VI. X-RAY BINARIES

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X-RAY BINARY SYSTEMS

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ABSTRACT

X-ray emission has now been detected from a large number and variety of binary systems. A brief survey of the properties of these binary systems is given, primarily from an optical standpoint.

I. INTRODUCTION

In the past few years, rapid progress has been made in the observations of X-ray binary systems and in the theoretical interpretation and understanding of the processes occurring in close binary systems and of their evolution. In this paper, I shall treat the X-ray binary systems primarily from an optical observational viewpoint, and try to relate these systems to conventional binary systems starting first with the massive binary systems and working down to the systems of lowest mass.

Although the initial impetus for studying X-ray binaries was to discover and to determine parameters of degenerate objects, we are learning considerably more about close binary systems as a whole, because the degenerate object essentially behaves as a test particle for which and from which we can determine precise orbital parameters, at least in the case of the pulsing, eclipsing systems. The complications which we encounter in trying to determine equally precise parameters from optical observations indicate areas or problems that need to be carefully scrutinized in the study of conventional systems.

II. BLACK HOLE CANDIDATES

Naturally, there is keen interest in establishing the existence of, and determining the parameters for the mythical black holes. Since Bolton is reviewing the object that is still the prime candidate, I will be brief. I would like to note, however, that HDE 226868 =

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Cyg X-1 is not particularly unusual optically, the He II λ 4686 A emission that has become the standard signature of the optical counterparts of X-ray sources being very weak, and the spectrum otherwise (except for broad Hα emission) being that of a normal B0 supergiant. The hypothesis that the unseen star is a black hole is still the most plausible interpretation of the observations, although by taking extreme values of all the parameters the mass of the degenerate object can be nearly reduced to that of a massive neutron star.

Two other X-ray sources exhibit very similar X-ray characteristics to Cyg X-1 and hence may contain black holes; Cir X-1 and GX 339-4. Samimi et al. (1979) have reported observations of the latter source and have summarized the X-ray observations of the prime black hole candidates. These objects all exhibit X-ray variability on timescales of milliseconds, have high and low states and have similar X-ray spectra. Although faint and reddened, we can look forward to optical observations of the optical counterparts of Cir X-1 and GX 339-4 to see whether they too have large mass functions.

III. THE MASSIVE SYSTEMS

It is the pulsing, eclipsing X-ray binaries from which we have learned the most, particularly those in the Magellanic Clouds since then the distances are known as well. Orbital elements for those binaries with relatively well-determined parameters are given in Table 1, with those of Cyg X-1 for comparison. For references, see Hutchings (1979).

TABLE 1. ORBITAL ELEMENTS

Name	P days	V_0 km s^{-1}	K_0 km s^{-1}	K_{HeII} km s^{-1}	K_X km s^{-1}	e_0	e_X	i
HD77581	9.0	0	22	-	273	.14	.09	>75°
SMC X-1	3.9	180	19	245	299	.36±.09	<.0007	∿65°
1538-52	3.7	-172	33	302:	323	.14:		70°
Cen X-3	2.1	+ 39	24		415		.0008	83°
LMC X-4	1.4	271	50	498	-	0:		75°
HD153919	3.4	- 75	19	-	-	.2, .05		87°
Cyg X-1	5.6	0	72			.06		∿60°

The following aspects of the quantities in the table are noteworthy:

- Periods are typical.
- Systemic velocities are not peculiar apart from that of

4U1538-52. A large stellar wind is probably responsible for the negative velocity of HD 153919.

- $K_{HeII} \sim 0.8\ K_x$, indicating that the He II emitting region is closer to the centre of mass. Actually, in several systems He II emission arises both from regions near the X-ray source and near the heated face of the companion.

- As revealed by SMC X-1, the spectroscopic eccentricity may be spurious due to a variety of reasons (Hutchings 1979). The eccentricity of HD 77581 is well determined and limits have been placed on the apsidal motion by Rappaport, Joss and Stothers (1979).

- $i > 60°$ for all systems. X-ray beaming or obscuration must be responsible for this anisotropy.

Some of the physical parameters which have been deduced for the massive binary systems are listed in Table 2. These systems are confined to a very restricted range in luminosity and effective temperature, and, despite their unusual evolutionary status (see, for example, van den Heuvel 1976), their spectra are completely normal.

TABLE 2. PHYSICAL PROPERTIES

Name	P_{pulse} s	Sp	M_v mag	M_{bol} mag	q	$\frac{M_o}{M_\odot}$	$\frac{M_x}{M_\odot}$	L_o/L_x
HD77581	283	B0.5Ia	-7.2	-10.0	12	23	1.9	1300
SMC X-1	0.7	B0 Ib	-6.6(-6.1)	- 9.0	16	16	1	4
1538-52	529	B0 I	-6.5	- 9.1	10	20	2	500
Cen X-3	4.8	O7 III	-5.9	- 9.3	17	17	1	100
LMC X-4		O7 III-V	-5.2(-5.0)	- 8.3	10:	25	2.6	30
HD153919		O6.5f	-6.5	-10.2	20:	27	1.3	5000
Cyg X-1		O9.7 Iab	-5.6	- 9.1	3	18	6	100

The intrinsic luminosities of the optical primaries derived from spectral classification and Hγ equivalent widths are also apparently normal, since the agreement between these and the values derived from the distance to the Magellanic clouds (absolute magnitudes given in parenthesis in Table 2) is very good. It is very clear now that the masses of the optical primaries are all low by a factor of two or more. This fact is dramatically displayed if these systems are plotted on an HR diagram with the stellar evolution tracks of stars of various mass (see Hutchings et al 1979 Fig. 3). Rappaport (1979) has shown that the masses of the neutron stars in the pulsing binary systems may all be very similar and equal to $\sim 1.4\ M_\odot$. Perhaps we should adopt this value in difficult cases and derive the other parameters on this basis. Although all of these systems have an X-ray luminosity $L_x \sim 10^{38}$ ergs sec^{-1}, the ratios of the optical to X-ray luminosities are very different from each other. No particular correlation with any of the system parameters except perhaps with the pulse period is evident.

There is one additional massive system for which we do not yet know the orbital parameters, 4U1223-62 or WRAY 977. From pulse timing measurements it is obvious that the orbital period is long, but the exact value is still unknown. The spectral type of WRAY 977 is B2Iae with strong P Cyg profiles in the lines of most of the elements. It is apparently the most evolved of the massive X-ray binaries and hence its parameters will be of considerable interest.

IV. Be SYSTEMS

The X-ray sources associated with Be stars have a lower X-ray luminosity, $L_X \sim 10^{34}$ ergs sec^{-1} ($L_0/L_X \sim 10^5$), harder spectra, transient behaviour and in general longer pulse periods ($\sim$ 300s) and orbital periods ($\sim$ 25d ?). None of these systems have both optical and X-ray orbits. The X-ray orbit (Rappaport et al. 1978) for 4U0115 + 63 indicates that the orbit is quite eccentric ($e = 0.3$), a factor which is probably related to the transient behaviour of the X-rays. It is not clear what is responsible for the observed 580-day velocity variations (Hutchings, Crampton and Redman 1975), in X Per because if assumed to be orbital, a massive black hole is implied by the deduced mass function. The discovery of a pulse period points to a slowly rotating neutron star rather than a black hole however. It may be relevant that Poeckert (1979) has recently discovered weak He II emission in the spectrum of the Be star ϕ Per which apparently is associated with an unseen companion that is probably a neutron star.

As for the supergiant systems, the optical counterparts to these X-ray sources are restricted to a very narrow range of spectral type and luminosity class (O9-B1, III - Ve). The SMC sources (Crampton, Hutchings, and Cowley 1978) again indicate that the luminosities are normal for their spectral classification.

V.1. LOW MASS SYSTEMS I: NON-DEGENERATE STAR VISIBLE

Two sources in this category, Her X-1 and Cyg X-2, now have reasonably well determined parameters. Thorstensen et al (1979) have recently shown that a probable third member, 4U2129 + 47, has a large 1.5 mag. photometric variation with P = 5.2 hours.

In the well studied Her X-1 = HZ Her system (e.g. Boynton 1978), a very large X-ray heating effect is primarily responsible for the large spectral type (B-F) and light (1.5 mag.) variation, and produces complicated radial velocity variations (Crampton and Hutchings 1974). It is still not clear where the weak variable emission lines are formed. Extensive observations by Boynton and his collaborators show that the 35-day ON-OFF X-ray variability is due to a large precessing disk. The masses of the components are $M_O \sim 2\ M_\odot$, $M_X \sim 1\ M_\odot$.

Recent observations of Cyg X-2 (Cowley, Crampton and Hutchings 1979) indicate that instead of being a short period system similar to the cataclysmic variables as once thought, the period is 9.8 days and the optical primary is an F giant located about 8 kpc from the sun with $z \sim 1.5$ kpc and a systemic velocity of -222 km s^{-1}. In this case, most of the He II emission probably originates from the heated face of the F star, although a variable component arising from a region near the X-ray source is also present. The light curve is very complex, being composed of an ellipsoidal variation, a single-peaked variation most prominent in U that is presumably due to X-ray heating, and erratic outbursts. A combination of the restrictions on q and i determined from the ellipsoidal variation together with the spectroscopic observations yields masses of $M_O \sim 0.7\ M_\odot$ and $M_X \sim 1.5\ M_\odot$.

The X-ray luminosity of these sources is $\sim 10^{37.5}$ erg s^{-1} and the ratio L_X/L_O is $\sim$ 10-100. Both Cyg X-2 and Her X-1 are situated far from the galactic plane and have high systemic velocities. Either these systems were imparted large velocities as a result of a supernova explosion or they are population II objects.

V.2. LOW MASS SYSTEMS II: SCO X-1 TYPE

There are now a large number of X-ray sources which are identified with objects having blue continuous spectra with He II emission, weak C III - N III emission, and, sometimes, H emission superposed as in the prototype, Sco X-1. A list of these objects which includes some of the burst sources is given by Cowley (1979).

While all the optical light of Sco X-1 appears to come from reprocessed X-rays originating from a luminous disk around the X-ray source, a neutron star, and the companion is not visible, it seems probable that it is a low-mass, slightly evolved, non-degenerate star which is losing mass by Roche Lobe overflow (Cowley and Crampton 1975). Analysis of the radial velocity variations of the He II emission combined with the light variations yields masses $M_O \sim 1\ M_\odot$, $M_X \sim 1\ M_\odot$ and $i \sim 25°$. The low amplitude of the light curve suggests a very low inclination, $i < 10°$, but this would lead to unreasonable masses and so it is probable that beaming or obscuration of the X-rays prevents the expected large X-ray heating of the primary.

If Sco X-1 is typical, the X-ray luminosity of this class of binaries is $L_X \sim 10^{37.5}$ ergs s^{-1} as in the case of Cyg X-2 or Her X-1, but L_X/L_O is $\sim 10^3$. Cowley (1979) shows that the galactic distribution of the Sco X-1 systems is concentrated about the galactic centre.

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V.3. LOW MASS SYSTEMS III: AM HER TYPE

According to Cowley (1979) there are now four X-ray sources identified which have optical counterparts characterized by strong emission-line spectra, short periods ($\sim$ few hours) and high polarization indicating large magnetic fields. These systems are related to the cataclysmic variables although the transitions from minimum to maximum light is not cataclysmic and is only a few magnitudes. The X-ray luminosity of these systems is $L_x \sim 10^{34}$ ergs sec^{-1} and the optical luminosity is comparable. It is generally assumed that these systems contain a low mass dwarf which fills its Roche Lobe and a magnetic white dwarf. The emission lines in AM Her, at least, originate primarily in a stream of material between the two stars and so they yield no direct information about the masses of the stars. Estimates of $M_O \sim 0.4\ M_\odot$ and $M_X \sim 1\ M_\odot$ have been given by analogy to the cataclysmic variables (Cowley and Crampton 1977).

V.4. LOW MASS SYSTEMS IV: X-RAY NOVAE

In some respects (e.g. a fast rise of $\sim$ 7 mag. to maximum light) the prototype of this class, Nova Mon 1975 or A0 0620-003 resembles the classical novae. At maximum light, however, the spectrum was nearly continuous with only weak He II and H emission and no substantial mass outflow was detected. The optical and X-ray outburst was accompanied by a non-thermal radio outburst. At minimum light Oke (1977) observed the spectrum of a late type K dwarf which is presumably the companion to a degenerate star in the system, but no convincing orbital periodicity has yet been observed.

Cen X-4 has recently undergone a similar outburst (Kaluzienski and Holt 1979) from which we may expect to determine further parameters for these systems.

VI. SOFT X-RAY BINARY STARS

There are two other classes of X-ray systems which emit predominately soft X-rays, the SS Cyg and RS CVn systems. These are both classes of binary systems in which accretion of material onto a white dwarf is responsible for the soft X-ray emission, although hard X-rays are apparently produced by coronal processes in a few of the RS CVn systems. The SS Cyg stars were discussed in detail at IAU Colloquium No. 53 in Rochester and the RS CVn stars at several workshops (e.g. Hall 1978).

VII. 4U1626-67

The optical counterpart to this pulsing source has colours similar to those of the Sco X-1 type sources. The 7 s pulsation has been

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observed in visible light (Ilovaisky, Motch and Chevalier 1979) as well as in the X-rays, but pulse timing observations have only yielded an upper limit to the orbital period of P < 1 hour (Rappaport 1979). The X-ray variations exhibit a characteristic time scale of $\sim$ 1000 secs and this has led to the suggestion that this system is a very close binary system containing a neutron star and white dwarf with P $\sim$ 1000 sec. (Rappaport 1979).

VIII. SS433

Recent spectroscopic observations obtained at Victoria indicate that this remarkable source (e.g. Margon et al. 1979) is a binary system with P $\sim$ 13 days, although it is not yet clear how it fits into the classes discussed above. The radial velocity variations of the Hβ and Hα emission peaks of the "stationary" system of lines are periodic with P = 13.0 ± 0.1 days, a semi-amplitude, K, of $\sim$ 75 km s^{-1}, and with time of maximum positive velocity occurring on JD 2444058.5 ± 0.2. An eccentricity of 0.2 ± 0.1 is deduced from the observations. The very broad emission lines are typical of those observed to originate in accretion disks, and so it is assumed that the observed velocity variation represents orbital motion of the X-ray emitting object. If this object is further assumed to be a neutron star with $M_X \sim 1.4\ M_\odot$, then the companion would have $M_O \sim 1.8\ M_\odot$ for i $\sim$ 90°. The period and mass function are very similar to those of Cyg X-2 although the optical observations are of the non-degenerate star in that case. The X-ray luminosity, $L_X \sim 10^{35.5}$ ergs s^{-1}, for an assumed distance of 3.5 kpc (Margon <u>et al</u>.1979) is lower than that of Cyg X-2 but higher than that of AM Her.

The He I "stationary" emission lines also probably exhibit the same 13 day velocity variation although poorer phase coverage and larger observational error preclude the detection of small differences. He I absorption lines which strengthened considerably in July 1979 probably also exhibit a variable velocity of comparable amplitude although their systemic velocity is $\sim$ 350 km s^{-1} more negative. The observations of the He II λ 4686 A emission are not adequate to determine whether they display a similar variation. No 13 day periodic variation of the intensities of any of the lines has been detected, although the profile of Hβ progressively changed during the period of observation, JD 2443987-2444085.

Current models deduced from the "moving" lines (Milgrom 1979, Margon and Abell 1979) ascribe the 164 day, 81,000 km s^{-1} variation to motion arising in two colinear rotating beams. The source of the energetics involved is still a mystery however, since our recent observations of a 13 day periodicity indicate that otherwise this system is similar to other low mass systems.

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CONCLUSION

Accretion of material supplied by a normal star onto a compact object is apparently responsible for the observed X-ray emission in most, if not all, of the binary systems considered here. In many cases there is evidence of considerable interaction between the components, gas streaming, accretion disks etc. Further studies of these systems should help us to understand these and other phenomena encountered in close binary systems, as well as revealing the nature of the compact objects.

REFERENCES

Boynton, P.E.: 1978, Proc. Int. School of Phys. "Enrico Fermi", R. Giacconi and R. Ruffini (eds.), North Holland, Amsterdam, pp. 111.
Cowley, A.P.: 1979, in Proc. NATO Advanced Study Institute, Cape Sounion, Greece. Cambridge U. Press.
Cowley, A.P., and Crampton, D.: 1975, Astrophys. J. Letters, 201, L65.
Crampton, D., and Cowley, A.P.: 1977, Publ. Astron. Soc. Pacific, 89, pp. 374.
Crampton, D., and Hutchings, J.B.: 1974, Astrophys. J., 191, pp. 483.
Crampton, D., Hutchings, J.B., and Cowley, A.P.: 1978, Astrophys. J. Letters, 223, L79.
Hall, D.S.: 1978, Astron. J., 83, pp. 1469.
Hutchings, J.B.: 1979, in Proc. NATO Advanced Study Institute, Cape Sounion, Greece. Cambridge U. Press.
Hutchings, J.B., Crampton, D., and Redman, R.O.: 1975, Monthly Notices Roy. Astron. Soc., 170, pp. 313.
Hutchings, J.B., Cowley, A.P., Crampton, D., van Paradijs, J., and White, N.E.: 1979, Astrophys. J., 229, pp. 1079.
Ilovaisky, S.A., Motch, C., and Chevalier, C.: 1978, Astron. Astrophys., 70, L19.
Kaluzienski, L.J., and Holt, S.S.: 1979, IAU Circ. 3360, 3362.
Margon, B., and Abell, G.O.: 1979, Nature 279, pp. 701.
Margon, B. et al.: 1979, Astrophys. J. Letters, 230, L41.
Milgrom, M.: 1979, Astron. Astrophys. in press.
Oke, J.B.: 1977, Astrophys. J., 217, pp. 181.
Poeckert, R.: 1979, Astrophys. J., in press.
Rappaport, S.: 1979, in Proc. NATO Advanced Study Institute, Cape Sounion, Greece. Cambridge U. Press.
Rappaport, S., Clark, G.W., Cominsky, L., Joss, P.C., and Li, F.: 1978, Astrophys. J. Letters, 224, L1.
Rappaport, S., Joss, P.C., and Stothers, R.: 1979, submitted to Astrophys. J.
Samimi, J. et al.: 1979, Nature, 278, pp. 434.
Thorstensen, J. et al.: 1979, submitted to Astrophys. J.
van den Heuvel, E.P.J.: 1976, in IAU Symposium No. 73, pp. 35, P. Eggleton, S. Mitton, J. Whelan (eds.), Reidel, Dordrecht, Holland.

COMMENTS FOLLOWING CRAMPTON

Ziolkowski: I would like to make a comment on Cyg X-2. We are working now with Bohdan Paczynski on a model of this system. We believe that the apparent lack of the X-ray heating effect tells us something not only about Cyg X-2 but also about other low mass X-ray binaries. It appears, for example, that, in order to explain the smallness of the X-ray heating effect in Sco X-1, it is enough to assume that X-rays are coming from a flat, limb darkened disc. However this would not work for Cyg X-2. It seems unavoidable that there is some screen between the optical component and the X-ray source. If this screen is a thick disc, then, in order to avoid observable heating of the outer parts of the disc, it has to be thick quite close to its center (at a distance of less than 5 percent of the separation between the components of the binary system). I will present preliminary results of our work on Cyg X-2 during the meeting of Commission 42 at Montreal.

Mitrofanov: Have you estimated the lifetime of a binary system containing neutron star and degenerate dwarf? It seems it may be very small due to the generation of gravitational waves.

Vanbeveren: The overluminosity with respect to the mass of the optical companions of massive X-ray binaries suggests that they have lost a large amount of mass due to stellar wind (see e.g. the paper by Vanbeveren and de Loore, this symposium). If these stars should be at the end of core hydrogen burning one therefore would expect a lowering of the hydrogen abundance in the surface by at least a factor of 2 or 3. Is it possible to observe an effect like that?

Crampton: As I indicated, the spectra which we have appear to be completely normal as far as abundances are concerned. However, I suspect that we would not detect a deficiency of H of a factor of 2-3.

Mayo: What is the latest news on the X-ray emission from V861-Sco? You have told us it is now not considered to be the source of the 38 sec pulsing. There was a Copernicus report of an X-ray eclipse in the IAU circulars (in June/July 77). Are these X-ray eclipses confirmed? Indeed, is V861-Sco now thought to be an X-ray source at all? And finally, in the light of your answers, what type of binary system do you now think V861-Sco is?

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