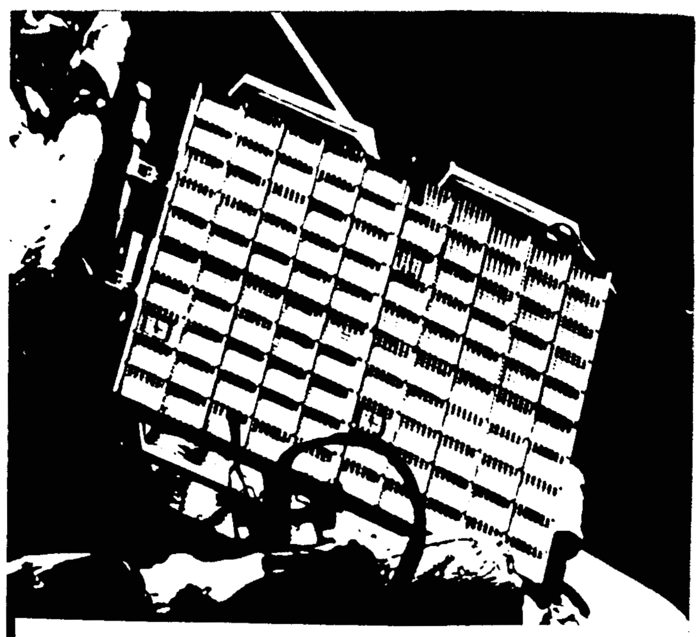

Figure 5. Mir Sample Return Experiment