IDENTIFICATION AND ANALYSIS OF STRUCTURES IN
THE CORONA FROM X-RAY PHOTOGRAPHY*

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Abstract. This paper summarizes the results of a program of rocket observations of the solar corona
with grazing incidence X-ray telescopes. A series of five flights of a Kanigen-surfaced telescope with
a few arc seconds resolution, together with the first flight of a newer telescope have resulted in the
identification of six classes of coronal structures observable in the X-ray photographs. These are:
active regions, active region interconnections, large loop structures associated with unipolar magnetic
regions, coronal holes, coronal bright points, and the structures surrounding filament cavities. Two
solar flares have been observed. The methods involved in deriving coronal temperature and density
information from X-ray photographs are described and the analysis of a bright active region (McMath
plage 11035) observed at the west limb on November 24, 1970 is presented as an example of these
techniques.

1. Introduction

The solar corona has a temperature in excess of one million degrees. Radiation from
such a plasma consists predominantly of resonance radiation from highly ionized
elements and of continuum radiation produced by free-free processes and recombina-
tion processes. Since the resonance lines of hydrogen-like and helium-like ions from
carbon and all heavier elements occur below 60 Å the characteristic radiation from
the corona lies in the soft X-ray region of the spectrum. Thus, the corona may be
studied at these wavelengths without risk of interference by background radiation
from the underlying chromosphere and photosphere. Measurements of solar soft
X-ray emission must however be made from rockets or satellites in order to avoid
absorption of the radiation by the Earth's atmosphere.

During the past decade the Solar Physics Group at American Science and Engi-
neering has carried out a program of development of soft X-ray imaging techniques in
order to study the structure of the solar corona. Early observations (pre 1968), carried
out by our group (Giacconi et al., 1965; Reidy et al., 1968) were restricted to approxi-
mately one arc minute in spatial resolution due both to limitations in grazing incidence
telescope technology and to the rocket fine pointing control systems available at that
time. Even with such coarse resolution, however, it was possible to distinguish active
regions, to observe the limb brightening of the general corona and to detect faint traces
of large scale structures on the disk (see Figures 1a, b). In 1968, however, a break-
through occurred with the development, at AS & E, of a grazing incidence telescope

* This paper originated in an invited talk presented by one of us (G.V.) at the COSPAR Symposium
In addition, it includes material presented at the three NASA OSO workshops, as well as more
recent work.

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with resolution capability in the arc second range. Simultaneously, NASA produced a solar fine pointing control system for rocket observations with a peak to peak jitter of the order of 2". Thus, the structure of the corona could finally be observed and the physical conditions existing within the observed features could be meaningfully determined.

Since that time a further six successful, high resolution, X-ray telescope sounding

**TABLE I**
Summary of sounding rocket flights (1968–1973)

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>Filters ( ^a )</th>
<th>Film</th>
</tr>
</thead>
</table>
| 8 June 1968   | 1740–1745 | 10.2 \( \mu m \) Be  
51 \( \mu m \) Be  
3.8 \( \mu m \) Mylar + 0.2 \( \mu m \) Al  
2.5 \( \mu m \) Fe (steel) | Panatomic-X  
untopcoated Panatomic-X  
untopcoated 103-0  
Ilford Special  
Panatomic-X  
untopcoated Panatomic-X  
Microfile |
| 8 April 1969  | 1700–1716 | 10.2 \( \mu m \) Be  
1.0 \( \mu m \) Parylene C + 0.3 \( \mu m \) Al  
3.8 \( \mu m \) Mylar + 0.3 \( \mu m \) Al  
0.15 \( \mu m \) Al | Kodak type 3400  
44.1 \( \mu m \) Be  
3.5 \( \mu m \) Parylene N + 0.2 \( \mu m \) Al  
3.8 \( \mu m \) Mylar + 0.2 \( \mu m \) Al  
3.2 \( \mu m \) Teflon + 1.1 \( \mu m \) Parylene  
N + 0.2 \( \mu m \) Al |
| 7 March 1970  | 1853–1859 | 10.2 \( \mu m \) Be  
0.85 \( \mu m \) Parylene N + 0.25 \( \mu m \) Al  
3.8 \( \mu m \) Mylar + 0.2 \( \mu m \) Al  
3.2 \( \mu m \) Teflon + 1.1 \( \mu m \) Parylene | Kodak SO-114  
44.1 \( \mu m \) Be  
0.85 \( \mu m \) Parylene N + 0.25 \( \mu m \) Al  
5.7 \( \mu m \) Parylene N + 0.32 \( \mu m \) Al  
10.2 \( \mu m \) Be  
44.1 \( \mu m \) Be  
1.0 \( \mu m \) Polypropylene + 0.3 \( \mu m \) Al |

\( ^a \) In addition to the filters listed, all flights except those of 8 June 1968 and 4 November 1969 carried a fixed heat rejection prefilter in the optical path. This filter consisted of 0.13 \( \mu m \) Al attached to a 78% transparent Ni mesh.

\( ^b \) A new payload with a low-scatter, quartz X-ray telescope and 2 collimated crystal spectrometers was used for this flight (Davis \textit{et al.}, 1973a).

Fig. 1. A representative set of solar X-ray photographs demonstrating the progress of the X-ray imaging technique. (a) The first X-ray image of the Sun made with a grazing incidence telescope (October 15, 1963). (b) An image obtained on March 17, 1965 by an electro-formed nickel X-ray telescope with resolution of about 30". (c) An X-ray image from the first successful flight of the series discussed in this paper (June 8, 1968). An importance 1B solar flare is close to the center of the disk. (d) An image obtained April 8, 1969. Numerous X-ray bright points are visible on the original negative. The cross-hatched appearance of the coronal structures was caused by the placement of the heat-rejection prefilter. (e) An image obtained November 4, 1969. An importance 1B flare is evident on the east limb. (f) An X-ray photograph obtained shortly after fourth contact of the solar eclipse of March 7, 1970. (g) An X-ray image obtained November 24, 1970. (h) An X-ray image obtained from the first successful flight of a new X-ray telescope of higher efficiency (March 8, 1973).
rocket payloads have been flown by our group (Figure 1c–h), each involving additional improvements in technique. Individual experiments were designed with specific observations in mind, such as the study of active region structure, flare dynamics, or the determination of the morphology of the quiet coronal features. However, in every case some new feature has been observed which was not anticipated. For example, the existence of X-ray emitting large scale coronal structures was detected in the June 8, 1968 flare observation (Vaiana et al., 1968). Bright points, active region interconnections and structures associated with large scale unipolar magnetic fields were seen first in the April 8, 1969 flight (Vaiana et al., 1970) and more clearly still in the 1970 flights (Krieger et al., 1971a). Filament cavities (Timothy et al., 1972) were spectacularly evident in the two 1970 flights which also gave the AS & E group its first views of coronal holes (Krieger et al., 1972; Krieger et al., 1973). Finally, in the most recent rocket flight, with a new low scatter, quartz mirror (Davis et al., 1973a) coronal loops have been seen surrounding a developing active region (Davis et al., 1973b). Table I lists the rocket flights which have been conducted. The complete results of the five flights between June 1968 and November 1970 are now available in the form of an atlas of photographs (Vaiana et al., 1973).

As may be seen from Figure 1, the image quality of solar X-ray photographs has improved very rapidly over the past ten years. It would therefore seem appropriate to pause and review the experimental techniques employed and the characteristics of the coronal features observed before moving on to the higher resolution studies planned for the new telescope and the time dependent observations which are now possible with the launch of the AS & E X-ray telescope on Skylab.

2. Instrumentation

The earliest images in X-ray astronomy were obtained with pin-hole cameras. The first historical photograph was obtained by the NRL group in 1960 (Blake et al., 1963). This photograph ushered in this new field of research. It demonstrated that one could use X-ray photography for the study of the structures of the high temperature plasma constituting the solar corona. At the same time, it showed the limitations of the techniques existing at the time. One of the major limitations was the drift in roll about the pointing axis of the attitude control system. This limitation was soon overcome by the development of three axis stabilization, first used by the group at the University of Leicester (Pounds and Russell, 1966) and quickly followed by others. The Leicester group used and optimized the pinhole camera technique, but the method suffers from a basic limitation. There is a conflict between light gathering power and angular resolution. Attempts to improve the spatial resolution, by the use of zone plates, were made by several groups (for example Einighammer et al., 1967) but resulted in only modest success. Zone plates suffer from chromatic aberration which limits their usefulness in studying a broad wave band emitter like the Sun. It is also extremely difficult to construct zone plates which combine large collecting area and moderate focal length with high resolving power.
In 1960, Giacconi and Rossi had suggested the use of paraboloid mirrors operating at grazing incidence, to increase the light gathering power of experiments designed to search for cosmic X-ray sources and ultimately to obtain X-ray images. It should be remembered that this was two years before they and their co-workers discovered the first unexpected bright X-ray source in the constellation of Scorpius.

As a result of this suggestion and the stimulus provided by the growing interest in X-ray astronomy a program to study and develop grazing incidence optics for X-ray observations was undertaken by American Science and Engineering under the sponsorship of NASA. This program benefitted from the comprehensive theoretical study of grazing incidence optical systems carried out by Wolter (1952) during an attempt to design practical systems suitable for X-ray microscopy. It appeared natural to first apply this technique to the study of solar X-ray emission. Following the successful construction of the first telescope, a program was proposed to NASA-Goddard Space Flight Center and a collaborative effort involving both groups resulted in the development of an imaging system for use on solar pointed sounding rockets. Several flights resulted in solar X-ray images with resolution of the order of an arc minute.

By the beginning of 1968 several rocket flights, conducted independently by both the GSFC group and the AS & E group, had established that grazing incident optics were already superior in sensitivity and resolution to the pin-hole camera and zone

Fig. 2. The Kanigen-coated beryllium X-ray telescope mirror used for rocket observations of the Sun between 1968 and 1970 in its mount. The view is from the hyperboloid (back) end of the mirror. A visible light aspect lens used on the early flights is mounted to the center plate of the telescope.
plate techniques (Giacconi et al., 1965; Underwood and Muney, 1967). A method of analysis based on the spectral transmission of several X-ray filters had also been formulated which was capable of distinguishing between temperature and density enhancements in the corona (Reidy et al., 1968).

The first successful rocket flight of the high resolution X-ray telescope mirror developed by AS & E took place on June 8, 1968 (Vaiana et al., 1968) and there have been four subsequent flights of this mirror all of which have been successful. The original payload has now been superseded by one carrying a new, low scatter quartz mirror and a collimated crystal spectrometer. Full details of this new instrument are presented by Davis et al. (1973a).

Fig. 3. The point response function of the X-ray telescope shown in Figure 2. The ordinate is in experimental units which do not reflect the absolute calibration of the telescope throughput. The dots represent measurements made by microdensitometry of photographic images of a pinhole. The triangles represent the result of inversion of proportional counter slit scan data.
The basic instrumentation of the 1968–1970 payloads, in addition to the X-ray mirror, consists of several filters which select appropriate wavelength pass-bands and a 35 mm camera mounted in the focal plane of the telescope which records both X-ray and visible light images. The payload also contains support electronics which provide power to control the filter wheel and camera, a programmer which selects filter wheel position and camera exposure time, the solar pointing control system, telemetry and other housekeeping functions. The X-ray telescope mirror flown between June 1968 and November 1970 is shown in Figure 2.

Fig. 4. The theoretical solar emission spectrum from 3 to 60 Å plotted for the temperatures $1.6 \times 10^6$ K (upper) and $5 \times 10^6$ K (lower). For convenience in computation (see text), the ordinate is the power (in units of erg cm$^{-2}$ s$^{-1}$) emitted by unit emission measure in a 0.2 Å wavelength interval.
In order to obtain information about the physical parameters of the solar corona from the X-ray photographs it is necessary to calibrate the energy response of the film, the spectral transmission of the filters, and the point response function of the mirrors.

The point response function describes the variation with radius of the energy emitted by a point source and imaged in the focal plane. The experimentally determined function for the 1968–1970 Kanigen mirror is shown in Figure 3. The initial slope is steep but it rapidly levels off due to scattering. The full width at half maximum

![Graph](image)

**Fig. 5.** The spectra of Figure 4 after filtering through a thin aluminized organic filter. At $1.6 \times 10^8$ K a significant fraction of the energy passing the filter is in the O vii lines at 21.6–22 Å. At $5 \times 10^6$ K, a number of lines contribute significantly, primarily from Fe xvi and Fe xvii.
is 2" but the width increases quickly to 20" and 120" at 0.1 and 0.01 respectively of the maximum value.

The energy sensitivity of the film is determined by producing an X-ray step wedge containing 16 known exposures generated with Al Kα radiation (8.3 Å). The intensities vary by a factor of 2 from one another so that the dynamic range in incident energy is nearly 10⁵. In general, this exceeds the range between grain noise and the saturation of the film. Since the range of surface brightness of X-ray emitting features

![Graphs showing filtered spectra](image)

Fig. 6. The spectra of Figure 4 filtered by a thin beryllium filter. At 1.6 × 10⁶K, the Ne ix (13.4 Å) line is the most important contributor with significant energy passed from Fe xv, xvi, and xvii. At 5 × 10⁶K, the lines of Fe xvii contribute as well as Mg xi (9.2 Å) and Si xiii (6.6–6.8 Å).
is at least this large, several exposures of varying duration must be taken through each filter during a rocket flight.

Finally the spectral transmission of the filters is required. Two types of filters are used. The first, made from various thicknesses of beryllium, transmit only short wavelengths (<20 Å); the second type is made from aluminized organic materials, such as Parylene, Polypropylene, or Mylar, which transmit X-rays both at the short wavelengths and also beyond the carbon K edge (44 Å).

In order to interpret the energies measured at the film plane in terms of coronal temperatures and emission measures it is necessary to know the spectral distribution of the incident soft X-ray emission. This has been achieved by use of a model spectrum, computed originally by Tucker and Koren (1971) and updated by Landini (private communication, 1972). The spectra computed for solar plasmas radiating at 1.5 × 10^6 K and 5.0 × 10^6 K are shown in Figure 4. They consist of a continuum component, produced predominantly by bremsstrahlung and radiative recombination, and a discrete line component. The wavelength distributions of the energy transmitted through two of the commonly used filters are shown in Figures 5 and 6 for the two incident spectra of Figure 4.

Fig. 7. Spectral hardness ratios for the two filters of Figures 5 and 6, together with a thicker beryllium filter. Spectral hardness is defined as the ratio of the total energies passed by two filters at a given temperature.
From these results it is possible to compute 'Spectral Hardness Indices' which are defined as the ratio of the energies transmitted through two filters at all wavelengths; as a function of coronal temperature (see Figure 7). Using these curves, it should be possible to determine the effective temperature (integrated along the line of sight down to the solar surface) at any point on a pair of solar X-ray photographs.

3. Morphological Results

Two kinds of information can be recovered from the X-ray images. These are qualitative descriptions of the images which relate to the morphology and evolution of the physical systems present in the corona and quantitative results which provide numerical values for the parameters of the solar plasma which will increase our basic knowledge of the magnetohydrodynamics of the corona. From measurements made in visible light at the limb we know that the corona is highly structured down to arc second resolution. Consequently, if we are to obtain significant information about the X-ray emitting structure we will need spatial resolution which is comparable to that obtained in the visible region. In this respect the resolution which has been attainable since 1968 places solar X-ray astronomy in the main stream of solar research.

Visual inspection of X-ray images, such as that shown in Figure 8a, provides information on the three dimensional structures which are present in the corona. Further comparison of such images with simultaneous measurements of the photospheric magnetic field (Figure 8b) immediately indicates the importance of the magnetic field in ordering the shapes of all coronal features. To date six distinct types of quiescent coronal structures have been tentatively identified from the rocket X-ray photographs. These are active regions, active region interconnections (arches), large scale

![Fig. 8. A comparison between the appearance of the Sun in soft X-rays and the photospheric magnetic field. Left: An X-ray exposure through a thin aluminized organic filter taken March 7, 1970 shortly after fourth contact of the solar eclipse. The limb of the Moon is visible to the southeast of the limb of the Sun. Right: A map of the longitudinal component of the photospheric magnetic field as observed by Livingston, Harvey and Slaughter (Kitt Peak National Observatory).]
quiet coronal structures (usually associated with unipolar magnetic regions), coronal holes, bright points, and the coronal structures enclosing filament cavities. The dynamics of two transient flare events have also been studied. It is currently unknown whether the active region threads (Davis, 1973b) seen during the March 8, 1973 flight came under the category of quiescent or transient structures.

3.1. Active Regions

Active regions are, apart from solar flares, the most striking features observed in the X-ray photographs. It became evident at a very early stage (Reidy et al., 1968) that the coronal appearance of active regions in X-ray photographs was not identical to their appearance at chromospheric wavelengths (e.g. Hα or CaK). The high resolution photographs have led to a coherent concept of active region structure in the corona and its relationship to the magnetic field which has been summarized by Krieger et al. (1971a). When active regions are observed at the limb of the Sun (Figure 9) they appear as complex tubular arches or loops of enhanced density and temperature which rise

Fig. 9. The appearance of active region structures in X-rays at the limb. Top: X-ray photographs in the 3–17 Å passband of active region associated coronal features. Left: A group of active regions near the limb. At least three arches connecting different portions of the group can be distinguished. Right: A loop structure associated with an active region very close to the limb. The coronal loop extends to an altitude of at least 150000 km. Bottom: Hα photographs of the corresponding portions of the disk taken two hours before the rocket flight (June 8, 1968) by NOAA Boulder Observatory.
Fig. 10. The appearance of active region structures in projection on the disk. Top left: A group of active regions observed November 4, 1969 in the 3–23 Å, 44–56 Å soft X-ray wavebands. Top right: The same regions observed in Hα (courtesy of Sacramento Peak Observatory). Bottom left: Ca K (courtesy of Sacramento Peak Observatory). Bottom right: Longitudinal component of the photospheric magnetic field (courtesy of Mt. Wilson Observatory).
Fig. 11. The appearance of a unipolar magnetic region in (from top to bottom): 3–23 Å, 44–64 Å X-rays; photospheric magnetic field (courtesy of Mt. Wilson Observatory); Hα and CaK. The Hα and CaK photographs were provided by the Sacramento Peak Observatory.
to heights of more than $10^5$ km above the photosphere (Vaiana et al., 1968). In Figure 10 an active region is shown where the loop is viewed at an angle and projected against the solar disk. When this picture is compared with the longitudinal magnetic field it is apparent that the loop connects regions of opposite magnetic polarity. This is a general result of active region observations. In the majority of the observations the intensity of the X-ray emission appears to reach a maximum above the vicinity of the neutral line of longitudinal magnetic field and in cases where the field gradient at the neutral line is large, or the neutral line configuration is complex, a bright core, whose width is unresolvable in our telescope, connects the regions of preceding and following polarity across the neutral line (Figure 10). The spectrum of such a core appears harder than that from the rest of the active region and consequently, if the emission has a thermal origin, it implies a higher temperature.

3.2. CORONAL STRUCTURES AND UNIPOLAR MAGNETIC REGIONS

Comparison of a CaK photograph of the Sun, taken on November 4, 1969, with the corresponding soft X-ray image (see Figure 11) shows that, in quiet regions the chromospheric supergranule structures are filled in at coronal altitudes by emitting material (Vaiana et al., 1970). In the case shown the emitting structures are seen to be associated with unipolar magnetic regions and a ‘ghost’ region. In Figure 11 the filled in cells are conjectured to form the foot points of large coronal structures which connect the two magnetic polarities. The temperature and density of such structures must be lower than that of the active regions because they are not seen in photographs taken through filters which pass only the shorter wavelengths. In the examples of Figure 11 gaps in the emission are observed over the positions of Hα filaments. These will be discussed under the topic of Filament Cavities.

Closed loops joining regions of opposite polarity photospheric field have been observed. A striking example of such a configuration was seen during the November 24, 1970 flight (see Figure 12). If these loops are in fact vertical their height is in excess of 100000 km. This is borne out by Hα observations at the limb of the prominence whose remnants are seen to underlie the coronal structure. The filament disappeared several days prior to the rocket flight.

3.3. CORONAL HOLES

In the November 24, 1970 soft X-ray observation (Figure 12) a clearly defined area of reduced coronal emission was observed (Krieger et al., 1972). A similar area was observed at the limb in the March 7, 1970 flight (Figures 1f and 23). Comparison of the November X-ray observations with images of the underlying Hα and CaK features and of the associated magnetic field distribution (see Figure 12) reveal several remarkable facts.

First little evidence can be seen of the structure in either the Hα or the CaK observations. Indeed, the network elements seen in the latter seem little different from those present in other quiet areas. The magnetic field configuration associated with the feature is however quite distinctive. In the center of the hole it is found that the pho-
Fig. 12. The southern portion of the solar disk on November 24, 1970. The X-ray photograph shows both high loop structure overlying the remnants of a filament which had disappeared several days before and a large coronal hole near the central meridian. The appearance of the coronal hole and surrounding in (a) 3-35 Å and 44-51 Å X-rays; (b) photospheric magnetic field on November 24, 1970, with the approximate position of the November 24th disk marked (courtesy of Kitt Peak National Observatory); (c) CaK spectroheliogram (courtesy of Sacramento Peak Observatory); (d) Hα spectroheliogram (courtesy of Sacramento Peak Observatory).

tospheric field is weak. Surrounding this area are regions of stronger fields of the same polarity which, in turn, are bordered by similarly intense fields of opposite polarity. The closed structure associated with the filament remnant mentioned in the previous section forms the eastern border of the hole while an arcade of closed loops associated with a ‘complex of activity’ runs the length of the western border. The surrounding structures emphasize the open nature of the hole by appearing to diverge from it. Very little evidence of any coronal emission from the hole can be seen on the solar disk. However, the presence of faint limb brightening in the south west indicates the presence of some coronal material in the hole. The geometry of the coronal structures associated with the March 7 hole appears very similar in the white light data (Figure 23).
A comparison of the X-ray photograph of November 24, 1970 with solar wind velocity data revealed that the coronal hole was probably the source of a recurrent high velocity stream in the solar wind (Krieger et al., 1973).

From the form of the coronal structures seen associated with the observed holes the conclusion must be drawn that coronal holes are the product of solar magnetic field configurations. The prerequisites for their formation are low photospheric field strengths and diverging coronal fields of a single polarity.

3.4. Active region interconnections

A further species of quiet coronal structure evident in the soft X-ray observations are active region interconnections. In addition to connecting loops within individual active regions, longer wavelength observations show that neighboring active regions are sometimes linked into ‘complexes of activity’ by means of large scale arch structures (Van Speybroeck et al., 1970). Inspection of an active region complex, seen on March 7, 1970 (see Figure 8) reveals interconnections spanning about 60° in solar longitude and about 90° in latitude. Comparison between the X-ray image and the underlying longitudinal photospheric magnetic field measurement indicates that the interconnections link regions of opposite magnetic field polarity. Usually, the interconnection is to an adjacent active region. There is also evidence that when connections occur across the solar equator they preferentially link the preceding polarities of the two hemispheres. Van Speybroeck et al. pointed out that these latter interconnections are exactly those called for by the Babcock (1961) model of the solar cycle. Hansen et al. (1972) have recently noted a similar phenomenon in the K-coronameter data which they have named ‘trans-equatorial arches’. It would appear that both the X-ray and white light observations show the same phenomenon.

3.5. Bright points

In addition to the large scale structures of the corona, there are also small pointlike features of relatively bright soft X-ray emission which are not associated with active regions (Vaiana et al., 1970) (see Figure 13). These features appear to coincide with some, but not all, of the brightest spots in the CaK network. Although several dozen bright points have been observed on the X-ray photographs, only a few of these features have been examined in detail. So far, all appear to be invariably associated with the occurrence of small regions of opposite polarity magnetic field in generally unipolar magnetic regions (Krieger et al., 1971a). They are thus, in all probability, the X-ray manifestation of low lying closed bipolar magnetic structures outside the active regions.

In view of the characteristics of these regions it is tempting to propose that they are miniature active regions, or represent an early phase in the development of active regions. Two factors however combine to throw doubts on this interpretation. First, in many cases the points are seen to be outside generally accepted active region latitudes (bright points are visible in the south polar region in Figure 12). In addition, a study of small bipolar magnetic regions (Harvey and Martin, 1973) indicates that
their lifetime is only of the order of a day. If the features studied by Harvey and Martin coincide with the X-ray coronal bright points, then the lifetimes of the bright points are short compared with 'standard' active region lifetimes and they do not develop into active regions. The X-ray latitude distribution and (if verified at X-ray wavelengths) the magnetic lifetime distribution lead one to believe, therefore, that these bright points represent a different phenomenon.

3.6. Filament cavities

In a previous section a brief comment was made to the effect that a cavity (observed as a reduction in coronal emission) is invariably observed to be above quiescent filaments. An excellent example of such a structure was observed on November 24, 1970 (see Figure 14).

The coronal configuration seen associated with the filament suggests that of the Kippenhahn and Schlüter (1957) model of filament geometry. The temperature and density characteristics of the coronal features seen are apparently similar to those of the other quiet coronal structures. Ray-like projections, which are probably the feet of coronal loops are seen radiating approximately perpendicularly to the filament. These appear to be aligned with the loops in the filament itself. The emission from the material directly over the filament (if any) is too faint to determine whether, in this case, the coronal loops close above the filament. Certainly they are seen to close over particular portions of the filament. In this case, as well as that of a large filament observed in the March 7, 1970 data, the closures take place over areas where the Hα absorption is weak. This may, however, be coincidental.

Directly above the quiescent filament and above all other quiescent filaments so far observed, a distinct cavity is seen. This was found in the case of the filament shown in Figure 14 to have a projected area in X-rays which was three times that of the enclosed filament as observed in Hα (Timothy et al., 1972). An analysis of the projection effects
on the X-ray image, showed that the non-emitting cavity extended to a height of at least $2 \times 10^4$ km above the top of the Hα filament. Observations at the limb showed the Hα feature to have a height of approximately $5 \times 10^4$ km. Thus the coronal cavity was more than $7 \times 10^4$ km in height.

The X-ray features associated with quiescent filaments (cavities over which apparently high closed structures may be observed) are in marked contrast to the low-lying bright loops observed over active filaments marking the neutral line of active regions. Davis et al. (1973b) observed bright loops over active filaments which can be traced back through active regions, on the one hand, and cavities around quiescent filaments which are associated only with remnants and unipolar magnetic regions, on the other (see Figure 1h). It would thus appear that, if active and quiescent filaments mark different stages in the evolution of the neutral line of the photospheric field, then the coronal structures follow this evolution by progressing from low-lying dense loops which are bright X-ray emitters to very high tenuous structures which do not emit observable fluxes of soft X-rays at their tops. Perhaps the high arches proceeding
between the unipolar magnetic regions associated with the remnant filament channel of Figure 12 represent an intermediate stage. This general evolution would be consistent with the K-coronameter observations of Hansen et al. (1972).

Filament cavities associated with quiescent filaments should not be confused with coronal holes for which no dark filament or even aligned fibril structure is observed in Hα. The former are apparently enclosed areas of low temperature or low density plasma while the latter are certainly open, low-temperature regions.

3.7. Solar Flares

On two of the rocket flights, we have observed importance 1 flares in progress (Vaiana et al., 1968; Krieger et al., 1970). In Figure 15 the appearance of the flare observed on June 8, 1968 in 3–18 Å X-rays is compared with Hα and CaK observations and with a magnetogram of the flaring region. The similarity between the X-ray and Hα emission

Fig. 15. Appearance of the solar flare of June 8, 1968 (1742 UT) in X-rays, Hα and CaK and the magnetic configuration at the time of the flare. Top left: 3–18 Å X-rays. Top right: Hα (courtesy of NOAA Boulder Observatory). Bottom left: CaK (courtesy of McMath-Hulbert Observatory). Bottom right: Photospheric longitudinal field (courtesy of J. Harvey, Kitt Peak National Observatory).
Fig. 16. The appearance of the solar flare of November 4, 1969 in Hα and X-rays. Top to bottom: Red wing Hα, Hα on band, blue wing, 3–12 Å X-rays. The photographs were taken at about 2030 UT. The Hα photographs were provided by H. Zirin, California Institute of Technology. The bracket below the photographs is 1' in length.
has been noted before (Vaiana and Giacconi, 1969); the important difference was also noted, however, that the X-rays show a bright feature which bridges the magnetic neutral line of the flare. This structure emits more than 50% of the total energy of the flare in this waveband.

The second flare, observed on November 4, 1969, occurred close to the limb. Its appearance is more difficult to interpret because of foreshortening; for the same reason, the magnetic field data is not available. Although the X-ray appearance, in this case, shows little correlation with the on-band Hα there exists a similarity between the brightest portions of the two X-ray flares insofar as the emission in both cases is localized in narrow structures. In the November 4 flare (Figure 16) two cores can be identified, and these correspond to the brightest emission regions appearing in the Hα wings. At least 98% of the total energy in the 3 to 18 Å band originates from these bright spots (Krieger et al., 1971a). In the flare of June 8, the surrounding X-ray plage contributed approximately 50% of the total emission (Vaiana and Giacconi, 1969).

It is probable that the similarity between the bright cores observed in the non-flaring active regions and the centers of emission in flares indicates a generic relationship. In both cases they are narrow linear structures associated with the neutral line of the longitudinal field at a position where the neutral line is complex. It is assumed that this region plays an important part in the flare process.

4. Quantitative Data Reduction and Analysis

The methods by which numerical parameters such as electron temperature and density as a function of position are deduced from the X-ray images are not very different from the methods used in the quantitative analysis of visible light images. Certain difficulties are introduced when working in X-rays; the broad scattering wings of the X-ray telescope point response function must be taken into account and the wavelength dependence of the film’s response to incident energy must be considered. The results that follow are preliminary in the sense that these factors are neglected. They do, however, serve to point out the techniques of quantitative interpretation of solar X-ray images, and to demonstrate the existence of temperature and density structure in X-ray emitting coronal active regions.

The X-ray images were digitized by an Optronics P 1000 scanning microdensitometer with an aperture of 25 micrometers (4°). Photographic density was converted to incident energy by comparison with a sensitometric step wedge, exposed to 8.3 Å aluminum Kα X-rays, and developed and scanned along with the flight film.

The quantity measured in any X-ray exposure through a given filter is the energy deposited on the film per unit area at a given point \( I_{\text{filter}} \). This quantity is related to the physical parameters of the given region by the equation

\[
I_{\text{filter}} = \frac{A}{4\pi f^2} \int_0^\infty N_\lambda^2 \, d\lambda \int_{\lambda_1}^{\lambda_2} p[\lambda, T(l)] \eta_{\text{filter}}(\lambda) \, d\lambda,
\]  

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where the first integral is taken along the line of sight, and

\[ A = \text{geometrical collecting area of telescope}, \]
\[ f = \text{focal length of telescope}, \]
\[ N_e = \text{electron density}, \]
\[ l = \text{distance along the line of sight}, \]
\[ \eta_{\text{filter}}(\lambda) = \text{filter transmission and telescope reflectivity at } \lambda, \]
\[ \lambda_1 \text{ and } \lambda_2 = \text{the wavelengths where } \eta(\lambda) \text{ becomes effectively zero}, \]
\[ p(\lambda, T) = \text{power emitted at wavelength } \lambda \text{ by unit emission measure at temperature } T. \]

The quantity \( F_{\text{filter}}(T) = \int_{\lambda_1}^{\lambda_2} p(\lambda, T) \eta(\lambda) \, d\lambda \) is currently determined from the modified version of the theoretical calculations of Tucker and Koren (1971) to determine \( p(\lambda, T) \) and from laboratory calibrations to determine \( \eta(\lambda) \).

Since the term \( (A/4\pi f^2) N_e^2 \) is constant for all filters, the spectral hardness index, the ratio of the intensity passed by two filters, \( R_{12}(T) = I_1/I_2 = [F_1(T)/F_2(T)] \), is a measure of the effective temperature of a region along the line of sight. If the filters are appropriately chosen \( R(T) \) is a monotonic function in the temperature range of interest. The effective emission measure along the line of sight is then given by the relation,

\[
\left[ \int N_e^2 \, dl \right]_{\text{effective}} = \frac{I_{\text{filter}}}{F_{\text{filter}}(T)} \frac{4\pi f^2}{A}.
\]

The above derivation assumes coalignement between images. In order to transform all images from a single rocket flight into a common coordinate system, the coordinates of up to nine common features (the exact number depends on the exposure) are determined from contour plots of the photographic density distribution. The necessary rotation and translation parameters are then computed by a least squares fitting procedure.

4.1. Analysis of active regions

In order to demonstrate this analysis technique it has been applied to a bright region (McMath 11035) which was situated on the west limb of the Sun on November 24, 1970. Figure 17 shows the appearance of the region of interest in exposures in two X-ray passbands. It is evident that the region is characterized by a bright core of short wavelength emission (implying higher temperature) and a structured extended region surrounding this core. The result of the first step in the analysis, a contour map of the energy deposited in the film plane in the 3–35, 44–51 Å waveband is shown in Figure 18. In order to investigate the physical characteristics within the region, intensity cross sections are computed for two wavebands along a line perpendicular to the limb (Figure 19a and b).

As mentioned in the previous section, X-ray photographs of active regions observed on the disk (for example Figure 10) show that active regions consist of bright low lying cores and higher well-defined loop and large-scale arch structures. Accordingly, the intensity scan data has been interpreted in two ways.
Fig. 17. X-ray images of the coronal active region above McMath plage 11035. Top: Photograph through a thin organic filter passing the bands 3–35 Å and 44–51 Å. Middle: Photograph through a thin beryllium filter passing the band 3–18 Å. Bottom: Photograph through a thicker beryllium filter (3–12 Å).
Fig. 18. A contour map of the energy deposited in the film plane made from the upper photograph of Figure 17. The isophotes represented linear energy intervals. The dashed lines labeled N–S and E–W are tangential and radial to the limb respectively through the point of maximum brightness.

In the lower two plots of Figure 19, a ‘slab model’ has been assumed in which the temperature along the line of sight is considered constant. This is analogous to assuming that all the emission along a given line of sight comes from a restricted region (e.g., an isothermal loop). Accordingly, the spectral hardness ratio $R(T)$ (related to effective temperature) and the effective emission measure $N_e^2 dl$ corresponding to that temperature are plotted as functions of position.

An alternative approach would be to assume spherical symmetry for the active region. This would be analogous to the assumption that the X-radiation is all emitted from a contained arch feature without significant fine structure. If the structure of the active region along the line of sight is identical to the structure perpendicular to the line of sight, a mathematical inversion of the intensity traces may be performed.
Fig. 19. The radial scan line through the peak of region 11035. From above: (a) X-ray intensity through the thin organic filter. (b) X-ray intensity through the beryllium filter. (c) Spectral hardness at each point along the scan line. The small peaks at 1' and 2' from the brightest point are probably statistical fluctuations, but the peak in spectral hardness at the brightest point is statistically significant. (d) The emission integral along the line of sight computed from the spectral hardness data and the intensities through the organic filter according to the formula of Equation (2).
The temperature and density can then be derived as functions of radial position. Figures 20 and 21 show the results of the inversion procedure applied to the two scans of Figure 19a and 19b.

Although neither of the two models chosen corresponds to the real structure of the active region, the results are indicative of the range of conditions to be found. The region appears to consist of a low-lying 'core' loop of high temperature and high density material surrounded by a less structured 'halo', probably composed of structures which are not resolved in the microdensitometer scans. It would appear, from these results, that the bright 'core' loop is primarily a temperature phenomenon and that the decrease in density between the 'core' loop and the 'halo' is less abrupt. The decrease of temperature with height in the 'halo' arch structure is slow, however, and the X-ray emission declines with the emission integral.

Several sources of ambiguity in this analysis must be mentioned. The conclusions are dependent on the correct assignment and interpretation of the spectral hardness index. The relationship between spectral hardness index and temperature is non-linear. Thus, a shift in either the experimental spectral hardness measurements or the theoretical calculations of $R(T)$ could change the character of the results significantly. Improper assignment of spectral hardness ratios could result from a variety of causes (e.g., spectral variation in the film sensitivity or telescope scattering function, im-

![Fig. 20. Electron temperature as a function of position for region 11035 computed by inverting the data of Figure 19 (a) and (b) under the assumption of spherical symmetry. The temperature decreases only slightly beyond 20″ from the center of the region.](image-url)
proper evaluation of the film fog level, etc.). Incorrect evaluation of the relationship between spectral hardness and temperature could result from an incorrect analysis of the solar X-ray spectrum. An effort has been made to use the best data available to resolve all of these ambiguities.

A more fundamental difficulty which arises, however, is the fact that the emission from a small quantity of very hot material along the line of sight can be masked by the emission from a much larger quantity of cooler material. For example, a conspicuous X-ray feature was observed behind the northeast limb in the November 24, 1970 photographs. This was identified as the active region McMath 11060. An analysis (Krieger et al., 1971b) of a conspicuous arch structure visible in this region indicated that the structure was essentially isothermal at a temperature of $2.5 \times 10^6$ K ($\pm 2 \times 10^5$ K) with a peak emission integral of $1.1 \times 10^{30}$ cm$^{-5}$ ($\pm 10^{29}$ cm$^{-5}$). However, a hot ‘core’ comprising up to 10% of the total plasma along the line of sight at $3.5 \times 10^6$ K or 4% at $4 \times 10^6$ K, would not have produced a statistically significant increase in the spectral hardness index of the brightest point in the active region. This difficulty can be overcome by finding a self-consistent solution to a combination of exposures taken with many filters passing different portions of the soft X-ray
waveband, or by a combination of imaging techniques (for structure perpendicular to the line of sight) with high resolution spectroscopy (for thermal distributions along the line of sight).

4.2. Analysis of Large Scale Structures

In principle, plasma conditions in the quiet corona can be determined by the same methods used in the analysis of the active regions. In practice, the exposure durations attainable from sounding rockets prohibited the assignment of accurate spectral hardness ratios to cool ($<2 \times 10^6$ K) features prior to the development of the low-scatter, high efficiency, X-ray telescope rocket payload discussed by Davis et al. (1973a). However, in certain special cases the temperature of the corona can be determined from the X-ray photographs by means of a different technique (Krieger et al., 1973). When long exposures are obtained through thin filters a distinct limb brightening is visible at the quiet limb (see Figure 8 for an example of this phenomenon). Microdensitometer scans through such areas are often found to be well fitted by simple exponential functions of the form:

$$I(h) = I(0) \exp(-h/h_1),$$

(3)

where $I$ is, once more, the X-ray energy deposited on the film per unit area and $h$ is the height above the limb.

If the intensity distributions at the limb, which are represented by Equation (3) are interpreted as radiation from an isothermal region with spherical symmetry about the limb and density $N(h) = N_0 \exp(-h/H)$ (where $N_0$ is the density at the base of the corona and $H$ is the density scale height) then the emission integral becomes:

$$\int N_e^2(h) \, dl \approx N_0^2 \exp(-2h/H) \frac{\pi R_\odot H}{(1 + h/2R_\odot)}$$

(4)

(The radial variation of the gravitational potential over the height range of the observations is neglected). Therefore $h_1 \approx H/2$. If in addition, it is assumed that the plasma is in hydrostatic equilibrium under the influence of gravity only, the temperature of the emitting material can be derived from the scale height using the barometric relation $H = kT \mu/mg_\odot$, where $\mu$ is the mean molecular weight (0.62) and $g_\odot$ is the acceleration of gravity at the solar surface.

As an example of this technique radial scans were made through the limb of the November 24, 1970 image. Two scans, one passing through an area of typical limb brightening, which is probably a closed region according to the discussion of Van Speybroeck et al. (1970), and the other passing through the coronal hole, are shown in Figure 22.

Fitting an expression of the form of Equation (3) to the data, it was found that of five closed structures scanned, four had scale heights lying in the range $6.62 \times 10^4$ km $< h_1 < 8.24 \times 10^4$ km. On the other hand, the scale height of the hole material was $(3.27 \pm 0.12) \times 10^4$ km. Thus, it is apparent that the intensity scale height $h_1$ in the hole is approximately half that in the typical closed structure.
Fig. 22. Graph of X-ray intensity as a function of radial position for the coronal hole and for a typical closed region. (November 24, 1970, 3–25 Å and 44–51 Å bandpass). The error brackets on the points represent the second to least significant bit of the microdensitometer. The data is quantized at the lowest levels. For each plot the intensity scale height $h_I$ is determined from a least squares fit to the data.

Numerical evaluation of the measured scale heights leads to barometric ‘temperatures’ of $1.3 \times 10^6 \text{K}$ in the hole region and $3.1 \times 10^6 \text{K}$ in the typical closed structure. However, the fact that the longest exposures through thin beryllium filters (passband 3–18 Å) taken during this flight showed only faint traces of the closed coronal structures or limb brightening implies that the temperature of the quiet coronal plasma was lower than that generally associated with active regions ($2–3 \times 10^6 \text{K}$).

The explanation of this apparent discrepancy can be found in the morphological results of the previous section. In general it has been established that X-ray emitting coronal structures indicate the presence of transverse fields (i.e., closed structures). In such a situation however the assumption made in this analysis, that the coronal plasma is in radial hydrostatic equilibrium, is invalid (although hydrostatic equilibrium along the field lines is allowed). Thus only in the case of radial magnetic fields, such as those in the coronal hole region, can the scale height be directly related to the temperature. Moreover, if the temperature and the field geometry of the closed structures
can be derived by independent measurements, the scale height can be used to determine the strength of the transverse field.

However, the temperature derived for the coronal hole region is probably valid.* If one assumes that the scale heights measured at the limb also define the range of values for the similar closed structures observed on the disk, the comparisons of intensity measurements made near the Sun center through the thin organic filter can be used to derive the conditions at the base of the corona. Krieger et al. (1973) found a temperature of $1.5 \times 10^6$ K at a density of $2.7 \times 10^9$ cm$^{-3}$.

5. Summary and Conclusion

The attainment of a spatial resolution capability of the order of several arc seconds in the AS&E soft X-ray observations has enabled a wide variety of coronal features to be recognized and their morphology studied. Quantitative data reduction and analysis

![A composite print of the solar corona on March 7, 1970 composed of an X-ray exposure in the 3–36 Å, 44–64 Å wavebands and the radial density gradient filter white light exposure of Newkirk and Lacey (1970). There is a one-to-one correspondence between the position of the bases of white light coronal structures and regions of enhanced limb brightening in the X-ray image.](image)

* Any plasma acceleration due to coronal expansion will reduce the scale height at a given temperature relative to a static corona, but this effect should be negligible in the first few scale heights.
<table>
<thead>
<tr>
<th>X-ray structures</th>
<th>Corresponding features at other wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Magnetic field (photosphere)</td>
</tr>
<tr>
<td>X-ray active regions</td>
<td>Strong bipolar fields</td>
</tr>
<tr>
<td>Bright loops crossing neutral line. Very bright, low core</td>
<td>Hard spectrum (high temperature). Very hard spectrum</td>
</tr>
<tr>
<td>Active region interconnections</td>
<td>Complex of activity</td>
</tr>
<tr>
<td>Large scale arches connecting active regions; may connect preceding polarities across equator a</td>
<td></td>
</tr>
<tr>
<td>Large scale coronal structures</td>
<td>Unipolar magnetic regions and 'ghosts' at footpoints of coronal structures</td>
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<td>Large scale loops and arches connecting regions of opposite polarity</td>
<td>Softer spectrum than active region interconnections</td>
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<tr>
<td>Coronal bright points</td>
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</tr>
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<td>Small bright features which appear randomly distributed on the disk in long exposures through thin filters</td>
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Table II (continued)

<table>
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<th>Filament structures</th>
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<th>Softer spectrum than active region interconnections</th>
<th>Bipolar fields bordering filament</th>
<th>Dark filament or aligned fibril structure (filament channel)</th>
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<th>Helmet structures</th>
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<td>Coronal holes</td>
<td>Large non-emitting area bordered by diverging structures; very low scale height at limb</td>
<td>Low scale height implies probably softer spectrum than large scale coronal structures</td>
<td>Weak, unipolar fields (diverging in corona)</td>
<td>No distinctive feature</td>
<td>No distinctive feature</td>
<td>Low density coronal hole</td>
</tr>
<tr>
<td>Soft X-ray flares</td>
<td>Extremely bright core of few arc seconds width at a point on the neutral line; may or may not be accompanied by enhanced emission from active region</td>
<td>Extremely hard</td>
<td>Strong bipolar fields</td>
<td>Flare</td>
<td>Flare</td>
<td>?</td>
</tr>
</tbody>
</table>

* Most active interconnections do not cross the equator rather they proceed from one active region to another adjacent one. Those which cross the equator are probably identifiable as trans-equatorial arches. The others probably manifest themselves as intermediate helmets in the K-coronameter data.
techniques are also being developed to permit the physical characteristics of these features to be studied.

Since many of the coronal structures identified in the X-ray photographs differ significantly in appearance from their counterparts at other levels in the solar atmosphere, it is valuable to summarize their observed characteristics in the form of a table (Table II).

Comparison of the different types of X-ray emitting features with the underlying magnetic field structures, or Hz and CaK features has been possible for most of the past AS & E rocket flights. Thus, in general, the correspondences between features seen at photospheric and chromospheric levels and those seen in the low corona are well known.

In the case of the outer coronal observations, however, the situation is less well defined. One flight, that of March 7, 1970, occurred at the time of a solar eclipse. Accordingly, the soft X-ray data were compared with the white light radial density gradient filter photograph of the corona of Newkirk and Lacey (1970). Figure 23 is a superposition of the soft X-ray photograph and the white light photograph. The detailed correspondence between inner and outer coronal structures on these photographs was discussed by Van Speybroeck et al. (1970). In the absence of additional eclipse data an attempt has been made to equate outer coronal structures with low coronal features on the basis of the published properties of the former (Hansen et al., 1972; Dunn, 1970).

The availability of higher resolution X-ray images in the near future will doubtless result in the discovery of other characteristic coronal features.

With the exception of the two flare observations no studies of the temporal variations of coronal features have been possible with the existing soft X-ray images. The observations have however triggered many questions concerning the temporal variations of the structures seen. The development of an active region, from its appearance as an emerging flux loop to its gradual disintegration into wide spread unipolar areas presents a fascinating study. The possibility of observable coronal field geometry changes being seen to accompany flare events, or radio bursts will also lead to interesting investigations; as will the life history of coronal bright points. The development of coronal holes, their evolution as a function of time, and their relationship to the solar wind also presents an interesting problem. These questions, as well as many others requiring variable time resolution data cannot be answered by sounding rocket observations. Hopefully, they will, however, be answered through analysis of the data returned from the AS & E soft X-ray telescope launched on the Apollo Telescope Mount (ATM).

Quantitative analysis of soft X-ray image data is still in its infancy. However, a number of refinements have recently been made in the techniques used to measure the surface reflectivity and scattering properties of X-ray telescopes and in the techniques of calibration of X-ray films. The result is that the determination of coronal temperatures and densities from the soft X-ray images is becoming more precise. The inclusion of collimated crystal spectrometers in the new telescope payload will also advance the
quantitative study of coronal conditions from X-ray images by providing simultaneous high resolution soft X-ray spectra of the coronal features observed.

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