Spectrum and Distance of Source Sco XR-1

Abstract. *In a broad sky survey for x-ray sources in the 44- to 60-Å range only Sco XR-1 was detected. The spectral evidence indicates that Sco XR-1 may lie within a few hundred light-years of the sun. Its spectrum appears to be complex—possibly a mixture of thermal sources at different temperatures or of thermal and nonthermal components, as has been predicted for an active neutron star with an associated corona or magnetosphere.*

Although the primary purpose of the Naval Research Laboratory's x-ray astronomy observations has been to survey the sky for discrete sources, qualitative spectral information has also been obtained from "filter photometry." In April 1965, a pair of argon-filled counters and a similar pair of helium-filled counters with ¼-mil and 1-mil Mylar windows were flown on an Aerobee rocket. In June 1964 the same type of counter, with neon gas, had been flown (*1*). If we assume a particular emission model, the ratios of counting rates for combinations of different counters can be computed. For example, in April 1965 the observed ratio Ar (¼-mil Mylar)/Ar (1-mil Mylar) was 1.8. If the spectrum has the form of bremsstrahlung from an optically thin, hot plasma, this ratio corresponds to a plasma temperature of 50×10^6 deg K. In this particular example, the spectral sensitivities of the counters (Fig. 1) are heavily weighted in the 1- to 6-Å or 10- to 2-kev range, and the apparent temperature (T) is consistent with that derived for the same spectral band by other observers. Giacconi *et al.* (*2*) found $T = (3.8 \pm 1.8) \times 10^7$ deg K over the range 1 to 15 kev. Chodil *et al.* (*3*) obtained $T \sim 5.8 \times 10^7$ deg K in the energy range 2 to 20 kev. More recently, Grader *et al.* (*4*) found $T \sim 4.6 \times 10^7$ deg K for 2 to 20 kev but observed a marked fall-off at the low-energy end of the spectrum. They noted that the indication of a peak in the spectrum near 2 kev was suggestive of blackbody radiation at $T \sim 9 \times 10^6$ deg K.

The helium-filled counter of Fig. 2 offers a means of discriminating long wavelength x-ray emission ($\lambda > 6$ Å) from the shorter wavelengths ($\lambda < 6$ Å). Because the gas is highly transparent to shorter wavelength x-rays, the efficiency is negligible below 5 Å. Toward longer wavelengths absorption in the gas increases steadily, and a peak is reached at 9 Å. The efficiency then rapidly decreases toward a cutoff at 15 Å because of the opacity of the Mylar window. At 44 Å, the carbon K-edge, Mylar becomes transparent again to x-rays and a secondary band of sensitivity appears from 44 to 60 Å. When this counter was flown in April 1965, the only source detected was Sco XR-1, and the counting rate was 1.2 $count/cm^2 \cdot sec$.

Because the helium counter has two sensitive wavelength bands, there is some ambiguity in the interpretation of the spectral data. However, the following analysis indicates that a major portion of the response must come from the 44- to 60-Å band. In Table 1, we list the computed ratios of counting rates for several pairs of counters in response to bremsstrahlung spectra at various temperatures. For each pair, two columns of ratios were computed. In one computation the spectral range was limited to 0.2 to 20 Å; in the other, the range was extended to 60 Å. For the Ne/He and Ar/Ne ratios, we are comparing measurements made on different flights almost a year apart, and we assume that the source has not varied.

Inspection of Table 1 indicates the following: (i) When the spectral sensitivity is weighted toward wavelengths shorter than 6 Å, as with the ratio of the value for Ar (¼-mil Mylar) to that for Ar (1-mil Mylar), the apparent temperature is about 50×10^6 deg K. The influence of wavelengths shorter than 20 Å is negligible. (ii) The Ar/Ne ratio shifts the weight of the spectral sensitivity region only slightly toward longer wavelengths, yet the apparent temperature is reduced to about 20×10^6 deg K. Wavelengths longer than 20 Å still have negligible effect. (iii) For Ar/He and Ne/He ratios, the apparent temperature is strongly influenced by the contribution of wavelengths greater than 20 Å. If the full range, 0.2 to 60 Å, is included in the computation, the apparent temperature is about 13×10^6 deg K for the Ar/He ratio, and 11×10^6 deg K for the Ne/He ratio. If, however, the range is limited to 0.2 to 20 Å, the apparent temperature is as low as 1 to 2×10^6 deg K. Such a low apparent temperature implies that essentially all of the spectrum detected by the Ar ¼-mil counter is crowded into wavelengths longer than 10 Å. This conclusion is totally inconsistent with the evidence from the Ar (¼-mil Mylar)/Ar (1-mil Mylar) ratio, that most of the response of the argon counters lies between 1 and 10 Å. We are thus led to conclude that the response of the helium counter is derived largely from wavelengths in the 44- to 60-Å range. Although the above discussion has been based on bremsstrahlung emission spectra, similar conclusions are derived if the source is treated as synchrotron radiation.

The galaxy should be relatively transparent to x-rays of wavelength less than 10 Å, but the opacity increases very rapidly toward longer wavelengths. If the cosmic abundance is taken as given in Aller (*5*) and if all the hydrogen is assumed to be atomic, the atomic absorption cross section of interstellar gas at 44 Å is found to be 7×10^{-21} cm^2 per hydrogen atom (*6, 7*). If we assume the average density of hydrogen in the galactic disk to be about 1 atom per cubic centimeter, we find that unit optical thickness is about 140 light-years. The half-thickness of the galactic disk near the sun, which lies close to the galactic equator, is about 4.2×10^{20} hydrogen atoms (*8*) or 420 light-years at one hydrogen atom per cubic centimeter. Sco XR-1 is at galactic latitude 24°, so that the path length through the disk in the direction of the source is about 1260 light-years —an optical thickness of 9. If the

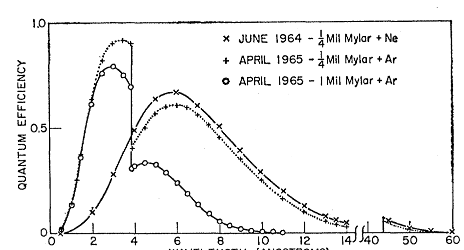

Fig. 1. Spectral efficiency curves for Geiger counters used in June 1964 and April 1965 Aerobee flights.

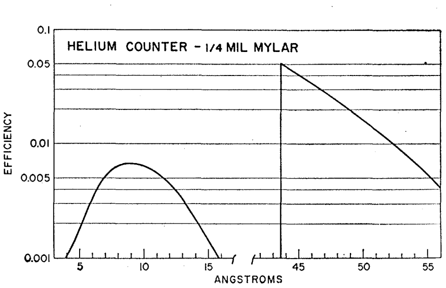

Fig. 2. Spectral efficiency of helium-filled counter used in April 1965 Aerobee flight.

Table 1. Counting rate ratios.

T (10^6 deg K)	Ar($\frac{1}{4}$ mil)/Ar(1 mil)		Ar/Ne*		Ar/He*		Ne/He*	
	0.2–20 Å	0.2–60 Å	0.2–20 Å	0.2–60 Å	0.2–20 Å	0.2–60 Å	0.2–20 Å	0.2–60 Å
200	1.5	1.5						
100	1.6	1.6	1.5	1.5	173	82	117	57
50	1.8	1.8	1.3	1.3	141	62	108	48
30	2.0	2.1	1.2	1.2	112	43	96	38
20	2.4	2.6	1.1	1.1	92	31	85	30
10	3.8	4.6	0.94	0.92	61	14	66	15
7			.90	.88	50	8	55	9
5			.88	.83	40	4	46	5
2			.82	.71	22	1.3	26	1.8
Observed	1.8 ± 0.1		1.1 ± 0.15		18 ± 3		16 ± 3	
	Apparent T (10^6 deg K)							
	50^{+20}_{-10}		20^{+18}_{-10}		1.7 ± 0.3	13 ± 2	1.1 ± 0.2	11 ± 2

* ¼-mil Mylar window.

source lies outside the disk, the x-ray attenuation in the disk alone would exceed a factor of 10,000. This would imply a low temperature component ($\ll 10^6$ deg K) of the source, fantastically brighter than the 50-million-degree component. We conclude that Sco XR-1 must lie well inside the disk and most likely within one or two optical thicknesses; otherwise the luminosity becomes implausibly high.

Gursky *et al.* (*9*) have obtained an upper limit of 20 arc seconds for the angular size of Sco XR-1. They rule out the possibility that the source is a supernova remnant within the galaxy, on the assumption that a hot gas cloud at a temperature of about 50 million degrees would expand unhindered and reach a diameter in excess of 20 arc seconds in less than 50 years. If a supernova had occurred within a distance of even a few thousand light-years in the past 50 years, they argue, it should have been observed. They also reject the neutron-star possibility because the 1- to 10-Å spectrum is inconsistent with the required blackbody distribution. Their argument against the supernova, however, assumes that the event produces all its energy in one flash and that the hot nebular material then expands steadily into interstellar space. It is equally plausible to propose an active source, which continues to deliver energy from the collapsed stellar core to a magnetically confined corona or a magnetosphere in such a way that most of the x-ray emission remains highly concentrated about the central source.

The evidence we have reported here for the long wavelength emission of Sco XR-1 suggests that the source may lie within a few hundred light-years of the sun. It also implies a combination of high- and low-temperature plasmas, or of thermal and nonthermal emission. Such complex source distributions have been suggested by A. G. W. Cameron (*10*) as a consequence of an oscillating neutron star. In the collapse that leads to the compacted star and the accompanying expulsion of the outer layers of the presupernova, he proposes that magnetic lines of force are drawn radially outward and then twisted by the stellar rotation until they reconnect to form a magnetosphere. Radial oscillations of the neutron star can then generate hydromagnetic waves, which travel through the magnetosphere, and electrons can be accelerated to energies high enough to radiate synchrotron x-rays. It is also possible that the neutron star may be surrounded by a higher temperature corona, which would produce x-ray bremsstrahlung. The observed spectrum would then be a superposition of the blackbody radiation of the neutron star and the bremsstrahlung, or synchrotron radiation, of its outer atmosphere.

Although a neutron star theoretically cools rapidly from about 10^7 degrees to a temperature of 2 million degrees, or less, by neutrino radiation processes, it can remain in the range of 1 to 2 million degrees for tens of thousands of years. Our estimate of the x-ray flux in the 44- to 60-Å range is about 10^{-7} erg/cm^2·sec, which is consistent with the blackbody radiation of a neutron star whose radius is 10 km and whose temperature is between 1.5 and 2 million degrees K at a distance of 50 to 100 light-years. The short-wavelength emission source ($\lambda < 6$ Å), which is characterized by a temperature of about 50 million degrees, radiates an energy flux of the same order of magnitude.

The foregoing discussion indicates that Sco XR-1 could be a remnant of an ancient supernova. At a distance of about 100 light-years, its 1- to 10-Å x-ray luminosity is somewhat less than 1 percent of that of Tau XR-1 in the Crab Nebula. The upper limit on its size would be only 0.01 light-year, also about 1 percent of the size of the x-ray nebula in the Crab. The debris of the original explosion would have expanded to very great distances and would long ago have become undetectable as an x-ray nebula. X-ray activity now observed would be confined to the stellar remnant of the supernova, possibly an oscillating neutron star, and its surrounding corona or magnetosphere. Since the x-ray luminosity in the 44- to 60-Å band is compatible with a blackbody temperature of only 1 to 2 $\times 10^6$ deg, the neutron star could be as much as 50,000 years old. As pointed out by Oda (*11*) and Shklovsky (*12*), Sco XR-1 may be associated with the radio source known as the North Polar Spur. This ring of radio nebulosity is believed to be the expanded debris of a supernova that exploded perhaps 50,000 to 100,000 years ago at a distance of about 150 light-years from the sun in the general direction of Sco XR-1.

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