OPTICAL OBSERVATIONS OF X-RAY BINARIES

J.B. Hutchings
Dominion Astrophysical Observatory

Recent progress in identifying the optical counterparts of X-ray sources has been slow, mostly because candidates are faint and X-ray data show no periodicities by which the identification can be confirmed. This report therefore deals with the investigation of some candidates to seek confirmation of their identity with the X-ray emitters, as well as details which are new or important concerning the few known binary sources. I shall also make some general remarks on the properties of the sources as they now appear, but leave a critical assessment of the masses to the next speaker.

Table 1. X-ray Binary Parameters

	M_O	M_X	Sp	$-\dot{m}$	Sep(R_*)	R/R_C	Pulsar
1) Supergiant primaries							
Cyg X-1/226868	25	15	B0Iab	2.6×10^{-6}	∿ 1		
1700-37/153919	27	1.3	06f	1.5×10^{-5}	∿ 0.5		
0900-40/77581	22	1.6	B0Ib	7×10^{-6}	< 1	∿ 1	P
Cen X-3/Krz*	17	0.7	06f	∿ 10^{-5}?	< 1		P
SMC X-1/Sk 160	20	1.6	B0I	∿ 10^{-6}?	∿ 1		P
2) Low mass primaries							
Her X-1/HZ Her	2.0	1.0	∿ A		∿ 1		P
Sco X-1	1.3	1.3	CV		∿ 1		
Cyg X-2	1.9	1.2	∿ F	∿ 10^{-8}?	∿ 1	= 1	
Cyg X-3	--	--	--		low		
0620+00/Nova Mon	--	--	CV		low?		
1809+50/AM Her	--	--	CV		low		
3) Be star primaries							
0352+30/X Per	20	≲ 40	B0Ve	∿ 10^{-7}	∿ 50?		P?
0535+26/245770	20	1 - 2?	"	≤ 10^{-7}	∿ 20?	≪ 1?	P
0053+60/γ Cas	20	≤ 6	"	1×10^{-7}	--		

Table 1 shows the known and probable X-ray sources into three groups, and gives the generally accepted parameters of importance,

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part I, 129-136. *All Rights Reserved.*

https://doi.org/10.1017/S1539299600002495 Published online by Cambridge University Press

some of which will be discussed further by the next speakers. I shall list significant new results on individual sources later, but first will make some general remarks on all the groups.

The first group has supergiant OB primary stars. These stars are very like non X-ray and non-binary objects which are known to lose mass by means of a fast moving stellar wind, at rates typically 10^{-6} $M_\odot$/yr. This rate is well in excess of the Eddington accretion limit for a collapsed object of any stellar mass, but there may be considerable inefficiency in accretion due to the high velocity and isotropy of the wind. In Cen X-3 and 1700-37 we have X-ray and optical evidence for a wake trailing the source which suggests that accretion is inefficient and may not even involve the formation of an accretion disk of any significant size. The optical evidence for a wake in 1700-37 is the presence of highly shifted absorption in some lines (principally He I λ 5875) at $\sim$ 0.7 phase (Conti & Cowley 1975, Hutchings 1976a). The direction of these wakes suggests that the wind velocity and orbital velocities are similar ($\sim$ 300 km/sec).

In view of the supposed inefficiency of accretion it is of importance to note that in all of these sources there is evidence from the light curve that the primary is tidally distorted by its companion. Opinions differ as to whether the stars fill their Roche lobes, or whether indeed such a concept is relevant in the presence of the radiative acceleration in the outer layer of the star. I will make two points, with minimal comment. 1) The expected Roche lobe overflow rates for stars of this type (supposed mass) are some orders of magnitude higher than those observed, and their duration very short. 2) In a survey of mass loss from some 70 OB supergiants (Hutchings 1976b), I find that mass-loss rates from known binary stars are higher (by roughly a factor 5) than similar single stars. A final comment on the primary masses. The two Of stars (153919 and Krz's star) seem to be under-massive for their spectrum and luminosity by a factor of 2 - 3. The mass of 77581 may be low, depending on what you believe its luminosity to be. These systems may be in a post rapid mass exchange state. The only other system I know of like this, HD 163181, has an undermassive primary which shows definite abundance anomalies. None of the X-ray binaries shows this, at least as far as we can tell at present.

The low mass group seems to have primaries of $\sim$ 2 $M_\odot$ and lower. The accretion in this case is supposed to be Roche lobe overflow, by evolution of the primary off the main sequence. The derived parameters for Her X-1 and Sco X-1, indicate that the optical stars have radii somewhat larger than main sequence objects. Optically, these systems are a mixed bag, as the spectra observed may arise principally from a) the primary, usually strongly heated by X-rays and thus peculiar and variable; b) the accretion ring around the collapsar, which has a featureless blue continuum, possibly with some emission lines; c) the gas stream or hot spot, which may give rise to very variable continuous radiation or line emission. These circumstances make optical determination of system parameters very difficult.

https://doi.org/10.1017/S1539299600002495 Published online by Cambridge University Press

The first two groups give rise to X-radiation which is similar in energy - near to the Eddington limit. The third group, whose existence at presence is not very certain, may be systems whose energies are generally considerably lower, due perhaps to a lower accretion rate. The primaries (whose identities I must note are still a little uncertain) are all BOVe stars. These are very different from OB supergiants. They are main sequence stars which have emission lines arising in a circulating equatorial ring of matter. It is not established whether the rings feed or are fed by the central star - both situations may exist, depending on the nature of the binary companion, if any. In our context it is relevant only to mention that in any case, mass appears to be lost from the outer parts of the disk, probably as a result of radiation and centrifugal forces. This mass flow is slower, and smaller than the OB supergiants by 1 - 2 orders of magnitude. It is not clear how this affects the accretion efficiency, but the accretion rate will be much lower if the objects are separated more widely. In these systems, the possible periods are long, implying wide separations. One of the sources is a transient and the others variable, and it seems probable to me that the accretion rate could vary more widely in systems of this nature than in the closer supergiant systems. The variability of the optical spectrum of these objects, the long periods and resultant low orbital velocities and lack of eclipses, make it very difficult to establish the identity and parameters of these sources. I should note that Marlborough (1976) has proposed a single star model for X-rays from γ Cas.

I will now discuss new results on individual sources. Even if I had time to mention all the work I am aware of in this field, there would be some omissions. What follows is therefore a personally biassed review, for which I apologise.

The most exciting results have come from the low mass systems and I shall mention these first.

I first note the most recent data - the discovery by Cowley and Crampton (private communication to this meeting) that AM Her, the optical candidate for 3U1809+50, shows a striking 3 hour periodicity in radial velocity and light, which fits with the X-ray variation. It appears to be a low mass system like the cataclysmic variables.
Her X-1. A careful analysis of the optical light curves and X-ray fluxes by Boynton, Crosa, Deeter & Gerend at Seattle has shown a close coupling between the 1.7 day orbital and 35 day X-ray intensity cycles. The analysis suggests very powerfully that there is a 35 day precession period (probably of the neutron star accretion disk), so that the same geometry in the system repeats every $\sim$ 1.62 days. They suggest that mass transfer is enhanced when the line of nodes is crossed, which is every 0.81 days. The observation of weak X radiation during the "off" period by Uhuru (Jones and Forman 1976) and 0.81 day modulation in the emission line intensity (Hutchings & Crampton 1976) lend further support to this idea. If this model is correct, it requires many new physical ideas to explain its operation, and has relevance to the whole class of mass exchange and cataclysmic binaries.

https://doi.org/10.1017/S1539299600002495 Published online by Cambridge University Press

New evidence on the shape of the "super-off" light curve (Wenzel & Hudec 1976) includes a broad secondary eclipse and lack of out-of-eclipse variations. These suggest the presence of an optically thick disk and the absence of tidal distortion, which appear to me to be mutually exclusive conditions, and to pose a puzzle. The observation of optical pulsations by the Berkeley group has shown them to arise near the neutron star and (reflected?) on the facing side of the primary, and to occur in the continuous radiation. Crampton & Hutchings (1974) have derived crude spectroscopic orbital parameters for both objects in the system.

Further spectroscopic studies with high line and wavelength resolution are needed to study this complex system. And a continued watch for a "super-off" state.

Sco X-1. After many years of study the source has been shown to be a binary of period 0.787 days, photometrically by Gottlieb, Wright & Liller (1975) and spectroscopically by Crampton & Cowley (1975). Orbital parameters yield probable masses of $\sim$1.3 $M_\odot$ for each object, the primary being evolved off the main sequence to fill its Roche lobe. Most of the light comes from the accretion ring and hot spot, as in many cataclysmic variables, and the plane of the system is probably inclined at some 50° to the line of sight. The absence of a large heating effect similar to HZ Her is strange in view of the high X-ray luminosity. A possible explanation is that X-rays are shielded in the orbital/disk plane. This possibility is made more likely by the requirement that a similar attenuation occurs in SMC X-1, from a discussion of its energetics by Primini et al. (1976).

Models have been proposed in which optical emission arises on the heated face of the primary star, rather than the vicinity of the X-ray source (Katz, Milgrom). These models seem to me to encounter serious difficulties in the observed low mass sources. There is not time for a full discussion of the points here, but I want to mention that such ideas do exist, and may have some validity.

Cyg X-2. The case for the binary nature of this source is less convincing than in Sco X-1, but is substantial. Crampton & Cowley (1976) find a 0.86 day period in radial velocities of the emission lines, which correlates exactly in phase which spectral type changes of the type expected from a heated primary star similar to HZ Her. The masses implied here are 1.9 $M_\odot$ and 1.1 $M_\odot$ for primary and X-ray source, from a consideration of all the evidence. In this system the primary is massive (and hence bright) enough to be seen, although there appears to be a considerable contribution from the disk/hot spot. Irregular optical variation of these components have so far masked a determination of the amplitude of the heating effect, which may be up to $\sim$ 1 mag.

0620+00. There is an enormous amount of X-ray data on this spectacular transient source. Optically, the story is less detailed. Eachus, Wright and Liller (1976) find that the object is like a recurrent nova and had outbursts in 1917 and in 1975 (coincident with the X-ray activity) of amplitude several magnitudes. The spectrum is blue and featureless, with the exception of weak N III + He II λ 4640-86 emission which developed after outburst, and later, Balmer emission with broad absorption wings. It shows a 4 (or 8) day periodicity in optical and X-radiation, which may be orbital. The analogy with recurrent novae leads to a conflict in distance/X-ray luminosity estimates. Either it is underluminous for a recurrent nova or its X-ray luminosity far exceeds its Eddington limit. Clearly, more basic data are required optically on this source. From the similarity to recurrent novae and its appearance as a red object on the sky survey, it is probably a low mass system, with perhaps an M giant primary if the period is as long as eight days. It has now faded by about $\geq$ 6m from outburst, but no late type spectrum has been seen or resolved.

Turning now to the supergiant primaries, we find less in the way of new optical results. Continued studies of Cyg X-1 have resulted in some controversy over the exact period, as the values derived from spectroscopic and photometric studies apparently differ significantly. The low amplitude light curve shows considerable scatter - as do all the light curves for these objects - presumably as a result of irregular changes in the surface and gas stream characteristics. Some season to season changes of the order of 0.01 m are suggested and these may result from long term changes in the mass transfer. These circumstances make simple interpretation of the light curves a very unreliable matter. The stellar wind results in a small velocity gradient with excitation of absorption lines and this too makes accurate orbital determination difficult. Milgrom (1976) has suggested that a small X-ray heating effect may also result in an apparent velocity shift of some absorption lines, but this is not confirmed.

Optical flickering has been reported with periods in the region of 80 m. sec. (Auriemma et al. 1975). There is no phase correlation with frequency and the observations remain unconfirmed.

Studies of the Hα emission line suggest that at times the emission originates in a region near the secondary - thus confirming the mass ratio of $\sim$ 1.6. This is not always so, however, (Fahlman, Glaspey & Walker 1976) and the emission may also appear near the primary or in the stream.

Finally, I should mention the 3 body hypothesis. This has been suggested to enable the secondary to be a main sequence B star and the X-rays to originate in a low mass collapsed object. So far no evidence is found for any periodicity other than the 5.6 day, and high signal to noise spectral data show no sign of a secondary. Limits need to be pushed further to obtain a definite conclusion.

Similar considerations apply to the other sources in this group, but as they are southern (and two of them faint) they are not as well studied. One interesting result is the direct mass determination of HD 77581 following the discovery of a 283 sec pulsation in the X-rays. The masses are $\sim$ 22 and 1.6 $M_{\odot}$ (lending some confidence to the light curve analyses which yielded q $\sim$ 12) and perhaps most significantly, there is an orbital eccentricity of $\sim$ 0.15 (also found optically but mistrusted). This is an interesting constraint on circularisation mechanisms, but, as the next speaker will mention, it may be a spurious result of reflection of the slow pulsar. It is important to look for periastron

https://doi.org/10.1017/S1539299600002495 Published online by Cambridge University Press

effects and precession of the orbit if it is real. There is some uncertainty as to the luminosity of the primary, the upper limit of which makes the star undermassive by a factor of about two.

The faint systems SMC X-1 and Cen X-3 are now within reach of the large southern telescopes and we may expect new spectroscopic results on them soon. They are both pulsing sources and very luminous in X-rays, so there are many points to explore.

Finally I want to mention the Be star candidates. Those of you familiar with these objects know the difficulties of measuring radial velocities and looking for regular changes. The chief of these are the width and shallowness of absorption lines (because of high rotation), the presence of emission in many lines, and the irregular spectrum variations these stars show anyway.

We have found what seems to be a regular 580 day velocity variation in X Per, with high amplitude. Interpreted as orbital motion, this implies a very high mass unseen companion, well separated, but we must be wary of believing in this too strongly. More recently, searches have been made for optical counterparts of the 13.9 minute and 22 hour period modulations seen in the X-rays. Liller (1976) has reported finding a variation in He II λ 4686 with a period of 13.9 minutes, but has not confirmed it in subsequent work. Hutchings & Walker (1976) find this period in changes at the 1% level over 2A at Hβ and λ 4686, but their significance is not convincingly high. I feel that more, and more convincing observational evidence is needed on this object before launching into any attempted explanations, tempting though they be.

A thorough radial velocity investigation of γ Cas (Cowley, Hutchings & Rogers, 1976) has shown no significant orbital motion and upper limits can be put on a secondary mass of 1 $M_{\odot}$ for P $\lesssim$ 10 days, 2 $M_{\odot}$ for P $\lesssim$ 100 days. Variations are seen in emission lines on time scales from minutes upwards. In this object the optical information far exceeds the X-ray, and we must probably await more observations of the latter to proceed.

Lastly, the optical candidate for the transient source 0535+26, HD 245770. Changes in the X-ray pulse period of $\sim$ 104 sec, indicate possible periods of 17, 19, 27, 26, 31, 39, 52, or 77 days. (Rappaport et al. 1976). For reasonable primary masses and inclinations, the last 3 are most likely. The optical star shows radial velocity changes which <u>may</u> be periodic on this timescale, with an amplitude of $\sim$ 10 km/sec. Phasing is anti on the 52 day, co on the 77 day and indeterminate on any shorter period. If these results are correct, the separation of the companion is large, and the peak X-ray energy $\sim 10^{36}$ erg.s^{-1} Clearly, continued observation is essential on this object.

One X-ray binary remains, which is different from all these. It is Algol, a triple system not known to contain any collapsed object, and in which mass exchange is occuring between the close pair at a moderate rate. The optical system is very well studied and I have no intention of (or time for) discussing the object in detail. It should simply be borne in mind as an anomalous which may fit into the general picture at some stage.

I have no summarising remarks which are not obvious. Clearly much work is in progress and remains to be done.

REFERENCES

Auriemma, G., Cardini, D., Costa, E., Giovannelli, F., Ranieri, M., 1976, NASA SP-389, p. 485.
Conti, P.S. and Cowley, A.P., 1975, Astrophys.J. 200, 133.
Cowley, A.P. and Crampton, D., 1975 Astrophys.J. 201, L65.
Cowley, A.P., Rogers, L., and Hutchings, J.B. 1976 (preprint).
Crampton, D., and Cowley, A.P. 1976, Astrophys.J. 207 (preprint).
Crampton, D., and Hutchings, J.B., 1975, Astrophys.J. 191, 483.
Deeter, J., Crosa, L., Gerend, D., and Boynton, P., 1976, Astrophys.J. 206, 861.
Eachus, L.J., Wright, E.L. and Liller, W., 1976, Astrophys.J.(preprint).
Fahlman, G., Glaspey, J., and Walker, G.A.H., 1976, (preprint).
Gerend, D., and Boynton, P., 1976, Astrophys.J. (preprint).
Gottlieb, E.W., Wright, E.L. and Liller, W., 1975, Astrophys.J. 195, L33.
Hutchings, J.B., 1976a, NASA SP-389, p. 529.
Hutchings, J.B., 1976b, Astrophys.J. 203, 438.
Hutchings, J.B., and Crampton, D., 1976 (preprint).
Hutchings, J.B., and Walker, G.A.H. 1976 (preprint).
Jones, C., and Forman, W., 1976 Astrophys.J. (preprint).
Liller, W., 1976 IAU Circ. 2888.
Milgrom, M., 1976 Astron. Astrophys. (preprint).
Marlborough, J.M. 1976 (preprint).
Rappaport, S., Joss, P.C., Bradt, H., Clark, G.W., and Jernigan, J.G., 1976 Astrophys.J. (preprint).
Primini, F., Rappaport, S., Joss, P.C., Clark, G.W., Lewin, W., Li, F., Mayer, W., and McQintock, J., 1976, Astrophys.J. (preprint).
Wenzel, W., and Hudec, R., 1976 IAU Comm. 27 Bull. 1082.

DISCUSSION

H.C. Thomas - 1. Stars losing mass at a fast rate may not look normal at all. They have to be highly underluminous, because energy is consumed by bringing matter up to the photosphere.

2. Boynton and collaborators have shown, that they can fit a model with six or seven free parameters to a very complicated light curve. This does not prove that this is the only model possible. One should use physics and determine some of these parameters from a theoretical point, to prove the validity of the model.

J.B. Hutchings - 1. The supergiant primaries are not losing mass unusually fast and look entirely normal for their type. In the low mass primaries the spectra are all far from normal, for reasons I summarized briefly in my talk.

https://doi.org/10.1017/S1539299600002495 Published online by Cambridge University Press

2. I fully agree that model building does not prove anything. I only say that Boynton's model is very attractive in the way it explains so many observed phenomena.

https://doi.org/10.1017/S1539299600002495 Published online by Cambridge University Press