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A STUDY OF VISUAL AND INFRARED OBSERVATIONS OF SCO XR-1

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ABSTRACT

Photoelectric spectrum scans from 3300 to 10830 Å and infrared photometric observations at 1.65 and 2.2 μ of Sco XR-1 have been obtained on many nights. The observed spectral energy distribution f_ν is nearly flat from 0.33 to 1.0 μ and then approaches a ν^2 law farther in the infrared. Synchrotron and free-free radiation can be ruled out unless a self-absorption mechanism operates in the visible spectral region. It is shown that the same mass of gas with $T = 5 \times 10^7$ ° K, which has been postulated to account for the X-ray data by free-free radiation can also account for the observed flux in the visible and infrared since it is shown that the optical depth in the visual and infrared is quite large. Very stringent conditions are imposed on such a model by the observations presented here, and the parameters characterizing the hot plasma are listed in Table 2.

I. INTRODUCTION

Since the optical identification of the Sco XR-1 X-ray source (Sandage *et al.* 1966; Johnson and Stephenson 1966) a large amount of photoelectric photometry on that object has been reported. Much of this work has been primarily a monitor of the brightness to study short- and long-period variations (Hiltner and Mook 1967*a;* Westphal, Sandage, and Kristian 1968). Some information concerning changes in the spectral energy distribution has been obtained by means of *UBV* photometry by Sandage *et al.* (1966), Mumford (1966), Hardie (1967), Mook (1967), and Stępień (1968). While the $B - V$ and $U - B$ colors tend to be concentrated near 0.22 and −0.77 mag, respectively, there are quite clearly substantial changes in the colors (Mook 1967). Photoelectric spectrophotometric observations covering the range from 3200 to 7500 Å have been published by Johnson *et al.* (1967) for three dates.

In this paper a report is given on two kinds of observations. (1) Photoelectric spectrum-scanner observations covering the wavelength range from 3325 to 6050 Å have been obtained on four nights and less extensive measurements from 5556 to 10830 Å on two nights. (2) Infrared fluxes have been measured at 2.2 μ on ten nights and at 1.65 μ on seven of these.

II. OBSERVATIONS

A record of all of the observations made with the scanner and the infrared photometer are listed in Table 1.

The scanner observations were made with the 200-inch Hale telescope. The blue observations below 6050 Å were made at successive 50 Å intervals with a band pass of 50 Å. In order to minimize the effects of brightness changes during the observations, measurements were made first from red to blue followed immediately by duplicate observations from blue to red. Integration times were restricted to 10 sec except for the observations on April 30–May 1, 1967, when 20-sec integrations were used. In most cases, to further restrict the total observing time, observations were done separately from 3325 to 4775 Å and from 4800 to 6050 Å. Differences between pairs of measurements are often as large as 10 per cent although the individual accuracy of measurements ranged from 1.5 to 3 per cent. Each pair of measurements was always averaged and reduced to absolute fluxes by standard techniques (Oke 1965), and the final absolute fluxes are based on the calibration of α Lyr given by Oke (1964) except that all points below the Balmer limit are made fainter by 6 per cent.

Red and near-infrared scanner observations were obtained on two nights at twelve selected wavelengths from 5556 to 10830 Å with a band pass of 200 Å. Two observations, made in reverse wavelength order, were obtained at each wavelength with integration times of 30 sec. The standard deviations of individual measures vary from 2 per cent at 5556 Å to as much as 5 per cent at 10830 Å with some indication of systematic differences of several per cent.

TABLE 1

RECORD OF OBSERVATIONS

DATE	U T.	INSTRUMENT	DATA REGION	m_V	LOG FLUX (erg cm^{-2} sec^{-1} Hz^{-1})		
					0 55 μ	1 65 μ	2 2 μ
April 9, 1967	12:56	Photometer	1.65 μ, 2.2 μ	...	...	−25 15	−25 21
May 1, 1967	11:03	Scanner	3325–6050 Å	12 55	−24 44	...	...
May 17, 1967	09:45	Photometer	1.65 μ, 2.2 μ	...	...	−24 81	−24 87
June 27, 1967	07:12	Photometer	1.65 μ, 2.2 μ	...	...	−24 65	−24 77
June 28, 1967	07:45	Photometer	2.2 μ	...	...	...	−24 83
July 9, 1967	06:03	Scanner	3325–6050 Å	12 31	−24 34	...	...
July 10, 1967	06:38	Scanner	3325–6050 Å	12 88	−24 57	...	...
August 10, 1967	04:00	Scanner	5556–10830 Å	12 99	−24 62	...	...
August 11, 1967	04:46	Scanner	5556–10830 Å	12.40	−24 38	...	...
August 26, 1967	03:53	Photometer	1.65 μ, 2.2 μ	...	...	−24.70	−24 94
September 15, 1967	04:06	Photometer	2.2 μ	...	...	...	−24 82
January 8, 1968	14:25	Photometer	2.2 μ	...	...	...	−24.73
February 25, 1968	13:15	Scanner	3325–6050 Å	12 36	−24 36	...	...
February 25, 1968	13:49	Photometer	1.65 μ, 2.2 μ	...	...	−24 59	−24 73
March 11, 1968	11:58	Photometer	1.65 μ, 2.2 μ	...	...	−24 65	−24 82
March 11, 1968	12:42	Photometer	1.65 μ, 2.2 μ	...	...	−24 78	−24 88

Photometric observations were also made in the wavelength intervals 1.5–1.8 μ (λ_{eff} = 1.65 μ) and 2.0–2.4 μ (λ_{eff} = 2.2 μ). All measurements were made at the Cassegrain focus of the 200-inch Hale telescope with the two-beam photometer described by Becklin and Neugebauer (1968). Observations were made by comparing the emission from the source with that from the sky separated from the source by 20″. Typically a night's data were obtained through 10 minutes of observation at each wavelength. Except for the night of April 8–9, 1967, the statistical standard deviation in the mean of the observations was less than 5 per cent. On the night of April 8–9, 1967, the observing technique was being developed with detectors of lower sensitivity than were subsequently used, and the standard deviation was 25 per cent. The observations were reduced to absolute flux values by comparison with stars previously measured by Johnson *et al.* (1966) and the energy calibration of Becklin (1968). The uncertainty in the absolute sensitivity of the system increases the assigned error to about 10 per cent for each observation except for the larger error assigned the night of April 8–9, 1967. The reduced data are plotted in Figures 1 and 2.

III. DISCUSSION OF OBSERVATIONS

One difficulty in interpreting the data presented here is the lack of simultaneity of the observations, particularly since changes in brightness as large as 0.8 mag over a 3-hour

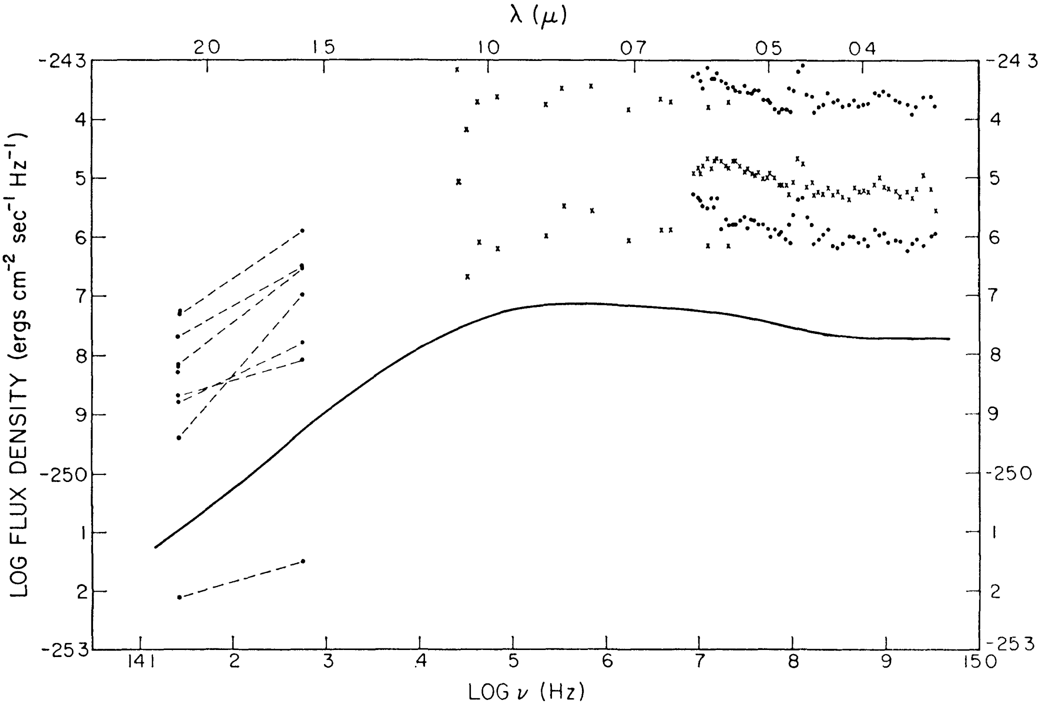

FIG. 1.—Visual and infrared observed fluxes are shown. Five sets of scanner observations, two in the red between log ν = 14.44 and 14.74, and three in the blue between log ν = 14.70 and 14.97 are shown. Pairs of infrared photometric observations at log ν = 14.142 and 14.275, made nearly simultaneously, are joined by broken lines. Solid curve is the adopted representative energy distribution apart from a constant vertical displacement.

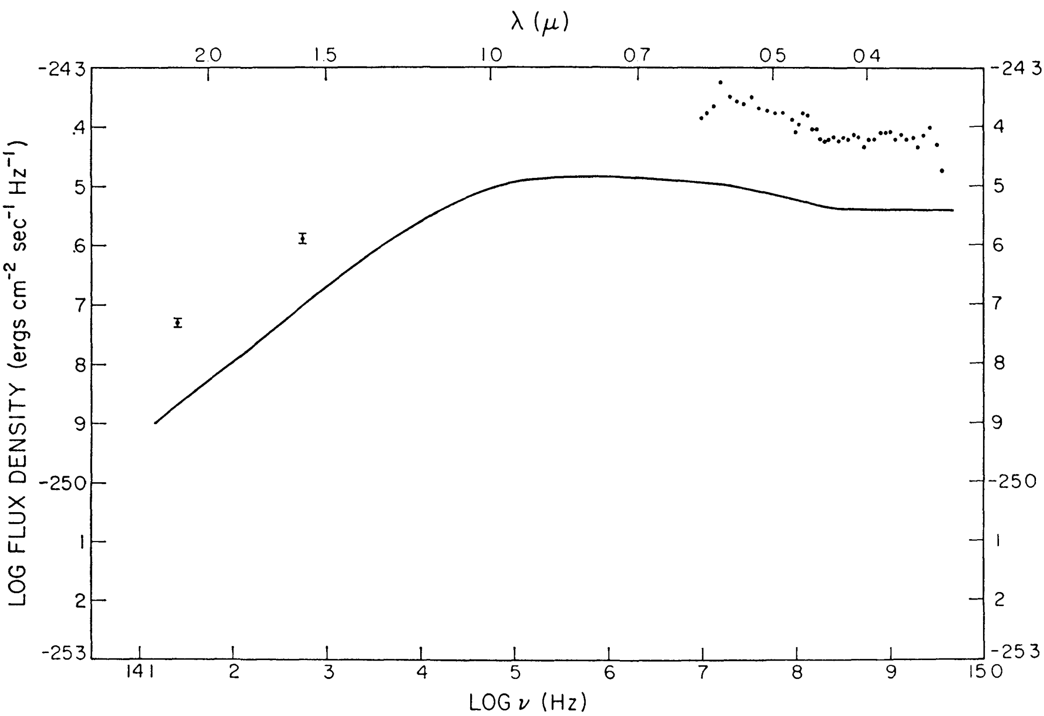

FIG. 2.—Same as Fig. 1, except that all visible and infrared observations were made with a time separation of only 30 min on February 25, 1968.

period and 0.2 mag over 3 minutes have been reported (Hiltner and Mook 1967*a*, *b*; Westphal *et al.* 1968). This effect has already been noted above where changes of 10 per cent occurred in the scan data during the observing periods. In spite of this difficulty, it is clear that the sets of observations between log ν = 14.69 and 14.96 are very similar, except for differences in over-all brightness by a factor of 2. The two sets of red scans from log ν = 14.44–14.73 also are almost identical, and since they overlap the blue observations, a reasonable mean energy distribution from log ν = 14.44–14.96 can be constructed. In the case of the broad-band infrared measurements at log ν = 14.14 and 14.275 no overlap with the scanner data exists in general. The exceptions are the data shown in Figure 2 where the spectral scans and infrared measures were obtained with

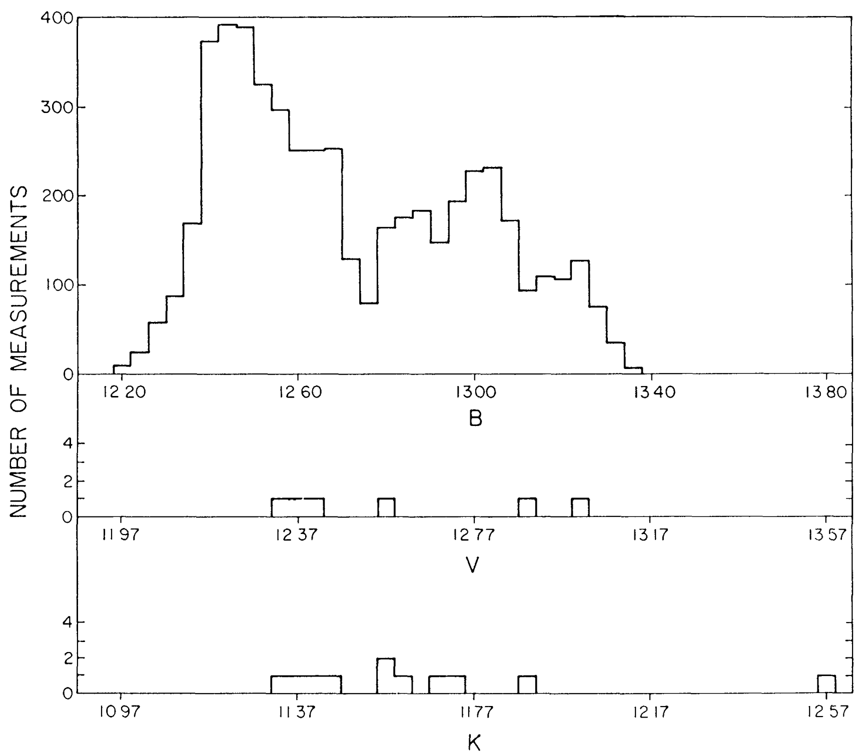

FIG. 3.—Histograms of the distribution of brightness found (*a*) in the *B* filter band by Hiltner and Mook (1967*b*), (*b*) in the scanner data at essentially the *V* filter band, and (*c*) in the infrared at 2.2 μ (*K*). Magnitude scales have been displaced, relative to each other, to allow for the color differences in the various spectral ranges.

the 200-inch telescope with a time separation of only 30 minutes. The magnitude of Sco XR-1 was monitored with a 20-inch telescope for over 1 hour, ending during the time when the blue scanner measurements were being made; the approach of dawn prohibited further monitoring. Brightness changes of approximately 0.8 mag were found during the interval before the scanner measurements were made, but the fluctuations were less than 0.2 mag during the 35 min immediately preceding and during the time the scanner data were obtained. If this rather quiet behavior persisted until the infrared measures were obtained, then Figure 2 provides a reasonably complete energy distribution.

In Figure 3 histograms are shown of the distribution of brightness found (*a*) in the *B* filter band by Hiltner and Mook (1967*b*), (*b*) in the scanner data at essentially the *V* filter band, and (*c*) in the infrared at 2.2 μ. The magnitude scales for the three histograms have been displaced relative to each other to take account of the mean differences in the colors in the various spectral ranges. These suggest that the various measurements are roughly comparable. The solid curve shown in Figures 1 and 2 is taken to be a suitable representation of the energy distribution from log ν = 14.14–14.96. The low-frequency end of the curve is probably correct within 0.08 in log f_ν.

This representative energy distribution can be compared with scanner measurements made by Johnson *et al.* (1967). The slopes are in fact surprisingly different. Their observations correspond roughly to a broad-band $B - V$ color of 0.35. The distributions in Figures 1 and 2, on the other hand, have a corresponding $B - V = 0.23$. The photoelectric photometry of Sco XR-1 by Sandage *et al.* (1966), Mumford (1966), Hardie (1967), Mook (1967), and Stępień (1968) show a range in $B - V$ from 0.13 ot 0.27 with a concentration around 0.23. Thus it is likely that the energy distribution found here is typical, while the three sets of energy distributions by Johnson *et al.* (1967) represent the less common, redder colors.

Within the accuracy of the data, one spectral feature clearly present in the scan data is a broad emission feature between 4500 and 4730 Å (log ν = 14.80–14.82). This is obviously caused by the He II line λ4686 and other emission lines of C III, N III, O II (Sandage *et al.* 1966). The other feature which is clearly present is the red-most point at 10830 Å (log ν = 14.44) due to the He I line at that wavelength. There is no consistent evidence for the He I line λ5876 (log ν = 14.71); and Hα (log ν = 14.71) and Hβ (log ν = 14.79) are not present.

IV. INTERSTELLAR REDDENING

Before the composite energy distribution shown by the curves in Figures 1 and 2 can be compared with theoretical sources of continuous radiation it is necessary to make corrections for interstellar reddening.

Sandage *et al.* (1966) have estimated the reddening by measuring *UBV* magnitudes for stars in the same region of sky as Sco XR-1. They find a color excess $E(B - V) \approx 0.23$ mag which, assuming the ratio between reddening and total absorption is 1 to 3, implies a total extinction in the V wavelength of 0.69 mag. Wallerstein (1967) has concluded from the strength of the interstellar lines that the extinction in V exceeds 0.75 mag. Johnson (1966) has reasoned, from counts of faint galaxies in the region of Sco XR-1, that an extinction around 2 mag is not impossible.

The composite energy curve has been rectified by assuming A_V = 0.7, 1.5, and 2.0 mag, and the reddening curve of Johnson (1968) for the region around Cygnus; this curve is in close agreement with that derived by van de Hulst (1949) for extinction by dielectric grains (curve No. 15). The resultant energy distributions are presented in Figure 4 along with a straight line corresponding to a ν^2 dependence of the flux on frequency, i.e., the energy distribution of a very hot black body. The deviations from a smooth increase in the corrected data may be due to inaccuracies in the absolute calibration of the scanner data. Hayes (1967) has presented evidence that the flux density around log ν (Hz) = 14.7 should be increased relative to that in adjoining spectral regions.

V. DISCUSSION

Although the unknown interstellar absorption must be taken into account to determine the true spectrum of Sco XR-1, there are some conclusions about the source of the radiation which do not depend critically upon the assumed reddening. In particular, the corrections to the infrared observations are quite small for the range of reddening discussed in the foregoing section.

X-ray spectral observations of Sco XR-1 indicate that at energies between 1 and 20 keV the observed radiation is consistent with free-free emission from an optically thin ionized gas at temperatures which range from about 40–100 × 10^6 ° K (Gorenstein, Gursky, and Garmire 1968; Chodil *et al.* 1968), The optical data cannot, however, be interpreted as free-free radiation from an optically thin gas. This conclusion is illustrated in Figure 5 where the X-ray data of Gorenstein *et al.* (1968) and of Chodil *et al.* (1968) are shown extrapolated to the visible, assuming that free-free emission from an optically thin gas continues to the visible band of the spectrum following the frequency dependence of the Gaunt factor (Karzas and Latter 1961). It is seen that the extrapolated X-ray flux is considerably higher than the observed optical flux. Furthermore, if the continuum is produced by hydrogen gas, its temperature must be greater than about 10^5 ° K since no Balmer jump is observed. Under these circumstances only free-free transitions are important, and the spectral energy distribution, if the gas were

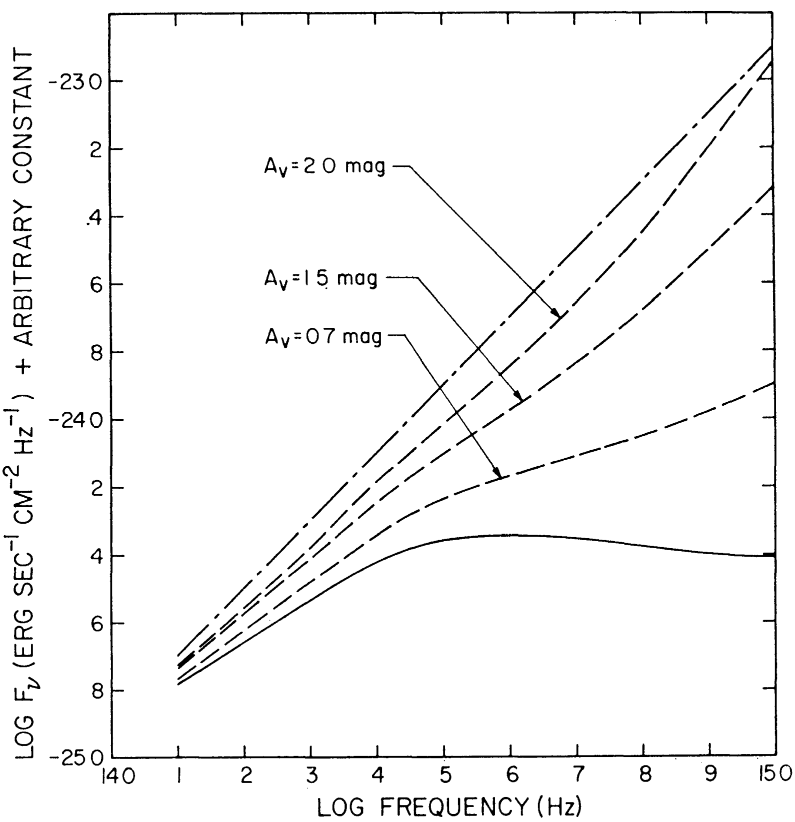

FIG. 4.—Representative energy distribution of Figs. 1 and 2 is the lowest solid curve. Next three curves have been obtained by correcting for interstellar reddening, assuming $A_V = 0.7$, 1.5, and 2.0 mag. Highest broken line corresponds to $f_\nu \propto \nu^2$.

optically thin in the visible spectrum, would be flat, except for a very small slope introduced by the change in the Gaunt factor. The results in Figures 1 and 2 rule this out since, if the reddening were arbitrarily picked to make f_ν agree with optically thin free-free emission in the visible part of the spectrum, then the drop in f_ν at 1.65 and 2.2 μ would be unexplained.

Manley (1967) has suggested that the X-ray and optical fluxes can be interpreted as synchrotron radiation from a distribution of relativistic electrons possessing a sharp, high energy cutoff. The observed infrared frequency dependence which clearly exceeds $f_\nu \propto \nu^{-1/3}$ eliminates synchrotron radiation as a dominant contribution unless some absorption mechanism is invoked. In view of the possible long-wavelength cutoff of synchrotron radiation in an ionized medium, however (Razin 1960), this source cannot be ruled out by the optical observations presented here. It is perhaps worth pointing out that such a cutoff implies that $N_e H^{-1} \approx 6 \times 10^{13}$ cm^{-3} gauss^{-1} (Ginzburg and Syrovatskii 1965), and for $H > 10^{-2}$ gauss (Manley 1966) $N_e > 6 \times 10^{11}$ cm^{-3}, which is a rather extreme set of conditions in which to find relativistic electrons.

It is, of course, possible that the radiation of Sco XR-1 arises from a complex configuration of stars and gas. The need for this complexity, however, may be obviated by a simple model, namely that the emitting volume of extremely hot gas is optically thin at X-ray wavelengths, but becomes optically thick in the near-infrared. Although such an interpretation is undoubtedly a gross oversimplification, it forms a basis for making some interesting order-of-magnitude estimates. Similar models have been suggested by Shklovskii (1968), Tucker (1967), and by Chodil *et al.* (1968).

The following assumptions are made: (*a*) the X-radiation is produced by free-free transitions in pure hydrogen with an electron temperature around 5×10^7 ° K; (*b*) in the near-infrared spectral region, the gas is opaque and radiates as a black body with a

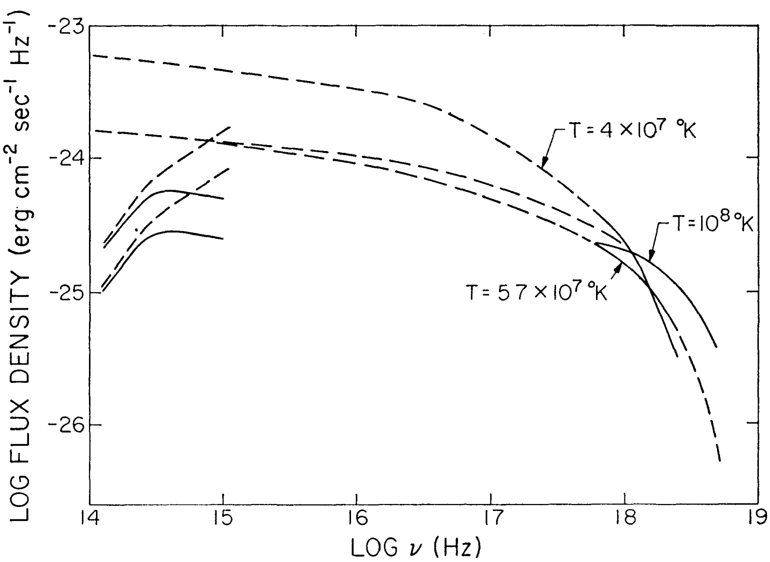

FIG. 5.—Solid curves near log ν = 18 are the X-ray absolute fluxes. These have been extrapolated (*broken curves*) to the visible region, assuming free-free radiation by hydrogen at an appropriate temperature. It is assumed that the gas is transparent. Between log ν = 14 and 15 are the limiting observed fluxes (*solid curves*) and fluxes corrected for interstellar reddening corresponding to A_V = 0.7 mag.

temperature also of 5×10^7 ° K; (*c*) all the radiation is produced by the same mass of gas, assumed for simplicity to be a sphere of radius R.

From the X-ray data (Gorenstein *et al.* 1968) one obtains typically

$$\frac{N_e^2 R^3}{d^2} = 10^{17} \text{ cm}^{-5}, \tag{1}$$

where N_e is the electron density (cm^{-3}) and d the distance of the object (cm). The constant has been observed to range from 1.0×10^{17} to 1.8×10^{17} cm^{-5}. In the near-infrared the observed flux, corrected for 0.7 mag of visual absorption, approximately follows the relation $f_\nu = 0.8\text{–}1.6 \times 10^{-53} \nu^2$ erg sec^{-1} cm^{-2} Hz^{-1}. If this is equated to the Rayleigh-Jeans approximation for the radiation from a black body at a temperature T, one obtains, from the relation $\pi B_\nu \propto \nu^2 T$,

$$R^2 T/d^2 = 10^{-17} \,^\circ K. \tag{2}$$

The optical variations in Sco XR-1 imply a range in the numerical value of equation (2) from 0.8×10^{-17} to 1.6×10^{-17}. It should be noted that it is relationship (2), obtained from these measurements, which distinguishes our comments from those of Chodil *et al.* (1968).

As illustrated in Figure 5, within the framework of this discussion, the optical depth must already be large at 1 μ where the data approach a ν^2 dependence but the gas is still relatively transparent in the violet. In the following discussion we will show that this behavior is consistent with the numerology of the model. At $5 \times 10^7\,{}^\circ$ K the opacity is almost certainly free-free absorption. The optical depth for free-free absorption by hydrogen for a path length R is

$$\tau_{\mathrm{ff}} = 0.018 g_{\mathrm{ff}} \frac{N_e^2 R}{\nu^2 T^{3/2}}, \quad (3)$$

where g_{ff} is the free-free Gaunt factor. Equations (1)–(3) yield

$$\tau_{\mathrm{ff}} = \frac{1.8 \times 10^{32} g_{\mathrm{ff}}}{T^{1/2}\nu^2} = \frac{1.4 \times 10^{29}}{\nu^2}. \quad (4)$$

Thus in this approximation τ_{ff} is independent of N_e, R, and d. It is also necessary to take account of electron scattering, which is given by

$$\tau_{\mathrm{es}} = 6.7 \times 10^{-25} N_e R. \quad (5)$$

To proceed, it is necessary to choose one of the variables such as the distance d of the object. Then both N_e and R can be determined and τ_{es} can be calculated from equation (5). Results are given in the first three columns of Table 2. It is seen that the dimensions

TABLE 2

CALCULATED PARAMETERS OF MODEL*

d (pc)	R (cm)$\times 10^{-8}$	$N_e \times 10^{-16}$	τ_{es}	τ ($\nu = 3.3 \times 10^{14}$)	τ ($\nu = 10^{15}$)
500...	6 7	2.7	12	6.9	2 3
1000...	13 4	1 9	17	8 2	2 7
2000...	26.8	1 4	24	9.7	3 2

* These values strictly represent lower limits for R and upper limits for N_e, τ_{es}, and τ.

are comparable with those of a white dwarf. For conditions in which the probability for electron scattering is large but not so great as to change the scattered photon energy by a significant amount before it escapes the gas, neutron diffusion theory can be used to show that the true optical depth is given by $\tau = \sqrt{(3\tau_{\mathrm{ff}}\tau_{\mathrm{es}})}$; this is also given in Table 2. When the optical depth becomes large, this approximation no longer holds, and the infrared photons are rapidly thermalized by Compton scattering from the much higher-energy electrons which are present in this object (Chandrasekhar 1960). It is clear that the optical depth is indeed large in the near-infrared but moderate in the ultraviolet. The observed color changes, in this interpretation, come about because of the changes in the frequency at which the emitting volume becomes optically thick. It is interesting to note that temperature changes by a factor of 2 have been observed in the X-ray data; this change in temperature, itself, could lead to changes in optical brightness of approximately a factor of 2 as observed.

It should perhaps be pointed out that if this model is valid, the data presented here set an upper bound on the visual extinction to Sco XR-1. If a visual extinction larger than 2.0 mag is assumed then the corrected energy distribution in the optical band becomes steeper than ν^2, contrary to our assumption that the radiation approaches that of a black body. An even lower limit on the reddening has been established by the simultaneous

X-ray and optical observations of Chodil *et al.* (1968), which places an upper limit of 0.9-mag visual absorption to Sco XR-1 if this model holds.

The picture presented above admittedly neglects many observational facets of Sco XR-1. Specifically no explanation of the observed emission lines (Sandage *et al.* 1966) which must originate in a gas with $T < 10^5$ ° K is attempted, nor is any attempt made to understand the source of the energy. Since the energy content is radiated away in times measured in milliseconds, the latter problem is an especially imposing one. Further observations, in particular simultaneous observations to determine the relative phasing of the X-ray and infrared data, would be extremely important.

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