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ON X-RAY LINE EMISSION FROM SCORPIUS XR-1

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ABSTRACT

A high-sensitivity measurement of Scorpius XR-1 made with a proportional counter gave no positive indication of line emission near 7 keV. It is shown that the energy in the iron line emission must be less than 5 per cent of that in the continuum between 1.5 and 6 keV. This limit rejects a theoretical thermal-plasma model derived for a low-mass supernova but does not exclude models derived for normal cosmic abundance or a high-mass supernova.

I. INTRODUCTION

Holt, Boldt, and Serlemitsos (1968) have computed line-to-continuum ratios for Fe XXV and Fe XXVI resonance line emission (6.64 and 7.15 keV, respectively) from thermal bremsstrahlung sources; the ratios were based on the calculations of Tucker (1966) and the use of relatively low-resolution (~15 per cent) devices such as gas-filled proportional counters. As Holt *et al.* point out, the relative amount of iron line emission is an important factor in characterizing X-ray sources (Tucker 1966). They state that the data of Hill, Grader, and Seward (1968) and of Gorenstein, Gursky, and Garmire (1968) (see Fig. 1) for Scorpius XR-1 seem to have an excess in photon intensity near 7 keV; and they predict that a higher-sensitivity experiment (60-sec observation time, with 100 cm^2 collecting area) would resolve the question.

II. EXPERIMENTAL RESULTS FROM SCO XR-1

We wish to report here the result of an observation, with essentially the proposed sensitivity, that was performed by the Naval Research Laboratory on September 7, 1967. An Aerobee rocket directed a proportional-counter detector toward Sco XR-1 for 40 seconds; the effective aperture was 100 cm^2, and the resolution at 7 keV was 18 per cent. The results were described briefly by Meekins, Fritz, *et al.* (1968) and are reported in detail by Meekins, Henry, *et al.* (1968).

A detailed spectrum from 1.5 to 10 keV was obtained, for which a simple exponential with $kT = 5.6 \pm 0.4$ keV (similar to thermal bremsstrahlung with an apparent temperature of $65 \pm 5 \times 10^6$ ° K) gave a good fit. A number of the spectral points (5–9 keV) are reproduced in Figure 1, relative to the theoretical line (C) for the plasma at 65×10^6 ° K. The error bars represent 1 standard deviation (plus and minus) in counting statistics. No averaging has been done. The resolution is about 1 keV. The indicated position is that of the Fe XXVI line, although at lower temperatures the Fe XXV line at 6.64 keV would be favored. For comparison the data of Hill *et al.* (1968) are shown, as well as data points relative to spectra fitted over a wider energy range (line A for March 8, 1966, and line B for October 11, 1966) due to Gorenstein *et al.* (1968). Comparison of these observations with the present data shows that the estimate of Holt *et al.* (1968) is correct regarding the sensitivity necessary to exclude the possibility of very strong iron line emission.

We have suggested (Meekins, Henry, *et al.* 1969) that our data can be used to exclude models of X-ray sources with a distinct overabundance of iron, such as low-mass supernovae (Tucker's model II), but not models with cosmic abundance (Tucker's model I) or a slight iron excess (Tucker's model III). This conclusion was arrived at by folding a spectrum, consisting of thermal bremsstrahlung plus a line of appropriate strength, through the instrumental resolution and sensitivity and then estimating by eye, from the statistical dispersion in our data points, whether the model was consistent with the data. Holt *et al.* (1968) suggested grouping data in 1-keV-wide bins, to obtain a more quantitative determination of the apparent line strength.

III. LINE-TO-CONTINUUM RATIO

Folding the models through the instrument characteristics as described above produces a result similar to that shown in Figure 2 (in the case illustrated, unit efficiency and negligible electronic noise were assumed). In the figure, dF/dV is the number of proportional-counter pulses per kilo electron volt of energy, and the individual curves are labeled with values of P, the percentage of the continuum energy between 2 and 8 Å (1.55 and 6.2 keV) that equals the line radiation. Now, in order to establish a criterion of line strength, let us define

$$R = \frac{F(7) - \langle F(7) \rangle}{\langle F(7) \rangle}, \tag{1}$$

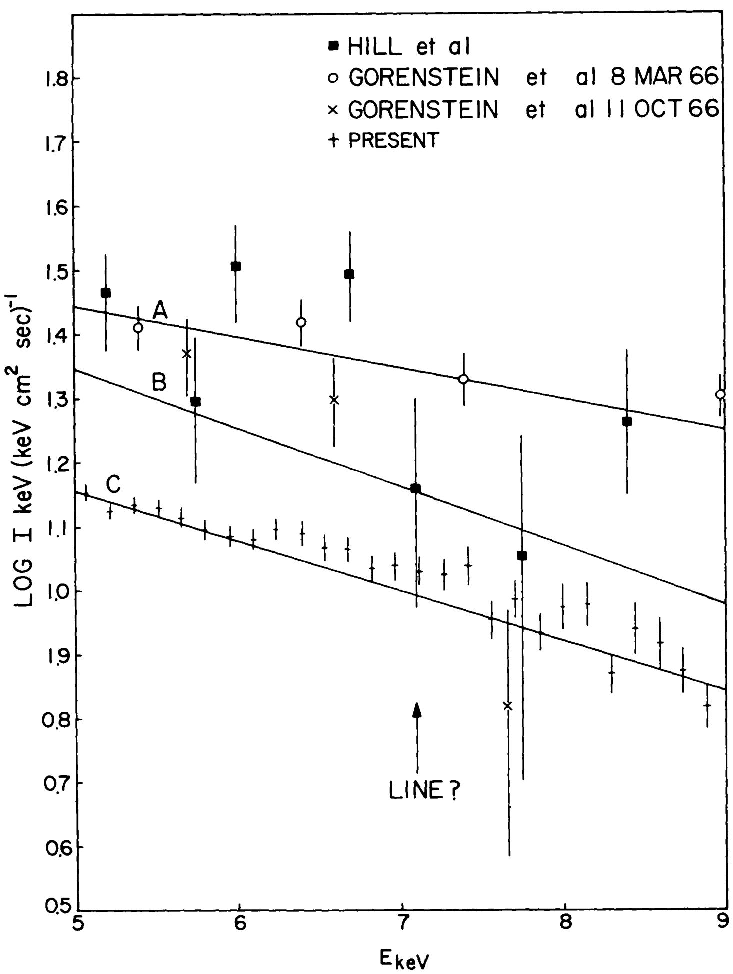

FIG. 1.—Iron line radiation might be expected in this region of the spectrum of Sco XR-1, but it has not yet been found. Data points of Gorenstein, Gursky, and Garmire (1968) are plotted relative to spectra (*A*, March; *B*, October) fitted over a wider energy interval. *C* is the same for the Naval Research Laboratory data (Meekins, Henry, *et al.* 1968).

where $F(V)$ is the integral of dF/dV over a 1-keV band centered on V keV and where

$$\langle F(7) \rangle = \frac{F(6) + F(8)}{2} . \tag{2}$$

R is a parameter related to the strength of the line, which for convenience may be called the "line-to-continuum ratio." It is not the same as the P_L/P_C of Holt *et al.* (1968), which is the ratio of counts (actually, power) due to the line to counts due to the continuum in a 1-keV-wide bin (centered on 6.9 keV).

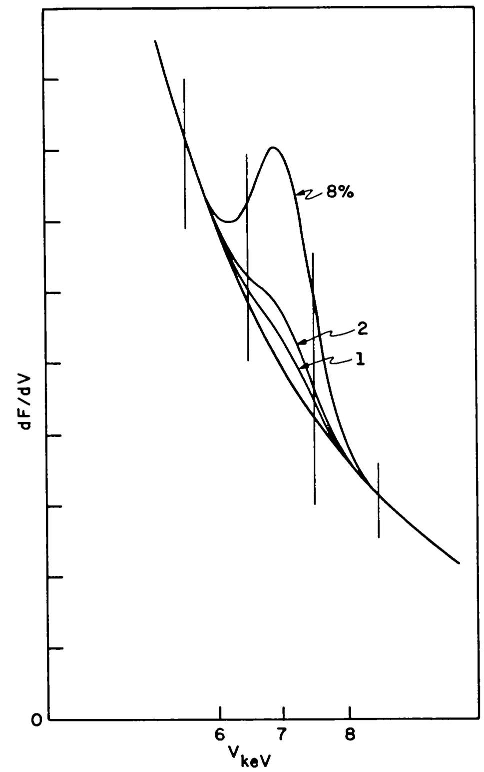

FIG. 2.—An ideal proportional counter, having 15 per cent resolution at 7 keV, would give the response shown, dF/dV (intensity per kilo electron volt), if exposed to sources at 65×10^6 ° K containing lines of power 0, 1, 2, or 8 per cent of the continuum power between 1.55 and 6.2 keV. Vertical lines indicate the regions used in defining the quantities F (6), $F(7)$, and $F(8)$ referred to in the text.

The parameter R has been calculated[1] for several values of P, with the assumption of a continuum source at 65×10^6 ° K and with our known instrumental efficiency and resolution; the values are listed in Table 1. The ratio R has the advantage that it is experimentally measurable: we obtain $R = -0.115 \pm 0.024$. This is the value expected for cosmic abundance (Tucker's model I). The fourth column of Table 1 gives the number of standard deviations by which each computed value of R differs from our measured value. It appears that in suggesting $P < 0.05$ (Meekins, Henry, *et al.* 1968) we were too conservative, at least if one considers only statistical uncertainties. The most serious systematic errors to be expected are due to possible deviations of the neighboring continuum from a pure bremsstrahlung spectrum (Holt *et al.* 1968). We have not explored this in detail. It is also clear on examination of the fourth column of

[1] A calculation of P_L/P_C for the same circumstances gives values rather smaller than those presented by Holt *et al.* (1968), because the effects of counter resolution were included in the present calculations.

Table 1 that we cannot exclude the interesting case $P = 0.00$, corresponding to zero line strength. That value is expected in any synchrotron model for Sco XR-1.

It appears that, to determine the presence of a line, we need a still larger detector *and/or* a longer integration time. The criterion for detecting with certainty $n\sigma$ a line having actual line-to-continuum ratio R can be shown to be, to a sufficient approximation,

$$\langle F(7) \rangle = \frac{2.5n^2}{(R - R_0)^2}, \tag{3}$$

where R_0 is the value of R expected for zero line strength. The last column of Table 1 gives N, the value of $\langle F(7) \rangle$ from equation (3) for which the equality holds if $n = 3$.

TABLE 1

EXPECTED LINE-TO-CONTINUUM RATIO R, AND NUMBER OF COUNTS N NEEDED FOR DETECTION WITH CERTAINTY 3 σ, AS FUNCTIONS OF P, THE INTRINSIC IRON LINE STRENGTH

P	Tucker's Model*	R	$\Delta R/0.024$†	N
0.00	....	−0.150	1.5	....
.01	I	− .115	0.0	18400
.02	III	− .080	1.5	4600
.03	....	− .052	2.7	2350
.04	....	− .021	4.0	1440
.05	....	+ .008	5.2	900
0.08	II	+0.095	9.0	375

* The upper curve in Fig. 1 of Holt, Boldt, and Serlemitsos (1968), labeled *III*, is Tucker's model II. Similarly, their curve *II* is Tucker's model III.

† ΔR is the difference between R and our measured value of −0.115, while 0.024 is the rms statistical uncertainty in the latter.

In our observation we had $\langle F(7) \rangle = 4100$. The detection with certainty 3 σ of a line for which $P = 0.01$ would therefore require an increase in our product (detector area $\times$ time) of $\frac{18400}{4100} = 4.5$. This suggests that it would be worthwhile to repeat the observation of Sco XR-1, using the full flight time of about 4 min and a counter of larger area.

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