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Spectroscopic confirmation of the optical identification of X-ray sources used to determine accurate positions for the anomalous X-ray pulsars 1E 2259+58.6 and 4U 0142+61⋆

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Abstract. Optical spectra show that two proposed counterparts for X-ray sources detected near 1E 2259+58.6 are late G stars, and a proposed counterpart for a source near 4U 0142+61 is a dMe star. The X-ray luminosities are as expected for such stars. We thus confirm the optical identification of the three X-ray objects, and thereby the correctness of the accurate positions for 1E 2259+58.6 and 4U 0142+61 based on them.

Key words. pulsars: individual: 1E 2259+58.6, 4U 0142+61 – stars: neutron – X-rays: stars

1. Introduction

Since all anomalous X-ray pulsars are in the plane of the Galaxy, deep searches for optical counterparts require accurate positions. Hulleman et al. (2000a,b) have improved the accuracy of the ROSAT positions of 1E 2259+58.6 and 4U 0142+61 by optical identification of X-ray sources in the same image as the anomalous X-ray pulsar (see Table 1). The proposed optical counterparts are relatively bright, and the identifications thus probably correct. However, given the importance of the accuracy of the positions of the anomalous X-ray pulsars, we decided to confirm the identifications of the sources on which they are based with optical spectroscopy. Besides the star LP 80-77 which is discussed in this paper, a second X-ray source was used by Hulleman et al. (2000a) to improve the position of 4U 0142+61, viz. the high-mass X-ray binary RX J0146.9+6121 that was optically identified with LSI +61 235 (Motch et al. 1991).

2. Observations and data reduction

Low-resolution spectra ($R \approx 1000$) of the three target stars were taken on July 31, 1999 with the 4.2 m William Herschel Telescope on La Palma using the ISIS dual-beam spectrograph. The seeing during these observations was $<1\farcs25$. The width of the spectrograph slit was set to $4''$, and was widened to $8''$ for the observation of the flux standard BD+28 4211. Observation times and exposure times are listed in Table 1. The coordinates of RP 1 and RP 3 (near 1E 2259+58.6) can be found in Hulleman et al. (2000b), those of LP 80-77 (near 4U 0142+61) can be found in SIMBAD.

The spectra of the blue arm of ISIS cover 3200–6260 Å, those of the red arm cover 5778–8726 Å. The bias signal was removed, the spectra were extracted, and a flatfield-correction was applied. Wavelength calibration was done with spectra of CuNe-calibration lamps. Counts were converted to absolute flux using the spectra of BD+28 4211 and the table by Massey et al. (1988), and the atmospheric extinction curve for La Palma as given by King (1985). We refer to van den Berg & Verbunt (2001, in preparation) for more details.

3. Spectral classification

The spectra of the three target stars are shown in Fig. 1. LP 80-77 is classified as an M3–M4.5Ve star using criteria for late K to M stars in Kirkpatrick et al. (1991). This is mainly derived from the strength of the CaH 6975 Å feature relative to the nearby continuum and of the CaII 8542 Å line relative to the nearby continuum (ratio A is 1.32 ± 0.01 and ratio D/ratio A is 0.85 ± 0.01; see Kirkpatrick et al. for definitions). From these features alone, we cannot rule out type M8–M9V; such a late type

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⋆ Based on observations made with the William Herschel Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

Table 1. X-ray and optical properties of RP 1 and RP 3 (near 1E 2259+58.6) and of LP 80-77 (near 4U 0142+61): the X-ray countrates (per ksec) in the ROSAT PSPC (channels 11-240) and in the ROSAT HRI; UT at start of the exposure and exposure time in seconds for the ISIS blue/red arm; spectral type, apparent magnitude and apparent colours derived from the spectra; and the estimated visual absorption and absolute magnitude

object	$ctr_{\rm PSPC}$	$ctr_{\rm HRI}$	UT	$t_{\rm exp}$	spect. type	V	$U-B$	$B-V$	A_V	M_V
RP1	4.8 ± 0.5	1.3 ± 0.3	2:09/2:09	180/120	G7-K1IV-III	11.8 ± 0.1	0.83 ± 0.14	1.45 ± 0.14	1.9	$\lesssim$5.9
RP3	12.4 ± 1.0	14.0 ± 1.0	2:15/2:15	180/120	G2-K0V	12.8 ± 0.1	0.35 ± 0.14	0.90 ± 0.14	0.6	5.2
LP80-77	76.7 ± 3.3		2:32/2:36	480/240	M3-M4.5Ve	14.1 ± 0.1	1.26 ± 0.14	1.68 ± 0.14	0.1	12.8

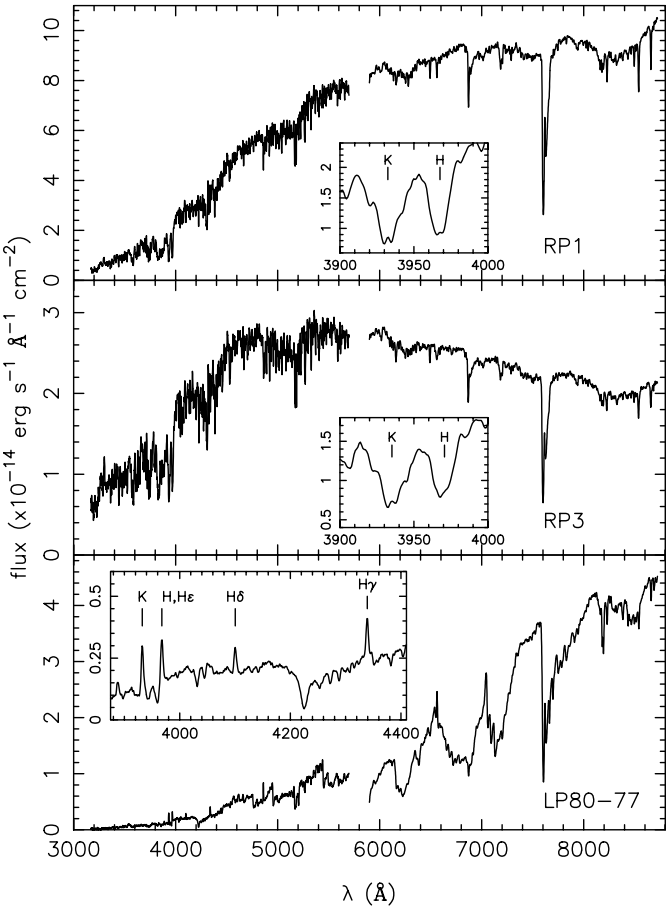

Fig. 1. ISIS-spectra of the three target stars. Some lines are identified in enlarged portions of the spectra shown in the insets (K = Ca II K, H = Ca II H)

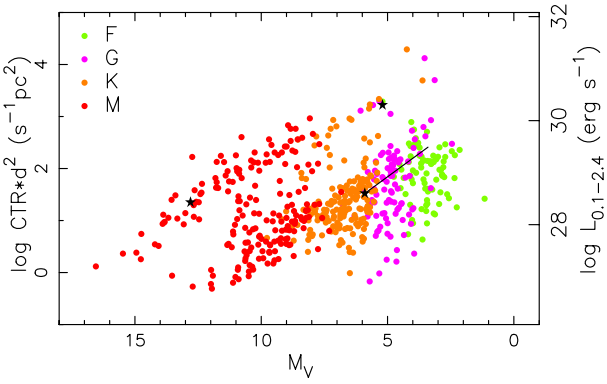

Fig. 2. X-ray luminosities as a function of absolute magnitude for nearby stars (unique identifications only, from Hünsch et al. 1999) and the stars discussed in this paper. The X-ray luminosity is expressed as the product of the ROSAT PSPC countrate with the square of the distance (left), and in erg s^{-1} (right, converting 1 cts s^{-1} to 10^{-14} erg cm^{-2} s^{-1}). For RP 1 we indicate its position for an assumed luminosity class V, with a line indicating the change for a ten times higher luminosity

can be excluded from the overall appearance of the spectrum, in particular from the absence of VO-bands.

The spectra of RP 1 and RP 3 appear earlier in type and were classified with criteria for F to K stars in Malyuto & Schmidt-Kaler (1997). A spectral type is derived from the index $I_{\rm S}$ (0.473 ± 0.007 and 0.510 ± 0.005 for RP 1 and RP 3, respectively), which represents features in the range 4215–4360 and 5125–5290 Å. For the luminosity class we also use the index I_2 (0.378 ± 0.009 and 0.490 ± 0.011 for RP 1 and RP 3, respectively; see Malyuto & Schmidt-Kaler for definitions) that includes the region 4120–4280 Å. We find a type G7-K1 IV-III for RP 1 and G2-K0 V for RP 3.

4. Discussion and conclusions

From the flux calibrated spectra we can estimate the apparent magnitude and colours of our targets. The results are listed in Table 1. The errors follow from comparing the resulting B and V magnitudes for the flux standard with their tabulated values. Comparison with colours of main sequence stars and subgiants then provides an estimate of the reddening and absolute magnitudes, also listed in Table 1. The spectral type of RP 1 indicates that it is slightly evolved, but its colours suggest that the star is close to the main sequence, i.e. of luminosity class IV rather than III.

We check that the X-ray luminosities are normal for the proposed counterparts, as follows. First, we analyse a ROSAT PSPC observation of 1E 2259+58.6 (obtained on 1991 July 9; effective exposure 33 368 s) and the PSPC observation of 4U 0142+61 (Hulleman et al. 2000a) to obtain the countrates listed in Table 1. We then compare the luminosities with those of nearby stars of the same spectral type, listed by Hünsch et al. (1999), in Fig. 2. To avoid uncertainties in the conversion of countrate to flux, we use the product of the countrate CTR with the square of the distance in parsecs d as a measure of the X-ray luminosity. No counts are detected for RP 1 and RP 3 below

0.5 keV, due to interstellar absorption; to correct for this we multiply their PSPC countrate with 2 before plotting them in Fig. 2. For RP 1 the magnitude limit corresponds to a lower limit in distance, and we indicate how its distance affects its position in the diagram. We conclude from the diagram that the X-ray luminosity for all three proposed counterparts are as expected. The Balmer lines are in emission in LP 80-77 and the Ca II K-core is in emission in all three stars; this optical signature of X-ray activity supports the identification with the X-ray sources.

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