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THE 15 JUNE 1973 1B/M3 FLARE: AN OVERVIEW OF ANALYSIS RESULTS

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16. ABSTRACT

An overview of the data analysis results reported in the literature, to date, of the 15 June 1973 1B/M3 flare is presented. Some 30 papers have been published relative to this event. This work was performed to assist the participants of the Skylab Solar Workshop Series B on Solar Flares to become familiar with one of the best observed flares during the Skylab mission.

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THE 15 JUNE 1973 1B/M3 FLARE: AN OVERVIEW OF ANALYSIS RESULTS

I. INTRODUCTION

One of the largest events of the Skylab mission was the flare of 15 June 1973. It was a two-ribbon flare located in McMath 12379 (NOAA AR131) at N17W32, which started at approximately 1405 UT, peaked at 1413 UT, and ended at 1455 UT [1]. In optical class notation, the event was designated "1B" (brilliant). Associated with this H-alpha flare was an x-ray event, which at peak intensity was designated "M3"; i.e., the peak x-ray intensity was approximately 3×10^{-2} erg cm^{-2} s^{-1} as measured by the 1 to 8 Å ionization chamber aboard SOLRAD 9 [2]. In x-rays, the event started at approximately 1355 UT, peaked at approximately 1414 UT (1 to 8 Å passband), and then slowly decayed to approximately 1×10^{-3} erg cm^{-2} s^{-1} at 1444 UT. The temperature peaked at 1412 UT, having a value between 12 and 16×10^6 K, derived from both x-ray and EUV data [3-7]. Peak density occurred at 1416 to 1417 UT, having a value of approximately 2.7 to 5.3×10^{10} cm^{-3}, dependent on assumed volume [3-7]. Type III radio bursts and 2.7 and 5.0 GHz microwave bursts preceded the maximum emission indicating that the event was extremely energetic.

Many papers have appeared in the literature concerning this flare. Because it was the major flare of the first manned Skylab mission, was observed by many instruments, is presently undergoing continued investigation by the Apollo Telescope Mount (ATM) experimenters' data analysis teams, and will be one of the flares discussed at the Skylab Solar Workshop Series B on Solar Flares, it may be useful to have a document which summarizes the analysis results to date of this truly complex event.

II. DISCUSSION

Widing and Cheng [3] have reported observations from the Naval Research Laboratory (NRL) slitless objective-grating spectrograph (Skylab ATM/S082A) of the 15 June flare and have determined some of the physical parameters of the plasma based on SOLRAD 10 data. The Fe XXIV (192.1 Å, 255.2 Å) emission was observed at 1411.7 UT at its maximum extent and approaching peak brightness. The Fe XXIV images remained visible for approximately 8 or 9 min after the first observation and showed considerable changes in structure and intensity. Further, the Fe XXIV emission was centered over the neutral line (as observed in the longitudinal component of the magnetic field), forming a bridge-like structure between magnetic regions of opposite polarity, and appeared as a cylindrical arch with a projected length of 26 000 km. Jordan [8] has shown that the emissivity of Fe XXIV is a maximum at 17×10^6 K, dropping off sharply with lower temperatures; thus, while the temperature at flare maximum was not strictly obtained from the Fe XXIV images, their disappearance at 1419 UT implied that the temperature in the main body of the flare had dropped below 10×10^6 K. Furthermore, the rapid brightening of typical coronal lines (Fe IX-XV) observed at 1423 UT indicated that the temperature had dropped to approximately 5×10^6 K. Widing and Cheng deduced a temperature of 16×10^6 K and a density of 5×10^{10} cm^{-3} (assuming a flare volume of 10^{27} cm^3) at 1412 UT. Following a method of Culhane et al. [9], they found that a cylindrical loop at an initial peak temperature of 20×10^6 K with the previously described physical properties would cool by conduction to 10×10^6 K in approximately 5 min. This is somewhat shorter than the 8 or 9 min observed lifetime, but is consistent with the data if the energy release occurred as late as 1415 UT. They also suggested the possibility that considerable turbulence was generated by the flare instability which may have inhibited the heat conduction and thus increased the cooling time [10-14].

Godoli et al. [15, 16] have reported results of optical studies of AR131 and the 15 June flare. AR131, located near latitude 15N and Carrington longitude 220°, was observed on two solar transits and was found to grow rapidly and decrease much more slowly, with flares occurring only in its first solar transit. The flare's eastern ribbon was observed to occur outside the spot group, while the western ribbon appeared to be located between the two spots of the group. The group was of the αp Mt. Wilson magnetic classification. Flare activity apparently was associated with the disappearance of a disk prominence whose western end was located just on the largest spot of the group. This occurred at 1405 UT. Prior to this at 1355 UT, the prominence, which had appeared as a short segment, assumed the appearance of a "cross." Godoli et al. also noted that an area contraction preceded the flash phase of the flare.

Brueckner [17, 18] has reported the identification of a number of UV lines (1170 to 1950 Å) in spectra obtained with the Skylab ATM/NRL spectrograph of the 15 June flare. For comparative purposes, Brueckner showed a spectrum which was photographed at 1412 UT near flare maximum and one which was photographed at 1438 UT. One of the most interesting findings is that of a line at 1354 Å, which is probably due to a forbidden transition of Fe XXI (1355 Å ± 3 Å), indicating an ion temperature of approximately 20×10^6 K. In addition, he found that (1) line profiles of medium ionized lines (transition-region lines) showed the most pronounced broadening and shifts, (2) typical values of these line widths corresponded to velocities of 70 km/s^{-1}, (3) shifts of the same magnitude were observed, (4) intersystem lines were not broadened or shifted, and (5) forbidden coronal lines, including intersystem lines, became enhanced in the flare spectrum at the moment when the turbulence seen in the allowed transitions disappeared.

Also, Brueckner [19] has described in detail the Skylab ATM/NRL XUV and UV observations of the 15 June event and contrasted it with the 9 August 1973 and 21 January 1974 flares. He described the flare in terms of a preflare phase, flash phase, explosive phase, and cooling phase. A change (i.e., the relocation of loops) in the Fe XV (284 Å) and Fe XVI (355 Å) emissions occurred between 0508 UT, prior to the flare, and 1411 UT, near flare maximum. Thirteen minutes prior to the flare onset (which he defined as being 1405 UT), additional changes in the Fe XVI emissions were noted. These changes included the brightening of an inconspicuous plage area whose Fe XVI emission became more intense than its Fe XV emission after flare onset, indicating a sudden heating of the plage. A growing absorption feature, attributed to a developing filament was also noted prior to flare onset. This feature was observed in Ne VII (465 Å) and Mg IX (368 Å), as well as Fe XV and Fe XVI. The first series of flare spectroheliograms was obtained at 1411 UT, approximately 6 min after flare onset, and thus are only representative of the latter part of the explosive phase. No coverage of the flash phase was accomplished. A comparison of Fe XV, Fe XVI, Fe XXIV, and He II images during and after the explosive phase showed a conspicuous narrow feature moving away with a projected velocity of 1100 km s^{-1} from a gap in the very intense bridge, indicating perhaps the location of its origin. Other small discrete broadened emission features were also noted and were interpreted to be clouds moving along or close to the direction-of-sight with high velocities. These features, again, seem to originate from a single small point within the active region. During the explosive phase, the entire flare ribbon seemed to consist of small, discrete, Doppler-broadened emission points. XUV images of the inner flare region in Ni XVII (249 Å), Fe XVI (263 Å), Fe XXIII (264 Å), Fe XIV (265 Å), Fe XXIV (255 Å), He II (243 Å, 256 Å), Fe XV (243.82 Å), and Fe IX (244.86 Å) indicated that, while most of the coronal lines seemed to outline the plage and the loop structure above it, the very hot emission from Fe XXIV and Fe XXIII was distinctly different. The formation of postflare loops appeared to begin when the Fe XXIV cloud began to disappear. As previously noted [17], lines from ions like Si III (1206 Å) or N V (1238 Å, 1242 Å) showed strong broadening and large shifts of the line profiles which lasted throughout the explosive phase of the flare until 1418 UT, when they suddenly disappeared. In contrast, all forbidden lines were not enhanced during the first part of the explosive phase but did appear strongly at the moment when the Doppler broadening of the resonance lines ceased. Further, they did not display the strong Doppler-broadening shifts like the transition-region lines. Brueckner has suggested that these lines may represent the recombination spectrum of the transition region and the cooling corona at the time when the nonthermal heating had stopped and the plasma returned to thermodynamic equilibrium. Brueckner concluded that the source of the prime-energy release in the flare was a small compact kernel, whose size was less than 2 arc s ($\sim$1400 km), determined by the spatial resolution of the NRL spectroheliograph [20]. Densities within the kernel exceeded 3×10^{12} cm^{-3}, and temperatures were greater than 20×10^6 K. Surrounding the flare kernel were hot clouds of coronal gas at 20×10^6 K, which were trapped below high magnetic structures and subsequently seemed to be the energy reservoir for heating postflare loops. The enhanced plages represent impact areas where high energetic particles were guided down to the solar surface along the loops and interacted with the photospheric materials. The high-speed mass motions had their origin in the exploding flare kernel.

Doschek et al. [21] have identified three forbidden lines [Fe XVIII (974 Å), Fe XIX (1118 Å), and Fe XXI (1354 Å)] observed with the NRL spectrograph from the 15 June flare. The lines are attributed to magnetic dipole transitions between levels of the ground configurations. Jordan [8] has shown that these lines have temperatures of maximum emitting efficiency of approximately 7×10^6 K for Fe XVIII, 9×10^6 K for Fe XIX, and 11×10^6 K for Fe XXI. The widths of the Fe XIX and Fe XXI lines were found to be approximately 0.5 Å, a value substantially greater than expected in ionization equilibrium. The mass motion deduced from these lines was greater at 1411 UT (the time of the first available spectrum), which was within 5 min of the microwave bursts that occurred near flare onset. No wavelength shifts of the forbidden lines larger than approximately 20 km s^{-1} were observed throughout the flare, which indicates that no large anisotropic motions occurred along the line-of-sight averaged over the bulk of material. Doschek et al. further deduced that the direct proton excitation rates in Fe XIX and Fe XXI appeared to be comparable to the rates due to electron excitation via cascades, and they obtained a total effective excitation rate ($cm^3\ s^{-1}$) for the upper level of the Fe XIX line that is larger by a factor of 1.45 than the corresponding rate for Fe XXI. Also, they found that the total integrated intensity of the Fe XXI line was comparable to the intensities of the N V (1239 Å, 1243 Å) lines.

Widing [22] has identified the intercombination line of Fe XXIII (263.7 Å) in NRL spectrograph observations of the 15 June event. He found that the intensity and time variations of Fe XXIII (263.7 Å) closely paralleled those of Fe XXIV (255 Å), except that the Fe XXIII emission was usually significantly weaker. Fe XXIII and Fe XXIV were present in the first spectroheliograms obtained at 1412 UT, a time that coincided with the end of the burst phase and the rise-to-peak flux in the SOLRAD 0 to 3 Å band. The temperature at this time was approximately 16×10^6 K. The Fe XXIII and Fe XXIV images disappeared together sometime after 1419 UT when the cooling trend became established and the flare temperature was below 10×10^6 K. The predicted intensity of Fe XXIII relative to Fe XXIV was found to be in qualitative agreement with the observed value. Significant characteristics of the Fe XXIII and Fe XXIV images included (1) an arch-like structure spanning the magnetic neutral line and (2) an emission core that may have been the site of the energy release. To explain the emission core, a temperature in excess of 20×10^6 K and, perhaps greater than 30×10^6 K, is necessary. Widing also noted that the pair of loops and bright knot observed in the Fe XIV and Si X images at 1423 UT may be structures which correspond to the Fe XXIV image with widened core at 1411.6 UT.

Cheng and Widing [23, 24] and Widing and Cheng [25] have summarized the results of spatial distribution and time evolution studies of flare plasmas obtained with the NRL XUV spectroheliograph (including the 1973 events of 15 June, 5 September, 16 and 17 December, and the 1974 event of 15 January). For the 15 June flare, the hot 10 to 20×10^6 K plasma as evidenced from Fe XIII and Fe XXIV images was located at the position of a gap in emission of the cooler plasma (He II to Fe XIV-XVI) which took the form of two ribbons. As the flare cooled, the Fe XXIII and Fe XXIV plasma disappeared and the region between the two ribbons filled gradually with emissions from lower-stage ions. Comparison between spectroheliograms and magnetograms shows that the basic magnetic field configuration associated with the flare was a low-lying (4 to 13×10^3 km) loop or arch structure. The flare may have resulted from a plasma instability in the loop which produced localized heating in a small volume near the top of the loop [26].

Poletto et al. [27, 28, 29] have investigated the correspondences between x-ray images and computed magnetic fields for the 15 June time frame (i.e., AR131). Although no magnetic field data immediately prior to the flare are available, postflare data (1522 UT and 1528 UT) reveal a general correspondence between the x-ray structure and extrapolated field line configuration (assuming the potential case). Poletto et al. noted that the preflare x-ray structure was quite similar to the postflare structure, differing only in the northern branch which appeared to be cooler. They concluded (where their conclusions are based on the 15 June 1973 Skylab and 7 March 1970 sounding rocket data) that (1) bright cores in x-ray images usually overlay the zero line of longitudinal magnetic field and are associated with field lines connecting adjacent areas of opposite polarity, (2) high x-ray loops inside active regions indicate an interconnection between widely separated areas and reach heights where the magnetic field intensity is of the order of a few gauss, and (3) magnetic interconnections between adjacent active regions correspond to weak, soft x-ray emitting structures interconnecting the active regions. Henze et al. [30] also have investigated the morphology and evolution of AR131 for June 1973.

Feldman et al. [31] have reported the identification of 193 C I lines between 1100 Å and 2000 Å in the XUV spectrum of the 15 June flare, based on observations obtained by the NRL normal incidence spectrograph on the ATM. Sixty-nine of these lines are new identifications. All identifications were based on spectra taken during the cooling phase of the flare to eliminate Doppler shifts. It was found that, in the flare spectrum, lines arising from high quantum states are comparable in strength to the C I resonance lines. Thus, it appears that recombination processes are dominant in solar flares and enhance the populations of the high quantum levels relative to the populations of low quantum levels.

Pallavicini et al. [4, 32] have investigated the x-ray spatial and temporal development of the 15 June 1973 flare [33] and also its correlation with radio emission. Using the Skylab ATM/S054 x-ray telescope (American Science and Engineering), observations of the event were obtained between 1411:14 UT and 1438:44 UT in sequences of five frames with exposures ranging from 1/64 to 4 s. The time interval between two consecutive frames with the same exposure was approximately 3 s for the first 4 min of observations and approximately 1 min for the remaining observations. All observations were taken with one filter having a passband of 2 to 17 Å. Pallavicini et al. have described the flare in terms of a preflare and early flare phase, flare evolution, and a postflare phase. The preflare phase [34, 35] corresponds to the time period 1352 UT to 1411 UT, flare evolution 1411 UT to 1438 UT, and postflare 1522 UT. AR131 in the preflare stage displayed a "V-shaped" overall appearance, with the two legs extending roughly to the NW and SW, and was of the order of 2 arc min in diameter. Brightening of the region and growth in the dimensions of the inner core were noted during this stage. An impulsive microwave burst and a group of type III bursts observed at frequencies of 4995 MHz and less were noted between 1408 UT and 1411 UT and are believed to be nonthermal in nature. During this period, the structure of the x-ray region changed from a single, bright filamentary structure to a rather complex system of loops. The bright core became elongated in an approximate NE-SW direction and was titlted by an angle of approximately 30° with respect to the filamentary structure observed at 1408 UT. A comparison of x-ray images (at 1359 UT and 1408 UT) and a Kitt Peak magnetogram obtained at 1507 UT indicate that the preflare brightening was localized in the general vicinity of the neutral line and was consistent with the brightening of loops extending from the same point east of the neutral line toward regions of opposite magnetic polarity in the NW and SW directions. The filamentary structure (1408 UT) was clearly seen to bridge the neutral line at a point along the NW branch and did not connect the most intense features on either side of the neutral line. H-alpha photographs taken before 1405 UT showed the filament to approximate the position of the neutral line in the flaring region. (McIntosh et al. [36] have examined the association between x-ray arches and chromospheric neutral lines.) After 1405 UT, the filament was no longer evident in on-band H-alpha filtergrams, and those taken at 1408 UT and 1409 UT indicated that the brightest regions of the optical flare lay on both sides of the neutral line in a location which suggests that they were the foot points of the x-ray filamentary structure (1408 UT). Thus, the preflare observations [37] suggest a heating of some material over a fraction of the active region much larger than that characteristic of the subsequent flare rise. X-ray images obtained after 1411 UT showed that the overall character of the flaring region was that of a compact structure changing in brightness but remaining well localized in the central part throughout the rise phase. (Poletto et al. [29] found that the bright compact core at the flare peak appeared to be associated with the clustering of the inner field lines in the field extrapolation.) The x-ray filamentary structures noted within the region suggest that the flare consisted of an assembly of loops of varying brightness seen superimposed in projection. During the decay phase, larger structures evolving in a NW direction approximately along the magnetic neutral line characterized the flare, which resulted in the flare assuming an elongated shape. (These structures attained calculated heights of $>10^5$ km.) A comparison of preflare x-ray images with the postflare-phase image (1522 UT) shows that substantial changes occurred in the active region. While the SW branch of the region was not greatly changed in size or brightness, the NW part, characterized by very large, filamentary loop-like structures extending in the NW direction well outside the flare core, was much more extended, with structures up to 2 arc min long and covering a region that was roughly twice the size of the SW branch. Pallavicini et al. [4] suggest that the formation of loop systems, as noted in the 15 June event, at successively increasing heights may be a characteristic feature of two-ribbon flares, not only at optical wavelengths but also in x-rays. The characteristic linear dimension averaged for the flare region along two orthongonal directions was estimated (within 20 percent) to be approximately 30 arc s near the flare peak (1415 UT ot 1420 UT) and to increase to approximately 43 arc s at approximately 1435 UT. Using SOLRAD 9 x-ray data, Pallavicini et al. deduced a peak temperature (10 percent error limits) of 12×10^6 K at 1412 UT and a peak emission measure (50 percent error limits) of 2.8×10^{49} cm^{-3} at 1417 UT. They noted that between approximately 1415 UT and 1435 UT, the temperature and emission measure decreased by factors of 1.7 and 4, respectively, and the volume increased by a factor of 2.7. The decrease in the emission measure with a corresponding increase in volume implies a decrease in density by a factor of 3.3. Pallavicini et al. also noted that for 15 400 MHz radio emission, the optical depth decreased from 0.1 at 1415 UT to 0.03 at 1435 UT, and the radio flux decreased from 18.3 to 7.6 solar flux units (SFU). These observed radio fluxes are in approximate agreement with theoretically derived values, which are 20.7 and 6.9 SFU, respectively. (These values were derived by using the SOLRAD values of temperature and emission measure.) Also, they noted that the 2695 MHz data yielded optical depths of 3.9 at 1415 UT and 1.0 at 1435 UT, and corresponding radio fluxes of 6.4 and 3.6 SFU, while the theoretically calculated values of radio flux were 5.3 and 4.0 SFU, respectively, for the same times. Following Culhane et al. [9], Pallavicini et al. compared the relative cooling times due to conduction and radiation. The comparison showed that radiation losses, assuming a Tucker and Koren [38] emission model, accounted for approximately one-half of the thermal energy lost by the region in the first 20 min after the flare peak. In contrast, assuming conduction along a cylindrical flux tube with a length of 2.2×10^9 cm and at an initial maximum temperature of 10×10^6 K, they found that the cooling proceeded much faster and, in fact, dropped to a temperature of 2.5×10^6 K instead of the observed value of 6.5×10^6 K in the 20 min period after the flare peak. Pallavicini et al. suggest that continued heating or inhibited conduction, perhaps by the constriction of lower magnetic flux tubes, played an important role in the cooling phase of the flaring region. It is to be noted that Pallavicini et al. have observed different parts of the flare to decay at different rates, and their analysis indicates that the central regions of the flare have shorter cooling times (perhaps conduction may be the dominant factor) than the regions surrounding the core which display more gradual decay. Also, while "kernels" are prominent features in the rise of most subflares [39-44] for the 15 June flare, they were not observed in the American Science and Engineering x-ray images to be a dominant feature.

Sandlin et al. [45] have reported new line identifications in the Li I, Be I, and B I sequences, including Ni XXVI (234 Å), based on a study of the 9 August 1973 and 15 June 1973 flares. They also classified a number of unidentified lines with respect to their estimated temperatures. The XUV lines are characteristic of plasma at 3 to 20×10^6 K, appear only in the early part of the flare, and decay after x-ray flare maximum. Because the Ni XXVI intensity was weaker than expected relative to other members of the Li I sequence for the 15 June event, Sandlin et al. suggest that the peak temperature must be $<20 \times 10^6$K (Ni XXVI maximizes at 20×10^6 K).

Widing and Dere [5,46] have reviewed the spatial and temporal evolution of the high temperature plasma (i.e., Fe XXIII, 263 Å, and Fe XXIV, 255 Å) associated with the 15 June 1973 flare, based on NRL/S082A XUV observations. They found that the overall event involved the successive activations of a number of different loops and arches which bridge the magnetic neutral line. Spatial shifts and brightening were observed in the Fe XXIII and Fe XXIV lines which are interpreted as the activation of new structures, and these phenomena continued for 4 or 5 min after the end of the microwave burst phase. Thus, additional energy release unrelated to the nonthermal phase of the flare is suggested. The "triggering" of loop instabilities may also have occurred. Further, Widing and Dere noted that the observed Fe XXIII and Fe XXIV intensities defined a postburst "heating phase" during which the temperature (based on the Fe XXIV/Fe XXIII ratio) remained approximately constant at 13×10^6 K, while the Fe XXIV intensity and SOLRAD 9 0 to 3 Å flux rose to peak values. This phase coincided with the activation of the densest structure ($N_e = 2 \times 10^{11}$ cm^{-3}).

Finally, the heating of higher loops continued into the decay phase, while the overall flux and temperature declined with the fading of the lower Fe XXIV arches.

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APPROVAL

THE 15 JUNE 1973 1B/M3 FLARE: AN OVERVIEW OF ANALYSIS RESULTS

By Robert M. Wilson

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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