LOW-MASS X-RAY BINARIES AND THEIR RELATION TO THE NON-X-RAY SOURCES

Anne P. Cowley*

Department of Astronomy
University of Michigan
Ann Arbor, Michigan 48109

Until recently most of the optically identified x-ray binaries appeared to be hot supergiants with compact companions (neutron stars or black holes). Some examples are given in TABLE 1; the notable exception to massive and luminous primaries was HZ Her. Masses and radii, determined by a variety of methods, showed these primaries to be close to filling their inner Lagrangian surfaces, though often somewhat undermassive for their radii and luminosities. In all of these systems mass transfer from the supergiant resulted from Roche lobe overflow or a strong stellar wind or both. The total masses for these systems generally were found to be greater than 15 $M_\odot$.

As the list of optically identified x-ray sources has grown and more detailed work has been done on previously unexplained sources (such as Sco X-1), it has become obvious that a variety of types of stellar x-ray sources exist. Undoubtedly, the range of types will continue to grow as weaker x-ray sources are identified optically. In TABLE 1 we list four types of stellar sources. Some of the type III and IV systems have been suggested as binaries, but it is unclear whether mass transfer in a binary is fundamental to the x-ray production in these cases. We note the Be stars (type III systems) probably have masses intermediate between the supergiants and the low mass (type II) binaries.

As low mass binaries we include those systems for which the total mass appears to be ≤ 5 $M_\odot$, and probably considerably less for some. In both HZ Her and Cyg X-2, the nondegenerate star is seen spectroscopically; in each the spectral type varies with the orbital phase, with the earliest type occurring when one sees the inward-facing hemisphere which is heated by the x-ray source. The spectra of Sco X-1 and AM Her show only emission lines on a blue continuum. These lines appear to be formed either in the accretion disk about the degenerate star or in the stream between the components. Because of the low luminosity of these stars, there can be no stellar wind, so we assume mass transfer results from the nondegenerate star filling its Roche lobe and spilling material through the inner Lagrangian point.

HZ Her has been discussed in the literature in considerable detail (e.g., Giacconi *et al.*,[9] Crampton & Hutchings,[8] Middleditch & Nelson[16]), so we will limit our discussion to the remaining three systems. Although Sco X-1, Cyg X-2, and AM Her are distinctly different from each other, they share certain unifying characteristics, such as low mass, and some optical properties that make them similar to old novae and other cataclysmic variables (CVs). All exhibit: (1) rapid flickering

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*Present address: Dominion Astrophysical Observatory, 5071 West Saanich Road, Victoria, British Columbia, Canada V8X 3X3.

TABLE 1

CHARACTERISTICS OF SOME STELLAR X-RAY SOURCES

Source	mag	P	Pulsing?	Mass_{op}	Mass_X	Spectrum	Remarks
I. Early Supergiant Binaries							
Cyg X-1 = HD226868	9	5.6^d	—	<25:	<14	09.7 Iab	Primary mass assumed.
Vela X-1 = HD77581	6*	8.9	283^s	22	1.6	B0.5 Ib	
Cen X-3 = Krzeminski's star	13*	2.1	4.8	17	0.7	B0 Ib–II	
SMC X-1 = Sk 160	13*	3.9	0.7	15	1.1	B0 Ib	
3U1700-37 = HD153919	6*	3.4	—	27	1.3	07f	
3U1223-62 = Wra 977:	10	8–20?	—	?	?	B I	
II. Low Mass Binaries							
Her X-1 = HZ Her	15*	1.7	1.2	2.2	1.3	B–A var.	
Cyg X-2 = —	{15	.9?	—	1.5?	1?	A–F var.	
		8–12?	—	1.5?	2–3		
Sco X-1 = V818 Sco	13	.79	—	1	1.3:	H, He II em	
3U1809+50 = AM Her†	13var	.13	—	.4:	1:	H, He II, He I em	
Cyg X-3 = ?	—*	.2	—	1?	1?	not seen optically	
III. Be Stars							
3U0352+30 = X Per†	{6	560?	835	20:	40:	BOe	
		.9?	835	20:	1:		
MX0053+60 = γ Cas†	3	—	—	25	< 3	BOe	No evidence this is a binary; masses are upper limits.
A0535+26 = HD245770	9	> 17	104	—	—	Be	X-ray pulsing gives P > 17^d; no known optical P; x-ray nova.
IV. Transient X-Ray Sources							
A0535+26 = HD245770	9	> 17	104	—	—	Be	See above; no optical outburst.
A0620 – 00 = Nova Mon 1975	12–20	4?	—	—	—	H em	Optical outburst with x-ray event.
3U1118 – 61 = —	12	?	405	—	—	Boe	Id. not certain.

*Eclipsing in x-rays.

†Low x-ray luminosity.

on the time scale of minutes, (2) colors that place them on or near the black-body relation in the U-B, B-V diagram, (3) spectra that resemble some old novae or U Gem stars.† Because these x-ray sources share a number of optical properties with the CVs, one might expect similarities in other physical characteristics. In particular, Kraft and Luyten[15] showed that in the old novae all systems with the period > 6 hours had composite spectra (cool absorption plus He II emission), whereas those with only emissions lines or a blue continuum had orbital periods < 6 hours. This is because the mass exchange due to Roche lobe overflow onto the degenerate star is ultimately responsible for the cataclysmic outbursts they suffer, so that a larger, and therefore brighter, star is needed to fill the inner Lagrangian surface in the longer period systems. It turns out that Sco X-1 does not obey this empirical relation, for a reason that is probably closely related to why it is also a strong x-ray source.

Sco X-1

After much effort, an orbital period of $.787^d$ was finally found for this system both photometrically[10] and spectroscopically.[2] The emission lines appear to be formed in the accretion disk about the degenerate star. The small amplitude light variations seem to be due to x-ray heating of the unseen secondary. There is little doubt that this system is viewed high above the orbital plane (i is probably less than 30°). Because the system does not eclipse, we only know the mass function ($f(M) = .016\ M_\odot$), which allows us to set lower limits on the component masses. The observed parameters are consistent with masses near 1 $M_\odot$ each (see Crampton *et al.*[7]), implying that the degenerate star is a neutron star. For any reasonable values of i and q (the mass ratio), one finds that the nondegenerate star can only fill its Roche lobe if it has begun to evolve away from the main sequence. It thus differs from the CVs in which the secondary is a lower main sequence star that slowly loses mass to its white dwarf companion. In Sco X-1, the mass loss is driven by the evolution of the nondegenerate star, resulting in a more rapid mass transfer than for the CVs. Thus the probable presence of a neutron star in the system and the inferred higher mass transfer rate may be why this system is seen as a bright x-ray source.

Cyg X-2

The situation with Cyg X-2 is not yet clear. From the spectrum one knows that the optical star in Cyg X-2 is above the main sequence. Several orbital periods have been suggested: Wright *et al.*[20] find $.92^d$ from photometric variations, Crampton and Cowley[3] give $.86^d$ on the basis of radial velocities, while Holt *et al.*[12] suggest 11.1^d on the basis of the x-ray modulation. Either of the short periods implies a model much like that for Sco X-1, but the periods differ sufficiently so as not to

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†Old novae may show either a cool absorption spectrum plus He II, λ4686 emission like Cyg X-2, or a purely emission spectrum similar to Sco X-1 or AM Her. Some illustrations are found in Kraft's[13] article on old novae. Spectra of Sco X-1 are illustrated by Sandage *et al.*[17] and of Cyg X-2 by Kraft & Demoulin.[14]

fit the other data set. New, high quality spectrograms obtained at KPNO in August 1976 over six consecutive nights seem to exclude both of the short periods. Although the data can be forced to (poorly) fit some periods near a day, the observations are more compatible with a period between 8 and 12 days.[5] It seems likely that the short periods are aliases of the true period, and that perhaps the 11^d x-ray modulation refers to the orbital period. There are two reasons to look cautiously at this longer period: (1) it requires a primary star twice as large as one would expect from the spectral type, and (2) for reasonable values of the inclination (*i* must be less than 60° as there are no eclipses) the mass of the degenerate star lies between 2 and 3 $M_\odot$. Crampton and Cowley showed that the spectral type of the primary varies with phase; this remains true regardless of whether the period is near one day or in the $8–12^d$ range, since the correlation is with the velocity and not with the period itself. Thus one still infers strong x-ray heating on the optical star. Further work is needed on this system, but because it is faint, quality observations are difficult to obtain.

AM HER

This, the most recently identified x-ray binary, has been found to be associated with the high galactic latitude x-ray source 3U 1809+50. In a flurry of observing activity during the summer of 1976, it was found to have a number of unique properties. Its 3-hour period was first announced by Cowley *et al.*[6] from both spectroscopic and photometric variations. Its spectrum shows strong emissions of H, He II, He I and other ions with large velocity variations.[4] Rapid flickering[1] and a continuously varying light curve[18] suggest a U Gem type system. The minimum in the soft x-ray modulation occurs about a half a cycle later than the optical (*V*) minimum,[11] whereas large variations in both linear and circular polarization occur not obviously phased with the other variations.[19] The polarization is the largest yet measured for a stellar source and implies a magnetic field of about 10^8 gauss.

In addition, the system has high and low states optically; as yet it is not known if the x-rays also show this longer term behavior. In its high state (approximately 12th magnitude) the system shows deep minima in *V* and *R* each orbital cycle, but in its low state (about 15th magnitude) apparently the variation is much smaller. Although spectroscopically and photometrically it resembles the U Gem stars, it differs in some important respects: (1) Its rise to its high state takes months rather than hours or days. (2) At maximum light the emission lines are more intense and of higher excitation, rather than being drowned by the continuum. (3) Although the short-term flickering is similar to the CVs, the 3-hour light curve does not show the canonical rise to maximum when the hot spot is presented to the viewer. Instead, in *V* two broad minima of unequal depth occur half a cycle apart. However, in *B* and *U* there is only one minimum/cycle, which is phase shifted with respect to *V* by .2 and .3P respectively. (4) Remarkable periodic polarization variations occur which suggest that the compact object is a magnetic white dwarf with its magnetic axis not aligned with the orbital axis. The polarization occurs predominantly in the *V* and *R* bands and is only weakly detectable in *B*.

Simple arguments related to the observed light, velocity, and spectral line variations imply the system may contain a white dwarf ($M \approx 1_\odot$) and a lower main sequence star of about .4 M☉. Probably much of the emission comes from an off-axis hot spot following the degenerate star. This model, however, does not treat the polarization variations or the x-ray changes. The latter may be modulated by a presentation effect (rather than an eclipse). If the x rays are produced in a limited region, for example at the magnetic poles, the phasing of the x rays with respect to the optical light variations may not be important. As yet no satisfactory model has been presented that adequately accounts for all the observed x-ray and optical properties. It should be noted that the x-ray luminosity for this source is several orders of magnitude lower than for Sco X-1 and Cyg X-2, implying a new class of x-ray binaries.

In summary, we already find among the few low mass x-ray binaries a variety of kinds of systems that may provide us with new information about the observed masses of neutron stars, the role of mass exchange in the evolution of x-ray binaries, as well as important insight into the relation of these systems to the non-x-ray producing, interacting binaries. Because of the intrinsic faintness of the optical counterparts of these low mass stars, the observations will be difficult, but if the few systems discussed here are examples of the wide range of extreme physical properties to be found, we can look forward to future work in this field with great interest.

REFERENCES

1. BERG, R. P. & J. G. DUTHIE. 1977. Astrophys. J. **211**: 859.
2. COWLEY, A. P. & D. CRAMPTON. 1975. Astrophys. J. Lett. **201**: L65.
3. COWLEY, A. P. & D. CRAMPTON. 1976. Astrophys. J. Lett. **207**: L171.
4. COWLEY, A. P. & D. CRAMPTON. 1977a. Astrophys. J. Lett. **212**: L121.
5. COWLEY, A. P. & D. CRAMPTON. 1977b. Pub. Ast. Soc. Pacific. In press.
6. COWLEY, A. P., D. CRAMPTON, P. SZKODY & D. BROWNLEE. 1976. Int. Astron. Union Circ. 2984.
7. CRAMPTON, D., A. P. COWLEY, J. B. HUTCHINGS & C. KAAT. 1976. Astrophys. J. **207**: 907.
8. CRAMPTON, D. & J. B. HUTCHINGS. 1974. Astrophys. J. **191**: 483.
9. GIACCONI, R., H. GURSKY, E. KELLOGG, R. LEVINSON, E. SCHREIER & H. TANANBAUM. 1973. Astrophys. J. **184**: 227.
10. GOTTLIEB, E. W., E. L. WRIGHT & W. LILLER. 1975. Astrophys. J. Lett. **195**: L33.
11. HEARN, D. R., J. A. RICHARDSON & G. W. CLARK. 1977. Astrophys. J. Lett. **210**: L23.
12. HOLT, S. S., E. A. BOLDT & P. J. SERLEMITSOS. 1976. Astrophys. J. Lett. **205**: L143.
13. KRAFT, R. P. 1964. Astrophys. J. **139**: 457.
14. KRAFT, R. P. & M.-H. DEMOULIN. 1967. Astrophys. J. Lett. **150**: L183.
15. KRAFT, R. P. & W. J. LUYTEN. 1965. Astrophys. J. **142**: 1041.
16. MIDDLEDITCH, J. & J. NELSON. 1976. Astrophys. J. **208**: 567.
17. SANDAGE, A. R., P. OSMER, R. GIACCONI, P. GORENSTEIN, H. GURSKY, J. WATERS, H. BRADT, G. GARMIRE, B. V. SREEKANTAN, M. ODA, K. OSAWA & J. JUGAKU. 1966. Astrophys. J. Lett. **150**: 316.
18. SZKODY, P. & D. BROWNLEE. 1977. Astrophys. J. Lett. **212**: L113.
19. TAPIA, S. 1977. Astrophys. J. Lett. **212**: L125.
20. WRIGHT, E. L., E. W. GOTTLEIB, W. LILLER, J. GRINDLAY, H. SCHNOPPER, E. SCHREIER, H. GURSKY & D. PARSIGNAULT. 1976. Bull. Am. Astron. Soc. **8**: 441.