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Final S020 Skylab Experiment Report

by

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PREFACE

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ABSTRACT

After the loss of the meteroid shield required using the solar scientific airlock to erect the sun shade, methods, were improvised to operate the S020 experiment on EVA's. Almost no data was obtained in the wavelength range 10-110 Å. From 110-208 Å the spectra were 10 to 100 times less intense than expected. A probable cause in loss of instrument sensitivity is the contamination of the filters by the spacecraft coolant. A list of observed lines is presented. Although less data was obtained than expected, several lines not previously observed were recorded; and the spectra serve to confirm many very faintly observed weak lines recorded from sounding rockets by other experiments.

Background and History of the Experiment

S-020 was a small grazing incidence spectrograph that recorded on photographic film. The objective of the experiment was to obtain as complete spectral information as possible on the extreme ultra-vilet and x-ray emission of the total sun in the wavelength range 10-200 Å, under various conditions of solar activity. The first flight of this type of spectrograph was made by the Naval Research Laboratory (NRL) in 1960[1] in an Aerobee rocket, and the coronal (Na D)-like lines of FE XVI were discovered . But sounding rocket experiments are limited to a maximum of approximately 4 minutes effective exposure time which is not sufficient to photograph the many fainter but important lines expected in this wavelength range. In 1965 the Apollo Program offered the opportunity to fly such a spectrograph and to make exposures of up to one hour in duration, more than an order of magnitude longer than is possible with a rocket. This was to be done by providing a scientific airlock in the hatch door of the CM. After the fire, the airlock was removed, and the project was not resumed until 1969, when it was decided that a scientific airlock would be installed in the dry workshop of Skylab.

The major objective of the S-020 experiment was to obtain as complete spectral information as possible on the extreme ultraviolet and x-ray emission of the total sun; 10-100 Å in the upper half of each film strip, and 20-200 Å on the lower half. Two functional objectives are listed under this major objective.

A. One objective was to obtain spectra of the quiet (non-flaring) sun in the wavelength region 10-200 Å.

This objective was to be performed on each of two missions in order to observe changes in the spectrum with different conditions of solar activity. For example, one with the longitudinal belts of maximum activity on the limbs, and again with a single belt on the central meridian. An exposure sequence starting with a 60 minute exposure and ending with a 5 minute exposure was to be taken four times in all on the two missions.

B. A second objective was to photograph solar spectra during one (or more) solar flares.

A total of 96 hours of flare wait-time during the last two missions, with the experiment in the solar scientific airlock, was specified as a requirement to accomplish this objective.

In addition to these functional objectives a detailed test objective was scheduled for SL 2, the purpose of which was to check out the experiment's performance and to optimize exposure times and filter selection for the remaining two missions, on which the functional objectives would be performed. This detailed objective specified a sequence of exposures from 60 minutes to 5 minutes.

The history of the experiment after it was launched is discussed in subsequent sections.

Methods

Figure 1 is an optical schematic of the instrument. Light from the sun passes first through a filter, which removes stray light of unwanted wavelengths, then through the slit onto the one meter radius concave grating at an angle of incidence of 88°. The grating diffracts the light into a spectrum which is focused on photographic film lying on the Rowland Circle. To double the spectral coverage, a grating with a split ruling was used; this produced a double spectrum as shown in Fig. 2. The upper half of the grating was ruled with 2400 l/mm and the lower half with 1200 lines/mm. The range covered by the upper half was 10-100 Å, with 0.04 Å resolution; and by the lower, 20-200 Å, with 0.08 Å resolution. The two spectra were separated by covering the upper and lower parts of the slit with different filters. The upper filter was a thin film of indium, that transmitted radiation from 10 to 105 Å; the lower filter of Be transmitted radiation from 110 to > 200 Å.

Figure 3 shows the experiment mounted for operation in the solar airlock as was originally planned. The experiment was to be pointed at the sun within its ± 1/4° tolerance in both axes with a projection boresighter which imaged the sun on its reticle.

This method was impossible after the loss of the meteroid shield required using this airlock to erect the [illegible]hade.

As a way to obtain at least some use of S-0[illegible], a crash program was initiated to prepare the experiment for operation on EVA. The hardware required to accomplish this was completely ready for operation and was launched with SL 3, but no film was permitted to be placed on board.

However, the stowage list for SL 4 did include the film magazine stowage container with its two film magazines and two sets of filters.

Instructions to the crew were to perform a sequence of 5 exposures beginning with the longest, 60 minutes, down to 5 minutes. This was to be done as many times as possible, and hopefully on every EVA, to expose as many as possible of the twenty film strips on board. To operate S-020 during EVA, a bracket was fabricated, which clamped the instrument to a strut on the spacecraft. A ball joint in the bracket permitted pointing the experiment at the sun. Once properly pointed, as shown by the boresighter, a screw was tightened to lock the joint.

Figure 4 shows S-020 and T-0-25 mounted on struts outside the EVA hatch door during EVA operations. Figure 5 shows a closer view of the mounting arrangements for S-020. This photo was made during a crew training session in the neutral buoyancy tank at MSFC.

Figure 6 shows a crewman pointing the experiment in the neutral buoyancy tank. The fact that an improvised work-around to operate the experiment could be completed and qualified in such a short time frame is a tribute to the versatility of the entire manned space operation. As one can see, the crewman had to leave his foot restraints to point the experiment and to advance the film, but in actual operation during the mission, the crew found it worked quite well.

Calibration and data processing techniques are discussed in the next section.

Results of the experiment

A. Pre-mission Research and Development Events

Several state of the art development items were required in order to prepare the experiment for launch. NRL conducted extensive tests at a 88° angle of incidence in the late 1960's of the sensitivity of most of the one meter radius of curvature graings in the Bausch and Lomb inventory. From these tests, two rulings were chosen to provide optimum efficiency over the wavelength range covered and a split-ruling grating was ordered. The development of this grating was much more difficult than anticipated due to problems involved in maintaining accurate alignment between the two segments during the production of the submaster; eventually split-ruling replica gratings were delivered and installed in the flight and backup units. The optical performance was as good for the individual segments as the single ruling gratings tested earlier.

Thin metal filters of Berylium (Be), Boron (B), and other materials with optical qualities and stability characteristics to make them useful as transmision filters in the XUV were first successfully produced as a joint effort of University of Pennsylvania and NRL personnel in the late sixties. When S-020 was re-selected for operation on Skylab, a rush program was initiated and successfully completed to qualiry these filters for use in the anticipated Skylab environment. Be has high transmission characteristics in the wavelength range above 110 Å; B above 66 Å. Before the development of these filters, no filter material transmitting in the region 110-150 Å had been produced. From 150-170 Å, Al transmits, but with low efficiency. It was originally planned to substitute B for Be during a portion of the experiments operations in order to take advantage of B's high transmission characteristics between 66 and 110 Å, where the transmission of the Indium filter is rapidly decreasing. When the number of exposures was limited by the operation of the experiment for limited periods only on EVA's, this plan was abandoned because of the better transmission of Be above 110 Å.

Several materials, used on the spacecraft and/or in the experiment were tested to determine if they would present contamination problems to the sensitive optical surfaces of the experiment[2]. Tests of white organic S13G paint showed that it did present a problem. The various centers initiated programs which eventually resulted in changes to the procedure for mixing, applying, and using the paint so that this problem was eliminated.

Other developments include the re-designing of the vacuum valve to enable the experiment to withstand the long periods of stowage without undue leakage, and the development of an optical/mechanical templet system which made it possible to optically align the experiment without taking exposures in a vacuum system and moving the optical components until the instrument was focused . This system, in addition to saving considerable time in the alignment of the individual units, provided an easy means of interchanging cameras, gratings, or slits as the need arose.[3]

6. Operational and mission chronology

Table I is a chronological list of exposures and comments on anomalies encountered.

The S-020 experiment was operated on EVA 2, 3, and 4 - but not on EVA 1. The hardware constructed for EVA operation worked well, and the crewman had no difficulty. However, he did not have sufficient time to expose but nine out of the twenty film strips.

There was one anomaly of an engineering type. The temperature of the back plate of the instrument increased on EVA 3 to 104° F and on EVA 4 to 103.7 °F at the termination of EVA operations. The predicted temperatures were between 0° and 10° on EVA 3 and 65° on EVA 4.

C. <u>Post Mission Activities and Performance Data of the Flight Hardware.</u>

A total of nine exposures were taken. On the short wavelength side of the most intense spectrum six very faint lines are present; on the long wavelength side the spectrum was similar to that produced with an S-020 prototype, flown on a rocket in 1972. The spectra were far less intense than expected, by a factor of 10 to 100. The reason for this is not known.

All 4 exposures taken on EVA 2, including the 60 minute, were very faint and less intense than the 7.5 minute exposure taken on EVA 4. However, one solar flare was recorded on EVA 2. It began 2.5 minutes after the commencement of the 7.5 minute exposure, which was the last to be made. The spectrum was slightly more intense than the 14 minute made immediately before. However, the only lines present on either spectra are at wavelengths greater than 170 Å. These are primarily middle stage ionization Fe lines which would not be expected to be particularly enhanced by a flare. Because of the generally anomalous performance of the instrument, it is not certain that the increased intensity was caused by the flare.

The 45 minute exposure obtained on EVA 3 produced the second most intense spectrum. It used the same filter combination as on EVA 2. Prior to EVA 4 the filters were changed. The 60 minute exposure on EVA 4 was the most intense spectrum photographed.

There is reason to believe that the low sensitivity of the spectrograph was caused by contamination of the filters. It is known that leakage of coolanol from the spacecraft coolant system occurred throughout the Skylab missions. After SL-2, pictures taken during the mission showed the presence of much discoloration around the EVA hatch door. The sample array of D-024, mounted on a handrail about four feet from the position of the S-020 instrument, showed a similar discoloration. This is discussed in a paper by Lehn and Hurley[4].

Measurement of the filters after return showed that the indium filters were almost completely opaque; this explains why noting was recorded in the 10-100 Å region. Transmittance of spare filters that were not flown, but which were from the same batches of material as those that were flown, were found to be unchanged. Therefore, it is clear that the indium filters lost transmittance during the mission. In the case of Beryllium the situation is less definite, but the transmittance at long wavelengths was found to have decreased.

Dr. Joseph Muscari of Martin Marietta has measured the transmittance spectrum of Coolanol XV (the spacecraft coolant). He has also measured the reflectance curves of samples from the array which was contaminated. The latter results show some of the characteristic absorption bands of Coolanol, but perhaps not enough to be conclusive. Measurement of the recovered S-020 filters showed similar Coolanol absorption bands for one indium filter; no absorption bands were found on the spare indium filters that were not flown. However, the second flight indium filter showed no such absorption after recovery. The beryllium filters appeared to show more absorption bands than the indium filters, but these bands include an absorption band not characteristic of Coolanol. Furthermore, the spare filters showed the same bands as the flight filters. Thus this evidence for Coolanol contamination of the flight filters as the cause of the faint spectra is is inconclusive.

Additional evidence comes from the study of the high instrument temperatures reached during EVA. If Coolanol, or some other material did contaminate the filters sufficiently to cause the tremendous decrease in speed, and if this occurred during EVA operations, it might also explain the temperature increase during EVA; that is the contamination would have also been deposited on the heat shield which was designed to have a very low α/ϵ ratio. The deposit would have inceased the α/ϵ ratio and in turn increased the temperature of the instrument. The α/ϵ ratios of the back-up unit heat shield and the qualification unit heat shield, which were made at the same time and from the same batch of materials as the flight unit, but were not flown, showed no signs of deterioration in post-flight measurements. Lehn and Hurley[4] have conducted different types of tests of the D-024 sample array and similar tests of laboratory samples exposed to Coolanol and other possible contaminents. They concluded that Coolanol in combination with water vapor and ultraviolet radiation is the most probable cause for the D-024 contamination and similar phenomena observed in nearby areas around the spacecraft.

Another unexplained phenomenon is that one exposed film showed tripled lines. Also, on examination after recovery, one film strip was missing from film magazine #4. A possibility is that these two film strips were loose in the film drum because the film from which they were cut did not have the same transverse curl property as normal 101 film. This curl serves to hold the film strip in place in the film drum. If this curl had not been present the film strip may have slipped out of the film drum after loading, if the film drum had been turned sideways. The loading operation was watched with an infrared viewer and nothing of this kind was recorded. Furthermore, no similar occurence had ever happened in any of the hundreds of pre-launch tests of the experiment.

The triply-split lines on the one exposure can also be explained by a loose film strip. Further indication of looseness comes from the fact that the curvature of the spectrum lines, present in all other exposures was absent in this particular exposure. Vibration of the instrument on its EVA mounting bracket could have caused slight movements of the film strip and produced this tripled line image. Additional evidence that indicates there was movement of some sort at some time is that the long wavelength cut-off for this exposure is 3 Å shorter than the long wavelength cut-off for all of the other exposures. The film drum in which this piece of film was mounted was re-inspected after its return and showed no faults which would create this situation.

D. Scientific Data and Special Analytical Processes

The spectral lines present in the long wavelength portion of the experiment from 111 to 208 Å are somewhat more intense than in the best rocket spectrum obtained by NRL to date. As stated earlier, the intensity of the spectera was 10 to 100 times less than was expected. Several weak lines not present in previous rocket spectra are present on the S-020 spectra; however, the converse is also true, several weak lines previously observed from rockets were not recorded by S020. Their absence can probably be attributed to two factors, variability of solar activity and film defects.

Three problems are involved, largely connected with the aging of the 101 film and the particular batch of film that was used. The batch of 101 film used was received in April 1973 (it was not possible to procure fresher film). However, the magnitude and type of aging effects that will occur in 101 film cannot be predicted. When loaded in October 1973, no degradation had occurred. Nevertheless in the flight film the grain size is two to three times larger than for fresh film; the background density of the flight film was higher than expected; and a modulation effect in the film resembling a picket fence exists along the length of the film which is in a direction 5 to 10 degrees away from the direction of the spectral lines. The latter effect is variable over a given film strip and unfortunately most pronounced on the two most intense spectra. The flight film does not appear to have been affected by the spacecraft environment; film from the same batch which was not flown was processed after the flight film and showed the same increase in background on grain size.

In order to extract the maximum amount of information from the spectra a combination of two different methods was used to attempt to integrate out these photographic effects. The individual film strip was placed in the enlarger at angles of 60 to 75° with the horizontal. It was then rotated around an axis perpendicular to the film plane until a good alignment was obtained for the region to be photographed. (The curvature of the lines varies along the spectrum and this effect is magnified by placing the film at an angle; consequently it was necessary to photograph different regions separately in order to obtain maximum integration along the lines.) A transparency enlargement was then made on Kodak high speed duplicating film #2575. The resultant transparencies show many lines to be present that can not be clearly seen on the original film or on high contrast prints. However, due to the increased curvature of the lines and non-linear changes in the transparencies during processing, accurate wavelength measurements are not possible.

For the second method, the film was held at angles of 0, 60, and 75 degrees and non-shrinkable Dupont Cronopaque Variable Contrast Print Film #CPF-7 print paper was moved in a direction parallel to the spectral lines. The resultant "smeared" prints clearly enhance the faint lines, but the effects of the film granularity and the modulation effect are not completely removed. Consequently there are many spurious features which have the same appearance as real lines. It was therefore necessary to make crude measurements between lines on the transparencies, average the measurements, and by ratioing the transparency scale to the scale of the smeared print, determine the position of the line on the smeared print. The wavelengths were then measured directly on the smeared print. Comparison between the smeared prints made with the film held at different angles in the enlarger was also useful in eliminating spurious features.

Table 2 is a list of spectral lines observed by S020. No intensities are given for the lines, rather they are characterized as being intense (I), medium (M), faint (F), or probable (P). This is done for the following reasons:

1. The soft x-ray light source needed to calibrate the film was unavailable for use for this purpose for an extended period after the recovery of the flight film. It was felt that the continued aging effects on the film would cast considerable doubt on any intensities obtained using a questionable calibration curve. The

unanticipated slow speed of the instrument and the variability in intensity between exposures of equal time length, but taken on different EVA's would make any listing of relative intensites open to doubt. The wavelengths listed are felt to be accurate to within $\pm$ 0.02 Å, with the exception of those lines listed as present on exposures 4-1 only. A combination of the tripling of the lines and the presence of spurious structure combined to make wavelength determination in some areas of that strip of film difficult. A few of the stronger lines have wavelength deviations as great as 0.06 Å; therefore no greater accuracy should be attached to those lines which were present and measured on 4-1 only. Where such large deviations exist, and a reasonably intense line is present the measurement on 4-1 has not been used in the table. Where the measurement on 4-1 is within the $\pm$ 0.02 Å accuracy range it has been averaged with the 3-5 measurement for listing in the table.

Where a line is present only on one S020 exposure, this is indicated in the table by specifying exposure 4-1 or 3-5 under comments. The lines observed by S020 are compared with lines observed in the best sounding rocket experiments in the column headed Previous Observation. N is used to designate the NRL spectra recorded in July, 1972, and G signifies the GSFC spectra obtained from rocket firings in May 1969 and September, 1973.[5]

Discussion of Results

The results of the experiment, when compared with the results anticipated with the order of magnitude longer exposure times were quite disappointing. However several new lines were observed and the spectra serve to confirm the observations of many lines which have been observed only weakly in previous spectra.

Conclusions and Summary

All-in-all, S-020 was plagued by bad luck from the beginning. First the fire; next the loss of the use of the solar SAL; and finally, greatly decreased effective sensitivity. In spite of all this, the experiment was operated and some new data were obtained. Should another opportunity arise, for example in shuttle, it would be well worthwhile to fly an instrument of the same type, but larger. In the shuttle era there will still be much of value to be learned about the spectrum from 10-200 Å.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the many people who helped to overcome the great number of problems that S020 encountered. Special thanks are due Edward Trexler, David Blizzard, and Brian Dohne of NRL, along with N. Paul Patterson of BBRC, our close colleagues. The list of those at JSC, MSFC, and KSC who assisted is very long. We thank especially Steve Mansur, our technical monitor at JSC. We are greatly indepted to the Skylab Crews; the crew of SL-3 pushed through the arrangements for operation of the instrument during EVA, and the SL-4 crew carried this out successfully with a minimum of time in training.

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1. Edlen, B. (1962) in "Space Age Astronomy" (A. J. Deutsch and W. B. Klemperer, ed.) Academic Press, New York 1962. Tousey, R. (1962) ibid, P. 104.
2. Ball Brothers Report #B5501-71.082 (May 6, 1971). NRL Test Report #71A01-30-2-1 (June 15, 1970).
3. Drawing Set titled Experiment S020 X-ray/UV Solar Photograph (Feb. 4, 1972).
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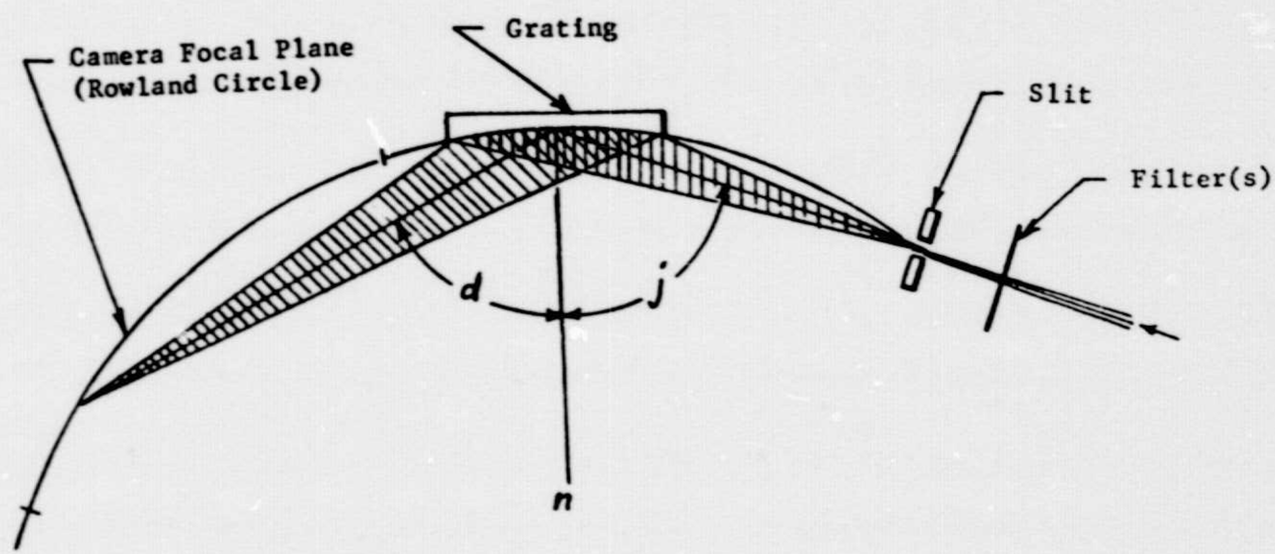
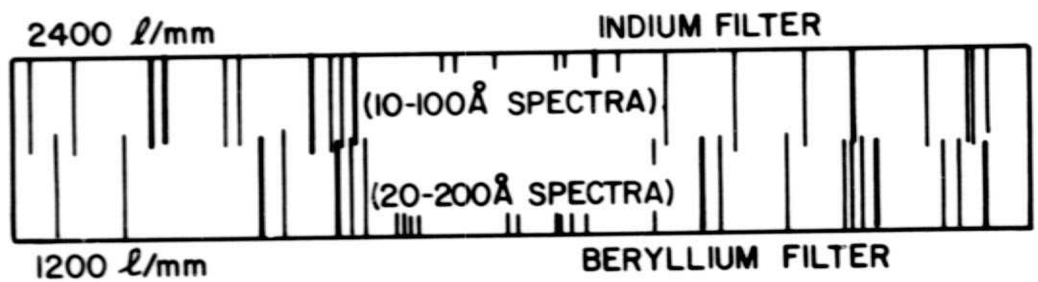
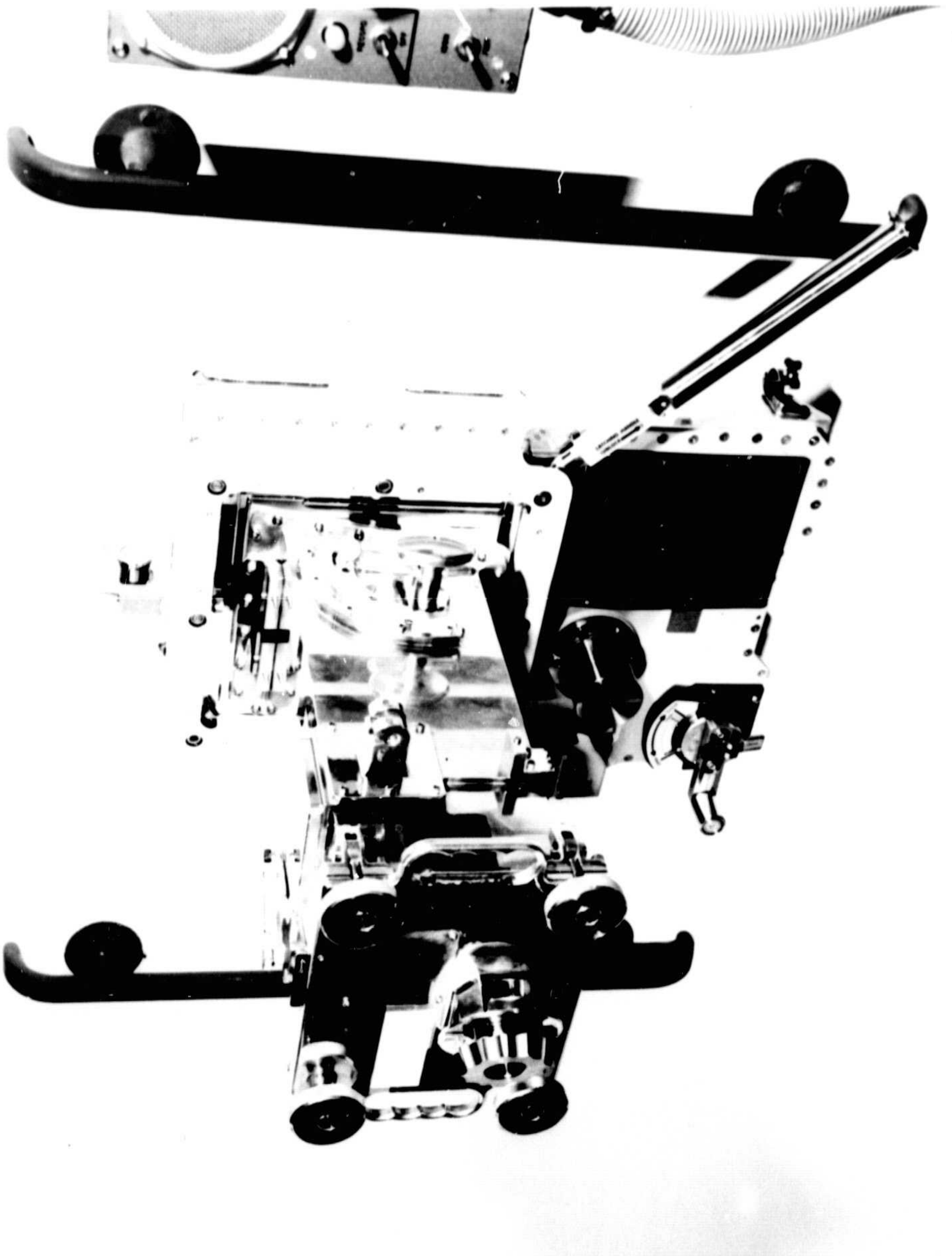
5. Unpublished NRL data.
   Behring, W. E., Cohen, L., and Feldman, U. (1972) Astroph. J. 175, 493.
   Behring, W. E., Cohen, L., Feldman, U., and Doschek submitted to Astrophys. J. for publication April 1975.

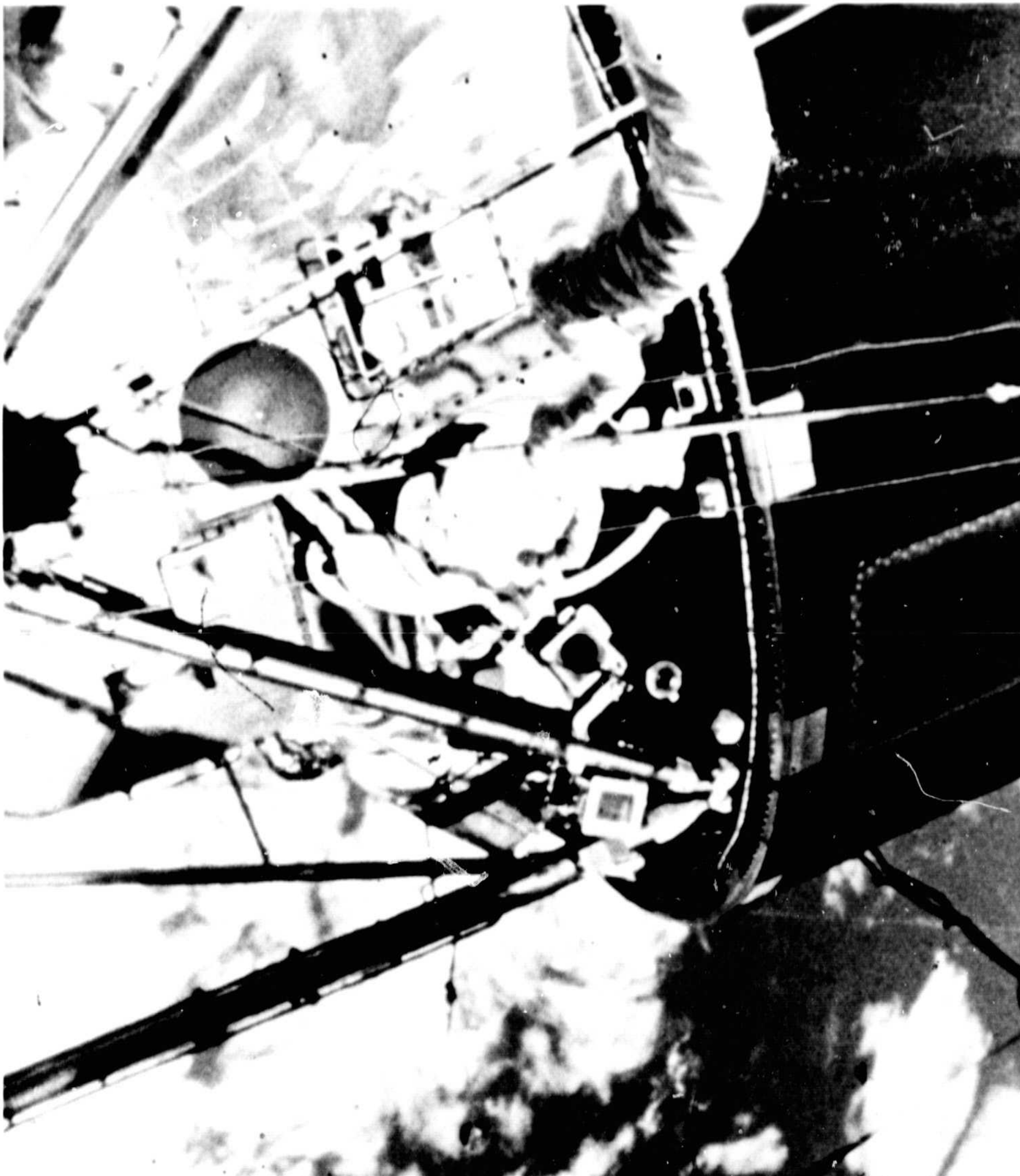


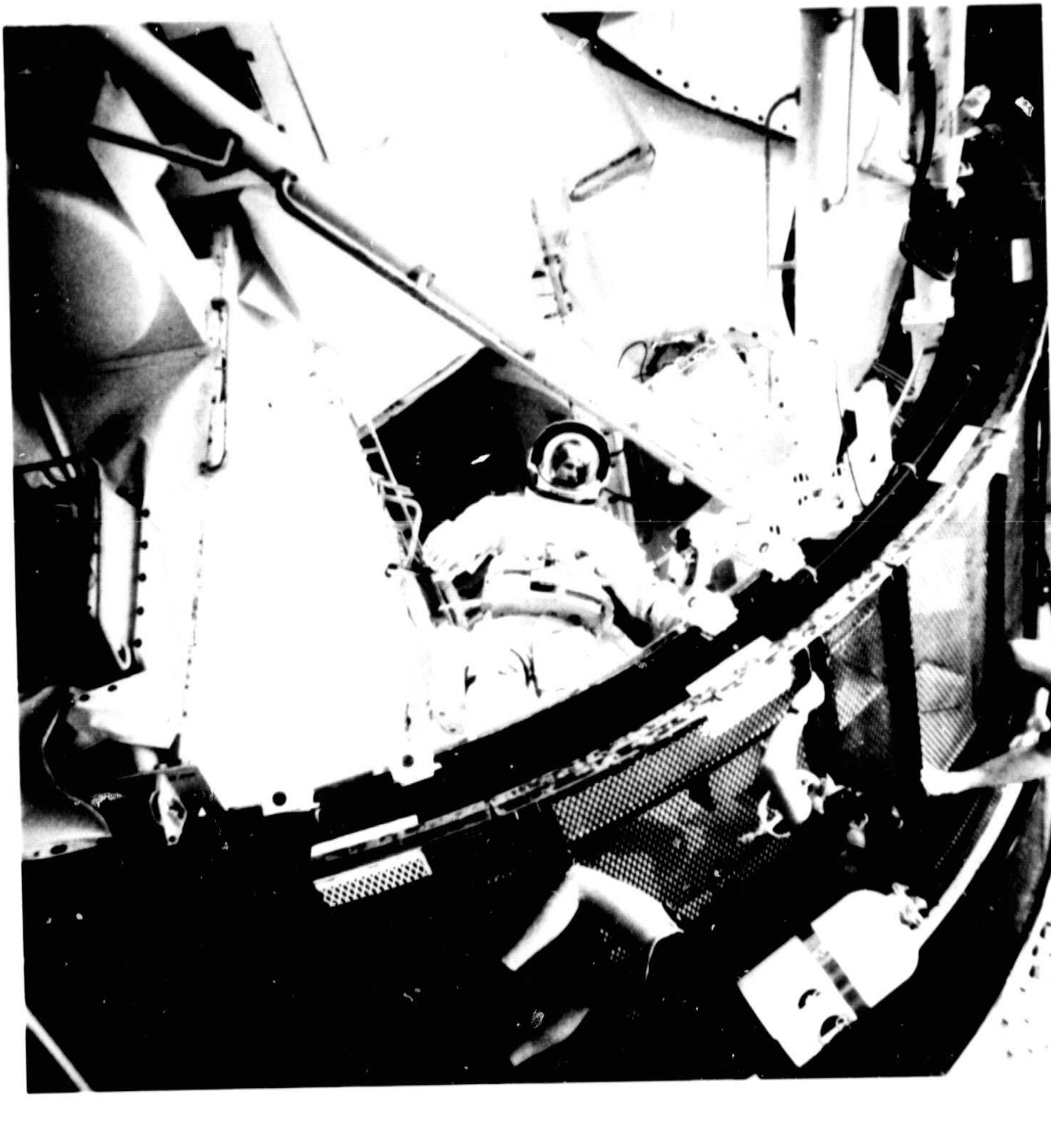
S020 Experiment Spectrograph Schematic

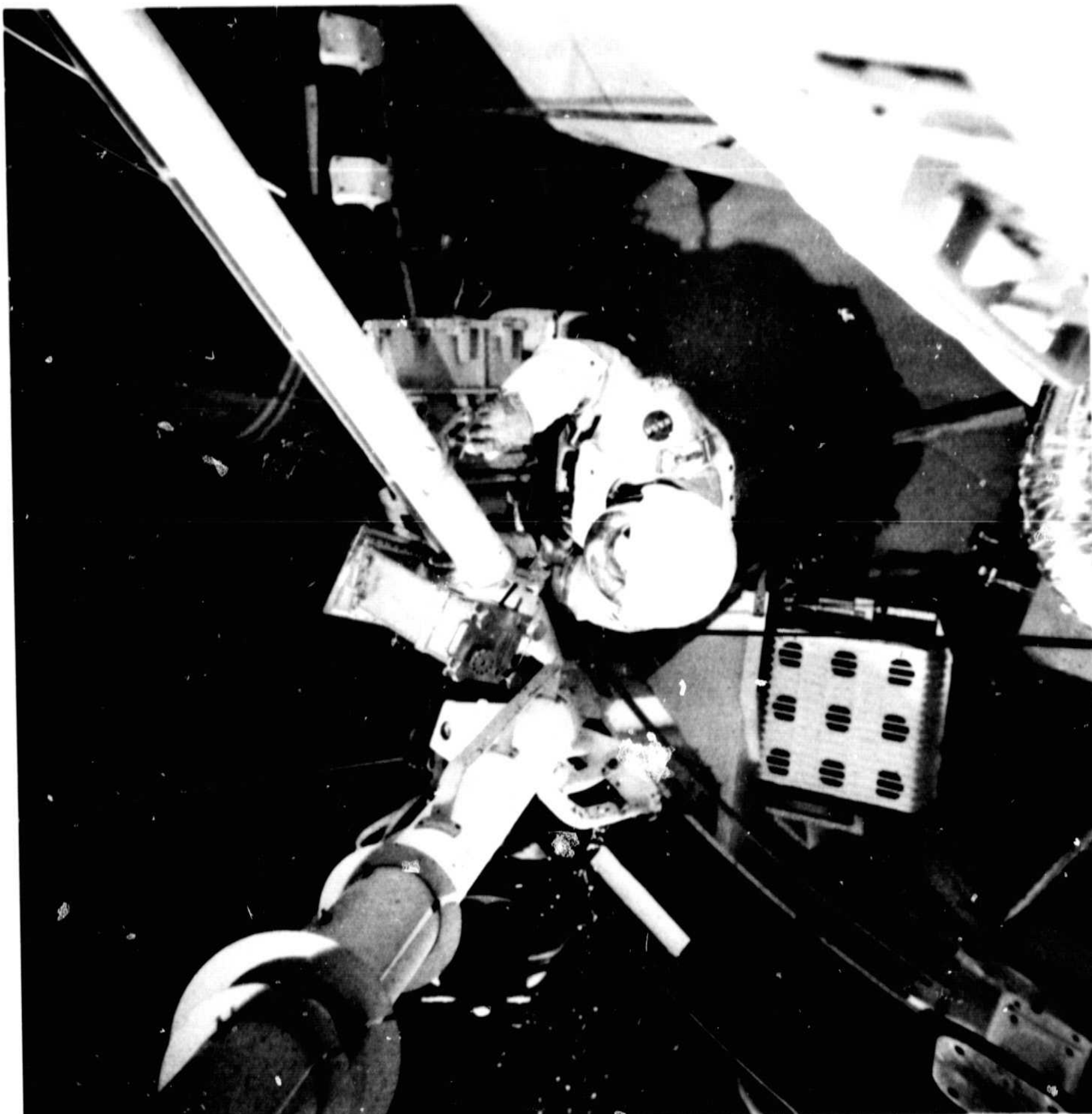

2400 ℓ/mm
INDIUM FILTER
(10-100Å SPECTRA)
(20-200Å SPECTRA)
1200 ℓ/mm
BERYLLIUM FILTER

FILM STRIP

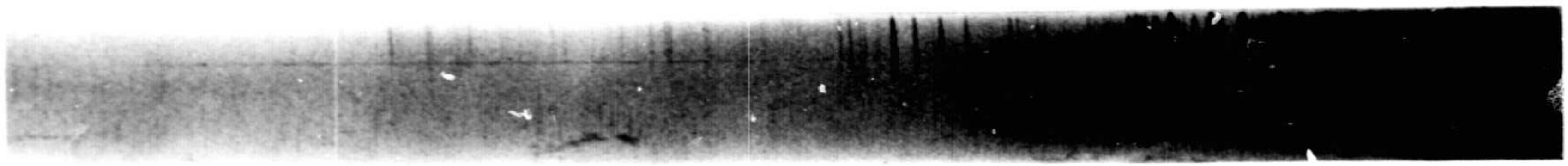




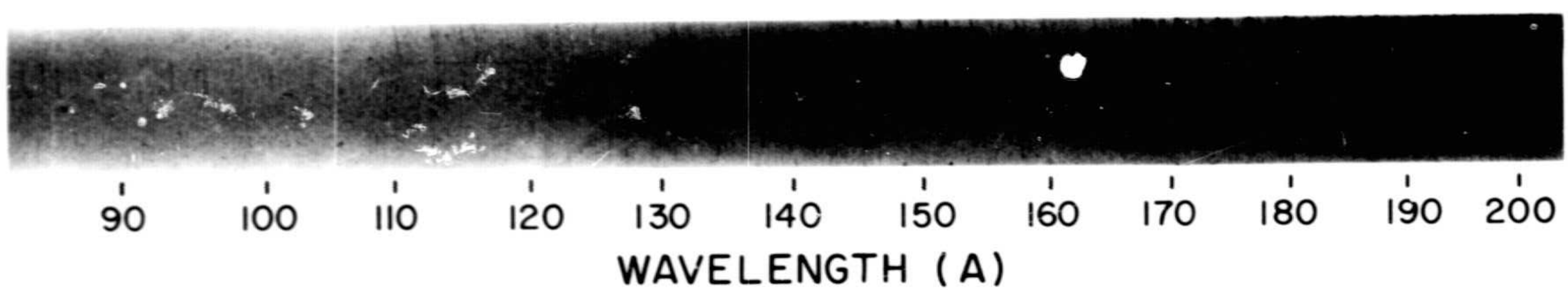


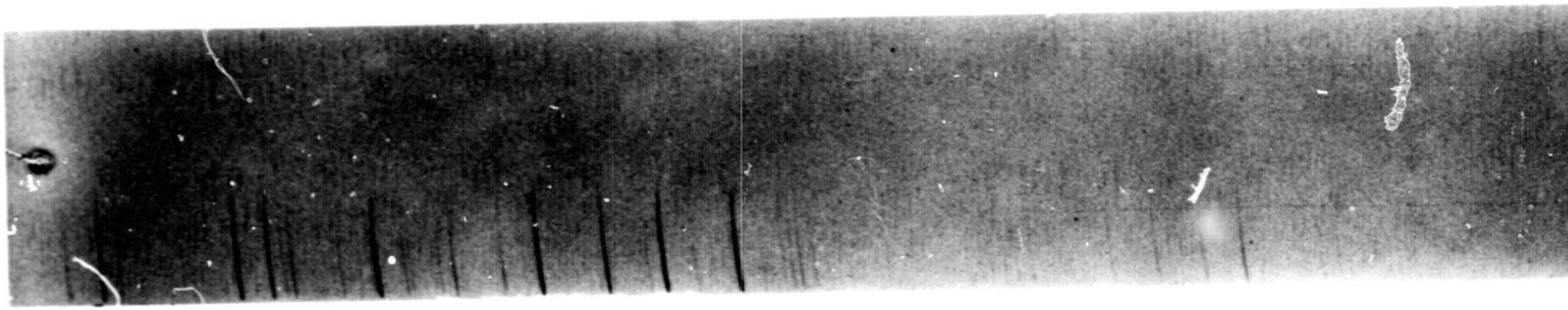


FRAME 4 - 1
(EVA 4; 60 MIN. EXPOSURE)



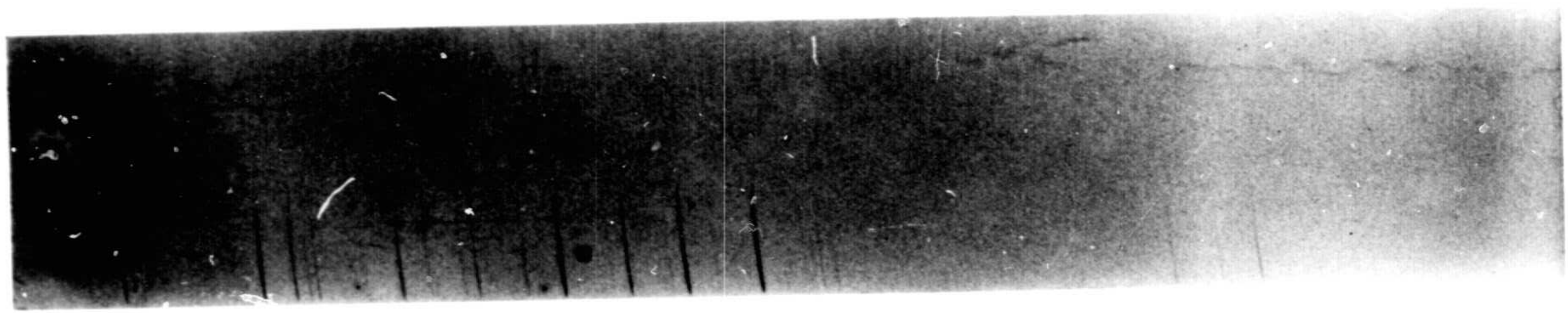
FRAME 3 - 5
(EVA 3; 45 MIN. EXPOSURE)





$\longleftarrow \lambda$

EXPOSURE 3-1
60 MINUTES



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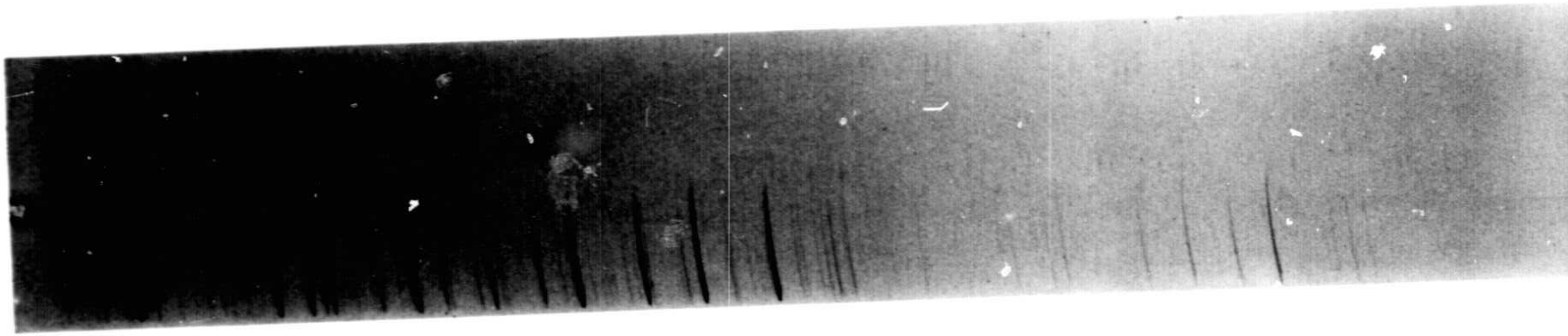
EXPOSURE 3-2
30 MINUTES



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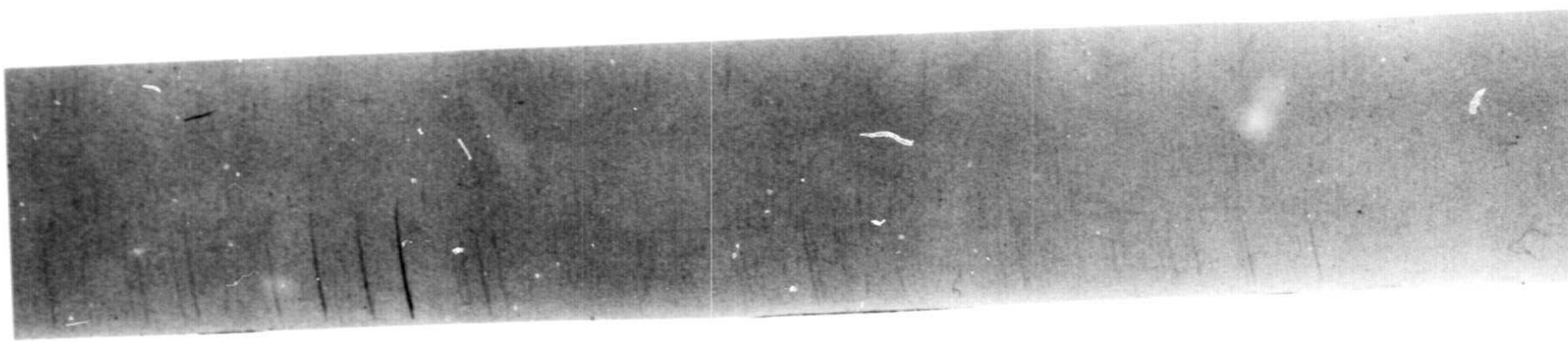

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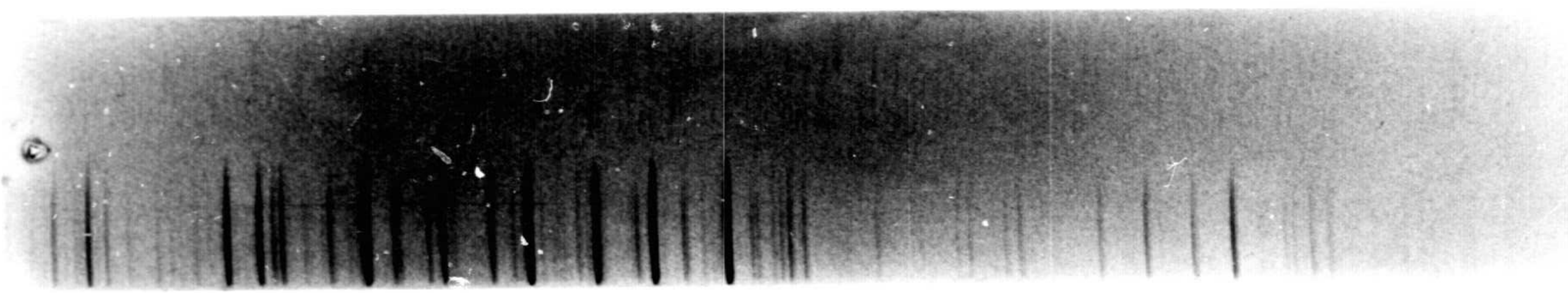
EXPOSURE 3–5
45 MINUTES



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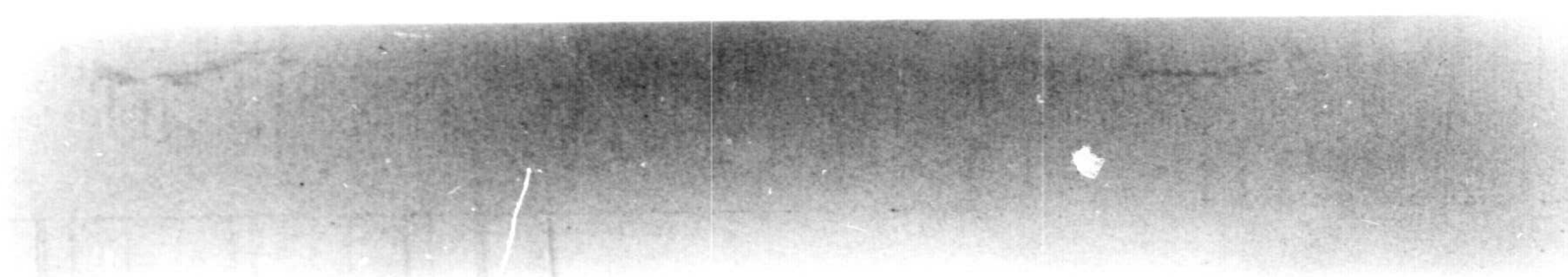

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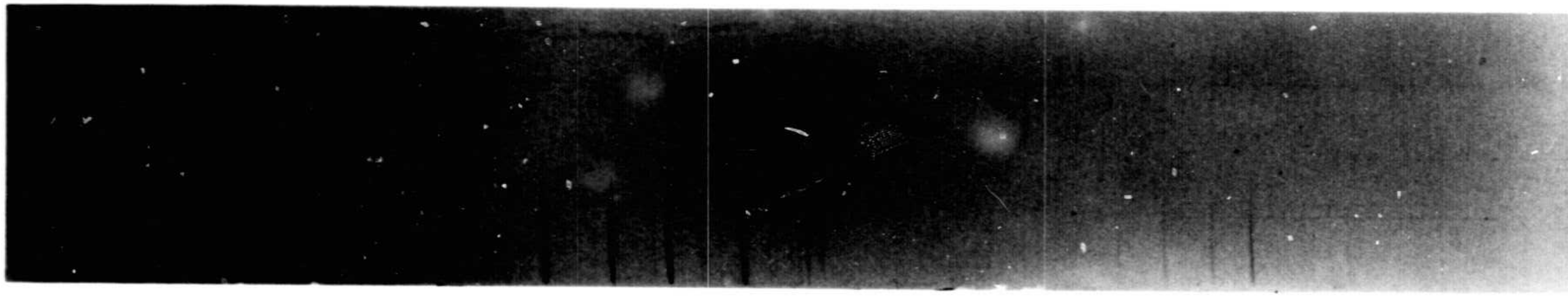
EXPOSURE 4-1
60 MINUTES



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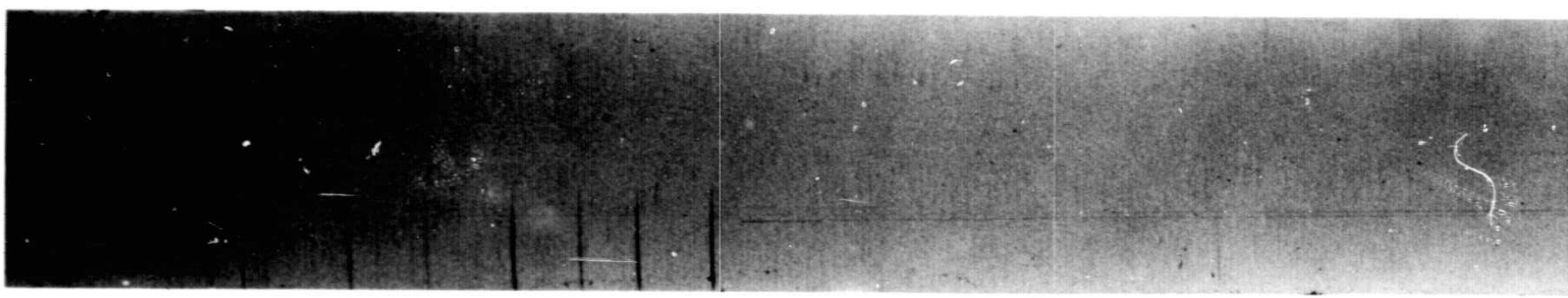
EXPOSURE 4-3
7.5 MINUTES



$\leftarrow \lambda$

EXPOSURE 4-4
4 MINUTES

TABLE 1

LIST OF EXPOSURES

Film Magazine Number and Film Slot Number	Exposure Time (min.)	EVA Number	Filter Number	Comments
3-1	60	2	31	This and all exposures made on EVA 2 are less intense than the 7.5 min. exposure on EVA 4
3-2	30	2	31	
3-3	14	2	31	
3-4	7.5	2	31	Made during a flare; more intense than exposure 3-3
3-5	45	3	31	Second most intense spectrum
4-1	60	4	41	Most intense
4-2	30	4	41	
4-3	7.5	4	41	
4-4	4	4	41	

Table II

λ	Int	Previous Observation	Identification	Comment
111.261	M	N/G		
113.815	F	N		
114.018	F	N		
115.870	P			
116.744	F	N		
118.978	F			
120.393	F			4-1
122.742	F			
123.810	F			
127.671	F	N		
129.879	F	N/G		
130.953	F	G		
131.245	F	G		
144.187	F	N/G	Ni X	
144.998	F	N/G	Ni X	
145.740	F	N/G		
146.089	F	N/G		
148.374	I	N/G	Ni XI	
150.136	M	N/G		
152.151	M	N/G	Ni XII	
154.190	M	N/G	Ni XII	
154.312	F			4-1
157.784	F			
158.379	F			
160.009	F	N		4-1
160.090	P			
160.546	F			
164.215	F	N/G	Ni XIV	
167.513	M	N/G		
168.199	M	N/G	Fe VIII	
168.550	F	N/G	Fe VIII	
168.901	F	N/G	Fe VIII	
169.634	F	N/G		
169.925	F	N/G		
171.075	I	N/G	Fe IX	
171.323	M	N/G		
172.136	F	N		
173.067	N	N/G	O VI	
174.523	I	N/G	Fe X	
175.237	M	N/G	Fe X	
177.211	I	N/G	Fe X	
178.035	F			3-5
178.068	M	G	Fe XI	4-1
178.971	P	G		4-1
179.589	F			4-1
179.707	F	N		3-5
180.035	F			3-5
180.375	I	N/G	Fe X, Fe XI	4-1
181.123	M	N/G	Fe XI	
182.145	I	N/G	Fe XI	

Table II (Continued)

184.096	F	N/G	O VI		
184.527	I	N/G	Fe X		
185.215	M	N/G	Fe VIII		
186.580	P	N/G	Fe VIII		
186.850	I	N/G	Fe XII		
188.269	I	N/G	Fe XI		Blend of two strong lines in GSF[C] spectra; Fe XI at 188.216 Å and Unidentified line at 188.299 Å
188.633	P				
189.950	F	G		4-1	
190.009	M	N/G	Fe X	3-5	
190.413	P			3-5	
190.817	P			3-5	
191.191	P			3-5	
192.392	I	N/G	Fe XII		
192.807	M	N/G	Fe XI		
193.518	I	N/G	Fe XII		
194.522	P			4-1	
194.616	P			3-5	
195.119	I	N/G	Fe XII		
196.505	P	N/G		4-1	
196.679	P			3-5	
197.438	P	N/G		3-5	
197.800	P	N/G		4-1	
198.626	P			3-5	
200.045	M	N/G			
201.010	F			4-1	
201.094	F	N/G		3-5	
202.027	I	N/G			
203.750	M	G			
204.771	P				
205.854	P			4-1	
205.945	P			3-5	