BINARY X-RAY SOURCES IN THE LMC

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ABSTRACT. We report new results on the X-ray binaries in the LMC since IAU Symposium 108 (see review by Hutchings 1984). These include an update of the point source identifications after further optical observations and a reprocessing of the Einstein database. We report major new results on several specific systems. Among low-mass systems (LMXB), we report periods and orbital determinations for LMC X-2 (long period), CAL 83, and CAL 87 (eclipsing black-hole binary). For the high-mass X-ray binaries (MXRB), we announce an $\sim$ 99 day (precession?) period in LMC X-3 and discuss orbital determinations for LMC X-1 and 0538−66.

1. Source counts

Wang *et al.* (1990) have reanalysed the Einstein database on the LMC and have a new list of 105 sources with $> 4\sigma$ detections. Thirty three of these are new, and 25 of the original ('CAL') list of 97 by Long *et al.*(1981) are omitted. Fifty of these sources are identified optically, as follows (with mean IPC counts in parentheses): 28 SNR (0.40); 13 foreground stars (0.03); three background AGN (0.03); six LMC binaries (down to 0.02). Of the remaining 55 unidentified sources, 20 are associated with OB stars or H II regions (0.03), and 35 have no known optical counterparts (0.01). Based on the fluxes, X-ray spectra, and deep survey results, we estimate the probable identifications for these 55 sources to be: $\sim$ 20 LMC SNR; $\sim$ 25 background faint AGN; $\sim$ 7 foreground stars; and perhaps up to three LMC binaries. For sources at the distance of the LMC, the luminosity limit is very roughly 10^{35} erg.sec^{-1}. In addition to the sources in this new list, we know of three additional LMC X-ray binaries: 0535−668, and 053109−66092 (Pakull *et al.* 1985) - both Be transients which were 'off' during the Einstein observations - and LMC X-3 (outside the area surveyed). Of the six 'identified' stellar sources, two are high-mass binaries (LMC X-1 and X-4), and one is an O star candidate (CAL 9) not yet confirmed as a binary. Thus, the LMC X-ray binary population is dominated by high mass systems (6/9), in contrast with the situation in the Galaxy where only $\sim$ 20% are MXRB. Furthermore, there are three black-hole candidates among the LMC sources; approximately 10 times the relative population in the Galaxy.

2. Low-mass systems

There are three identified 'low-mass' X-ray binaries in the LMC: LMC X-2, CAL 83, and CAL 87. They are all optically faint and have weak line features, so that optical spectroscopy has been difficult and time consuming. CCD photometry has been instrumental in determining their orbital periods. We note that these systems differ from the average Galactic LMXBs in having longer periods and, as noted above, a much smaller number of low-mass systems than expected. Based on the relative masses of the Milky Way and the LMC, one would have expected $\sim$ 15 LMXB in the Large Cloud.

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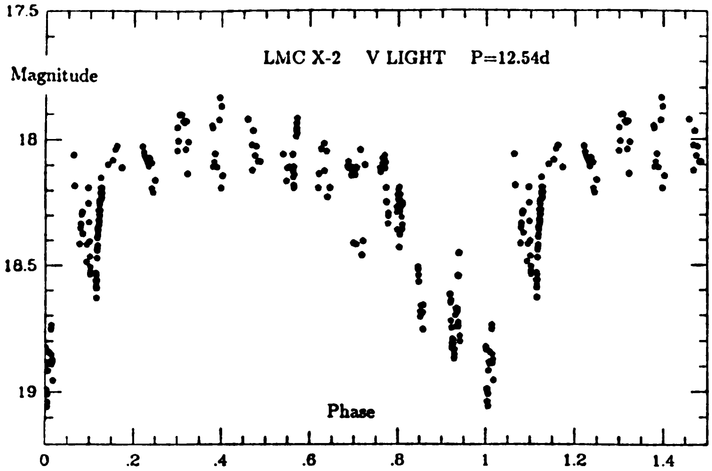

Figure 1. Light-curve of LMC X-2, combining all V data on 12.54 day period.

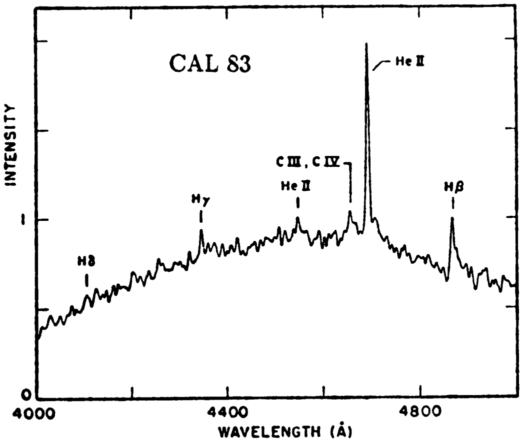

Figure 2. Mean blue spectrum of CAL 83, with principal emission features identified. He II 4686A strength indicates large intrinsic X-ray luminosity. Line base asymmetry varies over long timescales.

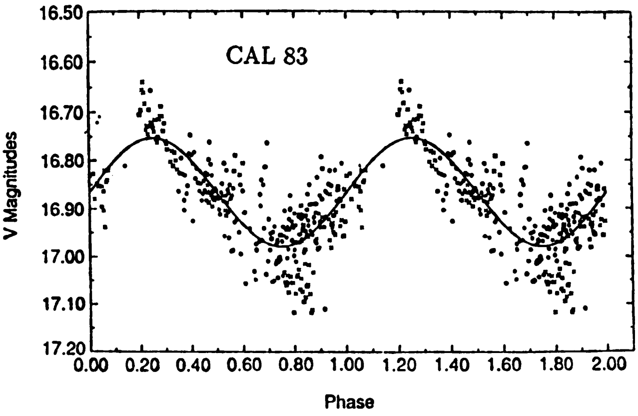

Figure 3. Light-curve of CAL 83 in V band from Smale *et al* 1988.

2.1 LMC X-2. (0521.3-7201)

Many years after its identification, this faint system has been found to have a long period (12.5 days; Crampton *et al.* 1990) (Figure 1), similar to Cyg X-2 and 0921−63. Thus, it presumably contains an evolved subgiant secondary. The secondary spectrum is not detected in the blue, but weak absorption lines of the Ca II infrared triplet at ~ 8600A are present at the 15% level (Cowley *et al.* 1990b). However, they are too weak to measure the star's radial velocity. Recent photometry confirms that the period is ~ 12.59 days. The velocity behavior of the He II (4686A) emission line suggests its origin is near the X-ray star and that masses are typical of LMXBs.

2.2 CAL 83. (0543.8-6823)

This is another faint system, observed for several years. Analysis of much data (Crampton *et al.* 1987, Smale *et al.* 1988 suggests a period of 1.04d for this system. The spectrum shows He II and Balmer emission and weak C III, C IV (and N V in the far UV). Radial velocity variations indicate typical LMXB masses. The He II emission lines show an asymmetry which may have a long period (69d?), perhaps indicating a disk precession. Figure 2 shows the mean spectrum of the system. The light-curve is roughly sinusoidal with an amplitude of ~ 0.25 mag. (Figure 3), but it has not been modelled in detail. Based on the He II 4686A line strength, the source-intrinsic X-ray luminosity is thought to be very high, and probably it is shielded from us by the accretion disk.

2.3 CAL 87. (0547.5-7110)

This faint system has recently been found to be eclipsing from optical data (Naylor *et al.* 1989). The broad, deep eclipses (Fig 4) and orbital mass function strongly suggest that the X-ray star has a mass large enough ($>5M_{\odot}$) to be a black hole (Cowley *et al.* 1990a)(Fig 5). We have recently found that there is a faint F-G star ~ 0.5 arcsec away which means that the true light mimimum is deeper than measured. In the near infrared a late type spectrum is marginally detected, but its velocity indicates that it is mainly due to this nearby field star. CAL 87 has similar masses to the Galactic black-hole binary 0620−00 (McClintock and Remillard 1986). Study of the spectrum and X-rays through eclipse offers the opportunity to learn about the structure of an accretion disk near a black hole.

3. High mass binaries

We give below a summary of work since 1984 on the previously known LMXBs: LMC X-1, LMC X-3, and 0538−68. Before doing so we also note that there are two other binary candidates: CAL 9 (Crampton *et al.* 1985) and a Be star for the transient X-ray source 053109−66092. Neither of these is established as a binary and both have (or have times of) weak X-ray flux. Further observations are required for these. We also note that Seward *et al.* (1984) found a pulsar in the SNR CAL 79, which is similar to the Crab pulsar. However, there is no indication that it is a binary. So far, no pulsar has been detected in SN 1987a.

3.1 LMC X-3 (0538.8-6406)

A number of new observations of this massive system has been made, including optical photometry, UV spectra (with IUE), and X-ray observations with EXOSAT and Ginga. Optical photometry (van Paradijs *et al.* 1987; Kuiper *et al.* 1988) reveals a double-peaked 'ellipsoidal' light-curve supporting the high mass of the collapsed star originally presented by Cowley *et al.* (1983). However, analysis of the light curve (Khruzina and Cherepashchuk 1984; Bochkarev *et al.* 1988; Kuiper *et al.* 1988) is subject to a number of free parameters describing disk shadowing and irradiation. Furthermore, the light curve also changes systematically, with longer-term changes in the mean light level (van

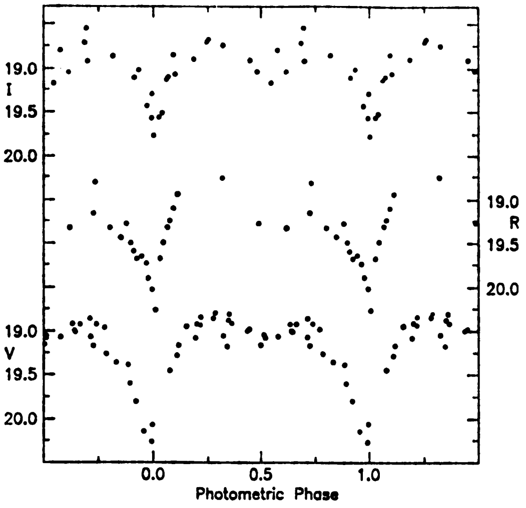

Figure 4. Light-curves of CAL 87, corrected for companion star. Note deep primary eclipse and colour changes.

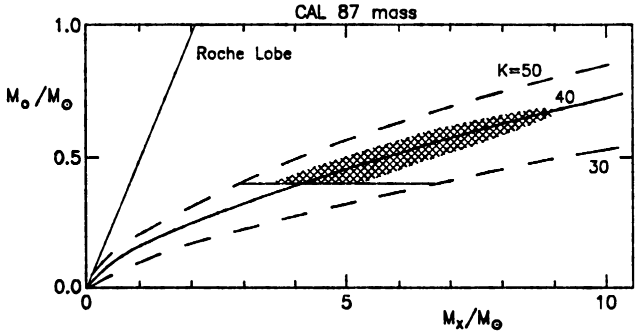

Figure 5. Masses of CAL 87 stars for limiting values of K. Main sequence Roche lobes do not fit, as shown by line. Low mass limit set by evolution timescale.

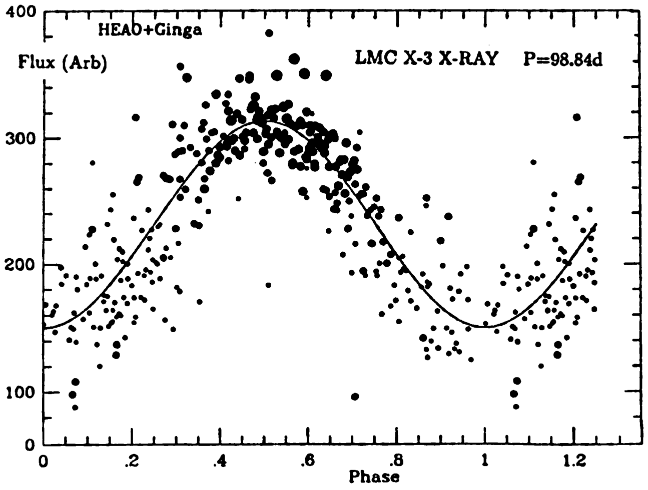

Figure 6. Combined HEAO and Ginga X-ray data for LMC X-3, on 99 day period. Weights indicated by point sizes. Curve is best sine fit.

Paradijs *et al.* 1987). A critical discussion of th e spectroscopic masses was given by Mazeh *et al.* (1986), which generally supports the original black-hole model. Unpublished spectra of ours continue to confirm the orbital parameters.

The UV spectrum as observed with IUE (Treves *et al.* 1988) indicates the presence of a luminous disk in the system, of variable luminosity. Modelling suggests an orbital inclination of 55^0.

We have obtained extended X-ray monitoring with Ginga. Together with HEAO-1 archival X-ray data we find strong evidence for a ~99 day period (Fig 6). The mean optical light level varies, possibly with the X-ray intensity. It is probable that this is caused by a disk precession. This new result affects all the spectroscopic and photometric analyses, and also may be an important way of modelling the disk and accretion processes in this object.

3.2 LMC X-1 (0540.1-6946)

This massive binary is also a black-hole candidate. There has been some uncertainty in the identification based on X-ray position alone, between R148 and the assumed 4-day binary star #32 (Cowley *et al.* 1978). Pakull and Angebault (1986) found an ionised nebula centered on star #32 and proposed that it is the optical counterpart, with the nebula being photoionised by the X-rays. This constitutes a valuable new tool for studying the EUV flux of the source. IUE UV spectra, published by Bianchi and Pakull (1985) and Hutchings *et al.* (1987), are variable but not strongly phase-modulated. The optical orbit was refined by Hutchings *et al.* , and continues to indicate a high-mass X-ray source.

Ebisawa *et al.* (1989) report that QPOs from LMC X-1 in its high state were observed by Ginga. They discuss possible implications of these pulses and their relatively long period (13 sec). They also point out the similarities in X-ray behavior and spectrum with the other black-hole systems Cyg X-1 and LMC X-3.

3.3 0535−668

This Be-star transient has a long (16.5d) orbital period. During extended high states the spectrum shows strong emission line fluxes during and after X-ray maximum which are assumed due to periastron effects in an eccentric orbit. The system was in a low state in 1984, presenting an opportunity to measure the radial velocity curve of the primary star and obtain an orbit. This was done by Corbet *et al.* (1985) and Hutchings *et al.* (1985), with different results. The crucial spectra obtained near periastron passage were the main cause of the difference. Smale and Charles (1989) discuss the matter and suggest that weak variable line emission may be responsible. It seems likely in any event that the orbit is highly eccentric ($e>0.8$) and that the component masses are normal for a B star and a neutron star.

IUE UV spectra of the system, obtained over a long interval, are discussed by Howarth *et al.* (1984). Their results confirm the Be nature of the primary and show some of its changes with X-ray state.

4. Conclusion

The LMC X-ray source population differs from the Galaxy in several significant ways. It contains few low-mass systems, emphasizing the relative lack of old population stars in the LMC. The three such systems known have high optical (and probably X-ray) luminosity and longer orbital periods than typical Galactic bulge sources. X-ray binary luminosities are either observed to very high compared with Galactic sources, or they are inferred to be high, but hidden from us by a thick accretion disk. The opacity of low metal abundance material in accretion phenomena is the likely cause of these differences. Finally, a high fraction of the X-ray sources have masses above the neutron star limit. Thus, the end stages of stellar evolution in the LMC appear to differ from the galaxy.

We anticipate that the Rosat survey will provide an independent survey of the LMC, probably discovering more transients. More importantly, it will also provide us with the first deep survey of the SMC, which was not performed with the Einstein observatory.

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