SPECTROSCOPY OF STELLAR X-RAY SOURCES IN THE MAGELLANIC CLOUDS

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ABSTRACT. In the Magellanic Clouds, about 75 candidate stellar X-ray sources have been detected. Most of these positions have now been investigated and optical identifications made for ~ 50%. The majority of sources are foreground dwarf stars or background active galaxies. Detailed investigations exist for 3 SMC sources and 6 LMC sources. It is possible to make a preliminary comparison with the population of galactic X-ray sources. The Magellanic Cloud X-ray binaries have a number of unique or remarkable properties and the most important ones are presented and discussed. These include the most rapid pulsars (SMC X-1, 0538-66), the possible precessing disk in LMC X-4, and the black hole candidates LMC X-3, LMC X-1. The properties of these objects relate to the evolution of stars in the Magellanic Clouds and how it differs from the Galaxy.

INTRODUCTION AND OVERVIEW

The two Magellanic Clouds offer us our best opportunity of studying complete populations of stellar X-ray sources. They are close enough for X-ray positions to yield good optical identifications, and do not suffer the large and variable optical and UV extinction found in galactic sources. We may also hope to identify optical counterparts of the principal types of known sources: OB stars, Sco X-1 like systems, and globular clusters. The X-ray properties of the Cloud sources are presumably described elsewhere in this volume (Helfand review). However, it is necessary to look briefly at the overall X-ray data base to start our discussion.

There are surveys of both Clouds, most completely made with the Einstein observatory. Seward and Mitchell (1981) report on 26 SMC field sources in ~ 40 square degrees with limiting luminosity 3×10^{35} erg s^{-1}, complete to 10^{36} erg s^{-1}. Significantly, they did not detect SMC X-2, X-3 which are two very luminous transient sources. The LMC has been surveyed by Long, Helfand and Grabelsky (1981), recently updated, with optical work, by Cowley et al. (1983). This survey covers the same area of sky and is complete to luminosities of 5×10^{35} erg s^{-1} in the LMC, and includes about 75 sources. The rough statistics of these surveys and

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their optical identifications to date, are shown in Table 1, together with some numbers for the galaxy and M31 (Crampton et al. 1983) for comparison. This table contains in parentheses my present best estimate of the final count, which will not be known for some years. Actual known numbers are given without parentheses. Estimates are all based on consideration of probable incompleteness and may be wrong by up to a factor two. With these uncertainties, not much can be said about the types and populations of the three basic source types, except that they appear to be consistent with the same basic fractions in all four galaxies, i.e. so far, no gross differences are apparent. The high X-ray luminosity of the MC sources is well known, so that the effects of the luminosity limit of the surveys is not easy to assess. If we regard the surveys as picking out the highest luminosity sources in each galaxy, the numbers suggest that this population is complete at ~ 10^{36} erg s^{-1} and that fainter sources do not occur in great numbers until say < 10^{34} erg s^{-1}. This again is consistent with what we find in the Galaxy.

TABLE 1
Approximate X-ray Source Comparison for Four Galaxies

PROPERTY	SMC	LMC	GALAXY	M31
Galaxy mass	1/60	1/10	1	2
L_x limit (erg s^{-1})	$5x10^{35}$	$5x10^{35}$	$5x10^{36}$	$5x10^{36}$
Survey area(sq°)	40	40	-	3
# Sources detected	28	75	-	>200
Foreground	2(12)	12(15)	-	(3)
AGN	2(5)	5(7)	-	(3)
SNR	4(6)	25(35)	-	(100)
Binaries	3(5)[3]	6(16)[5]	(150)	(150)
Pop I binaries	3(3)	4(8)	16(50)	22(50)
Pop II binaries	0(2)	1(8)	30(75)	20(60)
Cluster binaries	0(0)	0(0)	12(25)	25(35)

Numbers in parentheses are author's present guesses at final counts. Numbers without parentheses are present counts of identified objects, or in the case of M31, candidate objects. Numbers in square brackets give counts of identified sources to L_x $5x10^{36}$ limit.

At this stage, the completion of source identifications is necessary, requiring more accurate positions for the ~ 25 unidentified sources, before we can make detailed comparison with the Galaxy. We therefore proceed to discussion of the nine Cloud binary sources that have been identified and studied in detail. These binaries are remarkable in a number of ways, which may well relate to basic differences between the Clouds and our Galaxy. One, and quite possibly two of the 6 LMC sources contains a black hole, compared with less than one (possible) in a similar volume of Galaxy. Does this imply that stellar evolution is different in the Clouds? The cloud sources have much higher X-ray luminosities than galactic ones, as originally noted by Clark et al. (1978,9). Their supposition that the accretion rate and hence X-ray luminosity is governed by heavy element abundances which affect the opacity of an accreting cloud of gas about a compact object, seems very reasonable. The two fastest X-ray pulsars (SMC X-1 and 0538-66) are found in the Clouds, again possibly suggesting a more rapid accretion rate. The best evidence for the existence of accretion disks in massive X-ray binaries (SMC X-1, LMC X-3, LMC X-4) is found in the Cloud sources, once more suggesting high accretion rates. Finally, there are two unique systems in the LMC, the transient 0538-66, and CAL 83, which are described in the sections below.

INDIVIDUAL SOURCES

SMC X-1. This binary has all the requirements for complete mass determination - X-ray pulses, eclipses and optical radial velocities (Hutchings et al. 1977; Primini, Rappaport and Joss 1977). Rappaport (1982) summarizes Monte Carlo analysis of the basic parameters, and these are shown in Figure 1. The excellent X-ray pulse timing orbit shows up several interesting optical phenomena, which are probably general. The orbit is very circular, yet the optical radial velocities are best fit with appreciable eccentricity. Some of this can be modelled with X-ray heating and gravity darkening of the primary, but not all, and only in hindsight. Thus, the determination of orbital elements for such stars from optical spectroscopy is good to a first approximation only. Secondly, the ubiquitous He II λ 4686 emission is found to originate near to, but not at the X-ray star (see Fig. 2). From such studies, the accretion processes can be modelled, and in Fig. 2 it is seen that the entire roche lobe of the X-ray star may be occupied by an accretion disk. Van Paradijs and Zuiderwijk (1977) and Hutchings (1982) find evidence for a disk in analysis of the optical light curve. Similar conclusions are drawn from the UV light curve by Van der Klis et al. (1982). Are there other differences from galactic binaries? Not to a first approximation. The stellar masses are similar and the X-ray ionization of the stellar wind appears similar (Hutchings 1982,3) (Fig. 3). More detailed study of the UV resonance lines will probably show up stellar wind differences from the galaxy (Hammerschlag-Hensberge, Kallman and Howarth 1983), but will need careful work and, possibly, ST spectrographs.

SMC X-2,3. Very little has been done on these two sources, seen only once as very bright transients (Clark et al. 1978). The two proposed optical counterparts were observed by Crampton, Hutchings and Cowley (1978). They found both stars to be SMC members of type late O with weak lines, and weak He II emission. These sources need better positions to confirm the optical identifications, and the stars need better and more extensive observation if they are indeed the right ones.

LMC X-1. The identification of this source has been difficult

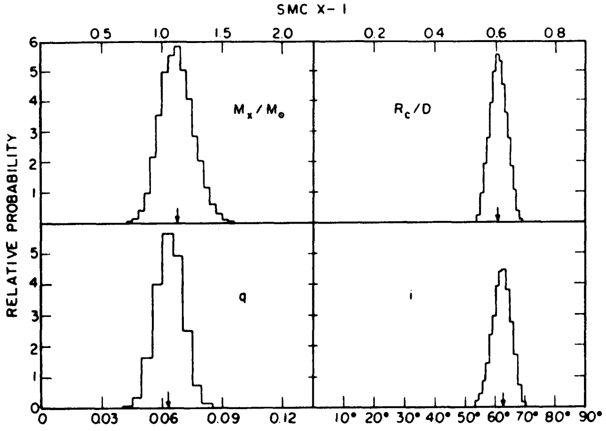

Fig. 1. Monte Carlo simulation of SMC X-1 binary parameters by Rappaport (1982).
Rc = primary radius
D = separation
q = mass ratio

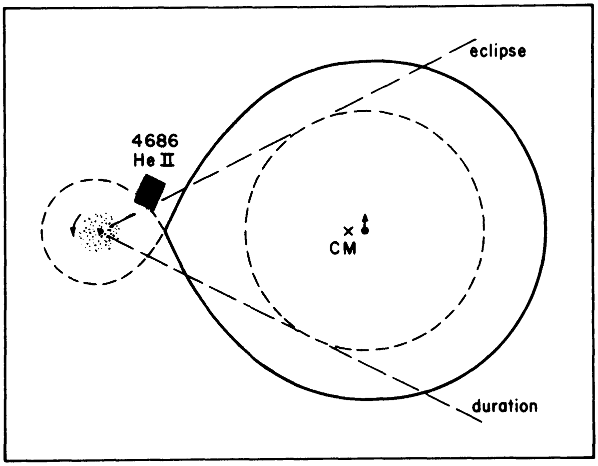

Fig. 2. Sketch in orbit plane of SMC X-1, typical of pop I sources. Note He II emission region offset from X-ray star.

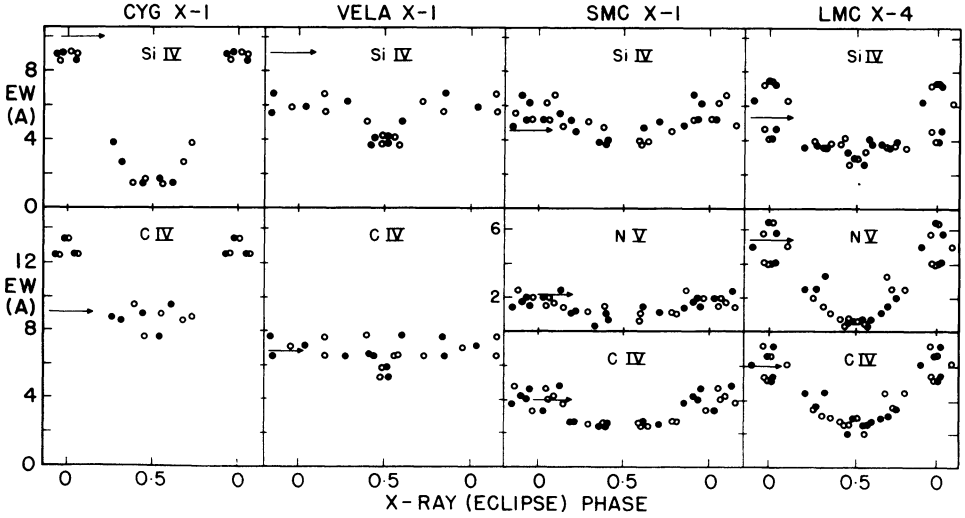

Fig. 3. Modulation of UV wind resonance lines with orbit phase due to X-ray ionisation.

because two excellent candidate stars lie within ~ 3 arcsec of the X-ray position. Both have variable velocity and lie in a nebula with λ 4686 emission. Very recently (Hutchings, Crampton and Cowley 1983) the fainter star has been found to be an O-type binary of ~ 4 day period, with antiphased N III λ 4640 emission (λ 4686 is overlaid by nebular emission). The brighter candidate star is a supergiant B star, with velocity variations typical of supergiants and no discernable period. Assuming the fainter star to be the correct one, the companion appears to have a mass between 2.5 and 8 $M_\odot$ (Fig. 4), making it a black hole candidate of very similar characteristics to Cyg X-1.

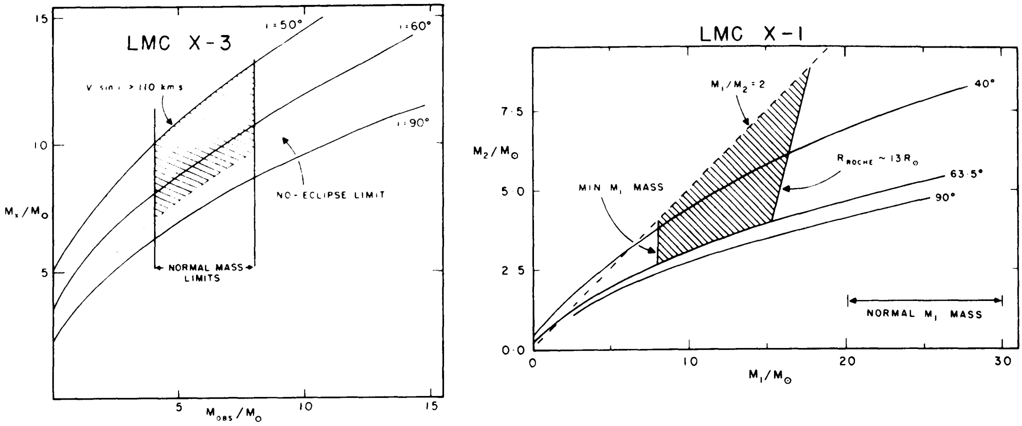

Fig. 4. Component masses in two black hole binary candidate systems in LMC, based on optical spectra. Shaded areas are allowed locations.

<u>LMC X-2</u>. This is identified with a faint blue star (~ 18m) with He II emission (Pakull and Swings 1979). Its velocity is somewhat low for the LMC and it is not completely certain that it is not a foreground object in the galactic halo. Little is known about it to date.

<u>LMC X-3</u>. This source is identified with a B type star, in a binary orbit of 1.7 day period with a very large (235 km s^{-1}) orbital velocity. The X-ray star in this system has a mass in the range 7-13 $M_\odot$ (Cowley, et al. 1983) and appears to be the strongest case yet found for a stellar black hole (Fig. 4). The overall weakness of the B star absorption lines and the large photometric variation of the system are evidence for the existence of a luminous accretion disk in this system. Unfortunately the star is too faint to be observed in the UV until ST is launched.

<u>LMC X-4</u>. This is another well-studied binary, as the X-ray data show pulses, eclipses, and a 30-day cycle similar to the Her X-1 precession cycle, and thought to be the same phenomenon (Li, Rappaport, Epstein 1978, White 1978, Chevalier and Ilovaisky 1977, Lang et al. 1981, Kelley et al. 1982, Van der Klis et al. 1982). The UV and optical light curves show time changes (Fig. 5) which are probably related to the 30-day cycle and can be modelled as precession of a luminous disk.

Optical orbit determinations by Hutchings, Crampton and Cowley (1978) and Petro and Hiltner (1982) show some disagreement in orbital amplitudes which may relate to variable "complications" connected with a disk precession, although they are not obviously 30-day phase related. This system is the only massive binary in which the three clocks are present (pulse, orbit and precession) and it offers a unique laboratory for studies of variable X-ray illumination, stellar wind modification, and disk behaviour, and should be the subject of detailed spectroscopy with ST.

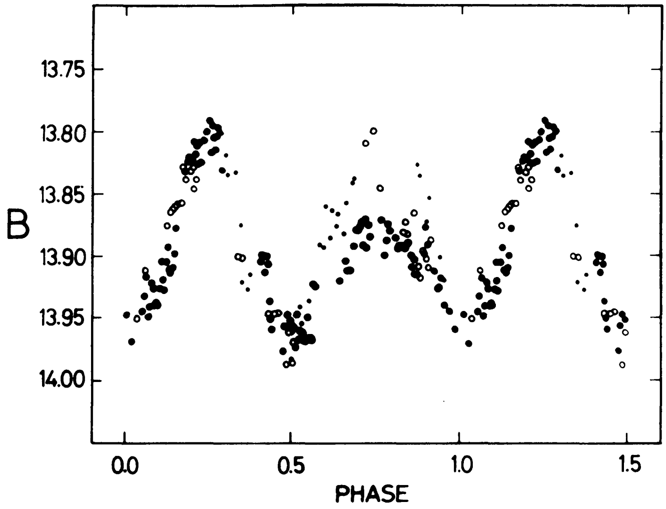

Fig. 5. Light curve of LMC X-4 showing 30-day phase variation, probably due to disk precession and changing X-ray heating (from Chevalier and Ilovaisky 1977).

<u>0538-66</u>. This is perhaps the strangest of the Cloud binaries. It is very variable, peaking at ~10^{39} erg s^{-1}, and has the very rapid pulse period of 69 milliseconds (Skinner et al. 1982). The system contains a B star, whose spectrum so far has been rarely seen, as the binary has been in an extended state of optical emission for a period of some two years. During this time the spectrum has pronounced P Cygni characteristics, modulated very strongly on the known 16.5 day X-ray intensity period (Figure 6). This long period, presumably that of the binary orbit, makes for difficult observing, but limited pulse arrival timing data suggest orbital motions. Charles et al. (1982) and Howarth et al. (1983) discuss much of the spectroscopic evidence and possible models for the system. It seems generally accepted that the primary in quiescence is a somewhat inactive B star or rapid rotator (Be), and that the X-ray activity arises from a very eccentric orbit of the pulsar, which brings it close to the B star surface. During the extended high states, the B star photosphere becomes very extended and possibly kept that way by strong X-ray heating. Mass-loss from the system must be very high at such times, and both the high X-ray luminosity and the very rapid pulse period indicate a high accretion rate by the pulsar. An alternative possibility is that a massive accretion disk builds up and dominates the optical luminosity. Until orbital parameters are derived for this system, and the full range of its activity is studied, many questions will remain unanswered. So far, the system is without parallel in other known X-ray binaries.

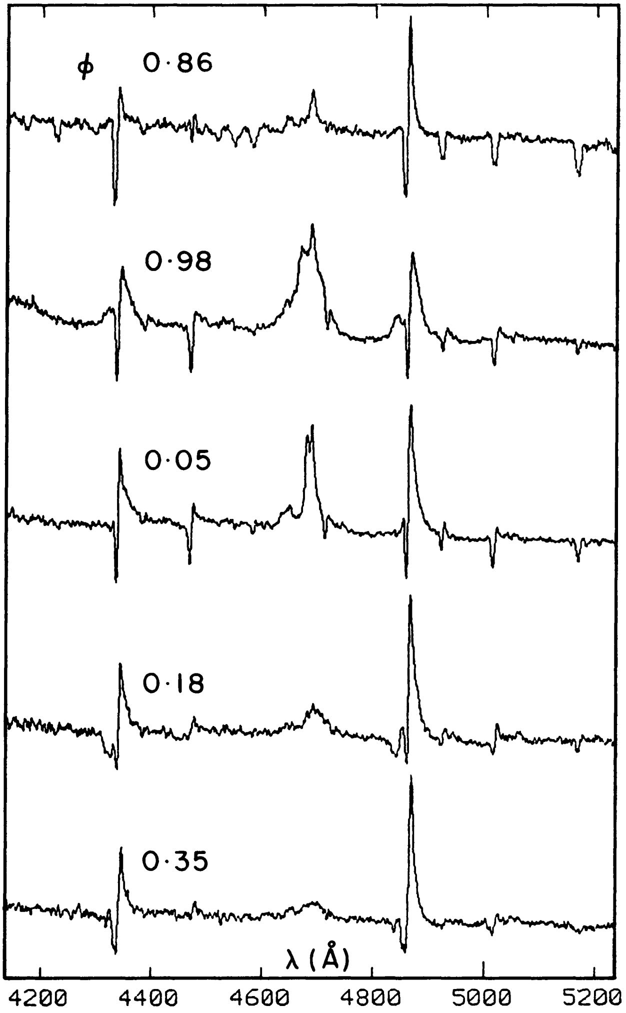

Fig. 6. Sequence of spectra of 0538-66 showing modulation of P Cygni type spectrum through X-ray maximum phase. All data are from the same cycle. (from I.B. Thompson, private communication)

CAL 83. This final identified source is faint and also unique. The star has a very broad emission complex in the λ4600-4700 region, and this is the principal line feature. In this respect it is perhaps similar to the galactic burst source 1735-44 (Hutchings, Cowley, Crampton, 1982). Velocity measures so far have suggested periods in the range of a few days or near one day, but the amplitude is so low that unlikely masses or orbital indications are required. It seems more likely that the velocities are not purely orbital, perhaps arising between the stars in the system. The λ4686 profile shows very rapid profile variations. The object has a luminosity similar to Sco X-1 and on this basis it is probably of low mass. Further study is needed to examine the unique properties of this object.

CONCLUSION

To conclude, it is clear that the full identification and study of Cloud X-ray sources is far from complete yet. Work to date has discovered a small number of very important binary sources, whose study has already suggested that a single parameter - the heavy element abundance - may account for a number of differences between Cloud and Galaxy sources. (However, we need to consider carefully whether the galactic halo sources should not also show these differences). A full understanding of these differences will almost certainly relate strongly to our understanding of stellar evolution and history in the Magellanic Clouds. Aside from the questions and needs already stated, I feel it is also important to study a number of normal binaries in the clouds, and at present we have little idea as to how fundamental normal stellar parameters may differ from those in the Galaxy.

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