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DETECTION OF THE [Fe XIV] CORONAL LINE AT 5303 Å IN THE CYGNUS LOOP

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ABSTRACT

Emission in the [Fe XIV] coronal line at 5303 Å has been detected in strong X-ray emitting regions of the Cygnus Loop. For the strongest region the flux measured was $(7.1 \pm 1.2) \times 10^{-12}$ ergs $(\text{cm}^2\ \text{s})^{-1}$, giving an average brightness of $(3.1 \pm 0.5) \times 10^{-8}$ ergs $(\text{cm}^2\ \text{s sr})^{-1}$ in the 1°.0 diameter field of view used, a result different from zero by 6 standard deviations. These fluxes agree well with calculations based on a thermal model for X-ray emission with normal iron abundance. Upper limits to fluxes in the line were obtained for the center of the Cygnus Loop and for Puppis A and IC 443.

Subject headings: nebulae — supernova remnants — X-ray sources

I. INTRODUCTION

Since X-rays from the Cygnus Loop were first detected by Grader, Hill, and Stoering (1970), several groups have made X-ray observations and have fitted model spectra. There is general agreement that the emission is thermal with a characteristic temperature of a few million degrees. Gorenstein *et al.* (1971) find that their data are fitted by a bremsstrahlung continuum at 4×10^6 ° K, with a line which they suggest is the O VIII Lα line at 19.0 Å, while Stevens, Riegler, and Garmire (1973) require a 2.8×10^6 ° K plasma with a line feature which may be the O VII lines at 21.6–22.2 Å or the O VIII line. Using data from similar instrumentation, Bleeker *et al.* (1972) obtained a good fit to their spectra from bremsstrahlung alone with a temperature $T = (2.7 \pm 0.4) \times 10^6$ ° K. Theoretical models of optically thin plasmas with solar abundance by Tucker and Koren (1971) and Mewe (1972) show that most of the X-ray flux comes from spectral lines for temperatures below 30×10^6 ° K. Tucker (1971) has used these models to reinterpret the data of Gorenstein *et al.* and estimates a temperature of 2×10^6 ° K. All the data obtained so far are limited by the poor spectral resolution of proportional counters in the 20–100 Å range, which does not permit clear distinction between line and continuum spectra, nor does it permit the separation of individual lines.

Although suggestive of a thermal plasma, the X-ray data could be fitted by nonthermal models, with appropriate choice of model parameters and interstellar absorption. Unambiguous detection of spectral lines is required to demonstrate the thermal nature of the X-ray emitting plasma.

As pointed out by Shklovskii (1967), those supernova remnants which emit thermal X-rays from hot plasma at a few million degrees will also emit optical coronal lines. Kurtz, Vanden Bout, and Angel (1972) estimate that at a temperature of 2×10^6 ° K the power in the [Fe XIV] λ5303 Å line is 5×10^{-3} of the total X-ray power, and at 3×10^6 ° K it is 2.2×10^{-3} of the total X-ray power. Kurtz *et al.* searched for the [Fe XIV] λ5303 Å line in various regions of the Cygnus Loop but without an X-ray map to guide the search area. No positive detection of the line was made.

II. OBSERVATIONS

We have used the interference filter photometer described by Kurtz *et al.* to search for the [Fe XIV] λ5303 Å line in the Cygnus Loop, Puppis A, and IC 443. For these new observations we used a filter of wider bandpass (5.9 Å FWHM) and higher transmission (50 percent), and used the X-ray map of Stevens and Garmire (1973) as a guide. The instrument consisted of an f/5 objective lens 15 cm in diameter with a 59′ diameter field stop at the focal plane. The beam was collimated, passed through the 5.1-cm-diameter interference filter, and refocused by a camera lens onto a cooled photomultiplier. The filter was rocked by an electromagnet so that for the ON-band position the filter was normal to the beam, and for the OFF-band position the filter was rotated 6.5°, which shifted the central wavelength 16 Å to the blue. This shift ensures that there is no overlap of the OFF-band bandpass with the iron line emission even

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if there is broadening up to ± 8 Å. High turbulent velocities causing such broadening are possible if the heating to the observed X-ray temperature is by shock waves (Woltjer 1972). As the filter was tilted periodically (1 Hz) to the ON-band and OFF-band positions, the photomultiplier pulses were gated synchronously into two scalers. In order to keep the transmission in the ON-band close to the coronal line wavelength, the filter temperature was kept in the range 5°–20° C, where it passed an average central wavelength of 5303.4 Å for the center of the field of view and an average central wavelength of 5302.2 Å for the 1° field. For normal operation and with the 1° diameter field, the temperature shift and field shift were small compared with the filter bandwidth. The filter could be heated to over 50° C to move the bandpass off the 5303 Å line by 6 Å to the red. The filter efficiency and bandpass were measured at the coudé scanner at McDonald Observatory by Dr. P. Vanden Bout, who used the Sun as a source. The instrument sensitivity was calibrated by measuring the counting rate from α Lyr and α Cyg, using the α Lyr fluxes from Oke and Schild (1970) and correcting for absorption variations with zenith angle.

The principle of the measurement is to determine the ratio of counting rates in the ON and OFF wavelength bands for the regions of interest in the remnant and the nearby field. Coronal line emission then appears as a small increase in this ratio, the brightness of the [Fe XIV] line emission being much less than the nightsky light from airglow, faint stars, and city lights. Because of variations in the airglow, it was found to be necessary to make frequent comparisons with the adjacent sky, and in these observations integration of 2–3 minutes were made alternately on the same region and surrounding sky. Several adjacent sky regions were chosen outside of the remnant to obtain the best average of the spectral slope of the nearby sky.

The counting rate from the line in the source is given by

$$R = \left[N_{\rm BS} - N_{\rm BK}\frac{N_{\rm AS}}{N_{\rm AK}}\right] T^{-1}\,, \tag{1}$$

where $N_{\rm BS}$ is the number of counts in the ON-band in time T on the source; $N_{\rm BK}$ is the number of counts in the ON-band on the adjacent sky; $N_{\rm AS}$ is the number of counts in the OFF-band on the source; $N_{\rm AK}$ is the number of counts in the OFF-band on the adjacent sky. The line brightness calculated in this way is insensitive to changes in absolute brightness of the night sky and is sensitive only to differences in the spectral ratio ON-band/OFF-band between the source and sky.

For the Cygnus Loop, the observed fields are shown as circles in figure 1, superposed on the 8–60 Å X-ray map of Stevens and Garmire (1973). For Puppis A and IC 443, the whole source was in the field of view. The results are presented in table 1.

For area 1, the observed flux of $(7.1 \pm 1.2) \times 10^{-12}$ ergs $(\text{cm}^2\ \text{s})^{-1}$ is significant at 6.0 standard deviations above zero, and the flux for area 3 of $(3.8 \pm 1.1) \times 10^{-12}$ ergs $(\text{cm}^2\ \text{s})^{-1}$ is significant at 3.4 standard deviations above zero. This significance is not affected by a possible uncertainty of about 10 percent in the absolute calibration. The values for the brightness of the line relative to the night sky in the 6 Å bandpass were about 0.7 and 0.4 percent for areas 1 and 3. The two regions of enhanced X-ray emission shown as areas 1A and 3A were observed by using a 0°.6 diameter field, and optical line radiation was positively detected in both these regions. Also, the line surface brightness was higher in both these regions than the average surface brightness over the largely overlapping 1° diameter fields. Each result in table 1 is a weighted mean of observations from several nights, the weights and the final quoted error being obtained from the internal scatter of each night's observations. The scatter is generally about 1.5 to 2 times worse than would be expected from photon sta-

TABLE 1

[Fe XIV] 5303 Å RESULTS FOR THE CYGNUS LOOP, PUPPIS A, AND IC 443

Source	Field Diameter (°)	Energy in Line [10^{-12} ergs $(\text{cm}^2\ \text{s})^{-1}$]	Line Surface Brightness [10^{-8} ergs $(\text{cm}^2\ \text{s sr})^{-1}$]	Statistical Significance (σ)	X-Ray Flux* [10^{-9} ergs $(\text{cm}^2\ \text{s})^{-1}$]	Number of Nights Observed
Cygnus Loop:						
Area 1	1.0	+7.1±1.2	+3.1±0.5	+6.0	2.9	7
Area 1, wavelength shifted to 5309 Å	1.0	−2.1±1.8	−0.9±0.8	−1.2	...	3
Area 2	1.0	−0.4±1.5	−0.2±0.7	−0.3	1.2	4
Area 3	1.0	+3.8±1.1	+1.6±0.5	+3.4	1.8	3
Area 1A	0.6	+4.1±0.7	+4.8±0.8	+6.0	1.6	2
Area 1A, wavelength shifted to 5309 Å	0.6	−0.2±1.0	−0.2±1.2	−0.2	...	1
Area 3A	0.6	+2.9±0.9	+3.4±1.0	+3.3	0.9	3
Puppis A	1.0	−2.6±4.1	−1.1±1.8	−0.7	...	2
IC 443	1.0	+8.2±4.5	+3.6±2.0	+1.8	...	3

* Stevens and Garmire 1973.

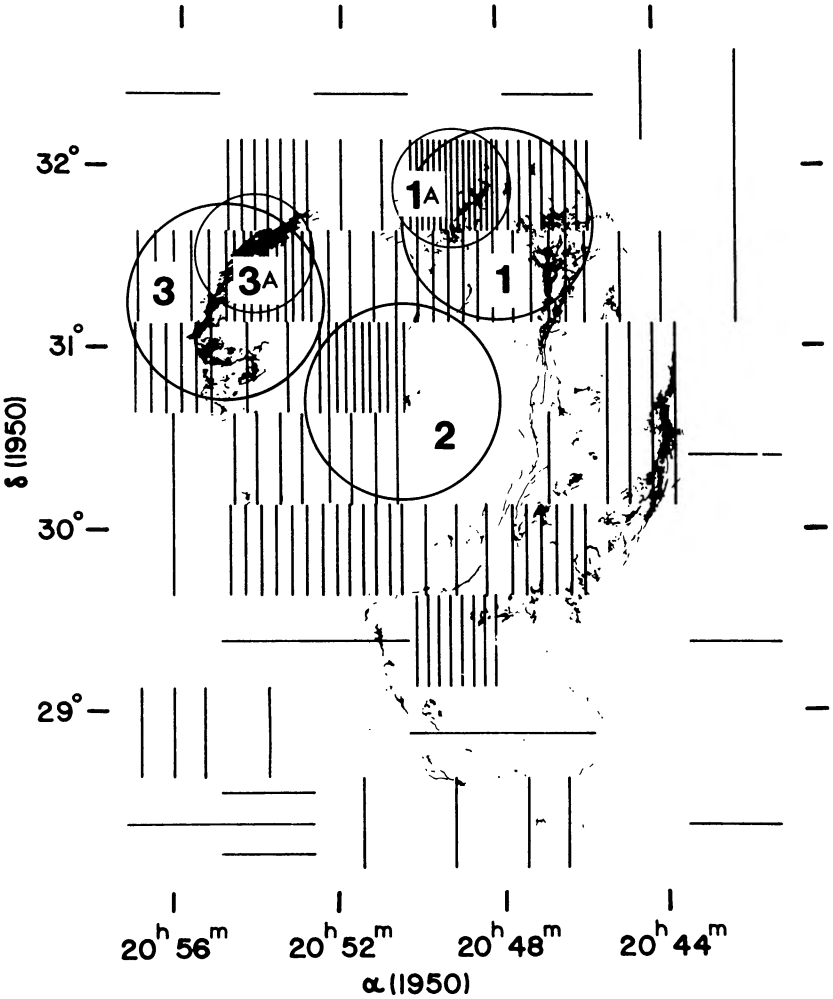

FIG. 1.—Reproduction of the Stevens and Garmire (1973) X-ray map, superposed on the Palomar *Sky Survey* photograph. The fields of view for which observations have been made are shown by the circles, numbered as in the table. The density of vertical lines is proportional to the X-ray flux.

tistics alone. The remainder was probably contributed by nightsky variations, as the scatter increased considerably if the chopping on and off the source was done more slowly than every 2 or 3 min.

III. DISCUSSION

Contributions to the line flux by starlight, continuum from the Cygnus Loop, and other known lines have been investigated and found to be negligible. In particular the heated filter results show that the [Ca v] 5309 Å line is not present.

Comparing our data with the results of Kurtz *et al.* for area 1, we find that the average surface brightness of the line in the field observed is $(3.1 \pm 0.5) \times 10^{-8}$ ergs $(\text{cm}^2\ \text{s sr})^{-1}$. This is just over 4 times brighter than the 3 σ upper limit given by Kurtz *et al.* for a field region which partly overlaps area 1. However, using the Stevens and Garmire X-ray map on Kurtz *et al.*'s region, we see that its X-ray surface brightness was about 0.25 of that of area 1.[1]

From the X-ray map of Stevens and Garmire we see that 20 percent of the X-rays from the Cygnus Loop come from our area 1 so that the X-ray power from the same field is $(2.9 \pm 0.4) \times 10^{-9}$ ergs $(\text{cm}^2\ \text{s})^{-1}$. Then the observed ratio of [Fe XIV] coronal-line power to total X-ray power is $(2.4 \pm 0.6) \times 10^{-3}$. This ratio fits the prediction of Kurtz *et al.* for a temperature of $(2.8 \pm 0.3) \times 10^6$ ° K if all the X-ray flux is of thermal origin, assuming an iron abundance of 2.6×10^{-5} of the hydrogen abundance. This temperature agrees very well

[1] Burginyon (1973) has pointed out that in the annular model assumed by Kurtz *et al.* to obtain an X-ray surface brightness, an error of a factor 4 was made. This does not affect the optical upper limits quoted there but only the ratio to the X-ray flux.

with those calculated from the X-ray spectra, suggesting that all the X-ray flux is thermal. Even if the optimum temperature for [Fe XIV] formation, 2.0×10^6 ° K, were assumed, the coronal-line strength would require that half the X-ray flux be thermal.

Similarly, the Stevens and Garmire map shows a flux of 1.2×10^{-9} ergs (cm² s)$^{-1}$ and 1.8×10^{-9} ergs (cm² s)$^{-1}$ from our areas 2 and 3. The ratios of [Fe XIV] line power to X-ray power are $(2.1 \pm 0.8) \times 10^{-3}$ for area 3 and a 3σ upper limit of 3.7×10^{-3} for area 2. The positive result for area 3 again demonstrates the thermal nature of the X-ray emitting plasma with a temperature of $(2.8 \pm 0.4) \times 10^6$ ° K if all the X-ray flux is thermal. The upper limit for area 2 does allow the X-ray flux to be thermal in the range $(2\text{–}3) \times 10^6$ ° K, although the recent rocket observations of Rappaport *et al.* (1973) indicate a harder X-ray spectrum for this region than for most of the Cygnus Loop.

The results from areas 1A and 3A with 0°6 diameter field show that the correlation of [Fe XIV] line power to X-ray power continues to exist at this smaller field, giving some confidence in the brighter parts of the X-ray map down to its half-degree resolution. The ratios of [Fe XIV] line power to X-ray power are $(2.6 \pm 0.6) \times 10^{-3}$ for area 1A and $(3.8 \pm 1.3) \times 10^{-3}$ for area 3A, giving temperatures of $(2.8 \pm 0.3) \times 10^6$ ° K and $(2.5 \pm 0.4) \times 10^6$ ° K, respectively.

For areas 1 and 1A, the absence of the line when the wavelength was shifted by heating the filter suggests that the line is not broadened by as much as about 8 Å FWHM, which would be the predicted effect if a shock of velocity 450 km s^{-1} were fully converted into mass motions. Minkowski's (1958) measurement of a radial velocity of 116 km s^{-1} has been used with proper motion measures to derive the distance and diameter. If the X-rays are produced immediately behind the present shock and are not fossil radiation, then Minkowski's radial velocity does not measure the shock velocity, and its use for comparison with proper motions is not straightforward.

The agreement between the temperatures derived from the ratios of [Fe XIV] line to X-ray flux and from the X-ray spectra using a normal iron abundance (2.6×10^{-5} of hydrogen) supports the assumption of this normal abundance. Observations of interstellar ultraviolet lines using the *Copernicus* satellite have shown that iron is depleted by up to a factor 100 (Jenkins 1973). Field (1973) has explained this by the condensation of heavy elements into grains. If the observed underabundances are general in the interstellar medium, then our observations show that the shock wave has destroyed the grains and released the iron back into the gas.

In conclusion, a spectral feature has been discovered at 5303 Å in the regions of the Cygnus Loop brightest in X-rays. We attribute it to the coronal line of [Fe XIV]. The observed intensity agrees very well with the hypothesis that the X-rays are emitted from an optically thin thermal plasma at $(2.8 \pm 0.3) \times 10^6$ ° K.

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