

**THE HIGH ALTITUDE OBSERVATORY OF THE
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH,
BOULDER, COLO.**

(Report from Solar Institute)

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In 1940, a high-altitude site for the first coronagraph in the western hemisphere was established near the mining town of Climax, Colo., by Harvard College Observatory. The Climax station remained under Harvard University auspices until the formation, in 1946, of the High Altitude Observatory as an independent research institution with Walter O. Roberts as its director. At the same time HAO became affiliated with the University of Colorado and transferred its headquarters to the campus in Boulder. In 1961 HAO became a research division of the National Center for Atmospheric Research, a national laboratory sponsored by the National Science Foundation and operated by a non-profit corporation of universities. At that time John W. Firor succeeded Walter O. Roberts as director.

HAO is now directed by Gordon Newkirk, Jr., and employs a staff of 17 scientists, 30 observers and research assistants, and about 20 technical personnel. Office and laboratory space is provided also for 10–15 visiting scientists and graduate students. Since its inception 29 years ago, the research program of HAO has centered around the study of the solar corona and chromosphere with a background of investigations in many other aspects of solar physics and solar terrestrial relationships. Programs undertaken in the last few years include descriptive and theoretical studies of the solar corona, solar rotation, solar activity, and magnetic fields in the photosphere, chromosphere, and prominences. Models of the chromosphere have been developed in an effort to produce an improved theory of the kinetics and transport of radiation in this region of the solar atmosphere. Laboratory astrophysical research has included the spectroscopy of very high temperature plasmas. Studies of the earth's magnetosphere are directed toward a greater understanding of various features of geomagnetic field changes and ionospheric effects.

1. Instrumental Facilities at Climax

The Climax station (lat. $+39^{\circ} 23' 29''$, long. $+106^{\circ} 12.6'$, altitude 3394 m) (Figure 1) continues as the main observing site and now has many new capabilities, including a 40-cm coronagraph-spectrograph and a magnetograph especially designed to measure weak fields at low light levels. The 13-cm coronagraph-spectrograph (which replaced the original Harvard coronagraph in 1955) and a flare patrol telescope are housed in a separate dome.

The 40-cm coronagraph has an equivalent focal length of 10.8 m and a useful field of 12 min of arc over which the final image is fully achromatic throughout the



Fig. 1. The HAO Climax station is located at an altitude of 3394 m on the continental divide. The larger dome contains the 40-cm coronagraph-spectrograph and magnetograph. The smaller dome encloses the 13-cm coronagraph-spectrograph and flare patrol telescope. Snow covers the ground during much of the year and dictates the use of conical rather than the usual hemispherical domes.

available photographic spectrum. The system (Figure 2) consists of the 40-cm single element objective, which forms a chromatic sequence of images immediately in front of the field lens, the occulting disk, which can be inserted to block the image of the photosphere at any desired wavelength from 0.35μ to 1.4μ , and two secondary imaging systems. The first of these, consisting of the field lens and a Mangin mirror, is followed by a field mirror and relay lens, which transfer the image by means of a coudé mirror to the spectrograph head in the observing room.

The spectrograph used with the 40-cm coronagraph is an over-and-under reflecting system similar to the Ebert design but with the grating approximately at the centers of curvature of the collimator and camera mirrors. It may be considered as a Schmidt system of such small aperture that no corrector plate is needed. The resulting spectral focal curve is circular, and any desired wavelength or order may be selected simply by rotating the grating. The focal length is 3.05 m and the focal ratio $f/26$. Three interchangeable gratings with rulings of 300 lines/mm, 600 lines/mm, and 900 lines/mm yield dispersions of from $0.4 \text{ \AA}/\text{mm}$ to $3.5 \text{ \AA}/\text{mm}$ in the single pass mode. At 5000 \AA the system is capable of a resolution of 0.017 \AA .

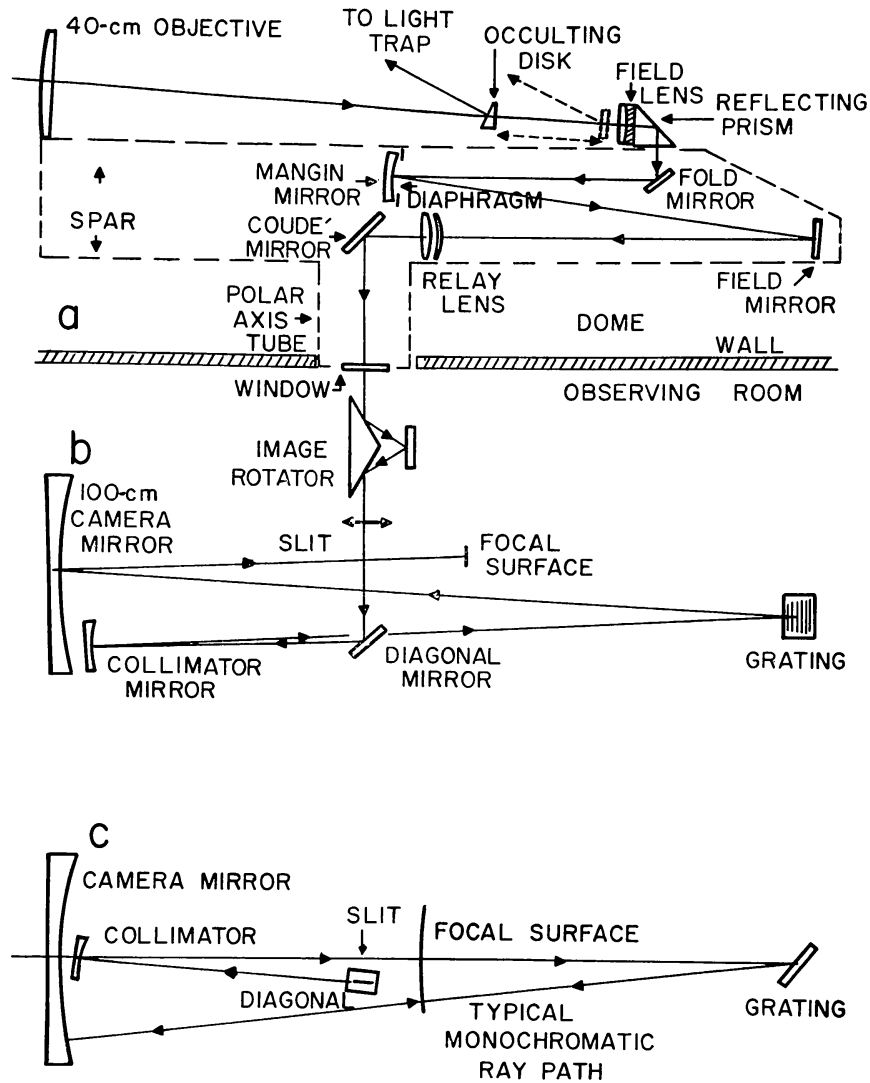


Fig. 2. Schematic diagram of the 40-cm coronagraph-spectrograph: (a) the coronagraph; (b) the spectrograph, in projection normal to the plane of dispersion; (c) the spectrograph, in projection parallel to the plane of dispersion. Auxiliary optics, magnetograph, and double-pass system are omitted for clarity.

The magnetograph, used in conjunction with the 40-cm coronagraph-spectrograph, was specifically designed to detect magnetic fields in prominences using the $H\alpha$ line. It has proved capable of measuring the Zeeman separation due to line-of-sight fields on the order of 2 gauss over an area of approximately 10×10 sec of arc in these objects. Recently, similar observations have been made in the brightest lines of helium, sodium, and magnesium. Used on the solar disk, the system can detect a minimum field of $\sim \frac{1}{2}$ gauss over an area of 2×2 sec of arc.

The 13-cm coronagraph combines the basic Lyot design with a coude' mirror which feeds a spectrograph similar in design to the one used with the 40-cm coronagraph. Besides being used to produce background spectra for studies with the 40-cm coronagraph, this instrument is equipped with an image tube for study of the near infrared.

2. The Mauna Loa Field Station

Early in 1956 the ability to examine the corona outside of eclipse in the brightest emission lines was expanded by the development of the K-coronameter, which could detect the polarization in the K-corona out to $2 R_{\odot}$. In 1963 this instrument was transferred from Climax to a lower-latitude site established on the Island of Maui in collaboration with the University of Hawaii. This coronagraph was moved again to the slope of Mauna Loa on the Island of Hawaii (Figure 3) (lat. $+19^{\circ} 31'$, long. $+155^{\circ} 35'$, elevation 3400 m) in 1965. The K-coronameter has an 8-cm aperture and a focal length of 193 cm, and operates at an effective wavelength of 6200 \AA . As a sensitive polarimeter it is capable of detecting signals as small as one part in 10^4 and continues to yield synoptic observations of the intermediate corona from 1.125 to $2R_{\odot}$. Data are analyzed primarily to determine the three-dimensional density structure and evolution of the corona and its relation to underlying surface features.

In March 1968 a second photoelectric coronagraph was added to the equipment at Mauna Loa. This instrument, the Coronal Activity Monitor, has a 13-cm diameter

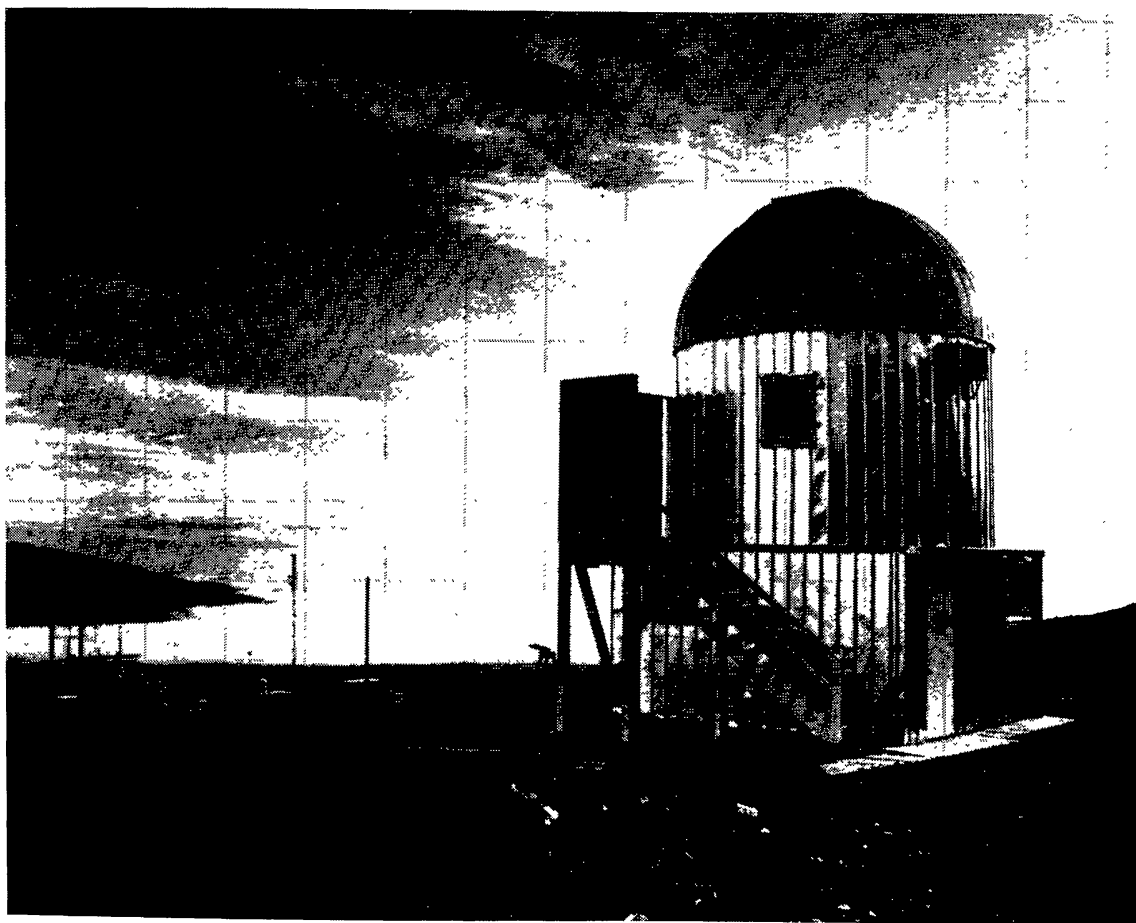


Fig. 3. The dome housing the K-coronameter and Coronal Activity Monitor on Mauna Loa, Hawaii, at an altitude of 3400 m. The combination of clear sky and high solar elevation has permitted an unparalleled series of observations of the corona out to $2 R_{\odot}$.

aperture and a focal length of 272 cm. It operates at an effective wavelength of 6200 Å and is similar in many respects to the K-coronameter. However, it is especially designed to permit rapid scans above limited regions to investigate rapidly developing transient phenomena in the corona. Meanwhile, the K-coronameter continues to be employed for once-a-day surveys of the entire corona.

3. Facilities at Boulder

For several years HAO's facilities for laboratory astrophysics have included high-temperature sparks, plasma shock tubes, and a theta-pinch plasma machine – devices which are capable of producing plasmas over a wide range of temperatures up to a few million degrees. Recently, a dense plasma focus machine has been installed to generate temperatures of over 30 million degrees at densities of 10^{19} ions per cm^3 . Used as light sources for spectroscopy in the X-ray and vacuum ultraviolet regions, these devices permit the duplication, in the laboratory, of temperatures similar to those found in the corona and corona-chromosphere interface and allow the investigation of the spectroscopic properties of many ions of astrophysical interest.

The NCAR Computing Facility and its Control Data Corporation 6600 Computer are available to HAO staff and visiting scientists for use in conjunction with their research. Programmers and operators of the Computing Facility work with HAO scientists on a wide variety of data analyses and theoretical studies.

The Boulder laboratory also houses standard analytical equipment, such as micro-densitometers, a photographic laboratory, machine shops, and a library (6250 volumes).

4. Expeditions

Because of their intense interest in the solar chromosphere and corona, HAO scientists have taken an active role in observing total solar eclipses since 1952. The latest expedition – to South America for the eclipse of 12 November 1966 – involved observation of the polarization of the Fe XIII emission lines in the corona both from the ground and from an aircraft (Figure 4), polarimetry of coronal streamers and, in connection with Johns Hopkins University, detection of the thermal radiation of the F-corona.

5. Balloon, Aircraft, and Satellite Research

In spite of the development of monochromatic coronagraphs and K-coronameters, observations of the solar corona are still restricted by the presence of the terrestrial atmosphere. The laboratory has been engaged in the acquisition of extra-atmospheric observations both of the corona and, most recently, of the disk in the extreme infrared. Experiments using balloons began in 1959 with a 'site survey' of the radiance of the sky in the stratosphere and have, to date, been devoted exclusively to the problem of photographing the intermediate corona ($1.5 R_{\odot} < R < 6 R_{\odot}$) outside of eclipse. The

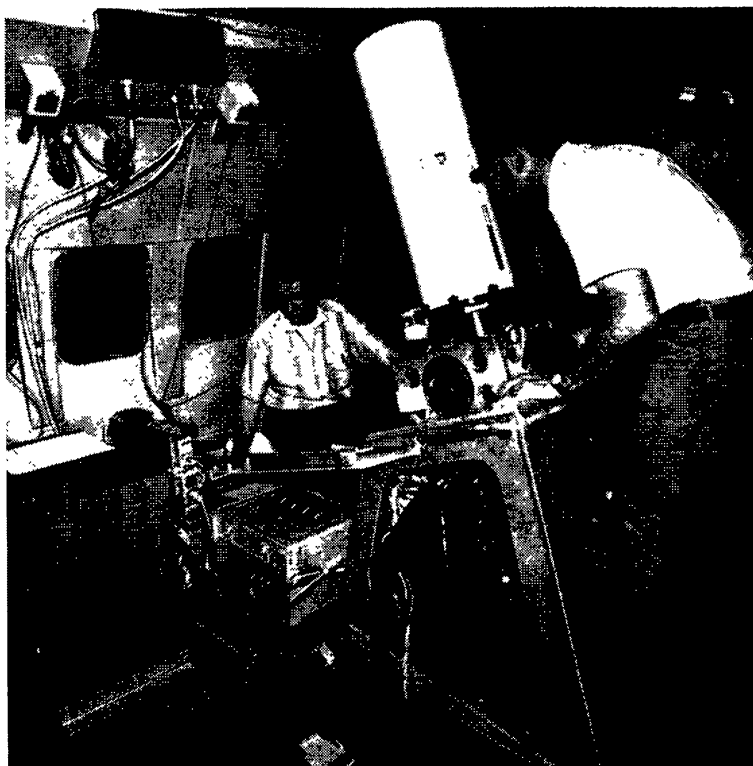


Fig. 4. The gyrostabilized telescope for the observation of the polarization of the FeXIII lines (10747 \AA) at the 1966 eclipse aboard the NASA CV-990 aircraft. (Photo courtesy of NASA.)

latest flights successfully produced a series of observations following the eclipse of 30 May 1965 to elucidate the three-dimensional structure of the corona.

The use of aircraft to increase the chance of success in observing total solar eclipses has already been mentioned. In addition, HAO has flown an airborne Fourier transform spectrometer to scan the far infrared ($50\text{--}500 \mu$) of the photosphere with sufficiently high spectroscopic resolution that the temperature at the minimum of the solar atmosphere can be established.

The long requirement of synoptic observation of the outer corona to determine the three-dimensional structure and evolution of coronal structures is the goal of HAO's participation in space research. At present a coronagraph, similar to those carried in the balloon gondola, is being constructed with the assistance of NASA for the Apollo Telescope Mount. According to plans, this manned orbiting observatory, which will carry several other solar experiments constructed by other laboratories, will be launched on a 56-day mission early in 1972.

6. Current Investigations

Interpretive and theoretical analyses carried on by the staff of HAO include a broad range of problems in solar and solar-terrestrial physics. A revival of interest in the differential rotation of the sun has led to theoretical investigations of the characteristic modes of circulation which occur in a rotating star containing a convective envelope.

Calculations which follow the distortion of an initially poloidal solar magnetic field by this differential rotation have shown that the occurrence and migration of the sunspot zone is a natural consequence of the fluid flow. The effect of the circulation of the solar atmosphere on the apparent oblateness of the disk has also been studied. An analysis of the interplay of magnetic fields and fluid motion on a somewhat smaller scale has yielded a sunspot model which demonstrates how the Evershed effect is produced by electro-motive forces in an atmosphere with conductivity varying with depth.

Problems concerning the transfer of radiation within the solar atmosphere are receiving considerable attention, not only by production of more accurate and new observations but also by the development of new theoretical tools. The profiles of the strongest Fraunhofer lines are of intense interest particularly with the advent of powerful computing machines which free the investigator from the restraints imposed by unrealistic, analytic approximations. Recent calculations using the coupled radiative transfer and statistical equilibrium equations for a multi-level atom, parametric representation of such variables as the turbulent velocity, and a new theoretical formulation of the problem have yielded profiles of the strong magnesium, sodium, and calcium lines which compare very favorably with the observations. This type of analysis also permits considerable insight into the role of various mechanisms in producing the lines.

Many features of the solar atmosphere observed in strong lines such as $H\alpha$ and the H and K lines cannot be adequately represented by the plane-parallel models typically assumed in radiative transfer calculations. New techniques using Monte Carlo and integral equation techniques for computing line profiles for such inhomogeneous objects as spicules, the H and K network, mottles, etc., have been developed and are being applied to the interpretation of these objects.

These new computer techniques for line transfer problems also permit more extensive calculations of line blanketing effects than previously have been possible. Work is presently in progress to arrive at an improved understanding of the role of blanketing in determining the structure of the solar atmosphere.

Observation of magnetic fields in prominences has shown that field strengths vary considerably from one type of prominence to another and that the fields and their connection to the surface influence the macroscopic motions of the material. Observations of the vector magnetic fields in active regions coupled with elaborate calculations have demonstrated that the orientation of prominences in the field is much more complex than some theoretical models have suggested. Moreover, in the most vital active regions, electric currents are such that the force-free magnetic field distribution is a more accurate representation than is the potential field. Changes in the magnetic field during flares, of course, result in substantial electric currents as well although their connection with the visible event appears to be complex. The interpretation of magnetograms relies upon often oversimplified theoretical models of the production of magnetically sensitive lines. Many of the uncertainties of these models are being removed by use of the Monte Carlo technique to calculate the polarization and

Zeeman pattern of lines appearing in the photosphere, prominences, and corona.

Laboratory production of spectra used to identify lines originating in the corona has previously been mentioned. However, these spectra frequently require elaborate quantum mechanical calculations for a complete understanding of the ions present and interpretation of the physical conditions existing in the corona and chromosphere-corona interface. Some of these calculations have been instrumental in making more secure the identification of the $K\text{-}\alpha$ lines due to Fe VII–XXIII.

The analysis of K-coronameter, balloon, and eclipse data has led to new insights into the three-dimensional density structure of the corona and its connection with active regions, filaments, and coronal magnetic fields. The latter are, of course, presently not measured but inferred from calculations using observed surface fields as a boundary condition. The rotation of the solar corona is also an area of keen interest. Most recent data have shown that the inner corona rotates with the long-lived filaments rather than the underlying photosphere.

Theoretical models of such structures as coronal streamers require calculation of the mutual influence of the solar wind and coronal magnetic fields. One such model has proved unusually successful in being able to reproduce the density structure and shape of streamers from quite general considerations of the physical conditions at the base of the corona.

Another study endeavors to determine what connection occurs between the inner solar corona and the solar wind as sampled by space probes at 1 AU. The interception of the solar wind by the moon and the possible role of photoelectrons expelled by the lunar surface are the subjects of yet another study. A further area of solar-terrestrial research is exemplified by the ionosphere although this region is so complex that the sun is only one of many agents influencing its structure. Recent work includes analysis of the quiet, diurnal solar-induced changes in the ionosphere, the influence of lunar tides, and the effect on both these phenomena of the diurnal variation of electrical conductivity in the atmosphere. Further investigations consider the role of wind shears in the ionosphere as an explanation for the apparently anomalous solar activity modulation of the F region. Research into this complex region of the atmosphere frequently requires critical evaluation of fundamental mechanisms of transport theory. A recent study, for example, involved the analysis of the dispersion of space charge waves in a partially ionized medium containing both external magnetic and electric fields and the role of these waves in explaining observed ionospheric phenomena.

ABSTRACTS OF FORTHCOMING PAPERS

ŠTEFAN PINTÉR: Longitudinal Distribution of X-Bremsstrahlung on the Solar Disc. (Received 21 November, 1968.)

In this paper, the dependence of the intensity of solar bremsstrahlung in the spectral range from 1–60 keV on heliographic longitude is investigated. Considering a flare mechanism, which assumes that the electrons move in a preferred direction in the course of their acceleration (according to the model of Takakura and Kai (1966) the electrons move parallel to the solar surface), we come to the conclusion that the maximum of the bremsstrahlung intensity is shifted with increasing electron velocity towards the direction of motion of electron beams. In the case of the Takakura and Kai flare mechanism, the slow electrons ($\beta=1/10-1/20$), i.e. with small energies of 1–10 keV, reach the maximum of the bremsstrahlung intensity round the CM; for higher velocities ($\beta=1/2-1/6$), i.e. for higher energies of 10–60 keV, the direction of the maximum is shifted away from the CM towards the disc limb. These theoretical conclusions were proved by experimental research conducted by means of satellites.

RICHARD C. ALTROCK: Interpretation of Infrared Oxygen Spectroheliograms. (Received 13 December, 1968.)

Spectroheliograms have been obtained in the line cores of two infrared multiplets of neutral oxygen. Those made in the lines of the 7770 Å multiplet show a very smooth intensity distribution, with faculae and sunspot penumbrae at a very low contrast with respect to the undisturbed photosphere. Spectroheliograms made in the core of 8446.37 Å show evidence of coupling with chromospheric features and of blending with a line of neutral iron.

An analysis of a 7772 Å spectroheliogram indicates that a magnetic field of approximately 1500 G is required to produce the 'disappearing penumbra' phenomenon. This value is consistent with recent observations of Beckers and Schröter.

V. P. KORBEINIKOV: On the Gas Flow due to Solar Flares. (Received 16 December, 1968.)

A hydrodynamical description of the gas flow due to a solar flare is considered. Use is made of the model of a point explosion in a gas with a variable initial density, velocity and pressure.

C. W. ALLEN: Systematic Photometry of XUV Solar Images. (Received 17 December, 1968.)

Units and methods have been devised to express the photometry of solar XUV images. The source and limb-brightened fluxes are given in terms of the Sun's quiet central intensity. Measurements made on this system can be meaningfully compared with solar data and with theoretical predictions. Calculations have been made of the XUV distribution for optically thin solar models, and results have been converted onto the measurement system. Photometric measurements have been made from four films lent by the Culham and Leicester Laboratories. Certain inconsistencies suggest that the measurement accuracy is not yet good enough for definitive results. However, there is evidence that (a) the X-ray emission sources are brighter, relative to the quiet Sun, than the longer wave EUV sources; (b) X-ray limb photons all escape (i.e. limb optically thin) but EUV limb emission is affected by absorption; (c) the observed image diameter fits an emission scale height of $0.05 R_{\odot}$.

W. M. BURTON: Solar Photography in the Extreme Ultraviolet. (Received 17 December, 1968.)

Pinhole camera instrumentation has been carried on stabilized Skylark rockets to record images of the sun at extreme ultraviolet wavelengths. This paper describes the equipment used and the results ob-