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A DESCRIPTION OF FOUR FAST SLITLESS SPECTROGRAPHS

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A DESCRIPTION OF FOUR FAST SLITLESS SPECTROGRAPHS

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SUMMARY

A description, comparison, and short discussion of four fast slitless spectrographs for use in low-light-level research are given. The spectrographs include three catadioptric systems, the Super Schmidt meteor camera, the Baby Schmidt, and the Maksutov and one refractive optical system, the Super Farron. The Baby Schmidt and the Maksutov systems have fused-silica transmission elements. Except for the Super Schmidt camera, which utilizes a light flint mosaic prism, all systems utilize objective transmission diffraction gratings. The four systems discussed have low-light-level spectroscopic recording capability. The Super Schmidt has the largest field, 57°; the Baby Schmidt and Maksutovs have the broadest effective spectral range (3200 angstroms to 9500 angstroms); and the Super Farron features the greatest versatility and portability.

INTRODUCTION

A spectrograph is an apparatus which effects dispersion of radiation for photographic recording. A slitless spectrograph consists basically of a dispersion element, prism, or grating, placed over the entrance of a camera so that images or the radiation source rather than the entrance slit of the more customary slit spectrograph are formed. A wide field and high optical transmission can be obtained with the absence of a slit and related collimating optics necessary in a slit spectrograph. Slitless spectroscopy is often used when at least one dimension of the radiation source image is small enough to allow acceptable spectral resolution.

Slitless spectroscopy has been used advantageously in stellar classification, meteor spectroscopy (refs. 1 to 4), and reentry spectroscopy (refs. 5 and 6).

Thin objective prisms on astronomical telescopes have been used for stellar classification for many years. Modified aerial and ballistic cameras with objective prisms and transmission diffraction gratings (refs. 7 and 8) have been used to obtain spectra of bright meteors (magnitudes brighter than -3). The strong emphasis on ballistic rocket reentries promoted much interest in slitless spectroscopy so that many aerial cameras and ballistic cameras were converted for this work. These instruments can be called first-generation slitless spectrographs. Novak (ref. 9) and Planet (ref. 10) discuss some of the characteristics and problems of these spectrographs.

The most important limitation of first-generation slitless spectrographs in meteor research is low sensitivity. The limiting magnitude for useful spectral information (generally more than five identifiable lines, blended groups of lines, or bands, in a spectrum) is approximately -3 absolute meteor magnitudes. The yield rate for useful spectra for first-generation spectrographs on a natural meteor patrol is about one per 100 hours of exposure time. Another very important limitation is their short spectral range. Residual chromatic aberration and transmission of the optics limit the spectral range from 3900 angstroms to 7000 angstroms with as much as a factor of ten difference in resolution within this range, primarily from residual chromatic aberration. The image quality and optical transmission usually vary strongly as a function of field angle. Poor grating transmission, or blaze efficiency, has also been a problem. Because of the limitations of the first-generation spectrographs, numerous refinements have been made, and a new generation of spectrographs is now being developed and used.

The purpose of this paper is to report the capability of current fast slitless spectrographs and to document the spectrographs used in the NASA Meteor Simulation Project. Four slitless spectrographs especially suited for the low-light levels and short-duration events of rocket-borne artificial meteor experiments and natural meteor patrols are described. The radiation sources monitored by these spectrographs occur in unpredictable locations in the sky; and hence, a wide field is required. The radiation sources are usually at distances greater than 100 kilometers, and last between 0.2 and 2 seconds. The effective exposure time for the film emulsion, because of the high writing speed of the image, is typically 10^{-3} seconds. This paper discusses the sensitivity or speed of each spectrograph with regard to these specialized sources. The image quality, resolution, spectral range, relative costs, and practical use in the field of each spectrograph are also discussed. A brief discussion of some films used in these spectrographs is given.

These spectrographs are believed to be significant because of their high sensitivity. Qualitative and quantitative data can now be obtained from short-duration, low-light-level events, such as faint meteors. Two of the spectrographs offer extended spectral range through the use of fused silica catadioptric optics. The salient features of simplicity, portability, low cost, and resolution are stressed.

SPECTROGRAPHS

This section will describe four basic spectrographs; the Super Schmidt, Baby Schmidt, Maksutovs, and Super Farron. Some of the more important characteristics of these spectrographs are given in table I.

Super Schmidt Meteor Cameras

The Super Schmidt meteor cameras (see fig. 1), designed by Dr. James E. Baker for the Harvard College Observatory and the Canadian meteor patrols, have for over 15 years been the best cameras available for meteor photography. A general, but limited, description of the cameras is given in references 11 to 14. The camera, as shown in figure 2, has symmetrical meniscus elements and an achromatic aspheric corrector. A more complete discussion of this type of system can be found in reference 15. The system was designed to photograph fainter meteors with a wider field than previously possible and was first put into operation in 1951. Six cameras have been built; two are in use at Canadian meteor stations and four are at the NASA Wallops Station. Two similar cameras have been manufactured in England for Jodrell Bank. With the fast emulsions now available, the Super Schmidt cameras under favorable conditions and without a prism can record meteors as faint as fourth magnitude.

Although the Super Schmidt camera nominally has a f/0.65 system with an aperture of 310 mm and a focal length of 203 mm, because of the obstruction by the film holder, the effective f-number is about f/0.85. With 6-percent reflection loss (average angle of incidence on lenses is $>20^{\circ}$) at the lens surfaces, and a 10-percent loss at the mirror, the calculated t-number (f-number of an equivalent system with no obstruction or vignetting and 100-percent transmission) is about 1.22. This calculated t-number assumes no absorption losses in the refractive elements. The short-wavelength cutoff is limited by the absorption of the refractive elements, and the long-wavelength cutoff is determined by the emulsion used. A significant amount of light at 3600 angstroms, probably between 5 and 10 percent relative to transmission at 5000 angstroms, is transmitted through the complete optical system.

The Super Schmidt optical image suffers from coma, second-order chromatic aberration, and residual spherical aberration. The optical system is best corrected for approximately 10° off axis. The image half-width varies between 20μ to as much as 500μ at the edge of the field, with an average of 50μ. In general, the image quality is determined by the optical system and not by density broadening from overexposure. The system is well corrected for a bandwidth of 1000 angstroms to 1500 angstroms in the blue-green region of the spectrum and requires a change of focus in going from blue-sensitive film to panchromatic film. Considerable difference exists in the Super Schmidt cameras; in general, the later manufactured cameras have better imagery than the earlier models. Some of the earlier models have been reworked.

The 57° image surface of the Super Schmidt camera is part of a spherical surface of approximately 200-mm radius and 190-mm chord. As a result of this strong curvature, film must be molded to conform closely to this radius. The molded film is held in place by a partial vacuum. At present, only blue-sensitive and panchromatic heavy base acetate emulsions can be satisfactorily and consistently molded. The cameras are limited by buildup of plate fog from night sky background to about 1 minute total exposure time with the fastest available emulsion. However, the cameras are usually operated with rotating focal plane occulting shutters so that the total look time per plate is 3 minutes.

The first prism used on a Super Schmidt camera was a three-element mosaic polystyrene prism. A full-aperture prism must be about 600 mm (twice the camera aperture) in diameter for full angle coverage without vignetting, because it must be located in front of the first meniscus correcting lens. The polystyrene prism severely degraded the imagery (by approximately a factor of five) of the system. An example of unreduced and reduced data from this spectrograph can be found in references 4 and 6.

This polystyrene prism has been replaced by a much more precise, full-aperture prism especially designed for the wide field of the Super Schmidt camera. The new prism is a light flint (LF-5), six-element mosaic prism with prism angles of 30°. A very marked improvement in spectral quality of the spectrograms has resulted from the use of the new prism. A similar prism, originally designed for the Baker-Nunn cameras, has also been acquired for use with the Super Schmidt cameras.

The Super Schmidt camera requires a permanent field installation and thus is not portable. The mass of the Super Schmidt camera assembly is approximately 700 kg. The total mass of the camera assembly and tracking mount, exclusive of the concrete pier, is approximately 2700 kg. Both hydraulic and electrical systems are used to drive and operate the camera. The optical system is hinged open for manual loading. The original cost, operation, and maintenance of the Super Schmidt systems are high in comparison with the other systems to be discussed, as would be expected when the large and unusual optics are considered.

A Super Schmidt spectrograph has recorded spectral information from low-meteoric-velocity iron artificial meteors at +2 apparent panchromatic meteor magnitude. An enlargement of part of a tracked negative from a Super Schmidt (with no objective prism) showing the Great Nebula of Andromeda is shown in figure 3. An enlargement of part of a trailed spectrum plate is shown in figure 4.

Baby Schmidt

The Baby Schmidt (see fig. 1), a Maksutov camera with a Schmidt corrector plate, was built for the Lincoln Laboratories of the Massachusetts Institute of Technology. The spectrograph was originally designed and built with fixed optics, and was later modified to include a three-cam adjustment on the mirror for focus and alinement. The optics, a f/0.83, 128-mm-focal-length catadioptric system, consist of a fused-silica meniscus, or Maksutov, corrector lens; a fused-silica aspheric, or Schmidt, corrector lens; and a spherical mirror. A diagram of the Baby Schmidt optical system is presented as figure 5. The t-number of the optical system with its 20° field is approximately 1.04. The useful wavelength region of this camera is limited by atmospheric extinction at 3200 angstroms, and the long-wavelength cutoff of a particular emulsion.

Twenty-micron half-width images can be obtained, but because of focus and alinement problems, forty micron and larger half-width images are more common. The instrument is subject to very large changes in alinement and focus with change in temperature. The optical elements are mounted in a massive one-piece metal case which provides no ready access or adjustment. The spectrograph is loaded by inserting the film and film holder through a hole in the mirror, and the film holder is held in place by a magnet on the film holder pedestal. A fused-silica transmission diffraction grating of 150 lines/mm is generally used as the dispersing element in this spectrograph.

This spectrograph has been used successfully in obtaining spectra of artificial meteors. (For example, see ref. 4.) The spectrograph has recorded spectral information from low-velocity iron and nickel artificial meteors at +2 apparent panchromatic meteor magnitude, but has not had sufficient use to demonstrate its full capabilities and operational characteristics under field conditions. An enlargement of a trailed plate from the Baby Schmidt camera is presented in figure 6 and an enlargement of a trailed spectrum plate is presented in figure 7.

Maksutov Camera-Spectrographs

Five fast fused-silica optics, two f/1.3 and three f/1 Maksutov camera-spectrographs, have been built by the Langley Research Center for meteor spectroscopy and related research. Photographs of some of these spectrographs are shown in figures 8, 9, and 10. The optical systems consist of fused-silica meniscus corrector lenses and pyrex spherical mirrors. A diagram of the 168-mm focal length f/1.3 optical system is presented in figure 11 and of the 150-mm focal length f/1 system is presented in figure 12. The t-number of the f/1.3 with a 21° field is 1.67 and the t-numbers of the f/1 with fields of 18°, 28°, and 38° are 1.22, 1.33, and 1.49, respectively. The useful wavelength region of these spectrographs is limited by atmospheric extinction to 3200 angstroms, and the long-wavelength cutoff of a particular emulsion. Twenty-micron line image half-widths have been measured for the f/1.3 system, and forty-micron line image half-widths have been measured for the f/1 system. The film is held by a retainer ring on a pedestal bolted to the corrector lens. Four fused-silica transmission diffraction gratings and a fused-silica 20° apex angle prism are available for the dispersion elements in these spectrographs. A more complete description and discussion of the Maksutov spectrographs is contained in appendix A.

An f/1.3 Maksutov spectrograph has recorded spectral data from a nickel artificial meteor at an apparent panchromatic meteor magnitude dimmer than +4. (A detailed discussion is contained in appendix B.) An enlargement of a trail star plate from the f/1.3 is presented in figure 13, and from the f/1 in figure 14. An enlargement of a trailed spectrum plate from the f/1.3 is presented in figure 15, and from the f/1 in figure 16.

Super Farron

The Super Farron lens is a commercially built, nine-element, f/0.87, 76-mm focal length lens which was designed primarily for low-light-level oscilloscope recording, television camera recording, and similar applications. Figure 17 is a photograph of a Super Farron slitless spectrograph. The spectrograph shown in figure 17 has micrometer focusing, variable aperture, and a six-step exposure time, iris-type shutter. Figure 18 is a sketch of the Super Farron optical system. The lens system which has coated optics, has a specified t-number of 1 and a weighted average resolution across the field of 40 lines/mm. Line half-widths of 35μ have been measured, and dense images, especially near the edge of the field, exhibit considerable flare. The nominal field is 30° and the effective short-wavelength cutoff of the lens is about 4000 angstroms. The film plane is flat and a slight vacuum is needed to keep the film from buckling. The limiting star trailing magnitude is approximately the same as that of a Super Schmidt. This lens, when fitted with a film holder and objective diffraction grating, has excellent transportability, handling, and versatility. An enlargement of a trailed star plate is shown in figure 19, and a trailed spectrum plate from a Super Farron spectrograph is shown in figure 20. The Super Farron spectrograph has recorded some spectral information from a nickel artificial meteor at +1 apparent panchromatic meteor magnitude, even though out of focus for this plate.

Films

Since energy limitation is the primary characteristic in applications of these spectrographs, only the fastest emulsions are generally used. Five different emulsions representing three different spectral bandwidths have been found suitable for artificial meteor research: 103-0 and single-coated medical X-ray for the near-ultraviolet and blue region of the spectrum; 2475 and SO-166 for the near-ultraviolet to the far red part of the spectrum; and high-speed infrared for the near-infrared part of the spectrum. These films are generally developed in high-energy developers such as DK-60a, D-19, and Ethol 90.

Qualitative descriptions of the films are as follows:

103-0 film.- 103-0 film is a blue-sensitive film commonly used for low-intensity or short-exposure scientific applications. The effective long-wavelength spectral cutoff is 4800 angstroms. The film is characterized by moderately low resolving power, moderately coarse granularity, and medium contrast.

Single-coated medical X-ray film.- Single-coated medical X-ray film is the fastest blue-sensitive film now used in these spectrographs. The effective long-wavelength spectral cutoff is 4800 angstroms. This film is about three times as fast as 103-0 film. It has low resolving power, coarse granularity, and extremely high contrast. This film is most often used in the Super Schmidt cameras.

2475 film.- 2475 film is a high-speed extended-red panchromatic emulsion with a current ASA speed rating of 800 and is the fastest panchromatic film in present general use. The effective long-wavelength spectral cutoff is 6900 angstroms. 2475 film has low resolving power, medium granularity, and medium acuteness.

SO-166 film.- SO-166 film is an experimental, extended-red panchromatic film with approximately the blue sensitivity of single-coated medical X-ray film and the green and red sensitivity of 2475 film. The effective long-wavelength spectral cutoff is 6900 angstroms. It has low resolving power, medium granularity, and medium acuteness.

High-speed infrared film.- High-speed infrared film has about one-third the maximum spectral sensitivity of 2475 film. This film is generally used for the bandwidth from 6000 angstroms to 9500 angstroms. It has moderate resolving power, medium granularity, and medium acuteness.

DISCUSSION

All the optical systems described herein have high sensitivity for low-light-level recording; however, each system has certain advantages and limitations. The Super Schmidt cameras have been used to obtain a large quantity of ballistic and photometric data on natural meteors. These data have been used to study meteor and cometary physics, and to study the meteoroid hazard problem. Its main disadvantages are large size and complexity of operation and maintenance. The Super Schmidt camera is restricted to those films that can be molded to a 200-mm radius without appreciably affecting the emulsion. Also, it is difficult to convert the system into a spectrograph. Even with the new LF-5 flint prism, the variation of dispersion with wavelength and field angle makes the spectrograms difficult to analyze, and the low dispersion at long wavelengths limits the useful spectrum to the region short of 5500 angstroms.

The Baby Schmidt and Maksutov spectographs are used in refined spectroscopic investigation of meteor phenomena. The most significant advantage of these spectrographs is their broad spectral range; however, the versatility of these systems with regard to interchangeability of film, gratings, field, and portability are important advantages. In principle, the Baby Schmidt with proper alinement can give monochromatic diffraction-limited images (100-percent blur circle of 2μ) on axis. However, chromatic aberration, misalinement, and film resolution limit the working resolution to about 20μ or comparable to the Maksutov spectrographs. The chief disadvantages of the Baby Schmidt and Maksutov spectrographs are their relatively small fields.

The main advantage of the Super Farron spectrograph is its versatility and portability. This optical system, with its accessible film plane, can easily be modified for single-exposure operation, framing camera operation, and can be used with film, image orthicon, or image intensifiers. It can be easily adapted to laboratory use, or field use. The chief disadvantages of the Super Farron are its short focal length and limited spectral range.

There is a wide gap between the inherent capability and the practical working results of a field spectrograph. Even with well established and engineered systems, careful and thorough operation and maintenance of the systems are necessary for optimum data yield. For example, the Super Schmidt cameras must be adjusted periodically during the course of a night for temperature effects. Also, adjustments for change in spectral region and for different applications must be made for optimum results. It has been found that individual cameras of the same design have different operational characteristics and these characteristics must be considered to get the most out of the systems. The effects of temperature, film, and dispersing elements upon alinement and focus must be known in order to make field adjustments which are necessary for optimum results. For fast optical systems, the depth of focus is about the same as the image size, that is, about 10μ to 50μ; therefore, focus is very critical. Film loading and unloading, calibration, transportation, protection, and maintenance of the spectrographs require extreme care. New instruments are subject to change from such things as metal warpage and deterioration of material. In summary, good field technique is of the utmost importance and necessary to obtain good spectra consistently.

With the development of these instruments, it is now possible to choose from several qualified slitless spectrographs for low-light-level applications. Some of the more apparent applications are absolute stellar photometry, cometary and faint meteor investigations, and vacuum-range and shock-tube studies. For faint meteor spectroscopy (-3 magnitude to +1 magnitude), gratings with 75 lines/mm and high blaze efficiency give spectral resolution of 20 angstroms to 50 angstroms. With 1200 lines/mm gratings this resolution would become 1 angstrom to 2 angstroms with a corresponding loss in sensitivity. The spectrographs discussed herein, exclusive of the Super Schmidt spectrograph, can be used, as shown in reference 16, to yield 20-percent-accurate absolute spectral photometry. Either the Maksutov or the Super Farron spectrograph can be built at relatively small expense.

At present, advancements are being made in imaging photoelectric sensors, such as image orthicons and image intensifiers. Applications of these sensors are presently underway in several areas of low-light-level research including meteor photometry, meteor spectroscopy, high-speed particle, wind-tunnel, and shock-tube spectroscopic research. These photoelectric devices will lower the detection limit of the measurements, but are not yet sufficiently well developed for routine field use.

CONCLUDING REMARKS

Fast slitless spectrographs are used in meteor spectroscopy and related areas where energy limitation is the dominant aspect of measurement. A description of four fast slitless spectrographs presently being used in meteor spectroscopy is presented. These spectrographs, Super Schmidt, Baby Schmidt, Maksutovs, and Super Farron, are capable of recording +1 magnitude meteor spectra or better. The Super Schmidt features the largest field, the Baby Schmidt and Maksutovs feature broadest spectral range, and the Super Farron features small size and versatility.

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Langley Station, Hampton, Va., June 27, 1967,
709-06-00-01-23.

APPENDIX A

MAKSUTOV SPECTROGRAPHS

In an effort to develop more sensitive, portable, wide spectral range spectrographs, a survey of fast optical systems was conducted. It was concluded that a catadioptric system would yield the required speed, the desired sensitivity, imagery, and spectral range, and that a Maksutov spherical mirror system would satisfy the requirements for large field and simplicity. Relatively high quality images can be obtained over a relatively large field with two elements, a refractive element and a mirror, both having spherical surfaces. Increased availability and lower cost of optical-grade fused-silica blanks and large high-blaze-efficiency diffraction gratings were important factors in the evaluation of these systems.

Design Considerations

The aberrations of any optical system increase rapidly with decreasing f-number. The aperture obscuration for a given field increases rapidly with increasing f-number for a Maksutov system; however, there is a range of f-numbers for which satisfactory results can be obtained. For large f-numbers (>2) the obscuration by the image plane limits the field to less than 10°, whereas for systems faster than f/1, residual spherical and chromatic aberrations render the image unacceptable (50 percent blur circle > 100μ for the focal lengths considered).

An important disadvantage of the fast Maksutov optical system is its relatively inaccessible and curved image plane. For fields up to 21°, heavy base film can be pulled by a retaining ring to conform to the curved image plane, and no vacuum or pressure plate is required. However, for larger fields, molded film or some form of field flattener must be employed.

System Characteristics

Two f/1.3, 168-mm focal length systems and three f/1, 152-mm focal length systems have been built. These two optical systems were chosen from about 15 designs on the basis of a computer analysis. The f/1.3 was built to realize good imagery and the f/1 was built for wide field utilization. The f/1 was designed so that it could later incorporate an aspheric corrector lens to give monochromatic on-axis high-resolution images. The meniscus lenses were fabricated from optical-grade fused silica and the mirrors from standard 200-mm and 250-mm-diameter telescope pyrex mirror blanks. The meniscus lenses and diffraction gratings are retained in high-density foamed plastic rings. The mirror cells are modified 200-mm and 250-mm cast aluminum telescope mirror mounts. Optical alinement is maintained by spacer rods made of low coefficient of thermal expansion nickel-steel alloy and the internal or optical structure is fastened to the camera case at only one point. Three different materials, aluminum, magnesium, and bakelite, have proven satisfactory for cases. Very fast coarse-grain film is used in these systems and little is to be gained by having diffraction limited or high optical tolerance images since such images for these systems would be at least 10 times smaller than a resolution element of the film. Therefore, high optical tolerances were not required for the optical elements. Since only three spherical low optical tolerance (1/2 λ on corrector surfaces and 1/4 λ on mirror surface) surfaces are necessary in the two Maksutov systems, the basic cost of the systems is very small. The total mass of the f/1.3 system is approximately 20 kilograms and the mass of the f/1 system is approximately 25 kilograms.

The f/1.3 system originally had a 16° field with a t-value of 1.57, but has been modified to have a field of 21° with a t-value of 1.67. The f/1 system can be used with 18°, 28°, or 38° interchangeable fields with t-values of 1.22, 1.33, and 1.49. The useful spectral range of these camera-spectrographs is limited to about 3200 angstroms at the short-wavelength end by the atmosphere and by the emulsion cutoff at the long-wavelength end. The f/1.3 is not a concentric system; the radii of curvature and thickness of the meniscus lens were chosen to minimize chromatic aberration and spherical aberration at the center of the field. The f/1 system is a concentric system and, hence, has uniform imagery (if the alinement is perfect) across the field. A stiff penalty is paid for the wide-field capability of the f/1 system in increased spherical and chromatic aberration. The computed energy blur circles for the two systems are presented in table II. The data of table II do not include flare, malfocus, misalinement, and optical imperfections of the mirror and lens. It is believed that under favorable conditions of actual operation, these numbers should be increased by approximately 20 percent.

It can be concluded from table II that the f/1.3 system can detect images significantly fainter than the f/1.0 system since the aberrations of the f/1.0 system spread the available energy over a larger area. For the three wavelengths considered, about 80 percent of the available energy is within a 20μ blur circle for the f/1.3 system, and about 10 percent for the f/1.0 system. However, the actual photographic resolution of the two systems are comparable because of the resolution limit of the coarse-grain emulsions generally employed for high sensitivity. The optical resolution, the half-widths for coarse-grain emulsions, and the 50-percent blur circles for both Maksutov systems are presented for comparison in table III. Under ideal conditions, it should be noted that all systems discussed in this paper are at least partially limited in resolution by the coarse-grain emulsions.

Film holder.- The film is held in position by a retaining ring on a film pedestal. The film pedestal is bolted to the meniscus lens through a 25-mm-diameter hole through the lens and is provided with micrometer focusing. The spectrographs are loaded by opening a side loading door and then screwing the threaded film retainer ring or twisting the bayonet lock retainer ring and film onto the film pedestal. Average film changing time for a threaded ring is 30 seconds and for a bayoneted ring 15 seconds. The film is uniformly pulled by the retainer ring into the focal surface for fields up to 21°, but film must be premolded to conform partially to the focal surface for larger fields. The lens cap is generally used as a capping shutter for the cameras.

Dispersing elements.- Five custom-fabricated dispersing elements have been obtained for these systems to provide optimum results for different spectral regions: four 75 lines/mm transmission diffraction gratings on 210-mm-diameter by 25-mm-thick fused-silica blanks and one 20° 160-mm-diameter fused-silica objective prism. One of the diffraction gratings is blazed for 3400 angstroms, two for 3800 angstroms, and one at 5460 angstroms. The prism yields maximum transmission and acceptable spectral resolution in the 3000-angstrom to 3600-angstrom region. The 3400-angstrom blazed and 3800-angstrom blazed gratings generally give good efficiency in the near-ultraviolet and blue, 3400-angstrom to 4500-angstrom, spectral region and the 5461-angstrom blazed grating gives good efficiency in the visible and near-infrared spectral region.

APPENDIX B

SPECTROGRAM OF A FAINT ARTIFICIAL METEOR

The spectrogram of figure 16 was obtained on the clear moonless night of September 16, 1966, at Wallops Island, Va. An enlargement of this artificial meteor spectrum is presented as figure 21. The artificial meteor was produced by a 0.88 ± 0.17 gram nickel pellet accelerated to a velocity of 11.35 km/sec by a shaped charge accelerator. This meteor was photographed by a f/1.3 Maksutov spectrograph and with a f/2.5 300-mm focal length camera with panchromatic film. The pellet was accompanied by much smaller particles of high-speed debris which considerably complicated the blazed first-order spectra, spectra from at least five pieces or groups of debris being recorded. Separation of blazed first-order spectra is based upon trail angle and intensity history along the trail of the spectrum. The spectral distribution of the radiation is very strongly grouped at 3500 angstroms. The trail of the blazed first-order spectra is approximately twice that of the panchromatic (4000 angstroms to 6900 angstroms) trail. The panchromatic meteor train begins at an altitude of 79 kilometers at approximately +3.2 absolute meteor magnitude and rises to +1 magnitude at 70.4 km. Blazed first-order spectrum on blue-sensitive film is recorded at an altitude of 90 km where the panchromatic magnitude of the meteor is definitely less than +4 panchromatic absolute meteor magnitude. It should be noted that the particular spectral distribution, the short-range distance (82.5 km at meteor maximum), and the low writing speed of this meteor were very favorable for spectroscopic recording.

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TABLE I.- DESCRIPTION OF SPECTROGRAPHS

Property	Super Schmidt	Baby Schmidt	Maksutovs		Super Farron
f-number	f/0.65	f/0.83	f/1.3	f/1	f/0.87
t-number	1.22	1.04	1.67	1.22,1.33,1.49	1
Focal length	200 mm	128 mm	168 mm	150 m	76 mm
Effective spectral range	3800 Å to 5500 Å	3200 Å to 9500 Å	3200 Å to 9500 Å	3200 Å to 9500 Å	4000 Å to 7000 Å
Field	57°	20°	21°	$18^{\circ},28^{\circ},38^{\circ}$	30°
Weight	700 km	40 kg	20 kg	25 kg	4 kg
Dispersing element	30° prism (LF-5)	150 l/mm grating	20° prism S_iO_2 75 l/mm grating	75 l/mm grating	75 l/mm grating
Dispersion	100 to 500 Å/mm	500 Å/mm	1300 Å/mm at 3500 Å 800 Å/mm	900 Å/mm	1800 Å/mm
Relative cost	High	Medium	Low	Low	Low
Minimum half-width	20μ	20μ	20μ	40μ	35μ
Molded film required	Yes	No	No	No, yes, yes	No
Portable	No	Yes	Yes	Yes	Yes

TABLE II.- BLUR CIRCLES OF MAKSUTOV SYSTEM FROM COMPUTER ANALYSIS

4300 Å blur circle		3400 Å blur circle		5900 Å blur circle	
f/1.3 (on axis)					
10 percent	2.5μ	10 percent	2.2μ	10 percent	3.3μ
50 percent	9μ	50 percent	12μ	50 percent	11μ
80 percent	15μ	80 percent	25μ	80 percent	15μ
100 percent	26μ	100 percent	33μ	100 percent	24μ
f/1					
4300 Å blur circle		3400 Å blur circle		5900 Å blur circle	
10 percent	13μ	10 percent	43μ	10 percent	26μ
50 percent	71μ	50 percent	112μ	50 percent	87μ
80 percent	100μ	80 percent	156μ	80 percent	181μ
100 percent	244μ	100 percent	436μ	100 percent	216μ

TABLE III.- IMAGE DESCRIPTION

Maksutov camera	Resolution (optical)	Half-width (coarse grain emulsion)	50-percent blur circle (computer analysis)
f/1.3	2.5μ	20μ	10μ
f/1	20μ	40μ	90μ

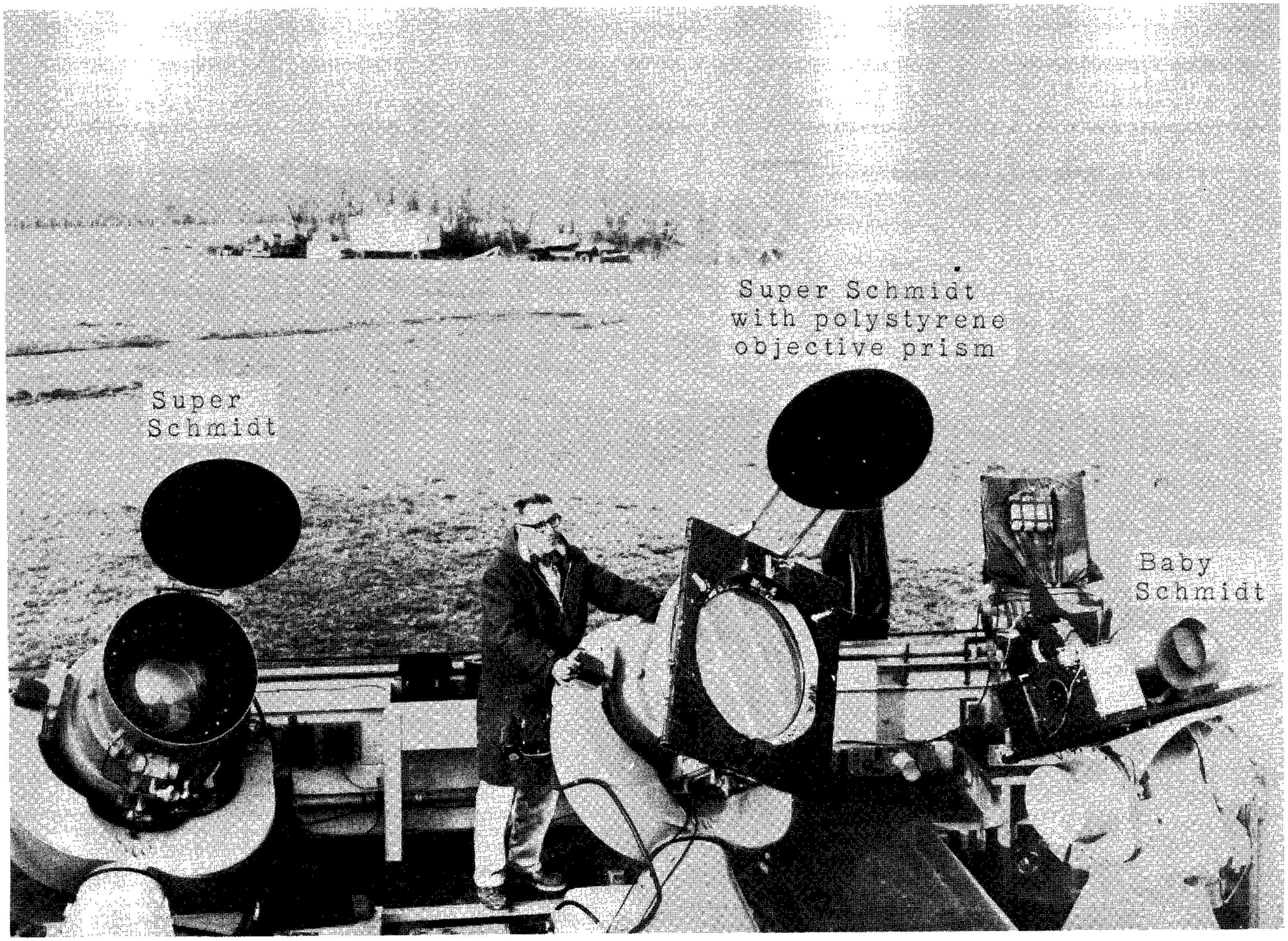


Figure 1.- Photographs of Super Schmidt spectrographs.

L-64-367

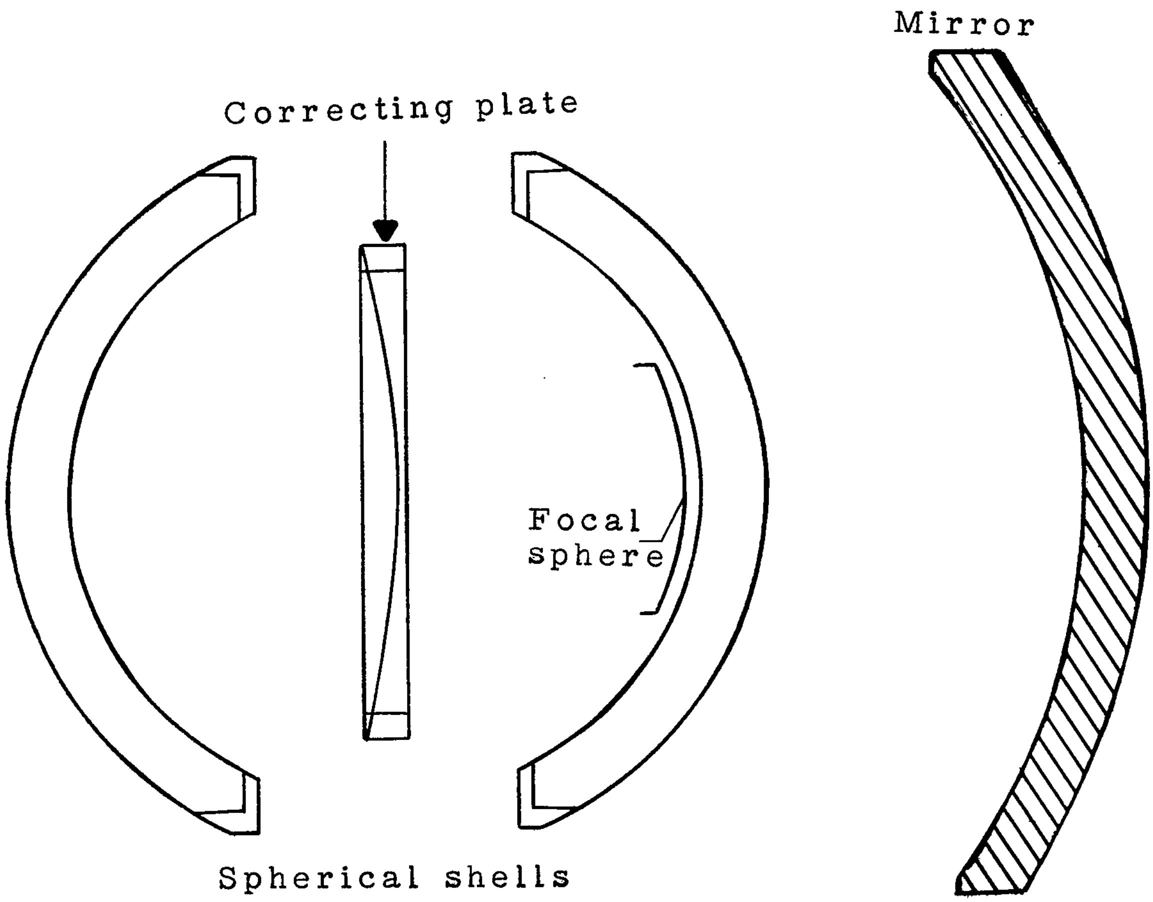


Figure 2.- Sketch of optical system of Super Schmidt meteor camera.

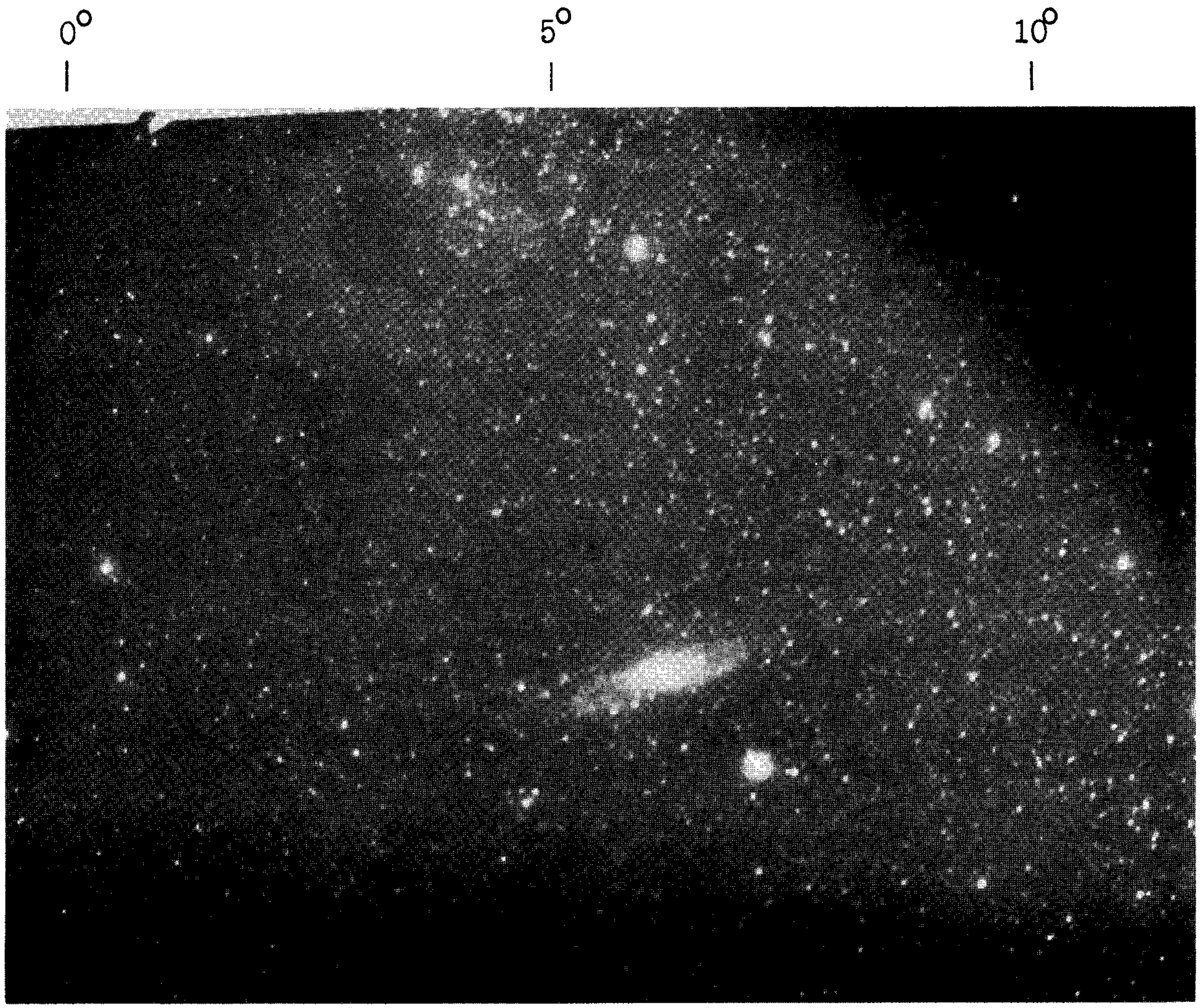


Figure 3.- Enlargement of tracked negative of Great Nebula of Andromeda from a Super Schmidt meteor camera. L-67-1063

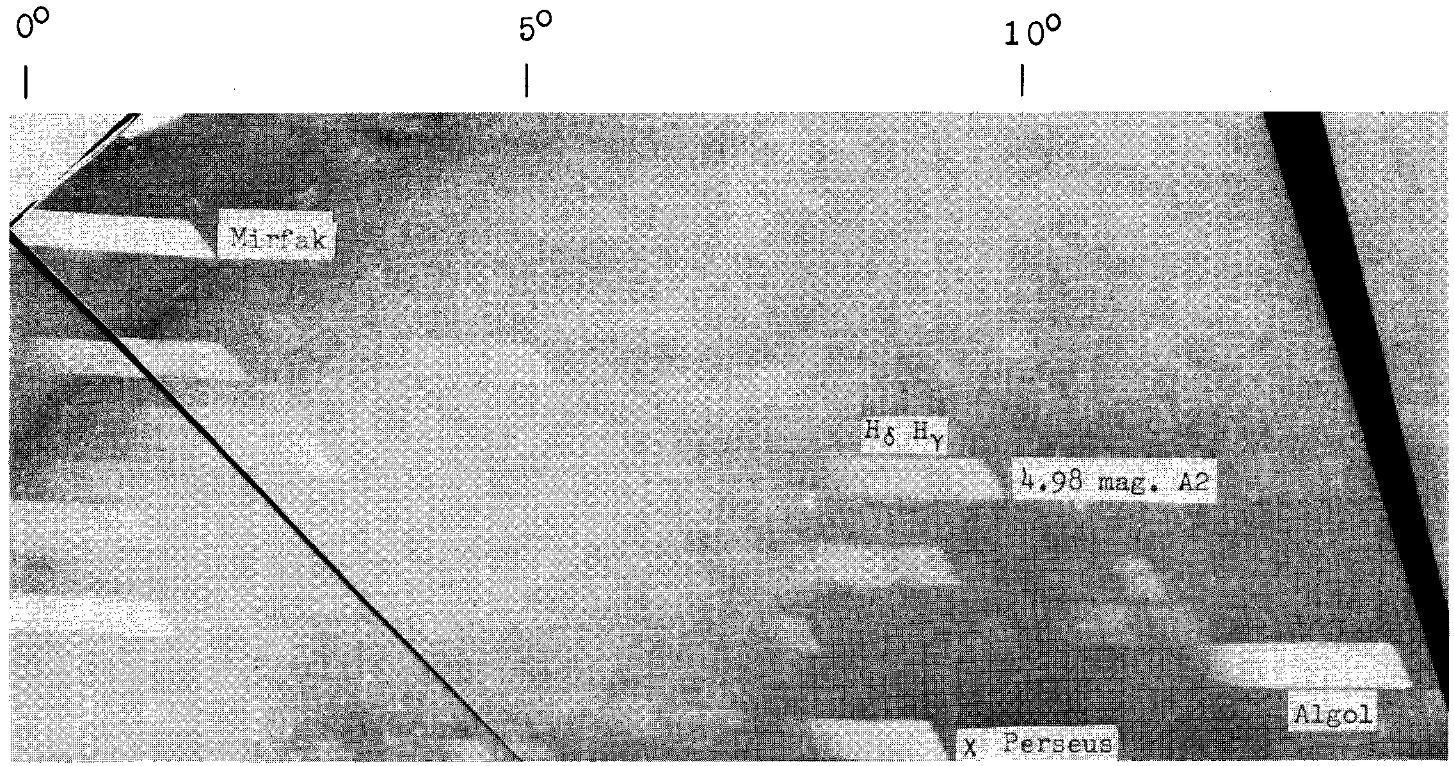


Figure 4.- Enlargement of trailed negative from a Super Schmidt meteor camera with mosaic objective LF-5 flint prism. L-67-1064

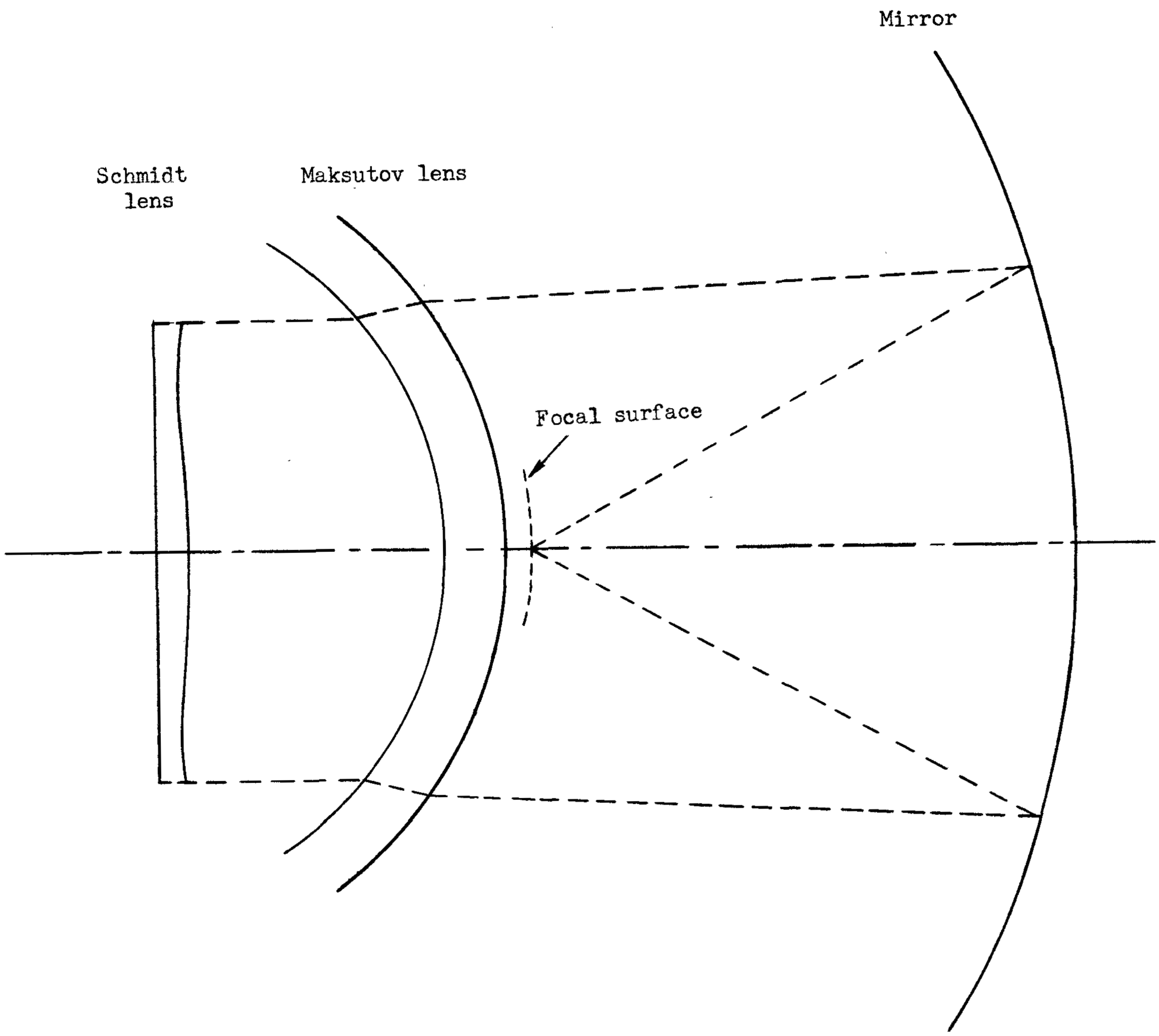


Figure 5.- Sketch of Baby Schmidt optical system.

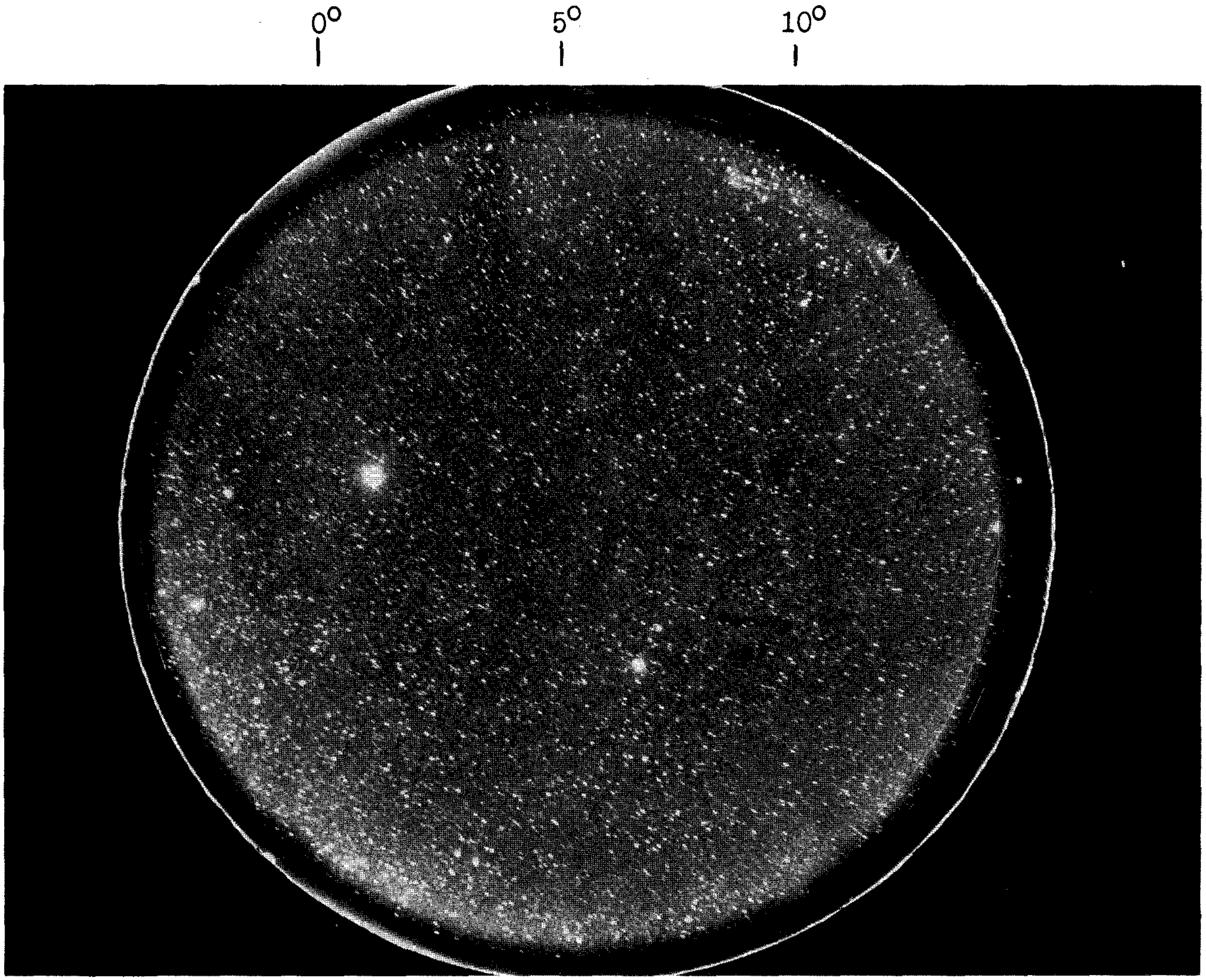


Figure 6.- Enlargement of trailed negative from Baby Schmidt camera (bright star is Capella). L-67-1065

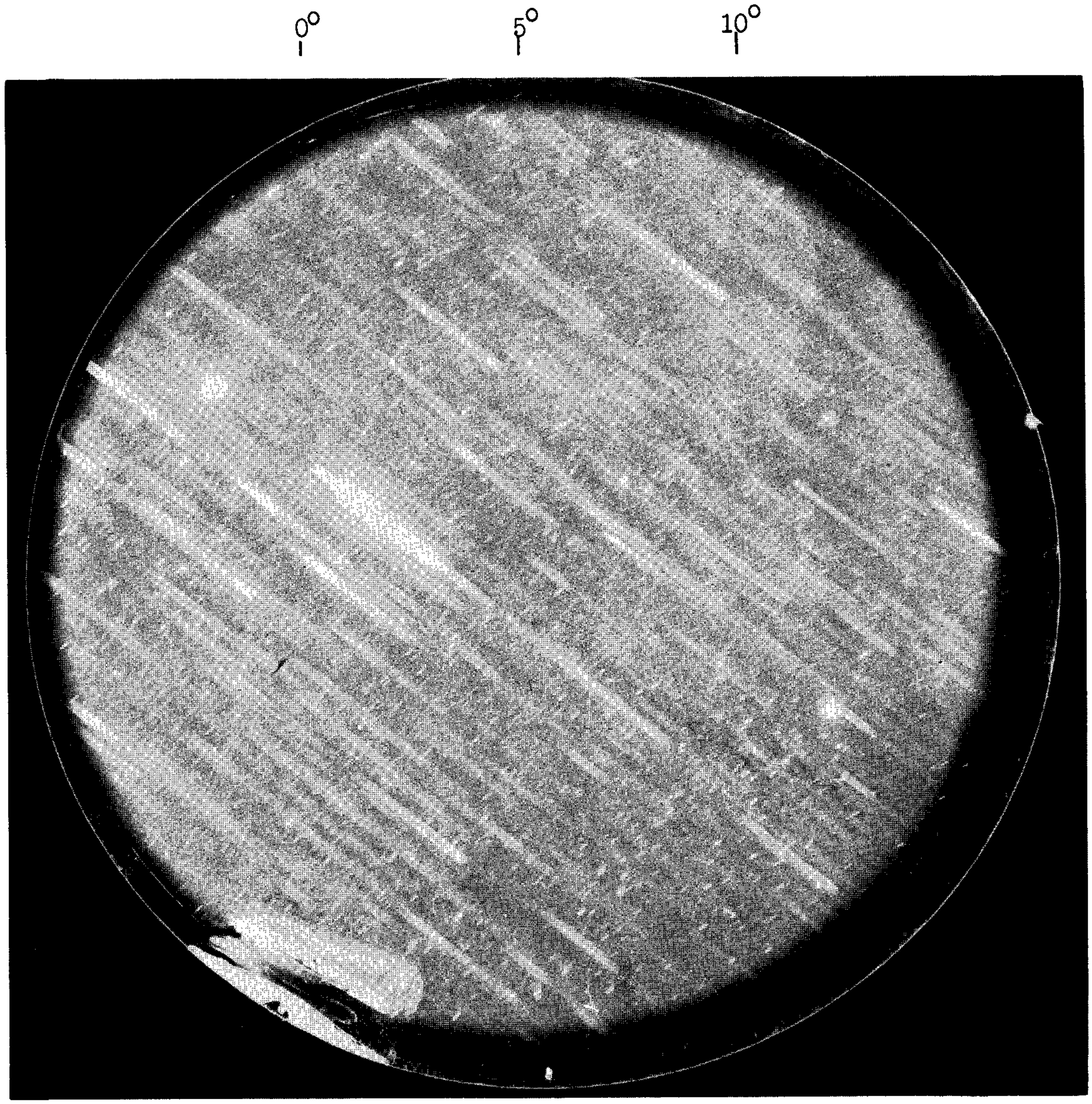


Figure 7.- Enlargement of trailed negative from Baby Schmidt spectrograph (bright star is Vega). L-67-1066

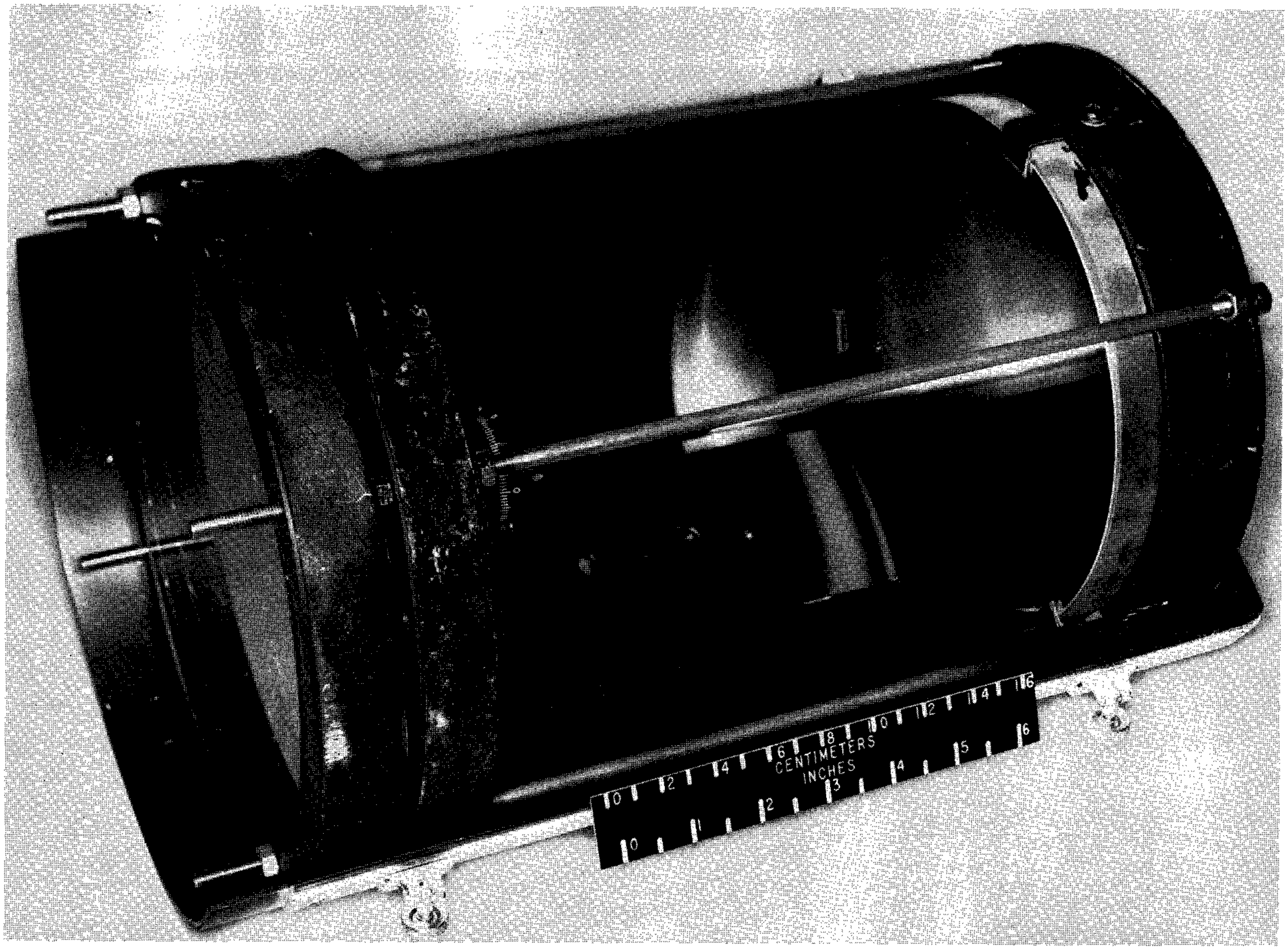


Figure 8.- Photograph of f/1.3 spectrograph. Aluminum case, exposed view. L-67-3914

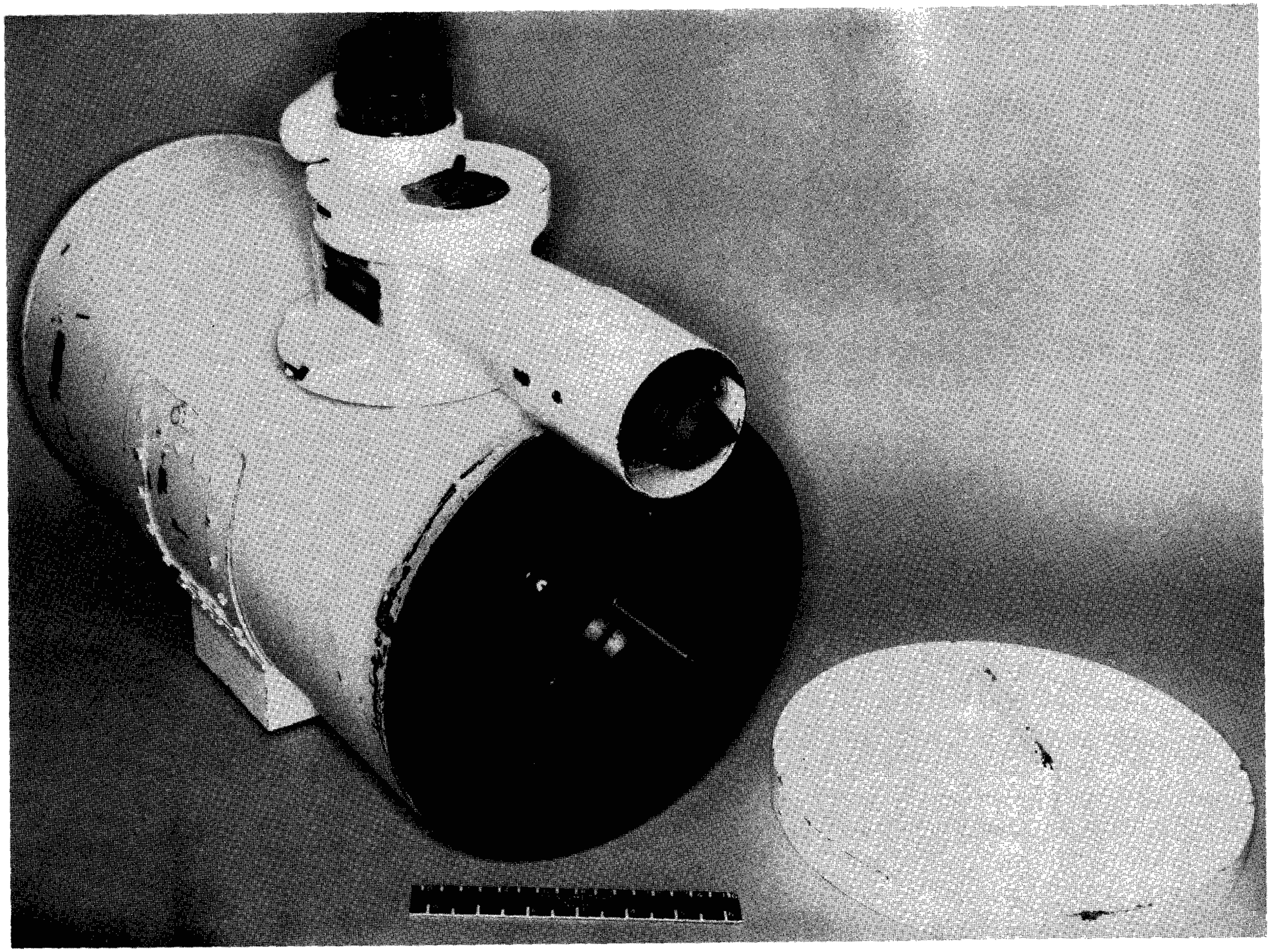


Figure 9.- Photograph of f/1.3 Maksutov camera. Bakelite case.

L-67-3916

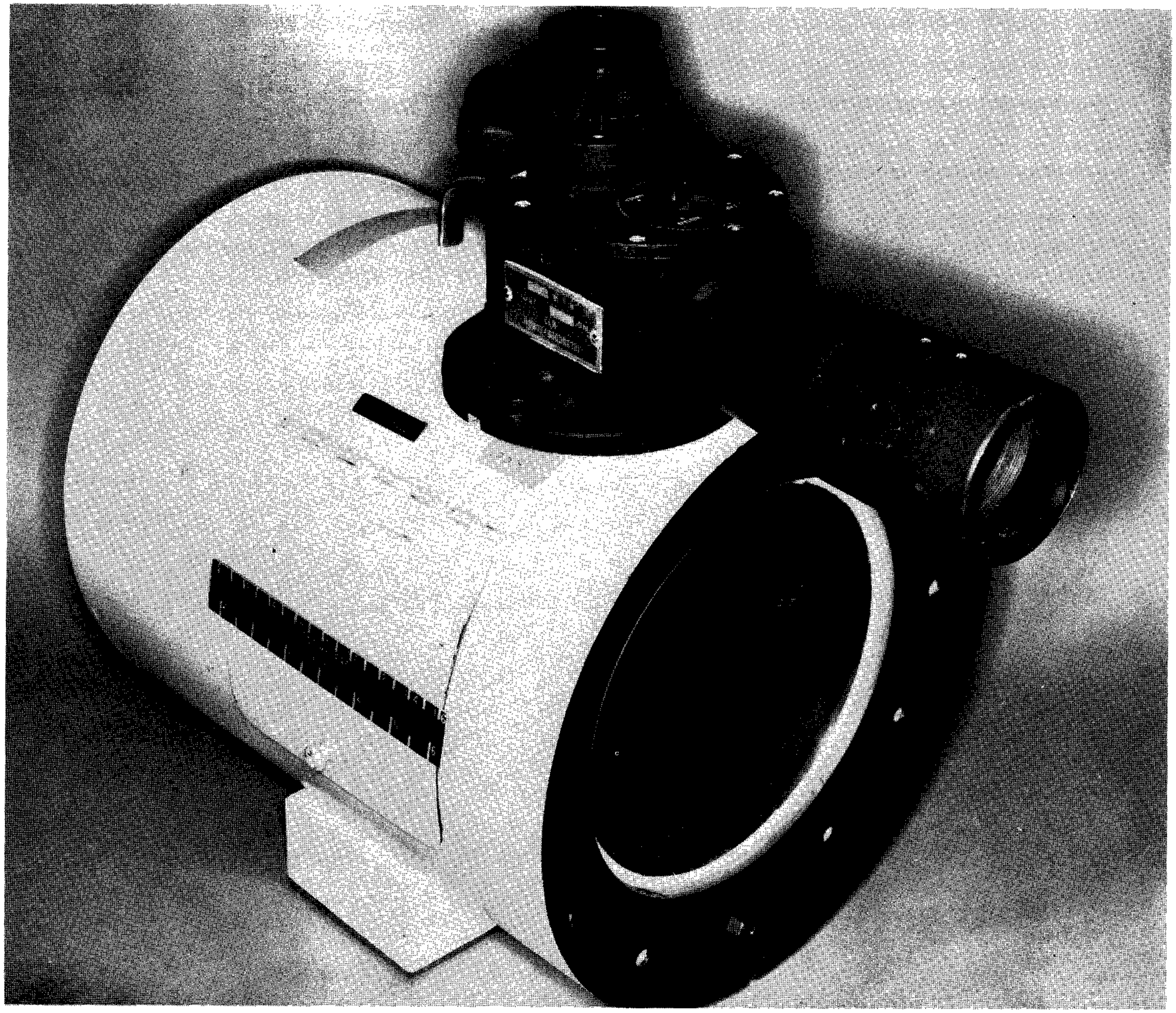


Figure 10.- Photograph of f/1 Maksutov spectrograph. Bakelite case. L-67-3913

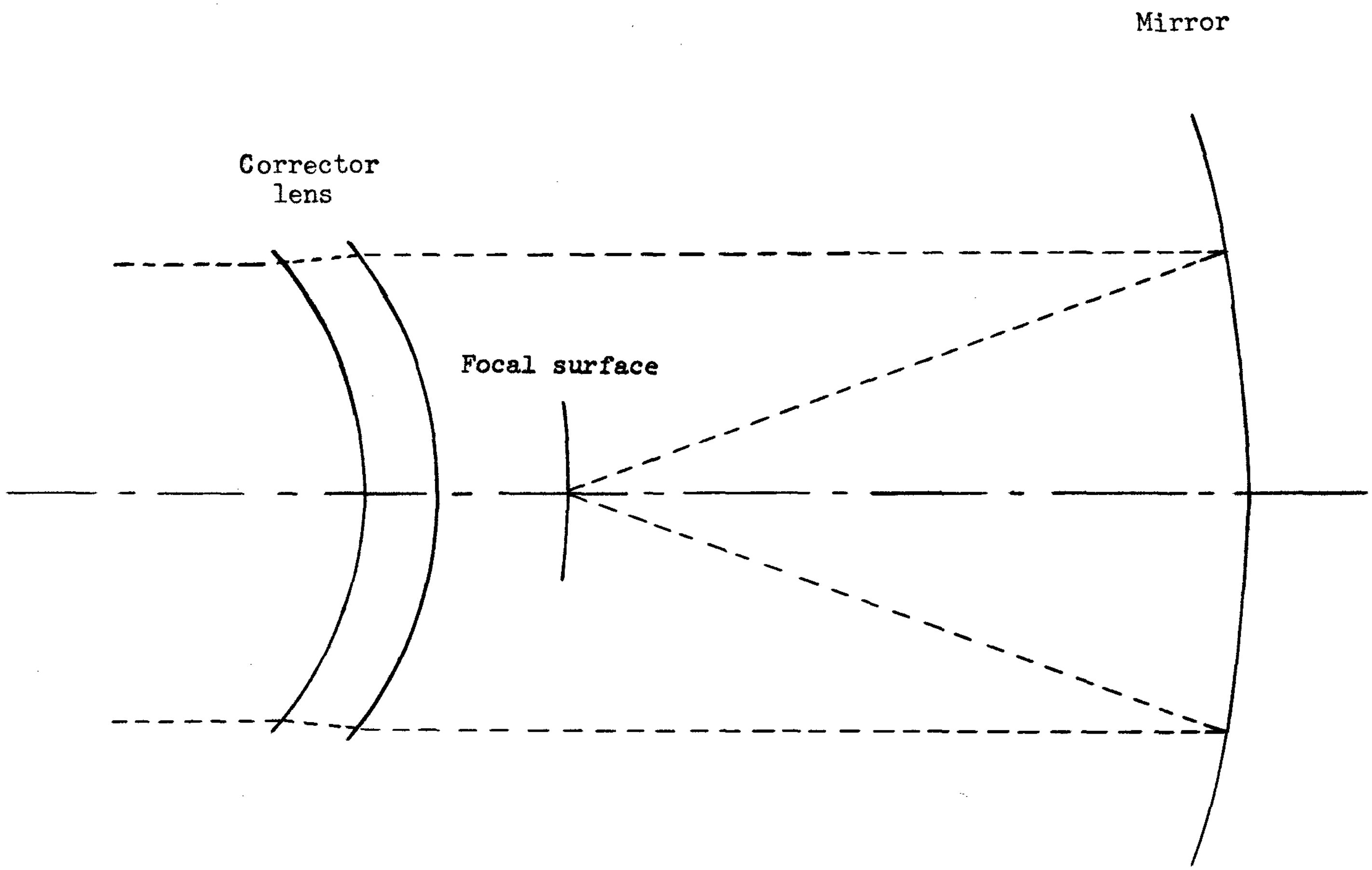


Figure 11.- Sketch of Maksutov 168 mm f/1.3 optical system.

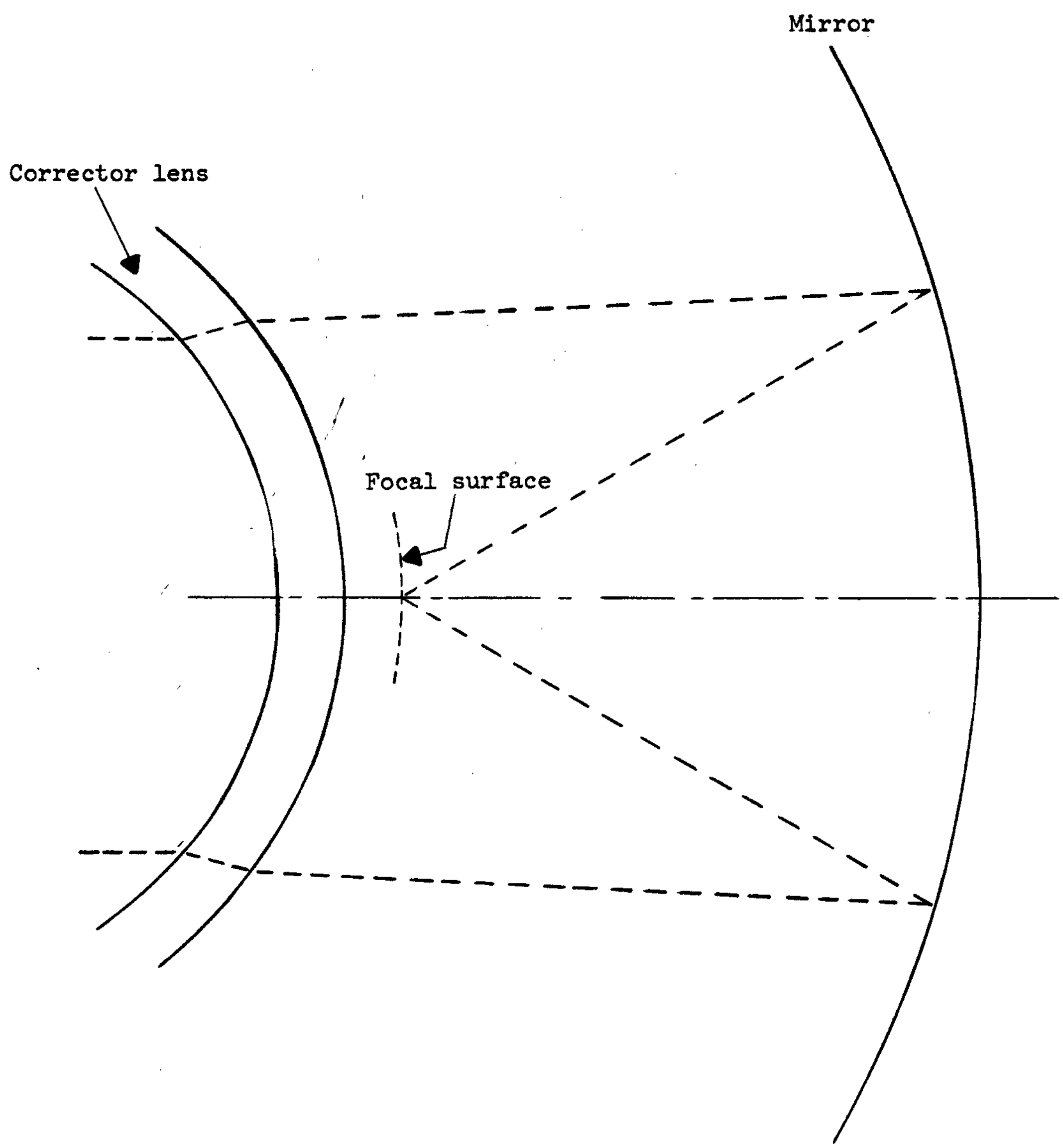
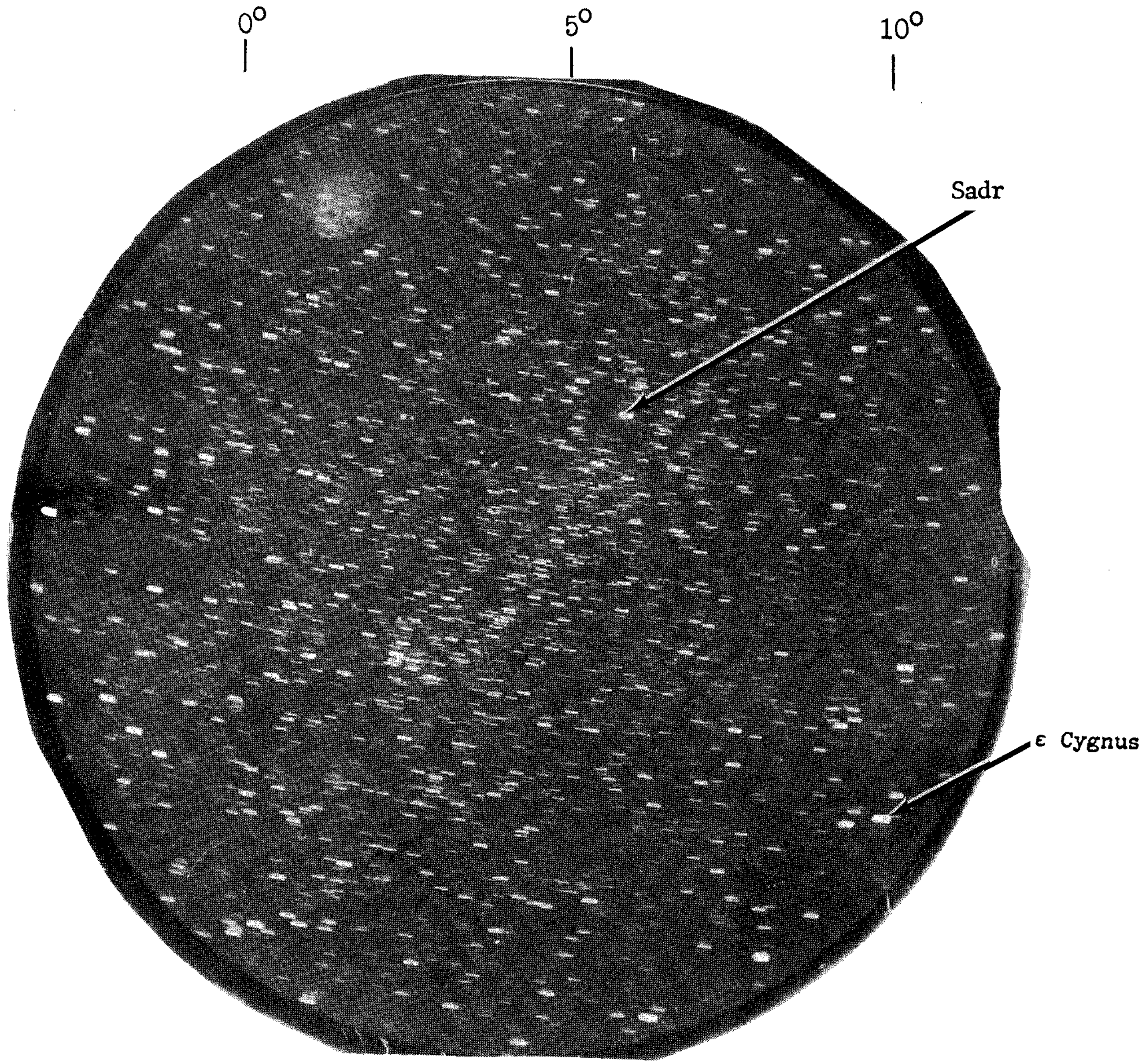


Figure 12.- Sketch of optical system of 150 mm f/1 Maksutov spectrograph.



L-67-6632

Figure 13.- Enlargement of trailed negative from f/1.3 Maksutov camera. (Center of plate exposed 20 hours 10 minutes, 38° declination.)

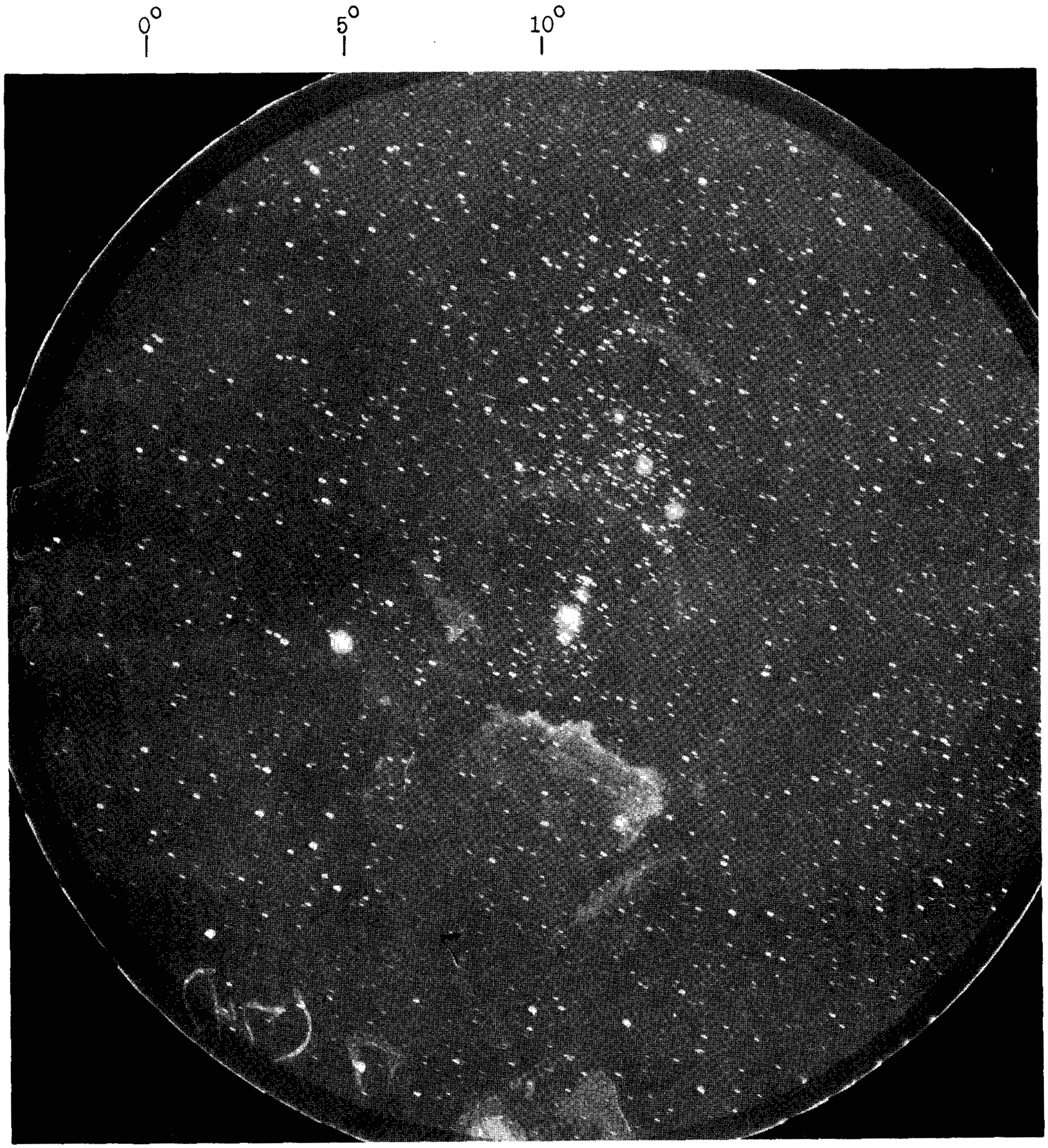


Figure 14.- Enlargement of trailed negative of 28° field f/1 with Orion's belt. L-67-1067

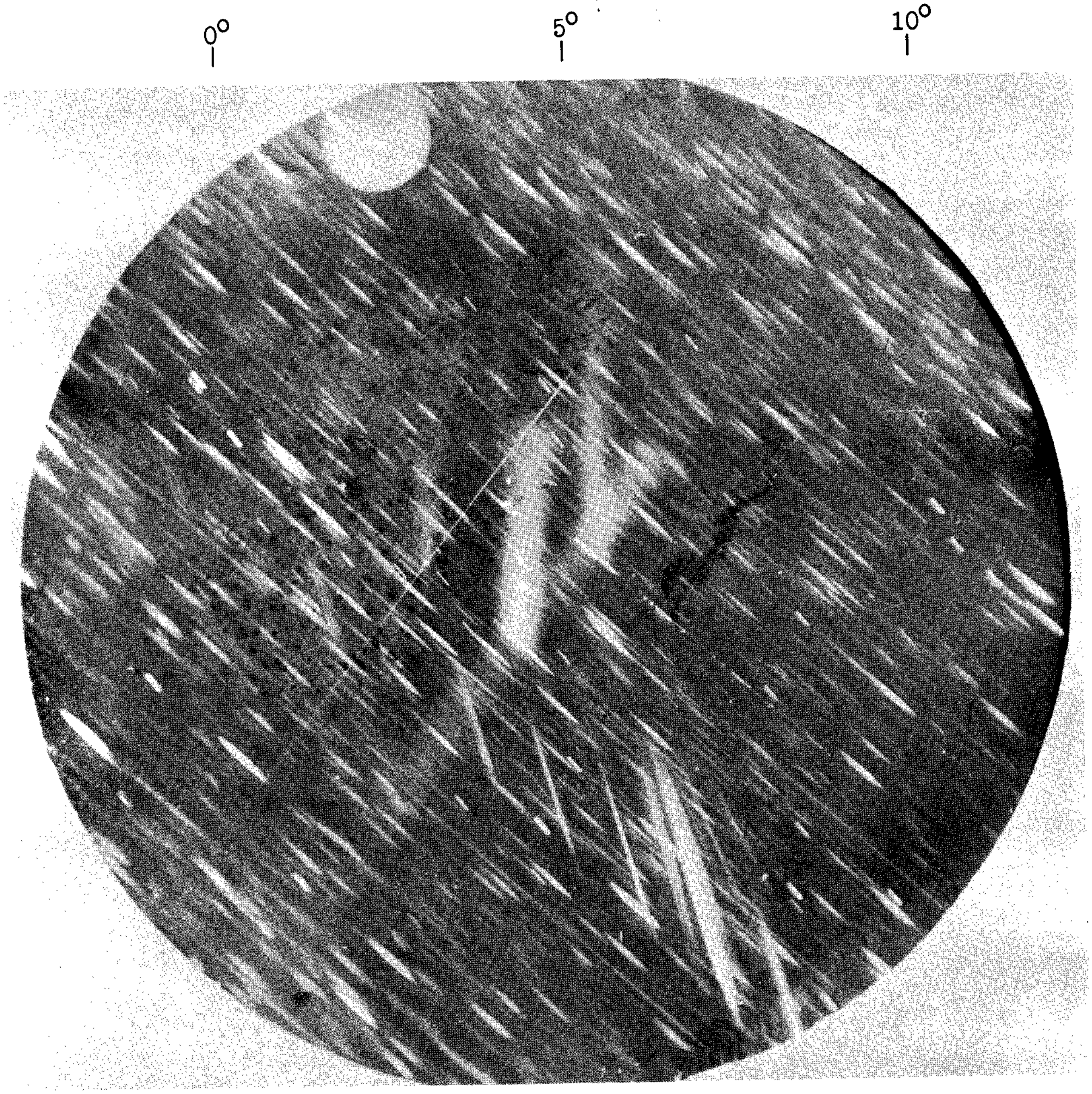


Figure 15.- Enlargement of artificial nickel meteor spectrum from Maksutov spectrograph.

L-67-1068

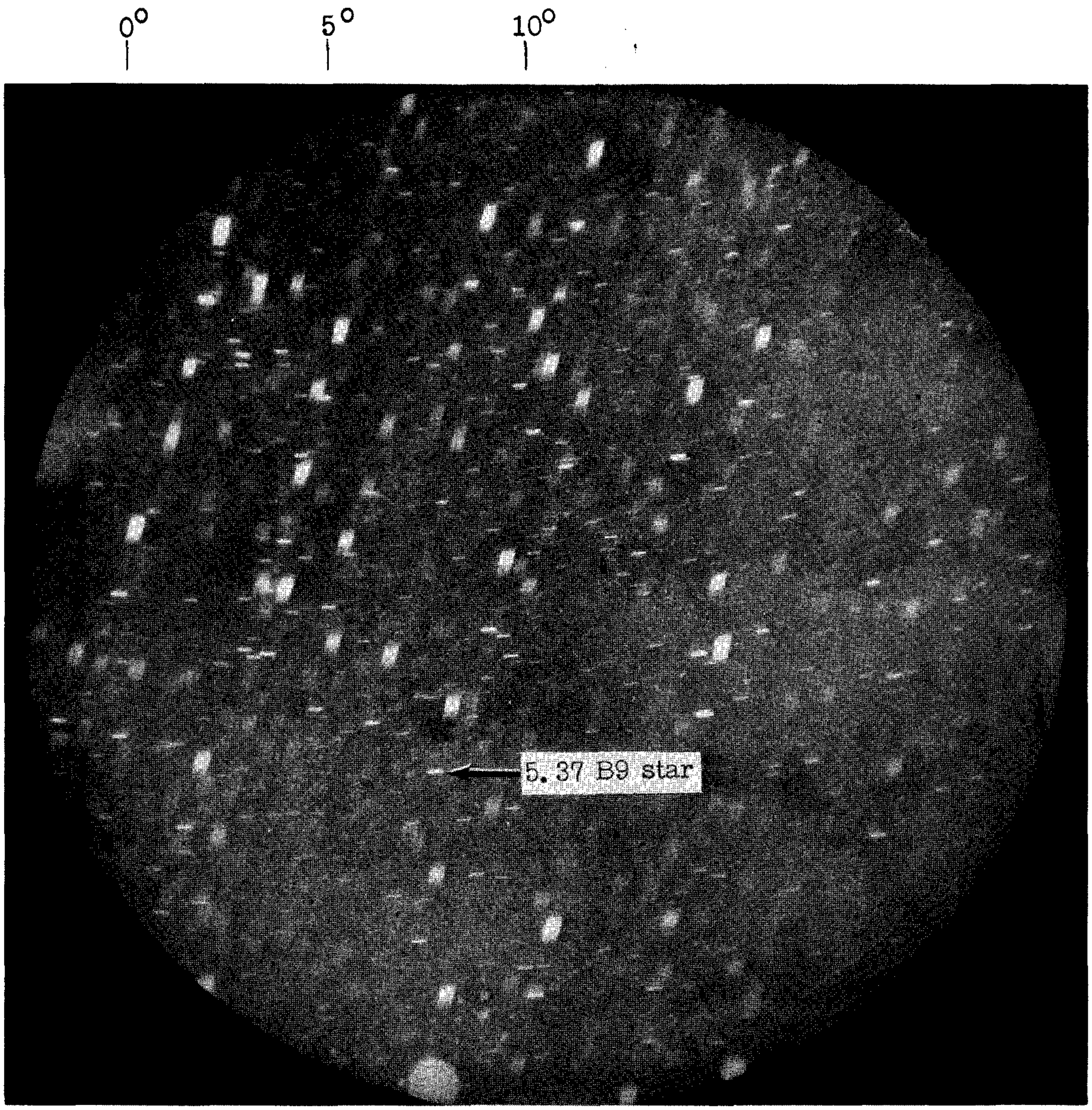


Figure 16.- Enlargement of trailed spectrum plate (exposed 11 hours, 38° declination) F/1 Maksutov spectrograph. L-67-1069

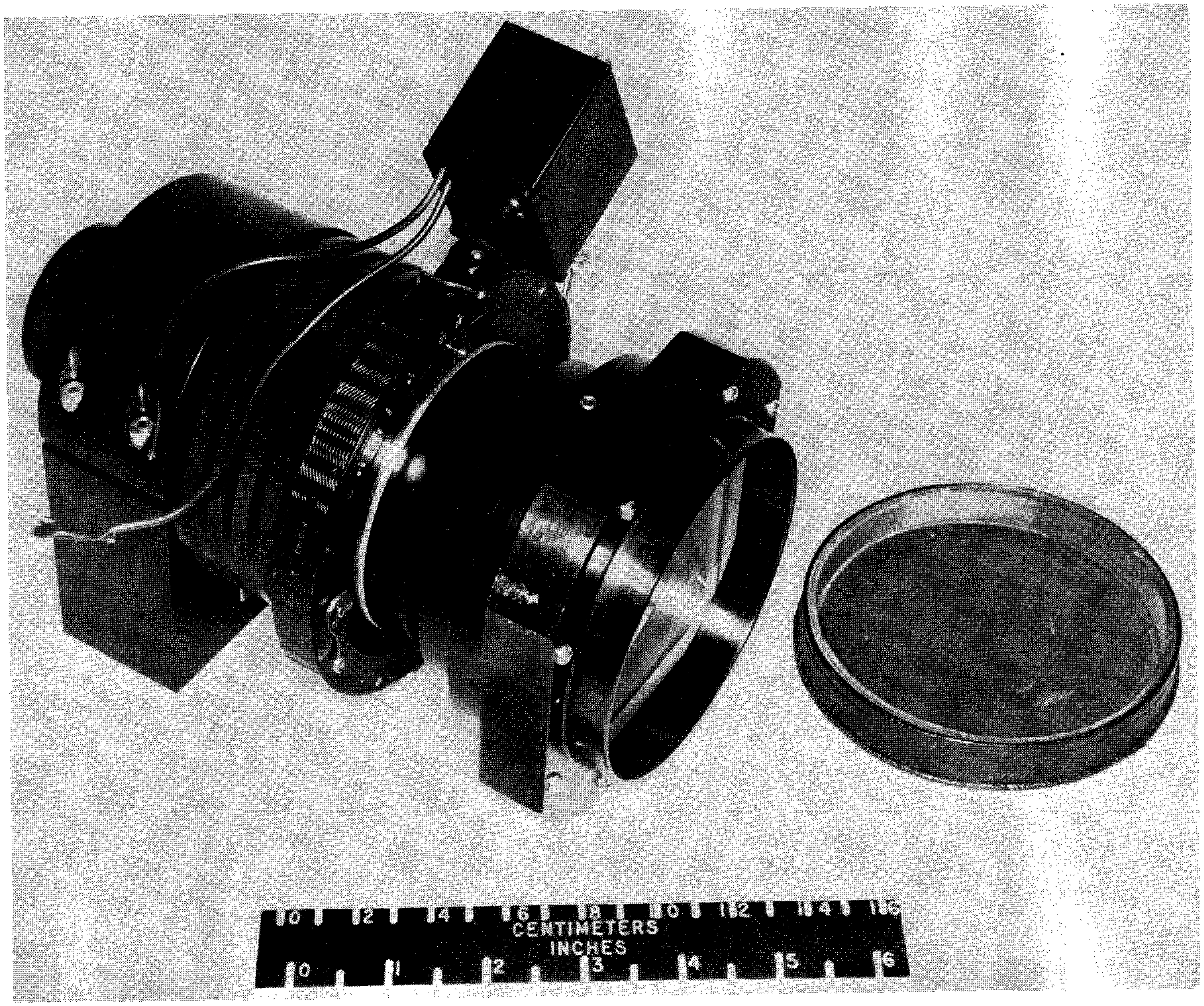


Figure 17.- Photograph of Super Farron spectrograph.

L-67-3912

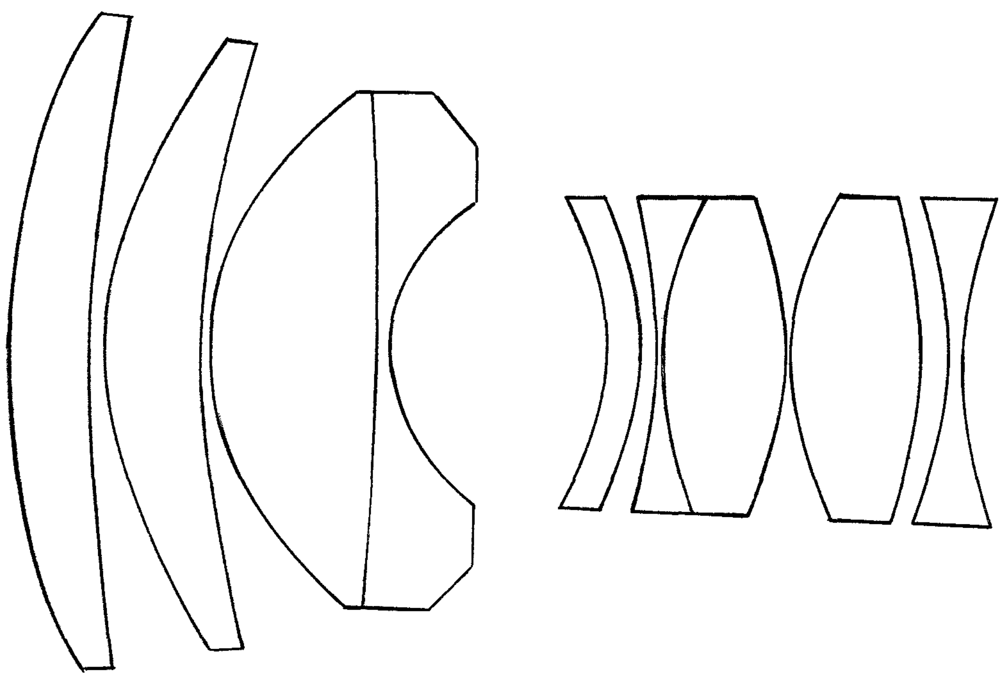


Figure 18.- Sketch of optical system of the Super Farron.

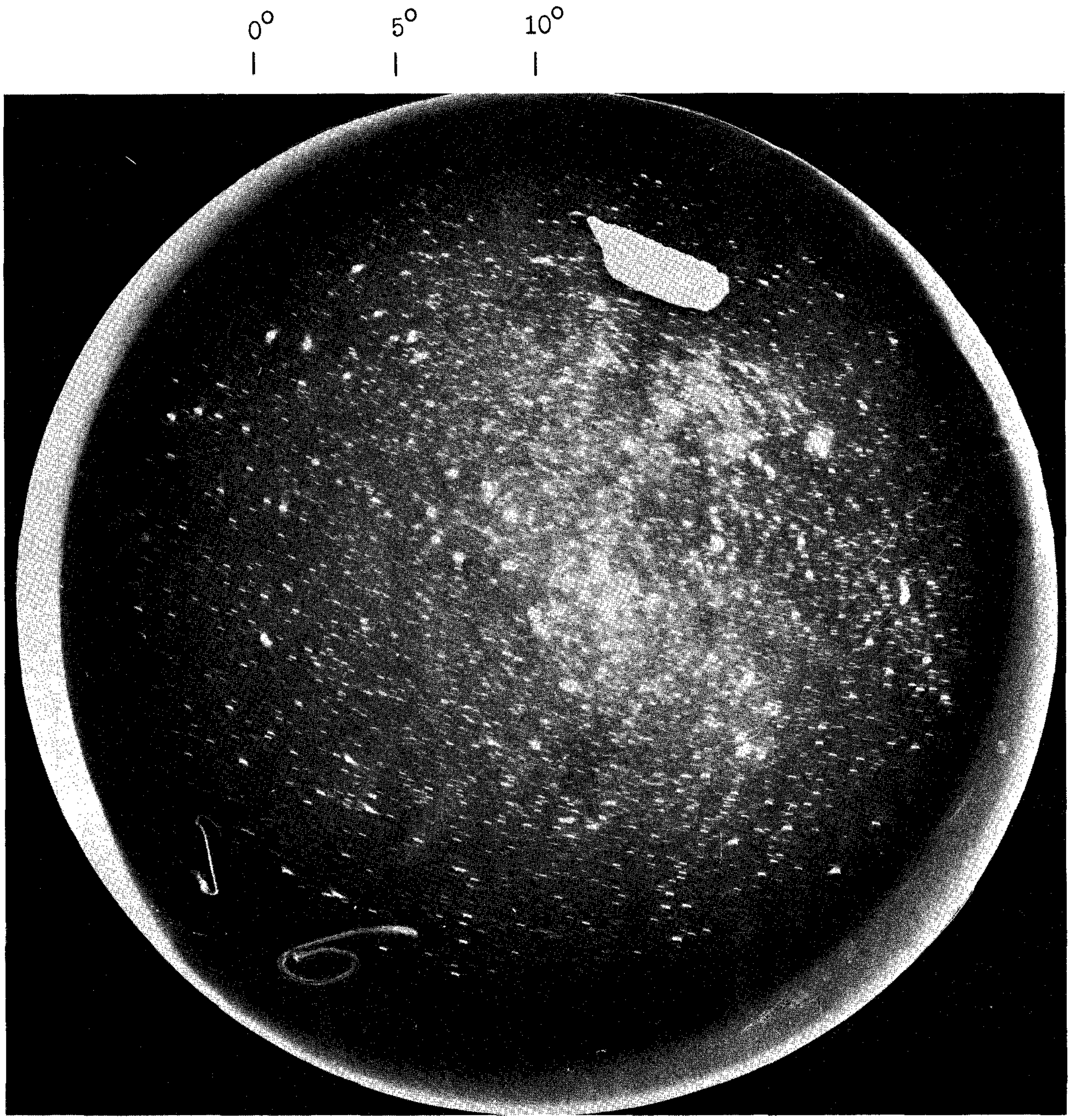


Figure 19.- Enlargement of trailed negative from Super Farron camera. L-67-1071

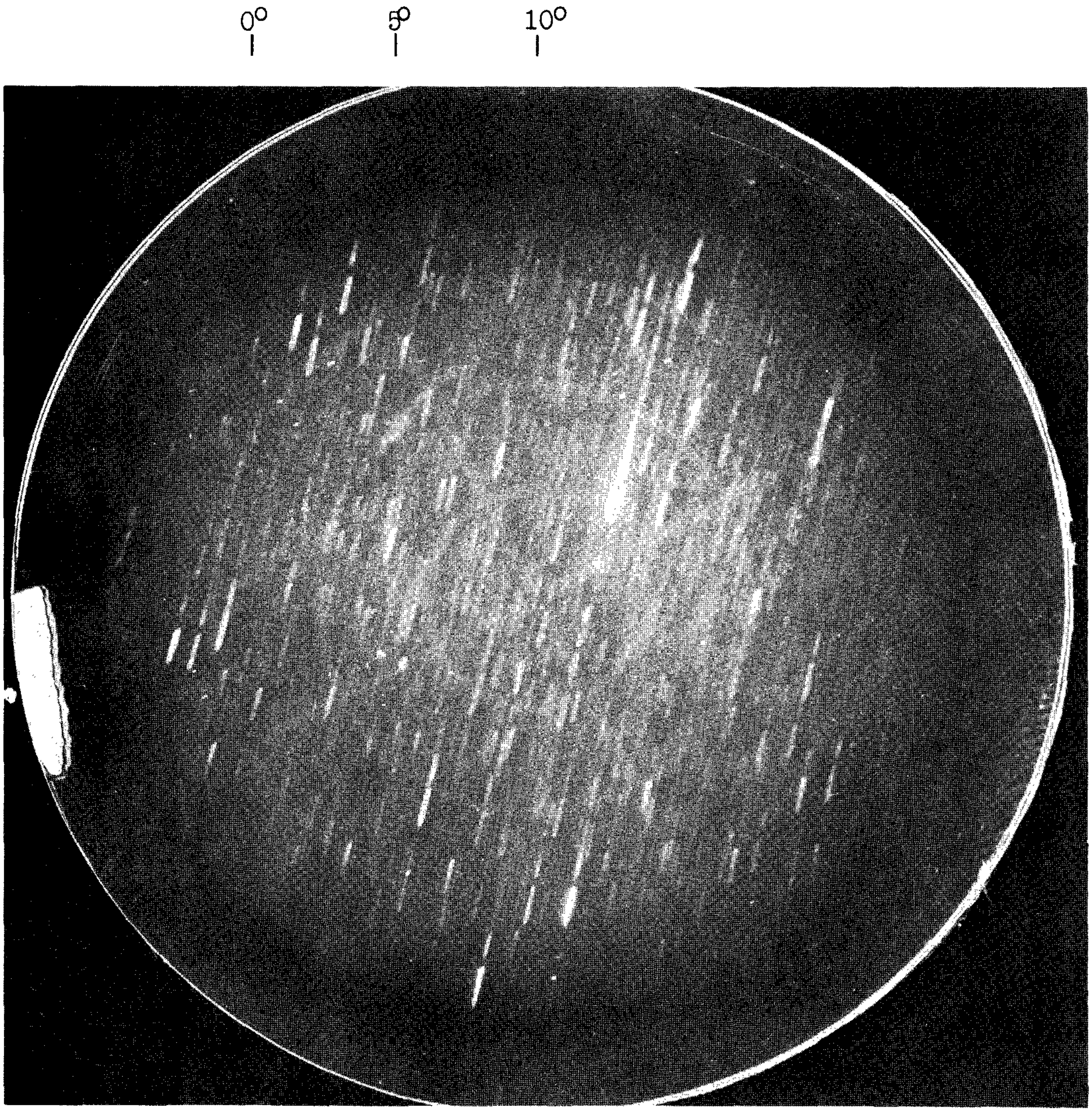


Figure 20.- Enlargement of trailed spectrum plate from Super Farron spectrograph (bright star is Vega). L-67-1070

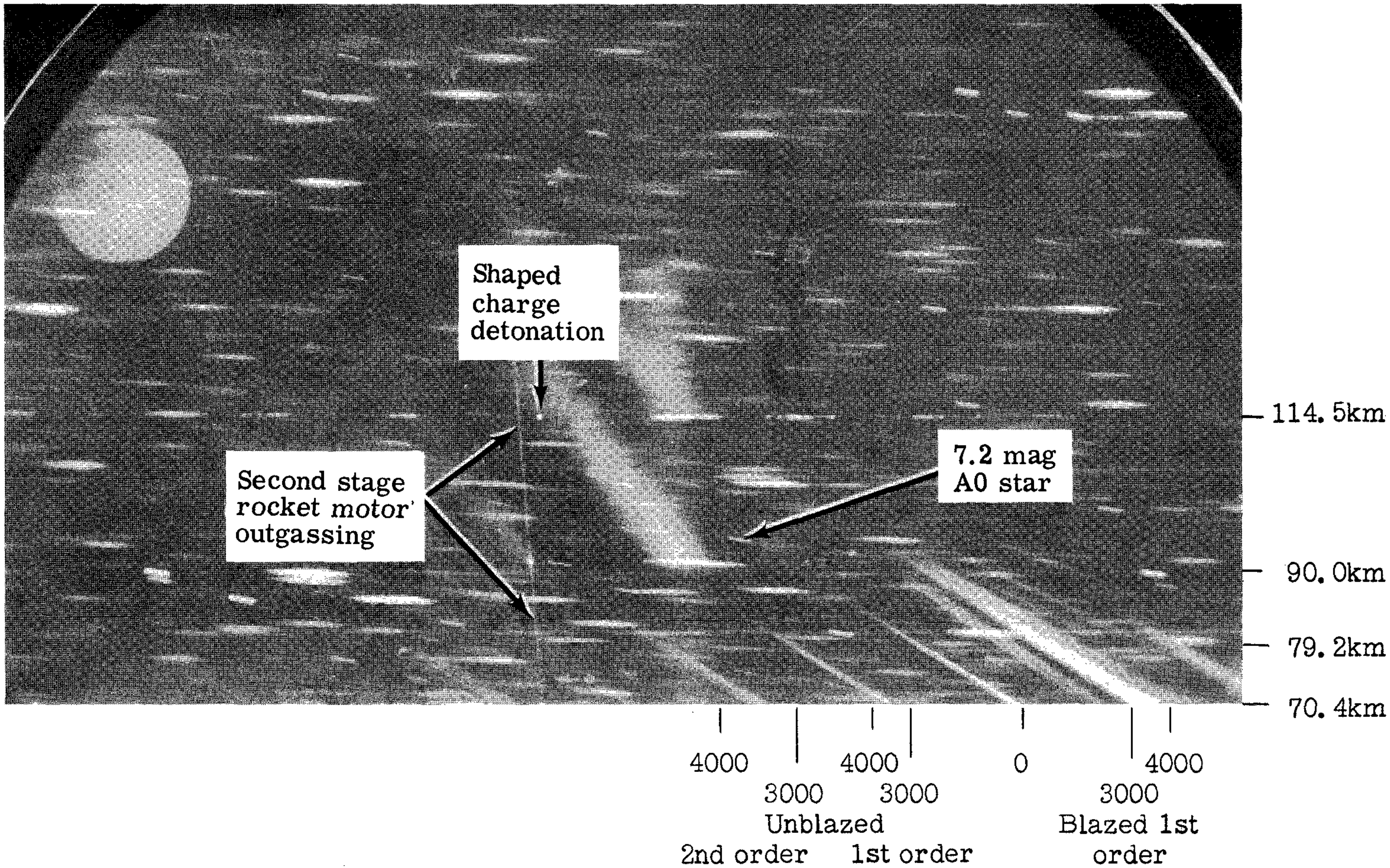


Figure 21.- Enlargement of near ultraviolet spectrogram of a nickel artificial meteor. L-67-1072

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