HIGH RESOLUTION CINEMATOGRAPHY OF THE SOLAR PHOTOSPHERE

By R. E. LOUGHHEAD* and V. R. BURGESS*

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Summary

A description is given of a new photoheliograph designed for time-lapse cinematography on 35 mm film of any selected portion of a 20 cm solar image. The interval between successive photographs can be varied from 5 to 120 sec. Air-suction devices have been incorporated to suppress bad seeing originating within the telescope. The performance of the telescope is briefly discussed and the advantages of the cinematographic technique indicated. A discussion of the effects of atmospheric seeing is given in order to emphasize the great caution needed in the interpretation of solar photographs.

I. INTRODUCTION

The improvements over the past 50 years in spectroscopic and spectroheliographic methods of observing the Sun have enormously increased our knowledge of the Sun's outer layers, but have not been paralleled by corresponding advances in the direct photography of the solar photosphere. Most of the telescopes used in spectroscopic studies during this period have been "towertype " instruments, which, however, are by their very nature somewhat handicapped in delineating the finest details on the Sun's surface. Even under conditions of excellent atmospheric seeing the actual performance of such instruments seldom attains the theoretical limit owing to disturbing air currents throughout the optical paths, thermal distortion of the mirror optics, and unequal heating inside and outside the dome or tower. To date most good photographs of the photosphere have in fact been taken with refractors of various types. The quality of the plates obtained by Janssen (1877) probably remains unsurpassed, but excellent results have been obtained by Hansky (1908) and Chevalier (1912) and more recently by a number of other workers. Most of the later investigators have avoided the introduction of enlarging cameras (cf. Keenan 1953) for fear that image distortions may result from heated air in the neighbourhood of the enlarging lens; this, however, has entailed the use of telescopes of considerable focal length to obtain the size of image needed for high resolution photography.

In the present paper we describe a 5 in. photoheliograph which is accommodated conveniently on a mounting of moderate size, but which nevertheless effectively provides a solar image 20 cm in diameter. Essentially the instrument is a 5 in. refractor designed for time-lapse cinematography of any selected portion of the solar image on 35 mm film. The interval between successive photographs

* Division of Physics, C.S.I.R.O., University Grounds, Chippendale, N.S.W.

can be varied from 5 to 120 sec. The smearing effect on the image due to atmospheric seeing is minimized by taking exposures of about 1 msec duration. In addition, devices have been incorporated to ensure that the whole telescope is shielded as much as possible from the Sun and that heated air formed at those surfaces unavoidably exposed is removed by an air-suction technique. The purpose of these devices is to reduce bad seeing originating within the telescope to negligible proportions, and thus enable full advantage to be taken of the available optical resolution during times of good atmospheric seeing.

II. DESIGN

(a) Mounting

The photoheliograph is mounted in the open air on one face of a 10 ft "equatorial spar" at the C.S.I.R.O. Division of Physics Solar Observatory, located in flat country some 30 miles south-west of Sydney at an altitude of about 200 ft. The equatorial spar consists of a rectangular box with sides 16.5by 12.5 in. made of $\frac{1}{4}$ in. steel plate, whose three clear faces provide mountings for instruments. A general view of the instrument and mounting is shown in Plate 1. The spar is made to follow the Sun by means of a synchronous motor driving in hour angle and a photoelectric guider fed by an auxiliary 3.5 in. This produces a solar image on an occulting disk behind which are telescope. placed four photoelectric cells. Servomotors providing motion in hour angle and declination are driven by the amplified signals from the photocells. Guiding to 1-2 sec of arc can be achieved under the best conditions. The guider and spar are based on designs kindly supplied by Dr. W. O. Roberts of the High Altitude Observatory, Climax, Colorado.



Fig. 1.—Layout of the photoheliograph. C, camera; D_1 , front shield; D_2 , diaphragm at primary focus; L_1 , objective; L_2 , magnifying lens; M_1 , shutter motor; M_2 , camera motor; P_1, P_2 , prisms; R, reflex mirror; S_1 , objective shutter; S_2 , sector-disk shutter; S_3 , blade shutter; W, clock.

(b) Optical System

Figure 1 gives a schematic drawing of the layout of the photoheliograph. L_1 is a 5 in. objective which produces a 16 mm image of the Sun on a small diaphragm D_2 . This lens is a cemented doublet mounted free of strain in a cell designed by Coulman and Norton (unpublished data). The portion of the image corresponding to the aperture in D_2 is magnified by a second lens L_2 and the image is formed at the gate of a 35 mm Debrie cinecamera C. Prisms P_1 and P_2 turn the light beam around the end of the spar, thus permitting the use of a high magnification in a relatively confined space. Alternative magnifying lenses L_2 are provided to give effective image diameters at C of $8 \cdot 5$ and 20 cm.

 L_2 is provided with graduated screws giving motions in the north-south and east-west directions, so that any desired region of the Sun can be brought onto the camera gate. The optical system is designed so that off-axis aberrations thereby introduced do not exceed the Rayleigh tolerance. R is a reflex mirror used in focusing the telescope and F is a glass filter of bandwidth 800 Å centred at 5400 Å. At this wavelength the theoretical limit of resolution is about $0.8 \sec$ of arc.

The film used is Recordak Micro-File, a fine-grained emulsion, which is developed for about 6 min in D19. Laboratory tests on this film at different levels of object contrast have shown that the performance of the telescope at the higher of the two magnifications is not limited by film resolution.

(c) Suction Devices

By the use of suction devices, heated air formed at surfaces exposed to the Sun is removed and replaced by air at the ambient temperature. The photoheliograph and the front of the equatorial spar are shielded by a hollow aluminium diaphragm D_1 . The suction system is used to draw air through numerous holes in the front surface of D_1 , which is thus kept at the ambient temperature. S_1 is a solenoid-operated shutter which excludes light from the telescope except for a short time when an exposure is due. Unwanted light at the primary focus is reflected away by the diaphragm D_2 , which also reduces scattered light in the optical system. Both S_1 and D_2 are kept at ambient temperature by air flow in the same way as D_1 . The suction system is also used to remove any heat generated by the solenoid operating S_1 and by the electric motor M_1 driving the rotating sector-disk shutter S_2 . The reduced pressure in the suction system is maintained by a $\frac{1}{2}$ h.p. electric forge-blower, which is situated some 15 ft from the telescope and connected to the suction devices by an underground pipe and flexible couplings.

The air-suction devices are based on the results of laboratory experiments. Plate 2 shows two interferograms obtained with light passing over a perforated metal surface, heated by radiation to about the same extent as by ordinary sunlight. The distortion suffered by the wave-front in passing over the irradiated surface is shown in Plate 2, Figure 1, while Plate 2, Figure 2, illustrates the suppression of this effect when air is drawn through the perforated area. In practice the quantity of air drawn through the suction devices in the telescope is sufficient to reduce the temperature of the irradiated surfaces to the ambient value within a few minutes, even after exposure to sunlight for several hours.

(d) Shutter Unit

The focal plane shutter mounted in front of the camera consists of a solenoidoperated blade shutter S_3 and a rotating sector-disk shutter S_2 . The latter consists of two coaxial sector-disks which are driven at a constant relative speed by an electric motor. The high speed disk controls the exposure time; with a sector angle of 4° the effective exposure is of the order of 1 msec. The second disk rotates at one-sixth the speed of the first and therefore, in the absence of a blade shutter, would permit an exposure every sixth rotation of the fast disk.

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The purpose of this arrangement is to give the blade shutter S_3 sufficient time in which to operate, and thus to sequence the exposures made by the telescope.

To record photospheric detail of low contrast, the film must be developed to a high gamma; therefore some form of exposure control is necessary to avoid large changes in film density due to changing atmospheric transparency and solar zenith distance. The exposure control unit is located on the lower face of the spar just beneath the 5 in. objective (cf. Plate 1). It consists of a photocell unit fed with sunlight by a small auxiliary telescope. The signal from the photocell, after amplification, controls the speed of the motor driving the rotating sector-disk shutter S_2 in such a way that the product of the light flux and exposure time remains constant. Laboratory tests indicate a constancy to within 1 per cent. over extended periods. The circuit is designed to provide stability against changes either in mechanical load or power supply voltage. A fuller account of this device will be published by one of us elsewhere.

(e) Programme Controller

The photoheliograph is designed to take photographs automatically on a cycle which can be varied from 5 to 120 sec. The automatic control is obtained by means of a timing device providing electric pulses at regular intervals to drive a slave uniselector in the programme control unit. This uniselector actuates a number of relays which, in conjunction with a commutator mounted on the slower shaft of the sector-disk shutter S_2 , control the operations of the devices in the photoheliograph involved in taking an exposure. These operations are as follows:

- (1) the camera motor $(M_2 \text{ in Fig. 1})$ winds the film on one frame,
- (2) the objective shutter S_1 opens,
- (3) the blade shutter S_3 opens,
- (4) the rotating shutter S_2 makes the exposure,
- (5) S_1 and S_3 close.

The times at which S_3 is opened and closed are controlled by the commutator on the shaft of the slower sector of S_2 ; this eliminates multiple exposures. The image of a clock (W in Fig. 1), together with the date, is recorded in a corner of each photograph. The programme controller ensures that the clock is illuminated within a fraction of a second of the actual exposure on the Sun.

III. PERFORMANCE

Plate 3 is an example showing the quality of the best photographs obtained to date. Although certain regions are slightly affected by seeing, the granulation is well resolved and other detail of the order of 1 sec of arc is clearly visible; this detail approaches the theoretical limit of resolution of the 5 in. objective. Series of photographs of this quality have been obtained even after the telescope has been exposed to the heating effect of the Sun for several hours. This fact illustrates the value of suction devices in reducing seeing in or near the telescope.

The quality of the usable photographs among the 1800 or so on a given film is visually assessed on a scale of 1 to 5. Although such an assessment is naturally somewhat subjective, it is useful in giving some idea of the proportion of good to bad photographs when the cinematographic technique is employed. Quality 1 refers to photographs comparable with Plate 3; quality 5 refers to photographs which resolve the granulation but are badly affected by seeing. Photographs of quality 3 or worse often show the familiar réseaux believed by some early workers to be a real solar feature. However, examination of neighbouring photographs, taken at 5-sec intervals, confirms the conclusion of Rosch (1955) that the phenomenon is due to poor seeing. Photographs of quality 5 are of value in studying small structures only when a number of other photographs of sufficient quality, taken about the same time, are available. On the best film taken to date the percentages of photographs of qualities 1 to 5 are respectively 1, 2, 3, 8, and 11 per cent. Thus even on a good film the number of usable photographs is a relatively small fraction of the total. On the other hand, if still photography were employed instead of cinematography, the observer would be fortunate to obtain any good photographs at all under comparable atmospheric conditions.

The study of good quality films obtained with this equipment has shown that it is essential to allow for the effects of atmospheric seeing when studying changes in photospheric structures (cf. Bray and Loughhead 1957). For example, a small bright point of light visible on a good quality photograph might appear on a later photograph of poorer quality as a faint diffuse patch or even fail to appear at all. The misleading impression due to poor seeing is enhanced by the non-linear response of the emulsion to fluctuating light intensities. Moreover, the pattern of seeing on a poor photograph is so complex that, while a given fine structure might be completely obliterated, neighbouring detail of comparable size may be practically unaffected. Finally, quite large structures, many times bigger than the smallest resolvable detail on a given photograph, can be distorted by seeing to a surprising extent.

One advantage of the cinematographic technique is that many photographs can be taken in a time short compared with the time scale of the phenomenon under study, and thus by examining a number of photographs one can detect spurious effects due to seeing. An awareness of the effects of seeing is a prerequisite to the successful interpretation of high resolution films of the photosphere.

IV. ACKNOWLEDGMENTS

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Photoheliograph and mounting. C_j camera; D_j , front shield; D_2 , diaphragm at primary focus; L_j , objective; L_2 , magnifying lens; M_2 , camera motor; P_1, P_2 , prisms; R, reflex mirror; S_1 , objective shutter; W, clock.







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Fig. 1.—Interferogram showing the distortion of the wave-front of a light beam passing over a heated metal surface. The heating effect of sunlight on the surface is simulated by artificial radiation.



Fig. 2.—Interferogram showing the reduction of the distortion when air is drawn through holes in the heated surface.

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Enlargement of a photograph taken with the photoheliograph on 35 mm film.