Optical studies of massive X-ray binaries
Zuiderwijk, E.J.

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INTRODUCTION AND SUMMARY

One of the most important recent developments in astrophysics was the discovery of several neutron stars in close binary systems. The existence of neutron stars had been predicted theoretically by Landau in 1933 and was confirmed by the discovery of the radio pulsars in 1967. These objects, however, - with the sole exception of the recently discovered binary radio pulsar PSR1913+16 (Taylor et al., 1976) - are always single rapidly rotating neutron stars and therefore no information about their masses - an important parameter in theoretical neutron star models - can be obtained directly.

X-ray observations with UHURU, the first satellite entirely designed for the detection of X-rays from celestial objects, have revealed since its launch in December 1970 several hundreds of X-ray sources; the final "4U"-catalog lists 339 sources (Forman et al., 1978). More than ten of them turned out to be members of close binary systems.

The binary character is - in most cases - firmly established from the regular occurrence of X-ray eclipses. Moreover, in various binary systems the X-ray source is a short period X-ray pulsar and the orbital motion is reflected by small Doppler changes in the observed pulse period. The short time variability (down to milliseconds) as well as the hardness of the X-ray spectrum indicate that the emitting region is very small and hot, and that the X-ray sources are very compact objects, such as neutron stars. The accurately known orbital periods (derived from the X-ray eclipse timing) made it possible to identify the optical companions of about a dozen of these sources. These stars usually show variations in brightness or radial velocity - or both - with the same periodicity as the X-ray source.

The optical counterparts in massive X-ray binaries are in most cases massive luminous early-type supergiants. The currently accepted model of such massive X-ray binary systems consists of an optically invisible neutron star orbiting the visible supergiant. The X-ray source is powered by mass transfer from the normal primary star to the neutron star either by means of a stellar wind or by Roche-lobe overflow (Davidson and Ostriker, 1973; van den Heuvel, 1975). The extremely compact neutron star constitutes a very deep gravitational potential well and the infalling material gains on its way down an amount of kinetic energy equivalent to some ten percent of its restmass energy. The very strong magnetic field of the neutron star
(10^{12} \text{ Gauss}) channels the inflow of the matter towards the magnetic poles. There the kinetic energy is converted into heat which leads to the formation of two hot X-ray emitting regions with an area of about one square kilometer each. The pulsed character of the observed X-ray flux is explained by the rotation of the neutron star: the non-alignment of the magnetic and rotational axes causes for an outside observer a periodically varying aspect of the "hot spots" near the magnetic poles, resulting in the pulsed modulation of the observed flux (Davidson and Ostriker, 1973; Lamb, 1977).

X-ray binaries are of great importance for astrophysics, because they constitute - so far - the only possibility to measure the masses of neutron stars. Current theoretical models predict the existence of a limiting mass for these compact objects, above which no stable configuration can exist; a neutron star more massive than this upper limit is expected to continue its collapse, presumably to become a black hole. Depending on the particular choice of the equation of state in various models the derived values of the limiting mass range from 1.4 M_⊙ up to 2.7 M_⊙ (Canuto, 1977). In order to distinguish between the various equations of state, the real limiting value has to be estimated from observations. Mass determinations of neutron stars can in principle provide us with a firmly established lower boundary value for the limiting mass.

In a binary system the masses of the components are determined by establishing the actual dimensions of both orbits around the common centre of gravity. This is performed by estimating the inclination of the orbital plane and by measuring the varying radial velocity (due to orbital motion) of each star individually throughout the binary period. For the neutron star in an X-ray binary this radial-velocity orbit is determined from delay measurements of the X-ray pulse-arrival times; the radial velocity orbit of the normal primary can be estimated in the classical way from the Doppler shifts of absorption lines in its spectrum. Knowledge of the inclination angle is required to correct the radial velocity measurements for the fact that these refer only to the motion with respect to the observer. In most cases the photometric variations of the primary, where possible in combination with the X-ray eclipse durations, are used to determine - or to set constraints on - the value of the inclination. These photometric variations result from the rotational and tidal distortions of the primary by the neutron star. Because in most X-ray binaries the contribution from the neutron star to the total optical luminosity is negligible, these systems also offer an unique opportunity to study the effects of these dis-
tortions on the photometric and spectroscopic characteristics of a binary component.

In this thesis photometric and spectroscopic studies of several optical counterparts of massive X-ray binaries are presented.

Subjects of study were the binary systems: HD77581/4U0900-40 (Vela X-1), HD153919/4U1700-37, Wray 977/4U1223-62 and Skl60/4U0115-74 (= SMC X-1).

The observational material was collected during many observing runs by several observers from the Astronomical Institute of the University of Amsterdam and from the Astrophysical Institute of the Vrije Universiteit at Brussels. Six observing runs at the European Southern Observatory in Chile were carried out by the author.

Strömgren (uvby) four-colour photometric observations of HD77581, HD153919 and Wray 977 were performed at the European Southern Observatory, using the ESO 50 cm telescope and the Danish 50 cm telescope with four channel photometer of the University of Copenhagen.

Walraven (VBLUW) five colour observations of Skl60 and HD153919 were collected with the 90 cm telescope and five channel photometer at the former Leiden Southern Observatory in South-Africa.

Spectrograms of HD77581 and Wray 977 were recorded with the Coudé and Echelle spectrographs of the 1.52 m spectroscopic telescope of the European Southern Observatory. Density tracings of these spectra were obtained with the Faul Coradi Microphotometer of the Astronomical Institute at Utrecht. The positions of absorption lines in the Coudé spectra were measured with the Grant comparator of the Kapteyn Astronomical Laboratory of the University of Groningen.

In the first chapter the photometric variations of HD77581, HD153919, Wray 977 and Skl60 are discussed. A computer program is described that has been developed to calculate theoretical light curves of X-ray binaries. These calculations are based on the Roche model for a tidally and rotationally distorted star; this model is extensively discussed. A set of model atmospheres given by Kurucz, Peytremann and Avrett (1974) was used to estimate the contribution of each visible surface element of the primary to the total luminosity (in a specified photometric passband). The light curves computed with this program agree well with results from similar programs discussed by Wickramasinghe and Whelan (1975)....
The B0.5Ib supergiant HD77581 was observed during 46 nights in 1975. The (uvby) ellipsoidal brightness variations have an amplitude of about 0.1 magnitude. We compared this light curve with theoretically computed curves; it turned out to be possible to set constraints on the inclination of the orbital plane, which is in the range 70°-90°. This result is in agreement with the constraint i > 74° derived by Avni and Bahcall (1975) from X-ray observations. We also found that the primary is on the edge of filling its critical equipotential surface.

The observed periodic variation of the cl colour index is also consistent with the model calculations. Deviations of individual observations (from the same night) from the mean light curve are often correlated. This may be due to some type of forced pulsation of HD77581, which is subject to the time dependent gravitational attraction of the secondary as a result of the orbital eccentricity.

The ellipsoidal brightness variations (uvby and VBLUW), of the 06.5f star HD153919 have an amplitude of about 0.04 magnitude. A comparison of the light curve with X-ray observations revealed a phase shift of about 0.06 between the moment of mid X-ray eclipse and the secondary minimum. This shift is interpreted as due to the very dense wind of this star, which is losing more than 10^{-6} M_\odot/yr (Hensberge, 1974); in fact the first part of the eclipse is due to absorptions of X-rays in the asymmetrically outflowing atmosphere. It appears to be impossible to reproduce the mean observed light curve by theoretical model calculations. A possible explanation of this result may be found in the very high temperature (35000K - 40000K) in the atmosphere of HD153919. Due to this, Thomson scattering contributes considerably to the total continuum opacity which makes the use of van Zeipel's law of gravity darkening in the Roche model less accurate. Therefore the light curve of the primary cannot be used to set any constraint on the mass of the X-ray source 4U1700-37.

The B1IIa supergiant Wray 977 has been the optical candidate star for the X-ray source 4U1223-62 for a long time, but only recently this identification has been confirmed by high precision X-ray observations with SAS-3 (Bradt et al., 1977). Our uvby observations suggest an ellipsoidal light curve with a period of about 23 days. This result has been confirmed recently by Pakull (1978).

The final paper of this chapter deals with VBLUW observations of the B0Ia supergiant Sk160. An accurate theoretical light curve could be computed because both the masses of the two components in this X-ray binary and
the inclination of the orbital plane were known from X-ray- and spectroscopic observations (Primini et al., 1977; Hutchings et al., 1977). The observed light curve strongly deviates from the theoretical one; especially the amplitude of the brightness variations is much larger than expected. However, it turned out to be possible to explain the light curve of Sk160 by assuming the existence of a gaseous disk around the neutron star, which contributes some five percent to the total luminosity of the binary system. The existence of such a disk is a strong indication that the mass transfer from the primary to the neutron star is due to the Roche lobe overflow of Sk160.

An extended radial velocity study of HD77581 is presented in the second chapter. The orbit of the X-ray pulsar, Vela X-1 (P = 283$^s$) was determined with great precision from pulse time delay measurements by Rappaport, Joss and McClintock (1975). Therefore, the accuracy of the mass determination for this neutron star depends critically on the precision of the estimated radial velocity orbit of HD77581. In order to eliminate non-orbital contributions to the radial velocity variations we investigated the effects of the deformation of the primary on the observed profiles of absorption lines. The light curve synthesis computer program was extended to enable the calculation of absorption line profiles; the contribution to the line profile from each surface element of the primary (dependent on the local temperature and gravity) was calculated by using the KPA model atmospheres. It turned out that large discrepancies can exist between the true orbital velocity of the center of gravity of the star and the "velocity" derived from the measured position of an absorption line in the spectrum.

Lines of various ions (HeI, OII, SiIV), however, have a completely different behaviour, which makes it in principle possible to recognize this type of distortions in the radial velocity orbit. The result of this study was the determination of the mass of Vela X-1 which is $1.74 \pm 0.13 \, M_\odot$; the mass of the supergiant HD77581 was estimated to be $21.3 \pm 1.1 \, M_\odot$, (the errors are 1 $\sigma$ limits).

The first results of spectroscopic studies of Wray 977 and HD77581 are presented in the last chapter. The software for the reduction of the digitized density registrations of the spectra was written and developed by the author. With these programs it is possible (among other things) to compute averaged spectra from several individual density tracings, which results in a much better signal to noise ratio compared with those of the individual tracings.
Averaged spectra of Wray 977 were used to determine the precise spectral classification of the star (B1Ia) and to study the time variations of H$_B$ and H$_γ$. The diffuse interstellar absorption lines are very strong in the spectrum, consistent with the reddening.

A similar study of the spectrum of HD77581 reveals interesting variations of H$_B$ and HeII $\lambda$ 4686 Å.

References