Be STAR DISK STRUCTURE AS IMPLIED BY X-RAY OBSERVATIONS

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1. Modelling the Circumstellar Envelope of the Be/X-ray Binary 4U1907+09

1.1. Objectives of the Study

Compared to several other Be/X-ray binaries, 4U1907+09 has been observed more frequently due to the fact that it is found in an 'on' state more often. It also has a short orbital period of $\sim$ 8 days as compared to the long orbital periods commonly found in these binaries. But despite the attention it has received, the exact nature of the primary remains elusive. While some observers maintain it to be a Be/X-ray binary, others prefer to put it into the class of OB supergiants.

During January 1980, the X-ray intensity of 4U1907+09 flared up to 20 times its normal value over a period of $\sim$ 10 days as observed with the SSI on Ariel V. The subsequent decline was also continuously monitored by the SSI for a further 20 days. We have attempted to model this light curve of the outburst and to make an estimate of the number density and the velocity of the gas in the circumstellar envelope (CE) of the Be star.

1.2. The Rotationally Enhanced Stellar Wind Model as applied to 4U1907+09

The currently understood picture of Be/X-ray binaries is one in which the compact object is in an eccentric orbit around the Be star. The orbital plane of the binary may be inclined to the equatorial plane of the primary star. The high X-ray luminosities observed from these sources suggest that the X-ray source is fueled by a dense, slowly moving and probably equatorially condensed envelope. The Be/X-ray binary 4U1907+09 provides a unique opportunity to test the predictions of this model due to its short orbital period of $\sim$ 8.4 days. The variations in the X-ray flux give information on the densities and velocities in the outer regions of the extended envelope of the Be primary traced by the orbital motion of the neutron star. The neutron star acts as a probe of the outer wind regions of the Be star. Using

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this model we demonstrate semi–quantitatively that the observed shape of the X-ray flare from 4U1907+09 during the January 1980 outburst can be reproduced fairly satisfactorily.

In order to obtain the X-ray emission at a given time, the rate of accretion of matter onto the neutron star during its passage through the ring has to be calculated. This is given by

$$\dot{M}(r) = A v_{rel}^{-3}(r)\rho(r) \tag{1}$$

To find ρ and v_{rel} at any given time, the neutron star has to be located with respect to the Be star and the ring/disk. A numerical code was written for this purpose. The Be primary was assumed to have emitted a circular gas ring in the equatorial plane with an initial density ρ_{oi}. The eccentric neutron star orbit was determined using the parameters given for 4U1907+09. It lies in the equatorial plane of the Be star. In order to obtain v_{rel} at any point, we assume that the matter in the ring at any point has a Keplerian velocity, v_g, and a constant outflow velocity, v_o. The neutron star velocity, v_n, is also calculated at that point from the orbital parameters and the coordinates at that point. Then,

$$v_{rel} = [(v_g - v_{nt})^2 + (v_o - v_{nr})^2]^{\frac{1}{2}} \tag{2}$$

where v_{nt} and v_{nr} are the tangential and radial components of the neutron star orbital velocity. For the density of the matter in the ring, we find that a constant value throughout the ring does not yield the observed light curves, and a density distribution described mathematically by the form

$$\begin{aligned} \rho(r,t) &= \rho_o(t)\left[\frac{r_o}{r}\right]^{\alpha} \quad \text{for r} \geq r_o \\ &= \rho_o(t)\left[\frac{r_o}{(2r_o - r)}\right]^{\alpha} \text{for r} \leq r_o \end{aligned} \tag{3}$$

has to be prescribed. Here r is the radial distance of the matter in the ring from the center of the star, r_o is the radial distance of the center of the ring from the Be star where the density is ρ_o(t) at that instant of time. We calculated the intensity of the X-ray emission from the neutron star at different positions of its orbit by obtaining v_{rel}(t) and ρ(t) at that position and time. The X-ray emission from the neutron star is attenuated by the matter in the portion of the ring between the observer and the neutron star. We found that to match the observed light curve, we have to postulate the existence of multiple rings ejected by the Be star. These rings have different values of density and propagate outwards at slightly different constant outflow velocities. The shape of the X-ray light curve strongly depends on the outflow velocity of the gas ejected by the Be star. The outflow velocities in the case of 4U1907+09 lie in the range 100–250 km s^{-1} while the densities

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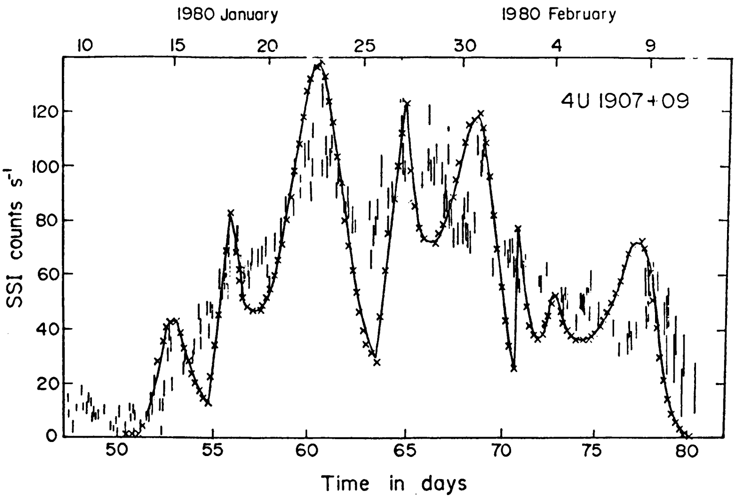

Fig. 1. Modelled light curve of 4U1907+09 with the Ariel V outburst superposed on it as determined on the basis of the disk model

in the rings vary between 10^9 to 10^{11} atoms cm^{-3}. The Ariel V light curve together with the modelled light curve superposed on it is shown in figure 1.

At certain phases in the light curve we see dips which are not present in the observed light curve. We postulate that the filling in of these dips in the observed light curve is due to the temporary formation of an accretion disk around the neutron star. This disk acts as a reservoir of material and results in a smoothening of the light curve at these points.

1.3. Conclusions from the Present Study

We can draw a few general conclusions from the above study. We find that if the source 4U1907+09 is a Be/X-ray binary (for a justification of this claim, see Saraswat, 1992) then the disk model is successful in explaining the X-ray light curve of this source to a reasonable degree of accuracy. We also see that the disk around the Be star is not a continuous one with a uniform density, but that the star ejects multiple rings, with different initial density values and gradients. Hence the circumstellar envelope is not a homogeneous medium but is segmented into rings, related to 'puffs' ejected from the Be star. The densities in these rings are $\sim 10^9$ to 10^{11} atoms cm^{-3}. Secondly, in addition to a Keplerian motion around the primary star, these rings also have a constant outflow velocity. However different rings have different outflow velocities. The shape of the X-ray light curve strongly depends on the outflow velocity of the gas ejected by the Be star. These velocities lie in the range 100–250 km s^{-1}.

Saraswat, P., 1992, Ph.D. thesis and references therein.