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Letter to the Editor

LHG 87, a new low-mass eclipsing X-ray binary in the LMC*

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Summary: We report the identification of the faint and soft EINSTEIN point source LHG 87 as a low-mass X-ray binary in the Large Magellanic Cloud. The 19 mag optical counterpart displays a spectrum characteristic of X-ray heated accretion disks. The Bowen excited NIII complex is much less intense than the HeII λ4686 emission, indicating low metal abundance. From the optical light curve we find evidence for a deep eclipse of the accretion disk by the secondary star. Therefore the X-ray source may be hidden from direct view and be intrinsically as bright as the luminous low-mass X-ray binary LMC X-2 which has a disk of comparable optical brightness. Scattering of X-rays, however, does not readily explain the extreme softness of the X-ray spectrum which has a blackbody temperature kT ~ 0.1 keV. In this respect, the system is similar to LHG 83 and both differ significantly from the known galactic low-mass X-ray binaries.

Key words: Low-mass X-ray binaries – stars: neutron – spectroscopy – photometry

1. Introduction

The optical counterparts of luminous low-mass X-ray binaries (LMXB) are blue UV-excess stars with a smooth energy distribution on which relatively weak HeII λ 4686, NIII λλ4634-41 (EW ≲ 10 Å), and sometimes H-Balmer and HeI emission lines are superimposed (see e.g. the compilation of line strengths by van Paradijs and Verbunt, 1984). Van Paradijs (1981) has surveyed the photometric properties of LMXB and found that their absolute magnitudes and colours are typically in the range of M_V = 2-0 and B-V between -0.25 and 0.25, respectively. These spectra are believed to represent X-ray heated accretion discs around the compact (neutron-star or black-hole) binary components with some contribution due to the X-ray heated part of the companion star not shielded from X-rays by the accretion disk. Although the spatial extensions and mass-flux rates in LMXB are comparable to those in some cataclysmic variables, the accretion disc spectra of the latter are typically at least 3 mag fainter and show in general much stronger emission lines (EW ~30 to 100 Å, van Paradijs and Verbunt, 1984). These differences indicate that X-ray heating plays the dominant role for the optical (and UV) emission in LMXB. This view is also supported by observations of optical bursts which follow the X-ray bursts and are due to light reprocessed in the disk (Pedersen et al., 1987). Unfortunately, many of the most luminious LMXB (L_x ~ 10^{38} ergs s^{-1}) reside in the galactic bulge, where high interstellar absorption inhibits their optical identification.

For the relatively nearby Magellanic Clouds, the observational situation is reversed: here we lack presently the necessary sensitivity to explore the X-ray properties in detail, such as the quasi-periodic X-ray oscillations (e.g. Lewin, van Paradijs and van der Klis, 1988), or to follow the long-term behaviour of the X-ray flux with small non-imaging satellites. On the other hand, the quality of optical and UV investigations of the counterparts of LMC X-ray binaries is comparable to, or even surpasses, that of the galactic sources since interstellar absorption towards and within the Magellanic Clouds is of relatively minor importance. Another advantage of these investigations is the relatively well established distance to the Clouds which allows to directly convert observed fluxes into luminosities. This is not possible for many galactic sources given the often ill-known distances.

Up to now only two low mass X-ray binaries are known in the Magellanic Clouds. LMC X-2 (Pakull und Swings, 1979; Motch et al., 1985; Bonnet-Bidaud et al., 1988) has a high X-ray luminosity of ~2 10^{38} ergs s^{-1} and a 19 mag "UV-excess" optical counterpart and in many respects resembles the galactic LMXB. The other source, LHG 83 (Pakull, Ilovaisky, and Chevalier, 1985; Crampton et al., 1987, Smale et al., 1988), on the other hand differs substantially from the galactic sources in that it has an extremely soft X-ray spectrum, a very low X-ray to optical luminosity ratio, an unusual optical spectrum (displaying, for instance OVI emission lines), and is surrounded by a spatially resolved highly excited emission line region (Pakull and Angebault, 1986).

In this Letter we report the discovery of a third LMXB in the LMC, which from its optical spectrum appears to be a twin of LMC X-2, but which has a very soft X-ray spectrum similar to that of LHG 83. In addition, we present evidence that this source, LHG 87 (Long, Helfand, and Grabelsky, 1981), is an eclipsing system. Hence, its inclination can be estimated relatively accurately.

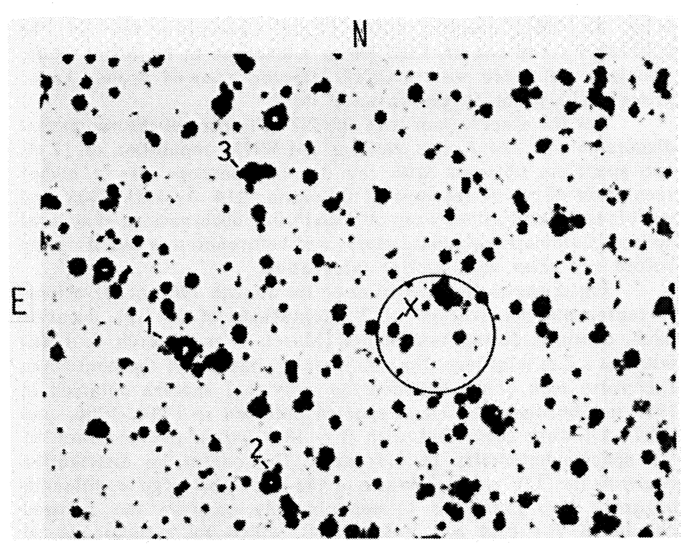

Fig. 1: Finding chart for LHG 87 prepared from a V-band CCD image. Stars 1, 2, and 3 refer to the denotations by Crampton et al. (1985). The error circle has a radius of 10 arcsec. Scale is 1.3×1.7 arcmin.

* Based in part on observations collected at the European Southern Observatory with the 2.2 m telescope of the Max-Planck Society, the ESO 3.6 m telescope and the Danish 1.5 m telescope.

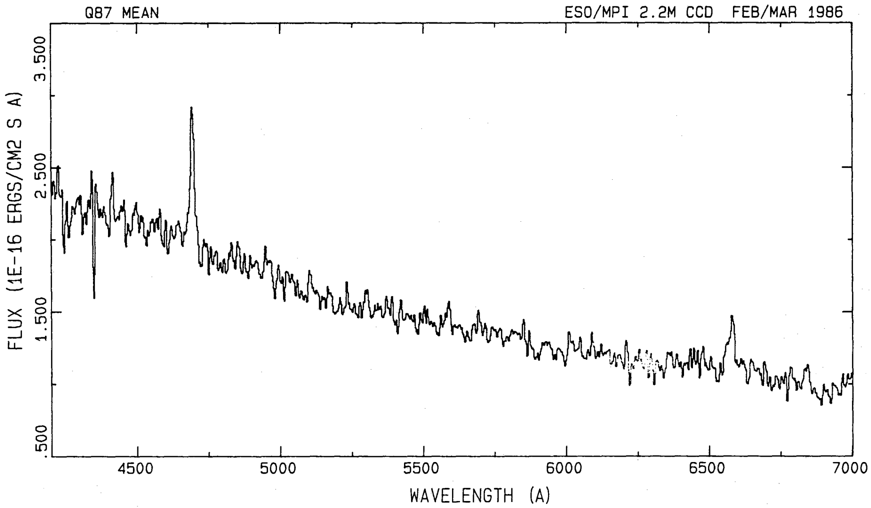

Fig. 2: Mean flux-calibrated spectrum of LHG 87 obtained on 1986 March 1 and 2. Total exposure time is 210 min.

2. Observations

As a first step towards optical identifications of LMC X-ray sources (Long, Helfand, and Grabelsky, 1981), ESO UBVRI Schmidt plates were searched visually for the presence of stellar objects in the vicinity of the X-ray position which displayed unusual colours. In this way, very red stars, e.g. foreground M stars with coronal X-ray emission and faint "UV-excess" objects, which could either be background AGNs, foreground CVs, or LMXB in the LMC, can easily be distinguished.

Fig. 1 shows the 10 arcsec radius error circle of LHG 87 (Cowley et al., 1984) superimposed on a V band CCD image of the field. Note that the finding chart given by Crampton et al. (1985) does not refer to the correct position of LHG 87. The star marked within the error circle exhibits by far the bluest colours as compared to the surrounding objects (these eye estimates cannot be easily quantified, however). A comparison of several Schmidt plates exposed with the same filter/emulsion combination, furthermore, indicates photometric variability within the range of 0.5-1 mag. For this reason, we performed further spectroscopy and photometry on this system.

a) Spectroscopy

Spectrophotometric observations of the "UV excess" star were secured in October 1984, March 1986, and January 1987, using the B&C spectrographs in the Cassegrain foci of the ESO/MPI 2.2 m and the ESO 3.6 m telescopes at La Silla, Chile. The long-slit mode with a CCD detector allowed proper background subtraction in the crowded field.

For the observations with the 2.2 m telescope the reciprocal dispersion was 224 Å/mm yielding a FWHM resolution of 12 Å, one spectrum obtained with the 3.6 m telescope has a higher resolution of ~6 Å (reciprocal dispersion 114 Å/mm). Flux and wavelength calibrations were obtained using observations of several spectrophotometric standard stars, and reference to a He-Ar lamp before and after each stellar integration.

Fig. 2 shows the spectrum of the March 1986 observations. It represents the average of 7 integrations of 30 min duration each, obtained during two nights (March 1 and March 2, 1986) with the 2.2 m telescope. No significant variations of the continuum flux were seen either between the individual spectra obtained in 1986 nor between the mean spectra obtained in 1984, 1986, and 1987. All were consistent with B ~ 18.9 within the accuracy of the spectrophotometry (± 0.3 mag). The continuum distribution confirms the "UV-excess" nature of the star. The large wavelength coverage also permitted to appoximately compute the Johnson colours B-V = 0.14 and V-R = 0.30, which we estimate to be accurate to within 0.06 mag. These colours have still to be corrected for reddening in the galaxy and possibly in the LMC. Hence, the system is intrinsically somewhat bluer with $(B-V)_0 \simeq 0.0$ (based on the galactic hydrogen column density, Heiles and Cleary, 1979). The only conspicuous spectral features are the HeII λ4686 emission line with a mean equivalent width (EW) of 8.3 Å and Hα in emission (EW 8 Å). Upper limits of ~ 3 Å are found for the EW of Hβ and the NIII λλ4634-41 complex. The latter is often of comparable strength to λ4686 in galactic LMXB. In our higher-resolution spectrum (observed in January 1987), the HeII λ4686 emission is clearly resolved with a FWHM (corrected for intrumental broadening) of 11 Å corresponding to a HWHM velocity of ~ 350 km s^{-1}. The EW of the line (~ 14 Å) was higher than found in 1986. No significant assymetry of the line is apparent.

The radial velocity (RV) of the λ4686 emission obtained by fitting a Gaussian to the line varied between 430 and 180 km s^{-1} (cf. Table 1). This is consistent with binary motion with an amplitude of about 120 km s^{-1} around a mean velocity of ~ 300 km s^{-1}. The latter value corresponds to the RV of HI in that part of the LMC (Rohlfs et al., 1984). This fact combined with the observed brightness and spectral characteristics leaves little doubt that LHG 87 is a LMXB in the Large Magellanic Cloud.

b) Photometry

During one night (January 23, 1988) LHG 87 was continuiously monitored for four hours in the Johnson B band with integration times of 6 min, using the CCD detector on the Danish 1.5 m telescope in La Silla. Differential magnitudes relative to six comparison stars were computed and the zero point of photometry was determined from observations of local standards in the LMC X-3 field. From the relative magnitudes of the comparison stars having similar brightness as LHG 87 we estimate a probable error (1σ) of 0.02-0.03 mag for the individual integrations. The lightcurve (Fig. 3) shows a continuous rise in

Table 1. Spectrophotometric Observations of LHG 87

Date	Exposure (min)	RV(4686)[4] (km/s)	EW(4686)[4] (Å)
1984 Oct 24[1]	20	300±100	24±10
1986 Mar 1[2]	120	430± 60	7± 2
1986 Mar 2[2]	90	325± 50	11± 2
1987 Jan 5[3]	30	175± 40	14± 2

[1] ESO 3.6 m Telescope, FWHM resolution 12Å
[2] ESO/MPI 2.2 m Telescope, FWHM resolution 12 Å
[3] ESO 3.6 m telescope, FWHM resolution 6 Å
[4] 1σ errors

brightness from B ~ 19.8 to B ~ 18.9 about 1.6 hours later. After that the brightness stays approximately constant at B ~ 18.9 for the remaining part of the observation (about 2.5 hours). Compared to most other optical counterparts the light variation of LHG 87 appears to be relatively smooth and strongly suggests that the initial rise should be interpreted as part of an eclipse which is at least 0.9 mag deep and has a full width of at least 3 hours. On the only condition that the components do not overfill their Roche lobes, the minimum implied orbital period is about 15 hours. For such a period, the relative width of the eclipse is equivalent to that observed in the optical light curve of EXO0748-676 (Crampton et al., 1986), and in many cataclysmic variables (see e.g. Horne, 1985).

In summary, the identification of LHG 87 as an LMXB rests on the following points. (i) The absolute magnitude ($M_V \sim 0.0$), the colour, and the spectral characteristics of the disk are typical of LMXB (van Paradijs, 1981). (ii) The radial velocity indicates LMC membership, and (iii) the lack of absorption-line spectral features indicates a spectral type later than F for a main sequence secondary.

c) X-ray

In the catalogue of EINSTEIN sources in the LMC field, Long, Helfand, and Grabelsky (1981) reported an IPC countrate for LHG 87 of 0.044 counts s^{-1}. Using the spectral-shape parameter Q = (H-S)/(H+S), it appears that the spectrum of LHG 87 is extremely soft with Q= -0.7. Here, H and S indicate the count rates in the 1.5-4.5 keV, and 0.15-1.5 keV energy ranges, respectively. The negative value of Q implies that most X-ray photons were recorded at energies E < 1.5 keV. This was confirmed by a blackbody fit to the reprocessed IPC net countrate spectrum of the source (sequence number 5845) which yielded kT between 0.03 and 0.20 keV for $N_H \lesssim 10^{22}$ H-atoms cm^{-2} (D. Harris and F. Seward, private communication). The 0.1 - 2.0 keV X-ray luminosity is $L_x \simeq 10^{36}$ (d/55 kpc)^2 ergs s^{-1} for $N_H \simeq 8\times10^{20}$ H-atoms cm^{-2} (galactic gas only, Heiles and Cleary, 1979) but may exceed 10^{38} ergs s^{-1} for $N_H \simeq 3\times10^{21}$ H-atoms cm^{-2} (galactic + LMC gas, e.g. Rohlfs et al., 1984). The softness of this spectrum is only rivalled by that of LHG 83 with Q = -0.9. These spectra are much softer than those of the other non-pulsating LMC X-ray binaries which already have unusually soft X-ray spectra (White and Marshall, 1984, for LMC X-1 and X-3; Long, Helfand, and Grabelsky, 1981, for LMC X-2 and LMC X-1 with Q = 0.1 and 0.3, respectively). Further evidence for an extremely soft X-ray spectrum of LHG 87 is provided by the IPC/HRI countrate ratio which was reported to be 1.3 by Cowley et al.. (1984).

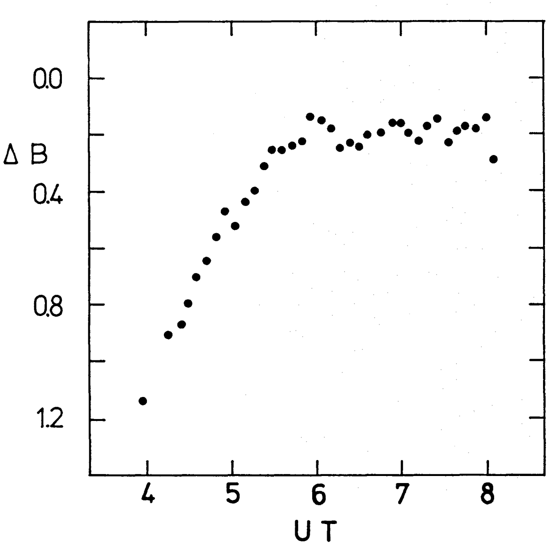

Fig. 3: B-band light curve of LHG 87 obtained on 1988 January 23. Individual data points refer to integration times of 6 min each. The zero point of the photometry refers to B = 18.70.

3. Discussion

Our conclusion that the soft X-ray source LHG 87 is a low-mass X-ray binary in the LMC raises several questions concerning our understanding of the system. To begin with, we note that the optical luminosity of LHG 87 is approximately equal to that of the "classical" high-luminosity source LMC X-2, whereas the IPC countrates differ by a factor of ~ 200 (Long, Helfand, and Grabelsky, 1981; Cowley et al., 1984). The optical observations suggest that in both cases we are seeing X-ray heated (T_{eff} ~ 30 000 K) accretion discs of similar dimensions and that the contributions of the secondaries (mass-donating stars) are negligible. For galactic LMXB with low **apparent** L_x/L_{opt} ratios (e.g. X0921-63, Chevalier and Ilovaisky, 1981) it has been suggested that the X-ray sources are hidden from direct view by the high inclination of the system and that, accordingly, we see only that fraction of the X-ray flux which is scattered by an accretion disc corona into the line of sight (White and Holt, 1982). A high orbital inclination is suggested for the LHG 87 system since the observed shape of the light curve most probably reflects an eclipse of the accretion disc by the secondary star. Although our observations unfortunately did not cover a complete orbital cycle, a lower limit of ~ 15 hours could be inferred for the orbital period. An orbital period of 15-20 hours is consistent with a 1.4 $M_\odot$ neutron star primary and a low-mass secondary which may be slightly evolved.

For such a system, the expected radial-velocity amplitude of the primary and the surrounding disc would be of the order of 100-200 km s^{-1} which is compatible with the observed range of velocities. If, on the other hand, the accreting star is a black hole with M > 3$M_\odot$, the expected RV variations would drop below the observed range. Such an interpretation is still possible, however, if the observed velocity changes do not reflect Keplerian motions.

Spectroscopically, LHG 87 is very similar to LMC X-2. In both systems, only HeII λ4686 and Hα emission have definitely been detected, whereas the Bowen-excited NIII complex is missing. In most galactic sources, on the other hand, these two emissions are of comparable intensity (van Paradijs and Verbunt, 1984; C. Motch, private communication). This difference is presently not well unterstood but is probably related to the lower metallicity of the LMC as compared to the Galaxy in general. This interpretation is supported by the unusual absence of the Bowen line in the globular-cluster X-ray source in M 15 (Aurière and Ilovaisky, 1988) which has an unusually low metallicity even among galactic globular clusters (Zinn, 1985).

In spite of the optical similarity to LMC X-2, the softness of the X-ray spectrum of LHG 87 as compared to LMC X-2 is a puzzling feature. While the low intensity of LHG 87 might be due to its high orbital inclination, the softness of the X-ray spectrum is not compatible with an origin in an accretion disc corona (White and Holt, 1982).

LHG 83 is another variable X-ray source in the LMC which displays an extremely soft (and in this case better defined) X-ray spectrum with kT ≤ 0.1 keV (Seward, private communication). This source is also interpreted as a LMXB (Pakull, Ilovaisky, and Chevalier, 1985; Crampton et al., 1987,Smale et al., 1988). Both sources display a remarkably similar X-ray vs. optical flux ratio F_x/F_o as measured from the IPC count rates and the optical spectra, but no explanation for the highly unusual X-ray spectral properties has so far been proposed. X-ray sources of the type of LHG 87 and LHG 83 have so far been identified only in the LMC. Their presence may be due to the less advanced chemical evolution of the LMC. An alternative possibility is that such sources are also present in the Galaxy but the large absorption near the plane strongly biases against their detection. A sizable population of such LMXB with ultra-soft X-ray spectra might (at least in part) account for the apparent lack of progenitors of millisecond radio pulsars in wide binaries (Kulkarni and Narayan, 1988; Coté and Pylyser, 1988).

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