Optical Observations of X-ray Binaries

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As part of my PhD study, and in the framework of a student-fellowship at La Silla as outlined by Prof. H. van der Laan in the March issue of the *Messenger*, I have been working on a research programme on accretion-driven stellar X-ray sources. Another part of my work at this moment is a long-term investigation of pulsation light curves in intermediate polars (a subtype of the cataclysmic variables), which will be concluded during this year. This research is done under the guidance of my thesis research advisor Prof. Jan van Paradijs of the University of Amsterdam, and Dr. Hugo Schwarz at La Silla. A brief outline of the background, and a short description of the research programme on accretion driven stellar X-ray sources is given below. To finish, some observational results on a particular object are presented.

Introduction

Luminous stellar X-ray sources are interacting binaries that contain an accreting neutron star or a black hole. Over one hundred X-ray binaries have been found since Sco X-1 was discovered nearly 27 years ago [1]. With the launch of the UHURU X-ray satellite in 1970, the binary nature of these objects was established through the detection of X-ray pulsations from Cen X-3 which showed regular Doppler variations of the pulsation period induced by the orbital motion [2] and the discovery of eclipses of the X-ray source. The subsequent launch of a great number of X-ray observatories in the 70's and 80's, of which GINGA and the MIR station are the only ones presently operating, greatly enlarged our knowledge of these objects.

Optical observations including identification, orbital light curves, and measurement of the orbital velocities of the optical counterpart of these sources also contributed considerably to our understanding of the basic properties of these systems.

X-ray Binaries

In X-ray binaries (see for reviews e.g. [3] and [4]), a neutron star or black hole accretes matter from a companion star. The X-rays are produced by the conversion of the gravitational energy of the infalling matter into radiation. This process generates energy ten times more efficient than nuclear fusion.

The X-ray binaries can roughly be divided into two groups on the basis of the spectral type of the mass donor (see e.g. [4]); massive X-ray binaries (MXRB) with O or B type companions and low mass X-ray binaries (LMXB) with a late type, or sometimes white dwarf, companion. The known orbital periods for these sources are in the range 1.4 to 41 days for MXRB and from 11 minutes up to 9 days for the LMXB.

The MXRB can be easily studied in the optical because the optical companions are intrinsically bright. Their structure and evolution is therefore relatively well understood. By contrast, much less is known about the optical properties of the more numerous (~100) detected LMXB. The companion stars in LMXB are intrinsically faint and most of the optical light emitted by a LMXB comes from an X-ray heated accretion disk. This, together with a mean distance of ~10 kpc, causes most of them to be fainter than 18th magnitude. Combined with the, in some cases, extremely short periods, this makes especially time-resolved observations difficult, and requires at least 4-m class telescopes.

LMXB

Better detectors on optical telescopes have made spectroscopic observations of the faint LMXB much more practical in recent years. Consequently, one of the three parts of my research programme is a spectroscopic study of these sources.

The optical spectra of LMXB generally show a few emission lines (mainly Hβ, HeII 4686, and the Bowen 4640 lines) superposed on a blue continuum. The latter lines indicate reprocessing of X-rays [5]; their relative strengths may be an indicator of the metallicity of the source [6].

The aim of my project is to study orbital variations of the wavelength and strength of the emission lines which could give us an insight into the line forming region and the mass of the companion star.

Black Holes

A very interesting aspect of X-ray binaries is that some of them may contain black holes as the accreting X-ray source.

The main problem for black hole candidates is that it is sometimes difficult to prove that the compact object is not a neutron star. For instance, the detection of coherent pulsations (the signature of a rotating magnetized neutron star), or bursts (see below) from a system are clear indications of the presence of a neutron star. The crucial evidence for the presence of a black hole (beyond the lack of these X-ray time signatures) is a measurement of the mass of the compact object which should be in excess of ~3 $M_\odot$, the upper theoretical limit to the mass of a neutron star [7].

Currently there are three strong candidates, LMC X-3 [8], Cyg X-1 [9], and A0620-00 [10], and one possible, LMC X-1 [11].

The mass of the compact object in these sources is derived, by optical spectroscopy, from the radial velocity curves of the absorption lines of the companion. From the radial velocity amplitude one can determine the mass function;

$$f(M) = \frac{M_x^3 \sin^3 i}{(M_{opt} + M_x)^2}$$

where M_x, M_{opt} are the mass of the compact object and the optical companion respectively, and i the inclination of the system with respect to the plane of the sky, By inserting $M_{opt} = 0$ and $i = 90$ (i.e. the system is seen edge-on), one gets a lower limit for M_x.

For the black hole candidate LMC X-3, Kuiper et al. [12] have, on the basis of the value of the mass function and modelling of the optical lightcurve, derived a mass of the compact object in the range (4.5–6.5) (d/50 kpc) $M_\odot$ with d the distance to the source. Taking a 2σ lower limit for f(M), a source distance of 40 kpc, and assuming a flat (instead of spherical) X-ray emitting region situated in the orbital plane, the authors find a lower limit to M_x of 2.8 $M_\odot$.

It is clear that a good determination of the radial velocity amplitude is essential for the conclusion that LMC X-3 contains a black hole (or not).

A major problem with the determination of the radial velocity curve is the possible contamination of the stellar absorption lines. This can be due, for example, to the deviation of the companion from spherical symmetry as a result of the tidal forces exerted by the massive compact object, or to some extra emission or absorption by either the disk or the X-ray heated side of the companion. These effects could distort the symmetry of the absorption lines and produce spuriously large values of the radial velocity amplitude. As the

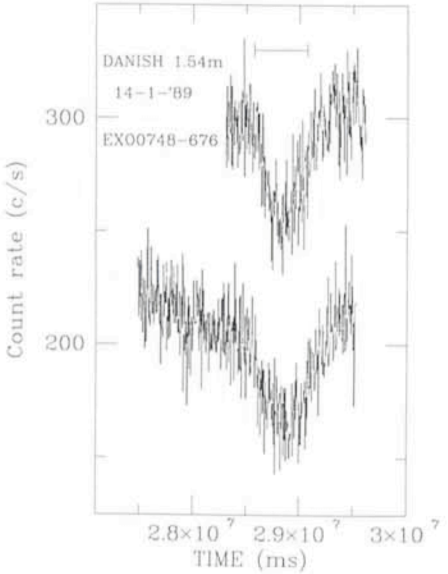

Figure 1: *The light curves of two consecutive eclipses observed on January 14, 1989. Each point is the average of four one-second integrations. The time-axis gives the time in milliseconds after UT = 0 h. The count rate is in counts per second. The upper curve is shifted upward by 70 c/s. The lower curve is shifted forward in time by 13,766,786 ms, or one orbital period.*

spectra used by [8] to determine f(M) had a resolution of ~150 km/s, the possibility of the effects described above, playing a role, cannot be excluded.

Part of my research programme is to determine, from high resolution, high signal-to-noise spectra of the optical counterpart of LMC X-3, an improved radial velocity curve. This will then be used to constrain the mass function and hopefully settle the question whether LMC X-3 contains a black hole or not.

Bursting, Dipping, and Transient Sources

LMXB show a variety of time variable characteristics.

A subgroup of the LMXB are the transient sources. Most of the time these transient sources are not detectable in either X-rays or optical emission – they turn on with typical rise times of a few days and then drop back below the level of detectability.

This phenomenon is the result of accretion instabilities which may be similar to dwarf-novae outbursts seen in some cataclysmic variables (interacting binaries containing a white dwarf and a low mass companion).

Another characteristic of a number of LMXB is the presence of X-ray (and optical) bursts. These bursts arise from a thermonuclear flash of the accumulated accreted matter on the surface of a neutron star.

A third phenomenon, observed in some LMXB, is the existence of intensity dips occurring at regular intervals. Generally, this is explained as periodic obscuration of the X-ray source caused by a turbulent thickening of the disk at the point where the gas stream from the companion hits the accretion disk surrounding the compact object (see [13] for a very clear depiction of such a system).

EXO 0748-676, the Source That Has It All!

The X-ray source EXO 0748-676 is a transient source that has remained detectable since its discovery in 1985 [14]. This source is unique in that it shows dips and bursts, and in addition it is one of the only two known LMXB to exhibit eclipses of the X-ray source, and of course also parts of the disk, by the secondary. The eclipses of the X-ray source make it possible to determine unambiguously the orbital period and phase, and to put constraints on the orbital inclination, as well as size and mass of the companion.

The third part of my research programme is to make detailed photometric observations, with a high time resolution, of the optical eclipse light curve of UY Vol, the optical counterpart of EXO 0748-676.

The aim of this project is to investigate the radial distribution of optical continuum and line emission, and the radius of the disk by studying the shape of the eclipse light curve. A comparison with cataclysmic variables, for which similar observations have been made, in which the accretion disk predominantly radiates by internal conversion of gravitational energy, can give some insight into the role of X-ray heating of the accretion disks in LMXB.

Observations

During 5 nights in January, observations with a time resolution of 1 sec were made of EXO 0748-676 using a two-channel photometer attached to the Danish 1.54-m telescope. One channel measured the source whilst the other constantly monitored the sky. Flux standards were measured with both channels to calibrate the system.

Due to some instrumental problems during the first night, little data were collected. The following nights gave much better results, though a part of the last night was affected by cirrus clouds.

Two examples of eclipse light curves, both observed on the third night, are shown in Figure 1. The data are background corrected. Each point is the average of four one-second integrations. The lower curve is shifted forwards in time by one orbital period [15], the upper curve is shifted upwards by 70 c/s.

The horizontal line near the top of the Figure indicates the predicted time interval of the X-ray eclipse of the neutron star [15]. The uncertainty in this value is only +/− 2 sec. The optical eclipse, including the partial eclipse of the disk, takes about three times longer [16].

The coincidence between the predicted times of the X-ray eclipse and the observed eclipse-like feature in the optical light curves suggests the presence of a region of enhanced optical emission closely associated with the X-ray emitting region.

Figure 1 further shows that the shape of the eclipse is highly variable, and can change from one orbital period to the next. Also, short time variability of the source is seen in all parts of the light curves.

An unexpected result of the observations was the detection of six optical bursts. Of the six bursts, five were observed in the second night and one in the beginning of the third night.

One of the bursts is shown in Figure 2. An interesting aspect of this burst is the possible detection of a second burst, at around $1.82 \cdot 10^7$ ms in Figure 2, which occurs only ~8 minutes after the first burst. Of course it is clear that a full and careful statistical analysis of the data is needed to determine if this feature is really significant.

However, the light curve shown in Figure 2 is remarkably similar to the one optical "double" burst detected in another burster, MXB 1636-53 (see [17]), in which the bursts are separated by ~6 minutes. The separation of ~8 minutes would also be comparable to that of the four double bursts detected during X-ray observations of EXO 0748-676 [18], which had separations of between 10 and 20 minutes.

In their paper, Gottwald et al. [18] show that as the persistent X-ray flux of the source decreases, the number of bursts increases. They also noted that double bursts are only observed when the persistent X-ray flux is low.

Extending this picture by taking into account that the main source of light in a LMXB is the X-ray reprocessing disk, this would mean that as the source showed many bursts (and possibly including a double burst), the X-ray source was in a low state, and consequently the optical counterpart should be faint.

Indeed, during the two nights that bursts were observed, the count rates of the optical counterpart ranged from ~200 to ~400 c/s, whilst during the

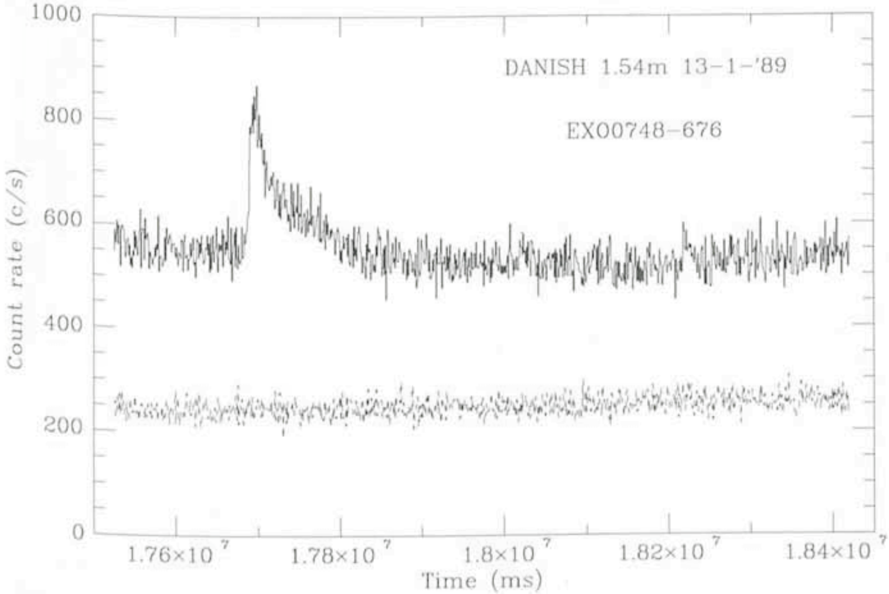

Figure 2: *The light curve of a burst from UY Vol, observed on January 13, 1989. The axes have the same definition as in Figure 1. Each point is a one-second integration. The sky counts are corrected for the difference in sensitivity of the two detectors.*

two following nights the count rates had risen to between ~400 and ~600 c/s. In this respect it is interesting to note that the shape of the "first" burst in Figure 2 is very simular to the "slow" X-ray burst profile seen in the low X-ray state.

Also, the source intensity during the second part of the third night was higher than during the first part. This can be seen by comparing the lower curve of Figure 1, which was observed during the first part of that night, and the upper curve, observed in the second part of that night, which is higher by more than the upward shift of +70 c/s. This would then also indicate an increase in the persistent X-ray flux and naturally explains the detection of only one burst at the beginning of that night and the lack of any further detection for the rest of the night.

In Figure 1 it can be seen that also during the X-ray eclipse the optical intensity of the source is significantly increased in the second part (upper curve in the Figure) of the night. Following the picture given above, this is in turn fully consistent with the idea that the disk radiates through reprocessing of X-rays, giving a rise in the optical emission with a rise in the X-ray flux also when only the side of the companion turned away from the X-ray source and (part) of the disk are visible. The depth of the eclipse also shows that the disk is a major source of optical light in the system.

To look further into the relation between optical and X-ray behaviour of this source, a separate night of observations, simultaneous with the X-ray satellite GINGA, was made on March 25 this year. Unfortunately, only three hours of data could be collected and a first quick look at the data did not show any special activity of the source, though a closer look, also at the X-ray data, will be necessary.

However, it still would be very interesting to follow this source closely in the future, if possible simultaneously in X-ray and optical, to further study this very unusual object.

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NEWS ON ESO INSTRUMENTATION

The VLT Adaptive Optics Prototype System: Status July 1989

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In June 1986 the conceptual design of the VLT Adaptive Optics Prototype system was started, based on the collaboration between the Observatoire de Paris (Meudon), ONERA, the Laboratoires de Marcoussis, and ESO after funding was assured by ESO and supporting French authorities.

In August 1987 began the construction of the major components. It was completed at the facilities of the various partners in May 1988. The major components are the 19-actuator deformable mirror (LdM), the Shack-Hartmann wavefront sensor (ESO), the wavefront computer and control electronics (ONERA, LdM), the tip/tilt mirror (OdM), the opto-mechanical support structure