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SOFT X-RAY SPECTRAL VARIATIONS IN SCORPIUS X-1

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ABSTRACT

We present soft X-ray spectra of Scorpius X-1 obtained with the low-energy detectors of the A-2 experiment on *HEAO 1*. The raw count spectra are deconvolved using the Kahn and Blissett technique to reveal the presence of oxygen absorption in the range 0.5–0.7 keV. The strength of this feature is shown to vary on a time scale of order hours. These results are interpreted as evidence for variable X-ray photoionization of circumsource material in the system. An alternative model, involving variable Compton broadening of an oxygen edge, is also discussed.

Subject headings: X-rays: binaries — X-rays: spectra

I. INTRODUCTION

As the first nonsolar X-ray source to be discovered (Giacconi *et al.* 1962) and one of the earliest to be optically identified (Sandage *et al.* 1966), Sco X-1 has been the subject of extensive study for nearly two decades (see review by Miyamoto and Matsuoka 1977). The system is a close binary with a period of $0^d.787$, discovered photometrically (Gottlieb, Wright, and Liller 1975) and confirmed spectroscopically (Cowley and Crampton 1975). The distance to the source is somewhat uncertain. Recent *IUE* observations of the 2200 Å interstellar absorption feature (Willis *et al.* 1980) yield an accurate measure of the color excess, $E_{B-V}=0.35\pm0.05$, but only a crude lower limit to the distance $\sim$350 pc. At 350 pc, the implied X-ray luminosity is 5×10^{36} ergs s^{-1}.

A number of investigators have suggested that the observed infrared, visible, ultraviolet, and X-ray continuum fluxes from Sco X-1 may all originate in a single, hot plasma cloud. For consistency, the plasma is required to be optically thick (due to free-free absorption) in the infrared, and partially opaque in the visible. Fits to the data yield plasma temperatures of $\sim5\times10^7$ K, densities of a few times 10^{16} cm^{-3}, and cloud radii of order 10^9 cm (Chodil *et al.* 1968; Neugebauer *et al.* 1969; Hayakawa, Kasahara, and Matsuoka 1974). The implied electron scattering depth, τ_{es}, is $\gtrsim10$. Support for this picture has recently come from high-resolution X-ray spectral observations which require scattering depths in the range 10–20, if the X-rays are assumed to arise due to thermal free-free emission (Laros and Singer 1976; Long and Kestenbaum 1978; Lamb and Sanford 1979).

However, it should be emphasized that despite the overall consistency of this simple model the observations do not preclude the existence of cooler circumsource material in the system. In particular, the X-ray and optical continuum fluxes will be dominated by emission from the hottest central regions, so emission from cooler matter farther from the source may not be observable. Such material will emit in the infrared. However, as long as the surrounding cloud remains optically thick, the infrared intensity may not differ significantly from that expected for the simple isothermal model.

An indication that cooler circumsource matter must be present in the system is provided by the observation of strong optical and ultraviolet emission lines (Cowley and Crampton 1975; Willis *et al.* 1980). The ions observed (He II; C III, IV; N III, IV, and V; O IV, V) are indicative of temperature $\sim10^4$–10^5 K and could not exist in the 10^7–10^8 K plasma which produces the X-ray emission. Milgrom (1976) has suggested that the optical lines may arise from the X-ray heated face of the binary companion star. However, the phase dependence of the line intensities indicate that they must originate closer to the X-ray source itself (Cowley and Crampton 1975).

The structure of this cool surrounding material is intimately tied to the physics of the accretion process and may be quite intricate. Many authors have suggested the presence of an accretion disk, although compelling evidence for the disk is lacking. In general,

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observational input on these questions has been somewhat limited due to the complexity of the problem. The emission line intensities, in particular, are difficult to interpret since one only observes the total line flux integrated over the unknown source geometry.

As noted by Tarter, Tucker, and Salpeter (1969), substantial information on the structure of circumsource material can be gleaned from studies of the detailed soft X-ray absorption in the spectrum. Intrinsic absorbing material, which is local to the X-ray source, is likely to be partially photoionized due to the X-radiation itself. Spectral observations with sufficient resolution and sensitivity to measure individual element absorption edges can yield information on the ionization structure and can thus provide some constraints on physical properties of the circumsource absorbing matter. The absorption measurements are specific to the line of sight at any given time, so that if variations are observed with binary phase, it may be possible to constrain the global structure of mass transfer in the binary system. Indications of general absorption variations in Sco X-1 have previously been reported by Derenberg *et al.* (1973) and Moore, Cordova, and Garmire (1973).

In this paper, we present soft X-ray observations of Sco X-1 using the low energy detectors of the *HEAO 1*/A-2 experiment.[3] Spectra obtained during these observations provide the first explicit detection of oxygen absorption edges in Sco X-1 and exhibit variations in the strength of these edges relative to the overall soft X-ray absorption. The existence of these variations provides direct evidence for cool circumsource material in the system.

II. OBSERVATIONS

The *HEAO 1*/A-2 experiment is described in detail by Rothschild *et al.* (1978). The data discussed here were obtained by the LED 1 detector which has a geometric area of 380 cm^2 and is sensitive in the energy range 0.15–3 keV. The experiment scanned the region near Sco X-1 between 1977 August 26 and 1977 August 30. At that time 18 independent 30 s scans by the source were obtained with LED 1 in spectral mode. The times of the scans and the phases (with respect to the $0^d.787$ period) are listed in Table 1. Pulse height spectra were accumulated over 40.96 s integration periods for which additional telemetry scalars (necessary to avoid saturation effects) were available. For each scan, background spectra were subtracted from nearby regions of sky. Due to the very high intensity of Sco X-1, systematic errors associated with the background subtraction are likely to be small ($\sim$0.2%) and are much less than the errors associated with normal counting statistics fluctuations. These scans were performed very early in the experiment lifetime when calibration tests were conducted frequently. The detector gain at the time of the observations is thus known to better than 1% accuracy.

Figures 1*a* and 1*b* show the aspect corrected total count rate of Sco X-1 (as derived from the scans) plotted as a function of time and binary phase, respectively. As can be seen, the source was variable at about the 10–20% level on hour time scales. Such modest variations are characteristic of the quiescent state in Sco X-1. To search for variations in spectral shape, we divided the background-subtracted count spectrum by the total count rate for each scan, and then computed a χ^2 for deviations of the normalized spectra about the weighted mean for each channel. Typical χ^2 values are in the range 27–45 for 17 degrees of freedom, indicating that spectral variations are significant in the data at above the 99% confidence level.

In order to ascertain the origin of these spectral variations, we make use of the direct deconvolution procedure outlined by Kahn and Blissett (1980). This technique allows us to deconvolve the instrument response from the raw count spectrum in an unbiased manner, free of explicit astrophysical assumptions. The result is a "picture" of the incident photon spectrum at an "effective resolution" determined by the signal-to-noise ratio. For strong sources like Sco X-1, this effective resolution is much higher than the intrinsic instrument resolution, and thus the deconvolved photon spectrum can be very informative. We have used this method previously in our analysis of *HEAO 1*/A-2 LED spectra of the Crab Nebula (Charles *et al.* 1979), the supernova remnant G65.2+5.7 (Mason *et al.* 1979), and the Cygnus Loop (Kahn *et al.* 1980).

TABLE 1

TIME AND PHASE OF HEAO-1 SCAN OBSERVATIONS OF SCORPIUS X-1

Scan Number	Time (Days of Year 1977)	Phase (with respect to $0^d.787$ period)
1	239.140	0.39
2	239.724	0.13
3	239.795	0.22
4	239.888	0.34
5	239.934	0.40
6	240.003	0.49
7	240.049	0.54
8	240.726	0.40
9	240.774	0.46
10	240.843	0.55
11	240.891	0.61
12	241.825	0.80
13	241.872	0.86
14	241.895	0.89
15	241.942	0.95
16	242.270	0.36
17	242.317	0.42
18	242.409	0.54

[3] The A-2 experiment is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at CIT, JPL, UCB, and GSFC.

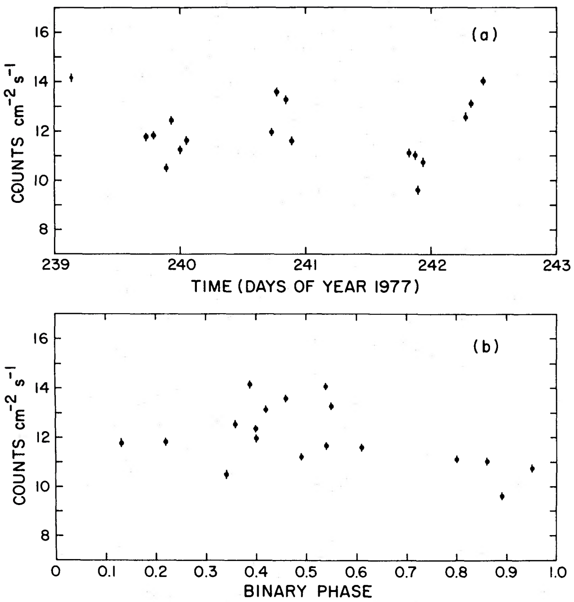

FIG. 1.—The count rate detected from Sco X-1 (in the energy band 0.15–3 keV) plotted as a function of time (a) and binary phase (b). Error bars are 1 σ.

We first performed the deconvolution analysis on the mean total spectrum and constructed a weighting function to remove sidelobe distortions (see Kahn and Blissett 1980). The resulting 1 σ envelope of deconvolved spectral estimates is depicted in Figure 2. The effective FWHM resolution for this picture is $\sim$15% at 1 keV. Note that apart from the low energy cutoff at $\sim$0.45 keV, the only apparent discrete feature in the spectrum is a partially resolved "dip" near 0.6 keV. The energy of this dip is consistent with the energy of the expected absorption edge due to neutral oxygen at 0.533 keV[4] and thus it may be readily identified with oxygen absorption along the line of sight.

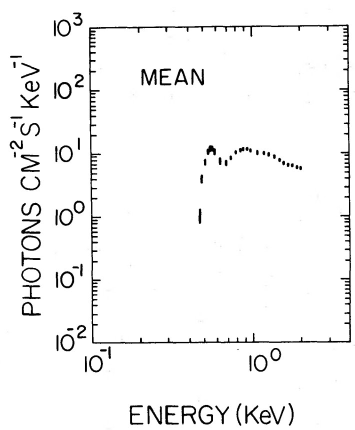

FIG. 2.—The photon spectrum of Sco X-1 deconvolved (using the Kahn and Blissett method) from the mean count spectrum of all scan observations. The vertical bars provide a 1 σ envelope of allowable curves.

The weighting function determined for the mean count spectrum was then used to deconvolve the incident spectrum for each of the 18 independent scans. The results are displayed in Figure 3. As can be seen, none of the independent deconvolved spectra is severely distorted by sidelobe effects so that additional weighting was not warranted. Thus essentially the same procedure was applied to all cases. Differences in the spectral shapes produced must have therefore resulted from the real differences in the count spectra themselves.

Examination of Figure 3 reveals that the most dramatic scan-to-scan spectral variations are not related to significant changes in the continuum or soft X-ray absorption, but to variations in the apparent depth of the oxygen absorption edge. Note the particularly striking contrast between the spectrum of 239.795 (Scan 3) where this absorption feature is quite strong, and that of 241.895 (Scan 14) where it is barely noticeable.

In order to justify these conclusions with more conventional methods, we performed simple model fits. We chose to represent the continuum by an exponential expression with a Gaunt factor (which has previously been shown to provide an adequate fit to the spectrum below 5 keV) and to allow for absorption by neutral intervening matter as described, for example, by Brown and Gould (1970). Free parameters for the fit were the continuum temperature, kT, the total absorbing column density, N_x, and the effective oxygen abundance in the absorbing medium, A_{ox}. If the apparent variations in the oxygen feature were spurious and no oxygen absorption was actually intrinsic to the binary system, then this model would indeed be appropriate to the spectrum and would provide an acceptable fit. In addition, the derived oxygen abundance would be found to be relatively constant from scan to scan.

In contrast, the model does not provide an acceptable fit in all cases and the derived oxygen abundance is not constant. This can be seen in Figures 4a and 4b where we have plotted A_{ox} as a function of time and binary phase, respectively. The error bars in these figures are derived from the second partial derivatives of the χ^2 function near minimum. With respect to these error bars, the observed scatter in A_{ox} is significant at above the 99% level, although such quantitative estimates of this significance must be interpreted with caution since the assumed spectral model does not adequately reproduce the data. In any case, the model fitting procedure does support the conclusion derived from the decon-

[4]A real absorption edge is infinitely sharp and thus must appear broadened in the deconvolved spectrum. The apparent energy of the oxygen absorption feature is therefore higher than would otherwise be expected. The effective resolution of the deconvolved picture is $\sim$21% in this region of the spectrum, so that the actual feature we observe is consistent with a sharp edge at $\sim$0.52–0.58 keV.

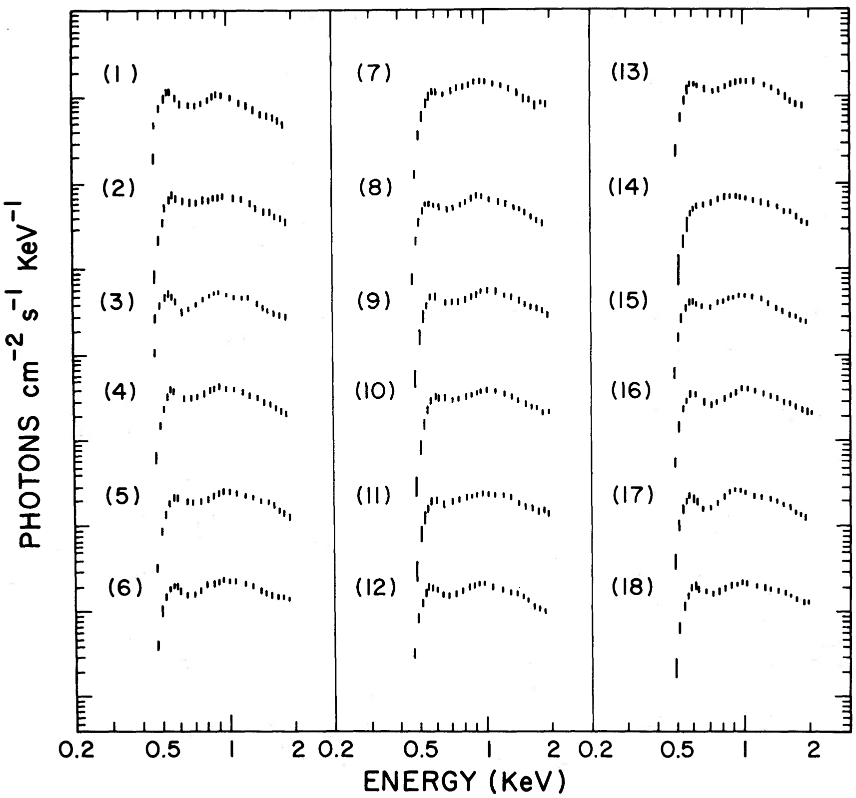

FIG. 3.—The photon spectra of Sco X-1 deconvolved from the separate count spectra of the individual scan observations. The number to the left of each spectrum corresponds to the respective scan number listed in Table 1. Representative decade limits only are given for the vertical axis. The error bars provide a 1 σ envelope of allowable curves.

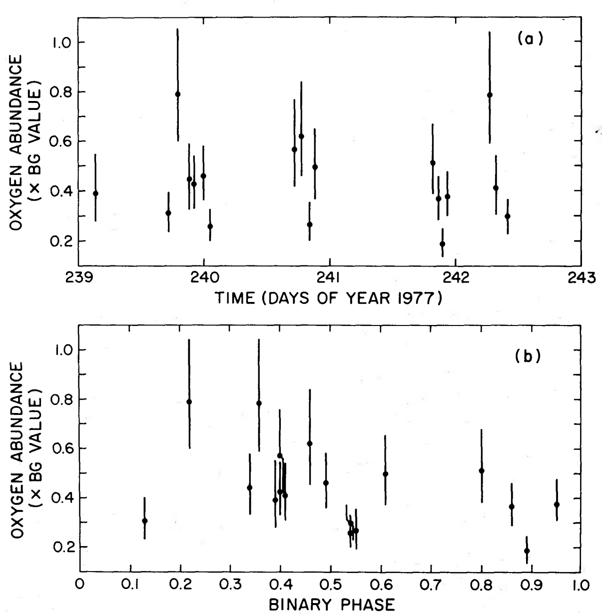

FIG. 4.—The best fit "effective neutral oxygen abundance" (relative to the Brown and Gould value) of the matter responsible for the soft X-ray absorption in Sco X-1, plotted as a function of time (*a*) and binary phase (*b*). The error bars are approximately 1 σ.

volution analysis in that significant variations in the oxygen absorption feature are inferred.

It is important to note that reductions in the apparent strength of the oxygen feature are not typically accompanied by significant reductions in the soft X-ray cutoff. In fact, Scan 14, in which oxygen absorption is at a minimum, exhibits a slightly steeper soft X-ray turnover than Scan 3 in which the oxygen edge is at a maximum. Since helium is the dominant absorber below the neutral oxygen edge, the data suggest that we are observing variations in the ratio of helium-to-oxygen optical depths, τ_{He}/τ_O. This conclusion is verified by our model fits since we observe variations in the *apparent abundance of oxygen*, not just in the total column density. In general, increases in τ_{He}/τ_O appear to be associated with decreases in τ_O.

Examination of Figure 4*b* shows that although the phase coverage of our observations is not complete, there does appear to be some correlation between the effective oxygen absorption and binary phase. In particular, the apparent reduction in the oxygen abundance near phase 0.55 is reproduced consistently over three separate cycles. Comparison of Figures 1 and 4, however, shows that no simple relation exists between the effective oxygen abundance and the soft X-ray intensity.

On day 242, a sharp increase in the count rate is accompanied by a sharp decrease in the oxygen absorption, thus suggesting that the two are anticorrelated. In contrast, on day 241, the data exhibit evidence for positive correlation. Considering the scarcity of data points, no such "short-term trends" are statistically significant.

III. DISCUSSION

The data presented above provide evidence for variations in the strength of the oxygen absorption feature in Sco X-1, relative to helium absorption. Such variations are most likely related to the photoionizing properties of the X-radiation itself. If oxygen is at least several times ionized, the total oxygen absorption will be distributed among a number of distinct absorption edges, so that, at the level of effective resolution of our deconvolved spectra, the overall feature will appear broadened. When only neutral oxygen absorption is considered in the model fits, an apparent reduction in the oxygen abundance will thus be inferred. As noted by Tarter, Tucker, and Salpeter (1969), the 10^7–10^8 K bremsstrahlung emission typical of X-ray binaries will ionize the abundant trace elements out to significant distances ($\sim 10^{10}$–10^{13} cm) comparable to the binary separation in many of these systems. The actual ionization structure observed depends sensitively on the X-ray luminosity and the density profile of the circumsource material. Thus, at different times and along different lines of sight, significant changes in the appearance of the oxygen feature are not surprising.

As discussed in § II, the observed reductions in the oxygen absorption are not accompanied by reductions in the helium absorption. From simple considerations, such behavior is unexpected since helium should get completely stripped before oxygen reaches its highest ionization states. One might assume that the observed helium absorption is interstellar and that the intrinsic helium is always fully ionized. However, if this were the case, then the minimum value of the oxygen abundance inferred from the model fits would represent an upper limit to the actual oxygen abundance of the interstellar medium. As can be seen from Figure 4, this would require at least a factor of 5 underabundance of oxygen in the ISM, an unlikely possibility.

If the helium absorption is intrinsic to the system, then the medium is certainly optically thick to photoelectric absorption. Detailed transfer studies have shown that inclusion of optical depth effects can significantly alter the expected ionization structure (Tarter and Salpeter 1969). When the medium is optically thick, most of the ionizing flux for the abundant elements is absorbed close to the source thus prohibiting photoionization farther out. Essentially, a "Strömgren situation" can develop in which the element recombines abruptly at a given radius, much closer than would be expected if only the r^{-2} dilution of the photon field were considered. Three factors tend to make this effect much more important for helium than for oxygen.

(1) Because of its much higher abundance, helium tends to build up optical depth faster even though the unstripped fraction may be significantly lower at low radii. Thus, the helium ionization front is much sharper than that of oxygen.

(2) The multiplicity of ionization states for oxygen and the wide separation between the absorption edges applicable to different ions (O I, 0.533 keV; O VIII, 0.870 keV) tends to dilute the effect of optical depth in suppressing further photoionization. For densities and luminosities appropriate to X-ray binaries, several oxygen ions can co-exist at the same radii (Hatchett, Buff, and McCray 1976). The helium ionization fronts, on the other hand, tend to be rather distinct.

(3) The position of the hydrogen ionization front in the optically thick case significantly affects the helium and oxygen ionization structures in different ways. Beyond the point where hydrogen recombines, very little ultraviolet flux is left to photoionize helium. Thus, all the helium recombines to He I. In contrast, the oxygen is actually shifted to higher ionization states (McClintock, Canizares, and Tarter 1975). Hydrogen absorption is negligible out near the oxygen edges above 0.5 keV, so the photoionization rate is relatively unaffected. However, the free electron density decreases by a factor of 10 or more following hydrogen recombination so that oxygen recombination is suppressed (see Fig. 1 of McClintock, Canizares, and Tarter).

These considerations suggest that for certain optically thick configurations, helium may be nearly entirely neutral in regions where oxygen is still heavily ionized. In that case, the hypothesized ionization variations in oxygen need not necessarily be accompanied by corresponding ionization variations in helium. Transfer calculations for specific sets of parameters have shown that this type of configuration may in fact arise for X-ray luminosities $\sim 10^{36}$–10^{37} ergs s^{-1} and densities $\gtrsim 10^{11}$ cm^{-3} (McClintock, Canizares, and Tarter 1975; Hatchett, Buff, and McCray 1976). The helium ionization front would then be at a radius $\sim 10^{11}$–10^{12} cm from the X-ray source, which is comparable to the binary separation in Sco X-1. Thus, if this interpretation of the data is correct, there is indeed a substantial amount of cool circumsource material in the Sco X-1 system. Further transfer calculations are required to more accurately constrain the physical parameters for this component. It should be emphasized that the X-ray measurements are quite sensitive because of the exponential dependence of the observed absorption features on element optical depths.

Since the actual shape of the oxygen edge is not explicitly resolved in our spectra, we shall also consider the possibility that the observed variations are related to changes in the feature itself, perhaps associated with Compton broadening, as opposed to intrinsic changes in the photoelectric absorbing properties of the system. Variations in the Compton depth of the X-ray emitting plasma have been inferred previously from the properties of the X-ray flares by Hayakawa *et al.* However, photoelectric absorption characteristic of the lower and middle ionization states of oxygen cannot be intrinsic to this hot plasma, since all abundant elements are nearly fully stripped at temperatures $\sim$a few times 10^7 K. The oxygen feature must thus be produced farther out in a cooler component. No Compton broadening can occur in this cool component since the Compton depth, τ_{es}, is of order 1% of the oxygen optical depth, τ_O, observed to be $\lesssim 1$. Thus, in order to Compton broaden the oxygen edge, we require a "sandwich structure" in which a Compton thick, hot component is interior to a Compton thin, cool component, which is itself interior to another Compton thick, hot component. Such a configuration might possibly occur for an accretion disk surrounded by a large hot corona.

For the edge to appear broadened at the level of effective resolution of our deconvolved spectrum

$$\Delta E/E > 10^{-1}.$$

For Compton broadening

$$\Delta E/E \sim \tau_{es} kT/m_e c^2 \sim 1.7\times 10^{10} \tau_{es} T,$$

where τ_{es} is the Compton depth and T is the temperature (in Kelvin) of the scattering component. Since $\tau_{es} = nr\sigma_T$ (where n is the density, r is the scale size, and σ_T is the Thomson cross-section), we require

$$nrT > 10^{33}\ \mathrm{cm}^{-2}\ K.$$

A second constraint comes from the requirement that the free-free radiation emitted by this exterior hot component be less than that which is detected from the source. Assuming a distance of 350 pc, this implies

$$nrT^{1/2} \lesssim 5\times 10^{62}\ \mathrm{cm}^{-3}\ K^{1/2}.$$

For $T \sim 10^8$ K, the above relations imply

$$r \lesssim 10^9\ \mathrm{cm}$$

$$n > 10^{16}\ \mathrm{cm}^{-3},$$

so that the entire sandwich configuration must be relatively close to the accreting object. For higher temperatures, slightly larger radii and lower densities are allowed. If the cool middle component is indeed an accretion disk, its density, n_{disk}, should be at least as high as that of the outer hotter components. Since the observed optical depth at oxygen is <1, we get

$$n_{disk} h \lesssim 10^{22}\ \mathrm{cm}^{-2}$$

and thus

$$h \lesssim 10^6\ \mathrm{cm},$$

where h is the thickness of the disk.

Whether such a picture is, in fact, physically realistic is an open question at present since very little is known about the geometry of the emitting regions in the system. Future high-resolution observations should be capable of actually measuring the Compton broadening of the edge if this model is applicable.

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REFERENCES

Brown, R. L., and Gould, R. J. 1970, *Phys. Rev. D.*, **1**, 2252.
Charles, P. A., Kahn, S. M., Bowyer, S., Blissett, R. J., Culhane, J. L., Cruise, A. M., and Garmire, G. 1979, *Ap. J.* (*Letters*), **230**, L83.
Chodil, G., *et al.* 1968, *Ap. J.*, **154**, 645.
Cowley, A., and Crampton, D. 1975, *Ap. J.* (*Letters*), **201**, L65.
Derenberg, A. J. M., Bleeker, J. A. M., DeKorte, P. A. J., Yamashita, K., Tanaka, Y., and Hayakawa, S. 1973, *Nature*, **244**, 4.
Giacconi, R., Gursky, H., Paolini, F., and Rossi, B. 1962, *Phys. Rev. Letters*, **9**, 439.
Gottlieb, E. W., Wright, E. L., and Liller, W. 1975, *Ap. J.* (*Letters*), **195**, L33.
Hatchett, S., Buff, J., and McCray, R. 1976, *Ap. J.*, **206**, 847.
Hayakawa, S., Kasahara, I., and Matsuoka, M. 1974, *Pub. Astron. Soc. Japan*, **26**, 309.
Kahn, S. M., and Blissett, R. J. 1980, *Ap. J.*, **238**, 417.
Kahn, S. M., Charles, P. A., Bowyer, S., and Blissett, R. J. 1980, *Ap. J. (Letters)*, **242**, L19.
Lamb, P., and Sanford, P. W. 1979, *M.N.R.A.S.*, **188**, 555.
Laros, J. G., and Singer, S. 1976 *Ap. J.*, **205**, 550.
Long, K. S., and Kestenbaum, H. L. 1978, *Ap. J.*, **226**, 276.
Mason, K. O., Kahn, S. M., Charles, P. A., Lampton, M. L., and Blissett, R. J. 1979, *Ap. J.* (*Letters*), **230**, L163.
McClintock, J. E., Canizares, C. R., and Tarter, C. B. 1975, *Ap. J.*, **198**, 641.
Milgrom, M. 1976, *Ap. J.*, **208**, 191.
Miyamoto, S., and Matsuoka, M. 1977, *Space Sci. Rev.*, **20**, 687.
Moore, W. E., Cordova, F., and Garmire, G. P. 1973, *Proc. 13th International Cosmic Ray Conf.*, **5**, 56.
Neugebauer, G., Oke, J. B., Becklin, E., and Garmire, G. 1969, *Ap. J.*, **155**, 1.
Rothschild, R., *et al.* 1979, *Space Sci. Instr.*, **4**, 269.
Sandage, A. R., *et al.* 1966, *Ap. J.*, **146**, 316.
Tarter, C. B., and Salpeter, E. E. 1969, *Ap. J.*, **156**, 953.
Tarter, C. B., Tucker, W. H., and Salpeter, E. E. 1969, *Ap. J.*, **156**, 943.
Willis, A. J. *et al.* 1980. *Ap. J.*, **237**, 596.

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