NASA CR-~~166794~~ 166 749

CAL-1471

N82-13030

DATA REDUCTION AND ANALYSIS FOR THE "GRAPHITE CRYSTAL X-RAY SPECTROMETER AND POLARIMETER EXPERIMENT" FLOWN ABOARD OSO-8 SPACECRAFT

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AUGUST 1980

FINAL PROJECT REPORT FOR THE PERIOD
JUNE 26, 1975 THROUGH JUNE 30, 1980

PREPARED FOR:

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

in partial fulfillment of the requirements
of NASA Contracts NAS5-22408 and NAS5-24152

CONTENTS

1. OVERALL DATA REDUCTION/ANALYSIS PROGRESS

1.1 Quick-Look Data

Quick-look data records were received and analyzed daily at Columbia from Day 176, 1975, to Day 273, 1980. Records not received due to transmission or reception difficulties were retransmitted and analyzed as soon as possible.

1.2 Production Data

Columbia received production data records from IPD at GSFC from Day 176, 1975, to Day 273, 1978. The records were received on magnetic tapes, each tape containing one day's data. The tapes were labeled CU5176 to CU8273.

Columbia reduced the data on tapes CU5176 to CU8273 with the exception of nine days in 1977-1978. The nine tapes were not reduced due to problems with orbital data or physical tape errors.

After initial data reduction, extensive analysis was made of the stellar Bragg crystal X-ray polarimeter observations shown in Table 1 and of the stellar Bragg crystal spectroscopic observations listed in Table 2. A large body of solar spectroscopic data were also reduced and analyzed. These data were obtained when the Sun was observed in the day sky with the graphite Bragg crystal spectrometer at all times when the polarimeter was not in use as well as from observations of solar active regions made with the PET Bragg crystal spectrometer on the dates indicated in Table 3.

TABLE 1. Stellar Bragg Crystal X-Ray Polarimetric Observations

X-Ray Source Name	Number	Observation Year	Dates
Perseus	0316+41.	1976	02/16-02/18
		1977	02/13-02/20
Crab	0531+21.	1976	03/11-03/17
		1977	03/11-03/17
		1978	03/11-03/17
Vela X-1	0900-40.	1976	05/22-05/26
Cen X-3	1118-60.	1975	07/18-07/26
		1978	07/16-07/27
Sco X-1	1617-15.	1977	08/25-08/30
		1978	08/25-08/31
Burster	1636-53.	1976	09/05-09/10
Her X-1	1653+35.	1975	08/29-09/02
...	1658-48.	1978	09/12-09/15
Sco X-2	1702-36.	1975	09/11-09/12
GX5-1	1758-25.	1975	09/20-09/21
Galactic Center	1820-30.	1976	09/24-09/29
		1978	09/25-09/30
Burster	1837+04.	1975	10/03-10/05
Cyg X-1	1956+35.	1975	11/07-11/10
		1976	11/03-11/10
		1977	11/02-11/14
Cyg X-3	2030+40.	1975	11/19-11/25
		1976	11/17-11/22
Cyg X-2	2142+38.	1975	12/09-12/11
		1976	12/03-12/10
		1977	12/04-12/13
Cas A	2321+58.	1976	01/22-01/23

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September 5, 1980

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Gentlemen:

Enclosed please find a copy of the final report on the Columbia OSO-8 experiments. I would like to take this opportunity to thank you for your support. We feel that the mission was eminently successful, and we were very pleased to be able to participate in it.

Sincerely,

Robert Novick, Director
Columbia Astrophysics Laboratory

RN:elb

TABLE 2. Stellar Bragg Crystal Spectroscopic Observations

X-Ray Source Name	Number	Observation Year	Days
Crab	0531+21	1975	286–288
		1975	307–308
		1975	349–353
		1976	348–357
		1977	348–355
Transient A0535	A0535+26	1975	346–355
Transient A0620	A0620–00	1975	290–291
		1975	299–300
		1975	365
		1976	001–009
		1976	018
		1976	027–032
		1977	001–002
		1977	121
		1978	003–004
Vela X-1	0900–40	1977	107–110
		1977	133–136
		1977	138–154
Cen X-3	1118–60	1976	092–100
		1977	087–099
		1978	197–209
Cir X-1	1516–56	1976	111–113
		1976	213
Flare	1543–47	1976	115–116
		1977	195–196
		1977	199
Sco X-1	1617–15	1975	190–195
		1976	149–154
		1976	337
		1977	142–145
		1978	151–158
Burster	1636–53	1976	117–131
		1976	164–170
		1976	178–183
		1977	212
		1977	247
		1977	252–253

TABLE 2 (continued)

X-Ray Source Name	Number	Observation Year	Days
...	1642-45	1976	132-133
		1976	166-169
		1977	195-196
		1977	209
Her X-1	1653+35	1975	214-215
		1976	161-162
		1976	218
		1977	105-106
...	1658-48	1976	132-133
		1976	160-164
		1976	170-171
		1976	179-182
		1977	197
		1977	200
		1977	211
...	1700-37	1976	135-141
		1976	154-169
		1977	193-194
Sco X-2	1702-36	1976	136-141
		1976	156-169
		1977	192-193
		1978	128-143
...	1705-44	1976	159-162
		1976	170
		1977	195-196
		1977	199
		1977	206-207
		1977	209
...	1728-16	1975	192
		1975	196
		1976	166-168
		1977	159-161
...	1735-44	1976	135-136
		1976	152-154
		1976	172-173
		1977	197-198
		1977	206
		1977	210

TABLE 2 (continued)

X-Ray Source Name	Number	Observation Year	Days
Flare	1735-28.	1976	170-171
		1977	168-177
		1977	184-189
...	1744-26.	1975	184-187
		1976	171-172
		1977	167-186
Burster M1746	M1746-20	1975	190-193
		1975	195
GX5-1	1758-25.	1975	176-179
		1975	184-188
		1976	172-173
		1977	167-184
		1978	167-175
GX9+1	1758-20.	1975	182
		1975	190-193
		1975	195
		1976	172-173
		1977	164-166
...	1811-17.	1976	173-174
		1977	164
...	1813-14.	1976	173-174
		1977	162-163
		1978	187-195
Galactic Center	1820-30.	1976	175-179
		1976	183-186
		1977	192-194
Burster	1837+04.	1976	104
		1976	174-177
		1977	120
		1977	129-130
		1977	156
Recurrent Transient	1908+00.	1975	208-211
		1976	181-185
		1976	223-224
		1977	122-127
		1978	159

TABLE 2 (continued)

X-Ray Source Name	Number	Observation Year	Days
Cyg X-1	1956+35.	1977	035-037
		1977	055-056
		1977	111-112
		1977	137-143
		1977	298-319
		1978	17- 33
Cyg X-3	2030+40.	1975	220-221
		1976	179-181
		1976	183-188
		1976	262-263
		1977	025-031
Cyg X-2	2142+38.	1975	251-253
		1975	257-259
		1976	265-267
		1977	227-228
Cas A	2321+58.	1975	223-224
		1975	268-270
		1975	285-290
		1976	281-289
		1977	223-224

TABLE 3. PET Bragg Crystal Solar Flare Spectroscopic Observations

Year	Dates	Days	Year	Dates	Days
1975	07/02-07/03	183-184	1976	01/15-01/21	015-021
1975	07/11-07/12	192-193	1976	03/30-04/03	090-094
1975	07/27	208	1976	08/03-08/11	216-224
1975	08/02-08/03	214-215			
1975	08/20-08/24	232-236	1978	08/04-08/14	216-226
1975	11/18-11/19	322-323	1978	09/02-09/11	245-254

2. SUMMARY OF DOCUMENTATION AND SOFTWARE PROGRAMS DEVELOPED FOR OSO-8 DATA ANALYSIS EFFORT

2.1 Data Reception and Initial Processing

2.1.1 Quick-look data

GSFC sent CAL daily quick-look data while the satellite was active. The data were transmitted over a modem line to a Data General Nova computer at Columbia. Two programs processed the data. Program GCSLA (Monthly Progress Report CAL-1325, Appendix A, August 1976) received the data sent by Goddard and transferred them to magnetic tape. Program DMQL1 (Feasibility Study CAL-1294, July 1975, pp. 9, 51) later read a GCSLA output tape and produced summary housekeeping and data analysis printout.

2.1.2 Production data (Monthly Progress Report CAL-1332, Appendix A, October 1976).

(a) Program CAL00 is written to execute on the IBM 360/65 at GSFC. The program reads input data tapes received from IPD at GSFC containing OSO-8 satellite data for experimenter number 5. Output data tapes and computer printouts are created. The output tapes contain the original data in a reorganized fashion, such that they are more easily accessible for further analysis. The printed output summarizes the housekeeping of the experiment so that the experimenter may easily determine the status of the instrument's operation at any given time.

(b) Documentation of first-step data handling and output. A step-by-step description of OSO-8 preliminary data handling procedures at GSFC and a description of CAL00 printout are given in Monthly Progress Report CAL-1312, Appendix A, March 1976.

2.2 Data Analysis

2.2.1 Solar spectroscopy

The primary purpose of program CAL03 (Monthly Progress Report CAL-1315, Appendix A, May 1976) is to provide a detailed analysis of the time evolution of intensities of eleven prominent solar spectral lines measured by the all-graphite crystal spectrometer and to give a summary of the solar activity in terms of the overall temperature and solar X-ray flux. Numerous housekeeping and spacecraft parameters are attached to the summary in order to monitor the position of the spacecraft and the particle flux environment. The program was written for the 360/65 at GSFC.

Separate solar spectrometer software (Monthly Progress Report CAL-1378, Sec. 5.2, December 1977) to be run on CAL's Data General minicomputer includes main program WK36 and several companion programs. These programs perform roughly the solar data analysis described for program CAL03. However, they act as an easily accessible experimental version and also produce more informative output through the use of the CAL plotter (no plotter is available at GSFC).

2.2.2 Stellar spectroscopy

The sequence of programs SPE 1, SPE 2, and SPE 3 (in Monthly Progress Reports CAL-1314, Appendix A, April 1976; CAL-1323, Appendix A, July 1976; and CAL-1325, Appendix B, August 1976, respectively) performs stellar spectrometric data analysis and executes on the GSFC IBM 360/65. The primary purpose of SPE 1 is to use housekeeping data to screen out science data that are not useful. SPE 2 takes SPE 1's laundered data and converts the data into Bragg scans and also calculates background rates. The final program SPE 3 converts the Bragg scans from SPE 2 into source spectra in keV $(cm^2$ s keV$)^{-1}$, where possible, and searches for narrow line features. Upper limits on line strengths are generated for lines of interest.

2.2.3 Polarimetry

Program CAL01 (Monthly Progress Report CAL-1312, Appendix B, March 1976) analyzes data obtained by the X-ray polarimeter by doing a modulation analysis of the arrival times of valid events at twice the rotation frequency of the satellite. The program executes on the IBM 360/65 at GSFC.

3. PRINCIPAL SCIENTIFIC OBSERVATIONS, INTERPRETATIONS, AND CONCLUSIONS

3.1 Introduction

During the three and a half year orbital lifetime of the OSO-8 satellite, the Columbia Astrophysics Laboratory made a number of measurements of the X-ray polarization of X-ray sources. The CAL also observed the X-ray spectra of both stellar sources and the Sun with a unique Bragg crystal spectrometer. Following a brief description of the instruments, we summarize the principal scientific results, and in an appendix the reader will find full texts of the scientific papers that contain the central results.

3.2 X-Ray Polarimetric Observations

The OSO-8 X-ray polarimeter was a unique instrument that employed Bragg crystal scattering. The crystals were located on the sector of a paraboloid of revolution, and a small detector was located at the focus of the parabola. The axis of the parabola was located along the spin axis of the OSO-8 satellite. When an observation was made, the spin axis was oriented toward the source under study, and the X-rays from the source which satisfied the Bragg condition were scattered into the proportional counter detector at the focus of the parabola. If the source was polarized, then the counting rate was modulated at twice the rotation frequency of the satellite. The depth of modulation provides a measure of the polarization, and the phase a measure of the position angle. This instrument has been described in a number of publications (Landecker and Novick 1973a; Novick 1975; Weisskopf *et al.* 1972, 1976; Mitchell *et al.* 1976, Wolff 1976; Novick *et al.* 1977).

The polarimeter was used to observe the Crab Nebula and pulsar, Cyg X-1, Cyg X-2, Cyg X-3, Sco X-1, Cen X-3, and Her X-1, as well as 4U1656-53 and 4U1820-30.

In the case of the Crab Nebula, we obtained a very high precision measurement of the X-ray polarization (Weisskopf *et al.* 1976, 1978a; Novick *et al.* 1977). The nebular polarization was 19.2% ± 1.0% at a position angle of 156°.4 ± 1°.4 at 2.6 keV, and 19.5% ± 2.8% at 152°.6 ± 4°.0 at 5.2 keV. This is the first high-precision X-ray polarization result obtained on any cosmic X-ray source. The polarization is essentially identical to that observed in the radio and optical domains. These facts together with the observed power law spectrum unambiguously show that the X-ray emission from the Crab Nebula occurs by the synchrotron process. It should be noted that the Ariel-5 X-ray polarimeter which employed a flat crystal rather than a focusing crystal array was not able to detect the polarization from the Crab Nebula.

The OSO-8 observations of the Crab Nebula permitted us to search for polarization in the X-ray emission from the Crab pulsar (Novick *et al.* 1977; Silver *et al.* 1978). Polarization is seen in both the radio and optical emission from the pulsar, and polarized pulsar X-ray emission is expected. Even in a rather extended observation, it was not possible to obtain a clear indication of X-ray polarization in the pulsar. There was an indication of polarization at about the 2.5 σ level on the leading and trailing edges of the main pulse. To the extent that we detected polarization, the X-ray polarization was roughly in the same direction as the optical polarization at the same pulsar phase. This result suggests that the prediction of Sturrock *et al.* (1975) that the optical and X-ray polarization vectors are orthogonal is not correct.

Observations of Sco X-1 were made in 1977 and 1978 with the OSO-8 polarimeter (Weisskopf *et al.* 1978b; Long *et al.* 1979). X-ray polarization of 0.39% ± 0.20% at 2.6 keV, and 1.31% ± 0.40 at 5.2 keV was detected from Sco X-1. There was no evidence for binary-dependent polarization. The position angle of the X-ray polarization is roughly parallel to the position angle of the multiple radio source associated with Sco X-1. This information clearly has an important bearing on the structure of the accretion disk in Sco X-1 and shows a definite association between the axis of the accretion disk and the axis of the multiple radio source. The fact that we were able to detect such a small polarization indicates the power of the OSO-8 polarimeter concept.

A search was made for polarization in the Cen X-3 and Her X-1 pulsars (Silver *et al.* 1979). Since these pulsars are believed to be rotating magnetized neutron stars, one expects a high degree of polarization. Unfortunately the flux from Her X-1 is so low that it was not possible to obtain a meaningful upper limit to the polarization. In the case of Cen X-3 marginal evidence for polarization at 2.6 keV was found that varies with the pulse phase. Further studies of these sources require a larger, more sensitive instrument. However, even the marginal detection in Cen X-3 of about 10% polarization on the leading edge of the pulse provides a basis for designing an experiment which should yield a precision measurement of the polarization of this and other pulsars.

Multiple observations of Cyg X-1, Cyg X-2, and Cyg X-3 were carried out (Novick *et al.* 1977; Weisskopf *et al.* 1977; Long *et al.* 1980). Evidence was found for variable X-ray polarization in Cyg X-2. In the 1975 observation polarization was detected at about the 2.5 σ level. In 1976 and 1977 there was no indication of polarization. These results suggest that the X-ray polarization of compact X-ray sources is highly variable.

Cygnus X-1 is well known to be the leading black-hole candidate. Polarimetry of Cyg X-1 is especially valuable, since it has been predicted that the position angle of the polarization should be a strong function of photon energy, if in fact Cyg X-1 contains a rapidly rotating black hole. The X-ray polarization, as determined from the OSO-8 experiment, is 2.44% ± 0.85% at a position angle of 162° ± 10° at 2.6 keV. The optical polarization results on Cyg X-1 by Kemp *et al.* (1978, 1979) indicate a different preferred position angle for the system. Kemp discovered a binary phase-dependent optical polarization which he interprets as indicating that the orbital angular momentum vector of the binary system lies at 16° measured east from north. Assuming that the accretion disk lies in the plane of the binary orbit, then the position angle of the major axis of the accretion disk should be 106°. If the accretion disk is optically thick at X-ray energies, then the X-ray polarization vector should lie along the major axis of the accretion disk, and the X-ray polarization position angle should be 106°. In fact, the X-ray position angle is 56° greater than the position angle of the major axis as suggested by Kemp. This discrepancy may be an indication of a black hole in Cyg X-1. We have also considered the possibility that the discrepancy arises from the Faraday effect. We note that we have evidence for X-ray polarization at 5.2 keV. The position angle of this result is essentially the same as that at 2.6 keV, indicating a negligible Faraday effect. Thus the OSO-8 polarization results may provide the first direct evidence for a black hole in Cyg X-1.

The OSO-8 polarimeter results clearly show that at least some X-ray sources are polarized and that the focusing Bragg crystal polarimeter concept is valid. For the future one will require a polarimeter with at least an order of magnitude greater area in order to make a systematic, high precision measurement of the polarization of the various sources that were marginally detected with the OSO-8 polarimeter. Also it is clear that long-time observations should be made of the compact X-ray sources to understand more clearly the nature of the temporal variations of polarization.

3.3 Stellar Bragg Crystal X-Ray Spectroscopy

The Columbia University OSO-8 experiment included a novel, very large area Bragg crystal spectrometer. The spectrometer was formed by two large-area crystal panels which were located along radial surfaces of the OSO-8 wheel section. Multiple proportional counter detectors were located along a radial plane which was mid way between the planes of the crystal panels. The X-rays from the source under study entered the spectrometer through an aperture in the side of the wheel section which faced the crystal panels. Since the X-rays from stellar sources are collimated, this system allowed for Bragg scanning as the satellite wheel rotated. In order to observe a source, it is necessary to orient the spin axis of the satellite so that the X-ray source is in the equatorial plane of the OSO-8 wheel section. This instrument has been described in detail in several publications (Landecker and Novick 1973b, Wolff 1976; Mitchell *et al.* 1976; Kestenbaum *et al.* 1976).

Evidence was found for iron line emission from Cyg X-3. The line had a strength of 0.020 ± 0.008 photons $(cm^2\ s)^{-1}$, corresponding to an equivalent width of 420 ± 170 eV. The energy of the line is 6.84 ± 0.17 keV and suggests Lα emission from Fe XXVI but does not rule out the resonance transition of Fe XXV or K-line emission from other highly ionized states of iron. The results exclude K-line fluorescence from neutral Fe. Our best estimate of the intrinsic width is 250 eV, although the data are also consistent with any line width less than or equal to 600 eV. This observation constituted the first detection of a sharp X-ray line from a nonsolar X-ray source (Kestenbaum *et al.* 1977a, 1978a).

Observations covering multiple orbital periods of Sco X-1 were carried out in 1975 and 1976 with the OSO-8 Bragg crystal spectrometer (Long and Kestenbaum 1978a). Time-averaged continuum spectra are featureless and are reasonably well described in terms of a Comptonized thermal bremsstrahlung in which kT is about 1.5 to 2 keV and in which the number of electron scatterings that each photon is believed to have undergone is of order 100. Line limits, typically with equivalent widths of a few electron volts, are established for important emission lines of Si XIII, Si XIV, S XV, S XVI, and Fe XXV as a function of binary phase.

The OSO-8 spectrometer was used to observe the strong X-ray transient source A0620-00 (Long and Kestenbaum 1978b). These observations yielded upper limits less than or equal to 10 eV to the equivalent widths of narrow emission lines of Si XIII, Si XIV, S XV, and S XVI. A strong continuum was observed which is characterized as blackbody with a temperature of about 0.5 keV.

The OSO-8 spectrometer was used to search for X-ray line emission from Cas A from ions from silicon, sulfur, and iron over the energy band from 1.865 to 8 keV. No evidence was obtained for line emission. Assuming thermal equilbrium, the limits on the line flux can be used to provide limits on the abundances of silicon and sulfur. This interpretation, however, may not be correct because Cas A may not be old enough for thermal equilibrium to have been established. If collisional equilibrium was not established, then it is not possible to derive abundance limits from the upper limits to the lines (Kestenbaum *et al.* 1978b).

One of the intriguing questions about the Crab Nebula is whether or not there is a thermal plasma shell which surrounds the synchrotron source. Palmieri *et al.* (1975) suggest that such a shell does exist. The OSO-8 spectrometer was used to search for X-ray emission lines from highly ionized silicon and sulfur which should arise from such a shell. No such evidence was found, and it was possible to establish new upper limits on the emission measure from the putative thermal plasma shell (Kestenbaum *et al.* 1977b).

The results obtained with the OSO-8 stellar Bragg crystal spectrometer show the importance of high resolution spectroscopy in X-ray astronomy. Clearly a more sensitive spectrometer than the OSO-8 instrument is required to detect the lines from a number of sources. While the OSO-8 instrument used very large crystal panels, the sensitivity was reduced because each resolution element of the spectrometer scanned the source for less than 1% of the rotation period of the wheel section of the satellite. It would clearly be better to employ crystal panels which continuously observe the source so as to increase the sensitivity of the instrument.

3.4 Solar X-Ray Spectroscopy

Since the OSO-8 Bragg crystal spectrometer viewed the sky through the equatorial plane of the wheel section of the satellite and the Sun always fell in this plane in the day sky, the Columbia University spectrometer provided a large body of data on solar X-ray spectra. These data were obtained over a wide range of solar activity, and they covered the energy region from 2 to 8 keV with very high sensitivity and modest resolution.

The OSO-8 observations of the solar X-ray spectrum provided the first clear evidence of a 1.9 Å feature corresponding to 1s—2p transitions in Fe XIX—Fe XXII. Most of the emission originates from the dielectronic recombination process, and when inner-shell excitation is included together with normal collisional excitation, the observed intensity of the feature can be accounted for adequately (Parkinson *et al.* 1979).

Observations of solar flare and active region X-ray spectra with the OSO-8 spectrometer revealed evidence for 29 lines between 1.5 and 7.0 Å (Parkinson *et al.* 1978). All these lines have been resolved and identified, including several dielectronic recombination satellite lines to Si XIV and Si XIII lines which have been observed for the first time. The OSO-8 X-ray spectrometer was the first spectrometer which was able simultaneously to detect both the continuum and the lines from active regions in the sun.

3.5 Conclusions

It is clear that the Columbia University OSO-8 instruments provided unique X-ray data on both cosmic sources and the sun. The polarimetric data was particularly important since it showed that some X-ray sources are polarized and that the focusing graphite Bragg crystal polarimeter is well suited for such observations. A much larger polarimeter of this type is required in order to perform the measurements that are necessary to fully understand the physics of X-ray sources. The scanning Bragg crystal spectrometer was ideally suited for the study of rapidly changing solar conditions.

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