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A MODEL OF A SEMI-OPAQUE X-RAY SOURCE, SCO X-1

Satio Hayakawa

Department of Physics, Nagoya University, Nagoya, Japan

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ABSTRACT: Plasma parameters that characterize the X-ray emitting region of Sco X-1 are obtained by reference to a series of simultaneous hard X-ray and optical observations of Sco X-1 and to theories of radiative **transfer**. For the spherical, isothermal plasma the electron temperature, the electron density and the radius are 3.6 keV, 3×10^{16} cm^3 and 4×10^8 cm, respectively, in the optically bright but quiet phase. At optical flares the plasma mass increases by a few tens of a per cent, whereas the electron temperature does not appreciably change.

1. INTRODUCTION

Several months after the discovery of cosmic X rays in 1962, a conference organized by Professor Vallarta was held at the Pontifical Academy of Science. The unexpectedly high flux of cosmic X rays reported by Professor Rossi naturally became one of the topics at an unscheduled session. The result obtained by Rossi and his collaborators indicated the existence of a diffuse component and a source towards the galactic center, both having high intensities (Giacconi et al. 1962). The observed intensities exceeded by orders of magnitude those I had estimated earlier, taking into account various conceivable astrophysical conditions, and I was only able to point out a contribution of the inverse Compton effect that could be considerable in the galactic centre if both relativistic electrons and radiation in the as yet unobservable range were strong.

This source has, however, been found to be located at about 25° north of the galactic centre in galactic coordinates and named Sco X-1. In order to explain the X-ray emission I suggested two possibilities at the Jaipur Conference in 1963 (Hayakawa and Matsuoka 1963). One is the neutron-star hypothesis, that is, the black-body radiation at about 10^7K which is expected for a young neutron star, and the other is the binary hypothesis, that is, the stellar wind from one component hits the other to produce a hot plasma of about 10^7K that emits thermal bremsstrahlung. We then made a rocket observation of Sco X-1 in 1965 and found an X-ray spectrum of the thermal-bremsstrahlung type but with a temperature as high as several times 10^7K (Hayakawa et al. 1966). If X rays are emitted by thermal bremsstrahlung, extension of the spectrum to the optical region should give an optical magnitude of about 13. Meanwhile Professor Oda and his collaborators (Oda et al. 1965) succeeded in measuring the position and size of Sco X-1 with the use of a modulation collimator. The smallness of its size indicated that Sco X-1 is not nebulous but likely to be stellar, and the error box of the position was small enough to search for the optical counterpart of Sco X-1. Oda then asked for the collaboration of optical astronomers, Jugaku and Osawa; they found a blue star at one of the expected positions in June, 1966 (Ichimura et al. 1966). The star was found to be variable and showed emission lines whose equivalent widths were also variable. Detailed properties of this unusual star were confirmed at Palomar Observatory in the next month (Sandage et al. 1966).

On the basis of these observations Matsuoka, Ogawara and Oda (1966) invented a model for Sco X-1. In order that a hot plasma be gravitationally bound by a star, the size of the plasma should be as small as 10^9 cm or smaller. The model has been confirmed by an infrared observation (Neugebauer et al. 1969), according to which the infrared spectrum of Sco X-1 follows the Rayleigh-Jeans law. This implies that Sco X-1 is optically thick in the infrared region and optically grey in the visible region. The fact that both X rays and optical radiation are emitted from the same plasma was proved by simultaneous observations in these two spectral ranges (Chodil et al. 1968). The electron density and size of the hot plasma responsible for optical and X-ray emission were derived by reference to a series of simultaneous optical and X-ray observations by Kitamura et al. (1971). They also claimed that the plasma temperature was anticorrelated with the emission measure. On the other hand, the hardening of the X-ray spectrum was observed at optical flares (Hudson et al. 1970, Evans et al. 1970).

In order to clarify further details of Sco X-1, a series of simultaneous observations of hard X rays and optical emission were performed by a collaboration between the Institute of Space and Aeronautical Science of University of Tokyo, Nagoya University, Nizamiah Observatory, the Tata Institute of Fundamental Research, and the Tokyo Astronomical Observatory. The results of the observations and their interpretation will be summarized in what follows, based on papers by Matsuoka et al. (1974), by Nishimura (1974), by Hayakawa et al. (1974) and by Kasahara (1974).

2. OBSERVATIONS

A series of hard X-ray observations with balloon-born scintillation counters were started in 1970 at Hyderabad, India. No simultaneous optical observations were available at the times of the two balloon flights in 1970. A photographic observation with an 8" astrograph at Nizamiah Observatory was available for a balloon flight on May 1, 1971. An enhancement of Sco X-1 was observed at about 2100 UT both in the X-ray and optical regions. Although the enhancement appeared to be a flare, the time resolution of several minutes prevented us from drawing the definite conclusion that the enhancement was associated with a flare. It was noticed that the X-ray intensity increased by a factor of about two while the optical emission was enhanced by about 20%. It is worth while to mention that the X-ray spectrum in the enhanced period was essentially the same as that in the quiet period, during which the B-magnitude was 12.6 (Matsuoka et al. 1972a, b).

On April 16, 1972 both a photographic observation with a 12" reflector at the Balloon Facility of Tata Institute of Fundamental Research and a photoelectric observation with a 48" reflector at Rangapur were available. Owing to their good time resolutions an optical flare at 2241-2246 UT was observed with an enhancement of 0.2 magnitudes in comparison with $B = 12.5$ in the pre-flare period, and at the same time an X-ray enhancement by a factor of about 1.6 was observed with similar balloon-borne counters. Again the X-ray spectrum remained the same at the optical flare (see Figs. 1 and 2).

On April 19, 1972 the optical brightness of Sco X-1 was declining. At a time when $B = 12.7$, the hard X-ray intensity was substantially lower and the spectrum was softer.

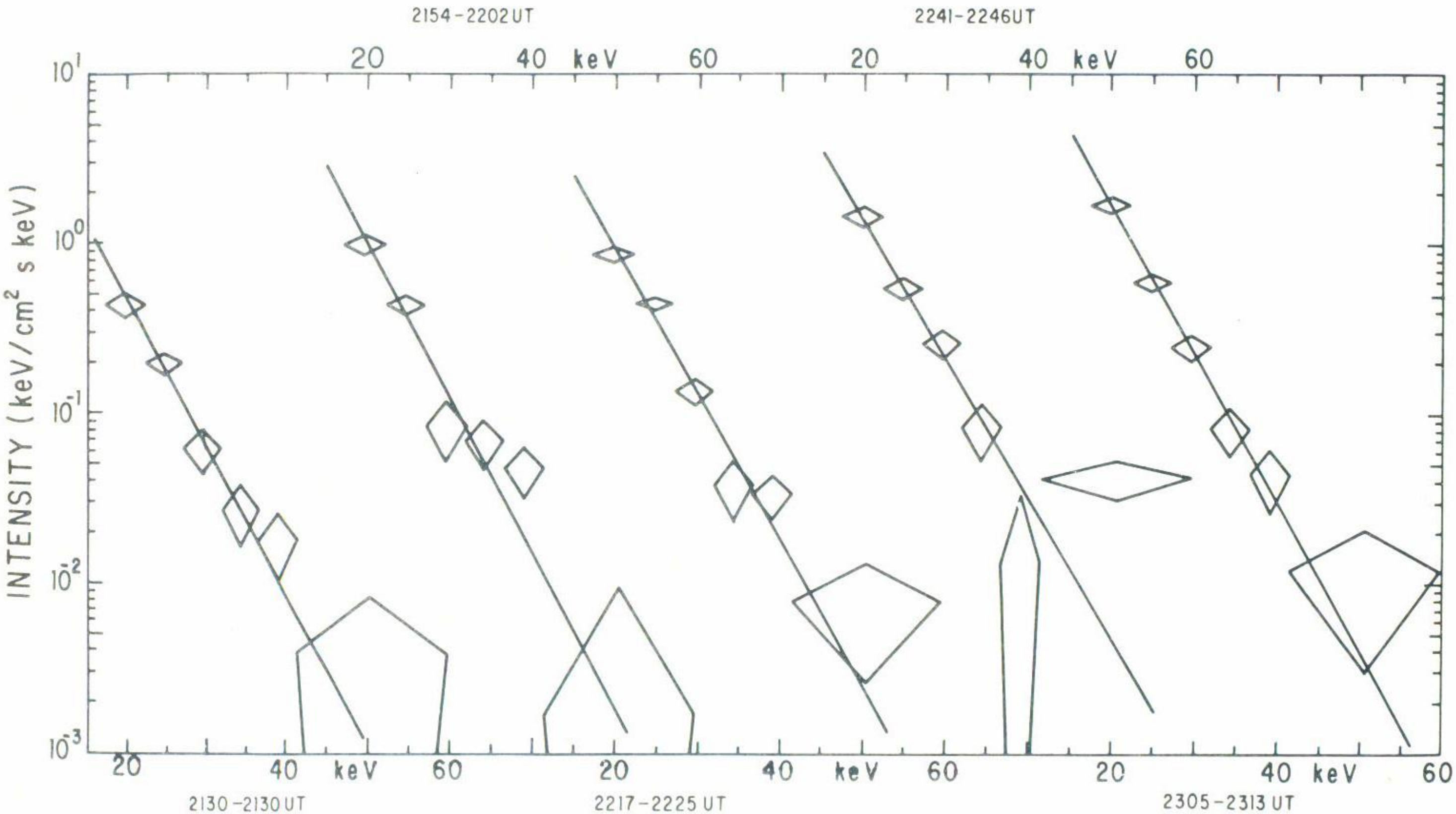

Fig. 1. Hard X-ray spectra observed in five successive periods including a flare period in the interval 2217–2225 UT on April 16, 1972.

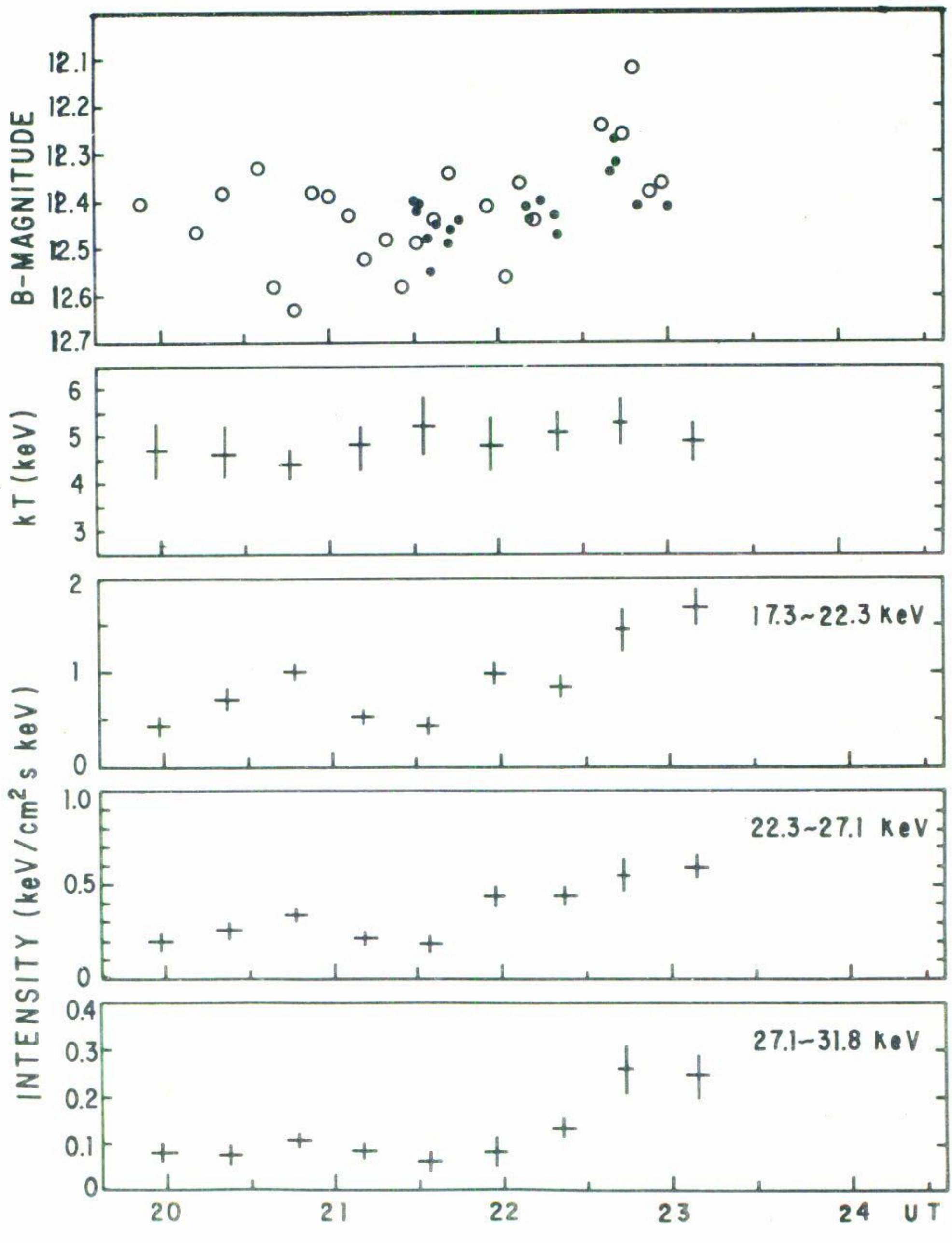

Fig. 2. Time variations of the B-magnitude (open and filled circles represent the results obtained by photographic and photoelectric observations, respectively), the apparent temperature derived by fitting the observed spectrum by the exponential law, and the X-ray intensities in the three energy ranges as indicated.

Let us now consider the characteristic features of Sco X-1 in the optically bright phase in which optical flares are known to take place rather frequently. At flares both X-ray and optical emissions are enhanced, but the enhancement of hard X-ray emission is considerably larger than that of optical emission. The hard X-ray spectra in the energy range 20 to 40 keV are essentially the same in both flaring and non-flaring periods. If the X-ray spectrum is represented by an exponential law, that is, $\exp(-E/kT_a)$ where E is the X-ray energy, the apparent temperature kT_a is about 5 keV independently of whether Sco X-1 is flaring or not. The observed results are summarized in Table 1. The X-ray spectra obtained on April 16, 1972 are shown in Fig. 1, and variations of B-magnitude, the X-ray intensities in three energy ranges and the apparent temperature are shown in Fig. 2. The X-ray spectra in five selected periods are shown in Fig. 3 along with the spectra below 20 keV observed with rockets in different periods.

3. SEMI-OPAQUE PLASMA MODEL

The observed properties of Sco X-1 are now interpreted in terms of the semi-opaque plasma model. Since details are described by Hayakawa et al. (1974) and by Kasahara (1974), where use was made of the theories of radiative transfer worked out for the optical region by Felten and Rees (1972) and for the hard X-ray region by Nishimura (1974), I here give only a qualitative description and essential results.

In a plasma of temperature as high as several keV, photons are emitted by thermal bremsstrahlung or free-free emission. If the plasma is isothermal and homogeneous with the electron temperature kT_e and the electron density n_e, the volume emissivity of photons in a given energy range, $4\pi j(E)\,dE$, can be obtained from the theory of thermal bremsstrahlung for a given chemical composition. If the plasma size r is so large that the optical depth for electron scattering

$$\tau_{es} = \sigma_{\text{Th}} n_e r \quad , \tag{1}$$

where σ_{Th} is the Thomson cross section, is much greater than unity, the photons emitted undergo a random walk in the plasma. Hence the average path length of photons in the plasma is as large as $\tau_{es} r$, if not absorbed.

At low photon energies the photons are subject to free-free absorption with an absorption coefficient μ_{ff}, which increases quadratically with wave-

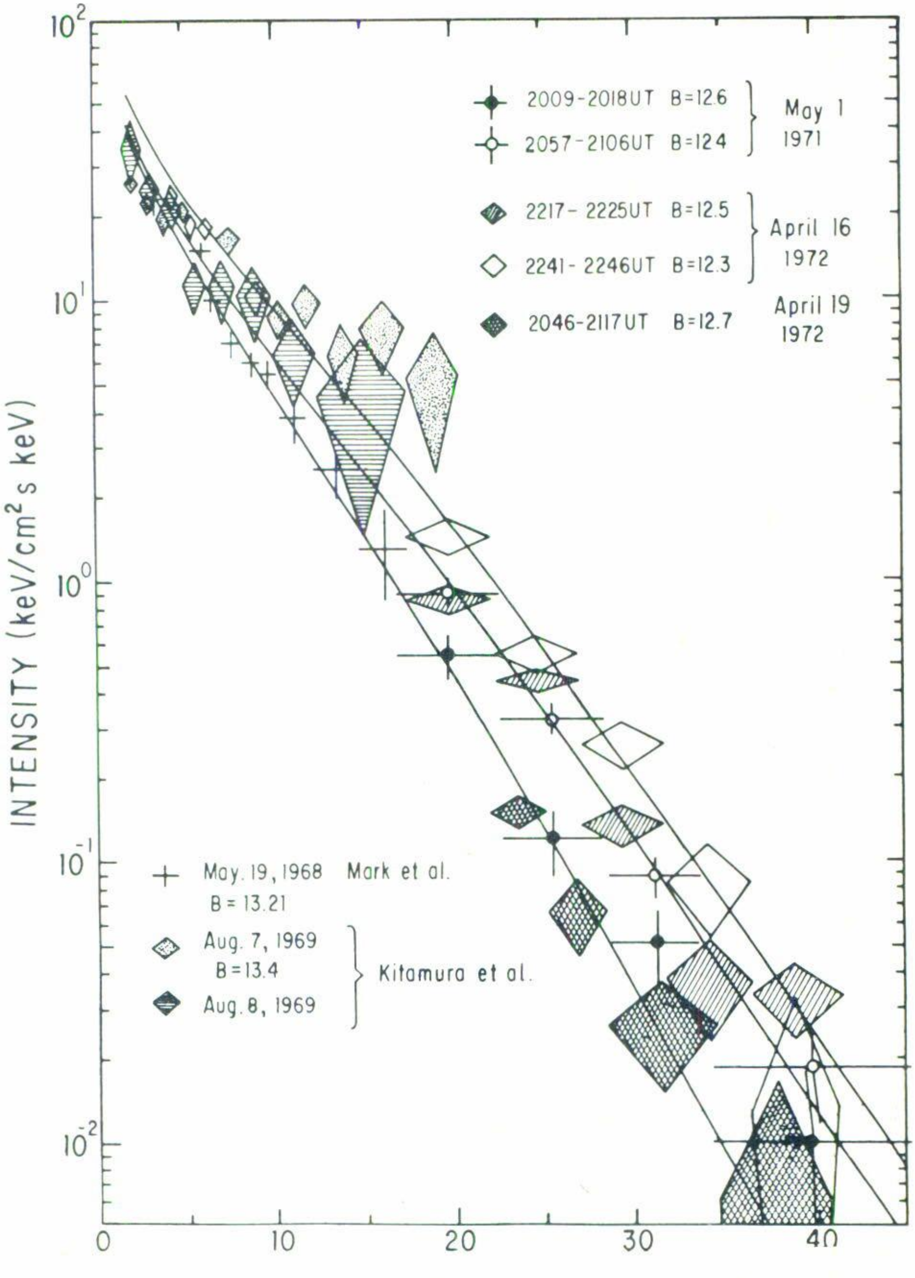

Fig. 3. X-ray spectra of Sco X-1 obtained by rocket and balloon observations. The solid lines represent theoretical spectra calculated for first three periods given in Table 1.

length. If the optical depth for free-free absorption

$$\tau_{ff} = \mu_{ff} r \tag{2}$$

is comparable to or greater than τ_{es}, the intensity of photons escaping out of the plasma is considerably reduced in comparison with that for a tenuous plasma. For a spherical plasma of radius r the intensity of photons emitted per unit solid angle is approximately given for the optical region by

$$I(E)dE = (\tau\tau_{ff})^{-\frac{1}{2}} rj(E)dE , \tag{3}$$

where $\tau = \tau_{es} + \tau_{ff}$. For $\tau_{es} \ll \tau, I(E)$ tends to the black-body spectrum.

The electron scattering of photons results in an energy exchange. If the energy of an electron taking part in scattering is greater than that of a colliding photon, the scattering results in the photon gaining energy with considerable probability. Hence photons of low energies are transported toward high energy. The effect of energy gain by Compton scattering distorts the energy spectrum, especially in the X-ray region where the spectrum falls off steeply towards high energy. The X-ray spectrum modified by Compton scattering is approximately expressed as (Nishimura 1974)

$$I(E) = \tfrac{4}{3} rj(E)\, W(x,y),\ W(x,y) = 1 + \frac{9}{\pi^2}\,\frac{xy}{1+y}(1 + xy + \tfrac{1}{2}x^2y^2) \tag{4}$$

where $x \equiv E/kT_e$ and $y \equiv 6\pi^{-2}(kT_e/mc^2)\,\tau_{es}^2$, mc^2 being the electron rest energy. The modification factor $W(x,y)$ is large and depends rather strongly on τ_{es} in the hard X-ray region, whereas it is small and weakly dependent on τ_{es} at a few keV, as shown in Fig. 4. On the other hand, the slope of the spectrum represented by the apparent temperature decreases rather rapidly at several keV as τ_{es} increases, but changes only slowly with τ_{es} in the hard X-ray region, as shown in Fig. 5.

The above feature demonstrates that the observation of hard X rays is appropriate in obtaining the value of τ_{es}. In the few-keV region, on the other hand, the shape of the spectrum depends on τ_{es} in a complicated way, and the electron temperature and consequently the value of τ_{es} are hardly obtainable from observation. The τ_{es} dependence of the spectrum is shown in Fig. 6. In fact, the slope of the spectrum in the hard X-ray region does

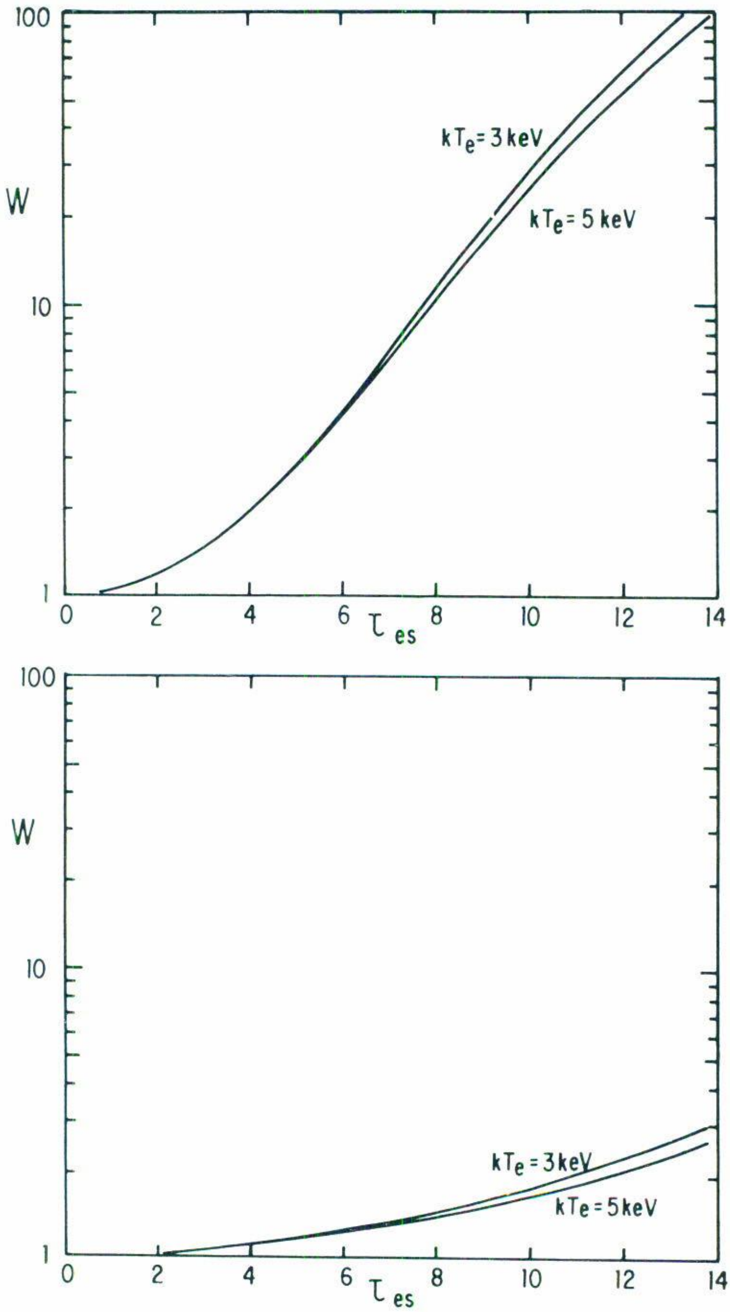

Fig. 4. The values of $W(x, y)$ for E = 30 keV (upper) and 5 keV (lower) versus τ_{es} for kT_e = 3 keV and 5 keV.

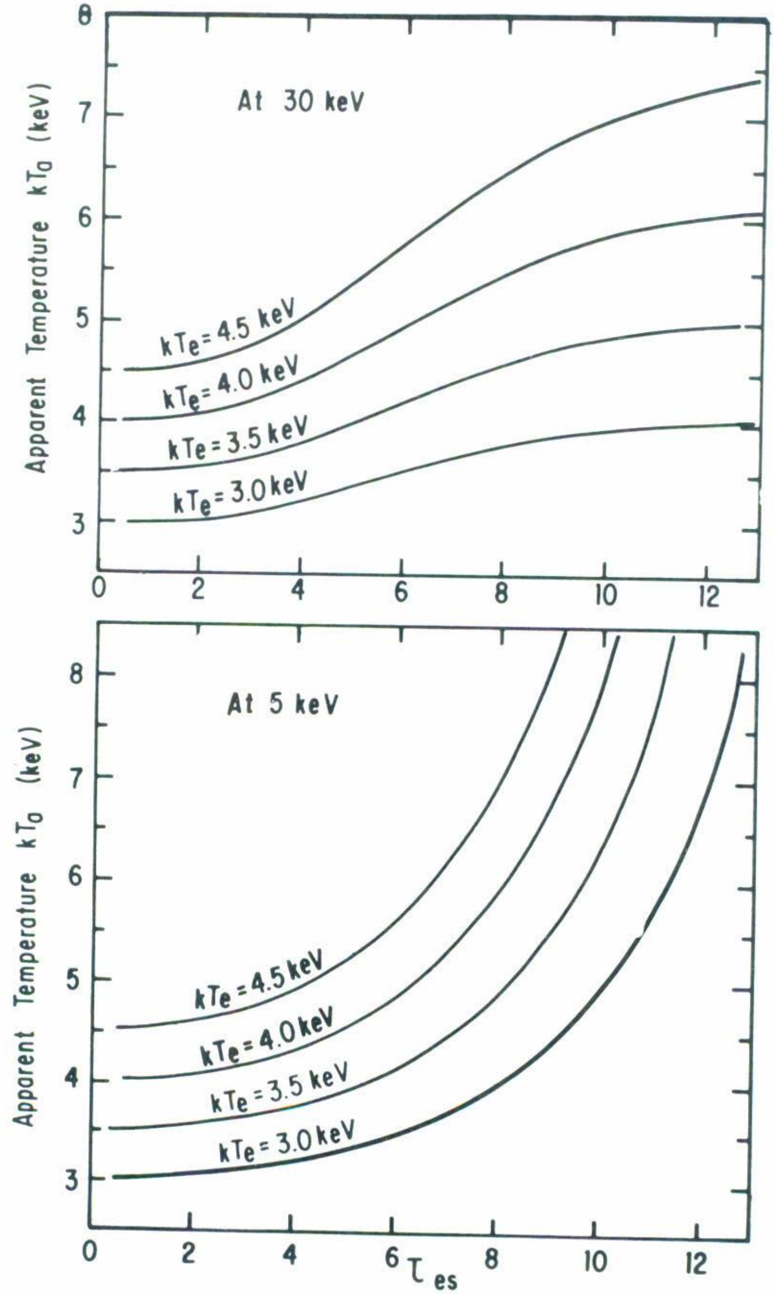

Fig. 5. The apparent temperatures for E = 30 keV (upper) and 5 keV (lower) versus τ_{es} for given values of kT_e as indicated.

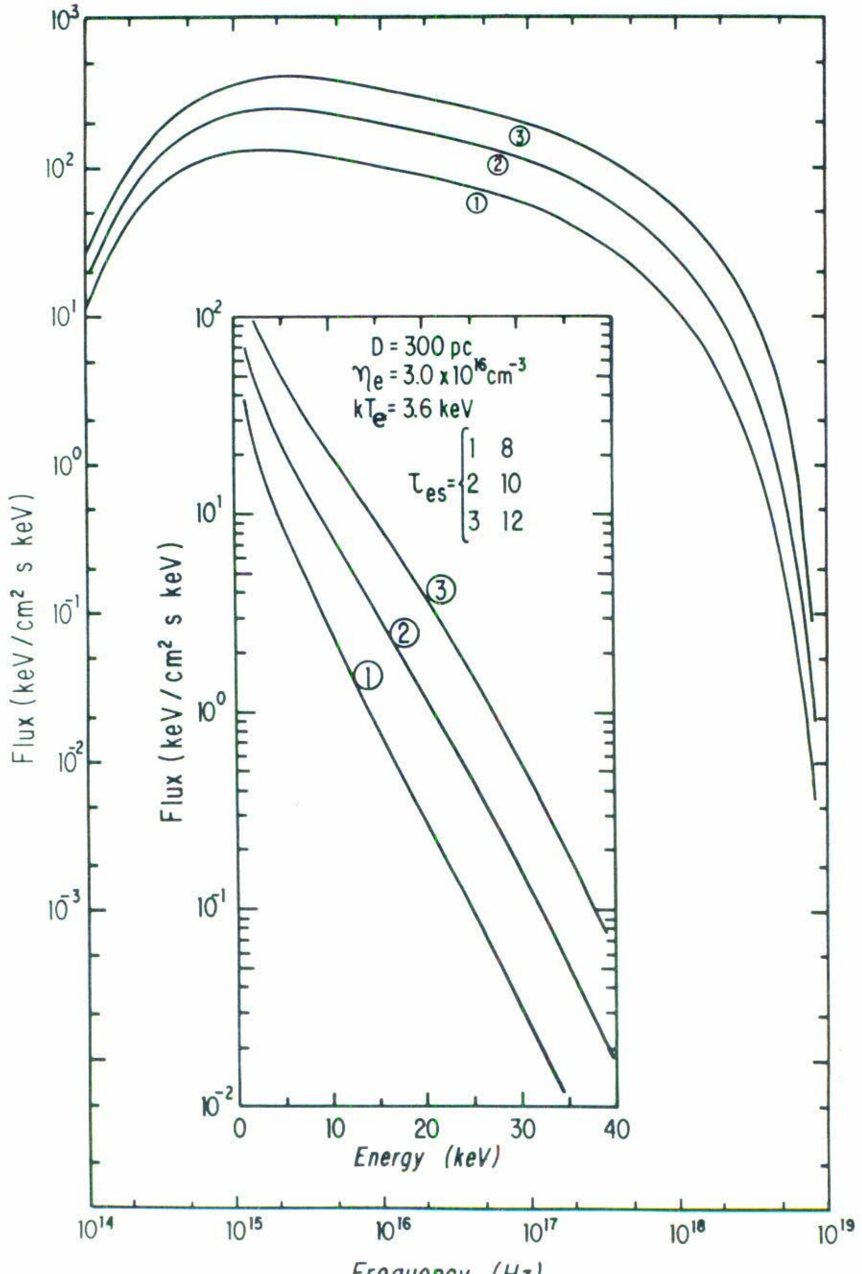

Fig. 6. The spectra of radiation of Sco X-1 for τ_{es} = 8, 10 and 12. The values of other parameters are as indicated.

not change appreciably as τ_{es} increases from 8 to 12, whereas the spectrum in the few-keV region becomes appreciably harder. The hard X-ray intensity increases rather steeply with τ_{es}, whereas the optical intensity increases only slightly.

The observed results can now be understood in the light of characteristic features of the semi-opaque plasma. The fact that the apparent temperature does not appreciably depend on the radiation intensity implies that the electron temperature of the plasma is essentially constant in the optically bright phase of Sco X-1, independent of whether it flares or not.

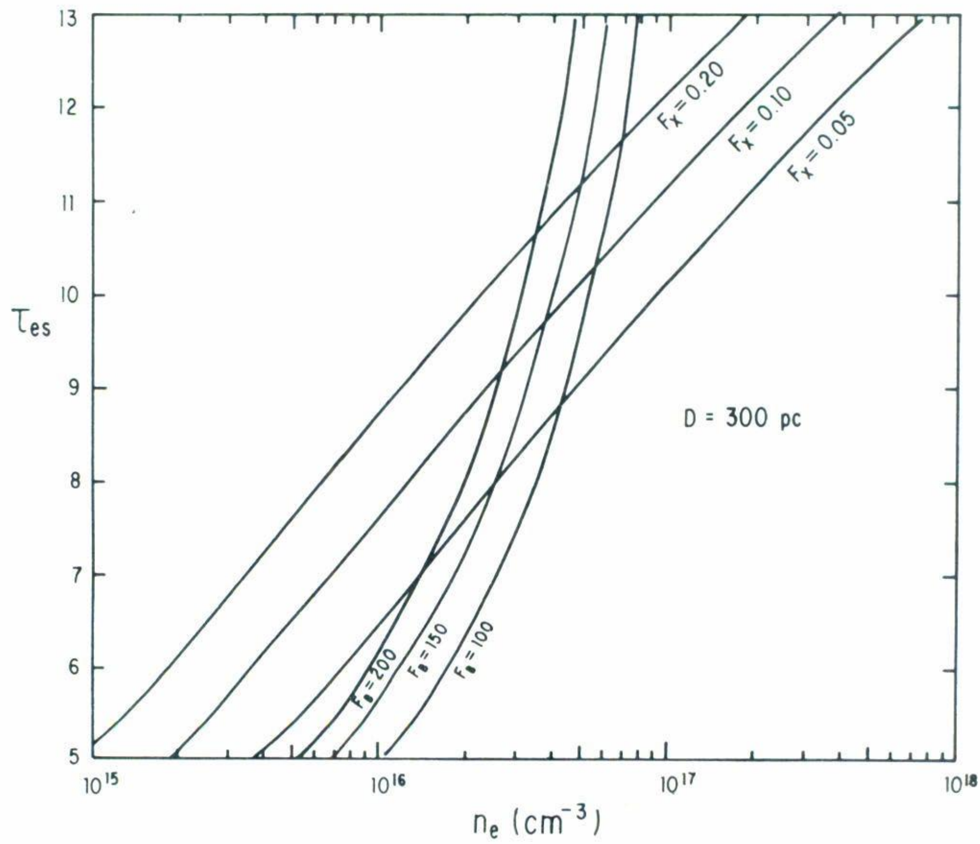

Fig. 7. The contours of the hard X-ray (30 keV) and optical (B-band) intensities in the $n_e - \tau_{es}$ plane for the spherical model. The intensities are expressed in units of keV cm^{-2} sec^{-1} keV^{-1}. An apparent temperature of 5 keV, a distance of 300 pc and an interstellar extinction of A_B = 1.0 are assumed.

The values of other plasma parameters can be derived by comparison between the hard X-ray and optical intensities. Because of the relation (1), only two of n_e, r and τ_{es} are independent variables. Choosing n_e and τ_{es} as independent variables, we draw contour lines of the hard X-ray and optical intensities in Fig. 7. There are three other parameters to be determined. They are the plasma shape, distance and interstellar extinction. As for the first, we examine the ratio of the radius to thickness of a disk, regarding a non-spherical plasma as a disk. Since a thickness larger than the radius is meaningless, the disk geometry is possible only for a distance greater than 300 pc. Since the interstellar extinction in the optical region and the soft X-ray absorption (Deerenberg et al. 1963) do not seem to favour too large a distance, we assume a spherical plasma at a distance of 300 pc. The interstellar extinction is assumed to be $A_B = 1.0$. Then a crossing point of two contour lines gives a set of parameters n_e and τ_{es}. The value of τ_{es} allows us to obtain the electron temperature kT_e. Their values in corresponding periods are listed in Table 1.

It is almost needless to remark that these values are subject to an uncertainty associated with the assumptions on other parameters, and that the uncertainty will be removed by simultaneous observations in more energy bands and an analysis along the lines described in the present paper.

4. ENERGY SOURCE

The values of the plasma parameters given in Table 1 indicate the following properties for Sco X-1.

The size of the hot plasma is as small as 4×10^8 cm. This gives an upper limit for the radius of the central star. If it is a white dwarf, its mass should be very close to the Chandrasekhar limit. The probability that a white dwarf has such an extreme mass is very small. It is therefore likely that the central star is a neutron star or a black hole, which have a much smaller radius.

At flares either the electron density or the plasma size increases. In either case the plasma mass increases. Since the duration of a flare is a few minutes, the excess mass supply rate is a few times 10^{16} g/sec. If the matter supplied brings energy, the energy per particle is of the order of 10^{-4} erg, in order to account for the excess radiation rate of about 10^{36} erg/sec. Energy supply by such high-energy particles has been suggested in connection with the coccoon model (Davidson et al. 1971). If high-energy particles are

TABLE 1

Plasma parameters of Sco X-1 in selected periods.

In deriving the values of these parameters the distance of Sco X-1 and the interstellar extinction are assumed to be d = 300 pc and A_B = 1.0 mag, respectively.

	2217 ~ 2225 UT APRIL 16, 1972	2241 ~ 2246 UT APRIL 16, 1972	2046 ~ 2117 UT APRIL 19, 1972	2009 ~ 2018 UT MAY 1, 1971	2057 ~ 2106 UT MAY 1, 1971
	preflare	flare		preflare	flare
B magnitude	12.5	12.3	12.7	12.6	12.4
X ray Intensity at 30 keV ($keV/cm^2 \cdot sec \cdot keV$)	0.12 ± 0.01	0.20 ± 0.01	0.035 ± 0.009	0.060 ± 0.023	0.12 ± 0.01
Apparent Temperature (keV)	5.1 ± 0.4	5.3 ± 0.5	4.0 ± 0.7	4.7 ± 0.7	5.1 ± 0.3
τ_{es}	10.0	10.7	11.0	8.6	9.9
n_e (cm^{-3})	3.7×10^{16}	3.6×10^{16}	5.0×10^{16}	3.0×10^{16}	3.4×10^{16}
r (cm)	4.1×10^{8}	4.5×10^{8}	3.3×10^{8}	4.4×10^{8}	4.4×10^{8}
Ω (steradian)	6.2×10^{-25}	7.6×10^{-25}	4.1×10^{-25}	7.0×10^{-25}	7.0×10^{-25}
Mass (g)	1.8×10^{19}	2.3×10^{19}	1.3×10^{19}	1.7×10^{19}	2.0×10^{19}
kT_e (keV)	3.6	3.6	3.0	3.6	3.6
Ratio of intensities at 15 keV and 5 keV	0.14	0.16	0.10	0.11	0.14
Luminosity (E > 1 keV) (erg/sec)	4.1×10^{36}	5.6×10^{36}	3.5×10^{36}	2.9×10^{36}	4.2×10^{36}

supplied, they may contribute to the high-energy tail of the X-ray spectrum. Our observations indicate enhancements at energies above 50 keV when the X-ray intensity in the range 20 to 40 keV is enhanced, but their statistical significance remains to be investigated.

The mass supply may also be needed in the stationary state in order to maintain the plasma mass against its loss by instabilities. The mass could be supplied by accretion. If this were the case, the circumstellar matter formed by the accreting matter should show absorption in the soft X-ray region (Hayakawa 1973). However, the soft X-ray spectrum does not show an absorption feature characteristic to the matter surrounding an X-ray source (Deerenberg et al. 1973). This would also suggest that the central star could be an energy source.

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RESUMEN

A partir de una serie de observaciones simultáneas en rayos X duros y ópticas de Sco X-1 y haciendo referencia a las teorías de transferencia radiativa, se obtienen los parámetros del plasma que caracterizan la región emisora de rayos X en Sco X-1. Para un plasma esférico e isotérmico la temperatura electrónica, la densidad de electrones y el radio son 3.6 keV, 3×10^{16} cm^{-3} y 4×10^{8} cm, respectivamente, mientras el plasma esté en fase ópticamente luminosa pero quieta. En erupciones ópticas la masa plasmática aumenta en unas decenas de por ciento, mientras la temperatura electrónica no cambia apreciablemente.