Naval Research Laboratory

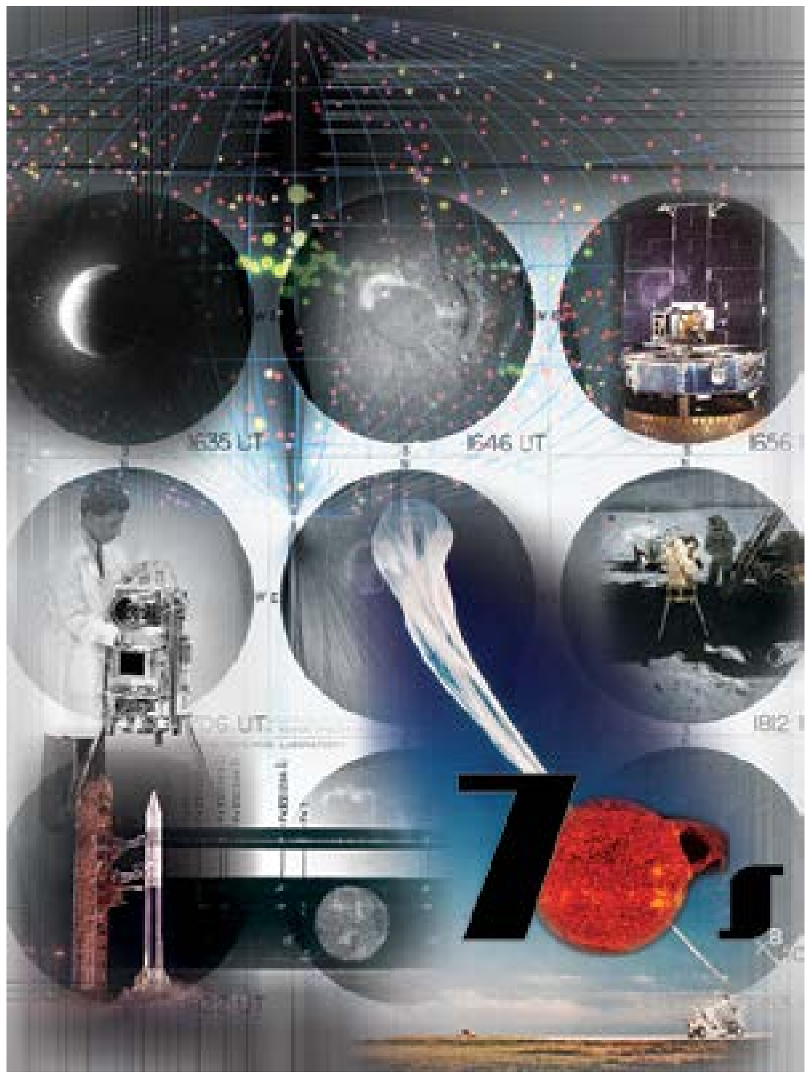
Washington, DC 20375-5320

NRL/MR/7600--15-9638

Volume 2.
NRL SSD Research Achievements: 1970–1980

Jill Dahlburg
George Doschek
Scott Budzien
Christoph Englert
Russell Howard
W. Neil Johnson
Dennis Socker
Kent Wood

Space Science Division



October 30, 2015

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
30-10-2015

2. REPORT TYPE
Memorandum Report

3. DATES COVERED *(From - To)*
1970 – 1980

4. TITLE AND SUBTITLE
Volume 2. NRL SSD Research Achievements: 1970–1980

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jill Dahlburg, George Doschek, Scott Budzien, Christoph Englert, Russell Howard, W. Neil Johnson, Dennis Socker, and Kent Wood

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/MR/7600--15-9638

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

10. SPONSOR / MONITOR'S ACRONYM(S)
NRL

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

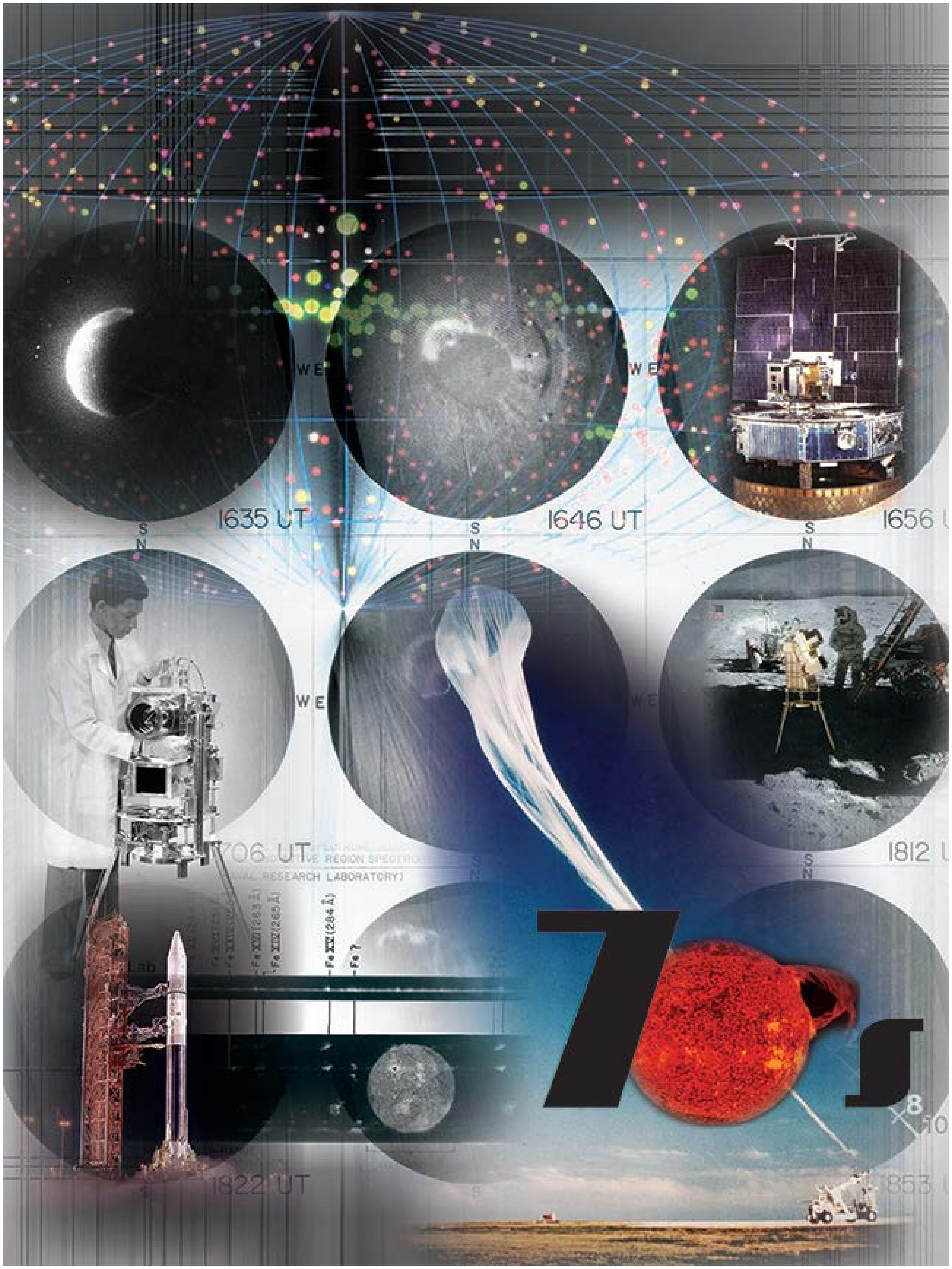
13. SUPPLEMENTARY NOTES

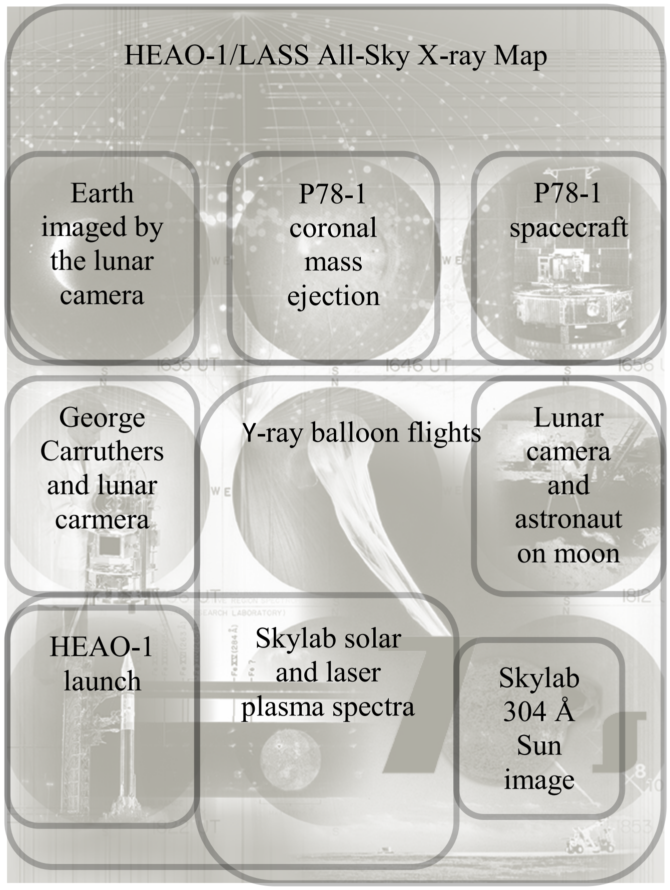
14. ABSTRACT
An extraordinary range of space science research was performed by the Naval Research Laboratory (NRL) Space Science Division (SSD) during the 1970s, and stunningly seminal results were obtained. This summary provides a technical overview of some of the major NRL SSD research achievements during this decade, 1970-1980.

15. SUBJECT TERMS
Space Science History

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited	45	Jill Dahlburg
					19b. TELEPHONE NUMBER *(include area code)* (202) 767-6343

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18


1635 UT
1646 UT
1822 UT



An extraordinary range of space science research was performed during the 1970's, and stunningly seminal results were obtained. In astrophysics, the exploration of the X-ray sky was just beginning. The first High Energy Astronomy Observatory (HEAO-1) was launched, which carried the very large NRL SSD Large Area Sky Survey (LASS) experiment (HEAO-1 A1). These X-ray detectors provided the most comprehensive X-ray catalogue of astrophysical sources in the 0.25 to 25 keV range available up to that time. Another incredibly exciting experiment was an NRL SSD far-ultraviolet camera/spectrograph that was operated as an observatory by Apollo 16 astronauts on the Moon. Images and spectra were obtained of the terrestrial atmosphere and geocorona in the wavelength range below 1600 Å. These images of the Earth from the lunar surface are still unique in the annals of space science. The same camera design was also used on rocket flights to obtain images and spectra of many diverse astrophysical objects. In solar and heliospheric physics, NRL SSD scientists developed groundbreaking ultraviolet spectroscopic experiments that were flown aboard the NASA Skylab manned space station, to study the Sun's chromosphere, transition region and the inner corona. SSD researchers also flew a white light coronagraph and X-ray Bragg crystal spectrometers on the DoD Space Test Program satellite P78-1. With the coronagraph they discovered coronal mass ejections, as discussed in Volume 1 of this series, and the X-ray spectrometers provided the highest resolution spectra yet obtained of key spectral features of high-temperature solar flares. SSD scientists also carried out high altitude balloon flights of gamma ray experiments, and they used solar rocket spectrometers and newly conceived instruments to probe the spectra of laser produced plasmas thereby extending our knowledge of solar-relevant spectra and also contributing to the understanding of high energy density laboratory plasmas.

PREFACE

We offer these summaries of Naval Research Laboratory (NRL) Space Science Division (SSD) research achievements to provide a technical overview of NRL space science accomplishments from the beginning of the Division in 1952 through the first decade of the 21st century.

These summaries are presented in five Volumes:

Volume 1. NRL SSD Research Achievements: 1960-1970
Volume 2. NRL SSD Research Achievements: 1970-1980
Volume 3. NRL SSD Research Achievements: 1980-1990
Volume 4. NRL SSD Research Achievements: 1990-2000
Volume 5. NRL SSD Research Achievements: 2000-2010

The importance of space science basic research in support of naval needs was robustly championed by Homer Newell, the Division's second Superintendent, who noted to the US Congress in 1957, "A strong basic research program is essential to continuing vitality of applied R&D in missiles or any other military or peacetime applications. New facts, new ideas, new techniques, new materials, new instruments, all come from the basic research effort..." As the dozens of summaries in these five Volumes tremendously attest, extraordinary ranges of research and results have been achieved.

To document significant SSD historical accomplishments, Drs. George Doschek and Jill Dahlburg requested current and former SSD researchers to contribute technical achievement summaries to these Volumes on the basis of their personal memories about the scientific activities in which they were involved. The contributions received were then loosely organized by decade into these five featured Volumes, after being edited for clarity by George Doschek, Tanisha Lucas, and Jill Dahlburg.

George Doschek would like to express his gratitude to all the researchers who have contributed to these summaries, and particularly to those with whom he has personally worked. The SSD has and is currently continuing to provide substantive and significant contributions to the developments of experimental space science since its origins after World War II, and it has been a privilege to be part of this effort. These Volumes convey stories about curiosity, hopes, and aspirations of scientists fascinated by exploration of the Universe with instrumentation placed beyond the Earth's atmosphere.

Tanisha Lucas wishes to acknowledge that she has benefited from the advice, assistance, and all of the contributions that our researchers put into these documents. She wishes to express her gratitude to the NRL SSD researchers for their remarkable scientific contributions, her appreciation for the advice on content and organization for this book provided by Dr. Jill Dahlburg, and her many thanks to Dr. George Doschek for closely working with her in compiling and arranging these Volumes.

Jill Dahlburg acknowledges with pleasure and gratitude the request from Dr. John Montgomery, NRL Director of Research, that these Volumes be developed. They present a unique account of exceptional contributions from the NRL SSD broad-spectrum research, development and experimentation program to study the atmospheres of the Sun and the Earth, the physics and properties of high-energy space environments, and solar activity and its effects on the Earth's atmosphere, and to transition these capabilities to operational use.

Finally, George, Tanisha and Jill would together like to thank Ms. Kathryn Grouss who worked with us to prepare these Volumes during 2014, for her exceptional cooperation, professionalism, assistance and advice, and to Dr. Angelina Callahan, NRL Associate Historian, for her many beneficial insights and suggestions, and her unswerving encouragement.

George Doschek, *NRL SSD Historian*
Tanisha Lucas, *NRL SSD Research Achievements Managing Editor*
Jill Dahlburg, *NRL SSD Superintendent*

Manuscript approved December 15, 2014.

Table of Contents

Overview of the NRL Space Science Division 1970's Decade

At the US Naval Research Laboratory (NRL), the story of space research formally began in 1952, with the creation of the NRL Atmospheres and Astrophysics (A&A) Division under the direction of Dr. John Hagen, and a Division charter to perform research and development in the field of space science. The Division's second Superintendent, Homer Newell (1956-1958), continued A&A's seminal space research both at NRL and then later at the National Aeronautics and Space Administration (NASA). Following Dr. Newell's departure to NASA in 1958, Herbert Friedman assumed leadership of NRL space science as the third A&A Division Superintendent (1958-1982). Dr. Friedman oversaw the renaming of the Division from A&A to Space Science, in 1968, and in 1982 he transitioned the Division to the leadership of Dr. Herbert Gursky, who served as SSD's fourth Superintendent from 1982-2006. Jill Dahlburg, the fifth and current SSD Superintendent, was appointed to the position in 2007 following her service as Acting SSD Superintendent from May 2006. The scope of the NRL Space Science Division encompasses theoretical, experimental and numerical research of geophysics science and technology, solar and heliospheric physics, and the high-energy space environment, and the conception, design, fabrication, integration, test, operation and experimentation with forefront space instrumentation, for the purpose of enabling Navy/ Marine Corps and wider DoD robust access to space assets.

An extraordinary range of space science research was performed during the 1970's, and stunningly seminal results were obtained.

In the area of geophysics science and technology, an NRL SSD far-ultraviolet camera/spectrograph was developed and built at NRL and in 1972 Apollo 16 astronauts installed this camera as an observatory on the Moon. Images and spectra were obtained of the terrestrial atmosphere and geocorona in the wavelength range below 1600 Å. These images of the Earth from the Moon's surface are still unique in the annals of space science. The same camera design was also used on rocket flights to obtain images and spectra of many diverse astrophysical objects. This Volume's Essay 70's.1 provides a summary of this exceptional research.

In NRL SSD 1970's solar and heliospheric physics research, scientists developed ground breaking ultraviolet (UV) and extreme-ultraviolet (EUV) spectroscopic experiments flown on the NASA *Skylab* manned space station to study the Sun's chromosphere, transition region, and inner corona. These instruments obtained spectra in the UV and EUV with very high spectral resolution and high spatial resolution in the EUV. Many seminal scientific papers on plasma diagnostics, the structure of the solar transition region, coronal holes, and the morphology of X-ray/EUV flares resulted from analyses of the data and some of the data are still unique in solar physics. NRL scientists spent about a year in Houston interactively working with the astronauts on *Skylab*. *Skylab* is one of the greatest of all the solar physics missions flown throughout the world up to this time. Essay 70's.2 describes this outstanding science. The OSO-7 spacecraft (see 1960's chapter in Vol.1 of this series) was launched in 1971 and coronal mass ejections were discovered. Further, NRL SSD scientists also flew a white light coronagraph and X-ray Bragg crystal spectrometers on the DoD Space Test Program satellite *P78-1* launched in 1979. The *P78-1* coronagraph was a much superior instrument compared with the *OSO-7* instrument and with the *P78-1* coronagraph many properties of coronal mass ejections were discovered, e.g., head-on mass ejections were recognized, and the relationships of mass ejections to X-ray flare class and to interplanetary shocks were quantified. The X-ray spectrometers on *P78-1* provided the highest resolution spectra yet obtained of key spectral features of high temperature solar flares. See Essay 70's.3 for an overview of this research.

High energy space environment research was fundamentally advanced in the 1970's. The first *High Energy Astronomy Observatory* (*HEAO-1*) was launched, which carried the very large NRL SSD Large Area Sky Survey (LASS) experiment (*HEAO-1* A1 experiment). HEAO-1 was much larger than any previously flown X-ray astronomy spacecraft, and the X-ray detectors provided the most comprehensive X-ray catalogue of astrophysical sources in the 0.25 to 25 keV range available up to that time (842 sources). In the 1970's, the exploration of the X-ray sky was just beginning. In addition, balloon flights of gamma ray experiments were carried out by SSD scientists. These balloons were a great testing ground for orbiting spacecraft instrumentation that ultimately lead to the SSD *CGRO*/OSSE (1980s chapter) and *Fermi*/LAT (2000s chapter) experiments. This work is overviewed in Essay 70's.4. Finally, NRL SSD laboratory spectroscopic instrumentation developments and studies, which contribute both to solar and heliospheric research and also to high energy space research, are described in Essay 70's.5.

70's.1: The First Extraterrestrial Telescope: Apollo 16 Far- Ultraviolet Camera Spectrograph

Contributed by Scott Budzien

1.0 Introduction

Humankind's first extraterrestrial optical-astronomy observatory is the Apollo 16 Far-Ultraviolet Camera/Spectrograph located at the Descartes Moon landing site (Fig. 70s.1.1), designed and built by pioneering Space Science Division researcher Dr. George R. Carruthers at the invitation of NASA. Also known as Experiment S201, the advanced far-ultraviolet (FUV) imager and spectrograph sensor was operated from the lunar surface by astronauts Charles M. Duke, Jr. and John W. Young in April 1972 to acquire numerous UV images of Earth and astronomical targets. The experiment objectives were to perform broad-band UV imaging and spectroscopy (50-160 nm) of the Earth's upper atmosphere, interstellar regions, galactic haloes, and nebulae; to search for evidence of a lunar atmosphere; and, to evaluate the lunar surface as a site for future observatories. The camera remains on the Moon, but a reconstructed flight spare is on display at the Smithsonian Air and Space Museum, and a mock-up resides at NRL.

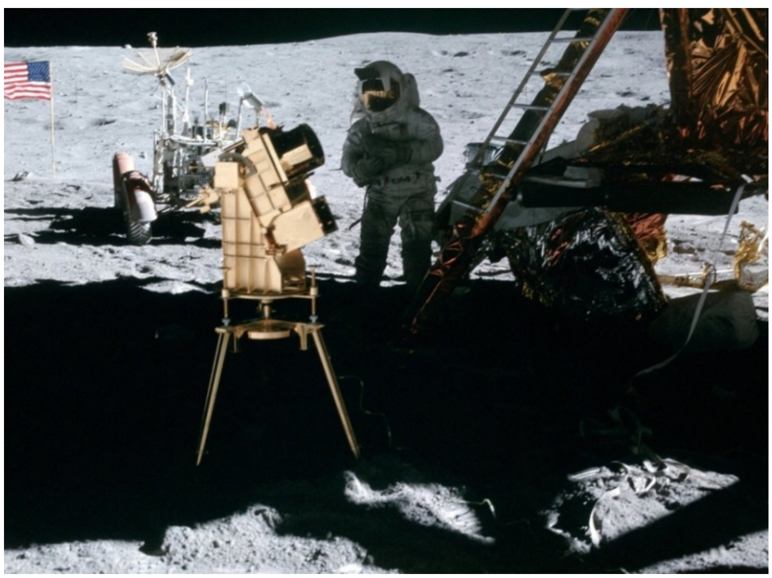


Figure 70s.1.1 - Astronaut Charles Duke observes the first telescope on the Moon as it views skyward from the shadow of the Apollo 16 lunar module in April 1972 (credit: NASA/John Young).

2.0 FUV Camera/Spectrograph Design and Operation

The instrument consists of an f/1.0 Schmidt camera using an electrographic imaging detector, which provides a wide-field UV imaging capability with images recorded on film (Fig. 70s.1.2 top). Incoming light passes through the corrector plate aperture to the spherical primary mirror, and is then imaged onto the curved prime focus surface. A potassium bromide (KBr) photocathode deposited on this surface emits photoelectrons when exposed to ultraviolet light of wavelength less than about 160 nm. These photoelectrons are then accelerated through a 25 kV potential and focused using a cylindrical magnet to form an electron image on the film behind the hole in the primary mirror. Designed before the advent of large-format solid-state UV imaging detectors, Carruther's innovative electrographic detector provided significantly higher detection efficiency, higher resolution, improved linearity of response, and better photometric accuracy than conventional photography and UV-sensitive film.

For its time, the FUV camera/spectrograph design packed quite a number of flexible operating configurations into a compact instrument payload. The camera has a 20° circular field-of-view, with an angular resolution of about 2 arc-minutes near the center of the field and 3-4 arc-minutes near the edges. The instrument operated in one of two modes: either as a panchromatic UV imager through a baffled aperture; or by rotating the camera 90-degrees to view a planar diffraction grating thereby converting the instrument into an objective grating spectrograph (Fig. 70s.1.2 bottom). The instrument also included options for operation using either of two interchangeable corrector plates or no corrector at all. Some of the materials used were somewhat exotic: The whole structure was constructed of magnesium, which was gold plated for thermal stability as it operated in the shadow of the lunar module, and the objective mirror and grating were coated with rhenium for enhanced extreme UV (EUV) reflectance.

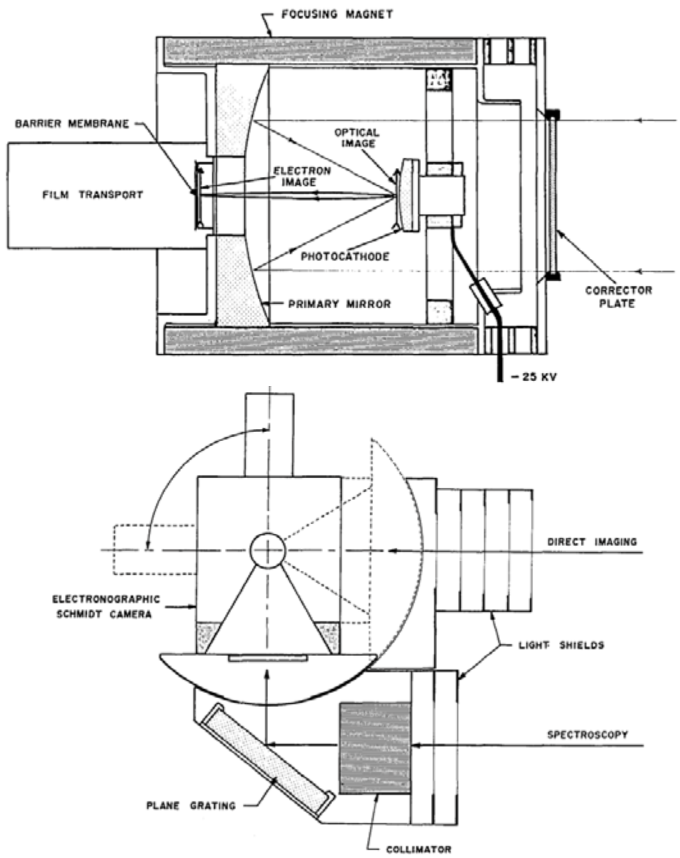


Figure 70s.1.2 - (Top) Optical design of the FUV f/1.0 Schmidt camera and electrographic detector. (Bottom) The swiveling of the FUV Schmidt camera allows both direct imaging through a baffled aperture and operation as an objective grating spectrograph (credit: NRL).

In the imaging mode, two interchangeable Schmidt corrector plates allowed imaging in different broadband spectral regions. One corrector, made of lithium fluoride (LiF), transmitted to a short-wavelength limit of 105 nm and was sensitive to the hydrogen Lyman-alpha 121.6 nm emission. A second calcium fluoride (CaF_2) corrector plate, transmitted to a short-wavelength limit of 125 nm, excluding Lyman-α signals. Comparison of images made with the both correctors enabled determination of the relative contributions of local diffuse Lyman-α emission and of longer-wavelength emissions.

In spectrograph mode the camera viewed an objective grating (1200 grooves/mm) in first order fed by a mechanical grid collimator. The collimator restricted the field-of-view in the dispersion direction to 0.5°, thus providing an effective field-of-view of 0.5°×20°. Two spectrograph passband modes were available. When using the LiF corrector plate, the sensor operated at 3 nm spectral resolution over the 105-160 nm passband. By removing the corrector plate, degraded image quality led to lower spectral resolution ~ 4 nm, but expanded the passband at shorter wavelengths to 50-160 nm.

3.0 Experiment Results

Earth FUV imaging: The far-ultraviolet observations of the Earth from the Moon provided, for the first time, a synoptic view of an entire hemisphere which revealed new features in the spatial distribution and intensities of upper atmospheric emissions. The airglow observations generally confirmed previous observations from low Earth orbit of the intensities and morphology of the polar auroras and tropical airglow belts. Notably, however, the lunar observations provided new details of the intensity distribution and morphology of intensity in the tropical airglow belts, including an apparent convergence near the midnight meridian; see Figure 70s.1.3. These morphological variations have been subsequently seen, are now attributed to dynamical interactions between the lower atmosphere and ionosphere, and represent a very active area of ionospheric research even to the present time.

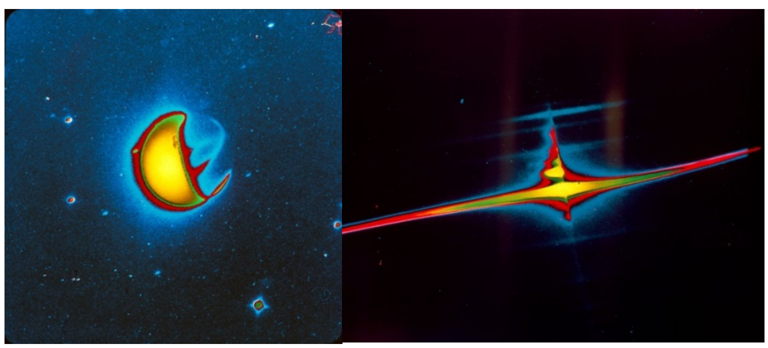


Figure 70s.1.3 - (Left) Iconic image taken of the far-ultraviolet Earth, showing the dayglow, aurorae, and equatorial ionization anomaly, and the diffuse geocorona. (Right) Far-ultraviolet spectrum of Earth showing the extended hydrogen Lyman-α geocorona on the dayside and nightside along with longer-wavelength emissions predominantly on the dayside (credit: NASA/NRL).

Hydrogen geocoronal imaging: The Apollo 16 FUV camera provided the first large-scale imagery of the hydrogen geocorona, as a result of being the first UV imager to actually observe from outside the geocorona. The Lyman-α intensity distribution was determined to distances of 10-15 Earth radii (R_E) with 0.02 R_E spatial resolution. These images provide clear evidence of a geotail effect in the outer geocorona and a marked asymmetry about the Earth-Sun line. Images of the geocorona close to Earth indicated diurnal variation of the hydrogen density by a factor of 2-2.5, and there was indication of temporal variation in the geocoronal intensity over the 29-hour observation period. The S201 experiment produced the first spectrally pure observations of the Lyman-β geocorona.

UV astronomy: The camera provided a photometrically accurate catalog of FUV objects for limited regions of the sky, and demonstrated instrumentation suitable for future UV astronomical surveys.

4.0 Experiment S201 Impact

The experiment was developed during the heat of the Space Race when US international prestige depended upon successful demonstration of advanced space technologies. In the early 1970s, understanding of the Earth's thermosphere, ionosphere, and geocorona was rudimentary by today's standards and based largely upon observations made by sounding rockets and by very few low Earth orbiting satellites. The new global view of the FUV Earth from the Moon contributed significantly to confirming scientists' understanding of the morphology of upper atmosphere, important for its operational relevance to satellite drag, reentry, communications, and radar. The electrographic camera and UV imaging technology from S201 led to subsequent DoD UV imaging experiments which flew under the Space Test Program (STP) and laid the foundation for later generations of UV sensors used for space weather research and operational space weather sensing.

5.0 George R. Carruthers

George Carruthers is one of the pioneering researchers in the design and construction of UV/EUV instrumentation for astrophysical research from space. His far-UV camera has been flown on a number of rockets to observe hydrogen Lyman-α radiation from comets (see, e.g., essay by Robert Meier, Essay 60's.1), and George was the first to discover molecular hydrogen in interstellar gas from rocket observations. For this and other achievements he won the coveted Helen B. Warner Prize of the American Astronomical Society in 1973. Over the years he has won many prestigious awards for the development of the far-UV camera and other instrumentation, including the 2012 National Medal of Technology and Innovation that was presented to him by President Barack Obama in February 2013.

References: 70s.1:

Carruthers, G. R., 1972, "Apollo 16 Far-Ultraviolet Camera/Spectrograph: Earth Observations", Science, 177, 788–791.

Carruthers, G. R., 1973, "Apollo 16 Far-Ultraviolet Camera/Spectrograph: Instrument and Operations", Appl. Optics, 12, 2501–2508.

Carruthers, G. R., 1974, "Electrographic cameras for the vacuum ultraviolet", in Electrography and astronomical applications; Proceedings of the Conference, Austin, Tex., March 11, 12, 1974. (A75-23926 09-89) (Austin, University of Texas), 93–116.

Carruthers, G. R., and T. Page (1976), "Apollo 16 Far Ultraviolet Spectra of the Terrestrial Airglow", J. Geophys. Res., 81(10), 1683–1694, doi:10.1029/JA081i010p01683.

Carruthers, G. R., and T. Page (1976), "Apollo 16 Far Ultraviolet Imagery of the Polar Auroras, Tropical Airglow Belts, and General Airglow", J. Geophys. Res., 81(4), 483–496, doi:10.1029/JA081i004p00483.

Carruthers, G. R., T. Page, and R. R. Meier (1976), "Apollo 16 Lyman Alpha Imagery of the Hydrogen Geocorona", J. Geophys. Res., 81(10), 1664–1672, doi:10.1029/JA081i010p01664.

Carruthers, G. R., and T. Page 1984, "The S201 far-ultraviolet imaging survey - A summary of results and implications for future surveys", Publications of the Astronomical Society of the Pacific, 96, 580, 447–462.

Meier, R. R., G. R. Carruthers, T. L. Page, and A. .-C. Levasseur-Regourd (1977), "Geocoronal Lyman β and Balmer α Emissions Measured During the Apollo 16 Mission", J. Geophys. Res., 82(4), 737–739, doi:10.1029/JA082i004p00737.

Page, T., G. R. Carruthers, and H. M. Heckathorn 1982, "Revised S-201 Catalog of Far-Ultraviolet Objects", NRL Report 8487, (Naval Research Laboratory, Washington, DC).

70's.2: The Skylab Manned Space Station and the Apollo Telescope Mount (ATM)

Contributed by George A. Doschek

1.0 *Skylab* – History, ATM Mission and Operations

Perhaps the most exciting solar physics space mission to date was the Apollo Telescope Mount (ATM) group of solar instruments on the *Skylab* manned space station. *Skylab*, the first US manned space station, was launched on 14 May 1973. For a period of about nine months, until 8 February 1974, it obtained solar and Earth observations both with and without astronaut crews. There were three astronaut missions of 28, 59, and finally 84 days in which a crew of three different astronauts for each mission took solar and Earth data as well as carrying out on-board medical and engineering experiments. It was a virtually perfect marriage of unmanned and manned science from a space platform. An excellent overview of *Skylab* and its science was written by Tousey (1977).

Briefly, *Skylab* arose out of an idea to use the leftover Apollo hardware after the lunar landings for space research in a program called the Apollo Applications Program. The ATM was conceived of as a self-contained addition of solar instrumentation to *Skylab*. The solar instrumentation in turn, had been previously designed for an *Advanced Orbiting Solar Observatory* (*AOSO*) as a continuation and great extension of the *Orbiting Solar Observatory* (*OSO*) program; for a discussion of the OSO program, see Essay 60's.2.

After initial approval of the *AOSO* around 1964 followed by a cancellation in 1965 the program was revived and re-invented in 1966 with modifications in the following years to fly as the ATM on the *Skylab* space station, which itself went through many designs. In 1964 proposals by NRL, GSFC, American Science and Engineering, Inc. (AS&E), Harvard College Observatory (HCO), and the High Altitude Observatory (HAO) were accepted for the *AOSO*. These investigators continued into the 1970s with the ATM program and provided the major solar instrumentation on *Skylab*. The solar instruments were re-configured from the *AOSO* for the ATM. NASA's Marshall Space Flight Center (MSFC) was assigned the task of building the NASA GSFC X-ray telescope contribution after the untimely death of John Lindsay. Thus, the principal institutions in the program were officially involved from 1964 until the ATM launch in 1973.

Skylab was a huge space effort. It weighed almost 100 tons. The Saturn Workshop (SWS) provided the living quarters for the crew and was an empty Saturn IVB hydrogen tank outfitted as a living quarters in space. It was 15m long and 6.7m in diameter. The ATM and interface adaptors for bringing new crew and leaving under emergency conditions were attached to the SWS. Plans for solar observing were drawn up by scientists working at the NASA Johnson Space Center (JSC) in Houston. These scientific observations were executed by the astronauts who could also initiate target of opportunity investigations. In addition, the instruments could be operated remotely from the ground. ATM had amazing solar pointing capability due to a solar pointing control system in addition to *Skylab* gyros. The *Skylab* is shown in Figure 70s.2.1.

Figure 70s.2.1 – Skylab as seen from the Skylab 4 Command Service Module (credit: NASA)

The launch of *Skylab* on 14 May 1973 was almost a disaster. After deployment it was found that the meteorite and thermal shield and one of the two solar cell arrays had been torn from the SWS and the other solar array had failed to deploy properly. Within one week fixes had been designed at MSFC and a repair crew had been trained. On 25 May astronauts were launched to *Skylab* and made the first repairs in space. The SWS was finally made habitable and the astronauts certainly proved to be the "right stuff" in making outstanding solar research observations over the duration of the mission.

The astronauts took their tasks seriously and studied solar physics intensively. Prior to launch, they each were required to take a college course in solar physics. During the training sessions the astronauts and the ground-based researchers from NRL and other laboratories got to know each other and were bonded by the *Skylab* adventure. As an example, NRL's Neil Sheeley relates that before the last mission NRL's Paul Patterson wanted one of the astronauts, William Pogue, to carry a Frisbee on board and fling it off into space during an EVA. However, this was not allowed because the Frisbee was made of plastic and was flammable. All human missions in space have stringent safety requirements for items taken on board. The protection of the astronauts can be judged by the fact that shortly before any *Skylab* mission began, the scientists in close contact with the astronauts had to wear masks, in order to minimize the chances that an astronaut might contract a cold and not be able to fly. When the company that had manufactured the Frisbee later found out the reason the Frisbee could not be flown on *Skylab*, they said that had they known about Patterson's request they would have made him a Frisbee out of silver. The publicity would be worth the cost.

Operation of the ATM at JSC in the context of the entire *Skylab* operation was a tour-de-force in planning, analysis, and on-the-spot decision making. All the experiment groups sent a team of scientists and support personnel to Houston to take part in the operations over the nine month interval over which *Skylab* obtained data.

ATM consisted of six main instruments along with a set of smaller supporting instruments. These were a diverse set of instruments designed to pursue different major solar science objectives. The crew time to operate all the ATM instruments was limited, and the crew also needed to support all the other *Skylab* experiments such as Earth-observing and medical experiments. For example, *Skylab* carried two living spiders on-board in order to study the effect of zero gravity on their web manufacturing. It was necessary to design a method for ensuring maximum use and scientific return from all of the instruments. After much thought and discussion, the ATM PIs designed the Joint Observing Program (JOP) system, which worked well throughout the mission.

Daily planning meetings were required to draw up the next day's ATM plan as well as interface with the rest of *Skylab*. In overall charge was a "Czar", who would present the ATM daily plans to Astronaut Robert Parker, who appropriated the crew time among all the *Skylab* activities and not just ATM. The ATM Czars were senior individuals from each of the experiment groups. The NRL Czars were Neil Sheeley and David Bohlin. Much discussion occurred among the various research teams for *Skylab* crew time. The ATM PIs were required to be available 24 hours a day, and sometimes were asked to make quick decisions (e.g., a new active region might rotate onto the solar disk and the PIs would be asked if they wanted observations of the new active region or instead were content to simply continue with the observational plan for the day). The astronauts became so proficient at operating ATM that by the end of each mission they had literally become solar physicists and could operate ATM better than anybody.

During the last mission, it was decided to have essentially a real-time interaction between the astronauts and the scientists. NRL's Neil Sheeley participated in such an activity. When a *Skylab* pass occurred, Neil would chat with the astronauts and suggest observations, and a scientific exchange would occur. This allowed the scientists to make last-minute changes in a plan based upon current solar activity.

2.0 The Major Apollo Telescope Mount Solar Instruments

The six major solar instruments on *Skylab* were: a white light coronagraph from HAO, two grazing incidence X-ray telescopes, one from AS&E and the other from MSFC, an EUV spectrometer-spectroheliometer from HCO, an XUV (EUV, extreme-ultraviolet) spectroheliograph from NRL and an EUV spectrograph from NRL. In addition to the two major NRL instruments, NRL also had an XUV broadband TV monitor as a support instrument and a grazing incidence "corollary" spectrograph that operated between 10 – 200 Å, below the wavelengths of the two main NRL instruments (Garrett & Tousey 1977). Unfortunately, the spectrograph suffered a great loss in sensitivity due to contamination and did not produce much useful data. The XUV monitor was used to image the inner solar atmosphere in real-time for the astronauts. In summary, NRL fielded four instruments and this was a major outstanding achievement of the Rocket Spectroscopy Branch in the SSD. An overview of the two primary solar instruments S082A and S082B is provided below.

3.0a The EUV Spectroheliograph (S082A), Richard Tousey, Principal Investigator

Imaging the Sun in selected wavelengths (spectroheliograph mode) was first accomplished with a rocket experiment built at NRL in 1959 by Tousey's group. The instrument obtained images of the Sun in H I Lyman-α with a spatial resolution better than 1 arcmin. By 1972 the feasible resolution was greatly improved to 2 arcsec, comparable at the time to average H I Balmer-α images. The ATM instrument was a Wadsworth spectrograph (Tousey et al. 1977). The instrument obtained monochromatic images of the Sun between about 170 and 630 Å (see Figures 70s.2.2 and 70s.2.3). This was accomplished by not using a slit, and having a grating that functioned as both a dispersive and imaging optic. Thus the spectrum consisted of full disk images in monochromatic spectral lines, and not merely images of the slit as in a conventional spectrometer. Many of the images overlapped with each other, but small features on the Sun did not overlap, and it is only the background around the images that is highly variable due to the overlapping. This is not a problem for intense features. The spectra have very high spatial (about 2 arcsec) and spectral resolution and were recorded on film, thus allowing the entire spectral region between 171 and 630 Å to be recorded. This region of the solar spectrum contains many transition region, corona, and flare lines, making it ideal for investigating many diverse regions of the solar atmosphere. The 1023 spectroheliograms from this instrument have produced a huge number of papers, and taught solar researchers much about the properties of coronal holes, active regions, and flares. Further, the S082A instrument, along with the other NRL EUV slit spectrograph (S082B) that is described in Sec. 70's.2.3 following, led also to a large burst of plasma diagnostic research activity, which enabled temperatures, densities and dynamics of the solar atmosphere to be determined from line intensities and profiles in high resolution spectra.

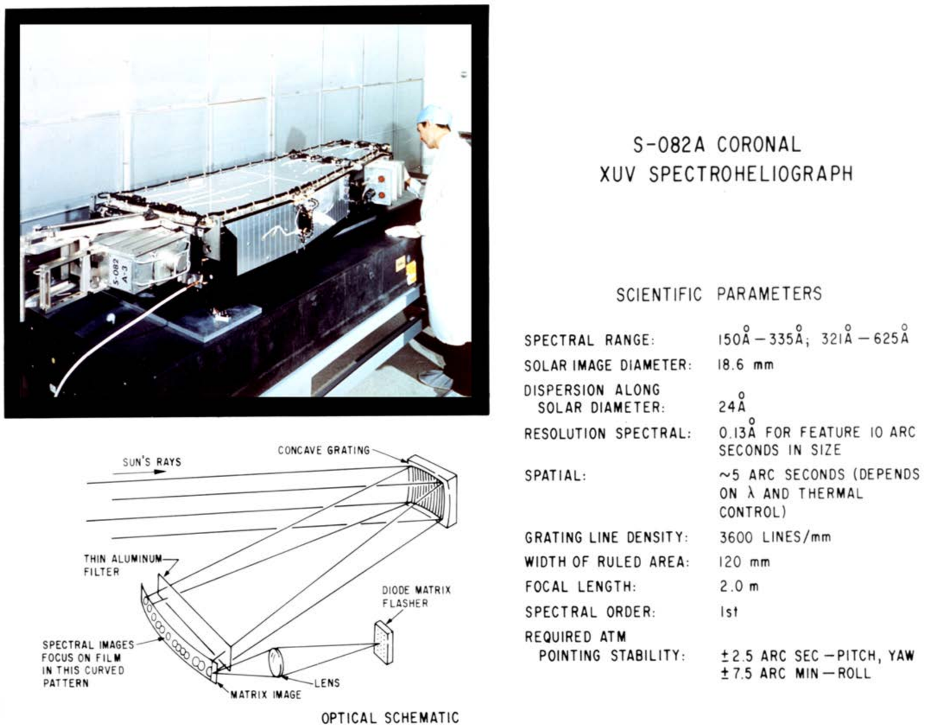


Figure 70s.2.2 – S082A instrument properties, and photograph of the largely assembled instrument (credit: NASA/NRL).

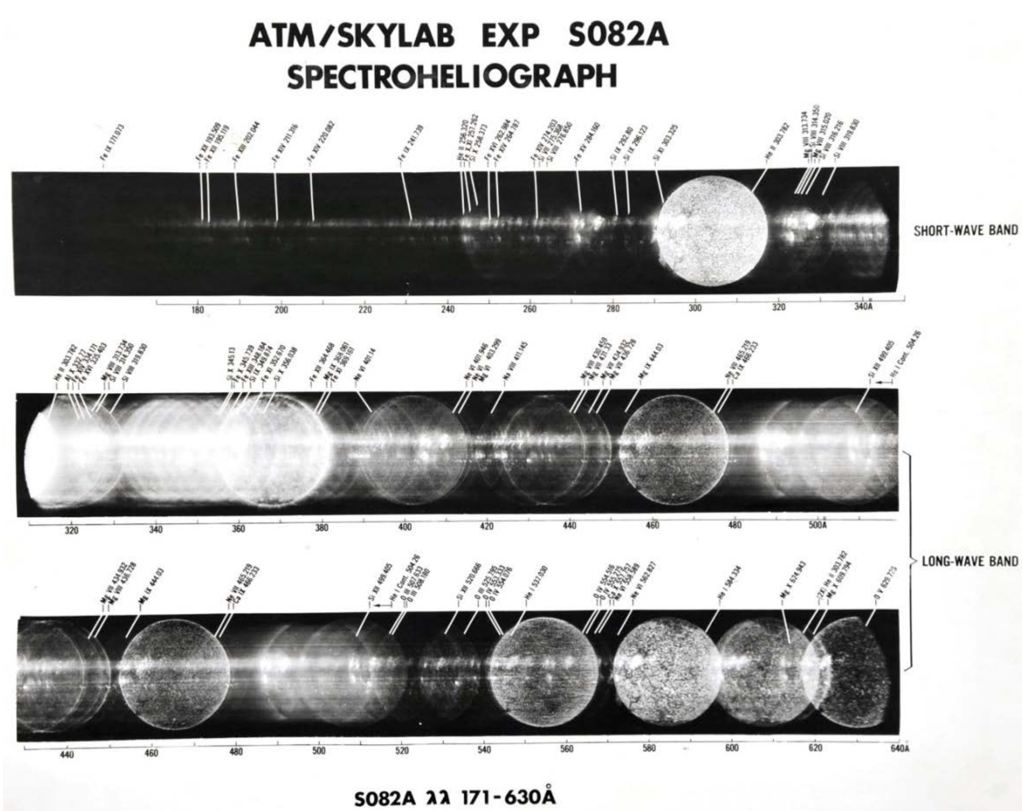


Figure 70s.2.3 – A sample Skylab S082A spectrum. Note that small structures on the Sun do not overlap significantly although the background for each spectral line does depend on overlapping (credit: NASA/NRL).

3.0b The EUV Spectrograph (S082B), Richard Tousey, Principal Investigator

The spectrograph S082B instrument was similar in concept to rocket spectrographs that were flown by NRL between 1960 and 1966. It was a slit EUV spectrograph using film, covering two wavelength regions: 970 – 1970 Å and 1940 – 3940 Å (Bartoe et al. 1977, see Figures 70s.2.4 and 70s.2.5). The slit was 2 arcsec wide and 1 arcmin long. Thus, although it did not provide high spatial resolution, by averaging it provided high quality average properties of many different regions of the solar atmosphere. The wavelength region was sensitive to chromospheric and lower transition region temperatures (about 10,000 – 200,000 K) but there are a number of forbidden coronal lines (e.g., Fe XI, Fe XII) and forbidden flare lines (e.g., Fe XIX, Fe XXI) which are quite useful for observations made outside the solar limb where the bright disk emission and the multitudinous cooler chromospheric lines are weak or absent. The flare lines can be used even for disk observations. It was from the thousands of spectra (6400) this instrument obtained that the average properties, including spatial properties, of the lower transition region were determined. The fundamental science results from this work have not been significantly improved upon as of this writing, although the results have been extended into the upper transition region and corona.

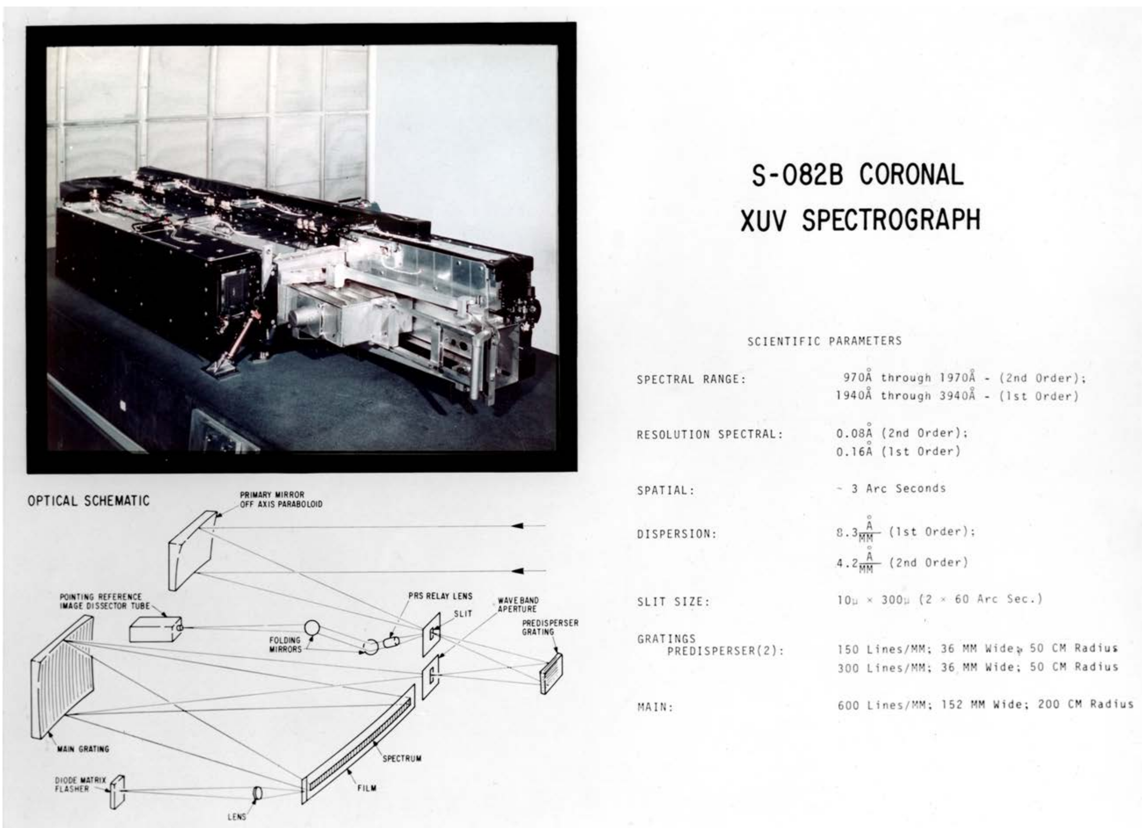


Figure 70s.2.4 – A photograph of the S082B EUV slit spectrograph and instrument properties (credit: NASA/NRL).

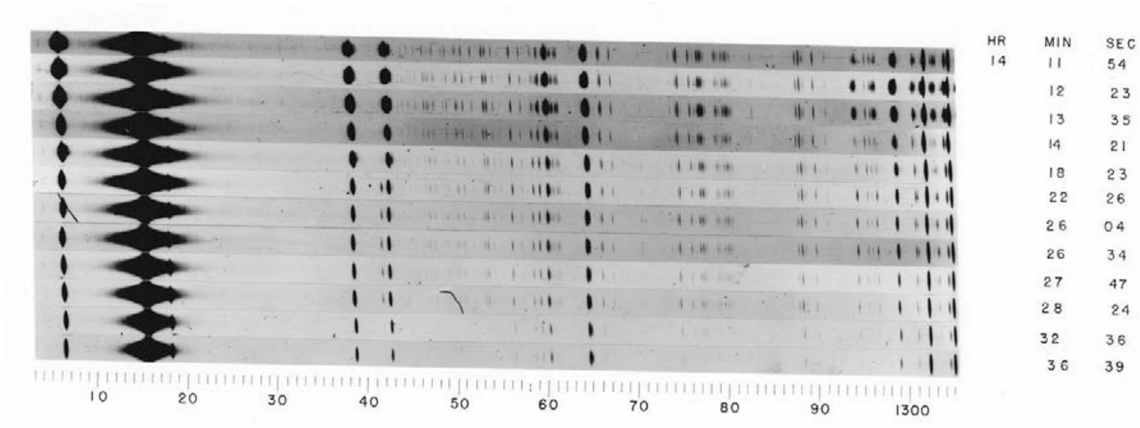


Figure 70s.2.5 – S082B spectrum. The abscissa scale is wavelength in Angstroms(1200 is not shown). Twelve spectra are shown stacked with the times of the exposures shown to the right. The bright feature near 1218 Angstroms is H I Lyman-α. The lines are wider in the topmost spectra due to a flare. Other strong lines near Lyman-α are: Si III near 1206 Angstroms and two strong N V lines near 1239 and 1243 Angstroms (credit: NASA/NRL).

4. 0 Impact of *Skylab* on the Scientific Community

The impact of *Skylab* on the solar world-wide physics research community was enormous. Never before had such abundant, high quality solar data from space been obtained. This was in part made possible by the use of film, since in *Skylab* days detectors did not have the small pixel sizes that they have today. In addition to major *Skylab* presentations at scientific conferences such as the American Astronomical Society Solar Physics Division meeting, NASA sponsored three large workshops dedicated to the analysis of *Skylab* data: a coronal hole workshop, a flare workshop, and an active region workshop. All of these workshops produced hard cover books. The impact of *Skylab* is still felt today. The forefront solar images from *Skylab* can be found almost everywhere; in government office buildings, schools, planetariums, etc. There exist *Skylab* data that still have not been superseded by data obtained by better instrumentation. The analysis of coronal mass ejections showed their importance for space weather and therefore relevance to both military and civilian operations.

Below are some of the scientific highlights from the two major NRL *Skylab* instruments.

5.0a S082A – The EUV Slitless Spectroheliograph

- For the first time high resolution full disk images of the Sun were obtained over a temperature range from about 100,000 K to about 6 MK. The observation of emerging bipolar magnetic fields connecting with previously existing flux in the vicinity of the bipoles indicated strongly that magnetic reconnection actually happens in the solar atmosphere. (e.g., Sheeley et al. 1975).
- Inspection of the solar poles in images of He II 304 Å revealed a nearly continuous band of jets, similar in appearance to spicules but substantially larger. These were called macrospicules, ranging in length from ~5” to more than 60” (1” ~ 720 km at the Sun). The macrospicules may play a role in coronal heating and are still under active investigation (see Bohlin et al. 1975).
- A *Skylab* atlas of coronal holes was made from the He II 304 Å images because He II is darker over coronal holes than over quiet Sun and active regions, and therefore coronal holes are easily visible in He II. The coronal hole locations and boundaries, which could be well-determined from the He II images, were compared to Kitt Peak magnetograms and

data such as these have taught us much about the formation and evolution of coronal holes (see Bohlin 1977).

- A comparison of observations of coronal holes, solar wind streams, and geomagnetic disturbances during 1973-1976 left little doubt that coronal holes are related to high speed solar wind streams and their associated geomagnetic disturbances. The data showed the now well-known fact that coronal holes are the sources of the fast solar wind (see Sheeley, Harvey, & Feldman 1976).
- Active region images in lines of Mg VI (low first ionization potential (FIP)) and Ne VI (high FIP) showed that abundances in the corona vary in different regions of the Sun from photospheric abundances depending on the first ionization potential, and that the evolution of this variability in active region loops could be determined. The FIP effect is now considered a promising technique for determining the still unknown origins of the slow solar wind (Sheeley 1995; Feldman 1992; Laming 2012).
- For the first time solar flares were imaged at high resolution in the EUV. It turns out that lines of Fe XXIII and Fe XXIV (15-20 MK) are also present in the spectrum which makes the EUV images very similar to X-ray images. Much was learned about the locations of hot plasma in flares and the morphology of the evolution into colder plasma as a flare progressed through the impulsive into the decay phase. These observations were also a great contribution for the development of EUV plasma diagnostics (e.g., Widing & Cheng 1974; Widing & Dere 1977).

5.0b S082B – The EUV Slit Spectrograph

- For the first time, the average geometry of the lower solar transition region (~20,000 – 200,000 K) could be mapped above the limb with arcsec accuracy in many spectral lines. The resulting average limb brightening curves showed that the classical thin transition region model based on constant conductive flux was oversimplified and did not agree with observations (e.g., see Feldman 1983).
- For the first time, adequate data existed to study the dynamics of the lower transition region which resulted in the discovery (Doschek et al. 1976b) that transition region lines are slightly redshifted relative to chromospheric lines. It is a key signature of transition region dynamics.
- Many plasma diagnostics were developed for the EUV, particularly density and emission measure diagnostics. This has led to the CHIANTI database used now by the entire solar physics community and developed with a significant NRL contribution. NRL scientist Kenneth Dere was a founding member of the CHIANTI consortium.
- It was confirmed that transition region spectral lines and forbidden coronal lines that could be seen in off-limb S082B spectra were wider than expected from thermal Doppler broadening in ionization equilibrium (e.g., Doschek et al. 1981). This broadening is referred to as nonthermal broadening. It may be due to turbulence, or alternatively the superposition of motions of unresolved structures. The S082B limb observations of coronal line nonthermal broadening (Cheng, Doschek, & Feldman 1979) were cited as evidence of magnetic reconnection in the corona by Parker in his famous paper, Parker (1988).
- For the first time detailed transition region physical conditions in a prominence could be determined by placing the spectrograph slit to view various positions within the prominence (e.g., Mariska et al. 1979). Similar measurements were made for a surge and the chromospheric network.

In summary, by means of NRL spectrographs S082A and S082B, the Sun was probed spectroscopically at a level never before possible, leading to a much better understanding of the properties of the atmosphere.

References: 70's.2:

Bartoe, J.-D., Brueckner, G. E., Purcell, J. D., & Tousey, R. 1977, Appl. Opt., 16, 879

Bohlin, J. D. 1977, Sol. Phys., 51, 377

Bohlin, J. D., Vogel, S. N., Purcell, J. D., Sheeley, N. R., Jr., Tousey, R., & VanHoosier, M. E. 1975, Astrophys. J., 197, L133

Cheng, C.-C., Doschek, G. A., & Feldman, U. 1979, Astrophys. J., 227, 1037

Doschek, G. A., Feldman, U., & Bohlin 1976b, Astrophys. J., 205, L177

Doschek, G. A., Mariska, J. T., & Feldman, U. 1981, Mon. Not. R. astr. Soc., 195, 107

Feldman, U. 1983, Astrophys. J., 275, 367

Feldman, U. 1992, Phys. Scr., 46, 202

Garret, D. L., & Tousey, R. 1977, Appl. Opt., 16, 898

Laming , J. M. 2012, Astrophys. J., 744, 115

Mariska, J. T., Doschek, G. A., & Feldman, U. 1979, Astrophys. J., 232, 929

Parker, E. N. 1988, Astrophys. J., 330, 474

Sheeley, N. R., Jr. 1995, Astrophys. J., 440, 884

Sheeley, N. R., Jr., Bohlin, J. D., Brueckner, G. E., Purcell, J. D., Scherrer, V., & Tousey, R. 1975, Astrophys. J., 196, L129

Sheeley, N. R., Jr., Harvey, J. W., and Feldman, W. C. 1976, Sol. Phys., 49, 271

Tousey, R. 1977, Appl. Opt., 16, 825

Tousey, R., Bartoe, J.-D. F., Brueckner, G. E., & Purcell, J. D. 1977, Appl. Opt., 16, 870

Widing, K. G., & Cheng, C.-C. 1974, Astrophys. J., 194, L111

Widing, K. G., & Dere, K. P. 1977, Sol. Phys., 55, 431

70's.3: The Space Test Program P78-1 Spacecraft:1979-1985

Contributed by George A. Doschek and Russell A. Howard

1.0 Germination of the SSD *P78-1* Program

Although most of the SSD's big space hardware projects were and continue to be funded by NASA, the *P78-1* spacecraft, flown by the US Department of Defense (DoD) Space Test Program (STP), provided major new results in solar physics in the areas of coronal physics and solar flare and active region X-ray spectroscopy. This was made possible as a result of the manifest for flight by the STP of the backup NASA spacecraft for *OSO*-7, which provided three-axis stabilization and could thus contain sophisticated solar physics instrumentation.

The concept of *P78-1* for solar physics originated in Dr. Tousey's Rocket Spectroscopy Branch of the SSD and the person most responsible for achieving the reality of the mission was Dr. Donald J. Michels, an NRL Federal employee scientist in the Branch. Don Michels was a pioneer in explaining the importance of coronal mass ejections (CMEs) to the military after their discovery from *OSO-7* (see *OSO* Essay in the 1960s section), and wished to have an STP re-flight of the *OSO-7* coronagraph, in which the observation cadence could be greatly increased. Don worked hard to convince the DoD of the importance of CMEs which drive geoeffective space weather storms in the Earth's extended operational environment. Eventually the STP office decided to fly a *P78-1* spacecraft with Don's coronagraph and a prime instrument, a gamma ray spectrometer from Lockheed. Don's coronagraph was called SOLWIND (solar wind). The STP office initiated a request for proposals for a spacecraft, and a proposal from Ball Brothers was accepted. STP then configured a total payload that included not only SOLWIND and the gamma ray spectrometer, but also other instruments from SSD and other organizations.

The SSD fielded a number of instruments. The Rocket Spectroscopy Branch was responsible for SOLWIND and another broadband extreme ultraviolet (EUV) (170 - ~310 Å) imager, modeled after a previously flown Skylab instrument. Unfortunately, the EUV imager failed to produce useful data because of scattered light. However, it enabled the group to learn about Charge-Coupled Devices, which were to play an important role in a later SSD led mission (the *Solar & Heliospheric Observatory* (*SOHO*), see Essay in the 1990s section). The SOLWIND instrumentation was built by about 8 Federal employees in the Branch. Three NRL Federal scientists, Dr. Donald Michels, Dr. Russell Howard, and Mr. Marty Koomen, were key scientists in the build program and they were joined by another NRL Federal scientist, Dr. Neil Sheeley, for the subsequent data analysis. The work was supported exclusively by NRL/ONR funds.

The SSD Upper Air Physics Branch fielded three instruments on *P78-1*: a high resolution X-ray spectrometer (SOLFLEX, solar flare X-rays), MAGMAP (Magnesium Mapping, a broadband X-ray imager (60") designed to image the Sun in radiation for Mg XI and Mg XII), and an X-ray astronomy detector. Perhaps 8 to 10 SSD Federal employees worked on these instruments, again funded only by NRL/ONR funds. The SOLFLEX spectrometer crystals were provided by Dr. Richard Deslattes at the National Institute of Standards and Technology (NIST). SOLFLEX also required a special barrier coating to be developed for one of its mechanisms in order to satisfy Air Force requirements for the spacecraft, and this was achieved by researchers in the NRL Chemistry Division. SOLFLEX provides a good example of the power of NRL; there is widespread expertise at NRL in many areas of physics, chemistry, and engineering, and a willingness to solve interesting and important problems.

P78-1 was launched on 24 February 1979 on an Atlas F rocket from Vandenberg Air Force Base in

California into a nearly circular polar orbit about 500 km above the Earth. The orbital plane was inclined 97 degrees to the equator and precessed such that it stayed at an approximately noon-midnight meridian as the Earth circled the Sun. The orbital period was 97 minutes. The spacecraft operated until 13 September 1985 when it was shot down in orbit by an F-15 Eagle fighter aircraft during a US Air Force ASM-135 ASAT (anti-satellite missile) test. The *P78-1* spacecraft is shown in Figure 70s.3.1.

Figure 70s.3.1 – The P78-1 spacecraft. It features a solar pointed section that housed the SOLWIND coronagraph and the SOLFLEX X-ray spectrometer package (credit Space Test Program, NASA).

2.0 SSD *P78-1* Solar Instrumentation

Not all instruments flown on *P78-1* worked as hoped, and some did not produce significant science. The solar instruments that produced the most significant science are overviewed below (More details on the *P78-1* solar instrument suite can be found in Doschek 1983):

White light coronagraph (SOLWIND), D. J. Michels (NRL), Principal Investigator

SOLWIND was a modified Lyot coronagraph that observed the entire corona between 2.6 – 10 solar radii with a spatial resolution of 1.25' in the 4000 – 7000 Å wavelength interval. The Sun was occulted by three circular disks mounted in tandem and supported in front of the instrument. There were polarizers for circular zones of the image near 5 and 8 solar radii. Images were recorded by a Secondary Electron Conduction (SEC) Vidicon detector. The coronagraph was the flight spare *OSO-7* instrument and was optically similar to the *OSO-7* coronagraph described by Koomen et al. (1975). The major differences between the *OSO-7* and SOLWIND coronagraphs were the slightly smaller occulting disk and the much greater telemetry rate. When *P78-1* was obtaining solar data, SOLWIND coronal images were obtained at 10 minute (and sometimes 5 minute) intervals during the about 1 hour sunlit portion of the orbit. The electronics package was also the flight spare *OSO-7* electronics, but had to be modified to enable the higher telemetry rate (5,000 bps rather than 200 bps). Having been built in 1969, David Roberts and Russell Howard found that some sections of the electronics had failed and needed to be isolated and new replacement electronics installed. Mrs. Grace Burroughs of the NRL Engineering Services Division performed the isolation tasks.

X-ray spectrometer, four bands (in Angstroms:) (SOLFLEX), R. W. Kreplin (NRL), Principal

Investigator

SOLFLEX recorded high resolution X-ray spectra in four narrow wavelength bands: 1.82 – 1.97 Å, 2.98 – 3.07 Å, 3.14 – 3.24 Å, and 8.26 – 8.53 Å. The bands were chosen in order to observe highly ionized Fe and Ca lines produced during solar flares, and the Mg XII Lyman-α line surrounded by emission lines of Fe XXIII and Fe XXIV. Three of the crystals were Ge (2d = 4.00 Å) and one was ADP (2d = 10.64 Å). The spectral resolution was about 8,500 for all the crystals. The crystals were mounted on a common shaft and scanned the spectral ranges in 20" steps at a rate of 8 steps/s for most of the spectra. It took 56 s for a complete spectral scan. The detectors were Ar and Xe filled proportional counters and the field-of-view was full-Sun. The Aerospace Corporation also had Bragg spectrometers on *P78-1* and the SSD scientists involved in Bragg spectroscopy worked closely with the Aerospace scientists in analyzing all the spectroscopic data.

3.0 Solar Physics Research Community Impact of *P78-1*

Before discussing some of the *P78-1* scientific highlights, it is helpful to set the stage for the importance of NRL research on *P78-1* by describing the position of NRL in coronal physics and X-ray spectroscopy in the US solar community at the time of the launch of *P78-1*. Although NRL had discovered CMEs (Tousey 1973), the data analysis and scientific understanding of CMEs was primarily being led by researchers at the High Altitude Observatory (HAO) in Boulder, Colorado. HAO had a coronagraph on Skylab (See Essay 70's.2) that was flown also in 1973; the HAO coronagraph used film and therefore produced much higher spatial resolution images (5"), greater dynamic range, and cleaner data than the images from NRL's *OSO-7* instrument. Eminent HAO solar scientists were involved in their coronagraph's data analysis and began dominating the research field. Furthermore, the NASA Solar Maximum Mission (*SMM*) scheduled for launch in 1981 contained another HAO coronagraph, this one with digital detectors. Before the launch of *P78-1*, it looked to scientists at NRL like HAO was going to be the dominant organization in the study of the corona from space because of their superior instrumentation and strong scientific expertise.

The situation in X-ray spectroscopy was better for NRL, but NRL was not yet positioned to be a significant player in future experiments. NRL's position in the field was based on its relatively low spectral resolution Bragg spectrometers on *OSO-4* and *OSO-6* and strong analysis of the data, but the Goddard Space Flight Center had Bragg instruments on *OSO-3* and *OSO-5*, and the Aerospace Corporation also had excellent satellite X-ray spectra. And both of these groups also were excellent in data analysis. Furthermore, United Kingdom scientists had good rocket X-ray spectra and the Soviets had obtained the first high resolution X-ray spectrum of Fe XXV and its associated satellite lines (Grineva et al. 1973), a very important line complex for solar flare research and for high energy astrophysics. Moreover, the *SMM* mission to be launched in 1981 contained a powerful X-ray spectroscopy suite, headed by the outstanding scientists Loren Acton at Lockheed, Len Culhane at Mullard Space Science Laboratory (UK), and Alan Gabriel at Rutherford Appleton Laboratory (RAL). Alan Gabriel with Carole Jordan had done seminal theoretical atomic physics work on understanding the solar X-ray spectrum. Finally, Japanese scientists with considerable experience in X-ray spectroscopy planned to launch their *Hinotori* (firebird) spacecraft, which would contain an outstanding solar X-ray spectroscopy experiment. NRL had attempted but failed to get an instrument on the highly touted NASA flagship *SMM* mission, and so something had to happen for NRL to remain a player in coronal space physics and X-ray spectroscopy. That something was *P78-1*. *P78-1* was launched a full year before *SMM* and two years before *Hinotori.*

P78-1 was not well-known in the outside solar community, so NRL scientists with their two Aerospace colleagues and other colleagues from different institutions were outnumbered by the *SMM* science team that emerged into the community after the launch of *SMM*. However, the NRL scientists actively attended meetings, and were even key participants in an *SMM* Workshop, working constantly to disseminate and inform the community of the exciting new scientific results they were obtaining from *P78-1*. NRL scientists succeeded very well in all of these activities.

Finally, it should be noted that much of the initial work in realizing *P78-1* and later capturing the opportunity on *SOHO* for a coronagraph (the Large Angle Spectroscopic Coronagraph, LASCO) was due to Don Michels. Not only was Don the key player in starting *P78-1*, but he also developed the consortium for the LASCO coronagraph on *SOHO* (see Essay in the 1990s section). Don's coronagraph ideas and his consortium resulted in a victory over the competing *SOHO* coronagraph proposal from HAO. This cemented NRL's scientific leadership role in space coronagraph instrumentation far into the future. Don was able to achieve these outstanding successes because of the excellent collaboration and support of his colleagues, primarily Russ Howard (NRL), Martin Koomen (NRL), and Neil Sheeley (NRL), as well as support from other scientists throughout NRL.

4.0 *P78-1* SSD Science Highlights

- SOLWIND produced the first large-scale comprehensive survey of CMEs (Howard et al. 1985). Howard et al. (1985) identified a total of 998 CMEs between about April 1979 through December 1981, and did a statistical analysis of their shapes, sizes, speeds, occurrence rate, masses, and energies. They found that CME properties depend strongly on their structure. This survey included far more CMEs than previous publications based on Skylab and *SMM* data. They discussed the relationships of CMEs to sunspot number and flares. The Howard et al. (1985) paper represents a landmark in attempting to understand CMEs. An example of a SOLWIND CME is shown in Figure 70s.3.2.

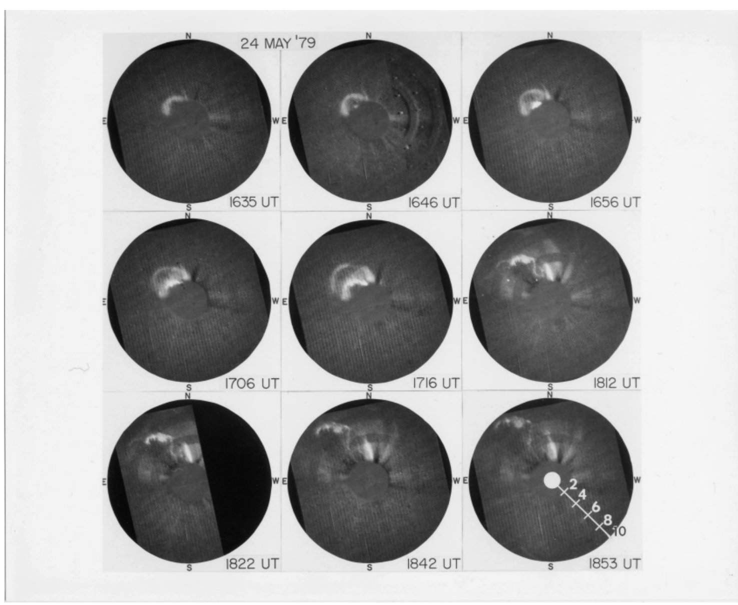


Figure 70s.3.2 – A large Coronal Mass Ejection (CME) that occurred on 24 May 1979. Note the rather filamentary and irregular structure also present in addition to the smoother and more large-scale emission. The filamentary structure does not suffer an intensity loss in the instrument's polarizer annuli because it is not very highly ionized. It is cool eruptive prominence material that is expelled and forms part of the total CME (from Sheeley et al. 1982, Space Science Reviews, 33, 219, courtesy Space Science Reviews).

- SOLWIND produced the first detailed study of the association of CMEs with interplanetary shocks (Sheeley et al. 1985). A comparison of SOLWIND CME data with Helios 1 observations of interplanetary shocks observed between 1979-1982 indicated that 72% of the shocks were associated with large, low-latitude CMEs. The number of possible associations was considerably larger, and only 2% of the shocks clearly lacked a CME association. The association of CMEs and shocks is still being studied today due to its relevance to the production of Solar Energetic Particles (SEPs) that can affect spacecraft operations.

- SOLWIND produced the first observations of CMEs directed at Earth – the so-called "halo" CMEs (Howard et al. 1982). CMEs directed at the Earth can produce a ring of brightening in the corona that extends entirely around the solar disk (see Figure 70s.3.2). The head-on CME detected on 27 November 1979 did exactly this and showed conclusively that CMEs are three dimensional structures. The ring of brightening gradually expanded with a projected radius that increased from 4 to 8 solar radii. The CME was the source of an interplanetary shock detected by the ISEE 3 spacecraft. The estimated frontal speed of the CME was about 1,000 km/s. Even today the three dimensional shapes of CMEs are the subject of much study and some debate; see, e.g., Essay 2000s.3 in Vol. 5 of this series for an overview about the NRL PI Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) aboard NASA's Solar Terrestrial Relations Observatory (STEREO) that was landed into space in 2006.

- SOLWIND produced the first study of the association of CMEs with soft X-ray events. It was found that the probability of the association of a CME with an X-ray event increases continuously with the duration time of the X-ray event. X-ray events with durations centered around 3.5 hours have a high probability of an association with a CME. The type of solar flare known as a long-duration event (from *Skylab* observations) is virtually certain to be associated with a CME. This is not the case for so-called impulsive flares with durations of say an hour or less. This type of study continues today in an attempt to understand the role of magnetic reconnection in produces both flares and CMEs.

- SOLWIND made the first discovery of a comet (1979 XI: Howard-Koomen-Michels) from an orbiting spacecraft (Michels et al. 1982). SOLWIND discovered a number of comets from the so-called Kreutz group of sungrazing comets (see Figure 70s.3.3) at the rate of about one a year. An analysis of the images revealed that the comet was completely vaporized due to its proximity to the Sun. The discovery of such comets continues with LASCO and STEREO and to date more than 2,000 comets have been found from the inspection of coronagraph images. The coronagraph data are freely available on the web and many comets have been discovered by amateur astronomers interested in making significant contributions to astronomy.

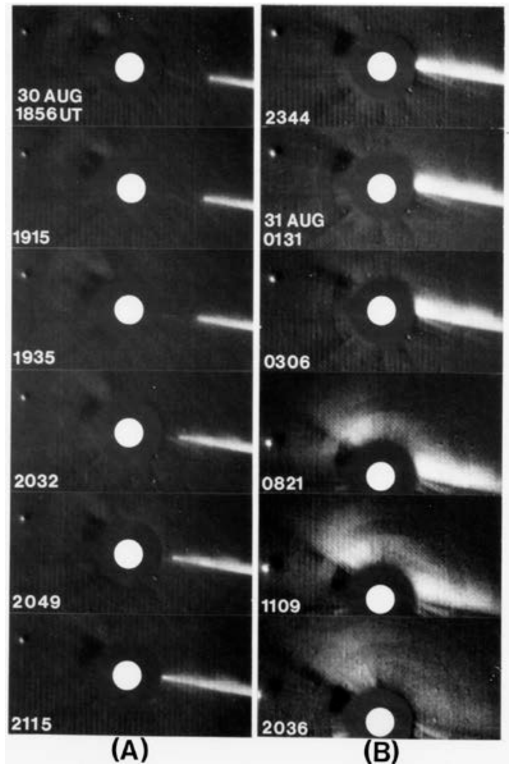


Figure 70s.3.3 – The streak of light in the left panel (A) is the Sungrazer comet moving closer to the Sun. The right panel (B) shows dust remaining in the orbit plane of the comet. This small comet is believed to have vaporized completely as it approached the Sun (from Michels et al. 1982, Science, 215, 4536).

- SOLFLEX obtained the first high quality solar flare spectra of the Fe line complex near 1.8 Å and the similar Ca complex near 3.2 Å (Doschek et al. 1979). The highly ionized Fe and Ca lines are due to He-like ions and their associated dielectronic satellite lines. The plasma diagnostics possible for these complexes is not available in any other part of the solar spectrum. Electron and ionization equilibrium temperatures for flare plasmas could be determined independently of each other (see Figure 70s.3.4).

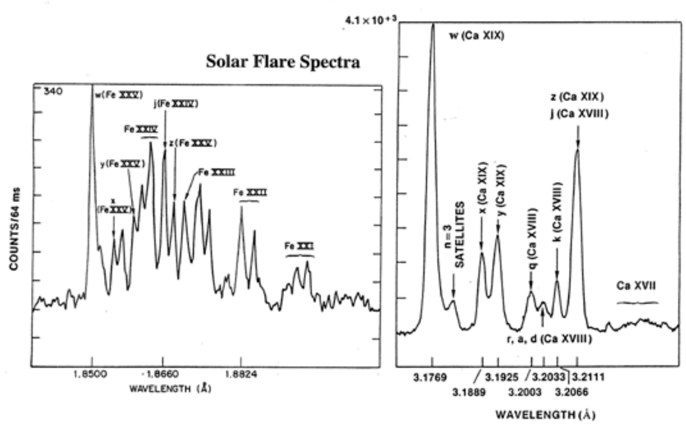


Figure 70s.3.4 – SOLFLEX Fe and Ca spectra of a large X-class flare. The lines marked w, x, y, and z are due to the He-like ions and are produced by electron impact excitation. The other lines are produced mostly by dielectronic recombination and provide unique flare temperature diagnostics. The line profiles are physical, and not instrumental (from Doschek 2006, Advances in Space Research, 38, 1482, courtesy Advances in Space Research).

- SOLFLEX made the first discovery of plasma at multimillion degree temperatures predicted as a result of chromospheric heating due to either conduction fronts or energetic non-thermal electrons released at the onset of solar flares (chromospheric evaporation). This was done from measurements of spectral line profiles. In addition, SOLFLEX made the first detection of non-thermal motions and turbulence during the rise phase of flares (Doschek et al. 1980; Feldman et al. 1980).

- In addition to the NRL-led instruments SOLWIND and SOLFLEX, the Aerospace Corporation Solar X-rays (SOLEX) spectrometer produced unique and important data also. SOLEX provided the first high resolution X-ray spectrum between 7.8 and 23.0 Å, enabling accurate plasma diagnostics of electron temperatures, densities, and abundances (McKenzie et al. 1980).

- Previously, spectra in this range were largely unresolved due to the close spacing of many lines. The data from both SOLEX and SOLFLEX were used to determine many of the plasma properties of multimillion degree flares. Also, SOLEX produced the first and only observations of the electron density and volume evolution at about a million degrees during solar flare chromospheric evaporation (Doschek et al. 1981). Using He-like lines of O VII, the electron density and volume of million degree plasma could be determined as a function of time as a result of energy transport from the flare reconnection site into lower temperature plasma. These observations have not been duplicated with *SMM*, *Hinotori*, or any subsequent solar space mission.

In summary, *P78-1* was a very important mission for solar physics research and for NRL solar scientists. The mission set the stage and provided the NRL researcher knowledge and the recognized credentials necessary for NRL spaceflight hardware involvement in many of NASA's subsequent solar missions to be described in this history.

References: 70's.3:

Doschek, G. A. 1983, Solar Phys., 86, 9

Doschek, G. A. 2006, Advances in Space Research, 38, 1482

Doschek, G. A., Feldman, U., Kreplin, R. W., & Cohen, L. 1980, Astrophys. J., 239, 725

Doschek, G. A., Feldman, U., Landecker, P. B., & McKenzie, D. L. 1981, Astrophys. J., 249, 372

Doschek, G. A., Kreplin, R. W., & Feldman, U. 1979, Astrophys. J., 233, L157

Feldman, U., Doschek, G. A., Kreplin, R. W., & Mariska, J. T. 1980, Astrophys. J., 241, 1175

Grineva, Yu. I. 1973, Solar Phys., 29, 441

Howard, R. A., Michels, D. J., Sheeley, N. R., Jr., & Koomen, M. J. 1982, Astrophys. J., 263, L101

Howard, R. A., Sheeley, N. R., Jr., Koomen, M. J., & Michels, D. J. 1985, J. of Geophys. Res., 90, No. A9, 8173

Koomen, M. J., Detwiler, C. R., Brueckner, G. E., Cooper, H.W., & Tousey, R. 1975, Appl. Opt., 14, 743

McKenzie, D. L. et al. 1980, Astrophys. J., 241, 409

Michels, D. J., Sheeley, N. R., Jr., Howard, R. A., & Koomen, M. J. 1982, Science, 215, 1097

Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., & Michels, D. J. 1985, J. of Geophys. Res., 90, No. A1, 163

Tousey, R., The Solar Corona, in Space Research XIII, edited by M.J. Rycroft and S.K. Runcorn, p 713, Akademie-Verlag, Berlin, 1973.

Warren, H. P., & Doschek, G. A. 2005, Astrophys. J., 618, L157

70's.4: The NRL Large Area Sky Survey Experiment on HEAO-1

Contributed by Kent S. Wood

1.0 Introduction

On August 12, 1977 NASA launched the first of three large satellites designed to study energetic photons and particles in space, collectively called the High Energy Astrophysical Observatories. The first carried the name "*HEAO-1*" throughout its orbital life; the second, *HEAO-2*, was renamed the *Einstein Observatory,* and the final one was called *HEAO-3.* The primary experiment on *HEAO-1*, produced by the Naval Research Laboratory, was the Large Area Sky Survey Experiment, abbreviated "LASS," but also known (almost interchangeably) as "HEAO A-1" or simply "A-1", where that designation distinguished it from three other experiments on the same satellite (A-2, A-3, and A-4), collectively developed and built by a total of six other institutions (Smithsonian Center for Astrophysics, Massachusetts Institute of Technology (MIT), NASA Goddard Space Flight Center (GSFC), California Institute of Technology (Caltech), University of California Berkeley, University of California San Diego). The LASS or A-1 was a bank of seven X-ray-sensitive proportional counters that constituted the largest X-ray detector array flown to that time. There were also two ultraviolet aspect sensors, capable of a modest survey. The other three major experiments were designed to survey the sky in various X-ray energies (sometimes including energies outside the A-1 bandpass) and perform other measurements, e.g., measuring point source positions more accurately for brighter sources. All four instruments aimed to produce sky catalogs and support research targeted to specific sources of interest. All of this ambitious program was eventually realized.

HEAO-1 represented a substantial size increment for X-ray satellites. Smaller spacecraft predecessors, *Uhuru, Ariel V, OSO-8,* and *SAS-3,* had earlier looks at the sky by varying their scanning and pointing, but that surveying was not systematic and the sensitivity achieved varied greatly from one sky region to another. In contrast, *HEAO-1* mapped the full sky as uniformly as possible, in scans perpendicular to the Ecliptic, with the scan plane advancing roughly a degree each day so as to cover the entire sky every six months. It was launched in a low-inclination Low Earth Orbit (LEO) orbit where it operated until March, 1979, during which time it completed three full sky scans and conducted many pointings on targets. NRL's LASS produced the primary survey catalog of 842 sources with energies in the range 0.25-25 keV, the most complete X-ray source catalog or survey up to that time.

2.0 The Large Area Sky Survey Experiment and the HEAO Mission

The Principal Investigator for HEAO A-1 was Dr. Herbert Friedman, Superintendent of the Space Science Division, NRL. He was among the founders of X-ray astronomy, for which achievement he later received the Wolf Prize in 1987. Dr. Friedman articulated the need for the larger satellites along with Dr. Riccardo Giacconi (then at American Science & Engineering), another founder of the field. They and their colleagues convinced NASA to fly the *HEAO* series.

HEAO-1 was the transition from sounding rocket to satellite experiments for the X-ray astronomy group at NRL. The LASS design grew out of earlier proportional counter experiments at NRL flown on rockets. (See astrophysical rockets essay 60s.4 of this history collection.) Dr. Friedman was an expert in proportional counters, having led their development for X-ray astronomy. The design heritage was a decade of accumulated experience on a mix of sources that had begun with the Sun itself, then bright sources such as Sco X-1 and the Crab Nebula, and later other classes of sources. It had become clear that desirable performance features included ability to measure fluxes repeatedly to explore variability on a wide range of time scales, broad spectral response, low background rate, and sometimes a fine point spread function (PSF) to isolate sources in crowded regions and detect extension of sources with angular sizes above a few arc minutes. Reaching lower flux levels would necessarily bring discovery of many new sources and possibly entire new classes of sources. One way to reach lower flux levels was with a large proportional counter array, equipped with a good veto scheme to minimize background.

Design. These considerations were incorporated in the A-1 design. In all, eight detector units were built and seven flown. Each had the same detector body with frontal area ~3,000 cm^2; effective areas ranged from 1350 to 1800 cm^2, varying with the collimator assigned to the unit. The different collimators were optimized for timing, positioning, and variability studies. Six detectors were on one side of the spacecraft (-y) while the seventh was on the opposite side (+y), where it shared accommodation space with the A-2, A-3 and A-4 experiments. In addition, A-1 had a Central Electronics module and a Central Gas module situated in the interior of the spacecraft in such a way that they could service all seven detector modules, irrespective of location. The detector design featured a thin mylar window that gave the instrument sensitivity down to X-ray energies of 0.25 keV. The counter gas was xenon and methane; the high atomic number of Xe provided useful sensitivity as high as 25 keV. This energy range of 0.25 – 25 keV meant A-1 extended both above and below the energy range of earlier satellites. (*Uhuru* had covered 2-10 keV.) The thin window required a gas flow system whereby gas that leaked through the thin window was resupplied from the central tank that carried the Xe-CH_4 mixture at high pressure. The thin-window gas-flow techniques were a specialty of the NRL group. The others who had developed the design were Friedman's long-standing collaborators, Dr. Talbot Chubb (NRL) and Mr. Edward T. Byram (NRL). They and other NRL scientists were the core team that proposed the experiment to NASA and led it through subsequent phases to launch, by which time they were joined by other scientists preparing for the mission phase. The lead contributor of this essay (K. Wood, NRL) initially led the data analysis preparation, and then scientific analysis in the post-launch phase. At Dr. Friedman's retirement he succeeded Friedman as Principal Investigator, and led the data analysis on the all-sky archive that had been created, one still maintained at NASA's High Energy Astrophysics Science Archive Research Center (HEASRC).

Development, Operations. In mission development and operations, HEAO-1 followed a model wherein the four experiment teams worked closely with NASA's project office as it developed and flew the spacecraft. NRL participated in spacecraft testing: *e.g.*, as A-1 PI, Dr. Friedman proposed, and the A-1 team tracked specific gyro test sequences that uncovered mission-threatening flaws whose correction was obligatory. After launch, A-1 scientists contributed to working technical issues and problems jointly with the engineering and technical staff as well as performing mission planning concurrently with data pipeline management, archiving, calibrations, and finally scientific analysis, covering all these multiple bases, quite different in character. During the mission life, priority went to instrumental issues. Important papers were published during the year and a half when the satellite was flying but *HEAO* publications that seem most significant today chiefly carry dates from the early 1980s. For the data pipeline, special credit is due to NRL's D. J. Yentis, D.P. McNutt, and J.F. Meekins. Computer technology initially was early technology – card decks, line printers, and tapes - and later evolved to terminals on VAX machines.

Pointing. Once the central HEAO-1 objective of full sky surveying was assured, targets of interest were followed up with 3-axis pointed observations. Pointings were interspersed between further full-sky scanning that added sensitivity and explored longer timescales of source variability out to several months. The four science teams shared planning of pointed operations. Representatives would negotiate a prioritized target list; then, commands would be prepared and sent to NASA mission operations specifying sky location, duration of observation, and commandable aspects of the observatory configuration. Instrument teams configured their respective instruments by command to modes appropriate to the targets, which called for generating and forwarding command sequences on a continuing basis. Pointings greatly advanced source variability work.

2.1 *Principal Scientific Results of the Large Area Sky Survey Experiment*

The central science product was the *HEAO A-1* All-Sky Catalog (Wood et al., 1984) which gave specifications on 842 sources distributed over the full sky. These were the brightest objects in the X-ray sky in the *HEAO-1* lifetime. To appreciate the nature of the catalog one must realize the X-ray sky shows astonishing diversity of classes among its brighter sources. The very brightest are supernova remnants and neutron stars as well as black holes, followed by active galaxies and quasars, white dwarf binaries, stellar coronae, nearby galaxies and clusters of galaxies, and miscellaneous Galactic populations including star-forming regions and certain unusual stellar types. All these occur among the brightest several hundred X-ray sources. (Contrast the visible sky where the ~6000 naked eye objects are primarily stars and some planets.) The brightest extra-solar X-ray sources in the sky are located in our own Galaxy and provide the outstanding feature of the all-sky map along the plane of the Milky Way, with the remainder distributed over all Galactic latitudes. *HEAO A-1* mapped this complex sky in an unbiased way. Other prominent results can be conveniently grouped by source classes. What follows is not exhaustive but gives the more remarkable items from each class.

2.1.1 *Extragalactic classes (I): Clusters of galaxies*

- A comprehensive survey of clusters of galaxies was carried out in addition to the catalog itself. This resulted in additional clusters and upper limits at positions of other known clusters, leading to the first accurate X-ray luminosity function for rich clusters (Ulmer et al., 1981, 1982; Johnson et al. 1983; Kowalski et al., 1984).

2.1.2 *Extragalactic classes (II)L Active Galactic Nuclei (AGN)*

- The *HEAO A-1* catalog itself identified and catalogued many new sources belonging to a variety of distinct active galactic nuclei (AGN) types. Establishment of new classes was initially done as early-mission papers on class prototypes, sometimes incorporating information being gathered simultaneously by the other *HEAO-1* experiments, particularly A-3 positions. The catalog paper incorporated and extended those results.
- In addition, variability studies were undertaken on prominent AGN sources, notably PKS 2155-304. That source exhibited some of the most extreme variability detected in any AGN up to that time. (Snyder et al., 1980).
- Special emphasis was placed on sources near the Ecliptic poles where all scans came together and sources could be observed for months. One was 3C371 which was detected continuously for 80 days to give a high-cadence variability timescale coverage not previously achievable. (Snyder et al, 1982). A survey that went deeper than the 1H catalog was conducted at the North Ecliptic Pole (Shrader et al.1986).

2.1.3 *X-ray Binaries and Galactic Sources*

- LASS saw the first eclipses in any low-mass X-ray binary, in the source MXB1659-29, which started a study of such eclipses that remained an NRL focus through the next three decades (Cominsky and Wood, 1984, 1989).
- The LASS detected the first quasi-periodic oscillations (QPOs) of the Normal Branch mode in the source Cyg X-2 (Norris and Wood, 1987).
- An extensive study was made of rapid variability in black hole candidates; this led to identifying the binary GX 339-4 as a black hole system, at a time when few were known (Samimi et al., 1979). Statistical methods for finding rapid variability in the presence of slower variability were developed for Cygnus X-1 (Meekins et al 1984).

- Two major black hole transients (Nova Oph 1977 and H1743-322) were worked collectively by all four *HEAO-1* experiments. These binaries continue to be studied. Their black hole nature was only recognized through later work.
- Orbital periods were discovered for GX 9+9 (4.2 h), GX 17+2 (19.5 h), and 4U2129+12 in M15 (8.6 h) along with confirmations of other proposed periods (Hertz and Wood, 1987). A-1 was good at finding periods from 2 hrs to 1 week.
- A transient periodicity was detected in a burst from MXB 1728-34, although from a limitation of the telemetry its true frequency lay outside the bandwidth of the instrument and the detected feature was an alias (Sadeh et al., 1982).

2.1.4 *Pulsars*

- A-1 was used to study pulsars; for example an extensive study on one slow accreting pulsar, Vela X-1, to characterize temporal structure of spin-up by accretion.
- The repeated outburst cycle of the binary source A0538-66 was tracked in detail along with nearby LMC X-4 (Skinner et al., 1980). Both are accreting pulsars; the pulse period of the former was not detected until later observations using *Einstein.*
- One new Galactic source later turned out to be in a new class of slow pulsars, the anomalous X-ray pulsars or AXPs (Wood et al., 1978; Davies et al., 1990).

2.1.5 *Stellar Coronae*

- Major flares were observed and characterized from several nearby stars, notably the RS C VN type system HD8357 and the dwarf M flare star EV Lac. These prodigious flares were several orders of magnitude beyond the brightest ever seen on the Sun, either by luminosity or emission measure (Ambruster et al., 1984).
- W Ursae Majoris stars (binaries where two G stars not unlike the Sun are in a close, near-contact, orbit) were seen in X-rays for the first time (Carroll et al, 1980).

2.1.6 *Other Phenomena*

- A remarkable bright transient (nearly as bright as the Crab Nebula) was seen on a single scan, positioned and characterized as to spectrum and variability, but left no detectable trace on subsequent scans of the same region hours later. This transient, designated H0547-14, was tentatively associated with a gamma-ray burst, but the classification remains somewhat uncertain to this day. It is not fully excluded that it was some kind of stellar flare but the lack of any recurrence makes it far more likely that it was related to gamma-ray bursts and that this may have been a rare detection of such an event in X-rays during its earliest stages. (Ambruster et al., 1983).
- A survey of fast transients was also conducted, looking for events of this kind and stellar flares. (Ambruster and Wood, 1986).

3.0 Impact and Legacy, for the Community and for NRL

The *HEAO* A-1 sky map continues to be reproduced in reference or educational materials to convey the overall layout and class makeup of the X-ray sky, or as a comparison baseline for later surveys. After *HEAO-1* re-entry into the Earth's atmosphere, A-1 results led NRL's X-ray group toward new research. The survey aspect helped build the case for the subsequent (deeper) Ṙontgensatellit (*ROSAT*) all-sky survey, where NRL scientists Cruddace and Kowalski participated following up cluster work begun with *HEAO* A-1. NRL's Spartan-1 Experiment (PI G. Fritz, NRL) also improved cluster measurements. Galactic source studies by *HEAO-1* led the way to the *Rossi X-ray Timing Explorer* (1996-2012). Within DoD another follow-on was the USA Experiment on the *Advanced Research and Global Observation Satellite* (*ARGOS*, see Essay in the 1990s section) which conducted further studies of binaries and AGN. In the 1980s the *HEAO A-1* effort led to a project with Stanford University to search for millisecond pulsations in low mass binaries using the *HEAO-1* archive plus later resources. This collaboration evolved from X-ray binary projects (including USA, for which Stanford provided hardware) to the *Gamma Ray Large Area Space Telescope* (*GLAST*), which became *Fermi*, (see Essay in the 1990s section). *HEAO-1* was NRL's first large astronomical data base; lessons learned were useful to later NRL missions such as the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* (*CGRO*, see Essay in the 1980s section). The satellite data handling and pointing experience informed the *Rossi X-ray Timing Explorer* (*RXTE*) mission design. Many scientific careers were advanced through A-1, *e.g.*, P. Hertz, J. Norris and C. Shrader, all of whom went on to hold major positions at NASA.

The original motivation for X-ray astronomy within NRL was to study and understand celestial backgrounds for whatever X-ray systems DoD might someday operate in space, and develop instrumentation and techniques toward such ends. This notion and *HEAO* fast timing studies led to X-ray Navigation – getting satellite position, attitude and time by observing X-ray sources -- which was then pursued using the USA Experiment, the first X-ray payload flown to have X-ray navigation as an explicit goal, and which was patented in 2007 as US Patent 7197381, "Navigational system and method utilizing sources of pulsed celestial radiation." *HEAO-1* and USA together were successive phases in NRL's pursuit of applied X-ray techniques for space operations. This topic continues today with a NASA payload, Neutron Star Interior Composition ExploreR (NICER), which extends the X-ray navigation development and, with Paul Ray as lead, may test X-ray communication in space.

Stellar binaries with accreting black holes, neutron stars, and white dwarfs continue to be one of the primary laboratories for X-ray astrophysics, revealing high energy-density plasmas in high magnetic and gravitational fields and providing diagnostics on neutron star structure. These varied conditions provide testbeds for, among other things, advanced codes that model fluids in extreme regimes. NRL's Plasma Physics Division collaborated with SSD in later modeling of such plasmas. Extreme stellar flares seen by *HEAO-1* in sources such as HD 8357 and EV Lac are the extension of the solar flare phenomenon to far more energetic active regions than those found on the Sun (and we who inhabit Earth may be grateful that the Sun does not produce such flares). Study of those extreme cases can advance or extend our understanding of solar physics as well as have bearing upon assessing particular extra-solar systems as sites for life.

References: 70s.4:

(References are arranged topically to correspond to text and figures.)
HEAO Catalog (1H); Intermediate Sensitivity Survey (2H)
Wood, K. S. et al., 1984, Ap J.Suppl. 56, 507
Shrader, C. et al, 1986, Ap. J. Suppl 61, 353
Extragalactic Classes:Cluster Surveys
Ulmer, M. P. et al. , 1980, Ap. J. Letters 235, L351
Ulmer, M. P. et al., 1981, Ap. J. 243, 681
Johnson, M. W., et al. 1983, Ap. J. 266, 425
Kowalski, M.1984, Ap J. Suppl 56, 403
Variability of Extragalactic AGN Sources PKS 2155-304 and 3C371
Snyder, W. A. et al, 1980, Ap. J 237, L11
Snyder, W. A. et al., 1982, Ap. J,. 259, 38
Studies of Variable, Galactic X-ray Stellar Sources:
Variability of GX 339-4 and identification as Black Hole Candidate
Samimi, J. et al., 1979 Nature, 278, 434
Eclipses in MXB 1659-29

Cominsky, L. and Wood, K.S, 1984, Ap. J. 283, 765
Cominsky, L. and Wood, K.S, 1989, Ap. J. 337,485

Vela X-1 accreting pulsar study
Boynton, P. et al. 1986, Ap. J. 307,545

Long term observations of LMC X-4 and A0538-66
Skinner, G. et al, 1980, Ap. J 240, L19

Stellar flares in EV Lac and HD 8357
Ambruster, C. et al., 1984, Ap. J. 284, 270

Millisecond Variability of Cygnus X-1
Meekins et al., 1984, AP. J. 278, 288

Quasiperiodic Oscillations in Cyg X-2 (Normal Branch Oscillations)
Norris, J.P., and Wood,K.S., 1987 Ap. J. 312, 732

Transient Period in MXB 1728-34
Sadeh et al., 1982, Ap. J. 257,214

Transient source H0547-14
Ambruster et al., 1983, Ap. J. 269, 779

Survey of Fast Transients
Ambruster et al., 1986, Ap. J. 311, 258

Orbital Period Discoveries in GX 9+9, GX 17+2, 4U2129+47
Hertz, P. and Wood, K. 1988, Ap. J 331,764

W Ursae Majoris Stars
Carroll et al., 1980, Ap. J., 235, L77

1H2258+585=1E2259+586 (AXP in remnant)
Wood et al., 1978 IAUC 3169
Davies, S. et al. 1990, MNRAS 245, 268

Discovery of Nova Ophiuchi 1977
Griffiths, R. et al, 1977 IAUC 3110
Share, G. et al.,1978 IAUC 3197

Discovery of H 1743-322
Doxsey, R. et al., 1977, IAUC 3113
Wood, K. et al., 1978, IAUC 3203

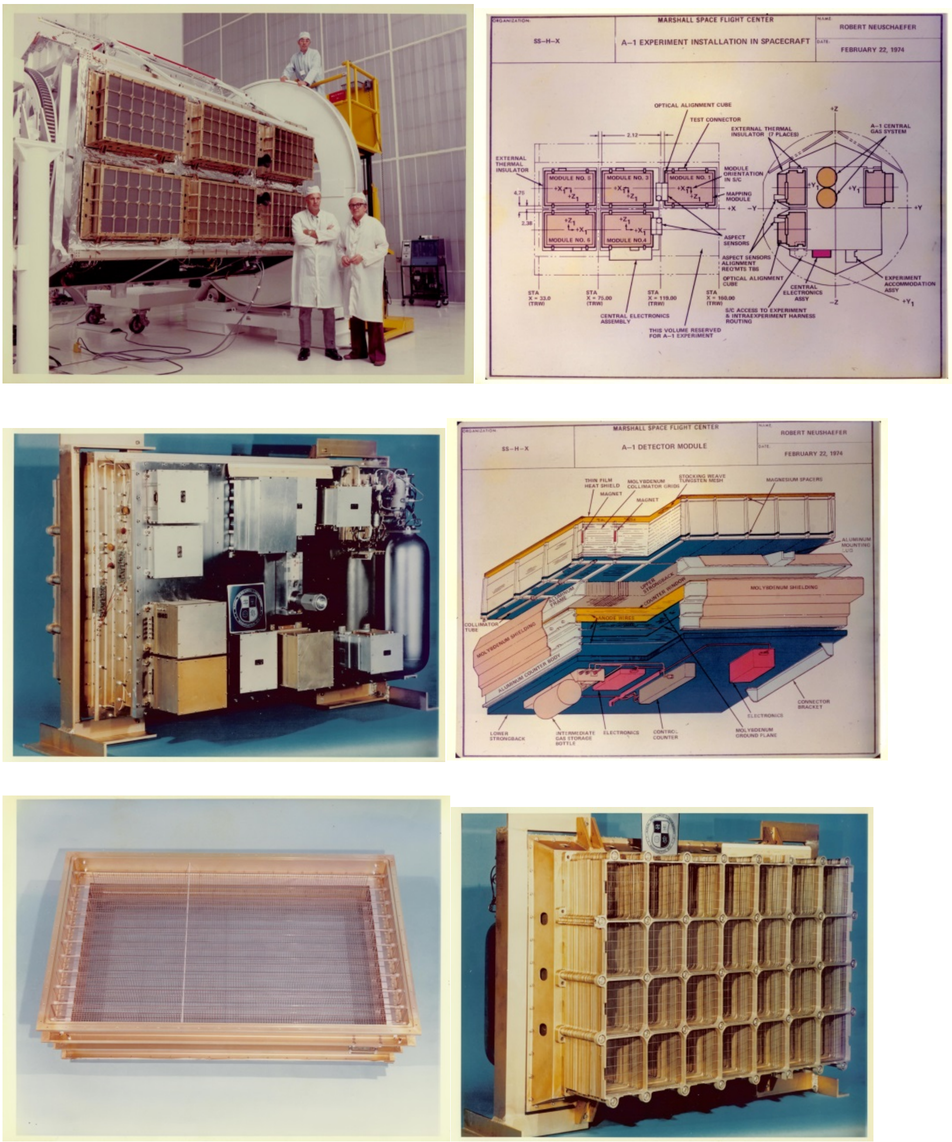


Figure 70s.4.1 - Aspects of the NRL HEAO A-1 instrument. Six panels illustrate the integrated A-1 array and its subsystems. The sheer size gave it a certain magnificence; the total effective area achieved is yet to be exceeded. Detectors were arranged so a total of 1.1 square meters of effective area looked in the observatory –y direction (upper left) and another 0.2 square meters looked in the +y direction. The system layout (upper right) had to deal with this arrangement. Central gas and electronics were in the interior near the –y face but gas lines and cables had to reach the opposite side. Detector modules had apertures on the front defined by collimators and all supporting electronic, gas, and calibration appartus mounted on the back side (middle left) including module gas tanks. Cutaway (middle right) shows the collimator, anode wire, and supporting subsystem arrangement. Anode wires (bottom left) ran the full length of the detector and were in three layers with mutual veto, and with higher threshold for signal acceptance on the back layer because the front layer was fully absorbing up to about 2 keV. The collimator (bottom right) was a 2-stage design in which the front stage was a precisely etched stack of molybdenum grids. The 1H catalog paper (Ref. Wood et al., 1984) has an instrument description (credit: NASA/NRL).

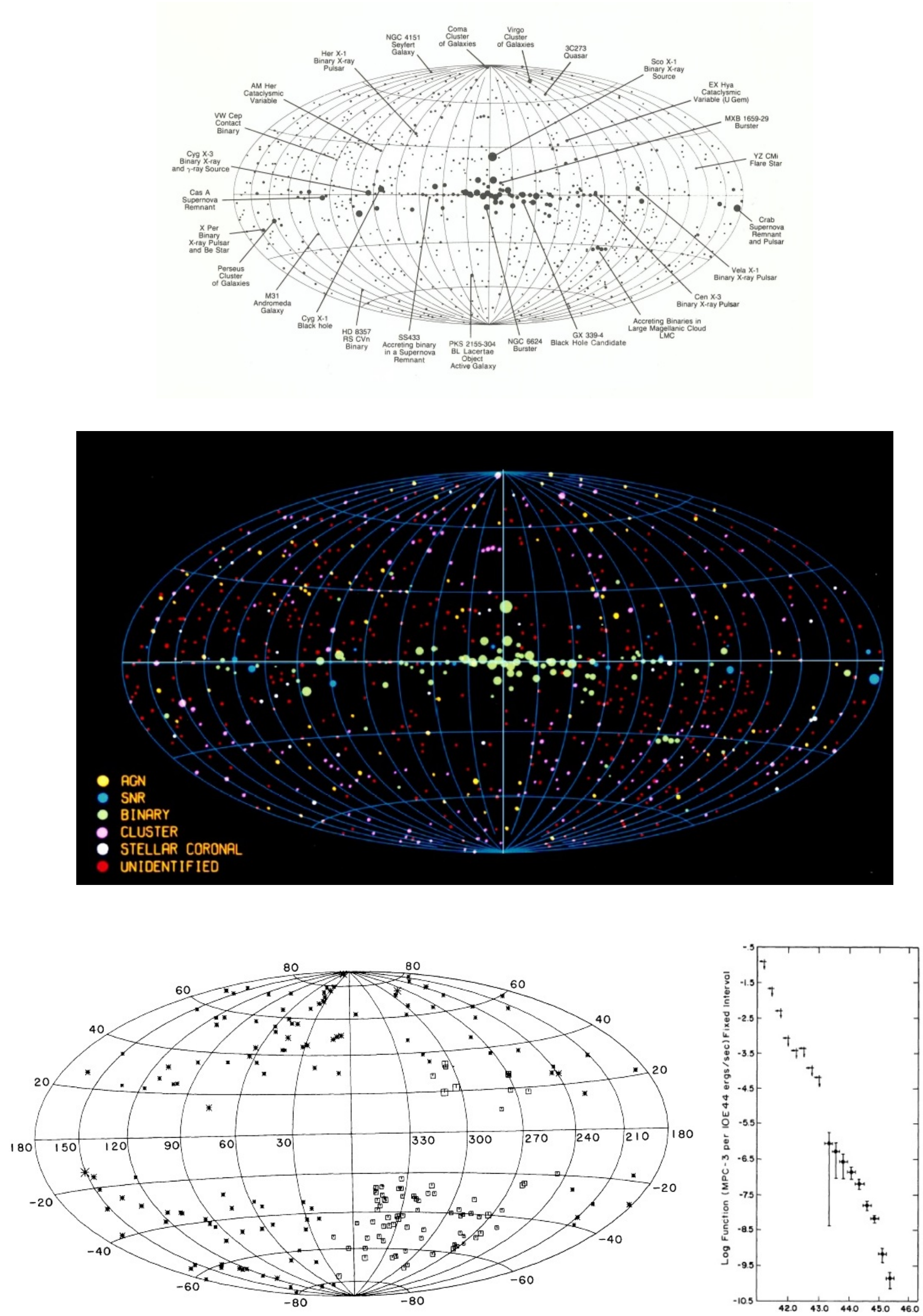
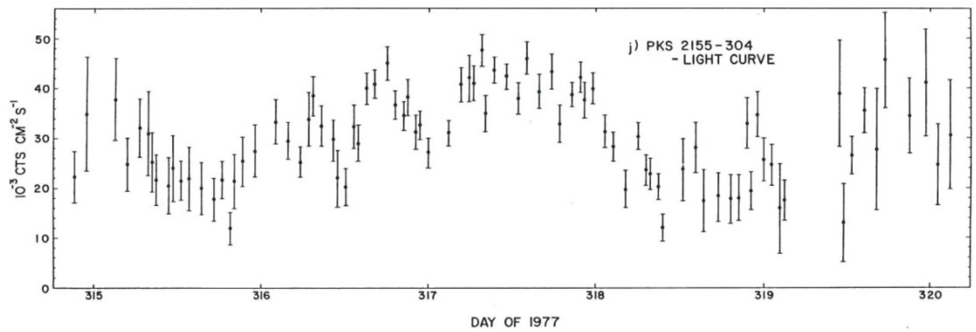
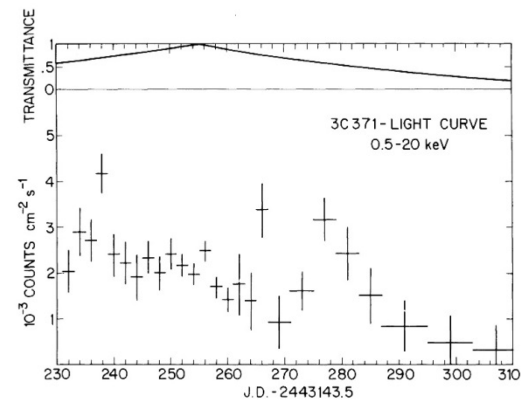
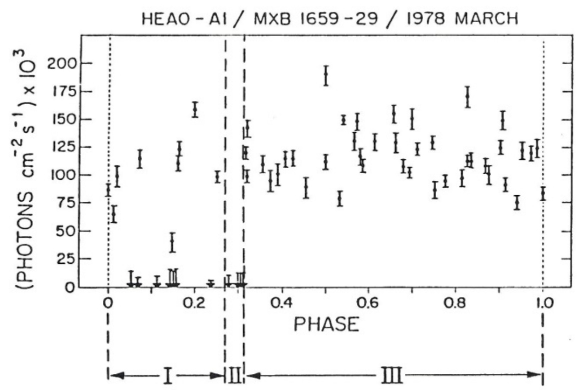
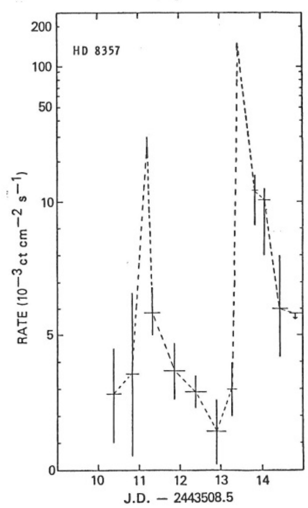


Figure 70s.4.2 - The time-averaged HEAO sky. (Upper left) one representation of the LASS catalog (1H) showing prototype members of various classes. Generally the prototype is the closest, brightest class member; going fainter leads to discovery of further similar objects. The X-ray sky in .25-25 keV is a confusing mix of thermal and non-thermal sources, variable or steady (but then extended), and Galactic or Extragalactic. Classes are not well-separated or stratified by apparent brightness; these prototypes are comparable in brightness to within factors of 10-100. Two decades of worldwide effort were needed to sort out ambiguities using spectral, timing, and angular information. (Middle) A different representation bringing out class affiliations by color coding. In addition, neutron stars (in and out of binaries) and black holes (Galactic and Extragalactic) are highlighted. (Upper right) While point sources are nearly all variable, clusters are constant but extended. This insert shows the luminosity function and upper limits derived from the cluster survey (Kowalski et al., 1984), from 202 detections, 149 of them discovery detections, plus fitting of upper limits and then combination into this luminosity function. (Bottom) A map showing only the cluster sources (credit: NASA/NRL).

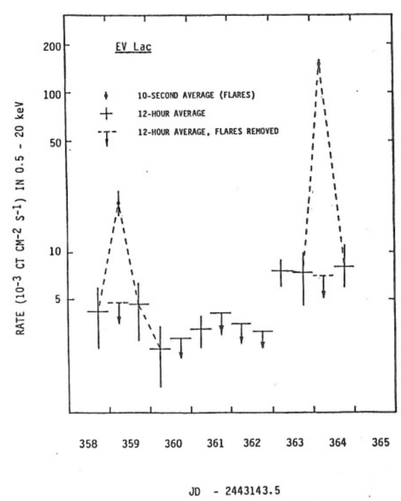








HD 8357: 2 FLARES IN 4 DAYS FROM AN RS CVn BINARY SYSTEM



EV LAC: 2 FLARES FROM A UV CETI-TYPE FLARE STAR

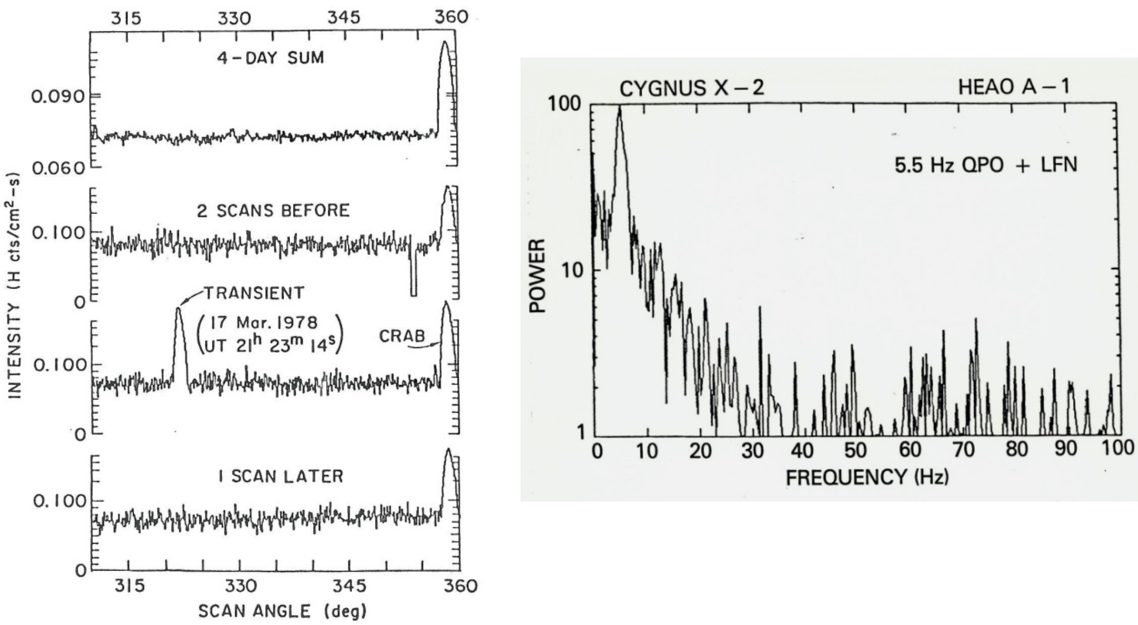


Figure 70s.4.3 - The variable HEAO sky. Most single-source studies from A-1 had to do with variability, often reporting first encounters with particular phenomena. From this era standard representations were typically light curves rendered black-on-white, demanding that the reader contribute imagination to visualizing tremendous implied phenomena from visually bland material. Items chosen cover all scales of activity from extragalactic to coronal. (Top& second from top) The light curves of PKS2155-304 and 3C371 (Snyder et al. 1980, 1982). (Third from top) Discovery of eclipses in MXB 1659-29, caused by the neutron star and accretion disk disappearing behind the companion, itself a normal star of modest mass, being ablated by accretion losses. (Fourth from top, left) Stellar flares in HD 8357, an RS CVn binary. In these systems G stars exhibit extraordinary coronal activity presumably because the binary interaction enhances MHD processes. (Fourth from top, right) Stellar flares in EV Lac, a dMe flare star. These are late main sequence stars with small masses and radii but high surface gravity. (Fifth from top, left) The bright X-ray transient H0547-14, seen on a scan that happened to include the Crab. It varied noticeably during the ten seconds of detection. (Fifth from top, right) discovery of 5 Hz QPO in Cyg X-2; QPOs led to searches for spin periods implied by prevailing models (credit: NASA/NRL).

70's.5: Space Science Division (SSD) Laboratory Spectroscopy Research 1970's- 2000's

Contributed by John F. Seely *(retired from NRL)*,
George A. Doschek, and Uri Feldman *(retired from NRL)*

1.0 Introduction

Since the early 1970s, laboratory research performed by SSD scientists has been fundamentally important for solar physics, extreme ultraviolet (EUV) astrophysics, and the development of novel spaceflight spectrometers. Laboratory plasma sources span the range of temperatures and densities found in solar flares, active regions, and cooler regions. A unique benefit of using laboratory radiation sources is that the plasma conditions such as temperature and density can be varied to produce transitions in selected elements and charge states, and this is not possible in remote sensing solar/astrophysical spectroscopy. The laboratory sources were utilized to expand knowledge of the atomic spectra of highly ionized atoms because high temperature plasmas were being increasingly observed and studied in astrophysics and in the fusion energy program, mainly with laser-produced plasmas and tokamak plasmas. The laboratory sources were particularly useful for the identification of unknown spectral lines in solar extreme ultraviolet and X-ray spectra, for developing spectroscopic techniques to diagnose physical conditions in various regions of the solar atmosphere, and for developing optical components such as diffraction gratings and crystals for high-resolution flight spectrometers. While the research was centered in the SSD Solar Terrestrial Relationships Branch, it also involved scientists from other SSD Branches and NRL Divisions, as well as scientists from other national and international laboratories and universities.

2.0 Origins in SSD – Early Years

Beginning in 1973, at the suggestion of Dr. J. David Nagel, Superintendent of the NRL Condensed Matter and Radiation Sciences Division, Uri Feldman (NRL SSD) and George Doschek (NRL SSD) began recording high-resolution EUV and X-ray spectra of iron, nickel, and other solar abundant elements that were produced by the NRL 100 GW glass laser in the NRL Plasma Physics Division. David Nagel's suggestion was prompted by the arrival of Uri Feldman, an expert in laboratory EUV spectroscopy from Tel Aviv University in Israel. Later Feldman and Doschek also obtained spectra from a CO_2 laser in the Plasma Physics Division. They used several different UV-EUV instruments for this work. Because the laser-plasma target chamber was not large, small instruments were preferable for laser-plasma observations. Feldman and Doschek realized that solar rocket spectrometers were ideal for application to laser-produced plasma experiments with the Pharos glass laser. They used spectrometers built by Dr. Richard Tousey, Head of the SSD Rocket Spectroscopy Branch, and colleagues in SSD, that were available in-house. In addition, they designed and had built an X-ray spectrometer by the SSD machinist, as well as a slitless spectrograph and other relatively simple but effective X-ray spectrometers. Perhaps the best instrument they used was a high-resolution EUV spectrometer built by Dr. William Behring at Goddard Space Flight Center (GSFC). In collaboration with Behring, they used this extremely high spectral resolution instrument to record solar spectra on GSFC rocket missions that enabled the identification of numerous solar spectral lines along with resolution of blends in the solar spectrum and the accurate measurement of solar wavelengths, still a standard used today in solar spectroscopy. Figure 70s.5.1 shows the experimental set-ups for the SSD spectroscopy experiments in the Plasma Physics Division with the Pharos and CO_2 lasers. Some results from the CO_2 laser are shown in Figure 70s.5.2.

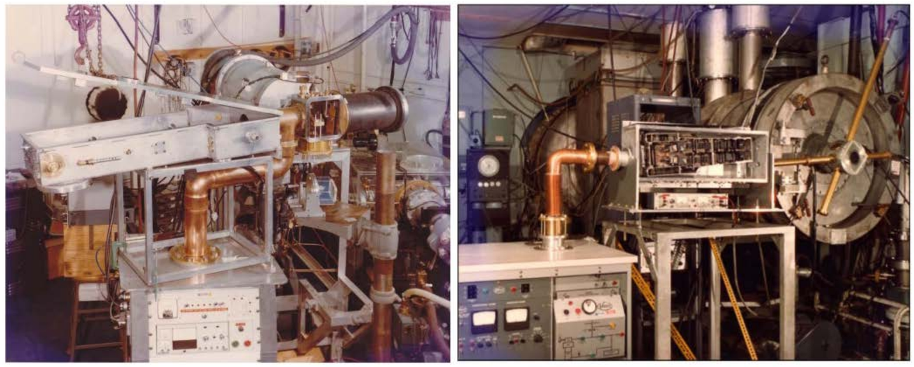


Figure 70s.5.1 – Left: SSD spectroscopic instrumentation attached to the target chamber of the NRL Plasma Physics Division 100 GW glass laser. The long tank with open lid holds either the GSFC 3-m grazing incidence spectrometer or a slitless spectrograph that formed images of the plasma. The black cylindrical tank opposite the long tank housed an X-ray crystal spectrometer. Right: the rectangular aluminum box holds a double-spectrometer SSD rocket instrument and is attached to a viewing port for the CO_2 laser (credit: NRL).

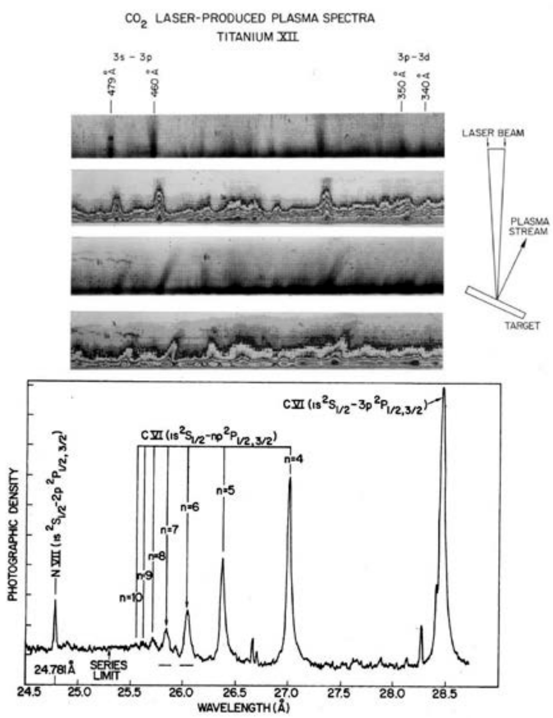


Figure 70s.5.2 – Top: images of the blow-off plasma produced by the Plasma Physics Division CO_2 laser for a titanium target. The ratio of the long-wavelength line pair to the short-wavelength line pair is sensitive to electron density. The angle of blow-off depended on the target orientation (credit NRL). Bottom: A spectrum of Lyman-α C VI obtained from the NRL CO_2 laser-produced plasma. Note that the high-lying members of the series merge into a continuum before the series limit. This is due to the Stark Effect and can be used to infer electron densities (bottom credit: Figure 9 in Doschek & Feldman 1976, Astronautics & Aeronautics, Vol. 14, July/August, page 24, courtesy of the American Institute of Astronautics & Aeronautics).

The collaboration between NRL and GSFC was highly productive. GSFC technical staff visited NRL and helped in the Laboratory with the SSD experiments. Doschek and Feldman similarly helped technically prepare the GSFC rocket experiment and they participated in the rocket flights. Science publication was carried out jointly without any concerns or snags. The entire collaboration arrangement was enabled by a simple telephone call.

With a range of spectroscopic instruments, they identified many lines in the 90 – 140 Å spectral range and imaged the laser-produced plasmas and applied plasma diagnostics to determine physical conditions in the plasmas. They compiled a database of n=2-2 type transitions in the F I through B I isoelectronic sequences, and this enabled the determination of detailed energy levels for a wide range of elements and charge states and laid the foundation for the interpretation of spectra from *Skylab* (see, e.g. 70's.2) and other missions.

3.0 Later Research and Spinoffs

During the 1980s, more powerful lasers became available at the DOE national laboratories, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory, and at the University of Rochester/Laboratory for Laser Energetics (LLE). Bright spectra were produced from plasmas having temperatures and densities greatly exceeding solar flare conditions and approaching astrophysical conditions. John Seely (NRL SSD) and Charles Brown (NRL SSD) joined the effort, dozens of papers were published, and the SSD group became a leading center for this type of fundamental laboratory spectroscopic research. The spectra extended into the X-ray region, and the range of elements extended to uranium. The spectra of highly-charged ions of iron and heavier elements enabled the study of the transition from LS to jj coupling of the atomic energy levels as well as relativistic and quantum electrodynamics effects. The high-resolution spectroscopic data were used to test and validate atomic physics computer codes that calculated the energies and intensities of transitions in highly-charged ions in dense and hot plasmas. In addition, methods were developed for achieving lasing in the X-ray and EUV regions, based on atomic level population inversions created by collisional and photo-pumping processes in dense plasmas, in advance of similar work in the 1980s at the DOE weapons Laboratories and at NRL.

While much of the laboratory spectroscopy work utilized laser-produced plasmas, other sources were used to study lower-density coronal radiation conditions. These included the Princeton Large Tokamak (PLT) and the Electron Beam Ion Trap (EBIT) at LLNL. Iron and other solar abundant elements were injected into the PLT plasma, and the high-resolution EUV spectra contained forbidden lines, normally having small populations and radiative decay rates, which were identified for the first time. This work led to the development of spectroscopic diagnostic techniques for the densities and temperatures of tokamak and solar coronal plasmas. Another diagnostic for measuring magnetic fields from the Zeeman splitting of forbidden transitions was developed and has been used in tokamak research.

At the LLNL EBIT, the first accurate laboratory measurement of the polarization of X-ray transitions in helium-like ions of iron and scandium was performed, and a diagnostic technique for electron beam generated X-ray emission was developed. Subsequently, SSD supported the development of an EBIT at National Institute of Standards and Technology (NIST), including an improved metal ion injection source which was patented by SSD personnel, and spectroscopic studies of magnetic-dipole transitions extending into the ultraviolet and visible regions were carried out.

In addition to purely spectroscopic research, techniques for recording high-resolution X-ray and EUV images were developed. These techniques included normal-incidence, concave diffraction gratings and crystals that were used to measure the spatial extent and density of hot plasmas. During the early 1990s, telescopes utilizing normal-incidence mirrors having highly reflecting multilayer coatings, of the type used to record high-resolution images of the solar corona, were used to record EUV images of laser-produced plasmas.

The extraordinary potential for recording high-resolution solar and astrophysical EUV spectra using multilayer coated gratings was widely recognized in the SSD, and Superintendent Herb Gursky initiated a project to develop flight ready gratings and mirrors. The experimental calibrations were performed at the NRL beamline X24C at the National Synchrotron Light Source (NSLS), and this work quickly attracted NASA and other funding. This work came to fruition with the launch of the Extreme-Ultraviolet Imaging Spectrometer (EIS) on the *Hinode* spacecraft and the *JPEX* rocket astrophysical spectrometer, resulting in numerous space science discoveries and many publications.

Largely as a result of the enhanced calibration facilities provided by the EIS project from about 1999 to 2005, the beamline X24C became a leading facility for the development and calibration of spaceflight and laboratory instrumentation including several *Geostationary Operational Environmental Satellite* (*GOES*) solar EUV radiometers, multilayer gratings for numerous flight missions, transmission gratings and zone plates for solar radiometers, and CCD detectors for the *Solar Terrestrial Relations Observatory* (*STEREO*) and other missions. In addition, spectrometers and other optical components were calibrated for projects in collaboration with the NRL Plasma Physics Division Nike laser. This included gratings and spectrometers for the first accurate measurement of laser-plasma instabilities produced by the krypton-fluoride Nike laser at wavelength 248 nm.

Scientists from several NRL Divisions had used reflection crystals to record high-resolution spectra of laboratory plasmas generated by low-inductance vacuum sparks (invented by Feldman when he was a visiting scientist at GSFC) and intense lasers at least since the early 1970s. In SSD, this expertise, and particularly the successful spectrometers flown earlier by Herbert Friedman and colleagues on the NASA *OSO*-4 and *OSO*-6 (see essay 70's.3) spacecraft, led to the development by Doschek and Feldman of the Bragg crystal spectrometer package for the *P-78* mission (see essay 70's.4) which recorded high quality ultimate-resolution X-ray spectra of highly-charged Fe, Ca, and Mg from solar flares. The crystals were provided by Dr. Richard Deslattes and his group at NIST, and this collaboration continued with the Bragg crystal spectrometer on the *Yohkoh* spacecraft.

Based on this experience with the NIST group, in 2001 Seely recognized the potential for using transmission crystals to record high-resolution hard X-ray spectra from laser-produced radiation sources. The crystals were provided by Larry Hudson at NIST and in collaboration with LLNL. Numerous spectrometers were designed, built, and fielded at national and international laser facilities including LLNL, LLE, and Nike. Hard X-ray spectra were recorded up to 100 keV energy and for the elements through uranium that were generated by MeV electrons created in the laser focal spot. The spectra were used to determine the generation mechanism and extent of the MeV electrons and their effect on nearby materials. This research is used to validate atomic physics computer codes relevant to inertial confinement fusion.

The laboratory work not only supported solar and astrophysical research but also resulted in numerous technical spin-offs and patents. For example, a portable hard X-ray source was developed and patented, and several versions of the source were provided for electronic device testing. One short-pulse source was used to record for the first time flash X-ray images of bullets passing through tissue and the resulting internal cavitation and trauma.

Examples of the work done by SSD scientists with plasmas at LLNL and Rochester University are shown in Figure 70s.5.3, and the calibration beam-line facility is illustrated in Figure 70s.5.4. A time-line summary of the laboratory spectroscopy work is given in Figure 70s.5.5. A short list of example references is given below.

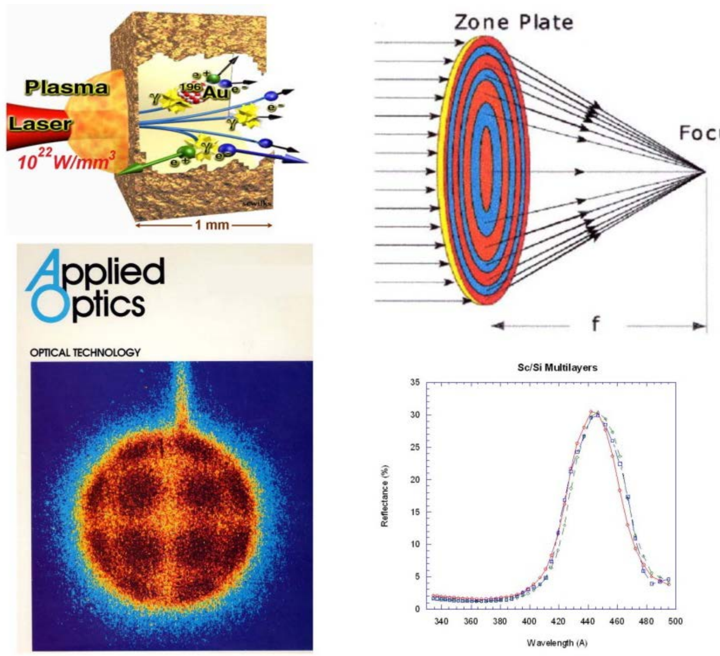


Figure 70s.5.3 – Clockwise from the upper left: MeV electrons and positrons generated in the focal spot of intense femtosecond laser radiation; zone plate developed for absolutely-calibrated solar EUV radiometers; reflectance of a Sc/Si multilayer coating measured at the NSLS beamline X24C, and monochromatic EUV image of a laser-irradiated gold target produced by a normal-incidence multilayer coated mirror (credit: Top left: LLNL/NRL; top right: with permission from Xradia; bottom left: NRL; bottom right: NRL).

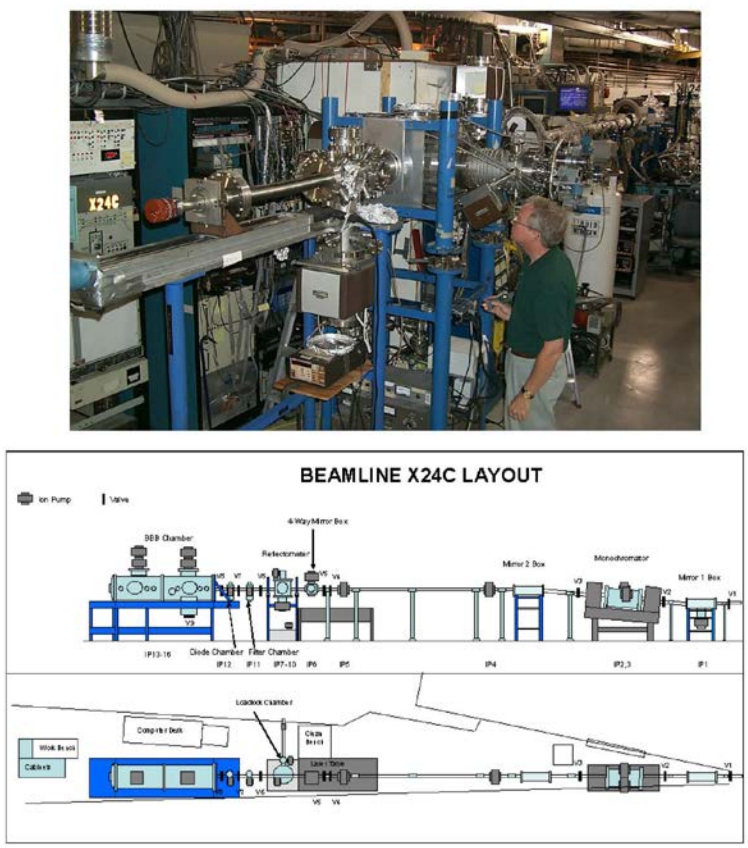


Figure 70s.5.4 – Top: NRL's John Seely operates the NSLS NRL beamline X24C; bottom: a schematic of the NRL beamline as designed and built by NRL's Bill Hunter and Jack Rife (credit: NRL).

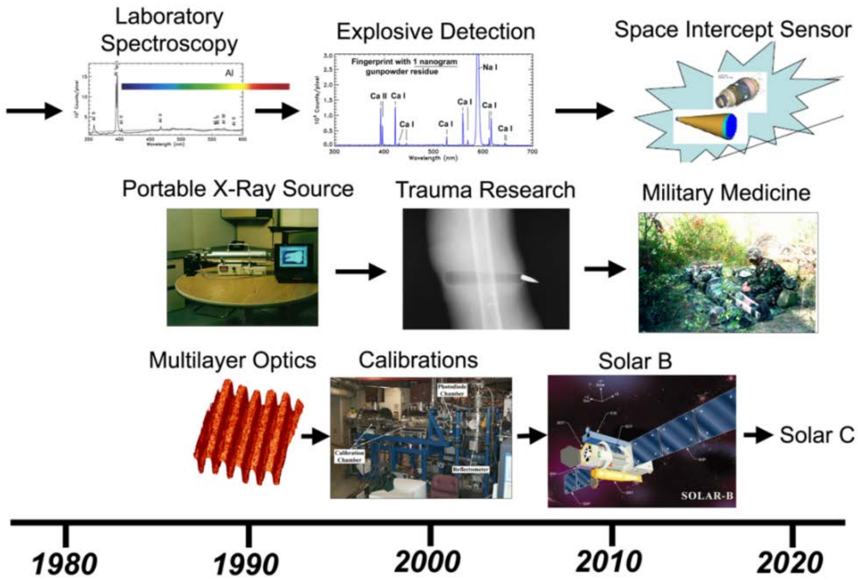


Figure 70s.5.5 – Timeline of existing and envisioned laboratory spectroscopy and technology projects leading to spaceflight instruments and terrestrial applications (credit: overall figure, NRL).

References: 70's.5

Doschek, G. A., & Feldman, U. 1976, Astronautics & Aeronautics, 14, 24.

Doschek, G. A., Feldman, U., Burkhalter, P. G., Finn, T., & Feibelman, W. A. 1977, J. Phys. B: Atom. Molec. Phys., 10, L745

Doschek, G. A., Feldman, U., Burkhalter, P. G., Finn, T., & Feibelman, W. A. 1977, J. Phys. B: Atom. Molec. Phys., 10, L745

Feldman, U., Doschek, G. A., Nagel, D. J., Behring, W.E., & Cowan, R. D. 1974, Astrophys. J., 187, 417

Feldman, U., Doschek, G. A., Nagel, D. J., Cowan, R. D., & Whitlock, R. R. 1974, Astrophys. J., 192, 213

Feldman, U., Doschek, G. A., Prinz, D. K., & Nagel, D. J. 1976, Journal of Applied Physics, 47, 1341

Feldman, U., Seely, J. F., & Bhatia, A. K. 1984, J. Appl. Phys., 56, 2475

Reader, J., Kaufman, V., Sugar, J., Ekberg, J. O., Feldman, U., Brown, C. M., Seely, J. F., & Rowan, W. L. 1987, J. Opt. Soc. Amer. B: Optical Physics, 4, 1821

Seely, J., Brown, C., Windt, D., Donguy, S., and Kjornrattanawanich, B. 2004, Appl. Opt., 43, 1463

Seely, J. F., Doron, R., Bar-Shalom, A., Hudson, L. T., and Stoeckl, C. 2003, J. Quant. Spect. Rad. Trans., 81, 421

Seely, J. F., Ekberg, J. O., Brown, C. M., Feldman, U., & Behring, W. E. 1986, Phys. Rev. Letters, 57, 2924

A1. **List of Terms and Acronyms**

70s.1

- FUV – Far-Ultraviolet
- UV - Ultraviolet
- EUV – Extreme Ultraviolet
- STP – Space Test Program

70s.2

- ATM - Apollo Telescope Mount
- AOSO - Advanced Orbiting Solar Observatory
- OSO - Orbiting Solar Observatory
- GSFC – Goddard Space Flight Center
- AS&E - American Science and Engineering
- HCO - Harvard College Observatory
- HAO - High Altitude Observatory
- MSFC - Marshall Space Flight Center
- SWS - The Saturn Workshop
- JSC - Johnson Space Center
- JOP - Joint Observing Program
- XUV - EUV, extreme-ultraviolet
- FIP - First Ionization Potential

70s.3

- DoD - US Department of Defense
- STP - Space Test Program
- CME - Coronal Mass Ejection
- OSO - Orbiting Solar Observatory
- SOLWIND – Solar Wind
- EUV - Extreme ultraviolet
- SOHO - Solar & Heliospheric Observatory
- SOLFLEX - Solar Flare X-rays
- MAGMAP - Magnesium Mapping
- NIST - National Institute of Standards and Technology
- SEC - Secondary Electron Conduction
- ASAT - Anti-Satellite Missile
- HAO – High Altitude Observatory
- SMM- Solar Maximum Mission
- RAL - Rutherford Appleton Laboratory
- LASCO - Large Angle Spectroscopic Coronagraph
- SEPs - Solar Energetic Particles
- SOLEX – Solar X-ray

70s.4

- HEAO - High Energy Astrophysical Observatories
- LASS - Large Area Sky Survey Experiment
- MIT - Massachusetts Institute of Technology
- NASA-GSFC - Goddard Space Flight Center
- Caltech - California Institute of Technology

- LEO - Low Earth Orbit
- PSF -Point Spread Function
- HEASRC - High Energy Astrophysics Science Archive Research Center
- AGN - Active Galactic Nuclei
- QPOs - quasi-periodic oscillations
- AXPs - anomalous X-ray pulsars
- ROSAT - Rontgensatellit
- ARGOS - Advanced Research and Global Observation Satellite
- GLAST - Gamma Ray Large Area Space Telescope
- OSSE - Oriented Scintillation Spectrometer Experiment
- CGRO - Compton Gamma Ray Observatory
- RXTE - Rossi X-ray Timing Explorer
- NICER - Neutron Star Interior Composition ExploreR

70s.5

- EUV - extreme ultraviolet
- GSFC – Goddard Space Flight Center
- DOE – Department of Energy
- LLNL - Lawrence Livermore National Laboratory
- PLT - Princeton Large Tokamak
- EBIT - Electron Beam Ion Trap
- NIST – National Institute of Standards and Technology
- EIS - Extreme-Ultraviolet Imaging Spectrometer
- GOES - Geostationary Operational Environmental Satellite
- CCD - Charge-coupled devices
- STEREO - Solar Terrestrial Relations Observatory
- NSLS - National Synchrotron Light Source