ULTRAVIOLET STELLAR ASTRONOMY

EXPERIMENT S019

FINAL REPORT

Contract NAS 9-5209

27 August 1965 - 31 December 1967

Lindheimer Astronomical Research Center
Evanston, Illinois 60201

NASA CR 92393

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Frontispiece. S019 spectrograph in operation in its originally configured command module location.

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I. Scope of work.

The objectives of the S019 experiment, which were to be carried out under this Contract, are:

1. to design and manufacture a wide-angle objective-prism ultraviolet spectrograph;
2. to obtain with the spectrograph a large number of moderate dispersion stellar spectra of sufficient resolution to permit the study of ultraviolet line spectra and spectral energy distributions of early-type stars;
3. to obtain with the spectrograph low-dispersion ultraviolet stellar spectra in a large number of Milky Way fields;
4. to gain experience in the techniques of making photographic astronomical observations from manned spacecraft.

During August 1967, it was agreed by representatives of the NASA Manned Spacecraft Center (MSC) and Northwestern University that Contract NAS 9-5209 was to be terminated at the end of December 1967, when objective 1 preceding would have been successfully achieved. The change was made desirable by the then current fiscal situation and by changes in mission planning which were made during 1967.

The primary objective of Contract NAS 9-5209 was therefore the design, manufacture and acceptance testing of the basic five units of the Northwestern University Ultraviolet Spectrograph (the S019 spectrograph). These five units are named as follows:

1. prototype unit;

2. qualification test/training unit;

*3. design evaluation and calibration unit;

*4. flight unit;

*5. flight backup unit.

*Units 3, 4 and 5 are flight-qualified.

Unit 1 is being used as the engineering prototype for study of the proposed modifications which will enable the spectrograph to be used during AAP missions. Unit 2 is at MSC for use in astronaut training. Unit 3 is used at Northwestern University in a continuing program of optical and mechanical performance verification testing. Units 4 and 5 are in bonded storage at Northwestern University.

II. Design of the S019 spectrograph.

A. Description of the spectrograph.

1. Optical components. The optical components of the instrument are the spectrograph camera, the objective prisms, the finding/guiding telescope and the focusing microscope.

a. Spectrograph camera. The optical system of the spectrograph camera is an f/3.0 Ritchey-Chretien with a two-element achromatized astimatism corrector. The primary clear aperture is 6 inches (15.24 cm) and the equivalent focal length is 18 inches (45.72 cm). The primary and secondary mirrors are of quartz, with hyperboloidal reflecting surfaces coated with aluminum and overcoated with magnesium fluoride. The front corrector element is of calcium fluoride and the rear corrector element is of lithium fluoride. The front corrector surface is a free aspheric, the two inner corrector surfaces are spherical, and the rear corrector surface is flat.

b. Objective prisms. One of a pair of 6-inch-diameter calcium fluoride prisms will be used as the dispersion element. The first, with a 4° wedge angle, will provide a reciprocal dispersion of about 56 Å/mm near 1400 Å. The second, with a $0\overset{\circ}{.}15$ wedge angle will provide a reciprocal dispersion of about 1500 Å/mm near 1400 Å/mm.

c. Finding/guiding telescope. A telescope of one-inch aperture, giving 7x magnification and a 7° field diameter is provided for visual finding and guiding by the astronaut. To facilitate guiding, the image field is erect and an illuminated reticle is provided.

d. Focusing microscope. A 30x focusing microscope is provided to enable the astronaut visually to check the focus at intervals during the observing period, using special translucent-screen focus slides.

2. Mechanisms. Two mechanical systems are incorporated—the film transport system and the focus control mechanism.

a. Film transport system. The film transport system consists of a lever-operated mechanism which positions film slides on the optical axis, moves them into the focal plane, then opens and closes the shutter. One hundred and sixty-three slides are stored in two stacks, one stack feeding unexposed slides and one stack storing exposed slides. During the course of the observations, the slide which begins at the top of the take-up stack moves down the stack, across to the bottom of the feed stack, up the feed stack to the top, finally to be exposed at the end of the observing program.

b. Focus control mechanism. The objective of the focusing microscope is mounted in the film-positioning carriage so that it remains in focus on the film plane (i.e., the focusing-screen plane). The camera is focused by turning a knob attached to a worm gear which in turn drives a helical gear. The helical gear is an integral part of the focus reference which locates the film position carriage.

3. Electrical components. The only electrical component is a battery-operated lamp which illuminates a frame counter and the reticle in the finding/guiding telescope.

4. Pressure body. The spectrograph components are enclosed in two canisters of aluminum alloy—the objective canister, which contains the spectrograph optics with the exception of the focusing microscope, and the film canister, which contains the mechanical components and the film. The two canisters are sealed together after film is loaded. In use, the spectrograph is sealed into the spacecraft scientific airlock becoming part of the pressure hull of the spacecraft. Vacuum tight penetrations of the film canister are provided for the film transport/shutter actuation mechanism, for the focus mechanism,

for the focusing microscope and for the finding/guiding telescope. The film canister is provided with a gate so that it can be sealed off from the objective canister before the spectrograph is removed from the airlock, thereby holding the film in space-vacuum conditions during its return to Earth. An end cap is provided to close the objective canister so that the entire spectrograph can be evacuated after loading.

5. Weight and volume. The spectrograph, loaded with film and with end cap in place, weighs 40.0 lbs (18.14 kg). The stowage structure weighs 5.3 lbs (2.4 kg).

The volume envelope of the spectrograph, with end cap in place, is 0.62 cubic feet ($1.76 \times 10^4 cm^3$). The volume envelope of the stowage support structure is 1.01 cubic feet ($2.86 \times 10^4 cm^3$).

B. Evolution of the design.

1. Optical design. The optical design evolved through a series of investigations by Mr. Howard Padgitt, then of the Tech-Center Division of Cook Electric Company, located in Morton Grove, Illinois. These investigations were carried out under NASA Grant NsG-674 and this Contract.

A variety of catadioptric systems were investigated; Baker-Schmidt systems with quartz transmission optics and an anastigmatic Schmidt with calcium fluoride transmission optics during the course of the Grant, and then Ritchey-Chretien systems with a single-element field flattener, achromatized Wynne-Rosin systems and finally Ritchey-Chretien systems with a two-element achromatized field flattenter.

The details of the investigations carried out under this Contract, reproduced from Mr. Padgitt's notebook, were sent to MSC as Appendix IV A to the Phase I Final Report, the Appendix being dated 1 February 1966.

A major change which was made in the course of the design involved the objective prisms. Whereas the original plan had been to mount a pair of prisms, one fixed and one rotating, in the spectrograph, the spectrograph as realized uses one of a pair of interchangeable prisms. The original design would have given a combined wedge angle of 6° with the prisms in series, and a combined wedge angle of 0°.15 with the apex of the rotating prism turned 180° from that of the fixed prism. As noted previously, the two interchangeable prisms have wedge angles of 4° and 0°.15. The change was made in order to ensure that the information to be gained from the stellar spectra near their short-wavelength limit would not be unduly diminished because of the effects of too great a dispersion combined with absorption in the thick double prism.

2. Spacecraft interface and the size of the instrument.

The size of the instrument was fixed by the stowage volume available in the Apollo Command Module. The volume assigned to Experiment S019 was Volume A of the lower equipment bay. Since the size of the spectrograph canister was then smaller than the size of the scientific airlock, an adapter was designed and built by North American Aviation (NAA), to be installed in the airlock and to which the spectrograph is mated.

3. Mechanical design. The choice of the then newly developed Kodak SC-5 film, available only in 35 mm strips, led to the design of individual holders for 35 x 40 mm pieces of film. The film is glued to precision-lapped stainless steel platens and pulled down flat against the platen by a vacuum-pumping device. Nylon cover frames are then snapped over the film to permit lateral movement of the slides between stacks without scratching the pressure-sensitive Schumann emulsion.

C. Design goals and final results.

1. Optical design. The focal length of the optical system is 457 mm and the plate scale is therefore 450″/mm. The dimensions of the nylon cover frames then give an angular field size of $4^{\circ}.2 \times 5^{\circ}.1$. Anticipated stabilization performance and film resolution led to the design goal of 20″ image diameters over a field of 5° in diameter and over a wavelength range from 1400 Å to 3000 Å. A 20″ angular diameter corresponds to a 44 micron linear diameter on the film.

It was felt that the optical design in its final state of perfection would give 15″ images over a 4° field and over a wavelength range from 1300 Å to 2500 Å—a 15″ angular diameter corresponding to a 33 micron linear diameter on the film.

The fine work of optical manufacturer Frank Cooke has resulted in imagery somewhat better than that specified. A series of tests have been carried out using the SPEX monochromator with an H_2 source. Block spectra were generated at one-hundred-Angstrom intervals from 1400 Å to 2000 Å, using a 10 Å passband. The spectrograph, with the 4° objective prism in place, was oriented so as to provide spectra on axis, 1° off axis and 2° off axis. Figure 1 shows a portion of one test exposure on SC-5 emulsion. The projected slit length is 1 mm on the film. Microdensitometer scans of portions of these spectra reveal that the optics, used with SC-5 and 1 mm widening, provide a linear resolution of less than 10 microns near the center of the field and about 25 microns at 2° off axis.

Figure 2 shows an enlarged 10 Å block spectrum with some H_2 lines identified. These lines were measured on all of the spectra to derive dispersion data and CaF_2 indices of refraction at 100 Å intervals from 2500 Å down to 1400 Å. Figure 3 shows the results of the latter investigation while a discussion of the analysis of the variation of dispersion with field position has been given in the Summary Report for Contract NAS 9-7222, 1 June 1967 - 1 June 1968.

2. Mechanical design. The design of the film transport system, in taking much longer than expected, was a major cause of delay in manufacture and assembly of the spectrograph. The transport system is an extremely complicated mechanism which had to be packaged in a relatively small volume. The design and manufacture were well enough done, however, that after a certain period of tuning and adjustment, and some detail redesign, the mechanism has routinely given smooth jam-free performance.

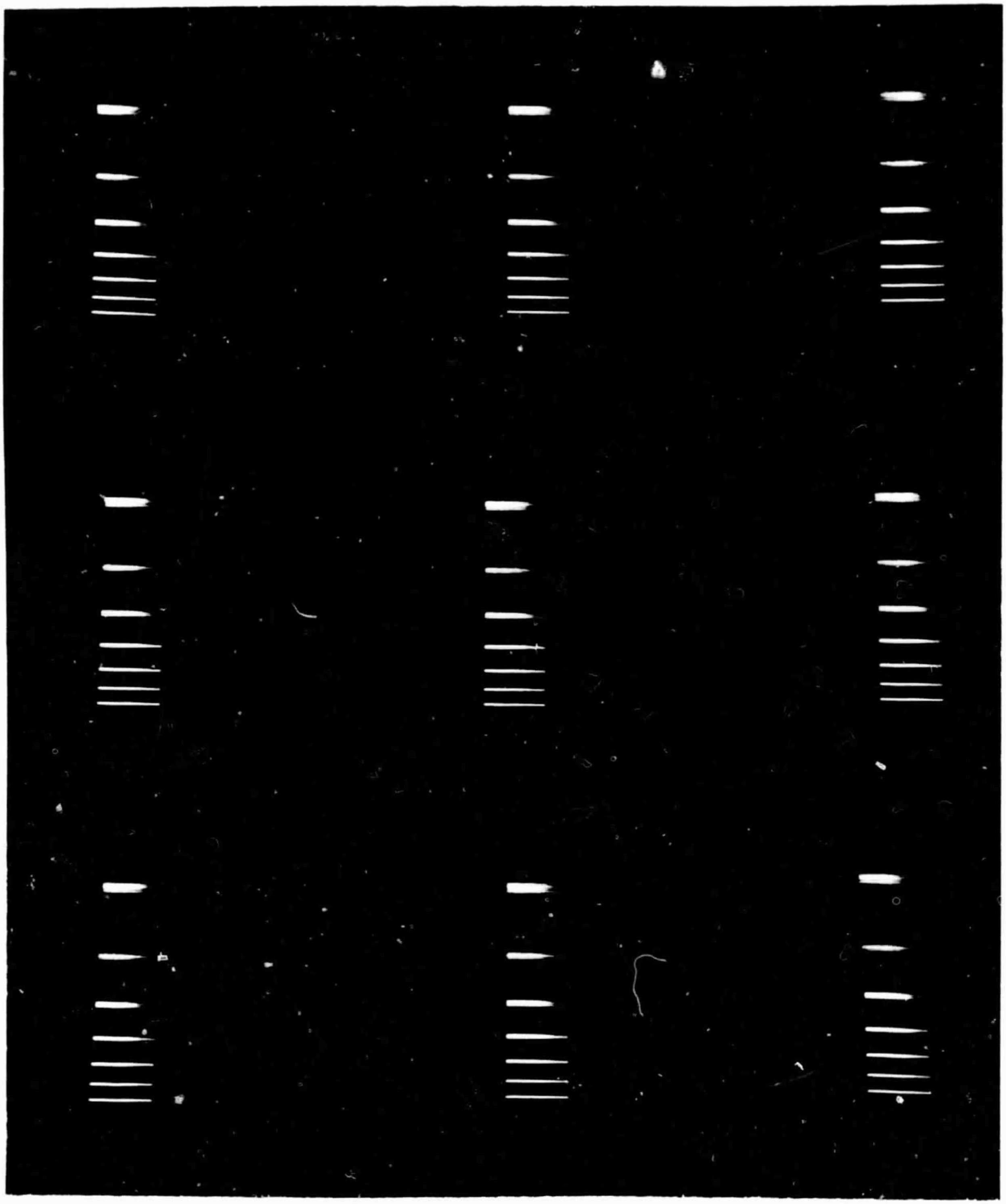


Figure 1. Block spectra of an H_2 source recorded with the SPEX monochromator using a 10 Å band-pass at 100 Å intervals from 1400 Å (upper) to 2000 Å (lower).

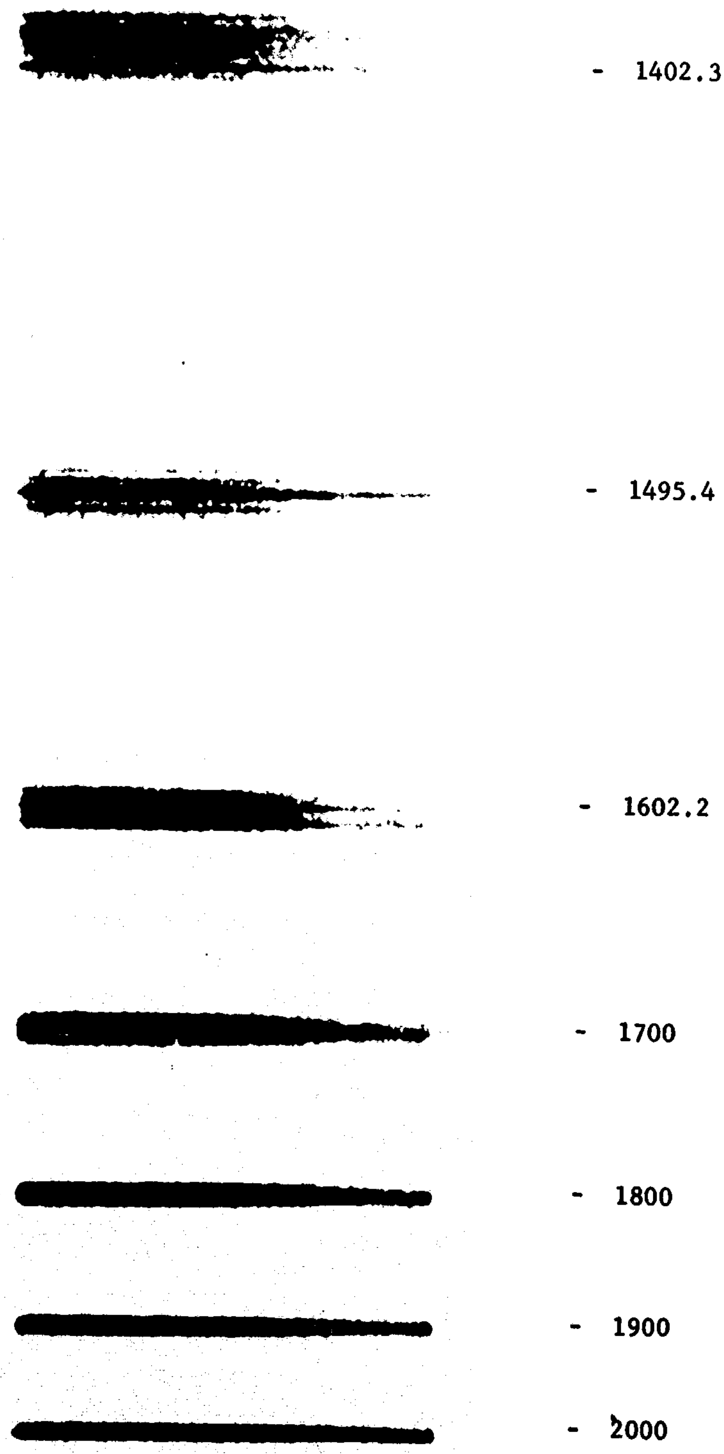
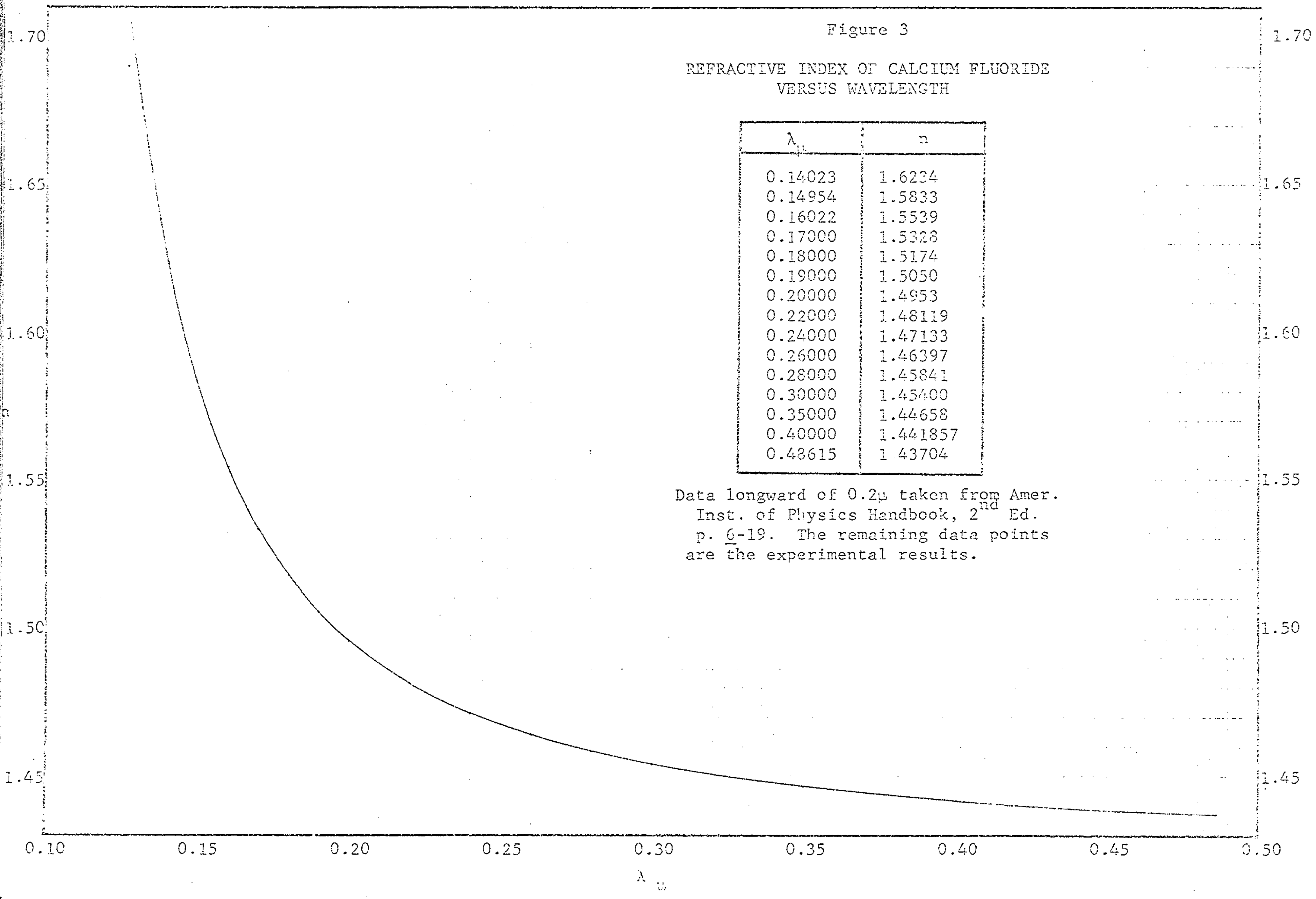


Figure 2. An enlargement of the top center spectrum of Figure 1.

Figure 3

REFRACTIVE INDEX OF CALCIUM FLUORIDE VERSUS WAVELENGTH



λ_μ	n
0.14023	1.6234
0.14954	1.5833
0.16022	1.5539
0.17000	1.5328
0.18000	1.5174
0.19000	1.5050
0.20000	1.4953
0.22000	1.48119
0.24000	1.47133
0.26000	1.46397
0.28000	1.45841
0.30000	1.45400
0.35000	1.44658
0.40000	1.441857
0.48615	1.43704

Data longward of 0.2μ taken from Amer. Inst. of Physics Handbook, 2^{nd} Ed. p. 6-19. The remaining data points are the experimental results.

The specified capacity was 150 film slides; the realized capacity is 163 slides.

3. Other. The most serious problems encountered in the manufacture of the spectrograph are treated in some detail in the following section. Suffice it to say that all optical and mechanical components of the spectrograph were in the end satisfactorily manufactured and found to perform to specification.

III. Major problems.

A. Optical system.

1. Design. The first major problem—the achievement of a satisfactory optical design under the pressure of an extreme crash schedule--was successfully overcome, as previously related.

2. Optical material. The material available for use in the fabrication of transmission optics was subject to acceptance testing at Northwestern University, in order to ensure high ultraviolet transmission. It was found that calcium fluoride of adequate purity is in fact quite rare. Tests were made over a period of two years of virtually the entire stock of material available from Optovac and Harshaw, the two major crystal manufacturers.

Frank Cooke at first acquired calcium fluoride and lithium fluoride from Optovac, Inc. for use in the astigmatism corrector. About 50 samples of CaF_2 and about 20 samples of LiF were tested. The lithium fluoride, though not of the highest ultraviolet quality, was quite adequate for our purposes.

The calcium fluoride, however, proved quite unacceptable. It was eventually necessary to obtain approved CaF_2 from Harshaw Chemical for use in the correctors.

When an order was placed for CaF_2 for use in making the 6-inch objective prisms, Harshaw sent samples of all perfectly grown 8-inch diameter boules in stock. All were rejected as unsatisfactory. Tests of the entire stock were thereupon begun, and one boule with a "seed" in the center was found to be acceptable. The "seed" is an imperfection due to a platinum probe inserted through the center of the boule during growing. Such crystals are perfectly acceptable for use in objective prisms, since the central part of the prism is blocked by the secondary mirror and therefore not used. The one acceptable boule provided enough material for five 4° prisms and two $0\overset{\circ}{.}15$ prisms. Harshaw then grew 8-inch crystals for a year, at the rate of one boule per month, in attempting to provide high-quality ultraviolet material. An acceptable 8-inch boule was finally produced, but did not quite provide enough material for the entire number of prisms required. In the meantime, Harshaw had brought a new, larger furnace into operation, and on the second or third try produced a high-quality 13-inch boule which sufficed to produce the rest of the prisms.

3. Figuring of crystal surfaces. The figuring of a free aspheric on the front CaF_2 corrector element surface provided a great challenge to the optician, Frank Cooke. Conventional

methods of grinding and polishing naturally tended to introduce astigmatism, the structure of CaF_2 being such that the crystal is "softer" along one axis than along another, so that material is not evenly worn off during polishing. It eventually proved necessary to generate the required surface on a quartz master and then use the master to shape a series of ring laps, which were then used to generate the corrector surface in about a dozen concentric zones. Polishing was then begun using a full-surface smoothing lap.

The process, though quickly described, proved long and tedious in the execution and required a great deal of skill to be carried through successfully.

4. Mounting of objective prisms. The objective prisms were polished at Harshaw, mounted in their cells and shipped to Northwestern for acceptance testing. It was quickly found that the prisms were useless, severe astigmatism having been introduced by warping of the prisms caused by mechanical strains due to the mounting gasket. A re-design of the mounting means was therefore necessary, and was carried out at Northwestern University. The prisms are now mounted using RTV-102 and RTV-112 as a gasket molded in place around the prism in its cell. The mounting of prisms by this technique has given completely satisfactory results to date; as previously noted, during optical verification testing excellent ultraviolet imagery is routinely obtained with the prisms in place.

B. Canister castings.

1. Objective canister castings. Universal Casting, Chicago, Illinois, undertook the production of the canisters. The task of pouring the long, thin-walled, flanged objective canisters proved extremely difficult from the start. Over a period of 1½ years, more than 100 castings were poured, with many changes in pouring techniques and many mold-pattern changes. It proved to be virtually impossible to meet class 1 X-ray specifications in the end. High-quality class 2 canisters which held dimensional tolerance were made in sufficient numbers for our purposes, however. A program of hydrostatic pressure testing to over pressures of 100 psi was devised and accepted by MSC. The castings finally accepted for use in the three flight units were of the highest quality thus far achieved.

2. Film canister castings. The film canister castings were successfully poured after a shorter series of attempts than were required for the objective canister castings.

C. Advances in state of the art.

The solution of the problems recounted in the preceding sections led to a number of significant advances in state of the art techniques. To summarize, the most salient of these advances are:

1. The very achievement of a successful optical design for an instrument of this size;
2. the successful manufacture of 13-inch-diameter ingots of high-ultraviolet-quality calcium fluoride;

3. the successful figuring of a non-astigmatic free aspheric on calcium fluoride;

4. the successful strain-free mounting of relatively thin calcium fluoride prisms; and

5. the considerable advances in casting techniques which were realized during the production of high quality objective canisters.

It should also be evident from the preceding discussion that the manufacturers cited were most generous in their efforts to overcome those problems which arose.

IV. Northwestern University Support Facilities.

A. Vacuum facilities.

During the course of this Contract, a first-rate vacuum facility was set up in Dearborn Observatory and was used in the extensive programs of material testing previously mentioned, for the application of high-quality coatings on the spectrograph mirrors and auxiliary optics, and for a number of investigations in the field of thin films directly related to the ultraviolet astronomy program.

Another facility was established at Cook Electric for optical testing of the individual units. After the termination of the effort at Cook Electric, this system along with all other equipment at Cook Electric, was torn down and transferred to Northwestern University.

Two facilities are presently to be in operation at Northwestern; one is to be used for thin-film investigations, filter production, mirror coating, etc., the other is to be used in the testing and calibration of the S019 spectrograph. As these facilities were established during the course of this Contract, a current description of each is included here.

1. Thin-film facility. This system, located in the basement of Dearborn Observatory, has recently been much improved by the installation of a new 2400 liter sec^{-1} diffusion pump which enables us to reach the low 10^{-7} torr ranges—an improvement of an order of magnitude. We may thus expect considerable improvement in future fast-fired ultraviolet reflection coatings. Much improved tooling has also been installed for use in lithium evaporation experiments.

The thin-film facility now consists of the following components.

a. The 24-inch stainless steel bell jar, with its associated oil-diffusion pumping apparatus, liquid N_2 traps, evaporation sources and power supplies, shutters, heaters and substrate holders.

b. The quartz-crystal thin-film monitoring apparatus.

c. The SPEX 3/4-meter Czerny-Turner monochromator, with its associated reflectometer, photometer electronics, Golay cell and electronics, 35-mm vacuum camera, 3¼ x 4 (non-evacuable) plate camera, and filter-sample holders. The SPEX has its own pumping system, with associated gauges and traps, which will bring it into the low 10^{-5} torr range.

d. An Evanson-cavity H_2 microwave-discharge lamp, with its associated pumping system and gauges, and driven by a 2400 MHz oscillator with 120-watt output.

e. A multi-beam interference microscope with Polaroid camera for direct verification of film thickness in metric units.

2. Calibration facility. This system, located in the Northwestern Technological Institute, is to be used solely for optical testing and will be the prime pre-flight calibration system for S019. As there will no longer be sharing of the system with thin-film work, contamination problems are considerably reduced. The system is currently under construction; 75% of the design drawings are done and all parts are on hand. The system will be comprised of the following components.

a. An 8-inch-aperture f/8 parabolic collimator (to be used in Newtonian form) with associated pumping system and traps. The pump is the 1500 liter sec^{-1} oil diffusion pump formerly used in the thin-film facility and which will bring the collimator into the low 10^{-5} torr range. The collimator was formerly located at Cook Electric.

b. The Northwestern airlock-bellows assembiy, replacing the Cook Electric bellows.

c. An f/5.6 criss-cross Czerny-Turner monochromator with its associated pumping system, traps and gauges.

d. An Hinteregger discharge H_2 source with a 1 kilowatt power supply.

e. Photometric apparatus for a direct measurement of the intensity of the collimator beam.

B. Data analysis equipment.

During the course of this Contract, plans were made to establish a first-rate data reduction facility for the S019 analysis. Equipment orders were placed and the facility was eventually set up. Again, though much of the work followed the termination of this Contract, a description of the equipment is included here.

A stock Jarrell-Ash microdensitometer, similar to the Yoss machine at the University of Illinois, was purchased, torn down and rebuilt in order to remedy a number of inadequacies. It was found that the proposed digitized output in transmission was inadequate for our purposes, transmission accuracies at densities greater than 1 were inadequate for SC-5 type emulsions, and the proposed punched-card output was not adequately reliable or fast enough.

The photometric system (both analytical and reference outputs) was therefore redone. The stock 931A photomultipliers, which were rather crudely mounted, were replaced by EMI 9524 S photomultipliers in completely redesigned mechanical and optical arrangements in order to best use the photocathodes, eliminate stray light and maximize S/N and dynamic range. The new system incorporates an all-electronic ratio-taker using the highest-stability logarithmic operational amplifiers available. The output of the ratio taker is optical density which is digitized by means of a high-speed digital voltmeter producing a BCD-compatible signal. This BCD density is then recorded on magnetic tape for direct input into the CDC 6400 computer system. The expected accuracy in density recording is ± 0.02 over a density range of 0 to 3.0, with even higher accuracy possible over smaller ranges in density. The optical density is also read out on a strip-chart recorder.

The plate-carriage position is digitized with 1-micron accuracy on the X-screw. A 2-micron accuracy on the Y-screw is gained with mechanical readout. The X-scanning is programmable—one can record optical density and position at intervals of from 1 to 99 microns or from 10 to 990 microns.

The system is also equipped with a magnetic-tape deck, a coupler and associated interface equipment. The tape format is compatible with the University's CDC 6400 computer. The tape deck also has a playback mode with which one can display computer processed data on a CRT for photographic recording. This entire system including modifications, which was procured for 30% more than would have been involved in simply digitizing the original Jarrell-Ash instrument for punched card output, must certainly be rated one of the most sophisticated microdensitometry systems in the astronomical community.

V. Personnel. The design, construction and testing of the SO19 spectrograph were carried out under the supervision of Dr. K. G. Henize, Principal Investigator. With the departure of Henize to become a Scientist-Astronaut, Dr. J. D. Wray was appointed Co-Investigator. Mr. F. G. O'Callaghan, staff engineer, supervised the construction of the Dearborn Observatory Vacuum Facility, in which he was assisted by Messrs. B. C. McKenna, E. Yelke. O'Callaghan closely monitored the work of Cook Electric during the later phases of instrument fabrication.

Mr. L. R. Wackerling, staff astronomer, participated in the initial formulation of the design and operational concepts, as well as the pursuit of relevant astronomical studies. Mr. R. K. Woo served as administrative officer and Mrs. D. Zimmerman as secretary. This Final Report was written by Wackerling and approved by Dr. Henize.

Lloyd R. Wackerling
Karl G. Henize

30 September 1968

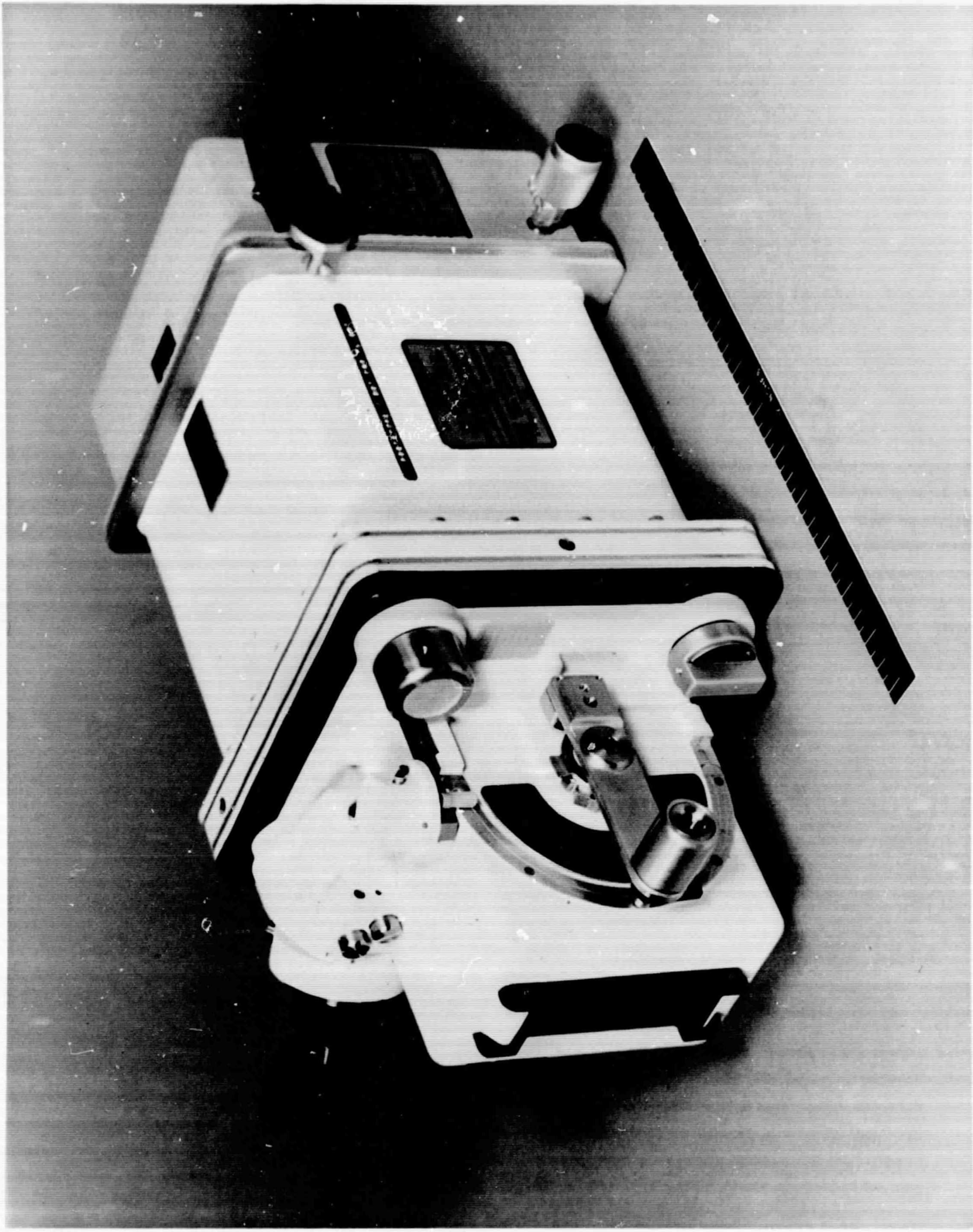


Figure 4. S019 spectrograph showing film advance lever, focus knob and film canister hatch control knob.

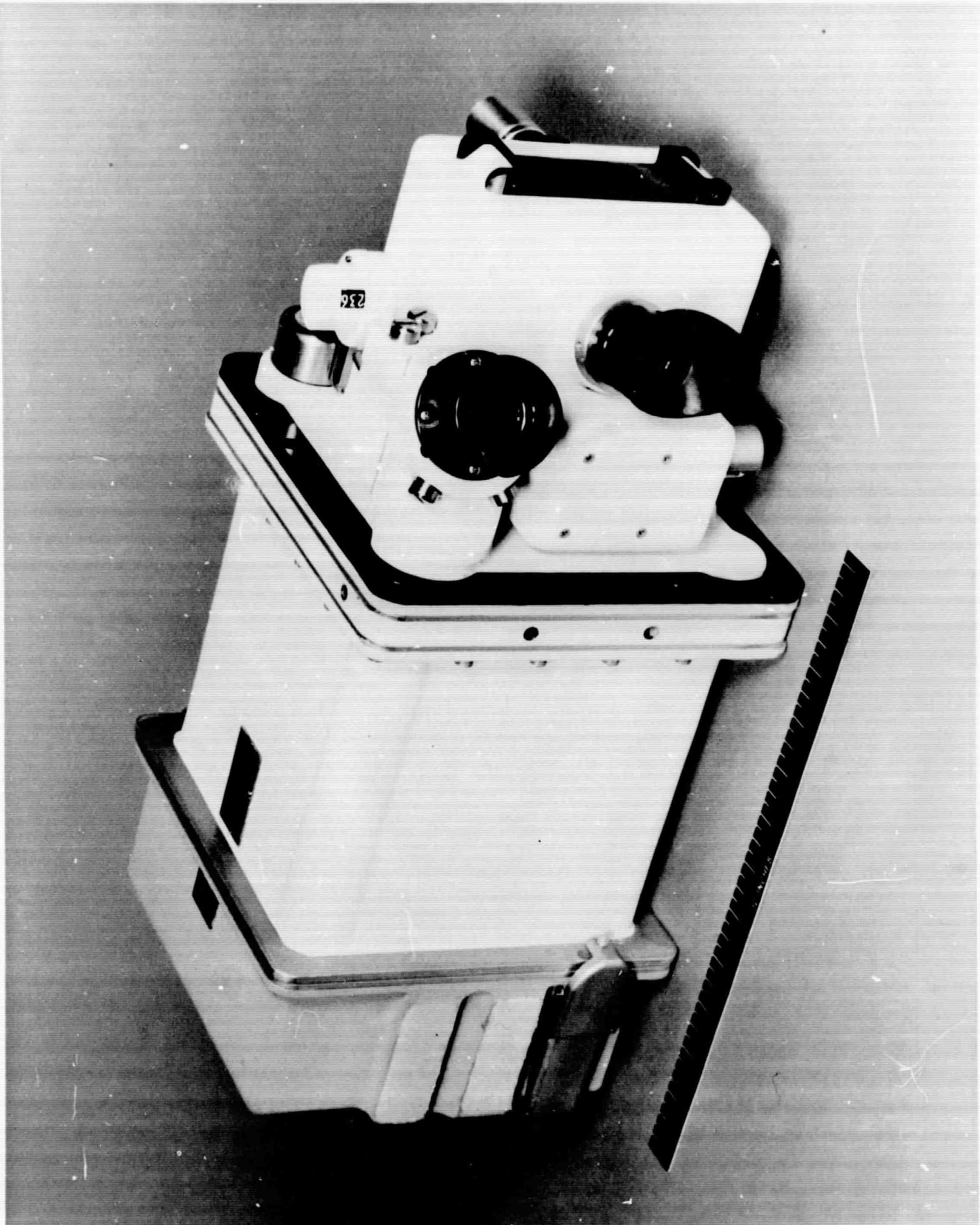


Figure 5. S019 spectrograph showing focus check and finder-guider eyepieces.

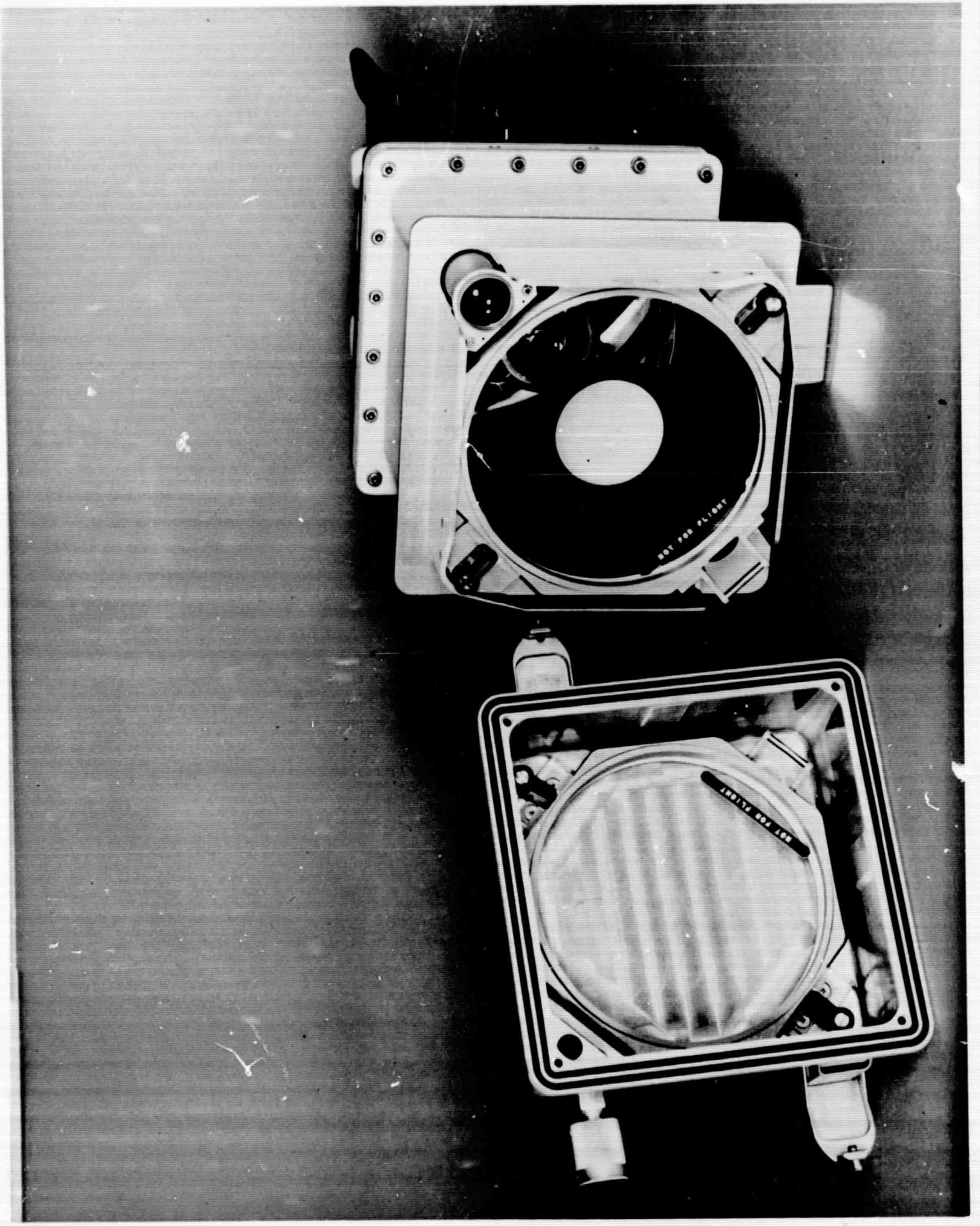


Figure 6. View showing prism stowed in cover and prism in place on spectrograph. Ritchey-Chretien optics and the finder-guider telescope are visible.