A spherical model for the transient X-ray source A0620–00

C. Dilworth  
*Istituto di Fisica del' Universita degli Studi via Celoria, 16 – 20133 Milano – Italy*

L. Maraschi and G. C. Perola  
*Istituto di Fisica del' Universita degli Studi and Laboratorio di Fisica Cosmica e Tecnologie Relative del CNR, via Celoria, 16 – 20133 Milano – Italy*

E. G. Tanti  
*Laboratorio di Fisica Cosmica e Tecnologie Relative del CNR via Celoria, 16 – 20133 Milano – Italy*

Received 1977 May 4; in original form 1977 March 23

**Summary.** The continuum spectrum of the transient X-ray source A0620–00, from infrared to X-ray frequencies, is interpreted as emission from a uniform spherical cloud of hot gas in which the free–free spectrum is modified by Thomson scattering. On this basis, the radius and the density of the cloud, and the distance of the source, are derived. The change of the spectrum with time indicates a decrease of both radius and density with decreasing luminosity. Considering the production of X-rays to be due to impulsive accretion in a low-mass binary system, these results open the question as to whether the accreting object is a white dwarf rather than a neutron star.

1 Introduction

The transient X-ray source A0620–00 has been extensively studied over a wide frequency range, from infrared to X-rays. Comparison of the infrared, optical and X-ray fluxes (Kleinman, Brecher & Ingham 1976; Citterio et al. 1976) indicated that the source was optically thick at infrared frequencies and therefore allowed an estimate of the physical parameters of the emitting region, assumed to be a uniform isothermal sphere, as a function of its distance. For a reasonable value of the distance, these authors found a high value of the optical depth to Thomson scattering $\tau_T \approx 60$. The standard theory of free–free emission is not strictly applicable in these conditions.

Since then further optical and ultraviolet observations have been published. In particular around the beginning of October ($\approx 1$ month after maximum) in addition to the X-ray flux, data are available which allow to construct a detailed spectrum from the infrared to the ultraviolet. The UV data give a reliable estimate of the extinction, $A_V = 1.2$ mag, and all measured fluxes are thereby corrected. Using these data a more detailed discussion of the source spectrum is possible taking into account the effects of Thomson scattering. The
spectrum is in remarkable agreement with what is expected for the assumed simple isothermal sphere model.

The parameters of the cloud, its density, radius and mass can be deduced from the form of the spectrum. The distance of the source can also be derived. The different decay rates in the X-ray and optical emission are naturally accounted for and some information on the decay rates of the physical parameters can be deduced.

2 The form of the spectrum

The modifications of a free–free spectrum due to Thomson scattering have been discussed by Illarionov & Sunyaev (1972, hereafter IS) and Felten & Rees (1972) for X-ray emitting homogeneous gas clouds.

The modified spectra can be described analytically in the two limiting cases $\gamma < 1$ or $\gamma > 1$ where $\gamma = \tau_T^2 kT_e/m_e c^2$. For $\gamma < 1$ and $\tau_T > 1$ the increased photon lifetime in the source introduces a region $\nu_1 < \nu < \nu_2$ where the spectrum is proportional to $\nu$. $\nu_1 = \nu_{sa} \tau_T^{-1/2}$, $\nu_2 = \nu_{sa} \tau_T^{1/2}$ and $\nu_{sa} = 0.13 g^{-1/2} N_e R^{1/2} T_e^{-3/4}$ is the free–free self-absorption frequency. For $\gamma > 1$ the energy gain of photons through cumulative Compton scattering becomes important. The $F(\nu) \propto \nu$ behaviour is found for $\nu_0 (kT_e/m_e c^2)^{-1/2} < \nu < \nu_0$

![Figure 1. Spectrum of A0620–00.](https://academic.oup.com/mnras/article-abstract/181/2/339/1746327)

where $\nu_0 = 6.1 \times 10^{15} N_e^{1/2} T_e^{-5/4} g^{1/2}$. At higher frequencies the spectrum is strongly modified and a Wien spectrum tends to be formed peaking at $h\nu = 3kT_e$. In the intermediate cases only numerical results are available. Fig. 1 shows the modified spectra at high frequencies taken from IS for $\gamma = 1, 0.6, 0.3, 0.1$ and normalized to the observed flux at 3 keV. The curves have been constructed for an electron temperature, $kT_e = 1$ keV, derived from the X-ray spectrum, assuming free–free emission.

From these curves it appears that consistency between the UV and X-ray fluxes requires $0.3 \leq \gamma \leq 0.6$. A consistent fit to a modified spectrum would tend to give a lower electron $^* g$ is the Gaunt factor.
temperature whereby all the curves would shift to the left, and the range of limits on \( y \) would be increased. For \( y \approx 1 \), however, this correction is small and can be neglected. It follows then that \( \tau_T = 6.7 \times 10^{-25}N_eR \) is contained between the limits

\[
[(0.3 m_e c^2)/(kT_e)]^{1/2} < \tau_T < [(0.6 m_e c^2)/(kT_e)]^{1/2}
\]
i.e.

\[12.4 \leq \tau_T \leq 17.5.\] (1)

The infrared, together with the optical and UV data, indicate a \( \nu \) rather than \( \nu^2 \) dependence of the emission between \( 10^{14} \) and \( 10^{15} \) Hz. Therefore the flux in this region can be written as

\[F_0 = 10^{-36} \nu_1 \nu T_e (R/D)^2\] (2)

with \( \nu_1 \leq 10^{14} \) Hz. The consistency of this assumption will be verified \textit{a posteriori}.

The X-ray flux can be expressed as

\[F_x = f(R/D)^{2.155} \times 10^7 T_e^{-1/2} (\tau_T^2/R) \exp \left[ -{(h\nu)/(kT_e)} \right]\]

(3)

where \( f \) is a factor taking into account the increased emissivity at high frequencies with respect to pure free–free emission.

3 The parameters of the cloud

Using measured values of \( F_0 \) and \( F_x \) one can determine from (2) and (3) \( R \) and \( D \). Taking \( F_0(5.46 \times 10^{14} \text{ Hz}) = 2.2 \times 10^{-24} \text{ erg}/(\text{cm}^2\text{s Hz}) \) and\( F_x(3 \text{ keV}) = 3.8 \times 10^{-25} \text{ erg}/(\text{cm}^2\text{s Hz}) \)

\[R = f(\tau_T^2/\nu_1) \times 6.46 \times 10^6 \text{ cm}\]

\[D = f(\tau_T^2/\sqrt{\nu_1}) \times 3.47 \times 10^8 \text{ cm}\]

where, as in the following, \( \nu_1 \) is expressed in units of \( 10^{14} \) Hz. From the curves of IS we estimate \( f \approx 5 \) for \( y = 0.3 \) \( (\tau_T = 12.4) \) and \( f = 10 \) for \( y = 0.6 \) \( (\tau_T = 17.5) \) and assuming \( \nu_1 = 1 \)

\[R = (5 \pm 20) \times 10^9 \text{ cm}\]

\[D = (2.7 \pm 10.7) \times 10^{21} \text{ cm}.\]

From these values, one has immediately the density of the cloud,

\[1.3 \times 10^{15} \leq N_e \leq 3.7 \times 10^{15}\]

its mass

\[3 \times 10^{21} \leq M_c \leq 6.6 \times 10^{22} \text{ g}\]

and luminosity

\[\phi 3.6 \times 10^{37} \leq L \leq \phi 3.9 \times 10^{38} \text{ erg/s}\]

where \( \phi \) is a factor taking into account the increased emissivity due to Compton scattering. For \( y = 0.3 \) \( \phi \approx 2 \), for \( y = 0.6 \) \( \phi \approx 2.5 \). We can now check that the critical frequencies agree with observations.

Since we are in an intermediate case, \( \nu \approx 1 \), we expect \( \nu_0 \approx \nu_2 \). In the ultraviolet data a break appears at \( \nu \approx 1.2 \times 10^{15} \) Hz. Using the formulae of IS and the parameters derived above

\[\nu_2 = 8.2 \times 10^{14}(\tau_T \nu_1/f)^{1/2} = (1.3 \pm 0.07) \times 10^{15} \text{ Hz}\]

\[\nu_0 = 8.7 \times 10^{15}(\nu_1/(f \tau_T))^{1/2} = (1.1 \pm 0.07) \times 10^{15} \text{ Hz}\]
It appears that the lower value of $\tau_T$ is preferred since it makes $\nu_0 \approx \nu_2$ and for this value $\nu_1$ is indeed $10^{14}$ Hz. The corresponding luminosity is of the order of the Eddington luminosity.

4 The decay of the cloud

The decay of A0620 in different spectral regions, which depend on different combinations of the physical parameters $N_e, R, T$ permits a discussion of the evolution of the cloud.

The optical and X-ray light curves are shown in Figs 2 and 3. The two fluxes show a rather regular decay which is more rapid in the X-ray band. Moreover, the two secondary X-ray maxima coincide in time with two secondary optical maxima of smaller amplitude. The optical variations are expected to be smaller in this model, since the dependence on the physical parameters is much weaker in the optical than in the X-ray region of the spectrum. In fact at the epoch of Fig. 1 (JD 2442684 – 692)

$$F_x \propto f N_e^2 R^3 T^{-1/2} \exp (-h/k T_e)$$

$$F_0 \propto N_e^{1/2} R^2 T_e.$$  

The e-folding times for the X-ray and optical intensities between JD 2442690 and 2442760 are $\tau_x = 22^d$ and $\tau_0 = 65^d$ respectively. In the absence of an analytical expression for $f$ as a function of $N_e$ and $R$, it is not possible to give firm values of the e-folding times of $N_e$ and $R$. However, noting that $f$ decreases by a factor 2, for a 40 per cent decrease in $N_e R$, for the range of values of $\tau_T$ at this epoch, and that $R$ varies as the fifth root of $f$ (neglecting temperature variations, which are known to be small at this epoch), one can state that the radius is slowly decreasing in time, as suggested by Citterio et al. (1975) on the basis of the time variations in the infrared. In fact if the cloud evolved at constant radius one would

![X-ray light curve](https://academic.oup.com/mnras/article-abstract/181/2/339/1746327)

**Figure 2.** X-ray light curve as derived from Kaluzienski et al. 1977. Experimental data are schematized either by dashed areas or by some representative points.
expect $\tau_0 > 4 \tau_\chi$ in conflict with the observed ratio $\tau_0 = 3 \tau_\chi$. Assuming $f \propto (N_e R)^\alpha$, with $\alpha < 2$, which is a reasonable approximation in the range considered here, $N_e$ turns out to be decreasing with time also. A rough estimate of the decay-rate of the mass of the cloud can be derived from the expression

$$M_e \propto F_0^{1/5} F_x^{1/5} T^{-11/10} \exp (h\nu/5kT) f^{-1/5}.$$  

The dependence on $f$ is slow. Estimating the correction through the assumption $f \propto (N_e R)^2$, one obtains an $e$-folding time $\tau_{M_e} \approx 49^d$, i.e. about twice that of $F_x$.

The final decline of the source fits into the same general scheme. Between JD 2442840 and 2442860 the X-ray decay is faster than the optical one. After JD 2442860 the X-ray intensity is below the detectability limit and the optical decay becomes extremely rapid. This can be understood if at this epoch the optical depth to Thomson scattering has become negligible and the cloud is transparent at optical frequencies.

5 Discussion and conclusion

The simple isothermal spherical model explains with remarkable consistency the continuum emission of A0620 – 00, over the whole spectrum, from the infrared to the X-ray regions, and can account for its temporal evolution. Although a colder region is required by the presence of optical lines, a composite model like the one discussed by Oke & Greenstein (1977) encounters more difficulties in explaining the high infrared flux, than the simple picture proposed here. This gives some confidence in the validity of the spherical approximation and the value of the parameters derived for the main emitting region.

One then faces the problem of the mechanism of the formation and maintenance of an X-ray emitting cloud of radius $R \approx 10^9$ cm and density $N_e \approx 10^{15}$. Thinking in terms of a standard model of accretion in a binary system on to the compact member, we note that the
optical magnitude of A0620−00 before the outburst together with the distance estimate as derived in this paper or from the reddening and the interstellar line measurements (Gull et al. 1976; Wu et al. 1976) suggests a low-mass close binary system, containing a late-type dwarf (Ward et al. 1975; Endal, Devinney & Sofia 1976). The envelope of this non-degenerate member has been shown by Bath (1975) to be unstable on a dynamical timescale, a property that could explain the 'transient' nature of the emission. A binary system of this kind has been proposed also for Sco X-1, a source with which A0620−00 has several spectral features in common, as noted since its discovery by Boley et al. (1976). In the case of our source, however, the observed period of ∼8 d (Mattilsky et al. 1976), as opposed to the 0.78 for Sco X-1 (Cowley & Crampton 1975) is too large to be interpreted as the orbital period of the close binary system, and should be thought of as a second periodicity like that exhibited by other X-ray binary sources, like Her X-1 (35 d) or Cyg X-3 (17 d), as suggested in Tanzi & Treves (1977). A search for a shorter periodicity (∼1 d) could give a definitive answer to this problem.

The question then arises as to the nature of the degenerate member of the system. The size of the cloud (R ∼10³ cm) poses a problem if the accreting object is a neutron star, as in standard models of X-ray sources, since most of the emission is expected to come from near the surface of the star (Rₙ ∼10⁶ cm). It has been suggested that the dynamics of the flow can be strongly altered away from the star surface if the object is magnetized. Magnetic stresses are likely to dominate the flow at r ≤ rₐ (the Alfvén radius),

$$rₐ = 2.9 \times 10^8 L_{37}^{2/7} \mu_{30}^{-1/7} (M/Mₖ)_{1/7} Rₙ^{2/7} \text{cm}$$

($L_{37}$ is the total luminosity in units of 10³⁷ erg/s, $µ_{30}$ is the magnetic moment in units of 10³⁰ G cm³). The physics of the magnetospheric boundary and the way the accreting plasma interacts with the magnetosphere have been studied by Arons & Lea (1976), Basko & Sunyaev (1976) and Elsner & Lamb (1976). Their results indicate that density enhancements should occur at rₐ, but with optical thicknesses much smaller than the $r = 15$ of this cloud, unless one can envisage a 'confinement' mechanism leading to a residence time $t = Mₙ/Ṁ$ of the order of 1000 times the free-fall time. Moreover, a value of rₐ of the order of 10³ cm would require a magnetic moment, $µ_{30} = 100$, a value much higher than is usually assumed for a neutron star.

Radiation pressure, reducing the infall velocity, will tend to increase both the density and scale-height of the cloud, but one would expect this effect to be reduced drastically as the luminosity falls below the Eddington limit. The fact that the optical emission falls much more slowly than that of the X-rays, implies that the radiation pressure should continue to sustain the cloud in spite of a large drop in luminosity. This may be possible if one takes into account the increased pressure through the photoelectric effect (Hatchett, Buff & McCray 1976) at the lower luminosities, and assumes that the source is super-critical at maximum light.

An alternative possibility is that the accreting object is a white dwarf endowed with a magnetic field with a not exceptional strength of 10⁶ G. The radius of the cloud is then of the order of magnitude of the Alfvén radius, the time $t = Mₙ/Ṁ$ of the order of the free-fall time, and the density consistent with that of the accreting matter. Fabian, Pringle & Rees (1976) have shown that the production of hard X-rays by accretion on a white dwarf can occur at a shock in the magnetic funnel. They conclude, however, that in general, for high luminosities, a high-energy cut-off will occur in the spectrum due to photoelectric absorption in the cold inflowing matter. The emission of high-luminosity X-rays in the keV region would require a particular geometry of the system where the hard (∼20 keV) X-rays are degraded by Thomson scattering by a factor of 10 and the low-energy cut-off is less than 1 keV over an appreciable fraction of 4 π.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System
If our interpretation of the spectrum is correct the observations imply that the size of the emitting region decreases with time and that the decay rate of the mass of the cloud $M_c$, as derived in Section 4, is smaller than the accretion rate, which is proportional to $L_X$. This implies that $M_c$ is not proportional to $M$, but the effective ‘residence’ time in the cloud, $t_r = M_c/M$, increases while the accretion rate decreases. While a decrease of $R$ with decreasing $M$ is not predicted by available models to the accretion flow at the magnetospheric boundary, the increase of $t_r$ with decreasing $M$ can find a natural explanation if $t_r$ is representative of the efficiency of the instabilities that cause penetration of the gas through the magnetosphere. In fact these instabilities are expected to be more effective when the density is higher (Baan 1977).

A further test for the neutron star or white dwarf hypothesis may be found in the nature of the high-energy emission (Coe, Engel & Quenby 1976) from 20 to 200 keV. Although the energy content in this spectral region is only $\sim 10^{-2}$ of the total luminosity, its existence, if of thermal origin would favour the underlying object being a neutron star. It would not, however, be difficult to explain on either model as a non-thermal component.

In conclusion, the spectral information leaves open the question as to whether the accreting object in this low mass binary system is a neutron star or a white dwarf. More detailed models of this particular source are needed.

Acknowledgment

We thank Dr J. Pringle for his critical contribution to the discussion.

References