The distances to the X-ray binaries LSI +61° 303 and A0535+262

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ABSTRACT

Chevalier & Ilovaisky (1998) use Hipparcos data to show that the X-ray binary systems LSI +61° 303 and A0535+262 are a factor of ten closer (i.e. $d \sim$ few hundred pc) than previously thought ($d \sim 2$ kpc). We present high quality CCD spectra of the systems, and conclude that the spectral types, reddenings and absolute magnitudes of these objects are strongly inconsistent with the closer distances. We propose that the Hipparcos distances to these two systems are incorrect due to their relatively faint optical magnitudes.

Key words: binaries:close – stars:emission-line, Be – X-rays:stars – stars:individual: LSI +61° 303 – stars:individual: A0535+262.

1 INTRODUCTION

In a recent paper Chevalier & Ilovaisky (1998 - CI98) presented Hipparcos distances to 17 massive X-ray binary systems. In particular they presented results that appeared to indicate that two systems (LSI +61° 303, A0535+262) were up to a factor 10 closer than previously thought. This has profound implications for any models one constructs for these systems, for instance suggesting they need only contain white dwarfs rather than neutron stars to explain their X-ray luminosity.

In this paper we use CCD spectra to redetermine the spectral type of LSI +61° 303 and A0535+262. In both cases we show that the derived spectral types and reddenings are strongly consistent with normal Be stars at the distances previously ascribed to the systems, and not with the new, closer distances. Finally we discuss how the discrepancy between the Hipparcos and our distances may be explained in terms of the faint nature of these particular sources.

2 SPECTRAL TYPES

2.1 LSI +61° 303

An optical spectral type of B1Ib was assigned to LSI +61° 303 by Gregory et al. (1979) using low dispersion image tube spectrograph observations. However using an extinction $A_V \sim 3.3$ they argued that the true luminosity is probably less than that implied by the supergiant classification. Based on UV line strengths Howarth (1983) also assigned a spectral type of around B1. However his analysis of the extinction in this object led him to fit a dereddened model atmosphere of temperature $\sim 15000$K, corresponding to a spectral type of B4.5III at a distance of 2.4 kpc.

Fig. 1 shows a CCD spectrum of LSI+61°303 obtained using the IDS spectrograph of the Isaac Newton Telescope (INT), La Palma on the night of 1995 July 7 using the 1200 line/mm grating and the 235mm camera. H$\beta$ presents a typical shell profile, but the line wings do not seem to be as extended as those of H$\alpha$. H$\gamma$ shows a weaker shell profile, while the asymmetric shape of H$\delta$ and the He i lines is an indication of an emission component on top of the underlying photospheric feature.

The presence of the He ii lines at $\lambda\lambda$ 4200, 4541 & 4686 Å implies an early spectral type, while their weakness indicates that it cannot be much earlier than B0. The Si iv $\lambda\lambda$ 4089 & 4116 Å lines (on the wings of H$\delta$) are very weak in comparison to He i $\lambda$ 4121 Å, indicating a main-sequence object (Walborn & Fitzpatrick 1990). A few O iii lines have been tentatively identified in Fig. 1, although none is certain. Their absence would make the object earlier than B0.5. The lines of the Si iii triplet are still visible, though very weak. The presence of C iii and N iii lines also argues for an early type. Overall we believe that the most likely classification is B0V, though an slightly earlier spectral type (up to O9.5V) is also possible.

We note here that one possibility to explain a low-brightness blue star at a distance $\sim 200$ pc is that the object is a hot subdwarf. At least one X-ray binary containing a hot subdwarf and a compact object is known (HD...
**Figure 1.** Blue spectrum of LSI +61° 303. The continuum has been normalized to 1.0 and a small degree of Gaussian smoothing ($\sigma = 0.6\text{Å}$) applied.

**Figure 2.** A comparison of the spectrum of LSI+61° 303 and 3 hot subdwarf (sdOB) spectra from the WHT data archive. The spectra have all been normalized to 1.0 and are plotted with a constant offset. Arrows indicate He I features. Lines indicate the strongest interstellar features.
49798 = 1WGA J0648.0-4418; see Bisscheroux et al. 1997). However, it is clear that the spectrum of LSI+61°303 is not that of a subdwarf. The presence of helium lines prevents it from being an sdB object, while the ratio between HeI/HeII argues against an sdO. All sdO stars show HeII λ4686 Å ≥ HeI λ4713 Å (generally, HeII λ4686 Å ≫ HeI λ4713 Å, see Hunger et al. 1981) while the opposite is true for LSI+61°303.

The only possibility therefore is an sdOB star. Figure 2 compares LSI+61°303 with three sdOB objects. Feige 66 is a very well-studied sdOB subdwarf (Baschek et al. 1982), while PG 1511+624 and PG 1610+519 have been classified as sdOB by Moehler et al. (1990) and analysed by Allard et al. (1994), who derive absolute magnitudes of $M_V = 6.1$ and 5.5 respectively. These magnitudes are compatible with their average value ($M_V = 5.9 \pm 0.5$) for hydrogen-rich subdwarfs, but are much fainter than the value we would derive for LSI+61°303 if it was placed at $\sim 200$ pc.

There are two striking differences between the spectrum of LSI+61°303 and those of the subdwarfs. First, the strong interstellar absorption lines, which are missing in the spectra of the subdwarfs, all of which are located at high galactic latitudes (the implications of the strong absorption lines in the spectrum of LSI+61°303 are discussed in Section 4.1). Second, the HeI lines are much stronger in LSI+61°303 even though there must be emission contamination in some lines (e.g. HeI 6678 Å is known to show shell emission — Paredes et al. 1994). He I 4026 Å and 4388 Å are much stronger in LSI+61°303 than in Feige 66 and the 5873 Å HeI feature is not visible in any of the sdOB spectrum. It is therefore evident that LSI+61°303 is a hydrogen burning star and not a post-AGB object.

2.2 A0535+262

The usually quoted spectral type of HDE 245770 (the optical counterpart of A0535+262) is O9.7IIIe, based on photographic spectra (Giandrada et al. 1980). Fig. 3 shows two spectra of HDE 245770 in the classification region. The spectrum covering the wavelength range $\lambda \lambda 4600–5000$ Å was taken on 1996 March 1, using the Jacobus Kapteyn Telescope (JKT) telescope, equipped with the Richardson Brealey Spectrograph (RBS) (Edwin 1988) and the R2400 grating. The spectrum covering $\lambda \lambda 3800–4200$ Å was taken on 1990 November 14, using the IDS and the 235-mm camera on the INT, equipped with the R1200Y gratings.

Hβ presents typical double-peaked emission (see Clark et al. 1998), but the higher Balmer lines seem to be relatively emission-free. The presence of the HeII $\lambda 4686$ Å line while HeI $\lambda 4200$ Å is absent indicates a spectral type close to B0. Once again, the main luminosity criteria are the strengths of the SiIV lines. Strong SiIV $\lambda\lambda 4089, 4116$ Å lines are clearly visible on the wings of Hδ. The ratio SiIV $\lambda 4089 /$ HeI $\lambda 4121$ is indicative of a giant star (Walborn & Fitzpatrick 1990). The strength of HeI $\lambda 4009$ Å argues against a spectral type earlier than O9.5, while the absence of O II and the presence of NiII make the object earlier than B0.5. Since both HeII $\lambda \lambda 4541, 4686$ and the SiIII triplet can be seen in lower-resolution spectra (e.g., Clark et al. 1998) we believe that B0IIIe is the most appropriate classification, though the previously accepted O9.7IIIe cannot be discarded.

3 REDDENING

3.1 LSI +61° 303

Howarth (1983) made an analysis of eight short wavelength and five long wavelength IUE spectra of LSI +61° 303. By flattening the 2200Å extinction bump he derives $E(B-V) = 0.75 \pm 0.1$. Such a large reddening is inconsistent with a distance of only $\sim 200$ pc (Ishida 1969). It is therefore important to determine the true value of the reddening to the system. We do this using two methods — the sodium D2 line in our spectra and the strength of optical diffuse interstellar bands.

3.1.1 Derivation of Reddening from the Interstellar Sodium D2 Line

The first method we employ uses the correlation between the strength of the interstellar Sodium D2, 5890Å line and extinction derived by Hobbs (1974). We have rederived $E(B-V)$ values for all of Hobbs (1974) objects for which he quotes Na D2 equivalent widths using spectral classifications and $B-V$ colours from the Bright Star Catalogue (Hoffleit & Jaschek 1982) and the intrinsic colours of Popper (1980) for dwarfs and giants and Johnson (1966) for supergiants. The correlation in plotted in Fig.4. The scatter in this diagram is large, and shows that this technique will not be particularly accurate in deriving $E(B-V)$. The dataset does not extend beyond $E(B-V) \sim 0.7$, and is sparse beyond $E(B-V) \sim 3$.

Recognising the limitations of Fig. 4 however, we may still attempt to use the Na D2 line to determine the extinction to the system. Two spectra of LSI +61° 303 were obtained in the region covering the Na D lines on the nights of 1994 March 26 and 27 using the RBS of the JKT. The mean Na D2 EW measured was 650 ± 90 Å. From Figure 4 this implies $E(B-V) = 0.7 \pm 0.4$, where the error is derived from the apparent spread in $E(B-V)$ in the figure. This supports the extinction determination of Howarth (1983).

3.1.2 Derivation of Reddening from Diffuse Interstellar Band Strengths

A similar method may be employed using the diffuse interstellar bands (DIBs) to measure extinction. Herbig (1975) provides plots of $E(B-V)$ versus EW for a number of diffuse bands. These plots show less intrinsic scatter than the Na relations of Hobbs (1974) and should therefore give a better measure of $E(B-V)$. In addition they extend to higher $E(B-V)$ values ($\sim 2.0$) than the Hobbs (1974) sodium data, and so better cover the range of interest here. We measure the lines in two CCD spectra taken during the previously described JKT observing run, and a total of eight spectra obtained on 1993 December 5 and 7 from the 1.5m telescope at Mount Palomar using the f/8.75 Cassegrain echelle spectrograph in regular grating mode (McCarthy 1988). The DIBs measured were those centred at 5750, 5797, 6269 and 6613 Å (we do not employ the strong 4430 Å DIB as Herbig shows that it is only poorly correlated with $E(B-V)$). The mean equivalent widths in each band are 480, 160, 110 and 250 mÅ respectively, corresponding to $E(B-V)$ values of 0.8, 0.4, 0.5 and 0.9. The mean $E(B-V)$ derived from this
method is therefore $0.65 \pm 0.25$, where the error reflects the scatter in the values derived for the various bands. This is again similar to the Howarth (1983) value.

### 3.2 A0535+262

The reddening to A0535+262 was determined from the 2200 Å feature to be $E(B-V) \sim 0.75$ (Giovannelli et al. 1980). Again this is larger than one would expect for an object at < 1 kpc, and we therefore apply a similar analysis to the Na D$_2$ and DIB features in spectra of A0535+262 as we did for LSI+61$^\circ$ 303. Using two JKT spectra obtained on 1994 March 26 and 27 we find a mean Na D$_2$ equivalent width of 500±100 mÅ, corresponding to an $E(B-V) = 0.6 \pm 0.3$. Similarly using eight Mount Palomar spectra from 1993 December 5 plus the two JKT spectra we find mean DIB strengths for the 5780, 5797, 6269 and 6613 Å bands of 530, 270, 100 and 180 mÅ respectively, corresponding to $E(B-V)$ values of 0.8, 0.8, 0.4 and 0.6, giving a mean $E(B-V) = 0.65 \pm 0.2$. Once again the similarity between all three measures (2200 Å bump, DIB, and Na D$_2$) is striking.

### 4 DISTANCES TO THE SYSTEMS

#### 4.1 LSI +61$^\circ$ 303

The previous best estimate of the distance to LSI+61$^\circ$ 303 was that of Frail & Hjellming (1991). They used the profile...
of the 21cm hydrogen and $^{18}$O lines along with a galactic structure model to place the object at a distance of 2kpc. Using a reddening $E(B-V) \sim 0.7$ (the average of the IUE, Na D$_2$ and DIB values) and the observed Hipparcos magnitude of the source, a distance of 2kpc corresponds to an $M_V \sim -4$. Vacca et al. (1996) quote $M_V \sim -4.2$ for a B0V star and $M_V \sim -5.4$ for a B0III star. Such a distance is therefore entirely consistent with our derived spectral type.

CI98 quote a Hipparcos distance of 177 pc to the system, with 1$\sigma$ limits set at 130 and 300pc. Assuming $E(B-V) \sim 0.7$ a distance of 177pc corresponds to an absolute $M_V \sim +2$. The intrinsic colours derived using such a reddening are $(B-V)_0 \sim 0.5$ and $(U-B)_0 \sim -0.8$. CI98 state that these colours are not typical of an early B star, but are those of an accretion disk, which also would have an absolute magnitude in the appropriate range. In order to explain the high reddening to the system, when $E(B-V)$ should be less than 0.4 for an object closer than 1kpc (Ishida 1969), CI98 invoke a circumstellar origin. Taking this into account, CI98 propose a new model for the system where the primary is a compact object surrounded by an accretion disk of $T_{\text{eff}} \sim 15000$K which hides the central X-ray source. The accretion disk mimics the atmosphere of a B star, giving the observed spectrum.

We have a number of objections against the distance and the model which CI98 propose. Firstly, we showed in section 2 that the spectral type of the object is B0Ve. For an accretion disk to mimic such a spectrum it would have to have not only the temperature ($\sim 30000$K not $\sim 15000$K) but the pressure ($\sim 2 \times 10^7$ dyn cm$^{-2}$) and structure of the outer layers of a B star, plus a region responsible for producing Balmer series emission. It is hard to imagine such a disk forming, let alone being stable. In addition we question why such an object should have the typical colours of an $\sim 10000$ K accretion disk when it would have the spectrum of a much hotter disk. Perhaps a better explanation for CI98 to have put forward would have been that the system consists of a hot subdwarf plus compact object. However, as we have shown in section 2.1, the spectrum is definitely not that of such an object either.

Next we consider our reddening measurements to the system. As stated previously, Howarth (1983) derived $E(B-V) \sim 0.75$ from the 2200 Å feature in IUE spectra of the source. We derive $E(B-V) \sim 0.70$ from our Na D$_2$ line measurements and 0.65 from the diffuse interstellar band strengths. The agreement between these three measurements is striking. It implies that the properties of the alleged circumstellar material proposed by CI98 are identical to those of the interstellar medium. This strongly implies that the observed reddening to LSI+61° 303 is interstellar, not circumstellar in origin. We also note that Porceddu et al. (1992) have shown that excess circumstellar extinction in Be stars does not produce strong diffuse interstellar bands.

Finally, CI98 propose the red $(B-V)_0$ and $(U-B)_0$ colours as an accretion disk signature, although as we point out above it is that of a cooler disk than they propose. Comparison with the intrinsic colours of normal B stars (Deutschmann et al. 1976) shows that they are $\sim 0.3$ magnitudes redder in $B-V$ and $\sim 0.2$ magnitudes redder in $U-B$. A more natural explanation of redenings of this size is simply free-free emission from the circumstellar envelope of the Be star (Schild 1983).

From all of the above we conclude that the simplest explanation is that LSI+61° 303 contains a B0Ve star at a distance of $\sim 2$kpc plus a compact object as was previously thought, and that the Hipparcos distance is somehow wrong. We also note that the line of sight to LSI+61°303 lies on the direction to the centre of the Cas OB6 association. Garmany & Stencil (1992) give an extinction corrected distance modulus of 11.9 to that association, corresponding to a distance of 2.4 kpc. Therefore LSI+61°303 is a likely member of Cas OB6.

4.2 A0535+262

We now consider the case of A0535+262. The previous estimates of the distance to this system were based on either the combination of a spectral type and photometry (Hutchings et al. 1978, Giangrande et al. 1989, Giovannelli and Graziati 1982) or Strömgren photometry (Reig 1996). They range from 1.3 to 2.4 kpc, the average being around 2kpc. The reddening from the 2200 ˚A feature is $E(B-V) \sim 0.75$ (Giovannelli et al. 1980), and we showed in section 3.2 that a similar reddening is derived from diffuse interstellar bands and the Na D$_2$ line.

CI98 quote a Hipparcos distance to the system of 330 pc, with a 1$\sigma$ range of 210 to 780 pc. They argue that the intrinsic $B-V$ of the system is in the range $-0.13$ to $-0.30$, and therefore prefer a spectral type of around B2. They claim this is evidence against an O9.7 spectral type, although such an object would have an intrinsic colour only a few hundreds of a magnitude bluer. In addition they fail to take into account any reddening of $(B-V)$ due to free-free emission (Schild 1983). They also state that the absolute visual magnitude corresponding to such a distance is more consistent with an early B dwarf than a late O giant. Such a distance implies a low X-ray luminosity of the system of only $\sim 10^{33}$ erg s$^{-1}$. CI98 propose that systems with such low luminosities may in fact contain white dwarfs rather than neutron stars, with perhaps only X Per standing out as a neutron star system.

Once again we have several problems with these argu-
ments. Firstly the spectra presented in Fig. 3 are clearly those of an O9.5-B0 star, and not a B2 object. This shows the danger of attempting to use colours to derive spectral types of reddened objects (especially when they may show free-free emission).

Secondly we note that using a distance of 330pc and $E(B-V) = 0.75$ we derive $M_V \sim -1$ for this object. This is not consistent with an early B dwarf as was stated by CI98, but with an object of spectral type B6V (Deutschmann et al. 1976). It is also certainly not consistent with the spectral type we derived in Section 2.

Next we again note the similarity of the three extinction measures presented in section 3 as evidence that the reddening material is interstellar rather than circumstellar. Such large reddenings are incompatible with a distance of only $\sim 330pc$ (Ishida 1969).

Finally we point out that the explanation for the low X-ray luminosity proposed by CI98 (white dwarfs rather than neutron stars in such systems) does not hold for A0535+262. X-ray spectra of the source in outburst show cyclotron features at around 50 and 100 keV (Kendziorra et al. 1994, Grove et al. 1995). These correspond to a magnetic field strength of $\sim 10^{13}$ G (Araya & Harding 1996), many orders of magnitude greater than that possible for a white dwarf. In addition both the measured spin-up of the X-ray pulsations from the system (Li 1997) and the presence of quasi-periodic oscillations (Finger et al. 1996) fit a neutron star model well. The presence of a neutron star in this system is therefore beyond any reasonable doubt.

From all of the above we conclude that the simplest explanation is that A0535+262 contains a O9.5-B0 IIIe star plus a neutron star. Using a spectral class of B0III ($M_V \sim -5.3$ - Vacca et al. 1996), a reddening $E(B-V) = 0.75$, and assuming a standard reddening law (Rieke & Lebofsky 1985) we derive a distance of $\sim 2$ kpc to the system. We therefore again conclude that the ‘traditional’ distance to the system is more or less correct.

5 CONCLUSIONS

We have shown that the Hipparcos derived distances ($\sim$ few hundred pc) to two Be/X-ray binary systems, LSI +61° 303 and A0535+262 are inconsistent with the spectral types, reddenings and apparent magnitudes of the objects. There is strong evidence that the ‘traditional’ distances to these objects (each $\sim 2$kpc) are in fact correct. We note here that these two objects have the worst goodness-of-fit values in the Hipparcos catalogue (ESA 1997) of the CI98 sample (although they do lie below the maximum “acceptable” value of 3). In addition they are the faintest in the sample. This appears to indicate that the application of the simple ‘goodness-of-fit’ criterion that anything less than 3 is a good parallax to faint objects is not reliable, and that the interpretation of Hipparcos parallax data should always be carried out with this in mind.

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