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SMM X-RAY POLYCHROMATOR
FINAL REPORT

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The objective of the XRP experiment was to study the physical properties of solar flare plasma and its relation to the parent active region to understand better the flare mechanism and related solar activity. Observations were made to determine the temperature, density, and dynamic structure of the pre-flare and flare plasma as a function of wavelength, space and time, the extent to which the flare plasma departs from thermal equilibrium, and the variation of this departure with time. The experiment also determines the temperature and density structure of active regions and flare-induced changes in the regions.

The X-Ray Polychromator was a collaboration of the Lockheed Palo Alto Research Laboratory (K.T. Strong, principal investigator), Mullard Space Science Laboratory (R.D. Bentley, principal investigator), and Rutherford Appleton Laboratory (K.J.H. Phillips, principal investigator).

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1. INTRODUCTION

This report documents the major contract activities under the X-Ray Polychromator (XRP) contract NAS5-30431, which began in June 1988. The contract, originally scheduled to expire in May of 1993, was extended through the 7th of July to allow more time for putting together a Monograph of scientific results from the *Solar Maximum Mission (SMM)* (see section 4). This contract followed a previous XRP Contract, NAS5-28713, which ended in May 1988 (see Final Report for XRP Contract NAS5-28713). This report includes a Final Report for the *SMM* Guest Investigation of "Coronal Abundances and their Variations" by J. Saba (see section 6), which was incorporated into the XRP contract in the second quarter of 1992.

Under the new XRP contract, operation of the XRP instruments continued until shortly before the premature reentry of the *SMM* spacecraft in December 1989, an event hastened by vigorous solar activity in the early maximum of solar cycle 22. A brief description of the XRP instrument and its operational modes is given in section 2.

One of the major undertakings during the contract period was the design and implementation of a major data and software archive effort. The XRP archive is outlined in section 3. This XRP archive design has become the model used for the current *Yohkoh* mission.

Despite reductions in funding for the XRP contract, which critically affected the area of science analysis, a major effort was made to increase the scientific output of the XRP team. The result was a number of significant papers, including several which followed through on themes initiated in the previous contract, several papers that broke new ground, several major reviews, and three books; the XRP publications are discussed in section 4 and listed in the attached Bibliography.

Under the new XRP contract, the XRP team continued its strong interactions with the solar physics community both in terms of Workshops funded all or in part by *SMM* funds, by support of *SMM* Guest Investigators and other guest scientists, including three successful Ph.D. candidates, and in collaboration in observing campaigns and joint data analysis. The results of three workshops and a NATO/NASA summer school are discussed in section 5, along with a major review of the scientific highlights of *SMM*, a book which is being edited by three XRP scientists. There were many XRP presentations at solar physics meetings, particularly of the Solar Physics Division (SPD) of the American Astronomical Society (AAS), the American Geophysical Union (AGU), the Committee on Space Research (COSPAR), and the International Astronomical Union (IAU); most of these are listed in the attached XRP Bibliography.

Several attempts to support rocket observations or Max'91 Observing campaigns and a major worldwide observing campaign, International Solar Month, in September 1988, met with only limited success because of (1) instrument difficulties of either XRP or the collaborating instrument, or (2) low levels of solar activity, so that the XRP flare observing modes which were still possible could not be fully utilized. For example, stereoscopic observing by the XRP and other *SMM* instruments with the TEREK instrument on the

Soviet spacecraft *Phobos* were not realized when TEREK was lost enroute to Mars, although several valuable joint observations with ground-based and other *SMM* instruments resulted, such as a rare joint VLA/ *SMM* coronagraph/XRP observation of a coronal mass ejection (see Willson et al. 1991). Moreover, there were a large number of good XRP flare observations during several periods of high activity in the early solar maximum of 1989 (see, e.g., Wulser et al. 1992, and Zarro et al. 1992).

Many of the important scientific results during the contract period came from a consolidation of work begun in the previous XRP contract. These included such areas as flare dynamics, energetics, and heating studies (see, e.g., Zarro and Canfield 1989; Fludra et al. 1989; Canfield et al. 1990, 1991; Metcalf et al. 1990; Antonucci et al. 1990a, 1990b; Wulser et al. 1992; Bornmann and Lemen 1992; Sylwester et al. 1990, 1992, 1993; Dennis and Zarro 1993), flare abundance studies (see, e.g., Fludra et al. 1991, Schmelz 1993, Schmelz and Fludra 1993), multiwaveband analysis of active region data obtained during the Coronal Magnetic Structures Observing Campaign (CoMStOC) in November/December 1987 (see, e.g., Nitta et al. 1991, Brosius et al. 1992, Schmelz et al. 1992), X-ray spectroscopic diagnostics (see, e.g., Bhatia et al. 1989, Bromage et al. 1989, Doschek et al. 1990, Keenan et al. 1990, Cornille et al. 1992, Phillips et al. 1992), and major progress in the area of active region dynamics (see Saba and Strong 1991a, 1991b). A new research area that was explored during the period was the investigation of elemental abundances in the corona above active regions (see Strong et al. 1991, Saba and Strong 1992, Saba and Strong 1993). Additional funding through the *SMM* Guest Investigator program allowed a small project to follow up on some intriguing preliminary FCS results on active regions abundance variations. A report on the FCS abundance work is given in section 6.

2. XRP INSTRUMENT DESCRIPTION

The primary objective of the X-Ray Polychromator (Acton et al. 1980) was to study the physical conditions in the corona for a variety of solar phenomena. This was achieved through the use of two complementary instruments: the Bent Crystal Spectrometer (BCS), which continuously monitored the spatially integrated high temperature flux from flares, and the Flat Crystal Spectrometer (FCS), which could image an area of up to seven arcminutes square in six bright spectral lines simultaneously, or make rapid scans over a wide wavelength range or at high resolution across individual line complexes. XRP gathered data during the peak of solar cycle 21 (February to November 1980), during its decline (following the in-orbit repair of *SMM* in April 1984), and through the rise phase of cycle 22, until November 1989, when spacecraft fine-pointing was lost prior to reentry.

The XRP experiment was conceived to observe the spectral region between 1.4 and 22.4 Å. In the temperature regime of solar active regions and flares (2 – 50 million K), this region exhibits a rich emission-line spectrum. The experiment was especially prepared to take advantage of the plasma diagnostic opportunity offered by the spectra of helium-like ions and their satellites (Gabriel and Jordan 1972; Dubau and Volonte 1980).

The BCS had eight bent Bragg crystal spectrometers with position-sensitive detectors covering important X-ray lines of highly-ionized calcium and iron. It was collimated to six

arcminutes FWHM and was capable of changing its time resolution from 11 s to less than 0.5 s by using dynamic memory and sacrificing spectral coverage or resolution. The BCS was sensitive to the high-temperature ($T > 10$ million K) component of the flare plasma; the data are used to determine electron temperature, emission measure, dynamics, and elemental abundances of the plasma, and to look for nonequilibrium effects. For large events, the measured BCS count rates must be corrected for a dead time of about 40 microseconds, part of which depends on the position of photons along the anode. At sufficiently high count rates, (e.g., from mid-X class flares in the *Geostationary Operational Environmental Satellites (GOES)* system), spectral distortion resulted from the dead time. At lower rates, there was a simple suppression of the count rate. This suppression was a 10% effect at about $2550 \text{ counts s}^{-1}$ (corresponding to about a *GOES* class M4 flare). The maximum observable count rate in BCS Channel 1 was $8760 \text{ counts s}^{-1}$, corresponding to an incident rate of $23800 \text{ counts s}^{-1}$.

The FCS had seven Bragg crystal spectrometers that could be scanned in wavelength over a broad spectral range. At the "home position" of the wavelength drive, each of seven channels could monitor the emission from a prominent soft X-ray line. An additional channel produced a coarse-resolution solar white light image which could be used for coregistration. The FCS was sensitive to a wide range of plasma temperature (2 – 70 million K) and hence could detect everything from quiescent active regions to flares. By scanning its wavelength drive, the FCS could access an even wider range of soft X-ray lines and measure Doppler broadenings and shifts. However, electrical and mechanical problems with the FCS wavelength drive limited its ability to take spectra. In 1980 only four FCS experiments involving wavelength scans were run; about 400 successful spectroscopic experiments were run throughout the mission. The FCS isolated specific areas in the corona for study by using its narrow 14-16 arcsecond collimation. Images could be built up by series of raster scans across the region of interest.

Over the life of the mission, several of the BCS and FCS detectors became nonfunctional. BCS detectors 2 and 8 (high resolution Fe $K\alpha$ and Fe XXVI Lyman α) failed during 1980; BCS detectors 1, 3, 4, 5, 6, and 7 operated throughout the mission, with slow gain changes over time requiring occasional gain step adjustments. Most of the BCS analysis has concentrated on data from detectors 1 and 4, so the failures of detectors 2 and 8 were important but not critical. FCS detector 6, with its Ca XIX resonance peak offset from home position, failed in 1980; FCS detector 2 (Ne IX at home position) failed in February 1985. After June 1987, FCS detectors 1, 3, and 4 (O VIII, Mg XI, and Si XIII at home position), the remaining FCS low-energy detectors, were used only in campaign mode, in order to conserve the remaining gas supply for these thin-window flow counters as far as possible into solar cycle 22. During periods when the thin window detectors were turned off, it was possible to make flare spectral scans in the S XV and Fe XXV channels, and produce flare images complementary to the BCS flare spectra. By September 1988, the FCS wavelength drive had lost scanning capability, although it could still be repositioned to the peaks of bright emission lines for imaging. In April 1989, the flow-detector gas supply for detectors 1 and 3 was exhausted; shortly thereafter, the supply for channel 4 was gone, and the FCS became a flare imaging instrument only.

3. XRP ARCHIVE

3.1 XRP Data Archive

The XRP instruments generated a relatively large amount of data – approximately 40 Megabytes (MB) during a typical 24 hour period. In practice, the data volume was somewhat lower due to passage through the Earth's radiation belts (when data were not taken), instrument and spacecraft calibrations, support of non-solar observations by other instruments, and data loss due to Shuttle missions and other causes. During the *SMM* lifetime, the XRP instruments generated approximately 100 Gigabytes (GB) of data, including On Board Computer spacecraft data. The data were initially stored on approximately 3000 half-inch magnetic tapes. Apart from the cost of maintaining the data in that form, which would have required a large amount of space with a controlled environment indefinitely, handling of data in that form was also cumbersome and slow. Further, such a database did not include the reduction software or the various engineering logs as integral components. It was desired to provide rapid, direct access to the data. This would have been best achieved by archiving the data, catalogs, and software onto optical disks, which would dramatically reduce the handling problems because of the large capacity of optical disks. However, it would have required approximately fifty double-sided optical disks to archive all the XRP data, and the cost was too prohibitive. Instead, the medium chosen for the bulk of the archive was 8-mm Exabyte cartridges, and only a selected portion of the archive was put onto a single optical disk, as discussed below.

The XRP data archive consists of three archive data sets, all of which reside at the Solar Data Analysis Center (SDAC), Code 682.2, at Goddard:

- (1) The “raw data archive” (RDA), the unreformatted XRP data for the entire mission, during the periods February-November 1980 and April 1984 to December 1989; the RDA fits on seventy-nine 1GB capacity 8-mm Exabyte tapes, with each tape containing a complete month of unreformatted data.
- (2) The “processed data archive” (PDA), which contains the reformatted FCS and BCS data (FDA and BDA files, respectively) for flares with BCS Ca XIX count rates above 100 cps. Initially also transferred to Exabyte tapes, this level of archive now resides on forty 4-mm DAT tapes; the files are saved in VMS backup savesets (organized by month) with typically 2-3 months of data per tape, and with FDA and BDA files in separate savesets. Each file contains approximately an orbit of data pertaining to the flare event.
- (3) The “Selected Data Archive” (SDA), for approximately 1000 flares with BCS Ca XIX counts above 250 cps and/or about 400 FCS crystal runs, resides on one double-sided Optimum Optical disk, as well as one of the workstations at the SDAC.

3.2 XRP Catalogues

Catalogues of the FCS spectroscopic experiments run and of the BCS flares detected are available on computer at the Solar Data Analysis Center at Goddard or in hardcopy

form. Copies of BCS light curves for event registering above 100 cps in the Ca XIX channel are available on microfiche.

Also available on computer are the Pointing Log, the Engineering Log, and detailed listings of the instrument observing modes. Most of the engineering and pointing information needed for data analysis is automatically incorporated into a data file in the reformatting process in a manner which is approximately transparent to the user. A variety of documentation of the detector histories and performance characteristics and other engineering information through early 1989 has been produced as internal reports (see, e.g., the XRP Final Report for Contract NAS5-28713) which are available on request.

3.3 XRP Software and Users' Guides

As a major part of the XRP archive effort, the XRP software was overhauled and made more uniform and user friendly. Initially written predominantly in Fortran, the emphasis for the analysis software was switched to Interactive Data Language (IDL) and then upgraded to IDL Version 2 (V2), and then supplied with a widget interface to take advantage of the capabilities of a window environment. The basic data reduction programs remain in Fortran. IDL V2 software to plot BCS time histories and spectra and FCS images and spectra, calibrate BCS spectra and overplot theoretical profiles, and compute temperature and emission measure from FCS intensities are available. IDL software to fit FCS spectra and convert the spectral fitting results into physical parameters requires further development; in the interim, the older Fortran software can be used.

An XRP Software Users' Guide has been prepared and updated several times as the XRP reduction, display, and analysis software has evolved through several stages. The current version of the Users' Guide is being improved by D. Zarro and J. Saba, as a task under the Solar Data Analysis Center contract, due in October 1993.

Detailed information on the XRP instruments have been gathered and largely reside on disk at the SDAC in text and tables as TeX files or in hard copy form (see, e.g., R.D. Bentley's Ph.D. thesis, University College London, 1986), available upon request.

4. PUBLICATIONS AND PRESENTATIONS

The attached XRP Bibliography includes most of the papers which have been written and presentations which have been made under the XRP contract(s) or done on XRP-related subject by XRP Co-Investigators, Guest Investigators, or other collaborators. In the recent years, it has been more difficult to keep track of the Bibliography items particularly from our foreign collaborators, and we still await replies on input to the Bibliography. However, since the start of the new contract, in the listing available there are over 80 refereed papers, an additional nearly 40 unrefereed papers in national and international conference proceedings, over 90 presentations at meetings and seminars, and at least 15 reports and popular articles; at least nine of the papers or talks were invited reviews.

Three Ph.D. theses which made use of XRP data were submitted during the contract period: *Interpretations of Energetic Phenomena in the Solar Corona*, by P. Paul L. Hick,

to the University of Utrecht (1988); *Plasma Properties of Solar Coronal Active Regions*, by Katrina Waljeski, to the Brandeis University Physics Department (1991); and a thesis comparing H α , Mg I, and soft X-ray observations of solar flares by Thomas R. Metcalf, to the University of California at San Diego (1990). That brings to at least eight the number of theses which are directly related to XRP science.

Three substantial books authored or edited by XRP scientists have been published in the contract period: *Solar and Stellar Flares*, the Proceedings of the 104th Colloquium of the International Colloquium of the International Astronomical Union held in Stanford, California, August 15–19, 1988 (Kluwer Academic Publishers, 1989), edited by Bernard M. Haisch (Lockheed Solar & Astrophysics Lab. (LSAL) and Marcello Rodonó (University of Catania and Astrophysical Observatory, Catania, Italy); *The Sun: A Laboratory for Astrophysics*, the Proceedings of the NATO Advanced Study Institute held in Crieff, Scotland, June 16–29, 1991, edited by Joan T. Schmelz (Applied Research Corporation (ARC)/Lockheed) and John T. Brown (U. Glasgow, Scotland) (Kluwer Academic Publishers, 1992); and *Guide to the Sun*, (ISBN 0 521 39483, Cambridge University Press, 1992) a popular book with many examples from and references to XRP science written by Kenneth J. H. Phillips (Rutherford Appleton Laboratory (RAL), Oxfordshire, UK).

A fourth book, a Monograph on the scientific highlights of the *Solar Maximum Mission*, entitled *The Many Faces of the Sun*, to be published by Springer-Verlag, is currently being prepared for referee review by editors Keith T. Strong, Bernard M. Haisch, and Julia L.R. Saba (LSAL); the various chapters were contributed by *SMM* Principal Investigators, Co-Investigators, Guest Investigators, and XRP team members. The Monograph contains both solar and nonsolar results from *SMM*, and contains chapters on: Total Solar Irradiance, Active Regions, Elemental Abundances, Coronal Mass Ejections, Pre-flare Activity, Flare Particle Energization, Nonthermal Hard X-ray and Radio Emission in Flares, Flare Transport Processes, Flare Atmospheric Dynamics, the Gradual Phase of Flares, Spectroscopy and Atomic Physics, Solar-Terrestrial/Heliospheric Observations, the Solar-Stellar Connection, Comets, Celestial High-Energy Observations, as well as an Introduction and a “Forward Look” closing chapter. Several XRP scientists have contributed major sections to the Monograph, particularly in the chapters on Active Regions (J. Saba), Elemental Abundances (A. Fludra and J. Saba), Flare Atmospheric Dynamics (E. Antonucci, P. MacNeice, D. Zarro), Spectroscopy and Atomic Physics (K. Phillips), the Solar-Stellar Connection (B. Haisch), and the Introduction and Conclusion chapters (K. Strong).

5. WORKSHOPS

During the contract period, the XRP team supported four workshops or meetings unwritten entirely or in part by *SMM* Project funding. These were:

- (1) *Solar and Stellar Flares*, the 104th Colloquium of the International Astronomical Union, was held in Stanford, California, 15–19 August 1988, and organized by Bernard M. Haisch (LSAL) and Marcello Rodonó (University of Catania and Astrophysical Observatory, Catania, Italy). There were 200 scientists from 29 countries in attendance,

about half of whom had travel support from NASA, or the IAU, COSPAR, or the European Space Agency (ESA). Logistical support for travel was provided by SLW Associates in California. The meeting produced the proceedings noted in the previous section, which was printed as a special issue of *Solar Physics* (vol. 121) with 24 papers. During eight sessions, solar and stellar topics were intermixed in 33 invited and contributed oral presentations; there were also 115 posters, many of which appeared in a companion volume published by the Catania Astrophysical Observatory (Special Publication – 1989).

- (2) *The Second Workshop on Thermal/Nonthermal Interactions in Solar Flares (TNT-II)*, organized by Ken Phillips (RAL), was held at Somerville College, University of Oxford, England, on 10–14 April 1989. This meeting had 57 participants from seven countries, many of whom had attended the *TNT-I* Workshop which had been organized by K. Strong in New Carrollton, Maryland, in 1987. *TNT-II* produced a proceedings (RAL-89-102) edited by K. Phillips which reviewed the four discussion topics of both meetings: Large-scale magnetic field phenomena, flare dynamics, energy release and deposition, and global energy balance.
- (3) *The Physics of Solar Flares*, a Royal Society Discussion Meeting held on 13 and 14 March 1991, was organized by J.L. Culhane (Mullard Space Science Lab. (MSSL) and C. Jordan (U. Cambridge). A proceedings of the same name (Phil. Trans. R. Soc. London, series A, Vol. 336, pages 321-495, 1991), containing the 14 invited papers and subsequent discussions, was edited by the organizers. A similar number of poster presentations were not published. The meeting reviewed the contributions of three space missions during the 1980 solar maximum (*P78-1*, *Solar Maximum Mission*, and *Hinotori*) to our understanding of the solar flare phenomenon: the study of the energy release and the related creation of high-temperature plasma, the transport of energy from the primary release site, the production of gamma-rays at energies up to 10 MeV, and the ejection of matter into interplanetary space. There were also discussions of the current theoretical basis of magnetic energy conversion, the role of magnetic loops in solar flares, and the acceleration of electrons and protons in the impulsive phase. The use of high-resolution X-ray crystal spectrometers in establishing the properties of high-temperature plasma was described and the status of the atomic data required to interpret the spectra evaluated. Last, there was a look forward to the Japanese *Solar-A* (now renamed *Yohkoh*) mission.
- (4) The NATO Advanced Study Institute (ASI) on *The Sun: A Laboratory for Astrophysics*, organized by Joan Schmelz (then of ARC, subcontracted to Lockheed) and John Brown (U. Glasgow) and held in Crieff, Scotland, from 16-29 June 1991, was funded jointly by NASA, NATO, and the NSF. Ninety participants from twenty-four (predominantly NATO) countries received a two-week immersion in the astrophysics of the solar interior, solar and stellar atmospheres, solar instrumentation, and solar and stellar activity. The series of thirty-two lectures given by 11 experts in the field of solar physics were published by Kluwer Academic Publishers in the book noted in the previous section. The intention of organizer Schmelz was that the summer school would provide a rigorous introduction to newcomers to the field – either graduate

students or those with training in other fields of astrophysics. It is expected that the published proceedings will make that background available to many more students who were unable to attend the school.

6. FCS ACTIVE REGION ABUNDANCES

One of the major new areas of research during the contract period was the investigation of anomalies and variability in active region abundances. In this section, the FCS abundance study is described in some detail, with emphasis on the redefinition of the problem arrived at during the *SMM* Guest Investigation, and the first stages of the solution.

6.1 Background

Evidence for variability in elemental composition of the corona above nonflaring active regions was discovered by K. Strong in 1986 during analysis to update the FCS Channel 1 instrument calibration using long spectral scans data. For successive lines from Fe XVII and from O VIII, the measured intensities were compared with those predicted by the line strength calculations. Either line species separately gave fairly consistent results, but the combined set did not. Because of the overlapping wavelength coverage of the two sets of lines, no adjustment of the instrument calibration could reconcile the two sets of values if the standard values of abundances (Allen 1976) were used. (The iron abundance listed in Allen is now known to be in error.) Further, not all spectra gave the same results, suggesting that the relative abundances of oxygen and iron might be variable. Acquisition of additional long spectral scans of active regions became a high priority of the XRP operations team.

Strong and colleagues began to examine the different temperature and abundance diagnostics accessible to the FCS. Adopting a method developed by Acton, Catura, and Joki (1975), they plotted the flux ratios for O VIII and Ne IX lines which have similarly shaped emissivity functions over a broad temperature range, versus a temperature-diagnostic ratio of two lines from the same element. Some of the flux ratios showed a large scatter around the predicted weak temperature behavior. Since the temperature responses for the two lines were similar, it seemed unlikely that the scatter at a given effective temperature resulted from different contributions to the emission from different volumes; rather, the most reasonable explanation seemed to be variations in the relative amounts of the emitting elements. The observed scatter in the O VIII/Ne IX ratio implied values of Ne/O ranging from about 0.1 to nearly 0.3 (Strong, Claffin, Lemen, and Linford 1988), where the highest values corresponded to the late stages of long-duration events (LDEs).

Dramatic anomalies were seen in some of the FCS spectra for certain line ratios, for example, large variations were noticed in the intensities of Ne IX lines relative to Fe XVII and Fe XVIII lines for active regions with similar electron temperatures (as measured by the sensitive temperature-diagnostic ratio Fe XVIII/Fe XVII). Calculations tabulated by Mewe et al. (1985) predict the ratio of Fe XVII at 15.01 Å to Ne IX at 13.45 Å should be

virtually temperature independent for T_e in the range from about 2 MK to 7 MK and the amount of hotter material in the instrument field of view was rigorously constrained by the flux limits in hotter lines, so it seemed unlikely that the variable ratios could be explained by multithermal plasma from multiple regions; a careful study seemed to rule out sources for the observed line ratio variability other than a variation in the relative abundances of iron and neon (Strong, Lemen, and Linford 1991).

Analysis of over 100 spectra from quiescent and postflare active regions yielded an extreme range of a factor of seven variation in Fe:Ne, with the bulk of the variation falling within a factor of about four. There are typical factor-of-two differences between different active regions, and frequent instances of factor-of-two variation in day-to-day samples of a given region and in successive 10-min samples during the late decay phase of LDEs. The variation in relative Fe:Ne abundance from one active region to another and over time in a given active region was reminiscent of the abundance variability in flares found earlier by the BCS, but now was occurring in quiescent or postflare active regions which otherwise seemed to be stable. Initially it was thought that neon was showing the variable abundance, since the iron line strengths seemed consistent with the other lines in the spectra (primarily the O VIII lines), while O:Ne variations had already been found, as noted above.

6.2 Expansion of the FCS abundance study

Under Saba's *SMM* Guest Investigation of FCS abundances, the original pilot study of Strong et al. was expanded to include the lines of O VIII at 18.97 Å and Mg XI at 9.17 Å in addition to the Ne IX line at 13.45 Å, the Fe XVII line at 15.01 Å, and the Fe XVIII line at 14.22 Å. (More recently, several additional lines of Fe XVII have been added, as discussed below in section 6.3.) The five lines (O VIII, Ne IX, Mg XI, Fe XVII, and Fe XVIII) of the expanded study provide the temperature-diagnostic line ratio Fe XVIII/Fe XVII and several abundance-diagnostic line ratios which yield relative abundances for various combinations of the elements magnesium and iron with low First Ionization Potential (FIP) and the high-FIP elements oxygen and neon, once the weak temperature dependences of the line ratios have been accounted for. A preliminary analysis found significant relative abundance variability for all combinations of the high-FIP elements oxygen and neon and the low-FIP elements magnesium and iron, with the low-FIP/high-FIP pair Fe:Ne still showing the largest relative variability (Saba & Strong 1992, 1993). However, during this analysis, it was found that a number of areas ancillary to the abundance study require further investigation.

To convert the observed flux ratios into relative abundance ratios with confidence, one must have good models of the expected line intensities. Required are the ion fractions (the proportions of a given element in the various relevant stages of ionization) and excitation rates (the probability that a given ion will make a given transition) as functions of temperature, and knowledge of any relevant transport effects. The atomic data and ionization balance calculations needed to interpret the line strengths are now being reexamined. In particular, emission lines of Fe XVII and Fe XVIII play a central role in the early FCS abundance analysis; use of their intensities relative to each other, for temperature diag-

nostics, and to the other FCS lines, for abundance measurements, depends strongly on the relative ion fractions of Fe^{+16} and Fe^{+17} , which have recently been recalculated (Arnaud and Raymond 1992), and on the excitation rates, which are harder to calculate for these multielectron ions than for the other lines used in the study which are H-like (O VIII) and He-like (Ne IX and Mg XI).

Further, the same extreme temperature sensitivity which make the Fe XVIII/Fe XVII ratio an attractive temperature diagnostic in principle makes the actual calculation of the corresponding temperature in the active region regime somewhat suspect. In general, calculations of the emissivity of any line become less valid far away from the peak response (C. Jordan, private comm., 1992). However, the ratio clearly provides a measure of the temperature and the trick is finding how to calibrate it. Other temperature diagnostics available in the FCS spectra are currently being compared with the Fe XVIII/Fe XVII diagnostic and incorporated into the abundance analysis.

In addition, although coronal emission lines are generally thought to be optically thin, results from a recent reconsideration of radiative transfer of Fe XVII in the corona suggest that resonance scattering may significantly deplete the flux in the Fe XVII resonance line at 15.01 Å from active regions (Schmelz, Saba, and Strong 1992). A preliminary check implies that resonance scattering is not a major contributor to the apparent abundance variability, at least not for Fe:Ne. However, it is not yet clear if resonance scattering could be responsible for a systematic offset in the actual abundance ratios derived.

This set of interwoven problems is being solved by making use of some of the redundancy available with the forest of emission lines in the FCS spectra. For example, there are five other Fe XVII lines for which the scattering opacities are much less but whose absolute intensities are somewhat harder to model; the relative strengths can be compared to the resonance line to monitor the occurrence of scattering, and one of the lines may be a good candidate line to use to repeat the first stage of the abundance analysis for comparison. Also, there are other abundance-independent temperature diagnostics, such as line ratios of the Ne IX or Mg XI triplets, or Mg XII to Mg XI, which generally have larger statistical uncertainties, but which can be used to examine systematic trends in temperatures derived from Fe XVIII/Fe XVII. These issues are addressed in greater detail in the next section.

6.3 Recent progress

a) Effects of different ionization balance calculations

The actual conversion of the Fe XVIII/Fe XVII ratio to temperature, as well as the exact behaviors of the abundance-diagnostic ratios with temperature, depend on the excitation rates and ion fractions adopted to model the line emissivities. It turns out that the largest uncertainties probably lie in the calculation of the ion fractions. In the original analyses by Strong and colleagues (Strong, Clafin, Lemen, and Linford 1988, Strong et al. 1991), atomic data from Mewe, Gronenschild, and van den Oord (1985), including their adopted scale factor for the Fe XVII lines, were used with the ionization balance calculations of Arnaud and Rothenflug (1985; hereafter ARO) for the five lines

listed above. In the followup study by Saba and Strong (1992, 1993), for comparison, the new ionization balance calculations of Arnaud and Raymond (1992; hereafter ARA) were substituted for the older ionization balance calculations for Fe XVII and Fe XVIII, both in converting the line ratio Fe XVIII/Fe XVII to temperature, and in abundance-diagnostic line ratios involving Fe XVII. The two sets of calculations predict different behaviors of the Fe XVII/Ne IX line ratio and yield different Fe:Ne relative abundances for a given set of Ne IX, Fe XVII, and Fe XVIII fluxes.

The ARO calculation is nearly independent of temperature and implies that Fe:Ne varies approximately between the photospheric and coronal ratios, where the photospheric Fe:Ne ratio = 0.24 [Grevesse and Anders 1989; note that this ratio differs substantially from the ratio gotten from the cosmic values tabulated by Allen (1976), =0.48, which was used in the initial FCS abundance analysis of Strong et al. (1991)], and the coronal ratio (=1.12) is estimated from solar energetic particle (SEP) values (J.-P. Meyer, private comm., 1992). The extreme range of variation between the regions is a factor of seven, with frequent instances of factor-of-two variation in day-to-day samples and in successive 10-min samples during LDEs. The ARA calculation implies a slightly larger range of variation for Fe:Ne, from about 0.08 to 0.9, with the bulk of the Fe:Ne ratios well below the photospheric value, and the maximum well below the SEP value. With the ARA curve, various series of LDE points could be explained by temperature evolution at a particular value of Fe:Ne; most of the instances of factor-of-two or more day-to-day variability in a given region would remain. The occurrence of many Fe:Ne abundance ratios that are well below the photospheric value would be problematic for a picture of coronal composition based on differentiation by First Ionization Potential; it would imply that enhancement of the high-FIP neon is common, which seems unlikely. However, there could be a systematic offset produced by either inadequate modeling of the excitation rates of the Fe XVII or Fe XVIII (see the next item), or by resonance scattering of the Fe XVII line at 15.01 Å, as discussed below in item c).

When the relative abundances for other element pairs were examined for a subset of 60 spectra which had well determined fluxes for all five lines of interest, results which are qualitatively similar to the Fe:Ne results were found for the other low-FIP/high-FIP line ratios (Fe:O, Mg:O, and Mg:Ne): that is, the ARO curves imply a range of low-FIP/high-FIP relative abundances in the FCS active region data approximately between the photospheric (Grevesse and Anders 1989) and SEP (J.-P. Meyer, private comm.) values, while the ARA curves imply a somewhat greater extreme range of variation, with systematically lower values and with much of the data showing relative abundances well below the photospheric ratio, if no allowance is made for possible effects of resonance scatter. Significant variability was also found for the low-FIP/low-FIP pair Mg:Fe and the high-FIP/high-FIP pair O:Ne. Each shows about a factor of three variation for either the ARO or the ARA curves, although again the values of the ratios differ between the two predictions, and Mg:Fe would be affected by resonance scatter.

The ionization balance calculations predict the relative amounts of a given element in the various stages of ionization, i.e., the ion fractions, which are more difficult to calculate than the excitation rates and correspondingly more uncertain. In the active region

temperature regime, the effect of substituting the ARA iron ion fractions is to make the temperature corresponding to a given value of Fe XVIII/Fe XVII somewhat hotter above about 3 MK and to make the predicted emissivity of Fe XVII somewhat lower below about 3.6 MK (e.g., about 30% lower at 2.8 MK) and somewhat higher above (e.g., about 30% higher at 4.2 MK). The differences between the behaviors of the various line ratios in the study as a function of temperature predicted by the two ionization balance calculations are profound – even the ratios not directly involving iron are affected. These differences are reflected in major differences in the conversions of the flux ratios at a given temperature (outside of a small range near 3.5 MK) to relative abundance ratios.

b) Evaluation of excitation rates

An investigation of the various calculations of excitation rates for Fe XVII available in the literature (Mewe et al. 1985, Smith et al. 1986, Landini and Monsignori-Fossi 1990) and from unpublished work (A. Bhatia, private comm. 1992; M. Cornille et al., private comm. 1991), shows that the calculations typically agree to within about 30% or better in the regime of active region temperatures, except for the calculations of Landini and Monsignori-Fossi (1990) which are being reexamined. The calculations of Mewe et al. (1985), with and without their normalization factor of 1.5 (adopted to match observational data), yield excitation rates representative of the spread in the calculations (other than those of Landini and Monsignori-Fossi 1990). Emissivity calculations for four Fe XVII lines other than the resonance line at 15.01 Å (lines at 15.26 Å, 16.78 Å, and 17.05 Å, plus a forbidden line at 17.10 Å) are being examined (Saba & Schmelz, work in progress) so that another line can be used in lieu of the resonance line in the primary abundance study (which uses the long spectral scan data where all the lines are available). The predicted temperature behaviors for the different lines vary somewhat between the different theories. Comparing ratios of the measured intensities of the various Fe XVII lines with the ratios of their respective excitation rates as a function of temperature removes the uncertain Fe^{+16} ion fraction from the picture and simplifies the data/theory comparison.

The excitation rate for the fluorine-like Fe XVIII should also be examined further. Predictions of new calculations by McKenzie et al. (1992) and by Bhatia (1992, private comm.) are being compared with results in Mewe et al. (1985). The excitation rates for the H-like line O VIII and for the He-like lines Ne IX and Mg XI are believed to be well understood (F. Bely-Dubau, private comm. 1992).

c) Impact of resonance scattering

It does not appear that, by itself, updating the iron ion fractions or the line excitation rates can account for the factor of ~ 2 “missing flux” in the observed intensities of the Fe XVII resonance line at 15.01 Å compared to the predicted values based on observed fluxes in other lines (cf. Schmelz et al. 1992). It is possible that resonance scattering, which should preferentially *deplete* flux from lines in active regions, could explain some of this “missing flux” and introduce a systematic offset in the Fe XVII/Ne IX data. A preliminary study of Fe XVII resonance scattering in the FCS data made by Schmelz et al. (1992) suggested that Fe XVII resonance scattering could be much more important in active regions than had been previously estimated by Rugge & McKenzie (1985); a more

extensive study is in progress.

Initially, it seemed that, since the optical depth to resonance scattering of the Fe XVII line at 15.01 Å could be large for coronal conditions plausible for active regions, much of the observed scatter in the Fe XVII/Ne IX ratios might be due to this effect rather than or in addition to abundance variation. However, this now appears extremely unlikely. The resonance line at 15.01 Å should by far be the line most affected by resonance scatter, yet the other Fe XVII lines do not show the large changes relative to the 15.01 Å line which would be expected if resonance scattering were responsible for the dispersion in the flux ratios of Fe XVII at 15.01 Å to Ne IX.

The Fe:Ne analysis is currently being repeated with another Fe XVII line, namely, the line at 16.78 Å, for which the scattering opacity is only about 0.04 times as great as that of the 15.01 Å line. To date, a sample of 16 spectra have been studied (Saba & Schmelz, work in progress), for active regions with an electron temperature in the range 3-4 MK (where the ARO and ARA calculations for the predicted Fe XVII/Ne IX behavior agree best). It was found that ratios of the 16.78 Å and 15.01 Å lines varied by at most $1.0 \pm 25\%$, a fraction of which could be due to a variation with temperature; at the same time, the variation in Fe:Ne inferred from the variation in Fe XVII/Ne IX ignoring any effect from resonance scattering was a factor of 4. Although the Fe XVII/Ne IX vs. Fe XVIII/Fe XVII plots differed in detail depending on which of the two Fe XVII lines was used, they looked qualitatively the same, and the magnitude of the inferred Fe:Ne variation was the same. That is, any effect of resonance scattering was not dominant in the observed variation in the Fe:Ne abundance ratios. However, the proportional effect on the apparent variation in Mg:Fe could be more substantial. Moreover, there is the strong possibility that Fe XVII resonance scattering could be important in active regions, but at about the same magnitude from one bright region to another, when observed through the 15 arcsec (FWHM) FCS field of view. Thus, it is possible that Fe XVII resonance scattering could be introducing a systematic offset of about the same magnitude to within 50% in the derived abundances even if though it is not an important contributor to the scatter of the data. Both the study of resonance scattering in a larger data base and the investigation of abundances using lines less subject to resonance scatter continue.

6.4 Assessment of FCS active region abundance results

While the preliminary FCS active region abundance results are exciting and add a new dimension to the picture of coronal abundances being assembled from a number of current research efforts, the FCS work is barely underway, and the final outcome is hard to predict. The discovery of Fe:Ne variations in time and space in nonflaring active regions seems secure, although the details of the magnitude, the extreme values, and the fastest timescales for variability are still being worked out, for these and other combinations of the elements oxygen, neon, magnesium, and iron. The primary issues needing further investigation appear to be the best way to divide out the temperature dependences of the various line ratios and the possible impact of resonance scattering.

The actual values of the various abundance ratios depend on the atomic data and ion

fractions adopted to interpret the line fluxes, but the magnitudes of the overall variations are less sensitive to which calculations are used. With the atomic data tabulated by Mewe et al. (1985) and the ARO ion fractions, the low-FIP/high-FIP pairs range roughly between the photospheric and coronal values. However, when the ARA ion fractions are substituted for Fe XVII and Fe XVIII, the values of the abundance ratios – even those ratios not involving Fe XVII except through the temperature – shift systematically to lower values, so that a large fraction of the data have ratios well below the photospheric values. However, the ARA ion fractions explain much of the short-term variability in flux ratios (i.e., variability on timescales less than an hour) in terms of evolution in temperature at fixed relative abundance. Abundance variability on time scales of a few tens of minutes would challenge the FIP models which incorporate diffusion timescales (unless sequential activation of multiple loops was involved, which would imply some horizontal gradient in abundances that the model would need to explain).

The possibility that errors in the shape of the predictions for the Fe XVII/Ne IX line ratio and for the other line ratios could be introduced by the extreme temperature sensitivity of Fe XVIII/Fe XVII or by poor knowledge of the Fe XVIII excitation rates is being investigated. Also under examination is whether Fe XVII resonance scattering could cause a large systematic offset in the derived abundances. The sense of such an offset would be in the direction to account for the depression of low-FIP/high-FIP relative abundance values below the photospheric values when the ARA ion fractions are used, even when Fe XVII is not one of the lines involved in the abundance-diagnostic line ratio.

Even if resonance scattering of Fe XVII should be responsible for producing a systematic shift in the data, it seems unlikely that resonance scattering could play a major role in the observed scatter of the data since there is no evidence of large unexpected changes in the ratios of the resonance line at 15.01 Å to the other Fe XVII lines that are optically thin to the resonance scattering process. These other lines are being examined as possible substitutes in the next stage of the study. If Fe XVII resonance scattering or some other factor is not found to be causing a systematic shift in the derived abundance ratios, then the ARO ion fractions would seem to give a more natural description of the abundance data, and would imply relative abundances for low-FIP/high-FIP element pairs which vary between the photospheric and coronal values, with means closer to photospheric than coronal (SEP) values in solar active regions with temperatures much above 3 MK.

In their analysis of *P78-1* SOLEX data, McKenzie and Feldman (1992) found also found a distribution of the Fe:Ne ratio, ranging approximately between the photospheric and coronal ratios, but a smaller (factor of 2.4-3.1) variation in the range of relative abundances of the low-FIP/high-FIP pair Fe:O, no significant variation of the low-FIP/low-FIP Fe:Mg, and a variation in the high-FIP/high-FIP pair Ne:O somewhat smaller in magnitude than that of the FCS data. The differences in the FCS and SOLEX results could be due to the way that the data were acquired in the two cases: The SOLEX data were collected with a 1-arcmin square field of view, pointed towards arbitrary locations in the active region, while the FCS data were collected with a 15-arc sec (FWHM) square field of view centered on the brightest pixel in a pre-scan survey image of the region. Such bright pixels also appear to coincide with the locations of the largest nonthermal

line broadening in the FCS data (Saba and Strong 1991a,b), so that the FCS abundance data may sample preferentially the most recently heated sites in the active regions. If active region heating occurs in a series of small, flare-like episodes, one might expect to find evidence of photospheric abundances as are sometimes seen in impulsive flares (see, e.g., Feldman and Widing 1990). The smaller FCS field of view and preferential sampling of brighter areas could also explain why the FCS data may show a significant (factor of 2-3) variation for the low-FIP/low-FIP pair Mg:Fe although the SOLEX data do not, and the FCS seems to show a larger magnitude variation for the high-FIP/high-FIP pair Ne:O, including values significantly *higher* than the photospheric ratio (which would not be explainable within the FIP framework – see section 3.2), as well as the significantly lower values found by McKenzie and Feldman. On the other hand, a comparison of neon with oxygen in a sample of four different features imaged in *SKYLAB* spectroheliograms (Feldman and Widing 1990) stayed approximately constant at a mean value of about 0.14, consistent with the photospheric value. The Ne:O results for both the FCS and SOLEX instruments, particularly for the flare and higher temperature active region data, should be reexamined with a multithermal analysis replacing the isothermal assumption used in both the FCS and SOLEX analysis.

The FCS would be more sensitive to transient local extremes in abundances, such as might occur in more dynamic situations. It should also be noted that a smaller field of view also makes the FCS more susceptible to possible effects from resonance scattering (see, for example, Strong 1978). An additional difference between the SOLEX and FCS data for the Mg:Fe case is the fact that the SOLEX analysis was based on measured line flux ratios involving an Fe XVIII line rather than the Fe XVII line at 15.01 Å. The Fe XVIII line has an opacity to electron scattering that is small (< 0.1) compared to that of the 15.01 Å line so that no artificial variation could be introduced in the SOLEX Mg:Fe data from scattering; on the other hand, the fact that the Fe XVIII line is a much weaker line than the Fe XVII line means that the statistical uncertainties on the Fe/Mg ratios are large and any real variations might be hidden. Further comparisons between the FCS and SOLEX results are planned.

McKenzie and Feldman did not discuss SOLEX results on Mg:Ne. However, Widing and Feldman (1989) studied the abundance ratio of magnesium to neon in a variety of emission features imaged in the 300-600 Å spectral range on *SKYLAB* spectroheliograms. For some features a multithermal analysis was performed in which ions of Ne V, VI, and VII were compared with Mg VI, VII, and VIII, as well as Na VIII, Ca IX and Ca X. For others, the Mg:Ne ratio was derived from the intensity ratio of Ne VI to Mg VI lines at 400 Å. A strong correlation was found, with the high-FIP/low-FIP Mg:Ne abundance ratio increasing as the magnetic field opens up. The features with photospheric-like abundance ratios – such as impulsive flares (Feldman and Widing 1990) – are associated with compact loop configurations and an active region shows the SEP coronal ratio, whereas the features with abundance ratios even higher than the coronal ratio, such as a polar plume (Widing and Feldman 1992,) are associated with open fields. That is, the low-FIP/high-FIP Mg:Ne ratio increases as magnesium becomes progressively more enriched relative to neon in the open-field structures. Thus, the *SKYLAB* spectroheliogram results show an even greater

range of variation of Mg:Ne from one kind of structure to another than the FCS results show between different examples of the same structure (i.e., active regions), and over time in the same example. The *SKYLAB* results could be considered as resulting from some single FIP selection mechanism operating under different boundary conditions suitable for a given kind of magnetic field structure; however, the FCS and SOLEX results show that the detailed local physical conditions for a given kind of structure can also change. Any complete model of abundance differentiation in the corona should be able to explain all these types of variation.

6.5 Summary and Forward Look

In carrying out the *SMM* Guest Investigation of coronal abundances and their variation, it was found that the scope of the problem had to be redefined to allow for various complexities that were hidden until the research was actually underway. A number of important issues have been identified and progress has been made on all of them. Presentations of work in progress have been made at several meetings (SOHO Workshop in Annapolis, August 1992; Committee on Space Research meeting in Washington, D.C., September 1992, American Geophysical Union meeting in Baltimore, May 1993; American Astronomical Society/Solar Physics Division meeting in Palo Alto, July 1993) and several papers have been presented on preliminary results (Saba and Strong 1992, Schmelz, Saba, and Strong 1992, Saba and Strong 1993). A paper on FCS active region abundance measurements is in preparation for submission to the *Astrophysical Journal*. The FCS active region abundance study will be continued under funding of a NASA Supporting Research & Technology investigation, a research opportunity made possible due to the success of the *SMM* Guest Investigation.

7. ADMINISTRATIVE AND CONTRACTUAL ISSUES

In September 1991, a \$60K reduction in the XRP budget essentially stopped XRP work at LSAL. One major impact this had was to drastically descope the outstanding archival efforts, including production of CD ROM sampler of XRP data and software for distribution to the community, and any further LSAL contribution to the XRP software effort, an XRP Instrument Guide, or to this Final Report. Further, funding was terminated to the XRP effort subcontracted to ARC as of December 1991. D. Zarro of ARC continued involvement with XRP analysis and software in his capacity as a staff member of the *SMM* Data Analysis Center (since renamed the Solar Data Analysis Center) at Goddard. J. Schmelz continued XRP analysis for several months as an NRC research associate.

In the first quarter of 1992, NASA HQ Code 370/MODA funds of \$59,988 were transferred by GSFC RTOP and applied to GSFC Contract NAS5-30431 to support J. Saba's *SMM* Guest Investigation of *Coronal Abundances and Their Variation*, which was selected by competition under NRA-91-OSSA-4. During the second quarter of the year, the funds showed up at Lockheed, allowing Saba to begin the *SMM* Guest Investigation and continue XRP analysis.

In December 1991, \$30K in funding for an *SMM* Monograph was provided by the *SMM* Project at Goddard. In February 1992, an additional amount of \$40,421 was provided by NASA HQ. These funds helped to underwrite some travel expenses to a small meeting of the *SMM* PIs or their representatives in Palo Alto, California, to outline the *SMM* Monograph, discuss what it should contain and provide a tentative author list and schedule. The funds have also covered part of the time of editors K. Strong, B. Haisch, and J. Saba in producing the book.

8. PERSONNEL

The XRP archive effort was carried out under the overall direction of the Lockheed XRP Principal Investigator, Keith Strong. Most of the work was carried out at Goddard and organized by Dnyanesh P. Mathur (of ARC at the beginning of the contract period, and later at LSAL). The engineering logs were compiled by the XRP Instrument Operations Team (IOT), headed by Shams-ur-Rehman (RAL) from December 1987 through summer 1991; others who made major contributions to the archiving and cataloguing efforts were XRP Instrument Engineer Greg Slater (then ARC, now LSAL) and IOT members Teri Belcher and Eric Carzon (ARC); Harinder Bawa (RAL) and Kermit Smith (LSAL) also contributed significantly. Much of the labor-intensive part of the archive effort, including transferral and compression of the XRP data from the half-inch magnetic tapes to 8-mm Exabyte tapes, was performed by IOT member Dennis Kemp and several area high school students, especially Jennifer Robinson, Erika Lin, and Jean Wang. J. Robinson (ARC) stayed past her high school tenure and gave further able assistance with processing data for catalogues and with logistical support for the NATO summer school. The XRP archive, catalogue, and analysis software was a joint effort primarily involving D. Mathur, Dominic Zarro (ARC), and G. Slater at Goddard, and Gary Linford, Mons Morrison, Jim Lemen, John Hawley, and Sam Freeland at Lockheed. J. Schmelz and J. Saba tested out the archive analysis software, wrote an early draft of the XRP Software Users' Guide, and wrote or compiled documentation about the instruments and the various catalogues. A more recent version of the Software Users' Guide, reflecting the software upgrades in a windows environment was written by D. Zarro and Michael McSherry (U. Belfast, Ireland). As the software continues to evolve, the Users' Guide is being updated by the SDAC staff.

After the cut in XRP funding in September 1991, most of the remaining XRP analysis effort was carried out by J. Saba (LSAL) at Goddard, funded principally by the *SMM* Guest Investigation Program. A portion of the *SMM* Monograph funding received in the period December 1991 – February 1992 supported a few working weeks of effort by Saba, and B. Haisch and K. Strong at Lockheed in Palo Alto, to organize and edit the Monograph.

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