FINAL REPORT

TO THE

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ON

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STUDY OF OPTICAL PROPERTIES OF X-RAY SOURCES

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SIMULTANEOUS OPTICAL AND X-RAY OBSERVATIONS

The first long series of X-ray observations of Sco X-1 by Uhuru was in March and during the week of 3/22/71-3/27/71 we arranged for extensive optical coverage from McDonald Observatory, even though this grant had not yet officially begun. The weather was good for three nights: On 3/23 and 3/26 Sco X-1 was monitored continuously with a high-speed photometer at the 30" telescope and for periods of several hours at the 82" telescope (B. Warner). In addition, plates were obtained using the 107" reflector. On 3/27 more spectra were taken during simultaneous photometric monitoring with the 30" telescope. The photometry was subsequently reduced and integrated with results from other optical observers, radio observers, and the Uhuru observers in two successive meetings at AS&E in Cambridge, Mass. These results show a definite correlation between optical and X-ray intensity -- indicating a common emitting region. Our spectral data do not show any such correlation although we confirm the result of Hiltner et al. that the emission lines are stronger when the optical intensity is low. A detailed study of line intensity and continuum intensity changes using simultaneous spectrograph and spectral scanning instruments would be most valuable to further understanding the nature of Sco X-1 optical emission. All these results were reported at the San Juan AAS meeting by H. Bradt (MIT); a paper is in preparation at MIT.

Optical photometric coverage of Sco X-1 was also provided under this grant during the X-ray observations which were made as part of the Apollo 16 mission 4/24/72 to 4/27/72. Sudden, last-minute changes in the Apollo schedule precluded making simultaneous observations (most Apollo observations occurred during daylight hours at McDonald observatory). However, we did get good photometric data with the 30" telescope on two nights in this interval and recorded a decrease in optical activity from a very active to a quiet state, this source behavior is also present in the X-ray data. P. Gorenstein (AS&E) is assembling our data with that of other observers into a paper presenting these results.

During the period 6/8/72-6/17/72 we used the 30" telescope to monitor Sco X-1 again, this time simultaneously with the MIT experiment (G. Clark) on the current OSO satellite. The X-ray experiment obtains crude spectra with a time resolution of 3 min.; our optical data (three good nights) recorded U,B,V, and open magnitudes in integrations of 5 seconds each. We are examining the data for correlated intensity/color changes.

During June, 1971 Uhuru observed Cyg X-2 and we were able to monitor it photometrically using the 36" telescope and obtain spectra with the 107" telescope on two nights - 6/21 and 6/23. The X-ray data has not been fully reduced. Our data show the source to be quiet with no short-term fluctuations bigger than 10%. The spectra reveal the presence for the first time of the high excitation complex at λ4650 due to NIII-CIII. A note reporting this result has been published in P.A.S.P. and a reprint is attached to this report.

The availability of precise coordinates for Cyg X-1 from radio data prompted us to investigate this object in July. On 7/24 and 7/25 we used a 2-stage image tube spectrograph to obtain spectra of the faint

15-mag red object 9" to the NW of the radio position. Spectral studies had already revealed the bright star at the radio position (BD+34°3815) to be an ordinary BOIb star and scanner data (A. Sandage) suggested the faint red object was an M dwarf with a possible variable UV excess. Our spectra are not of the highest quality because the instrument was being tested for the first time during this run. However, emission lines as found in Sco X-1 would have been easily detectable and were not found. Before our doubts about the suggested red object candidate could be published it became apparent from very precise radio coordinates that Cyg X-1 must be associated with the bright B supergiant star.

We also monitored Cyg X-1 during the Apollo 16 Mission. The source was optically constant as expected.

CORONAL LINE OBSERVATIONS OF SOFT X-RAY EMITTING SUPERNOVA REMNANTS

During the summer of 1971 a λλ5303, 6374 coronal-line detector was constructed. It uses on narrow bandpass (~2Å) interference filters of 2" diameter to select these lines and is operated by chopping the filter from head-on to some angle off axis thus changing the passband by ~ 4Å. Counts are recorded in the two positions by standard pulse counters driven by the photomultiplier detector. The apparatus can either use its own objective of 2" aperture (2° x 4° field of view) or 5" aperture (1° x 3° field of view), or, it may be mounted on a telescope using a standard off-set guider.

The Cygnus loop was observed in the intervals 9/13/71-9/20/71 and 10/11/71-10/18/71. The reduced data do not show the presence of either coronal line but do place severe limits in the amount of X-ray emitting high-temperature plasma in this thermal bremsstrahlung X-ray source. A paper describing these results has been submitted to the Astrophysical Journal and a preprint is attached to this report.

The soft X-ray source in Vela and the Monoceras loop were also observed with this instrument. The data reveals no coronal lines.

IMPETUS FOR FUTURE RESEARCH RESULTING FROM ACTIVITY UNDER THIS GRANT

1) In July of 1972 we will monitor Cyg X-2 simultaneously with the MIT experiment on OSO. We plan to record spectra with the 107" telescope and do photometry with the 36" telescope.

2) We plan to photograph the Sco X-1 region with an Hα filter + image tube camera to search for optical features at the sites of the companion radio objects.

3) We will monitor Cyg X-1 for the presence of the 0.1 mag eclipses reported by Russian observers.

4) We plan to take spectra and do photometry on some objects which might be candidates for identification with Uhuru X-ray sources.

5) We are constructing a grating nebular spectrograph for further observations of coronal line emission in soft X-ray sources like the Cygnus loop.

OTHER GRANT ACTIVITIES

Grant funds were used for two months (June and July 1971) of P/I summer salary support. Other personnel (unsupported) included: B. Bopp, T. Moffett, G. Grupsmith, and D. Kurtz, all graduate students; and Dr. J.R.P. Angel of Columbia University who contributed equipment and time to the coronal line detector. Equipment purchases included the construction of the coronal line detector, a photomultiplier tube, a cold box, and a pulse amplifier/discriminator.

During May 1972; the P/I attended the Joint IAU/COSPAR Symposium on X- and Gamma-Ray Astronomy in Madrid, Spain. Results were presented to the scientific community and information vital to future research was received.

APPEARANCE OF λ4650 EMISSION IN CYGNI X-2

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The C III-N III λ4650 line has been detected in Cyg X-2 An absorption feature is present to the blue of He II λ4686 Both lines and continuum appear to vary independently in intensity

Key words X-ray source — emission lines

The broad emission feature near λ4650, previously seen in Scorpii X-1, appears in considerable strength on a spectrogram of Cygni X-2 obtained on 22 June 1971 at McDonald Observatory The Meinel spectrograph and Carnegie S-20 image tube were used at the Cassegrain focus of the 272-cm reflector The wavelength region from λ4400 to λ6700 was recorded at a dispersion of 210 Å/mm in an exposure time of 86 minutes using baked II a-O plates The λ4650 feature is visible in the spectrum of Sco X-1 (Sandage et al 1966, Westphal, Sandage, and Kristian 1968), and is ascribed to a blend of C III and N III However, this high-excitation feature has never been seen in the spectrum of Cyg X-2 Spectrograms obtained by Lynds (1967), by Burbidge, Lynds, and Stockton (1967), by Kraft and Demoulin (1967) and by Kraft and Miller (1969) show only He II λ4686 in emission Figure 1 is a transmission tracing of our spectrogram over the region of interest

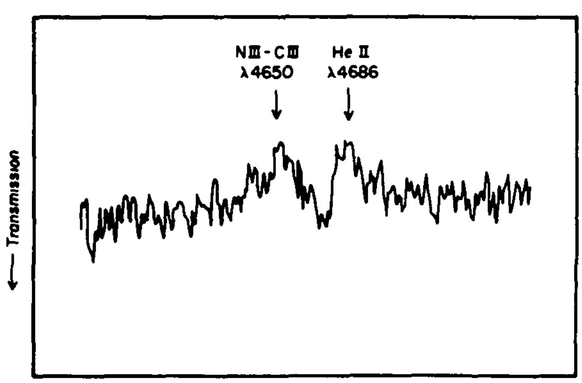

FIG 1 — A tracing of the spectrogram of Cyg X-1 with transmission increasing down and wavelength to the right

In addition to the C III-N III feature, our spectrum shows the Balmer lines Hα and Hβ weakly visible in absorption, and He II λ4686 in emission The measured radial velocity of the helium line is −400 km/sec Further, an absorption feature at the blue edge of the He II emission is visible If this is interpreted as P-Cygni structure, the radial velocity displacement between absorption and emission components is approximately 1000 km/sec Cyg X-2 was monitored photometrically on the McDonald Observatory 91-cm reflector during the exposure No flares or fluctuations greater than 10% were seen, suggesting that the C III-N III emission is not a flare-associated feature Westphal et al (1968) have suggested that in Sco X-1 the emission lines do not change in absolute intensity and are decoupled from the continuum which does vary Mook, Hiltner, and Lynds (1971) have published evidence that this is not the case in Sco X-1 and that both the continuum and the lines vary in intensity The sudden appearance of the λ4650 feature in Cyg X-2, with strength comparable to the nearby λ4686 line observed in all previous spectrograms, strongly suggests this latter behavior is true for Cyg X-2 as well

We wish to thank Dr M H Ulrich for pointing out the absorption feature shortward of He II λ4686 The assistance of Dr P Thaddeus in obtaining a tracing of the spectrogram is gratefully acknowledged This research was supported by NASA Grant NGR 44-012-209

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SEARCH FOR CORONAL LINE EMISSION FROM THE CYGNUS LOOP*

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ABSTRACT

The flux from the edges of the Cygnus Loop in the coronal line [Fe XIV] λ5303 is measured to be less than 5×10^{-9} erg cm^{-2} $sterad^{-1}$ s^{-1} (0.017 R) in a 3-Å band centered on the line. This upper limit is an order of magnitude lower than the predicted total flux in the line and implies that there must be substantial broadening of the line profile by mass motion or that the temperature is somewhat higher than the present best estimate from X-ray data.

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INTRODUCTION

The Cygnus Loop is a strong source of long wavelength ($\lambda > 10$ Å) X-rays identified by Grader, Hill, and Stoering (1970) and studied further by Gorenstein et al. (1971) and Bleeker et al. (1972). X-ray emission is extended over the region of about 3° in diameter shown by the optical filaments, with an intensity distribution indicative of a shell structure. The most accurate spectral data by Bleeker et al. show a thermal X-ray spectrum, with a plasma temperature $T = 2.7 \pm 0.4 \times 10^{6}$° K. This is consistent with the data of Gorenstein et al. which was initially fitted with a simple exponential spectrum having $T = 4 \times 10^{6}$° K and a single emission line of $\lambda = 19$ Å. Tucker (1971), analyzing the same data, estimates that the best fitting optically thin plasma might well be lower, $T \simeq 2 \times 10^{6}$° K. Recently Stevens, Garmire, and Riegler (1972) have confirmed the thermal emission spectrum and find strong evidence of line emission. The identification and further study of X-ray emission lines, which could give valuable information about physical conditions in the plasma, are difficult because Bragg crystal and grating techniques cannot easily be applied to a diffuse source of radiation. However, the possibility arises that the same information can be derived from ground-based observations.

If the X-rays are indeed emitted by a hot plasma with a temperature of a few million degrees, then, as Shklovskii (1967) has argued, optical coronal line emission should also be produced. The observed temperature is such that diffuse emission of [Fe XIV] λ5303 can be expected from the same regions producing X-ray emission. If this emission were detectable against the background of starlight, then the high temperature regions could be mapped, and physical parameters such as expansion velocity could be determined.

ESTIMATED STRENGTH AND PROFILE OF CORONAL LINES

The relative strength of thermal X-ray emission and coronal line emission from an optically thin plasma depend only on the temperature distribution and abundance of elements, and estimates of the total X-ray flux from thin plasmas have been made by several authors. It is convenient to use the recent results of Tucker and Koren (1971), shown in Figure 1, which are for solar abundance. The power expected in the green, [Fe XIV] λ5303, and red, [Fe X] λ6374, coronal lines is also shown in Figure 1. Here we have adopted the emissivities calculated by Nussbaumer and Osterbrock (1970) and assumed that log $(N_{Fe}/N_H) = 7.5 - 12$, yielding the ratio $N_{Fe}/N_H = 2.59 \times 10^{-5}$. It will be seen that at the most favorable temperatures, 2.1×10^{6}° K for [Fe XIV] λ5303 and 1.2×10^{6}° K for [Fe X] λ6374, the power in coronal lines is only a few hundred times less than the total X-ray power, and so the two photon fluxes are comparable. The total X-ray flux obtained by both Gorenstein et al. (1971) and Bleeker et al. (1972) is 2×10^{-8} erg cm^{-2} s^{-1} and is insensitive to the choice of temperature. Adopting this value, we can with the aid of Figure 1 calculate the coronal line flux for any assumed single temperature or distribution. If the plasma temperature is 2.7×10^{6}° K, as indicated by the X-ray data, then the predicted total flux in λ5303 is 6×10^{-11} erg cm^{-2} s^{-1}. Spread uniformly over the whole nebula, which we take to be an annular region of inner radius 2° and outer 3°, the corresponding surface brightness is 4.8×10^{-8} erg cm^{-2} sterad^{-1} s^{-1}, that is, 0.16 Rayleighs.

The practical difficulty in detecting the optical coronal lines arises because of the relatively bright continuum background of starlight from the Galaxy and because the line profiles will be broadened by thermal and mass motions. The width from thermal Doppler broadening at $3 \times 10^{6\circ}$ K is 1 Å (FWHM) for λ5303. Mass motions in the remnant are a more serious potential source of broadening. If the plasma is indeed heated by a shock of velocity 500 km s^{-1}, as suggested by Tucker (1971), then maximum shifts of ± 10 Å can be expected. Taking a simple model of an expanding spherical shell, the observer would see the outline of the shell as a ring of maximum brightness and small radial velocity. However, allowing for the finite thickness of the shell and deviations from a perfect sphere, it is apparent that broadening of 5 Å (FWHM) or more could arise, even in the bright ring region.

INSTRUMENT AND OBSERVATIONS

An instrument was made with interference filters, which are especially useful when diffuse radiation is to be analyzed for one or two relatively broad spectral features. It consists of an objective lens of either 50 or 125 cm diameter with an aperture stop in the focal plane which limited the field of view to 90′ × 195′ and 33′ × 77′, respectively. The light is collimated by a second lens, passed through a 5.080-cm diameter interference filter, and refocused by a third lens onto a photomultiplier tube cathode. The interference filter is enclosed in an isothermal housing of controlled, variable temperature, which allows the central bandpass wavelength to be tuned exactly to the coronal line wavelengths. The filter could be rocked by an electromagnet between two positions, one normal to the optical axis and the other tilted such that the central bandpass wavelength was shifted 4 Å to the blue. Narrow filters were obtained for both the green and red lines and were calibrated at the Coudé scanner of the 107-inch (2.7178-m) telescope a McDonald Observatory, giving the temperature dependence of central wavelength and the bandpass. These were 3.2 Å for the λ5303 filter and 2.5 Å (FWHM) for the λ6374 filter. In operation the filter is maintained at the correct temperature for maximum transmission of the coronal lines in the normal position and switched periodically (1 Hz) to the tilted position. The phototube pulses are gated synchronously into two scalers.

Observations were made with the 5303-Å filter of the four smaller areas in the Cygnus Loop shown in Figure 2. For each area an integration was made to determine the counting rate for the two filter positions, and this was compared with a similar integration on a region with similar density of background stars a few degrees out of the remnant. Any difference in the two spectra would then show as different ratios in the two scalers. Frequent observations of the nearby bright star α Cyg were used to convert the counting rates to absolute fluxes incident at the earth. Table 1 lists for each of these regions in the Loop the excess flux in a band centered on 5302.9 Å and also for the large region (1) in a band centered at 6374.5 Å. The excess is expressed as a fraction of the mean flux in the bands due to sky background, and as an absolute flux in ergs cm^{-2} $sterad^{-1}$ s^{-1}. The quoted errors are the standard deviation calculated from counting statistics alone. It will be seen that in no position is there any significant increase in the background continuum at the coronal-line wavelength. In the 3-Å band at 5303 Å where most of the data are taken, the fractional increment in the background continuum is no more than a percent or so, at least relative to the flux at 5299 Å.

From the tabulated values of absolute flux we deduce that for the best observed positions, 2 and 3, an upper limit (3 σ) of the excess in the λ5303 band is 5×10^{-9} erg cm^{-2} $sterad^{-1}$ s^{-1}. This upper limit is an order of magnitude less than the best estimate above of 4.8×10^{-8} erg cm^{-2} $sterad^{-1}$ s^{-1} for the line flux. The discrepancy can be explained if either there is rather more Doppler broadening than expected, if the temperature is higher than assumed, or if the iron abundance is low. For linewidths greater than the filter width of 3 Å, the sensitivity is reduced because not all the energy falls in the bandwidth. A further reduction occurs if the line is so wide that a significant amount of energy falls in the comparison channel 4 Å away. The shock wave model, summarized in a recent review by Woltjer (1972), yields a shock velocity $V = 0.263\ T^{1/2} = 430$ km s^{-1} when $T = 2.7 \times 10^{6}$° K. If the emission is from a spherical shell expanding uniformly with this velocity, then, in regions 2 and 3 at the edge of the shell, lines of width ~ 5 Å are predicted, and about half the line flux would appear in the 3-Å band. More severe broadening or shifting of the line center is required to explain the low limit to the observed flux, but this could easily arise if the expansion is not very uniform. Alternatively, we note from Figure 1 that the λ5303 emission drops off quite steeply with increasing temperature. If the plasma temperature is really 3.5×10^{6}° K, which is the upper limit obtained by Bleeker *et al*., then a surface brightness of 6×10^{-9} erg cm^{-1} $sterad^{-1}$ s^{-1} is predicted, consistent with our data if there is only little Doppler broadening.

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TABLE 1.

Excess flux in regions in the Cygnus Loop

Position	λ	Relative Fractional Excess Flux (percent)	Absolute Excess Flux (10^{-9} erg cm^{-2} $sterad^{-1}$ s^{-1})
1	6374	-1.8 ± 1.3	-8.4 ± 6.1
2	5303	-0.34 ± 0.50	-1.1 ± 1.6
3	5303	0.31 ± 0.60	1.1 ± 2.2
4	5303	1.6 ± 1.1	5.2 ± 3.7
5	5303	-2.2 ± 1.6	-6.9 ± 5.2

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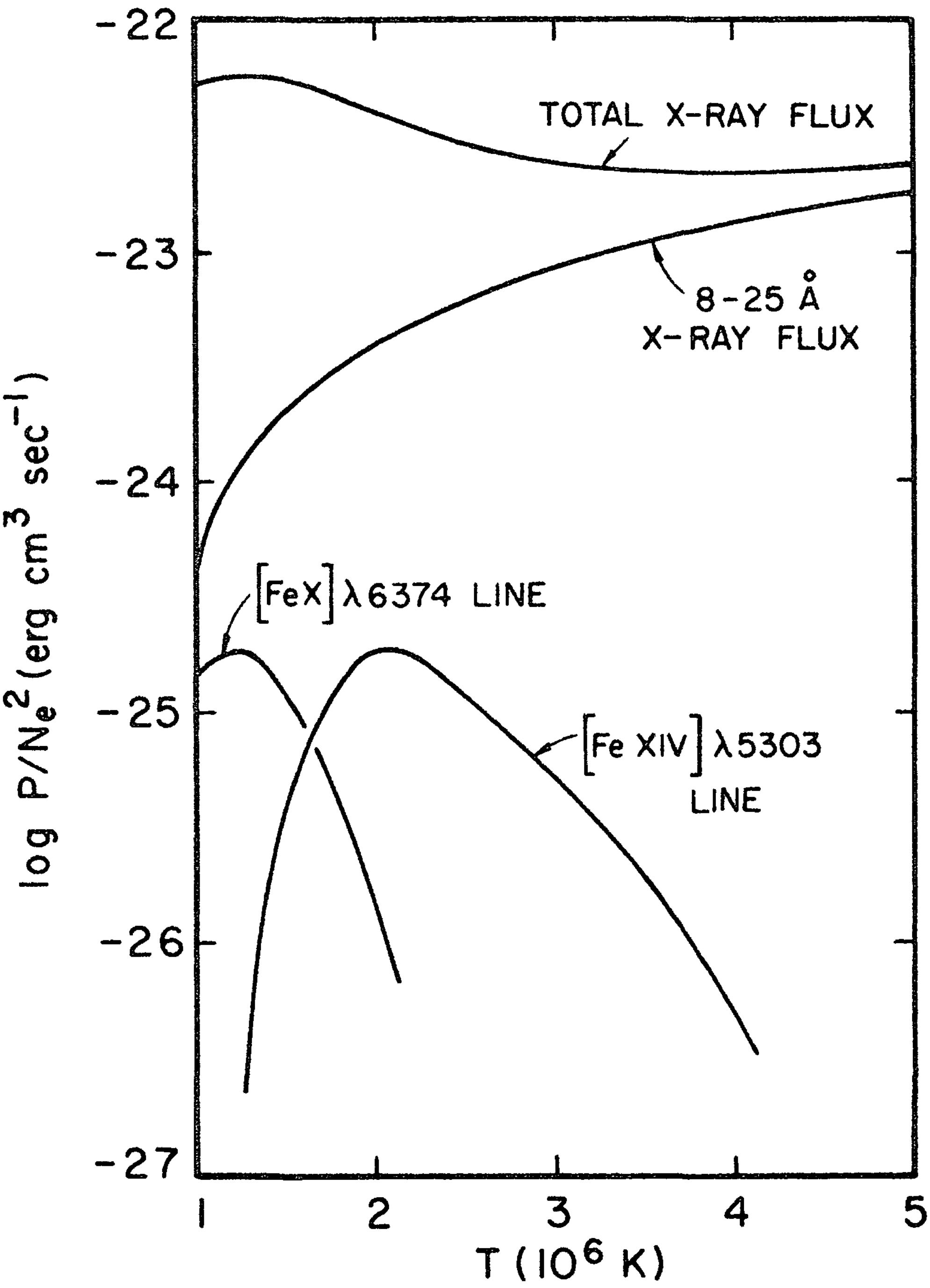
FIGURE CAPTIONS

Fig. 1. — Power radiated in X-rays and coronal lines as a function of temperature.

Fig. 2. — Areas and wavelengths observed in the Cygnus loop; position 1, λ6374; positions 2 — 5, λ5303.



TOTAL X-RAY FLUX
8-25 Å
X-RAY FLUX
[FeX] λ6374 LINE
[Fe XIV] λ5303
LINE
-22
-23
-24
-25
-26
-27
log P/Ne2 (erg cm3 sec-1)
1
2
3
4
5
T (10^6 K)

Figure 1

Figure 2