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SOFT X-RAY IMAGES OF THE SOLAR CORONA USING NORMAL INCIDENCE OPTICS

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ABSTRACT

A solar coronal loop system has been photographed in soft X-rays using a normal incidence telescope based on multilayer mirror technology. The telescope consisted of a spherical objective mirror of 4 cm aperture and 1 m focal length, a film cassette, and a focal plane shutter. A metallized thin plastic film filter was used to exclude visible light. The objective mirror was covered with a multilayer coating consisting of alternating layers of tungsten and carbon whose combined thicknesses satisfied the Bragg diffraction condition for 44 Å radiation. The image was recorded during a rocket flight on 1985 October 25, and was dominated by emission lines arising from the Si XII spectrum. The rocket also carried a high resolution soft X-ray spectrograph that confirmed the presence of Si XII line radiation in the source. This image represents the first successful use of multilayer technology for astrophysical observations.

The purposes of this paper are threefold: to describe our normal incidence soft X-ray telescope system; to discuss the results of our first solar observations with the instrument, reported recently in Science [1]; and to discuss these results in the context of the physical conditions in the solar atmosphere.

During the past fifteen years, significant advances have been made in the field of X-ray optics that are relevant to the observation of astronomical objects [2,3]. Among these is the development of multilayer mirror coatings, consisting of alternating layers of two materials with widely differing atomic weights. These layer systems are deposited on a highly polished substrate that can be optically figured to give it the desired imaging properties. The dimensions of the layers are carefully controlled, and are chosen such that the layer spacing satisfies the Bragg condition for X-ray diffraction at the desired incidence angle and operating wavelength. The layer system acts as an artificial Bragg crystal, exhibiting greatly enhanced reflectivity at the design wavelength. The resulting mirror can be used as part of a conventional optical system, allowing soft X-ray instrumentation to be developed at a small fraction of the cost usually associated with glancing incidence telescopes. One can take advantage of the limited bandwidth of a multilayer mirror to isolate individual lines or groups of lines in the source spectrum.

Multilayer mirrors can be made for wavelengths down to a few angstroms, the practical limit being set by the smoothness of the substrate and the uniformity with which the individual layers (only a few atoms thick) can be deposited. The shape of the X-ray reflectivity peak is controlled by two factors, the number of layer pairs in the coating and the uniformity of the layers making up the coating. Increasing the number of layers both increases the peak reflectivity and reduces the width of the peak, provided that all the layers are identical and perfectly smooth. Anomalies in layer smoothness or thickness tend to reduce peak reflectivity and broaden the reflection peak.

For our experiment, we selected an operating wavelength of ~ 44.5 Å, where a pair of strong Si XII lines are found in the solar spectrum. The emission function for the Si XII lines maximizes at ~ 2 x 10^6 K, a typical coronal temperature. This choice has the advantage that the lines lie just above the carbon K edge at λ43.68 Å, making the system less sensitive to hydrocarbon contamination and enabling us to use thin plastic film filters to suppress shorter wavelengths. Our mirror coating consisted of 20 layer pairs, alternating between tungsten and carbon. The mirror was 4 cm in diameter and had a spherical figure of 2 meter radius.

The optical system is extremely simple, consisting of the single mirror, a shutter, and a film holder as shown in Figure 1. The mirror is tilted ~ 1.7 degrees away from normal incidence,
allowing the film to be at the prime focus. The solenoid operated shutter controls exposure times in the range 1 to 300 seconds. Each film holder carries a single piece of film, and an aluminized plastic filter to exclude visible light. Eight film holders are mounted on a rotating turret (not shown), allowing multiple exposures to be made. An electronic exposure sequence timer completes the system.

Figure 1. Optical components of the Multilayer Mirror Telescope. Light enters the system from the left, striking a spherical mirror carrying the multilayer coating. The coating consists of alternating layers of tungsten and carbon and has a 2-d spacing of 44.2 Å. The image is recorded on film placed at the prime focus. Visible light is excluded by an aluminized plastic film.

The components of the X-ray telescope system were mounted on the spar structure of a NASA sounding rocket payload that has been developed at Lockheed for high resolution X-ray studies of the solar corona [4]. Other elements of the rocket payload included a high resolution soft X-ray spectrograph, a high resolution UV filtergraph [5] and an Hα video filtergraph. The spectrograph was sensitive in the ~20 – 120 Å range and the filtergraph operated at Lα and at two ultraviolet bands near λ1600 Å.

The experiments were carried by a Black Brant V sounding rocket launched from the White Sands Missile Range on 1985 October 25. We were fortunate in that a large active region, NOAA 4698/99, was present on the solar disk at the time of launch, as the sun is normally very quiet in this phase of the activity cycle. The rocket system performance was nominal, and the payload was recovered by parachute. Only two of the eight planned exposures with the X-ray telescope were made, due to an anomaly in transmitting commands to the rocket. The X-ray spectrograph recorded about 40 emission lines from a point near the eastern boundary of the active region, and the UV filtergraph obtained an excellent series of images. Concurrent observations were also made from the SMM satellite and at several ground based observatories including those at Sacramento Peak, Kitt Peak, the Marshall Space Flight Center (MSFC), and Big Bear. Results of these concurrent measurements will be reported elsewhere.

Both of the X-ray exposures, made on SO-212 film, contained images of the active region, though with very low densities. An enlarged image of the longer of the two exposures (70 seconds) is shown in Figure 2. The photograph shows a complex of diffuse loop-like structures that is typical of the X-ray corona above an active region. There are two major domains of activity; a small compact one on the eastern side, and a larger extended set of structures to the west. The small, irregular linear features in the image are film artifacts and should be ignored. We have compared the structures seen in the X-ray image with the MSFC magnetograph observations, finding that the data are consistent with interpreting the image as a set of magnetically confined coronal loops [1]. The eastern region appears to consist of two or possibly three loops oriented in a NW - SE direction. The western region is considerably more complex; at least five different
loops can be identified. The central part and the eastern extension of the larger region have the appearance of hollow shells, rather than uniformly filled loops.

Figure 2. Soft X-ray photograph of a solar active region made with the Multilayer Mirror Telescope. The image is dominated by radiation from the Si XII lines at 44.02 and 44.16 Å which radiate most efficiently at a temperature of $\sim 2 \times 10^6$ K. The image displays two distinct regions of activity, each consisting of a complex of magnetically confined coronal loops. The photograph was digitized using a CCD system. The area outside of the active region was masked, obvious dust particles were removed by numerical interpolation, and a box filter was run over the matrix to reduce grain noise. The white cross marks the location of the spectrograph slit.

Figure 3. Emission Measure Distribution derived from line intensities measured with the Soft X-ray Spectrograph carried in the rocket payload.

An independent check on our interpretation of the images as coronal material is provided by the X-ray spectrogram made during the rocket flight. The spectrograph sampled radiation from the eastern footpoint of the largest of the loops in the eastern region, as shown in Figure 2. About 40 emission lines were observed (including the Si XII lines), enabling us to perform an emission measure analysis whose results are shown in Figure 3. The emission measure distribution maximizes at a temperature of about $6.5 \times 10^6$ K, verifying that coronal material in the appropriate temperature range was indeed, present.

In Figure 4 we compare the emission measure distribution for the 1985 Oct 25 data with distributions taken from the literature for two different active regions [6,7]. The temperature of the maximum in the 1985 distribution is consistent with these, though the level is higher. We also show the distribution for a compact flare that was observed during the Skylab mission [8]. The coronal material in the present observations appears to be in an intermediate state between the active region and flare plasmas. More details on the spectrograph can be found in the same book. W.A. Brown et al.
Figure 4. A comparison of the emission measure distribution for the 1985 spectrum (solid curve) with three other emission measure models taken from the literature.

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