CLM-P74

United Kingdom Atomic Energy Authority

RESEARCH GROUP

Preprint

OBSERVATIONS OF THE SUN IN THE EXTREME ULTRAVIOLET

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1965

UNCLASSIFIED
(Approved for publication)

CLM - P 74

OBSERVATIONS OF THE SUN IN THE EXTREME ULTRAVIOLET

A B S T R A C T

Observations of the sun in the extreme ultraviolet (XUV) have recently been made using instruments carried on Skylark rockets fired from Woomera, S. Australia. This work has been made possible by the development of an attitude control system which will point the rocket nose cone towards the sun with an accuracy of a few minutes of arc. The performance of the first two prototype stabilized Skylarks is described in Part I together with preliminary results obtained from the scientific payload. An optical fine alignment system demonstrated a pointing accuracy of a few seconds of arc which will allow detailed observations of the solar corona. Results obtained include photographic records of the solar XUV spectrum and the distribution of soft X-ray emission over the solar surface.

Results obtained from experiments in the third stabilized rocket are described in Part II. These gave new data on the chromospheric and coronal ultraviolet spectrum and new XUV spectroheliograms at shorter wavelengths.

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May 1965 (C/18 ED)

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PART I

SOLAR SPECTROSCOPY IN THE EXTREME ULTRAVIOLET USING STABILIZED SKYLARK ROCKETS

by

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B.B. Jones, D.B. Shenton, R. Wilson

(Submitted for publication in Nature)

1. INTRODUCTION

Astrophysical developments in space research have tended to be slower than geophysical developments, largely because of the more sophisticated requirements of the former which need, for their full application, a stabilized platform in space. Such platforms have so far been developed mainly in the U.S.A. and confined to stabilization on the sun. Our present knowledge of the extreme ultraviolet (XUV) spectrum of the sun has been obtained almost entirely from observations using the bi-axial stabilization system on the Aerobee-hi rocket[1,2,3] and from the first orbiting solar observatory (OSO-1)[4].

In 1961 the need for a British stabilized rocket was examined by the National Committee for Space Research and after a survey of experiments proposed by a number of groups, that body authorised the commitment of funds for the development of an attitude control unit (ACU) to operate on payloads carried by the well-proven Skylark rocket. The initial (Stage I) specification was for the unit to be sun pointing and stabilized in 3 axes, the lateral control to be better than 1 degree and the roll control to be of the order of a few degrees. Further stages of development are included in the programme, firstly to improve the sun-pointing accuracy and secondly, to develop a moon pointing system for night sky observations.

The responsibility for the development of the attitude control unit lies with the Royal Aircraft Establishment, Farnborough who, after initial studies, placed a development contract with Elliott Bros. in 1962. On the initial launchings, carried out as flight tests of the prototype attitude control system, it proved possible to include experimental payloads for solar studies in the soft X-ray and extreme ultraviolet regions. Two prototypes have now been launched from the Woomera range in Australia, the first in August 1964 and the second in December 1964. These flights had a high degree of success and the purpose of this paper is to describe them and to indicate the kind of results obtained.

2. EXPERIMENTAL INSTRUMENTATION

Both flights carried experiments prepared by Culham Laboratory and also included equipment prepared by the University of Leicester. The Culham experiments were in three parts, each representing the start of a series of studies in solar XUV physics.

The first series of experiments aims to investigate the spectrum of the solar corona and chromosphere in the wavelength region between 500-3000 Å by means of normal incidence grating spectrographs. A concave mirror forms an image of the solar disk positioned so that the limb of the sun is set tangentially to the spectrograph slit, thus providing maximum spatial resolution of the emission region.

The full wavelength range, stated above, is not covered by a single spectrograph, but the dimensions of the optical components (collector mirror and concave grating) have been fixed so that identical mechanical mountings can be used for different spectral ranges. The reflecting coatings of mirror and grating, together with the blaze of the latter are optimised for the particular spectral range. The spectra are recorded photographically by a camera which allows up to six exposures to be programmed during flight.

A further important factor affecting the observations in the range 500-3000 Å is the fact that the photosphere is dark at wavelengths below ~ 1800 Å and bright at longer wavelengths. The problem of reducing scattered light is therefore somewhat different for these two regions. In the latter case, no information as yet exists on the coronal or chromospheric spectrum (with the exception of the emission components of the MgII doublet at 2795, 2803 Å) and so the kind of approach described here, involving the off-setting of the main solar image, will allow such observations to be made. However, the strict demands made on the pointing system and the possible coronagraphic techniques which need to be employed make this a more advanced experiment which was originally planned for a later stage in the programme.

The pointing accuracy required by these experiments is much better than 1 minute of arc which exceeds the specification for the attitude control unit. An optical servo alignment system has therefore been developed at Culham which orientates the collector mirror so as to maintain the position of the solar image to the required accuracy. This system comprises a photoelectric error detector and a platform actuator. The error detector is of the split field type and is located in the same plane and adjacent to the spectrograph slit. It consists of four light sensitive components in a square array on which a solar image is formed by a subsidiary mirror located on the same platform as the main collector mirror. The error signals are fed to the actuator system which responds by tilting the mirror platform about two mutually perpendicular axes in order to maintain the alignment. The actuator consists of servo motors which drive cam shafts through precision reduction gears to adjust the position of an arm rigidly connected to the mirror platform.

The second series of experiments is designed to observe the soft X-ray spectrum of the integrated solar radiation from 400 Å down to ~ 10 Å with grazing incidence spectrographs. These use concave diffraction gratings of one metre radius of curvature and can be set at grazing angles between 1^{o} and 4^{o}. As in the case of the normal incidence spectrograph, a single instrumental body has been designed and optimisation for different spectral ranges can be made by a suitable choice of grating and grazing angle. The instruments record photographically and operate without a collector mirror, relying on the main vehicle stabilization for solar alignment. The problem of scattered light within the instrument, made severe by the intense flux at longer wavelengths, is met by the use of a thin metallic filter placed over the spectrograph slit in order to eliminate visible light but to allow observations in pass bands at short wavelengths. Two such instruments are flown in each payload.

The third series of experiments has the objective of photographing the sun in extreme ultraviolet radiation. Initially, these experiments use a simple pinhole camera with a thin aluminium filter covering the pinhole aperture to exclude long wavelength radiation. Later flights will carry a development[(5)] of this pinhole camera in which a plane diffraction grating is incorporated and used at grazing incidence to provide wavelength resolution and record monochromatic images of the sun.

All experiments have been designed to fit into a single assembly as shown in Fig. 1 which is a photograph of the Culham payload flown in the first stabilized Skylark. Also shown is a shield which covers the equipment throughout flight, and the split nose cone covers which are detached, together with the rocket motor, soon after burn-out. All experimental data are stored photographically and recovered from the rocket head after parachute return.

3. RESULTS

GENERAL

The first test flight[(6)] (Skylark SL 301) took place at 05.40 U.T. on 11th August 1964 and the second (Skylark SL 302) at 03.35 U.T. on 17th December 1964. The main results of these flights are summarized in Table 1. In addition to these, the University of Leicester team obtained X-ray photographs of the sun[(7)].

In both of the prototype flights the attitude control unit[(8)] operated successfully, pointing the vehicle towards the sun throughout the scheduled part of the flight with an accuracy of control about the lateral and roll axes as indicated in Table 1. The fine optical alignment system also functioned successfully through the scheduled part of the flight, maintaining the position of the solar image with the accuracy indicated. Thus the primary objective of these flights was fully achieved with a performance much superior to that initially specified. For comparison, the well proven bi-axial pointing system, developed for use in the Aerobee-hi rocket, gives control in the lateral axes to about one minute of arc but without control in the roll axis.

TABLE 1

Performance and Results for First Two Stabilized Skylark Flights

	SL 301	SL 302
Date of launch	11th August 1964	17th December 1964
Local Time	1510 hours	1305 hours
Motor Type	Raven 7A plus Cuckoo booster	
Motor jettison (Time after launch)	76 sec	75 sec
Attitude control initiated	85 sec	86 sec
Attitude control achieved	106 sec	105 sec
Peak Altitude	145 km at 202 sec	167 km at 215 sec
Attitude control ceased	332 sec	363 sec
Parachute recovery	No	Yes
Attitude control errors Lateral: Peak to Peak (max) P + Y P - Y	 3 arc min 8 arc min	 5 arc min 3 arc min
Roll: Peak to Peak (max)	10°	14°
Fine Alignment Errors Lateral: Peak to Peak (max) RMS	 12 arc sec ± 2 to 3 arc sec	 13 arc sec ± 2 to 3 arc sec
Normal Incidence Experiment	1 spectrogram solar limb 100-120 km	6 spectrograms total sun
Grazing Incidence Experiment	Partially fogged	Unfogged exposure over whole flight
Solar Disc XUV Photography	Cassette broken at hard landing	Single exposure over whole flight

In the first firing the parachute failed to deploy but most of the photographic cassettes were recovered intact. In the second firing the parachute deployed successfully and all photographic cassettes were recovered intact together with the experimental equipment.

The experiments were launched with the well proven Raven 7A motor which carried the 301 and 302 payloads to peak altitudes of 145 km and 167 km respectively. These heights are too low to enable observations to be made over the full range of the spectrum, atmospheric extinction severely limiting observations at wavelengths from 1000 Å down to the soft X-rays. R.A.E. Farnborough and the Rocket Propulsion Establishment, Westcott, are currently carrying out a development programme for a high performance Skylark motor (Raven 6A) which would have the capability to carry the heavier payloads associated with these experiments to heights significantly in excess of 200 km. Such apogees are essential for the successful execution of the experiments described here, but the 6A motor will not be available until proved flight worthy.

NORMAL INCIDENCE SPECTROSCOPY

In SL 301, the fine alignment system was set so as to maintain the image of the solar limb on the centre of the slit of the normal incidence spectrograph. This was set to record the wavelength range 500-2500 Å but was optimised for the range 500-1500 Å. The concave grating (radius of curvature 40 cm, ruled at 1200 1/mm) gave a blaze maximum at ~ 1000 Å. An uncoated quartz collector mirror was used, together with an uncoated red glass replica grating, in order to minimise the scattered light due to the intense photospheric emission. The operational spectral resolution of the instrument, during its last pre-flight tests, was 0.3 Å.

The camera was programmed to take two exposures on Kodak Pathé SC-5 emulsion, the first for 25 seconds (including the acquisition phase) and the second for the remainder of the flight (~ 200 seconds). After the first exposure was completed the camera jammed in an intermediate position and remained there for the remainder of the flight. Consequently, the only successful exposure was the first and this was recovered from the light-tight cassette after the hard landing.

The spectrum is reproduced in Fig.2a and was recorded between 100 km and 120 km altitude. Allowing for the acquisition time, it represents an exposure time of 17 seconds on the solar limb. During this time, telemetry of the mirror servo amplifier outputs indicated that the maximum excursion of the sun's image relative to the slit was less than 5 seconds of arc. This is confirmed by the lengths of the recorded spectral lines which closely correspond to the astigmatic lengths of images in the spectrograph.

A preliminary examination of the spectrum of the solar limb has been carried out. The short exposure time of 17 seconds at a rather low altitude (100-120 km) results in a spectrum of reduced intensity at wavelengths below 2000 Å and its elimination for wavelengths below 1000 Å. Emission lines were recorded (e.g. OVI 1032 Å and Lyman α 1216 Å) and a continuous spectrum with superimposed emission and absorption lines extending from 2000 Å to 2500 Å. The resolution deteriorated from the pre-flight laboratory focus tests and corresponded to an instrumental line width of about 0.4 Å at 1000 Å, increasing to about 0.8 Å at 2500 Å.

The results obtained from SL 301 confirm that the peak altitude provided by the Raven 7A motor is not sufficient for solar spectroscopy at wavelengths below 1000 Å. However, the success of the optical servo alignment system offered the possibility of a reliable spatial separation of the photosphere and the inner corona. Since SL 302 was also to use the Raven 7A motor it was decided to bring forward the more advanced experiment at longer wavelengths and the normal incidence spectrograph was set for optimum performance in the range 1500-3000 Å. Both the collector mirror and the diffraction grating were coated with aluminium + magnesium fluoride. The grating was ruled at 1200 l/mm and blazed to give peak efficiency at about 2000 Å. The instrument was set to record the wavelength range 930-2950 Å and its resolution, as set up in the laboratory, was 0.3 Å.

The servo alignment system was adjusted so that the spectrograph slit viewed the inner corona, 0.5 minutes of arc from the solar limb. The camera was fully loaded with 6 strips of film and a timer unit was used to programme the full number of exposures during the flight. At launch the first strip of film was in position to record the acquisition period. Exposure No. 2 began after acquisition was complete at 110 seconds after launch and continued until peak height was reached about 100 seconds later. At peak height a series of shorter exposures began: Exp 3 = 3 seconds; Exp 4 = 10 seconds; Exp 5 = 30 seconds and finally Exp 6 covered the remaining 70 seconds until the shutdown pulse closed all shutters and terminated the recording period shortly before stabilization was lost on re-entry. The entire programme was correctly carried out and six exposures were obtained during the flight.

The collector mirror had been exposed to rather unfavourable environment conditions during several days of alignment tests which were carried out in the open air in a dusty atmosphere. By the time that the instrumentation was sealed for flight the mirror surface had been badly affected by a film of deposited material. Most of the larger dust particles were removed with an air jet but the surface film remained which could not be removed without risk of damage to the coating on the mirror. The scattered light resulting from this mirror surface increased the amount of solar photospheric radiation which entered the spectrograph slit and the spectra recorded were consequently characteristic of the photosphere. The resolution of the spectra is good and no loss of focus was detectable in the flight exposures.

Fig.2b shows a composite spectrum obtained by combining exposures 3 and 5, taken on Kodak Pathé SC-5 film. The spectrum is representative of the total sun and its width corresponds to the slit length used. Any emission lines localised in the inner corona would appear much shorter than the spectrum observed and cannot be detected. The emission lines which are recorded have the full length and are chromospheric in origin. The spectrum shows emission lines from 1216 Å (Lyman α) through to 1994 Å (CI) and absorption lines superimposed on continuum from about 1800 Å to the long wavelength limit at 2950 Å. Prominent absorption lines included AlI 1932 Å, 2026 AgI and 2124 SiI. Also observed is the MgII resonance doublet at 2800 Å. Comparison of these spectra with those previously obtained on SL 301 in the 2000-2500 Å region may reveal differences in the nature of the disk and limb spectra.

GRAZING INCIDENCE SPECTROSCOPY

Photographic spectroscopy in the range 10-400 Å is not possible at the limited altitudes achieved in the prototype flights, but the grazing incidence spectrographs were flown for flight testing. In SL 301 the cassettes were recovered after a hard landing but were partially fogged. Investigations revealed that this was caused by scattered light within the instruments due to a puncturing of the aluminium filters, located in front of the entrance slits, during the launch phase. The instruments were flown with redesigned filter mountings in SL 302 and survived the launch. The recovered films were free of fog but only one spectral feature (the intense line at 171.1 Å, recently classified by Gabriel et al[9] as FeIX $3p^6\ {}^1S - 3p^5 3d\ {}^1P$) was detectable. These instruments have now been satisfactorily flight tested and will not be flown again until a sufficiently high apogee can be achieved.

SOLAR XUV PHOTOGRAPHY

For the XUV solar photography experiments, each flight carried the first and simplest instrument, i.e. a pinhole camera of 10 inch optical length with an 0.006 inch pinhole covered by a 3000 Å thick unbacked aluminium filter. This system has two transmission bands, one in the soft X-ray region and the other above the aluminium $L_{2,3}$-edge at 170 Å.

In SL 301 the cassette was broken on impact by the hard landing and the film was fogged. In SL 302 the data was successfully recovered and the photograph obtained is reproduced in Fig.3. This was obtained between altitudes of 110 km and 167 km on Kodak Pathé SC-5 emulsion with an exposure time of about 180 seconds. At these heights the aluminium transmission band above 170 Å is effectively eliminated by atmospheric extinction, and hence the photograph is produced by soft X-ray radiation, the upper limit in wavelength being about 60 Å. The recorded image shows pronounced limb brightening, except in the regions near the poles, together with localised emission areas. This localised emission originated from active plage regions as can be seen from a comparison with the spectroheliogram taken in CaII light taken at Kodaikanal at 2.15 U.T. on December 17th. This is also reproduced in Fig.4 and the correlation between the X-ray emission and the CaII emission is very apparent. The X-ray photograph is also indicative of the stabilizing performance of the attitude control unit. The photograph is a single exposure taken throughout the stabilized part of the flight and confirms the performance data given in Table 1. Similar X-ray photographs were obtained by the University of Leicester.

4. CONCLUSION

These initial results, which have yet to be fully analysed, and the excellent performance of the stabilization systems indicate the great possibilities for research in XUV solar physics which can now be carried out using British facilities. The most important technological requirement is now the successful proving of the high performance Raven 6A rocket motor in order to carry the payloads to apogees in excess of 200 km. In addition to the experiments described here by Culham Laboratory, experiments using the sun pointing stabilized Skylark are being undertaken by the University College London and the University of Leicester for studies in the soft X-ray region. Future experiments, requiring the more advanced moon pointing vehicle are also being planned by the Royal Observatory Edinburgh and the Meteorological Office.

5. ACKNOWLEDGEMENTS

These investigations have only been made possible by the combined action of several individuals and departments in the U.K. and Australia. We greatly acknowledge the following:

Sir Harrie Massey and the British National Committee for Space Research for their support and approval of the experiments; Mr J.J. Gait and his group at R.A.E. Farnborough who were responsible for the rocket technology; Mr P.E.G. Cope and his colleagues at Elliott Bros. Frimley for the development and successful proving of the attitude control unit; Mr H. Whiteside and the staff of W.R.E. Australia who were responsible for the launching of the vehicles; Mr A.C. Ladd of the Space Research Management Unit for the administration of Skylark projects; Professor C.W. Allen for astrophysical advice; Professor Vainu-Bappu of Kodaikanal for permission to use the spectroheliogram in Fig.4; Dr J.B. Adams and Dr R.S. Pease of Culham Laboratory for their continuous interest and support, and finally our colleagues Mr H.J. Paxton, Mr K.R. Fenemore, Mr F.F. Freeman, Mr J.G. Firth and Mr R.W. Higham for their direct and valuable participation.

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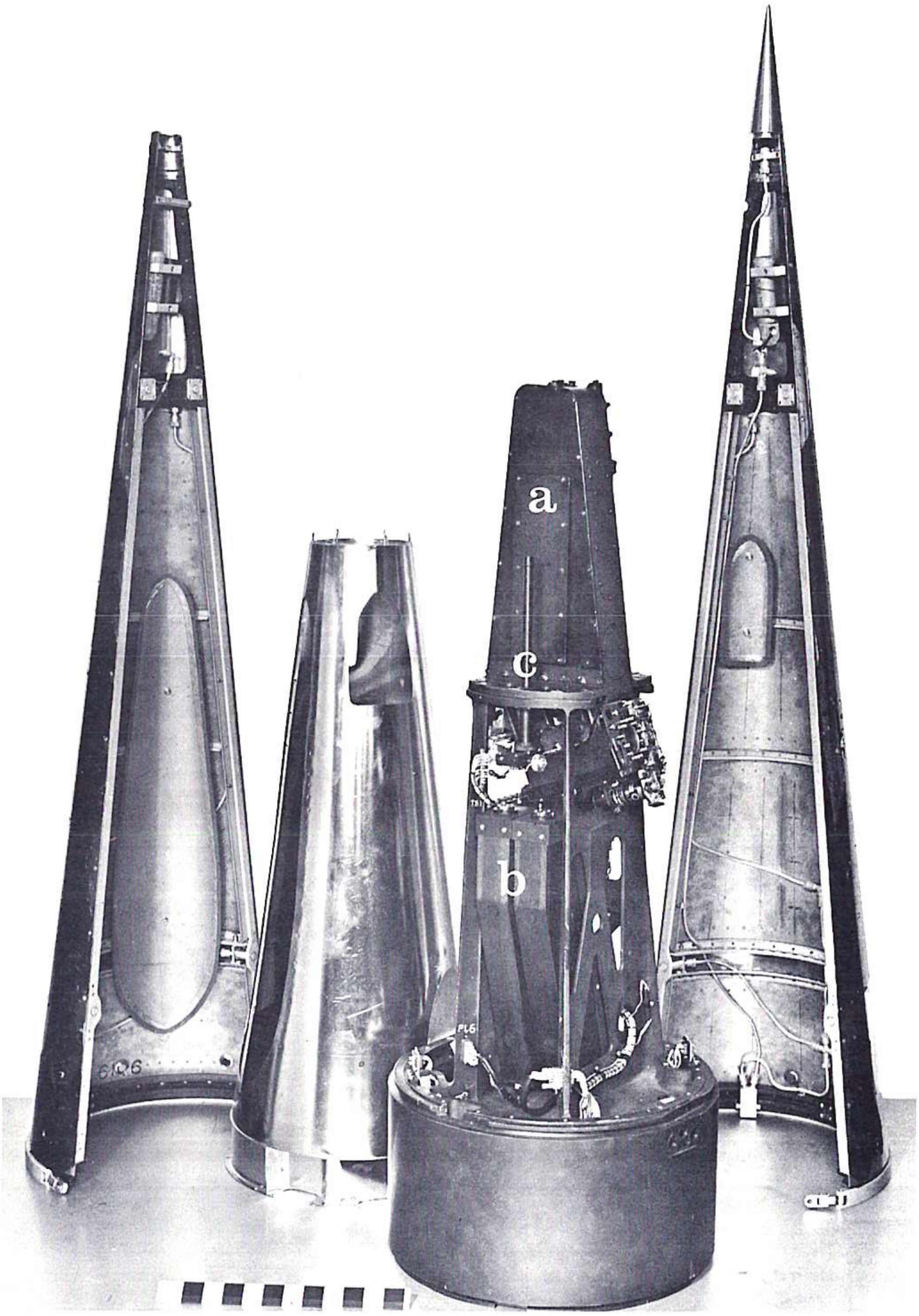

Fig. 1 (CLM-P74)

Assembly of the Culham payload flown in the first stabilized Skylark rocket, showing (a) the normal incidence spectrograph, (b) two grazing incidence spectrographs and (c) the pinhole camera, together with the cover shield and the split nose cone.

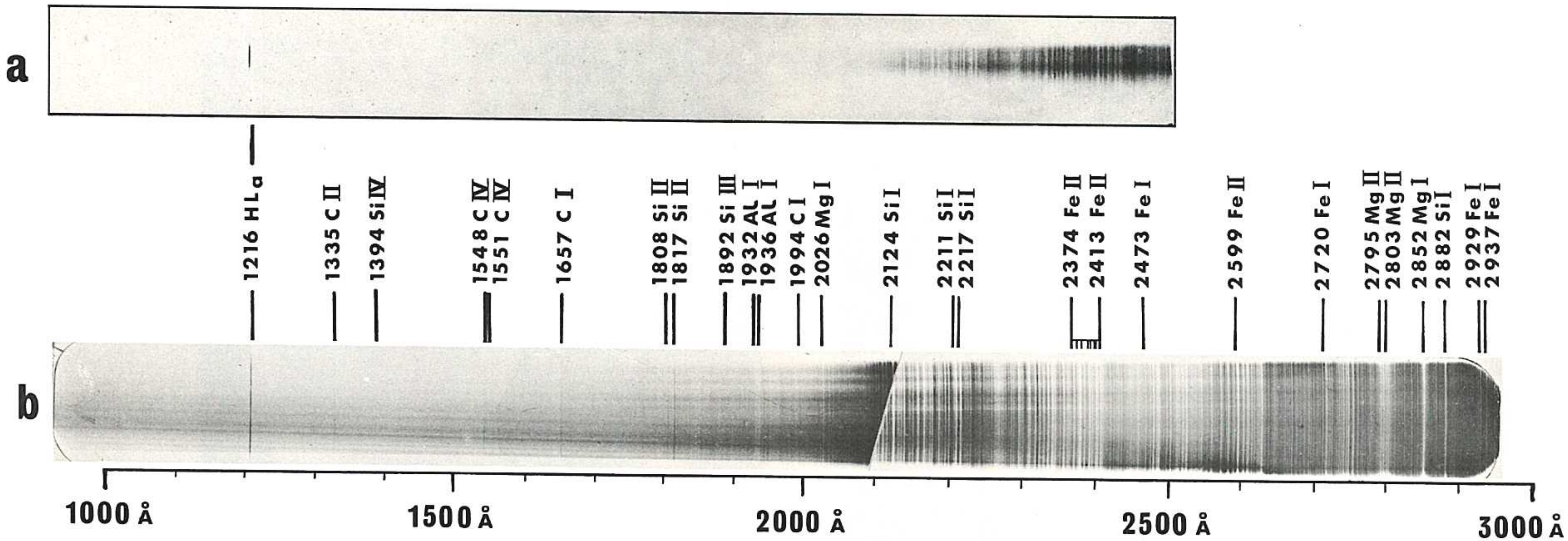

Fig. 2

(CLM-P74)

(a) Spectrum of the solar limb recorded by the normal incidence spectrograph on SL 301 between 100 km and 120 km altitude. Exposure time 17 seconds Slit width 0.012 mm. SC 5 emulsion.

(b) Composite spectrum of the total sun recorded by the normal incidence spectrograph on SL 302 at 165 km altitude. Slit width 0.012 mm. SC 5 emulsion.

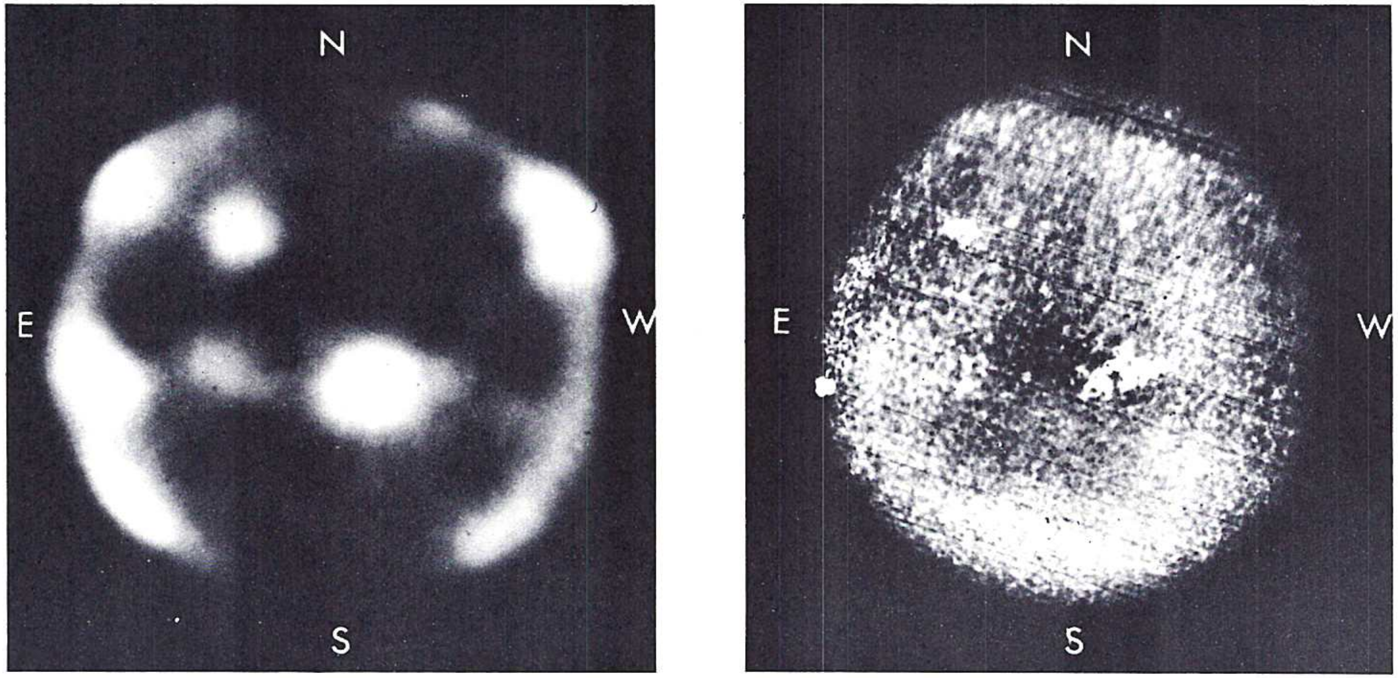

Fig. 3 (CLM-P74)

X-ray pinhole camera photograph, recorded on SL 302, and the spectroheliogram in CaII light taken at Kodaikanal, by Professor Vainu-Bappu

PART II

RECENT OBSERVATIONS OF THE SUN IN THE EXTREME ULTRAVIOLET MADE FROM A STABILIZED SKYLARK ROCKET

by

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R. Wilson

(Submitted for publication in Nature)

1. INTRODUCTION

The successful launching of the first two stabilized Skylark rockets from Woomera, South Australia in August and December 1964 was recently reported together with the results obtained by experiments prepared at Culham Laboratory[1]. These flights demonstrated accurate solar pointing and obtained photographic records of the extreme ultraviolet (XUV) spectrum of the sun and the distribution of XUV radiation from the solar disk. The third stabilized Skylark rocket was launched on 9th April 1965 at 01.00 UT and carried two Culham experiments. These were particularly successful, giving new data on the chromospheric and ultraviolet spectrum and new XUV spectroheliograms at shorter wavelengths. The purpose of this paper is to indicate the nature of the latest results.

2. NEW ULTRAVIOLET SPECTRA OF THE SOLAR CHROMOSPHERE AND CORONA

The instrumentation prepared for the recent flight included a normal incidence grating spectrograph with a servo-controlled alignment system similar to that used on the first two payloads. An electromagnetic actuator developed by Sperry Gyroscope Co. Ltd., Bracknell was used to control the mirror alignment and the spectrograph was set to cover the wavelength range 950-2950 Å. The alignment system stabilized an image of the sun so that the spectrograph slit was set ten seconds of arc outside of the solar limb in order to view the chromospheric and coronal layers separately from the bright solar disk. The rocket attitude control unit and the optical alignment system both operated correctly and the solar image was stabilized at the spectrograph slit with an accuracy (RMS) of ± 2 seconds of arc. This coronagraphic type of experiment based on the accurate control of the image position enabled the spectrograph to record new emission lines originating in the chromosphere and corona at wavelengths where the solar spectrum is normally dominated by emission from the photosphere.

Fig.1 shows a part of the spectrum recorded during a 95 second exposure at a mean altitude of 150 km. The central strip of the spectrum is produced by that region of the chromosphere and corona which was imaged on the centre of the slit, although there is some increase in the length of the spectral lines caused by astigmatism in the spectrograph. The spectrum recorded along the outer borders of the film results from photospheric radiation which is scattered from the primary concave mirror and enters the full length of the spectrograph slit. It therefore represents the spectrum of the total sun and can be compared at any wavelength with the central strip of spectrum which represents the chromospheric and coronal emission. This is illustrated in Fig.2 which shows a detail of the spectrum at 2800 Å. The resonance doublet ($3s\ ^2S - 3p\ ^2P$) of MgII is seen in the photospheric spectrum as two strong absorption lines with faint emission cores, but the central limb spectrum shows the two emission lines as the dominant features. Many emission lines are recorded in the central spectrum which do not appear in the outer borders and have not previously been observed in the solar spectrum.

A preliminary analysis of the new spectra shows many features of interest. The strong line at 1908.6 Å is identified as the $2s^2\ ^1S_0 - 2p\ ^3P_1$ forbidden intercombination line of CIII which will determine the $2p\ ^3P_1$ term level. The similar transition in SiIII produces the adjacent strong line at 1892 Å. Many strong emission lines between 2000 Å and 2400 Å cannot be identified with certainty and probably include forbidden transitions in highly ionized atoms related to the visible emission line spectrum of the corona. A complete analysis of the new solar spectra is now in progress and will be published in due course.

3. MONOCHROMATIC XUV SOLAR PHOTOGRAPHY

Photographs of the sun in soft X-rays have been previously obtained using pinhole cameras carried in stabilized rockets[1,2,3]. The wavelength response of this type of camera is determined by the transmission of thin metal filters which cover the pinhole aperture. These filters transmit broad wavebands of radiation and cannot provide monochromatic images of the sun in particular spectral line wavelengths. A concave grating spectroheliograph has been used by Tousey[4] to record monochromatic solar images in certain strong emission line wavelengths but this technique cannot be used at short wavelengths because of the low reflectance of normal incidence optics. The need for suitable techniques to record spectroheliograms at wavelengths below 250 Å became evident after the observation of a group of intense emission lines at 170-220 Å in the solar spectrum[5]. These lines have recently been produced in plasma devices at Culham Laboratory and have been classified as allowed transitions in ionized iron FeVIII to FeXII[6]. Information about the intensity distribution of these spectral line emissions on the solar disk would be a valuable aid to our understanding of the structure of the solar atmosphere.

An instrument which can be used to record monochromatic images in the wavelength region below 400 Å has recently been developed at Culham[7]. The imaging properties of a pinhole camera are combined with the dispersion of a plane diffraction grating used at grazing incidence to form a compact XUV spectroheliograph. This instrument was flown for the first time on the stabilized Skylark rocket launched on 9th April 1965. A single exposure on Kodak Pathé SC-7 film was obtained during 250 seconds of stabilized flight, the peak altitude being 160 km. The attitude control unit stabilized the nose cone within the extremes of ± 5 minutes of arc relative to the sun.

Fig.3 shows the XUV spectroheliograms together with a comparison photograph obtained with the same instrument viewing an ionized helium plasma in a laboratory discharge tube. The only important spectral lines produced by the helium plasma in this wavelength region are the first two members of the HeII Lyman series at 304 Å and 256 Å. Monochromatic images of the discharge tube window can be seen at these wavelengths. Two series of solar images are reproduced together with the helium comparison spectrum. These were obtained using two different sizes of pinhole aperture each covered by thin aluminium filters to exclude visible light. The upper pinhole was 0.75 mm diameter giving 10 minutes of arc resolution. The lower pinhole was 0.25 mm diameter to give less exposure, but a greater resolution of about 3 minutes of arc (about one tenth of a solar diameter). The zero order image in the upper spectrum is over-exposed but the HeII 304 Å image is correctly exposed and shows only slight limb brightening on a uniformly emitting disk image. The image formed mainly by FeIX 171 Å radiation is best seen in the centre spectrum. Equatorial limb brightening is marked but the emission from active spots is less obvious than in soft X-ray images obtained with a simple pinhole camera in the same flight. Initial considerations indicate that the limb brightened emission between 60 Å and 150 Å is real. A more detailed analysis of these results will be published in due course.

4. ACKNOWLEDGEMENTS

The results described in this paper were obtained by the combined efforts of several groups and individuals as listed in reference (1). We particularly acknowledge the essential contributions of the groups at R.A.E. Farnborough, Elliott Brothers of Frimley, W.R.E. Salisbury and our colleagues in the Natural Plasma Group at Culham.

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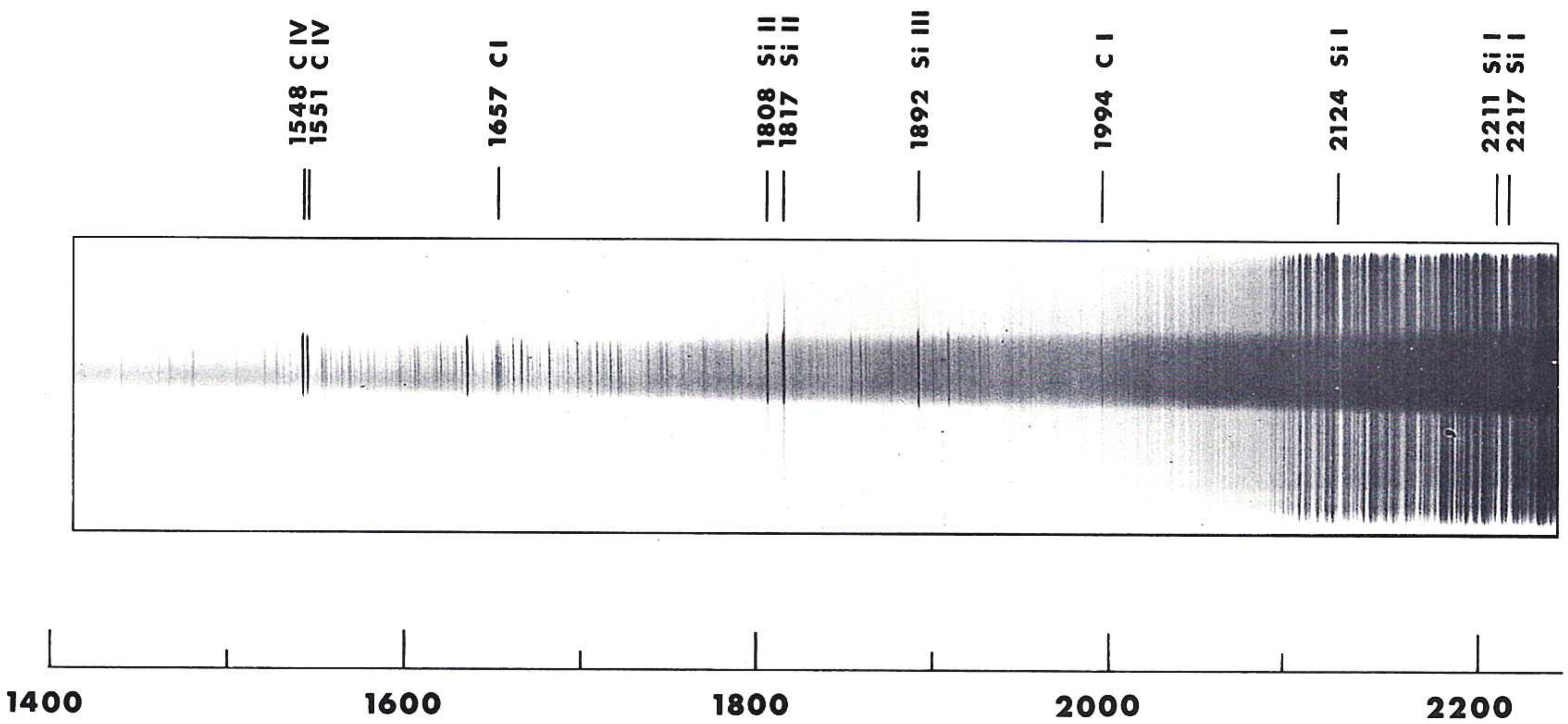

Fig. 1 (CLM-P74)
Solar limb spectrum 1500 - 2300 Å (Skylark SL 303, 9th April, 1965)

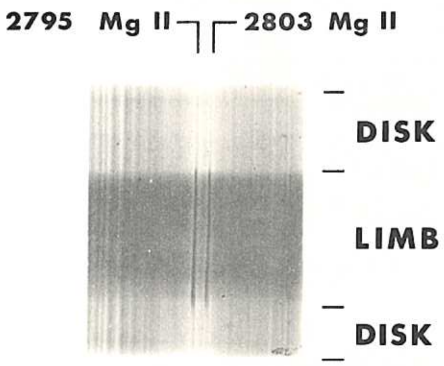

Fig. 2 (CLM-P74)
Chromospheric emission of Mg II doublet (Skylark SL 303, 9th April, 1965)

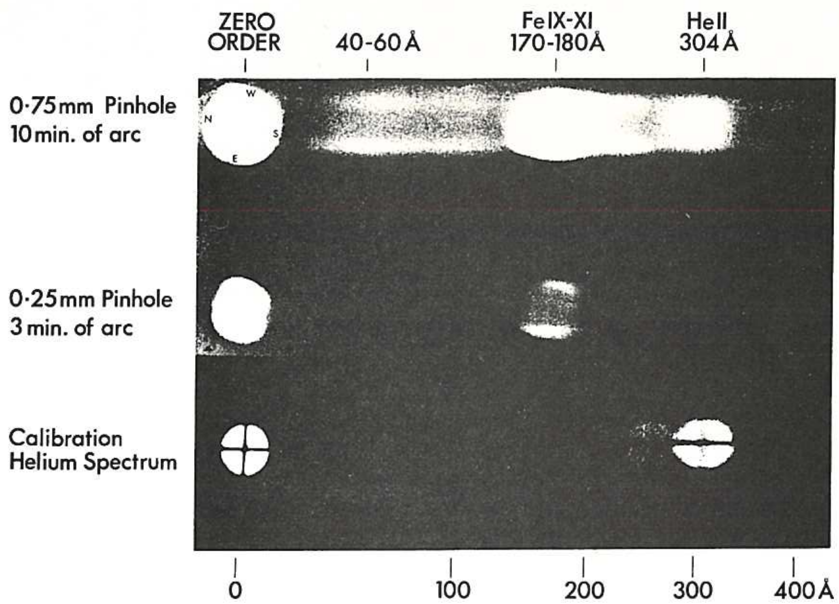

Fig. 3 (CLM-P74)
XUV Spectroheliograms (Skylark SL 303, 9th April, 1965)