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A Brief History of the *FUSE* Mission

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Abstract. A brief history of the *FUSE* mission is given from the point of view of two participants, the Principal Investigator and the NASA Project Scientist.

1. Introduction

Many at the Victoria meeting requested information about the history of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) mission. In response, we decided to add this paper to the proceedings, telling the story as best we know. Warren Moos was a member of the first NASA study group convened in the early eighties and is the Principal Investigator. George Sonneborn has been the NASA Project Scientist since 1988 and is a Co-Investigator. The creation of a space mission is a challenging and complex enterprise, both technically and also in terms of human dynamics that we sometimes try to describe with the words political or sociological. In such a brief paper we cannot adequately name and praise the many participants who gave so much of their time and talent to accomplishing the mission. To those who participated, but are not named, we apologize in advance. You and we know who you are and your contributions. Your investment in this mission has paid off dramatically. Our point of view probably emphasizes the view "in the trenches" rather then that from "Headquarters" and may have missed some of the larger picture. Still, *FUSE* was almost two decades in creation and we believe that the history of this mission may provide some help (or warning) to those contemplating similar endeavors.

With the decommissioning of the *Copernicus* mission in the late seventies, there was a growing desire among users of that satellite for a follow-on mission. To the best of our knowledge more intensive activity, following discussions between Jeff Linsky, Ed Weiler and Don York, first began during the 1980-1 decadal study. The Astronomy Survey Committee of the National Academy of Sciences (the Field committee) named a facility with far ultraviolet capabilities as its highest priority moderate cost mission for the 1980s, second only to improving the funding of the Explorer program itself.

In the early 1980's, a study of a possible mission was begun at Goddard Space Flight Center (GSFC) led by Al Boggess, then the head of the *International Ultraviolet Explorer* (*IUE*) project. In April 1983, the Final Report of the Science Working Group for the *Far Ultraviolet Spectroscopic Explorer* was issued.

That report lays out the basic science rationale. Deuterium, hot gas in the disks and halos of galaxies, winds in massive stars and many other ideas that are front line today: It's all in the report. Our understanding of these scientific issues was much more sophisticated by the time *FUSE* was launched, but this report demonstrated the scope of the research that could be accomplished by the *FUSE* mission.

Ideas about instrumentation were still preliminary. The report pointed out that a normal incidence design would not be feasible. Warren Moos wrote that section and finds it ironic that in the 1990's a normal incidence design saved the mission from cancellation. Grazing incidence telescopes and objective gratings were also under consideration, with the former being favored in the U.S. The lesson in the history of *FUSE* instrumentation is the importance of the continuing development of technology and new approaches. Also, it is striking how ambitious the first ideas were. A one meter grazing incidence telescope was baselined. (A spectrograph covering 100-900 Å was also included.) In addition, the satellite was to be placed in a high earth orbit, requiring a more capable launch vehicle. Although a grazing incidence telescope for the far ultraviolet (FUV) would not be as challenging as that of the *Chandra* mission, it is clear that the anticipated program was well outside the scope of the Explorer program as we know it now.

About this time, similar interests were being pursued in Europe, Canada and Australia. Alfred Vidal-Madjar investigated an objective grating concept named *Magellan*. The European Space Agency (ESA) completed a Phase A study in 1982, but the *Magellan* mission did not go forward. This work was important for this story, because the concurrent grating studies supported by the Centre Nationale d'Etudes spatiales were the seeds of the grating technology development necessary for the *FUSE* gratings. Several countries investigated instrumentation contributions. The European Space Agency and the Australian government called their mission concepts *Lyman* after Theodore Lyman (1874-1954), a professor at Harvard University who was the first to carry out spectroscopy in the 900-1200 Å spectral region and was the discoverer of the Lyman series of hydrogen. Like the U.S., they baselined a grazing incidence telescope and set the 900-1200 Å region as prime with a secondary capability in the 100-900 Å region. However, unlike the U.S. the 1200-2000 Å region was also included as a secondary capability. The latter wavelength range was a tribute to the success of the *IUE* mission, then still a highly productive satellite. NASA, looking forward to the *Hubble Space Telescope*(*HST*), was less interested in such a capability. In addition, the scientific emphases were somewhat different on the two sides of the Atlantic.

2. Phase A

Through the 1980's all of these groups were talking to each other. Meetings were held between the science and technical study teams of NASA, ESA, the Canadian Space Agency, (CSA) and the Australian Department of Industry, Technology and Commerce (DITAC). A cooperation analogous to IUE with major support for the mission by both Europe and the U.S. was envisioned by many of the scientists in these discussions. In 1988, ESA completed a Phase A study of the

Lyman mission. An 80 cm grazing incidence telescope in high earth orbit was the baseline.

Following the 1983 report to NASA, interested scientists in the U.S. continued to discuss a potential mission. In July 1986, in response to a call for Explorer proposals, a group led by Warren Moos submitted a proposal for *Lyman The Far Ultraviolet Spectroscopic Explorer*. An 80 cm diameter grazing incidence telescope and a Rowland mount spectrograph for 900-1200 Å as well as an instrument for 100-900 Å was proposed. The proposal listed as spacecraft options, either a mission-unique spacecraft with an Expendable Launch Vehicle (ELV) or the use of the Explorer Platform with a shuttle launch. The proposal planned to study *FUSE* as a joint mission with other space agencies, in a mode similar to *IUE*. In February 1986, the Challenger accident took place and as with the more recent Columbia accident, NASA was in turmoil and self evaluation. As a consequence, selection was delayed until February 1988, when *FUSE* and three other missions were selected for a competitive Phase A.

Table 1 lists the *FUSE* Science Teams for Phases A, B and C/D. Most joined at the start of Phase A. A few joined later and a few could only serve for the early phases of the mission. The vision and hard work of this group provided the drive and leadership for the mission.

With the commencement of the Phase A study, the need for solid international agreements increased. It is remarkable how extraordinarily difficult it is to secure international cooperation when the partners are making essentially equal contributions. On the one hand, there is an opportunity to create facilities that are far beyond the resource capabilities of any single partner. On the other hand, different entities often have very different agendas and funding schedules.

ESA also undertook a Phase A study of a similar mission, *Lyman*. In October 1988 along with *Lyman: Report on the Phase A Study*, a short memorandum *Addendum to the ESA Phase A Study Report on ESA, NASA and Canadian Collaboration* was issued by ESA. The addendum describes how shortly after the selection of *Lyman FUSE* for Phase A study in the U.S., a resolution was adopted by both the ESA and NASA study teams urging the two agencies to investigate the possibility of a collaborative mission. This led to a series of meetings and technical studies both at GSFC and at ESTEC. During a meeting between NASA and ESA representatives on September 22-23 1988 at ESA Headquarters the basis for agreements on collaboration was reached. It assumed that ESA would select its mission in November 1988 and that NASA would select its mission in the following summer. As it turned out, although NASA would select *FUSE* for Phase B, ESA did not, choosing to use its resources to provide the Huygens probe of the atmosphere of Titan as part of NASA's *Cassini* mission. At this point, the U.S. became the majority owner of the mission. In the end, both Canada and France made significant, indeed critical contributions, but NASA had to provide about 90% of the resources needed to implement the mission.

The final report of the NASA Phase A study was completed in 1989. It baselined a 70 cm telescope with a Rowland spectrograph and an EUV instrument. To minimize the cost of the mission, the study baselined the Explorer Platform with a mid-1996 shuttle launch. The Explorer Platform was planned as a reusable spacecraft with astronauts replacing instrument packages in the future. The platform was placed in orbit in 1992 carrying the *Extreme Ultraviolet Explorer*. The final report also carried letters of support from officials in both

Table 1. *FUSE* Science Team Participants and Roles Starting with Phase A

Albert Boggess Goddard Space Flight Center CoI Phases A & B	John B. Hutchings Dominion Astrophysical Obs. Canadian Scientific Rep.	Theodore P. Snow University of Colorado CoI
William P. Blair Johns Hopkins University Co-I & Deputy PI	Edward B. Jenkins Princeton University CoI	George Sonneborn Goddard Space Flight Center CoI, NASA Project Sci.
C. Stuart Bowyer Univ. of California, Berkeley CoI Phases A & B	Jeffrey L. Linsky Universtiy of Colorado CoI	J. Gethyn Timothy Stanford University CoI Phases A & B
Webster C. Cash, Jr. Universtiy of Colorado CoI	Roger F. Malina Univ. of California, Berkeley CoI	Leon P. Van Speybroeck† Smithsonian Astrophysical Obs. CoI Phases A & B
Lennox L. Cowie University of Hawaii CoI	Andrew G. Michalitsianos† Goddard Space Flight Center CoI	Alfred Vidal-Madjar Institut d'Astrophysique de Paris French Scientific Rep.
Arthur F. Davidsen† Johns Hopkins University CoI	H. Warren Moos Johns Hopkins University PI	Edward J. Weiler NASA Headquarters Program Scientist
Andrea K. Dupree Smithsonian Astrophysical Obs. CoI	John F. Osantowski Goddard Space Flight Center CoI Phase A & B	Willem Wamsteker† ESA Villafranca Sat. Track. Stn CoI Phase A
Paul D. Feldman Johns Hopkins University CoI	M.V. Penston† Royal Greenwich Obs. CoI Phase A	Allan J. Willis University College London British Scientific Rep.
Scott D. Friedman Johns Hopkins University CoI, JHU Project Sci.	Blair D. Savage University of Wisconsin CoI	Bruce E. Woodgate Goddard Space Flight Center CoI
James C. Green University of Colorado CoI	J. Michael Shull University of Colorado CoI	Donald G. York University of Chicago CoI
Richard F. Green Kitt Peak National Obs. CoI	Oswald H. W. Sigmund Univ. of California, Berkeley CoI	

† Deceased

Canada and England, but no firm commitments were made. In the summer of 1989, *FUSE* was selected to continue into Phase B.

3. Phase B

Without a major partner, cost constraining the mission assumed high importance. The Phase A concept baselined the shuttle and astronaut installation on the Explorer Platform, a concept that was becoming less and less attractive in the aftermath of the Challenger disaster. From the point of view of the Office of Space Sciences, though, the use of the shuttle and the Explorer Platform were relatively low cost in terms of funds charged to the space science budget, whereas a dedicated spacecraft and ELV would require significant additional funds.

By this time, another decadal study began. In 1991, the Astronomy and Astrophysics Survey Committee, chaired by John Bahcall, published *The Decade* *of Discovery in Astronomy and Astrophysics*. Under space-based projects the committee recommended as its highest priority "that NASA augment the Explorer program sufficiently to convert the *FUSE* mission into a Delta-launched experiment using its own dedicated spacecraft". The committee reaffirmed the Field Committee a decade prior, stating that it "believes *FUSE* will produce extraordinary scientific results." The committee also expressed its concern that continuing to link *FUSE* to the shuttle through the Explorer Platform would delay the mission and increase its cost.

The same report asked for dramatic increases in the launch frequency for the Explorer program, calling for six Delta-class Explorer missions for astrophysics in the next 10 years and an acceleration of the Small Explorer (SMEX) program with the goal of five astronomy SMEX missions in the 1990s. Although it cannot be said that NASA took the committee's advice on these matters directly, both in the scientific community and within NASA, there was growing concern that the frequency of scientific launches increase - and in 1994 this concern would have a major impact on the *FUSE* mission.

In the early 1990's, NASA began to look carefully at the feasibility of reusing the Explorer Platform. It was quickly realized that refurbishment of the Platform itself was necessary; either in-orbit or by returning it to earth. The associated costs were high enough to make the dedicated spacecraft/ELV approach more attractive. In 1991, NASA decided to proceed with dedicated spacecraft for the X-ray Timing Explorer and then *FUSE*. The combination of delays for funding availability and a more realistic development schedule pushed the launch date to beyond 2000.

Major advances in instrumentation technology were also under way. *FUSE* required large format ultraviolet detectors, the largest ever built. Also, they had to be fabricated within the cost limitations of an Explorer mission. Delay-line readouts for microchannel plate detectors offered a low-cost way to handle these large formats, although the PI had reservations about the lack of geometric references such as reseaux marks or discreet anode arrays. The continuing improvement in delay-line readouts, coupled with a clearer picture of the financial realities and a little strong-arming of the PI by the GSFC Explorer project manager finally led to adoption of the delay-line readout as the baseline approach in November 1992.

Far ultraviolet mirror coating technology also advanced. Silicon carbide has the best normal-incidence reflectivity of any material in the 900-1000 Å band, but at that time it was not known how to fabricate large pieces or to coat gratings with SiC. In 1988, J.B. Kortwright of the University of California, Berkeley and David Windt, then a graduate student working with Webster Cash at the University of Colorado, showed that SiC coatings with reflectivities greater than 30% were feasible. The Hopkins Ultraviolet Telescope (HUT) was a shuttle-based instrument covering the far ultraviolet. Following a successful mission in 1991, it was rescheduled for launch in 1995. The HUT project pounced on this opportunity and GSFC, working with both the Hopkins sounding rocket program and the HUT project, showed that gratings and optics as large as 90 cm in diameter could be coated reliably, and the second flight of HUT used SiC coated optics. Thus, the availability of SiC coatings with normal-incidence reflectivities of about 35% was now demonstrated.

In late 1992, the PI and others on the Science Team began to have doubts about the grazing incidence telescope approach. The industrial studies were neither encouraging nor discouraging - although a person at one manufacturer took it upon himself to call the PI and urge consideration of a normal incidence approach over grazing incidence. However, nine years previously, in 1983, the PI had argued in the *Final Report of the Science Working Group for the Far Ultraviolet Spectroscopic Explorer* that a single reflection prime-focus telescope with an interesting size aperture would be too long to fit in a standard ELV. Even with the modest improvements achievable by using SiC coatings, that basic argument was still valid and he decided to soldier on. In early 1993 Steve Conard, the head optical system engineer at Hopkins, had a brilliant idea based on a HUT-like instrument designed for a proposed Explorer Mission. He had this idea in the middle of the night and was so excited with the implications that he jumped up and wrote it down. High spectral resolution requires an f-number for the optics of 6 or larger. Thus, a 1 m diameter mirror implies a 6 m long telescope and a Rowland spectrograph with a huge grating. The Berkeley group solved this for the ORFEUS mission by using a fast telescope and sharing the beam between three gratings. However, at higher spectral resolution, the gratings start to obscure the mirror significantly. Conard's idea was simple. Cut the telescope optic into pieces and separate them enough to remove the obscuration. This began a time of furious design activity and discussion that lasted into the summer of 1993. Some argued for maintaining a single optic. Others looked at various numbers of channels. Jim Green of the University of Colorado played a major role in turning a crude concept that was little more than a chalkboard sketch into a real optical system. After some debate we settled on the four-channel design that flew.

This activity got under way just in time. In May 1993, the PI was summoned to participate in a status report to John Klineberg, the Director of GSFC, and a number of his upper level managers. The PI was not aware that GSFC management had serious doubts about the grazing incidence approach. Their concerns were twofold. First, the estimated costs could explode. A more fundamental objection was the 3 1/2 year period required to build the telescope. The thermal/mechanical design of the satellite would have to be completed before telescope fabrication began and the engineering team then would be maintained until launch. Such a long development cycle is very expensive and outside the scope of an Explorer mission. This objection is so fundamental that in later years, when it looked like Germany might be able to provide a grazing incidence telescope, the Explorer Project recommended that *FUSE* not pursue this option.

Following the status report with lots of charts and some of the results from the industrial studies, there were a number of unhappy faces. If forced to continue with the grazing incidence approach, GSFC would have likely recommended cancellation of *FUSE* as an Explorer mission. The PI was asked if there was an alternative approach to the grazing incidence telescope. "Yes, there is" he answered and started to talk about the normal incidence design work. When he came to the size of the primary mirrors (35 cm x 39 cm) and described how one or two people could carry a mirror across the room, the project crossed a continental divide. By the end of the meeting, the Director endorsed the normal incidence approach on the grounds that it appeared doable within schedule and available resources - and the project would control its own destiny. In July 1993, the Science Team approved normal incidence telescopes as the baseline.

The fabrication of gratings for the *FUSE* mission was an ongoing concern. They would be large, ~ 30 cm, and would need extremely high ruling densities, ~ 6000 lines mm^{-1}. Scattered light was a serious concern. In addition, conventional rulings on a spherical blank would produce an astigmatic elongation of the stellar image that was so long, the associated background signal would seriously limit the mission sensitivity. In 1992 Robert Grange at the Laboratoire d'Astronomie Spatiale in Marseille showed that a holographically recorded grating on a spherical blank could reduce the astigmatism significantly, to zero at one wavelength and remain quite small, ~ 0.5 mm, at nearby wavelengths . With the urging of Alfred Vidal-Madjar and other French scientists, the Centre National d'Etudes Spatiales funded the development and testing of a prototype. In 1994, a resolution of 30,000 was demonstrated for a molecular hydrogen emission spectrum. Warren Moos has a 1995 New Year's card signed by Grange and others at LAS showing the spectrum on the cover. They deserved to be proud!

Canada provided the Fine Error Sensor (FES), which was responsible for the stable pointing, much better than one arcsec, achieved by FUSE. Both Canada and France have signed letters of agreement with NASA and each receives 5% of the observing time. French and Canadian scientists have participated in the analysis of FUSE data both through the Science Team and as Guest Investigators (GI). France and Canada have also helped to staff the operations team at Hopkins.

The understanding of the *FUSE* science goals continued to mature all through the 1990's. For instance, the determination of D/H in a variety of astrophysical environments was increasingly seen as a sophisticated investigation in which the issues of astration and mixing would be as important as the determination of the primordial value. The IMAPS instrument showed in 1996 that the D/H ratio in the local interstellar medium varied, confirming the previous, but not widely accepted *Copernicus* results. The complex nature of the structure of the galactic halo with chimneys and other structures thrown up by supernova events became clearer with implications for the planned O VI studies. The *HST* and *HUT* measurements of the He II Gunn-Peterson effect motivated the Science Team with the need for measurements of He II absorption at higher spectral resolution in the *FUSE* wavelength range.

Following the decision to baseline normal incidence in 1993, the project began a period of productive design activity for the instrument. GSFC was responsible for the spacecraft, satellite integration and mission operations after launch. Hopkins had overall responsibility for the instrument and the Science Team. GSFC with Swales Associates, Inc. took the lead for the mechanical structure. The University of Colorado group led by Jim Green was responsible for the spectrograph optics and the spectrograph assembly. The detectors were the responsibility of the group at the University of California, Berkeley led by Ossie Siegmund. In the summer of 1994, Dennis McCarthy came to Hopkins as the Hopkins program manager. His prior experience at GSFC on the first *HST* repair mission and other missions was to prove invaluable as the program developed. We became optimistic that the *FUSE* mission would enter Phase C/D soon, starting hardware development for launch.

4. Cancellation, Restructuring and Phase C/D

At this point, disaster struck. Both NASA and the scientific community wanted to increase the frequency of Explorer missions. Because of budgetary restrictions, this could not be accomplished without reducing the cost of future missions. The mantra was "faster, better, cheaper". Even with this step, the cost of the *FUSE* mission would put a major lien on the Explorer budget past the year 2000. A decision was made at a high level in NASA to cancel *FUSE*. On the day after the Labor Day holiday in September 1994, NASA Headquarters informed Dennis McCarthy and Warren Moos that *FUSE* was canceled. At the same time, the Chief of Astrophysics at NASA Headquarters, Dan Weedman, began discussions about salvaging as much of the critical science as possible. An intense few days followed. On late Friday afternoon of that week, Dennis McCarthy, Mark Perry, the Hopkins instrument manager, and Warren Moos met with Wes Huntress, the NASA Associate Administrator for Space Science. By the end of the meeting we had an agreement. Hopkins was directed to evaluate and, if feasible, propose to NASA a low cost *FUSE* mission. In particular, the Principal Investigator would assume control of all segments of the *FUSE* mission except launch, reduce the development cost to $100M, and retain as much of the *FUSE* Phase A science as possible. NASA was responsible for the launch. NASA Headquarters also promised to seek additional international cooperation. It did not materialize and the budget was increased to $108M. The proposal was to be delivered in January 1995, only four months later.

It was an intense four months. It is a credit to the team members at Hopkins, Colorado and UCB that they did not falter in the face of a seemingly impossible task. We literally redesigned the mission. The basic instrument structure that had almost a year of engineering and optical design was maintained to reduce the schedule. To cut cost, low earth orbit was selected. A ground system concept was designed based on an autonomous ground station, eventually located at the University of Puerto Rico-Mayaguez, with the satellite control center at JHU. The Science Team evaluated the descopes to bring down cost in order to determine if the reductions in scientific capability were acceptable. Decisions that in the past had taken months were made in days. We were learning about the importance of schedule, even in the proposal stage. We quickly realized that the biggest cost driver would be schedule and many of our pet ideas fell before it. For instance, the survey spectrometer was removed from the design.

After delivery of the proposal in January 1995 and evaluation by NASA, the *FUSE* project was directed to proceed into Phase C/D development. A contract was signed between GSFC and Hopkins on November 25, 1995.

This began a forty-two month period that is somewhat of a blur for most of us associated with the mission. We originally planned a launch in October 1998, a thirty-five month schedule; thus, every day counted. Ultimately, because of problems with gyroscopes and the Delta launch schedule, we were forced to delay until June 24, 1999. The engineering and science team members worked side by side. This had the benefit of making clearer the nature of the scientific requirements to the engineers, who often over designed because they misunderstood the requirements. Alternatively, the scientists sometimes reevaluated some of their requirements after they better understood the difficulty of meeting them. The dedication of these teams was incredible. More than 600 people were associated with the Phase C/D development. The successful development of the *FUSE* mission is a credit to their dedication and talent. *FUSE* was launched June 24, 1999 at 11:44 am EDT. Immediately after launch, Warren Moos ran outside the Mission Directors Center; it is true that as he stared at the Delta II rumbling overhead, the thought "No more descopes!" went through his mind.

5. Mission Operations

After a flawless launch, in-orbit checkout began. We had estimated 90 days, but in the end it was 120 days before Early Release Observations began followed by the formal commencement of science operations on December 1, 1999. Part of the reason for the long checkout period was a concern with the possible reduction in mirror reflectivity, if the mirrors were exposed to the ultraviolet light from earth airglow while the satellite was outgassing significant amounts of molecular material. Thus, we remained pointed near the pole of our orbit into September. This caution coupled with a careful program to prevent swept up gas from striking the telescope mirrors (ram avoidance) throughout the mission paid off as demonstrated by the high and stable sensitivity of the *FUSE* instrument. This was also a period of enormous frustration as the engineers and scientists on the operations team waded through one small software problem after the next. The team was small, totaling less than 40 people, so team fatigue became a serious issue. In later years, the byword of warning from Warren Moos to members of the operations team contemplating a new activity was the statement "no more summers of 1999". Even after working through these problems, low observing efficiency, minor operational mistakes and scrambling to stay on schedule, symptomatic of task overload continued to persist. Finally, after consultations between the NASA Project Scientist and the PI, the operations staff was increased by four people a roughly ten percent increase. Remarkably, the operations process rapidly settled down and quickly demonstrated observing efficiencies higher than our prelaunch estimates. This was an important lesson on the fine line between a minimally staffed, but efficient, operations team and a significant breakdown in observing capability.

During in-orbit checkout, we uncovered a major problem: The four telescope channels did not remain aligned as the earth and solar angles changed from observation to observation. At first, we regarded this as a significant setback, but quickly realized that the obvious work-around was to schedule observations with similar solar and earth angles together and then perform alignments when we moved between positions that differed significantly. The prime science goals of *FUSE* were not affected by this change in procedure, although it can have an impact on observations that require critical timing. Despite the need for more frequent alignments than planned before launch, as mentioned above, the observing efficiency was higher than the prelaunch estimate. However, the real lesson of in-orbit checkout was that this mission, like most missions, would have hardware and software problems - and the *FUSE* operations team was capable of meeting them.

The satellite and the *FUSE* program now settled down for a period of steady scientific productivity. The Early Release Observations appeared in a dedicated volume: 2000, ApJ, 538, L1-L98. The first set of deuterium papers occupied another dedicated volume: 2002, ApJS, 140, 1-114 and the O VI results in a third: 2003, ApJS, 146 1-208. Meanwhile the number of papers based on both PI Science Team observations and Guest Investigator observations continued to grow rapidly.

Although the Science Team played a major role in guiding the mission through launch, a strong GI program was planned from the beginning, and the percentage of time going to GI programs increased each year. During the Prime Sciece Mission, from launch through March 2002, GIs obtained slightly more than half of the observing time. During the Extended Mission, all of the observing time goes to GI programs. Proposals are accepted from all nations and ranked for NASA by a Time Allocation Committee of U.S, French and Canadian astronomers convened by the NASA Project Scientist.

6. Two reaction wheels and two gyroscopes

At the end of November and beginning of December 2001, the mission almost came to an untimely end: The pitch and yaw reaction wheels, used to control the angular position of the satellite on the sky, failed. Even before launch, we were concerned with potential failure of the Attitude Control System (ACS). However, our concern was with the lifetime of the laser gyroscopes. By launch, we knew that the probable lifetime of the lasers would be significantly below the estimates made when they were selected. However, we judged that because a backup gyroscope was available for each axis, the system would complete three years, the design lifetime for the mission. The reaction wheels were considered to be reliable. However, two events in 2000 and 2001, in which the pitch and yaw wheels stopped working and then were restarted, raised serious concerns and led to the discovery of a design flaw that could cause the wheels to jam, particularly if they underwent significant thermal fluctuations, as the pitch and yaw wheels did. Following the failure of the yaw wheel on November 25 and the pitch wheel on December 10, only two control axes remained and the satellite could not remain at a fixed position in the sky. As a result, the spacecraft was in danger of depleting its battery within a few orbits. The operations team was able to get the satellite to rotate like a pinwheel about the yaw axis in a plane perpendicular to the sun line with the solar cell paddles oriented towards the sun. The control was imperfect, however, and the satellite occasionally lurched out of the plane and dipped down towards the sun. One such passage was close to the sun and the Bright Object Sensor closed the door in front of the telescope, saving the instrument.

With the failure of the reaction wheels, Jeff Kruk at Hopkins and Brian Class at Orbital Sciences Corporation immediately started working on an ingenious idea. Could the magnetic torquer bars be used to replace one of the failed wheels? The magnetic torquer bars are normally used to bleed the excess angular momentum induced largely by gravitational torques on the satellite, and have a peak torque about a tenth that of a reaction wheel. In addition, the effectiveness of the magnetic torquer bars would be sensitive to the angle of the satellite with respect to both the earth's magnetic field and the pole of the orbit, where gravitational torques were minimized. At the same time, we convened a meeting on December 14 of a number of attitude control specialists from the Baltimore-

Washington area. The support of these busy engineers, turning out for an all day meeting with just a few days notice, was gratifying. Following considerable discussion and debate, it was decided that using the magnetic torquer bars had a chance, although no one could say how constrained the pointing of the *FUSE* satellite would be. Six weeks of long hours of effort began. On January 25, 2002, *FUSE* returned to science operations. The instrumental capabilities of concern, sensitivity and resolution, were unchanged. The initial sky coverage averaged over an observing year was modest, sufficient to provide data for 60% or more of the science programs. With continuing improvements in the planning and execution of observations led by Bryce Roberts of the operations team, sky coverage has improved significantly and in the spring of 2004, the mission reached complete sky coverage again.

This recovery was not expected by all. Many experienced engineers had serious doubts. While reporting the recovery to NASA Headquarters in February 2002, several officials confessed that they had already been replanning the *FUSE* funds for other uses. It is to their credit that they kept their doubts private and let us get on with the recovery.

In June 2002, the Senior Science Review recommended to NASA that *FUSE* enter an extended mission phase, a recommendation that NASA headquarters accepted and funded. Consequently, operations without a full complement of gyroscopes would be needed. Additional motivation was provided by the loss of the roll gyroscope in May 2001, requiring use of the backup unit. The basic scheme was to use the signal from the magnetometers for coarse pointing of about one degree and then the Fine Error Sensor with a 20 arc minute field of view to provide the fine pointing. However, a complex set of new computing algorithms and software would be required. The Goddard Space Flight Center, Orbital Sciences Corporation, the Johns Hopkins University Applied Physics Laboratory, and the Canadian Space Agency with COM DEV, Ltd. all participated in this complex development with Hopkins. In retrospect, the construction and testing of the software turned out to be a larger task than estimated. Finally, installation of the software was completed in June 2003. On July 31, a gyroscope failed during target occultation. The observation continued on two gyroscopes without loss of data. As this article is written in October 2004, *FUSE* is operating on one gyroscope with a noisy second gyroscope taken out of the control loop. Two other gyroscopes are off, held in reserve for future needs. The system also can work without any gyroscopes if needed.

7. Scientific Contributions

With the fifth observing cycle under way, the mission is mature enough that a fair question is to ask what *FUSE* has achieved scientifically. From time to time, one of us is invited to give a colloquim or seminar on *FUSE*, to tell what the mission has achieved scientifically and give an overall accounting of what the *FUSE* has found. It is daunting to think of reducing the contents of this volume to a one hour lecture and impossible to reduce the intellectual content herein to a few glib paragraphs.

Major advances in astronomy are often brought about when new techniques open new "windows". *FUSE* certainly has opened up a new window, both in terms of spectral coverage (905-1187 Å) and in terms of access to a wide range of astrophysical environments. There are any number of species of astrophysical importance that have all or most of their strong transitions in this spectral region. They include D I, O VI, H_2 and many more. It is striking how many spectra of hot subdwarfs contain lines unidentified because the atomic data do not exist. *FUSE* also has dramatically increased access to distant objects for studies in this spectral region. The *Copernicus* mission covered the *FUSE* spectral region with similar spectral resolution. However, the sensitivity was much lower and at wavelengths below 1000 Å, the sensitivity was almost nonexistent. It is ironic that an unsolved (and possibly unsolvable) problem for *FUSE* with its superb sensitivity is to observe stars as bright as those studied by *Copernicus.* Because of the low sensitivity, *Copernicus* was limited to distances beyond the Local Bubble, but less than a kiloparsec. On the other hand, *FUSE* can observe not only stars throughout the Milky Way and in a few nearby galaxies, but also Active Galactic Nuclei, opening up studies both of the objects and of the intervening gas. *Copernicus* explored the local neighborhood - *FUSE* is exploring the Universe.

Publications are another measure of a mission's scientific impact. As of September 30, 2004, approximately 750 papers reporting or analyzing *FUSE* data have appeared. About 250 of these are in refereed journals and the number of refereed papers grows by about six papers per month. In the early years of the mission, the papers were dominated by the PI Science Team observations, but observations by Guest Investigators now dominate. In these publications as in this volume, a broad range of subjects is covered, from white dwarfs to the missing baryon problem in the intergalactic medium.

FUSE has also served as a springboard to other experiments. The *FUSE* grating and detector technologies were adapted by Jim Green and Ossie Siegmund for the Cosmic Origins Spectrograph. The construction of the Fine Guidance Sensor for the *James Webb Space Telescope* with John Hutchings as the Canadian Project Scientist will utilize the experience gained building the *FUSE* FES.

The biannual Senior Science Reviews held by NASA have continued to support the operation of the *FUSE* mission. The review in June 2004 led to a recommendation to continue the mission through Fiscal Year 2008, the limit of the review's purview. NASA has directed the *FUSE* project to submit a plan for operation of the mission through this period. The only certainty about space hardware is uncertainty. However, we are optimistic that the *FUSE* mission will continue to produce exciting scientific results in the coming years.