Reports

X-ray Structures of the Sun during the Importance 1N Flare of 8 June 1968

Abstract. *High-resolution solar x-ray images were obtained with a rocket-borne grazing incidence telescope. The x-ray flare is large in extent, has fine structure, and follows a neutral magnetic line. X-ray emitting coronal links interconnect active regions. The general coronal emission at the limb and several faint regions on the disc are observed.*

In order to study the physical processes that govern the onset and development of solar flares, we have flown an x-ray telescope on a pointed rocket platform and obtained high-resolution x-ray photographs of the sun while a flare was in progress. The principal result was that structural features only a few arc seconds in extent were observed in the x-ray flare. The photographs also show x-ray emitting regions associated with plages and the general x-ray coronal emission. Spectral data were acquired by means of broad band filters; dispersed spectra of individual active regions were also obtained by means of a new slitless spectrograph.

X-rays from the sun are the most sensitive indicators of solar activity, and they are useful for studying the physics of regions containing extremely high temperature plasmas or high energy electrons. The study of solar x-ray emission has been well reviewed (*1*).

The cogent physical parameters can only be defined if spatial and spectral distribution of the radiation from the regions being investigated are known. Several groups of investigators using pinhole camera techniques have obtained x-ray images of the sun (*2, 3*). Grazing incidence telescopes of the type suggested for x-ray astronomy by Giacconi and Rossi (*4*) have been used by others (*5, 6*).

Structural details of 20 arc seconds could be resolved in the best (*6*) x-ray photographs previously obtained. The information on the spectral distribution of the radiation from particular solar regions was obtained with the use of broad band filters. On the other hand, dispersed x-ray spectra of the sun as a whole have been obtained by numerous groups (*7*). Our group has directed its efforts to obtaining high-resolution x-ray images and spectra of each individual emitting region at the same time (*8*).

The x-ray telescope carried in this rocket payload consists of a paraboloid and hyperboloid which are co-axial and con-focal (*5*). The incident soft x-rays are reflected once from each mirror at a grazing angle and form a real image of the distant x-ray source in the focal plane. The telescope has a collecting area of 34 cm^2 and a focal length of 132 cm and is larger and more sensitive than any flown before. The speed is sufficiently high so that a relatively slow, high-resolution film (Panatomic X) may be used even in one of the shortest exposures (2 seconds) and still yield adequate film densities both in the plage regions and in the flare. In the flare region, details only 2 arc seconds in size can be distinguished in the original negatives.

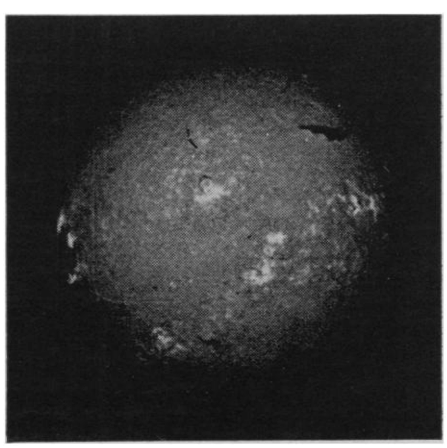

Fig. 1. Photograph of the sun in Hα light at 1555 U.T., approximately 2 hours before the x-ray observations. There is a striking correlation between the Hα active regions and the x-ray emitting regions (cover). The orientation is the same as the cover photo, heliocentric north being approximately 30° counterclockwise from the bottom, and east on the right. [Courtesy of ESSA Boulder Observatory]

The camera consists of a rotating 12-sided drum to which individual film and filter combinations were attached. The different filters transmit different x-ray wavelength intervals and exclude solar visible and ultraviolet radiation from the film.

A soft x-ray transmission grating, successfully used for the first time, was positioned immediately behind the telescope, was launched in a folded position, and was deployed for the last four exposures. The combination of the telescope and the grating constitutes a soft x-ray slitless spectrograph (*9*). The grating disperses part of the radiation being focused on a given point into spectra of various orders which then bracket that point. The grating for this flight consisted of a Parylene substrate (1 μ thick) upon which 1440 parallel gold strips per millimeter had been deposited by vacuum evaporation. The dispersion in the first order is 0.50 arc min/Å, or 0.15 mm/Å in the focal plane.

The rocket was launched within a few minutes of the observation of a solar flare by an alarm network of ground-based solar observatories. Simultaneous ground observations were made in the Hα and Ca II chromospheric lines, in the centimeter and decameter radio wavelengths, and in the 5303-Å coronal line. In addition, three experiments (*10*) carried on the OSO-4 (Orbiting Solar Observatory) satellite should furnish the following: (i) spectra obtained with Bragg crystal spectrometer on the sun as a whole (Naval Research Laboratory group), (ii) life history of the flare with high time resolution obtained with proportional counter technique (University of Leicester–University College of London group), and (iii) images of the sun obtained every 300 seconds, before, during, and after the flare with a resolution of 4 arc minutes (American Science and Engineering group). We now describe certain qualitative features resulting from the inspection of the x-ray pictures and from the correlation with data now available to us.

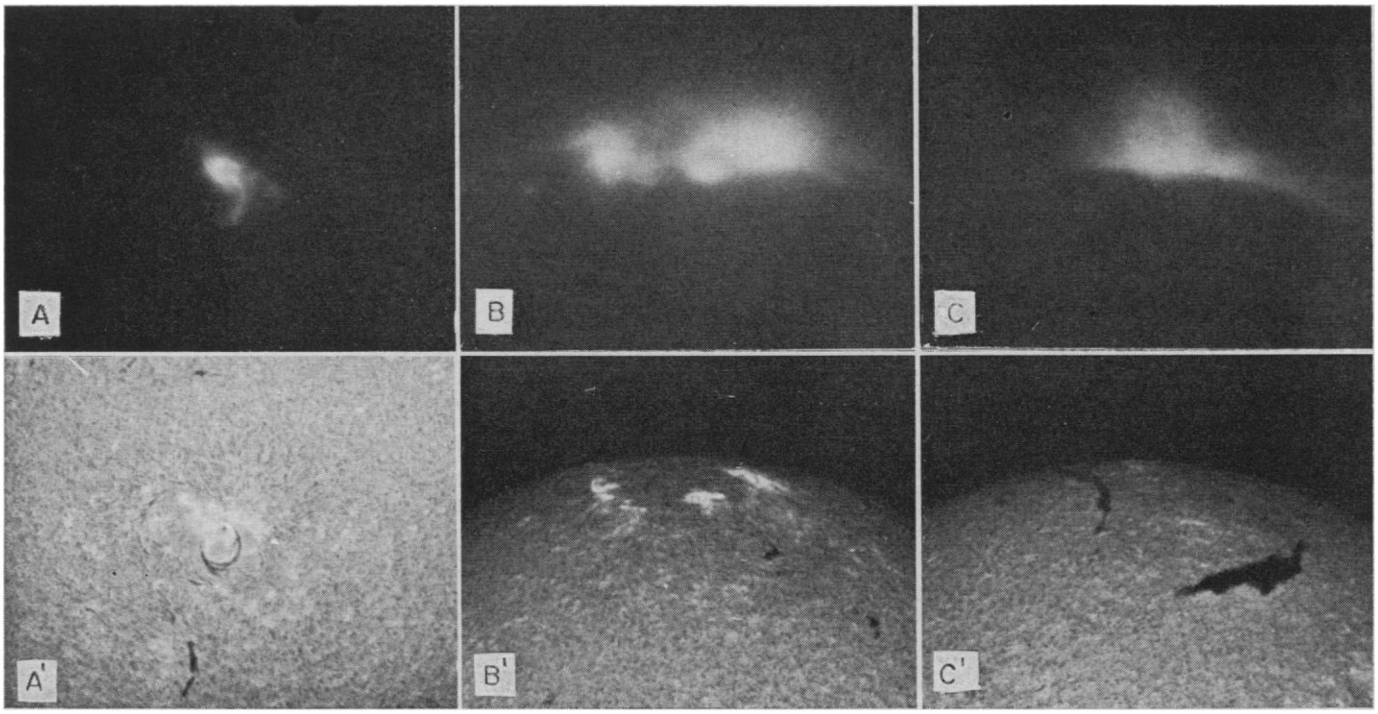

Fig. 2. A, B, and C are x-ray images of selected portions of the sun. A′, B′, and C′ are Hα photographs of the corresponding portions taken 2 hours before the flight. Corresponding images are oriented the same way. A is the flare region in the 3.5 to 14 Å passband (exposure V). The S-shaped structure (brightest portion of the flare) follows the neutral line marked by the filament (A′), which had disappeared, as discussed in the text. Portions of the filament extend to the top and left of the sunspot and then up. B is the group of plages in the southwest quadrant close to the limb. At least three arches that interconnect regions can be distinguished. The connections are absent in Hα. C is the loop structure at the southeast. It extends over 150,000 km above the limb; no counterpart of the loop is visible in Hα, but the green coronal line (5303 Å) was strong in that portion of the limb, and a plage region rotated from the limb 2 days later. [The Hα photographs by courtesy of ESSA Boulder Observatory]

On 8 June 1968, the sun was moderately active. Over a dozen active regions were present on the disc, the most prominent being the one where the observed flare developed. This region (identified as McMath No. 9429) had, since its first appearance on the east limb on 2 June increased in plage area and intensity, spot group area and number, flux at 9.1 cm, and flare activity. For a number of hours before the flare, the active region had shown brightening fluctuations. A filament associated with this region had been active in the blue wing of Hα and underwent a *disparition brusque* some 30 minutes before the flare. Prior to disappearance the filament was located along the neutral line of the magnetic configuration, as inferred by the polarity of the sun spots and the fine structures of the Hα (*11*). The observed flare was a large 1N flare of the parallel ribbon kind. It was accompanied by centimeter-microwave bursts superimposed on a very small gradual rise and fall in all the microwave region of duration comparable to the Hα flare. Continuum decameter emission began at 1600 U.T. and lasted through 1900 U.T. The flare was also accompanied by an ionospheric disturbance. The Hα flare onset was at approximately 1732 U.T., reached the maximum at about 1745 U.T., and lasted about 1.5 hours. The rocket was launched at 1740 U.T., acquired the sun at 1742 U.T., and obtained exposures until 1745 U.T. The pointing control, developed by the Sounding Rocket Branch of Goddard Space Flight Center, achieved the unprecedented accuracy of ± 1 second of arc (jitter) throughout all of the exposures.

The exposure time, filter, film, and nominal wavelength passband for each of the exposures are listed in Table 1. There are a number of new significant facts which have emerged from our "quick-look analysis" of the photographs. A few selected images (*12*) (or portions of images) are presented on the cover and in the figures. The most significant results are summarized below.

1) *Flare*. The flare itself is by far the most impressive of all the x-ray emitting regions. A 6-second exposure (cover) on Pan-X film with a 3.8-μ Mylar filter shows the flare somewhat overexposed in the central portion of the image. The inner structure of the flare is better displayed in Fig. 2A, a 2-second exposure with a 13-μ beryllium filter and Pan-X film.

We first observe that the flare region is more than an order-of-magnitude (*12*) brighter than all of the other plages, and that the x-ray emission is distributed into two main structures, each several minutes of arc in length and approximately 20 seconds of arc across. One of the structures is a ribbon running from northeast to southwest; the other structure, to the south of the first, is an S-shaped feature. We have not yet received the Hα photographs taken during the rocket flight. However, from correlation with an Hα image (Figs. 1 and 2A′) taken before the flight, and from discussion with McIntosh, the observer at Environmental Science Services Administration (ESSA) at the time of the flare, we have been able to establish that the general structure of the x-ray flare strikingly resembles the one of Hα. The portions of the flare brighter in Hα are also brighter in x-rays and with much higher contrast. The brightest portion of the x-ray flare (part of the S-shape structure) seems to follow the location of the active filament that had disappeared (Fig. 2, A and A′). The flare also shows many

Table 1. Films, filters, and exposure times.

Frame	Exposure time (sec)	Filter size (μ)* and material	Film †
I	22	13 Be	103-0 un-TC
II	2	50 Be	Pan X TG
III	6	13 Be	Pan X TC
IV	19	13 Be	Pan X un-TC
V	2	13 Be	Pan X TC
VI	6	3.8 Mylar ‡	Pan X un-TC
VII	18	2.5 Steel	103-0 un-TC
VIII	2	Visible	Pan X TC
IX	6	3.8 Mylar ‡	Ilford Special §
X	6	13 Be	103-0 un-TC §
XI	22	13 Be	103-0 un-TC §
XII	52	13 Be	103-0 un-TC §

* The filter thicknesses given are nominal. The approximate wavelength passbands are: 13 μ beryllium (3.5 to 14 Å); 50 μ beryllium (3.5 to 10 Å); and 3.8 μ Mylar (3.5 to 14 Å and 44 to 60 Å). † "TC" or "un-TC" are with or without a protective gelatin layer, respectively. ‡ About 2200 Å of aluminum was evaporated on the Mylar. § Exposures with the transmission grating.

small features that are not observed in nearby active regions; for example, in the original negative of Fig. 2A, two filaments about 2 seconds of arc across and separated by 5 seconds of arc are clearly visible (*13*).

2) *Active regions.* All regions active in Hα (Fig. 1) have counterparts in the x-ray photograph (cover); even small Hα brightenings like those at approximately 30°W and 70°W close to the equator have corresponding brightenings in x-rays. Closer examination reveals that correspondence between the Hα and x-ray images of a region depends upon the position on the solar disc. The x-ray emitting regions, when close to the center of the disc, seem to conform rather well with the shape and boundaries of Hα bright regions. The x-ray images near the limb (Fig. 2B), however, show a looping and interconnecting of active regions which are not found in the Hα images (Fig. 2B′); one sees x-ray structures extending 100,000 km or more above the Hα plage. Finally, at the limb (Fig. 2, C and C′) there are loops and structures similar to those seen in white light photographs of the corona. The x-ray loop structure does not have a corresponding Hα counterpart; however, spectra taken at Sacramento Peak show that the green line (5303Å) was strong in that portion of the limb, and 2 days later a weak plage region rotated onto the disc.

The x-ray emitting regions appear to be the same size in the wavelength intervals from 44 to 60 Å and from 3.5 to 14 Å. This observation is based upon a comparison of exposures with Mylar and beryllium filters, which had equivalent photographic densities as a result of appropriate exposure-duration ratios.

3) *General corona.* The general coronal emission not associated with flares or plages is evident in the Mylar filter exposures, such as the cover page, which include the 44 to 60 Å region. Since this emission does not appear in the longest exposure with the beryllium filter (3.5 to 14 Å), we conclude, in agreement with conclusions from previous observations, that the general coronal emission is somewhat softer than the emission associated with the plages or the flare. We also find distributed over the disc weakly emitting regions which are not plage-associated, and thus confirm an observation made in one of the earlier flights (*5*). These features are seen in the Mylar filter exposure, for example in the north portion of the disc (cover), but cannot be found in the beryllium exposures; therefore, this emission is also softer than that associated with plages.

Finally, the results show that the x-ray slitless spectrograph technique is valuable where high speed is required; and it should be particularly useful in the study of transient phenomena and in obtaining spectral data separately from each of several small active solar regions. The four transmission-grating exposures contain spectra of each of the active regions including the flare. Exposure X (Table 1) is shown in Fig. 3. Several emission lines or blends can be observed in the original negatives; the lines are particularly evident in the higher spectral orders. The most prominent flare line (also found in some of the plage spectra) occurs at about 9.2 Å. This is consistent with either Mg XI or Fe XXI lines which have been observed by other experimenters (*3*, *7*). The envelope of the spectra from the several regions can also be observed.

The following considerations indicate certain qualitative features which must be included in models of flares and other manifestations of activity. Consider first the flare. It has been shown that the x-ray emission contributes a large fraction of the energy released (*14*). From the film density and the flare size, we estimate that the soft x-ray output of this flare is of the order of 10^{30} to 10^{31} ergs. We consider it important that the x-ray flare is extended in area at the time of the Hα maximum brightness. If we make the conservative assumption that the ribbons of the flare have circular cross sections with diameters equal to their observed widths, we find that the apparent volume of the flare is in excess of 10^{28} cm^3.

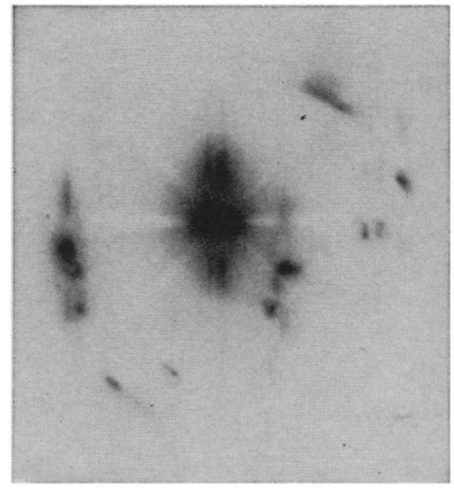

Fig. 3. One of the four exposures of the sun obtained with a slitless spectrograph technique. The direction of dispersion is top to bottom, and the orientation is the same as that of Fig. 1 and the cover photo.

The spatial correspondence between the x-ray and the Hα flare indicates a close link between the two emission phenomena; this is puzzling because of the large difference in degree of ionization required to account for the x-ray and the Hα emissions. One possibility is to envisage a strong magnetic connection between the two regions to account for the similarity in shape. The x-ray emission associated with the other plage regions suggests such a magnetic link. For the flare, however, there is the difficulty of having to assume a strong stable magnetic link, while at the same time of having to require a sudden change of the magnetic configuration in order to account for the observed radiation.

Finally, we note the significance of the spatial association of the x-ray emission with the disappeared filament, and hence with the magnetic neutral line. A number of flare theories emphasize the role of the neutral line not only in the magnetic storage mechanism, but also in the trigger and first-release process. Previously only observations in visible light yielded data bearing on this question, but the x-ray emission is more directly connected to the energetic particles involved in the primary process.

We discuss next the active regions. The x-ray images are descriptive of the three-dimensional coronal structure of the plages. The overriding impression from the photographs is that the x-ray emitting regions resemble the Hα regions at the base of the corona, but that at higher levels the x-ray emitting regions are rich in looplike structures which interconnect Hα active regions and are largely determined by the magnetic field. This interpretation strengthens theories that attribute the extra heating in upper layers of active regions to the presence of an enhanced magnetic field. We interpret the similar size of the x-ray emitting regions in the 44 to 60 Å and 3.5 to 14 Å wavelength intervals, both at the limb and on the disc, as evidence that the x-ray active regions as a whole do not show large-scale temperature structure. On the other hand, temperature structure may be present on a scale small with respect to the size of the regions, perhaps in a multilayer ropelike volume with strong magnetic field confinement.

With regard to the general corona, the following considerations apply. By comparing the x-ray with the Hα image we associate the weakly emitting regions with the brightest portions of the chromospheric magnetic network. It has been suggested that, in the heating mechanism of the corona, the magnetic field of the network plays an important role (*15*). We believe that the general x-ray corona at the limb is related to the weakly emitting regions on the disc associated with the brightest features of the network. The softness of the spectra from both regions is also consistent with our opinion that these are two views of the same type of activity.

Several flare events must be studied before we can determine whether the features we observe are a common characteristic of all flares. Our overriding impression from the analysis of these photographs is that more detailed understanding of solar phenomena can be achieved by modest improvement of spatial resolution in the x-ray region of the spectrum. The dominant role played by magnetic fields in the storage and release of energy in the solar atmosphere can be perceived from the correlation between Hα and x-ray structures, the existence of loops interconnecting active regions, and the development of the x-ray flare along a neutral magnetic field line.

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References and Notes

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8. This effort is being conducted under the sponsorship of the Solar Physics Branch of NASA Headquarters. The payload used in this experiment is a scaled-down version of a more sophisticated experiment we are preparing for flight in a manned solar mission (Apollo Telescope Mount) carried out by NASA's Marshall Space Flight Center.
9. The spectrograph was suggested by H. Gursky and T. Zehnpfennig, *Appl. Opt.* **5**, 875 (1966), and developed by T. Zehnpfennig, *ibid.*, p. 1855.
10. Papers on the performance of, and on the preliminary result from, the three instruments have been presented at the American Astronomical Society Special Meeting on Solar Astronomy, Tucson, Arizona (1 to 3 February 1968) by H. Friedman *et al.;* J. L. Culhane *et al.*; and F. R. Paolini *et al.*; and at the Midwest Cosmic Ray Conference, Iowa City, Iowa (1 and 2 March 1968) by F. R. Paolini *et al.* and G. S. Vaiana *et al.*
11. P. S. McIntosh, personal communication; a magnetogram taken 9 June 1968 by R. Howard (Mount Wilson and Palomar Observatories) confirms the statements on the neutral line.
12. The 10^3 dynamic range of the negatives is larger than that of the printing paper, and we have had to compress the original density of the negatives in order to show both the brightest and faintest features; this has resulted in a considerable loss of contrast in the print. The faint halo visible around very intense features is an instrumental effect due to the wings of the telescope response to a point source. The dark rays in the halo are shadows of the ribs in the telescope aperture plates.
13. Such fine details can only be observed near the optical axis where the best resolution is obtained; there are, however, active regions that are as close to the optical axis as the flare and do not show the same type of fine features.
14. A. Bruzek, in *Solar Physics*, R. S. Xanthakis, Ed. (Interscience, London, 1967), p. 414.
15. D. E. Osterbrock, *Astrophys. J.* **134**, 347 (1961).
16. We thank the staffs of ESSA, Sacramento Peak, McMath, Lockheed, and Sagamore Hill Observatories for providing flare alarm and ground measurements, in particular, D. Bucknam and R. Decker (ESSA) for coordinating the alarm network. We are indebted to R. Howard and H. Zirin (Mount Wilson and Palomar Observatories); W. Livingston and N. Sheely (Kitt Peak Observatory); W. Curtis (High Altitude Observatory) for additional ground measurements; also P. S. McIntosh for help in interpreting the Hα features discussed. We thank the personnel both of the Sounding Rocket Branch of Goddard Space Flight Center and of the White Sands Missile Range who supported us while we waited for the flare; we thank A. De Caprio, R. Haggerty, H. Manko, and D. Yansen (AS&E) for technical support. Supported by contracts NASW-1555, NASW-1700, and NAS 5-9041.

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The Effect of Mass on Frequency

Abstract. *Two experiments are described where an apparent decrease in frequency was detected when the optical path was in the vicinity of a mass. In the first experiment the 21-centimeter absorption line from Taurus A was observed near occultation by the sun. In the second experiment the frequency of a portable cesium clock was compared with the frequency of a similar clock which transmits its signals from Cape Fear, North Carolina. A decrease of frequency of the received signals as a function of the distance between the two clocks was apparent. Several relevant observations (the red shift of lines from the sun, the Mössbauer determination of the gravitational red shift, and the cosmological red shif) are discussed in view of the present results.*

Two known effects can change the frequency of a spectral line: the Doppler effect and the gravitational red shift. Because so much importance is attached to deviations of the frequencies of lines coming from stars and galaxies, we tried to devise and perform experiments that may disclose further influences on the frequency of a line. This report describes experiments aimed at finding an effect of mass on the frequency of light passing near the mass.

During the annual approach (every June) of the radio source Taurus A to the sun, one can measure whether the 21-cm absorption line from Taurus A changes its frequency. Such an experiment was performed by us (*1*) and the results indicated a decrease of the frequency when the optical path approaches the sun. This same experiment was repeated with better instrumentation this year and once again a decrease was detected. Figure 1 shows the observation of a decrease in frequency upon closest approach. Several controlled experiments were performed to avoid any instrumental or systematic error (*1*).

If the Taurus A experiment showed