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ON THE NATURE OF THE SOURCE OF X-RAY EMISSION OF SCO XR-1

Recently the brightest source of X-ray emission Sco XR-1 was identified with an optical object of 13 mag (Sandage, Osmer, Giacconi, Gorenstein, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, and Jugaku 1966). This object is by all its characteristic features reminiscent of an old Nova. At the present time most investigators believe that the mechanism of the X-ray emission of the source may be explained by the bremsstrahlung of an optically thin layer of very hot plasma ($T \sim 5 \times 10^7$ ° K). According to this interpretation the main part of the optical emission is a low-frequency continuation of the bremsstrahlung.

However, the latter conclusion in our opinion does not seem to be right in view of the following considerations.

1. The recently discovered soft X-ray emission from Sco XR-1 in the region 60 Å > λ_2 > 44 Å (Byram, Chubb and Friedman 1966) has a rather high spectral flux density; $F_{\nu_2} \sim 5 \times 10^{-24}$ ergs cm^{-2} sec^{-1}. If the emitting hot plasma were transparent at optical frequencies, the optical intensity can be extrapolated from F_{ν_2} according to the bremsstrahlung spectral law. The apparent magnitude of the optical object, which is identified with Sco XR-1 would then be brighter than 9 mag, which is contradictory to observation.

2. The optical object shows changes of color. The observed variations in intensity of the emission lines of H, He II, C III, and N III are insufficient to cause these color changes, because of the small equivalent widths of the lines. In the case of bremsstrahlung from a very hot plasma, such variations in color are impossible. The absence of a sufficiently bright optical object in the proximity of the source may be explained if we assume that the hot plasma is opaque at optical frequencies

$$\frac{2\pi kT}{\lambda_1^2}\,\frac{4\pi R_1^2}{4\pi r^2} < F_{\nu_1}\,, \tag{1}$$

where $F_{\nu_1} \sim 3 \times 10^{-25}$ ergs cm^{-2} sec^{-1} is the flux density from the optical object with apparent magnitude $m = 12.6$, which is identified with Sco XR-1, r is the distance to the source, and R is its radius. The temperature of the plasma responsible for the emission in the spectral region 44 Å < λ < 60 Å must be higher than 2×10^5 ° K, since otherwise the flux of the X-ray emission for a given F_{ν_1} would be too low. The upper limit of the temperature is about 2×10^6 ° K, as computed by comparing the flux at $\lambda_2 = 50$ Å with the previously measured flux at $\lambda_3 \sim 10$ Å (Hayakawa, Matsuoka, and Yamashita 1966).

From equation (1) we may obtain the upper limit of the linear dimension R of the source (using the upper limit on temperature)

$$R_1 < 10^9 \, (r/200) \text{ cm} , \tag{2}$$

where r is expressed in parsecs.

In addition there must be some much hotter plasma with temperature $T \sim 5 \times 10^7\,^\circ$ K in the source Sco XR-1. This conclusion is derived from its spectrum in the region of $\lambda < 10$ Å (Hayakawa *et al.* 1966). The ratio of optical emission in the visible to emission at $\lambda < 10$ Å shows that this plasma must also be optically thick in the visible. Equation (1) applied to this region at $T \sim 5 \times 10^7\,^\circ$ K gives an upper limit for its linear dimension,

$$R_2 < 1.5 \times 10^8 \left(\frac{r}{200 \text{ pc}}\right) \text{cm}. \tag{3}$$

The conception that two small, very dense plasma clouds exist side by side seems to be rather artificial. It is much more natural to suppose that there is one source; that is, one hot ball whose temperature and density are increasing toward its center. According to such a model the emission of Sco XR-1 in the region of $\lambda < 12$ Å arises in the inner, hotter part of the source, while the emission in the region $\lambda > 44$ Å arises in the outer, colder part.

Using this model we can estimate the lower limit of the dimensions of the source from the requirement that emission from the inner part with the $\lambda < 12$ Å is not absorbed in the outer part of the source for which $T < 2 \times 10^6\,^\circ$ K. The requirement is

$$\tau_2 = \phi_2 R_1 = \frac{1.5 \times 10^{-2}}{\nu^2 T^{3/2}} N_e N_i g R_1 < 1 , \tag{4}$$

where g is the gaunt factor (which for this spectral region is close to unity), ϕ_2 is the X-ray absorption coefficient, and τ_2 is the optical depth of the outer part of the source.

On the other hand, considering that the emission in the region 44 Å $< \lambda <$ 60 Å arises in an optically thin layer of plasma with the temperature of about several hundred thousand degrees, we may derive from the F_{ν_2} the "volume emission measure" on the basis of the well-known formula

$$E_2 = \frac{4\pi}{3} R_1^3 N_e N_i \sim 10^{61} \left(\frac{r}{200 \text{ pc}}\right) e^{\tau_\text{X}} , \tag{5}$$

where τ_X is the optical depth of the interstellar medium for X-ray emission. If the plasma in the region of 44 Å $< \lambda <$ 60 Å is not yet transparent, then E_2 will be higher. From equations (4) and (5) it follows that

$$R_1 > 3 \times 10^8 \left(\frac{r}{200 \text{ pc}}\right) e^{1/2\tau_\text{X}} . \tag{6}$$

Comparing equations (2) and (6) we come to the conclusion that the dimensions of the source Sco XR-1 must be close to 5×10^8 cm if the distance $r \sim 200$ pc, which seems to be most probable. With such dimensions the mean electron concentration in the outer layers of the source (where T is less than $3 \times 10^6\,^\circ$ K) is $N_e \sim 2 \times 10^{17}$ cm^{-3}. The total mass of the plasma is 3×10^{20} gm. and its heat content is $\frac{4}{3}\pi R_1^3 \times 3kT \sim 3 \times 10^{34}$ ergs. This store of heat energy will be sufficient to maintain an emission of the observed power only for one tenth of a second. Consequently a powerful and highly efficient mechanism for continual heating of the plasma is needed.

The volume emission measure corresponding to an emission in the spectral region of $\lambda < 12$ Å is $E_3 \sim 2 \times 10^{59}$ cm^{-5}. It is quite natural to assume that for a hotter plasma with the temperature $T \sim 5 \times 10^7$ ° K in the inner part of the source the electron concentration is higher than in the outer part. Thus it follows that the dimensions of this inner hotter part are less than 10^8 cm. The lower limit on the dimensions of this region, determined from the condition that for $\lambda \sim 10$ Å the plasma remains optically thin, is equal to 2×10^6 cm. It is possible that the dimension of the region with $T \sim 5 \times 10^7$ ° K is close to 10^7 cm. In this case $N_e \sim 10^{19}$ cm^{-3}, and the total mass is very small, 10^{17} gm. One more circumstance must be taken into account. As we may see from the spectrum of Sco XR-1 there is a very flat secondary maximum in the region of $35 \pm h\nu < 50$ keV (Peterson and Jacobson 1966). In the frame of our model of the source this spectral feature may be naturally explained as the thermal emission of a still hotter and denser plasma in the central part of the source. The temperature of this plasma is about 5×10^8 ° K. The volume emission measure of this innermost source may be estimated as $\sim 10^{58}$ cm^{-5} and the dimensions as $\sim 10^6$ cm.

The "three-layer" model of the source Sco XR-1, described above, is certainly a very rough approximation to reality. In fact it must be expected that the physical properties of the source change more or less continually while the plasma remains transparent for sufficiently energetic X-ray quanta.

By all its characteristics this model, obtained only from the analysis of the data of observations without any a priori hypothesis about the nature of the source, corresponds to a neutron star in a state of accretion. If the identification of the optical object similar to an old nova with the X-ray source is correct, then the natural and very efficient supply of gas for such a accretion is a stream of gas, which flows from a secondary component of a close binary system toward the primary component which is a neutron star. In this case it may be that we observe a binary system similar to WZ Sagittae in which one of the components is a neutron star.

From the analysis of the emission lines we may first of all conclude that the regions of emission for He II, H, and C III–N III do not coincide. The emission in the lines of H and He II is caused by recombinations while the emission in the lines of C III–N III is due to electron collisions. The ionization equilibrium of different elements in the stream is governed by the intensity of X-ray radiation which is very high. From the observed intensities of the lines the volume emission measure of the comparatively cold plasma in the stream may be estimated as 10^{55} cm^{-5}. From this we may infer that the electron concentration in the stream is 10^{13} cm^{-3}, the latter being opaque for X-ray radiation. The emission in H-lines arises in the remotest part of the stream from the neutron star where $T \sim 10^4$ ° K. The emission in the lines of C III–N III arises in the part of the stream which is nearer to the neutron star and where $T \sim 5 \times 10^4$ ° K. Finally the region of emission in the lines of He II (partly overlapping the preceding region) is placed still nearer to the neutron star.

The flux of gas in the stream is estimated as 10^{16}–10^{17} gm/sec ($\sim 10^{-9}$ $M_\odot$/year). When this gas falls on the neutron star the production of energy per unit mass may amount to $\sim 10^{20}$ ergs/gm. Thus it follows that the suggested modification of the mechanism of the accretion of gas on the neutron star gives the possibility of explaining the power of X-ray emission of the source Sco XR-1.

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