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PHYSICAL CONDITIONS IN SCO X-1

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In this Letter some restrictions on the parameters characterizing Sco X-1 are discussed, and a model for Sco X-1 and other X-ray sources is suggested. The basic assumptions are (1) the X-ray flux observed in the 2–30 keV range is due to bremsstrahlung from an optically thin plasma with a temperature $T = 5 \times 10^7$ ° K, and (2) the gas has the cosmic abundances given by Aller (1961).

Consider first the requirement that Sco X-1 be transparent to X-rays in the 2–30 keV range. For a hot plasma with the cosmic abundances the absorption of X-rays around 2 keV is principally due to neon and magnesium. At a temperature of 5×10^7 ° K about 3 per cent of the magnesium and about 0.5 per cent of the neon are still in the form of hydrogenic ions (Tucker and Gould 1966). If we assume relative abundances of $N_{\rm Ne}/N_x = 4 \times 10^{-4}$, $N_{\rm Mg}/N_x = 1.2 \times 10^{-5}$ (where N_x is the electron number density in the hot gas), the opacity due to photoelectric absorption is

$$\kappa_{\rm abs}(2\ {\rm keV}) = 7 \times 10^{-26}\, N_x\,. \tag{1}$$

On the other hand the electron scattering opacity is about a factor 10 higher, so that a 2 keV X-ray is scattered about ten times before it is absorbed. Therefore, when $\tau_x = \kappa_{\rm abs} R_x$ is close to unity, the photons must diffuse out of the gas. This increases the time spent in the gas and enhances the probability for an absorption. In the diffusion approximation, the optical depth is (Davison 1957)

$$\tau(2\ {\rm keV}) = (3\kappa_{\rm abs}\kappa_{\rm sc})^{1/2}\, R_x = 3 \times 10^{-25} N_x R_x\,, \tag{2}$$

where $\kappa_{\rm sc}$ is the electron scattering opacity and R_x is the characteristic dimension of the hot gas. The requirement that τ(2 keV) be much less than unity then becomes

$$N_x R_x \ll 3 \times 10^{24}\ {\rm cm^{-2}}\,. \tag{3}$$

With the assumption of a uniform spherical gas, the observed flux in the 2–30 keV range (Peterson and Jacobson 1966) implies

$$N_x^2 R_x^3 = 1.4 \times 10^{17} d^2\ {\rm cm^{-3}}\,, \tag{4}$$

where d is the distance to the source in centimeters. Optical observations have set an upper limit of 1″ on the angular diameter (Sandage, Osmer, Giacconi, Gorenstein, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, and Jugaku 1966; Johnson 1966*a*). The observations also indicated that the observed optical continuum is consistent with the extrapolation of a flat spectrum from X-ray to optical frequencies, such as would be produced by a hot X-ray emitting gas. Therefore the upper limit for the X-ray source may be taken equal to the upper limit for the optical object, and

$$R_x < 5 \times 10^{-6} d\ {\rm cm}\,. \tag{5}$$

In the optical range, absorption is primarily due to free-free transitions, so the opacity for absorption is

$$\kappa_{\rm ff} = 1.3 \times 10^{-42}\, N_x^2\ {\rm cm^{-1}} \tag{6}$$

for $\nu = 5 \times 10^{14}$ c/s, $T = 5 \times 10^7$ ° K. When we take into account the effects of electron scattering, it follows that the gas will be transparent to its own radiation if

$$R_x N_x^{3/2} \ll 4 \times 10^{32} . \tag{7}$$

Equations (3) and (7) show that a sufficient condition for no absorption at optical and X-ray frequencies is $N_x < 10^{16}$ cm^{-3}. Shklovsky (1967) has proposed a model in which the inequality in equation (7) is the other way around, i.e., the hot plasma is opaque to its optical radiation. Equations (3), (4), and (7) show that this is impossible, so long as the gas has anywhere near the cosmic abundance of oxygen, neon, etc., and the distance is greater than about 5 parsecs. Qualitatively this follows, since to make $\tau_{\rm opt} > 1$, while keeping $\tau_x < 1$, one needs large densities and small radii. As the density increases and the radius decreases in such a manner as to satisfy these requirements, the emission measure N^2R^3 decreases so d must decrease, according to equation (4).

The observed line emission (Sandage *et al.* 1966; Johnson, Spinrad, Taylor, and Peimbert 1967) can be understood only if a cool gas is assumed to exist in the vicinity of the X-ray source. The emission from the C III, N III, and O II structure around 4640 Å appears to be comparable to, or greater than, the Hβ emission. Hβ emission can occur over a wide range of temperatures whereas the intensity of the C III, N III, and O II lines depends critically on the temperature, since C III, N III, and O II will be present only over a narrow range of temperatures. Therefore, unless the temperature of the cooler gas varies over only a narrow range, the integrated Hβ and optical continuum emission from all the gas at all temperatures will be in contradiction with the observations. Because the abundance of hydrogen is about a thousand times greater than the abundance of carbon, nitrogen, and oxygen, it is obvious that the cross-section for producing the C III, N III, and O II lines must be much larger than the cross-section for producing the Hβ line.

Production of the observed lines by cascades following recombination can be shown to lead to a negligible intensity relative to Hβ. Consider the N III line at 4640 Å, for example. An upper limit on the intensity of this line due to radiative recombination is obtained by assuming that all recombinations to N IV for principal quantum number $n > 3$ lead to the production of a 4640 Å quantum as the electron cascades to the ground state. Treating the excited states as hydrogenic, and using the expressions given by Burbidge, Gould, and Pottasch (1963), we find that, for $T_e = 2 \times 10^4$ ° K, $I(4640) < 1.5 \times 10^{-23} N(\text{N IV}) N_e$ erg cm^{-3} sec^{-1}. According to Pengelley (1964) the Hβ emissivity at 2×10^4 ° K is $I(\text{H}\beta) = 6.4 \times 10^{-26} N_e N(\text{H II})$ erg cm^{-3} sec^{-1}. Therefore,

$$I(4640)/I(\text{H}\beta) < 240\, N(\text{N IV})/N(\text{H II}) < 2.4 \times 10^{-2}$$

for a gas with the cosmic abundances. Hence, if the cosmic abundances are assumed, the only feasible way of producing the C III, N III, and O II lines seems to be collisional excitation of levels of 30–40 keV above the ground state. This in turn implies that the temperature in the cooler gas must be close to 10^5 ° K.

The radiation field of the X-ray source will heat the gas by photo-ionization, the amount of heating being dependent on the intensity of the X-ray source at the cool gas and the density in the cool gas. However, one can show quite generally (Tarter 1967) that, *if* a radiation field maintains a temperature of 10^5 ° K in the cool gas, the ions will be almost completely stripped of their electrons and the amount of C III, N III, and O II present will be completely insignificant. Since both a temperature of 10^5 ° K, and C III, etc. seem to be required to account for the observed emission lines in Sco X-1, the temperature most probably is maintained by some means other than the radiation from the X-ray source.

The requirement that C III, etc. not be ionized by the radiation from the X-ray source yields an inequality involving the radius of the X-ray source and the density in the cool gas. The ionizing flux is proportional to the flux measured at Earth times d^2/R^2, so the number of photo-ionizations is proportional to $N\, d^2/R^2$. On the other hand, the number of collisional ionizations is proportional to N^2. Therefore the amount of photo-ionization will be negligible if $N > C\, d^2/R^2$, where C is constant involving the atomic parameters and the luminosity of the X-ray source, having dimensions of (length)$^{-3}$. From Tarter's (1967) work and the X-ray observations for Sco X-1, we find that C III, N III, and O II will not be photo-ionized if

$$R \gg 3 \times 10^{-2}\, d\, N_c^{-1/2}\ \text{cm}\ , \tag{8}$$

where N_c is the electron density in the cool gas (cf. Johnson 1967*a;* Williams 1967). If the cool gas is imbedded in the hot gas, the geometrical dilution will be less important and inequality (8) will be stronger. If it is assumed that the upper limit in equation (5) applies to the line emitting volume, equations (5) and (8) imply

$$N_c \gg 4 \times 10^7\ \text{cm}^{-3}\ . \tag{9}$$

From the equivalent widths quoted for the Hβ line, its luminosity can be estimated at

$$L(\text{H}\beta) \approx 4 \times 10^{-12}\, d^2\ \text{erg/sec}\ . \tag{10}$$

The luminosity of the C III, N III, and O II complex around 4645 Å is roughly equal to this value also. The Hβ emission from the cool region (assumed to be a spherical shell at radius R) is

$$L(\text{H}\beta) \approx 4\pi R^2 \Delta R N_c^2 P(\text{H}\beta) \gg 2 d^3 \left(\frac{\Delta R}{R}\right) P(\text{H}\beta)\ , \tag{11}$$

according to equations (8) and (9). At 10^5 ° K, $P(\text{H}\beta) \approx 10^{-26}$ ergs cm^3/sec, so equations (10) and (11) imply

$$\Delta R/R \ll 2 \times 10^{14}/d\ . \tag{12}$$

For d greater than 10 persecs, or 3×10^{19} cm, equation (12) shows that $\Delta R/R$ is much less than 10^{-5}.

If it is assumed that T decreases away from the X-ray source according to the law $T = T_x(R_x/R)^y$, and the density is constant and equal to the cool gas value, then the Hβ emission from this region can be shown to be too large unless y is very large ($> 3 \times 10^{-15} d$). The temperature must drop sharply from the hot gas to the one at 10^5 ° K, which must then occupy only a thin shell around the X-ray source. It was pointed out before by Johnson (1966*b*, 1967*a*) that the volume of the cool gas must be much less than that of the hot gas, if the densities in the cooler gas are equal to or greater than those in the hot one. The arguments given here extend this to arbitrary densities compatible with the observations.

Thus we are led to consider a model in which the line emission comes from a small volume compared to that of the X-ray source. Since the ionizing flux is proportional to the flux measured at Earth times d^2/R_x^2, the radius of the X-ray source must be sufficiently large that the ionizing flux is diluted to the point where it has a negligible effect on the ionization of C III, etc. Equation (8) now gives a lower limit on the radius of the X-ray source. Note that the out-of-phase variation of the Hβ and other lines results naturally from this model. For example, the strength of the C III line is proportional to (C III/C) exp $(-372000/T_e)$. As T_e increases in the vicinity of 10^5 ° K, this product will increase (Cox and Tucker 1967), whereas the intensity of the Hβ emission decreases with increasing temperature. The concentration of He III is also increasing rapidly near 10^5 ° K, so the recombination line of He II (4686 Å) would become stronger when Hβ weakens, in accord with observations. Since the C III, etc., lines are so strongly temperature dependent, it is not difficult to construct a model in which their variations relative to He II (4686 Å) can be understood.

Two difficulties associated with the "hot gas" model for Sco X-1 are the confinement of the hot plasma and coexistence of a 10^5 ° K plasma with a much larger amount of 5×10^7 ° K plasma. One possible model is one in which the hot gas is confined by a magnetic field connected to a central object, with the line emission coming from cooler filaments which are inslated from the hot gas by means of the magnetic field.

If the magnetic field is assumed to be connected to a central object, or "star," then the total magnetic energy must be less than the gravitational energy in order for the "star" to be stable. For a dipole field with dipole moment a this requirement becomes

$$R_0 > 2 \times 10^{-30}\, a/M \text{ cm}\,, \tag{13}$$

where R_0 is the radius of the "star" and M its mass in solar units. If the magnetic field is to confine the X-ray source at R_x, then $B^2 = a^2 R_x^{-6} \geq 16\pi N_x k T_x$, or using equation (4),

$$a \geq 10^{14} d^2 N_x^{-3/2} \text{ gauss cm}^3\,. \tag{14}$$

If it is further assumed that the pressure in the hot gas is greater than or equal to that in the cool gas, then equations (4) and (8) give limits on N_x and R_x:

$$N_x < 3 \times 10^{51} d^{-2} \text{ cm}^{-3},\; R_x > 2 \times 10^{-29} d^2 \text{ cm}\,. \tag{15}$$

Equations (13), (14), and (15) imply $R_0 > 10^{-93}\, d^5/M$. Unless d is much less than 100 parsecs, the central star must have a more or less normal stellar radius. (For R_0 to have the dimensions of a neutron star, d would have to be less than about 20 parsecs.)

The existence of stellar magnetic fields of 10^6 to 10^8 gauss is possible, in theory. Indeed, Mestel (1964) has commented that the problem is to explain why strong surface fields are the exception rather than the rule. X-ray sources may represent that stage in the evolution of stars when they get rid of their large "fossil" magnetic fields, as suggested by Manley (1966). The energy of the magnetic fields would eventually be degraded into thermal energy by means of flare-like events. Since the source is much more extensive and massive than the solar corona, most of the non-thermal energy normally associated with flares would be transformed into thermal energy by means of ionization, absorption of radio-frequency radiation, etc. An observable amount of optical synchrotron radiation and high-energy non-thermal bremsstrahlung ($\gtrsim$100 keV) could conceivably be produced. If the initial magnetic energy is comparable to the gravitational energy, and the theories of star formation suggest that it might well be, then the conversion of magnetic energy into thermal energy with only 10 per cent efficiency would provide $\sim 2 \times 10^{47}$ ergs for a typical main-sequence star. An X-ray source such as Sco X-1 with a luminosity of 5×10^{36} ergs/sec would then have a lifetime of about 1000 years. From Salpeter's (1959) discussion of star formation one can estimate the rate of star formation to be around 1 star per year in the Galaxy. Thus the existence of some 1250 X-ray sources in the Galaxy, as estimated by Friedman, Byram, and Chubb (1967) can easily be accounted for by this model. Also the positions of X-ray sources should be correlated with regions of star formation, if they represent an early stage of stellar evolution. The work of Braes and Hoevenier (1966) and O'Dell (1967) indicate that this is probably the case (cf. however, Johnson 1967*b*).

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