Optical follow-up of new Small Magellanic Cloud wing Be/X-ray binaries

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ABSTRACT
We investigate the optical counterparts of recently discovered Be/X-ray binaries in the Small Magellanic Cloud (SMC). In total four sources, SXP101, SXP700, SXP348 and SXP65.8 were detected during the Chandra survey of the wing of the SMC. SXP700 and SXP65.8 were previously unknown. Many optical ground-based telescopes have been utilized in the optical follow-up, providing coverage in both the red and blue bands. This has led to the classification of all of the counterparts as Be stars and confirms that three lie within the Galactic spectral distribution of known Be/X-ray binaries. SXP101 lies outside this distribution and is the latest spectral type known. Monitoring of the Hα emission line suggests that all the sources barring SXP700 have highly variable circumstellar discs, possibly a result of their comparatively short orbital periods. Phase-resolved X-ray spectroscopy has also been performed on SXP65.8, revealing that the emission is indeed harder during the passage of the X-ray beam through the line of sight.

Key words: stars: emission-line, Be – Magellanic Clouds – X-rays: binaries.

1 INTRODUCTION
Over the past 10 yr the number of known high-mass X-ray binaries (HMXBs) located in the Small Magellanic Cloud (SMC) has been steadily increasing. There are now approximately 50 such systems known in the SMC (Coe et al. 2005). Until recently the majority of X-ray observations by Chandra, XMM–Newton and RXTE have concentrated on the bar, since the large fraction of HMXBs are located in this region. Coe et al. (2005) analysed the locations of the known X-ray pulsars and believed that there is a relationship between the HI intensity distribution and the distribution of the pulsars. This prompted a large survey of the wing of the SMC using Chandra. A total of 20 individual pointings were made of approximately 10 ks each. The survey was successful in finding two new pulsars (SXP65.8 and SXP700) and detecting two previously known pulsars (SXP101 and SXP348). Due to Chandra’s high spatial resolution the counterparts to all four sources were identified (SXP348 being previously known). Table 1 shows the positions and V-band magnitudes of the counterparts to the detected pulsars. A more detailed description of the survey can be found in McGowan et al. (2007). In order to evaluate where these new pulsars lie in relation to the Galactic spectral distribution of Be/X-ray binaries we need to classify the counterparts. This paper reports the follow-up optical observations of these systems.

2 OPTICAL DATA
Since the Chandra observations were completed in 2006 March a number of telescopes have been used for the optical follow-up. Table 2 presents a list of the data collected for each of the sources. The telescope configurations and reduction processes used are as follows.

(i) AAT – 3.9-m telescope, Anglo-Australian Observatory, Australia. The AAOmega optical spectrograph was used. It is fed by the 2dF robotic fibre positioner covering a 2dF at prime focus with 392 fibres. Each observation consists of three 1800-s exposures made on 2006 August 31. The data reduction was performed using the latest 2DFDR package version 3.46. All traces were extracted using a tram line optimization. The spectra were then corrected for the detector response and then the red and blue arms were scaled and stitched together by forcing them to meet at 5900 Å allowing the complete range to be viewed; this was all performed using tasks within the 2DFDR package. The red arm has a dispersion of 1.5 Å pixel−1 and the blue of 1.03 Å pixel−1. The total wavelength range covered is approximately 3700–8800 Å. There are several bad columns in the AAT CCD. These columns have been removed and they appear as spaces in the spectra.

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The spectra have a dispersion of 1.99 Å pixel\(^{-1}\) and the SITe detector. Data reduction was performed using standard IRAF packages. The dispersion of the spectra is fairly consistent over the years since the same set-up has been used, approximately 0.43 Å pixel\(^{-1}\). The wavelength range varies slightly due to small changes in the grating angle, the wavelength range covered in all spectra is approximately 6230–6970 Å. A few cosmic rays have been removed by hand. All the spectra except for those from ESO (due to their lower resolution) have been smoothed with a boxcar average of 5. An arbitrary offset has been applied to some of the spectra to allow visual comparisons of the spectral lines.

### 3 OBSERVATIONS

#### 3.1 Classification method

Spectral classification of Be stars in the SMC is particularly difficult. Classification of Be stars in the Galaxy relies on using the ratios of many metal lines (Walborn & Fitzpatrick 1990); unfortunately the metallicity of SMC stars is lower than those in the Galaxy and so many metal lines (Walborn & Fitzpatrick 1990) are used. The spectra have a dispersion of 1.99 Å pixel\(^{-1}\) and a wavelength range of approximately 3800–4880 Å. The SALT detectors consist of three chips aligned along the dispersion axis each separated by a small gap (evident in the spectra). Full data reduction and mosaicking of the three chips were performed using the SALT IRAF pipelines and the standard IRAF packages in version 2.12.1 provided by the NOAO. No flux calibration has been made.

(ii) SALT – 11-m Southern African Large Telescope, SAAO, South Africa. The Robert Stobie Spectrograph (Burgh et al. 2002) was used in conjunction with two gratings in long-slit mode.

(1) Blue: 2300 lines mm\(^{-1}\) grating at an angle of 30\(\degree\). This gives a dispersion of 0.34 Å pixel\(^{-1}\) and a wavelength range of approximately 3800–4880 Å.

(2) Red: 1800 lines mm\(^{-1}\) grating at an angle of 36.5\(\degree\). This gives a dispersion of 0.40 Å pixel\(^{-1}\) and a wavelength range of approximately 5930–7210 Å.

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(iii) ESO – 3.6-m telescope, La Silla, Chile. The EFOSC2 faint object spectrograph was used combined with a grism with 600 lines mm\(^{-1}\). The data reduction was performed using standard IRAF packages. The dispersion of the spectra is fairly consistent over the years since the same set-up has been used, approximately 0.43 Å pixel\(^{-1}\). The wavelength range varies slightly due to small changes in the grating angle, the wavelength range covered in all spectra is approximately 6230–6970 Å. A few cosmic rays have been removed by hand. All the spectra except for those from ESO (due to their lower resolution) have been smoothed with a boxcar average of 5. An arbitrary offset has been applied to some of the spectra to allow visual comparisons of the spectral lines.

### Table 2. Observations.

| SXP ID | Telescope | Date          | Exposure time (s) | Hα EW (Å) | Hβ EW (Å) |
|--------|-----------|---------------|-------------------|-----------|-----------|
| SXP101 | SALT red  | –             | –                 | –         | –         |
|        | SALT blue | 2006 October 10 | 450               | –         | 0.0 ± 0.7 |
|        | ESO       | 2006 September 14 | 2400             | –         | 1.1 ± 0.2 |
|        | AAT       | 2006 August 31  | 5400              | 0.2 ± 0.3 | 4.7 ± 0.3 |
|        | SAAO      | 2004 September 07 | 2 × 1000        | 1.7 ± 0.2 | –         |
|        | SALT blue | 2006 October 16 | 600               | –         | 1.0 ± 0.1 |
|        | ESO       | 2006 September 13 | 2400             | –         | 0.7 ± 0.1 |
|        | AAT       | 2006 August 31  | 5400              | 13.4 ± 0.2| 0.8 ± 0.2 |
|        | SAAO      | 2006 November 10 | 1800              | 12.9 ± 0.4| –         |
| SXP348 | SALT red  | –             | –                 | –         | –         |
|        | SALT blue | –             | –                 | –         | –         |
|        | ESO       | 2006 September 14 | 1800             | 0.3 ± 0.2 |
|        | AAT       | –             | –                 | –         | –         |
|        | SAAO      | 2004 September 12 | 2500             | 8.7 ± 0.9 | –         |
|        | SAAO      | 2005 October 30 | 1000              | 2.9 ± 0.6 | –         |
|        | SAAO      | 2006 November 08 | 1200             | 6.3 ± 0.3 | –         |
| SXP65.8| SALT red  | –             | –                 | –         | –         |
|        | SALT blue | –             | –                 | –         | –         |
|        | ESO       | 2006 September 13 | 2000             | 1.2 ± 0.1 |
|        | AAT       | 2006 August 31  | 2 × 5400          | 21.3 ± 0.3| 0.9 ± 0.2 |
|        | SAAO      | 2006 November 13 | 1800              | 13.5 ± 0.6| –         |

\(^{a}\)McGowan et al. (2007), \(^{b}\)Massey (2002), \(^{c}\)Hughes & Smith (1994).
circumstellar discs affect on the higher order balmer lines though infilling. As a result we use the classification criteria and methods as set out by Lennon (1997) and Evans et al. (2004).

For the luminosity classification we have adopted the classification method set out in Walborn & Fitzpatrick (1990); however, since this method relies on line ratios we face all the same difficulties as previously mentioned. We have also performed a check on this luminosity classification by comparing the absolute magnitude of the source in the V band with the spectral classification obtained. Here we have adopted a distance modulus for the SMC of 18.9 (Harries, Hilditch & Howarth 2003) and we use the relevant tables in Wegner (2006). These tables are based on absolute magnitudes from Hipparcos data. Although the luminosities of Be stars in the SMC may differ somewhat from those in the Milky Way we have adopted this method as a check and recognize that in some cases the results obtained may be uncertain.

3.2 SXP101

This source was detected by both ROSAT (RX J0057.3–7325) and ASCA (AX J0057.4–7325; Kahabka et al. 1999; Torii et al. 2000). Coherent pulsations were first detected in the ASCA data at a period of 101.45 ± 0.07 s. The resultant overlapping error circles allowed some counterparts to be tentatively assigned (Edge & Coe 2003). The detection of pulsations at 101.16 ± 0.26 s in the Chandra data (McGowan et al. 2007) has allowed the counterpart to be clearly identified as the source previously labelled E in fig. 3 of Edge & Coe (2003). MACS J0057–7341 10 (Tucholke, De Boer & Seitter 1996). This source had first been identified as a possible counterpart in 2000 January due to its r–Hα colour revealing an excess of Hα. Subsequently this source was observed 4 yr later in 2004 using the 1.9-m SAAO telescope, two spectra taken on the night have been co-added and are shown in Fig. 1. We can clearly see the Hα line to be in absorption, hence the source was not considered to be a prime candidate. Strangely the AAT spectrum (Fig. 1) shows neither absorption nor emission in Hα. In fact it is perfectly filled in. Curiously the higher order Balmer lines in the AAT spectrum (Fig. 2) show no signs of infilling; they are all clearly in absorption with no peculiar features. A third red spectrum (Fig. 1) was taken recently at SAAO in 2006 November. Two spectra were taken consecutively and have been co-added to increase the signal-to-noise ratio. The Hα profile now appears to be slightly in emission, suggesting its Be nature. There have been several observations of the Hβ emission line during the last few months of 2006 (Figs 2–4). These observations appear to show that in the course of little more than one month the line has completely filled itself.

Classification has been made using blue spectra taken by AAT, ESO and SALT (Figs 2–4). The counterpart is extremely difficult to classify due to a severe lack of metallic lines. No He II lines are visible; hence the counterpart must be B1 or later (Lennon 1997). There is some evidence for the presence of the O IV 4640–4650 Å band in the SALT spectra; however, it seems to be lacking in the other spectra. Comparison of all three spectra with those given in fig. 4 of Evans et al. (2004) would seem to place the counterpart in a broad spectral range of B1–B5. Mg II 4481 Å is possibly present in all three spectra in particular the SALT and AAT ones; however, the resolution of the ESO spectra is not sufficient to deblend the line from the neighbouring He I line. If the presence of this line is to be believed, then combined with the lack of Si IV 5535 Å allows a lower classification limit of B3 to be made (Lennon 1997). Visible in the AAT spectra is the Si II blend of 4128/4132 Å and He I line at 4143 Å. He I 4121 Å is possibly visible on the red shoulder of the Hβ line. However, it is heavily obscured and cannot be used for classification. The ratio of Si II to He I line would suggest a classification around B8 (Evans et al. 2004). This line ratio is not seen in the ESO spectra, in fact Si II is barely seen and the He I line appears strongly suggesting a classification more like B5. A classification range of B3–B5 would agree with the Balmer lines appearing very broad and deep which is typical of a mid-range Be star. The luminosity classification method of Walborn & Fitzpatrick (1990) only goes as far as classifying B2 stars; hence we will only use the estimate from the V-band magnitude. We would estimate the luminosity class to be about Ib-II from table 10 presented in Wegner (2006). A luminosity class of Ib-II would make the counterpart a supergiant and not a Be star. This luminosity classification should be treated cautiously due to the methods used.

3.3 SXP700

SXP700 is one of the new pulsars detected on 2006 February 06 in the SMC wing survey. The Chandra source is coincident with [MA93] 1301 (Meysonnier & Azzopardi 1993). Three red follow-up spectra taken within a few months of each other by SALT, AAT and SAAO reveal the counterpart star to have a very strong Hα line in emission (Fig. 5). This strongly suggests the identification of this object as a Be/X-ray binary. The three observations were roughly spaced a month apart from each other. It can be seen in Table 2 that the equivalent width (EW) of Hα has barely changed over the course of these observations indicating that the circumstellar disc was in a fairly stable state.

Classification of the counterpart has been possible through the three blue spectra taken by AAT, ESO and SALT (Figs 2–4). Weak He II at 4686 Å can be seen in all the spectra; using the classification guide set out by Evans et al. (2004) we can immediately place this object as earlier than B1. No other He II lines are visible in either the AAT or SALT spectra; however, He I 4200 Å is present in the ESO spectra. This combined with the lack of He II 4541 Å allows the classification of B0–B0.5 to be made (Evans et al. 2004). Hβ can also be seen to be strongly in emission in all three blue spectra. A luminosity classification can be made by comparing the ratio of Si IV 4089 Å to both He I 4026 and 4144 Å. The ESO spectra show strong He I lines compared with slight evidence of Si IV in the blue shoulder of the Hα line. Using the ratio of these lines results in a luminosity class of V (Walborn & Fitzpatrick 1990). Using the
Figure 2. AAT spectra taken on 2006 August 31. Top to bottom: SXP101, SXP65.8, SXP700 (smoothed with gaps for dead pixels).

Figure 3. ESO blue spectra taken on 2006 September 14. Top to bottom: SXP700, SXP348, SXP101, SXP65.8 (no smoothing).
method based upon the $V$-band magnitude yields a classification of III–V.

### 3.4 SXP348

This is the only detected pulsar from the *Chandra* wing survey with a previously known counterpart. It was first detected by *BeppoSAX* in 1998 (Israel et al. 1998) with a pulse period of $345.2 \pm 0.1$ s. The *Chandra* source is coincident with [MA93] 1367 (Meyssonnier & Azzopardi 1993), a Be star (Hughes & Smith 1994; Israel et al. 1998). Spectra taken in 2004 and 2005 by the 1.9-m SAAO telescope (Fig. 6) show that the Hα line has been varying over recent years. In 2004 the line was strongly in emission with a small second peak on its red shoulder, just over a year later in 2005 the line appears to have dropped in strength and displays a shell profile. A recent spectrum (Fig. 6) taken on 2006 November 8 shows Hα to be back in emission, this time with a slightly more prominent feature on the red shoulder making it appear more double peaked. The ESO spectrum (Fig. 3) taken near to this most recent red spectrum shows the Hβ line to be largely filled in with an emission peak at its centre. The Hα profile has also shrunk in size quite dramatically since it was observed in 1992 (Hughes & Smith 1994). They report an EW of $-22$ Å; however, they did not note anything about the physical shape of the emission. The Hβ line has also reduced in size since 1992, where they reported an EW of $-1.7$ Å.

From the ESO spectra (Fig. 3) we can see a strong He II line at 4686 Å; this firmly restricts the spectral class to earlier than B1.
Further constraints can be made based on the presence of very weak He\textsc{ii} at 4541 and 4200 Å in the ESO spectra. A spectral classification of B0–B0.5 can be placed on this counterpart (Evans et al. 2004). This agrees with the spectral range of O9–B1 (V–III) determined in Hughes & Smith (1994), where they estimate the spectral class to around B0 based on the strength of He\textsc{i} 4471 Å relative to its neighbour Mg\textsc{ii} 4481 Å. The presence of He\textsc{ii} 4686 Å was uncertain in their spectrum due to a flat-fielding correction. Using the same He\textsc{i} and Si\textsc{iv} lines in the ESO spectrum for the luminosity classification as used for SXP700 yields a very similar situation, strong He\textsc{i} lines and a moderate bump representing Si\textsc{iv} on the shoulder of H\textsc{δ}. Using this ratio a luminosity classification of V is made (Walborn & Fitzpatrick 1990); this is consistent with the range of III–V estimated from the V-band magnitude.

3.5 SXP65.8

3.5.1 Optical

SXP65.8 is the second of the new pulsars detected in the SMC wing survey on 2006 February 10. The Chandra source is coincident with the emission-line star [MA93] 1619 (Meyssonnier & Azzopardi 1993). Follow-up red spectra were taken by SAAO and AAT (Fig. 7). The counterpart was observed twice with the AAT on the same night, roughly one hour apart. Each observation was 5400 s long. Since these spectra are both of high quality and show no astrophysical difference we have only included one of them here. The strong H\alpha emission line present in the AAT spectra strongly suggests that the counterpart is indeed a Be/X-ray binary. In the few months between the AAT and SAAO spectra the H\alpha line has significantly modified its profile to a double-peaked structure. This would indicate that the circumstellar disc has shrunk in size and now the absorption in the stellar photosphere is becoming a more dominant effect.

The classification for this counterpart has been based on AAT and ESO blue spectra (Figs 2 and 3). Clear O\textsc{ii} absorption bands present in both the spectra, the He\textsc{ii} lines have also completely disappeared. These lines we can also say that O\textsc{ii} is stronger than Si\textsc{iv} 4088 Å and hence refine the classification to B1–B1.5. Si\textsc{iv} 4116 Å is irresolvable in both spectra due to the width of the H\δ feature. We cannot be certain of its presence or absence; hence a final classification of B1–B1.5 is made. There are also notable Fe\textsc{ii} lines in absorption at 4924 and 5018 Å. Using the ratio of Si\textsc{iii} to He\textsc{i} 4387 Å we can make a luminosity classification of II–III (Walborn & Fitzpatrick 1990), which agrees with that obtained using the magnitude method.

3.5.2 X-ray

Using Chandra data (for more details see McGowan et al. 2007) we have extracted phase-resolved spectra for SXP65.8 using CIAO v3.4 standard tools. The spectra were regrouped by requiring at least 10 counts per spectral bin. The subsequent spectral fitting and analysis were performed using XSPEC v12.3.0. A phase-binned light curve was created (Fig. 8) based on MJD 53776.82172 and a pulse period of 65.78 s (McGowan et al. 2007). The two phase-binned spectra were extracted using the phase ranges 0.0–0.5 and 0.5–1.0. We fitted each of these with an absorbed power law, and fixed the column density at the value for the SMC of 6 $\times$ 10$^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). The low-phase spectrum is well fitted with a $\Gamma = 0.34 \pm 0.08$ with a reduced $\chi^2 = 0.85$, and the high-phase spectrum well fitted with $\Gamma = 0.52 \pm 0.10$ with a reduced $\chi^2 = 1.42$. These values are consistent right at the extremes of their errors. However, they would also seem to indicate that the pulsed emission from the beam is harder than the persistent emission. The pulse fraction has been calculated for both soft and hard energy bands (0.5–2.0 and 2.0–8.0 keV, respectively). The values were calculated by taking $(F_{\text{max}} - F_{\text{min}})/(F_{\text{max}} + F_{\text{min}})$ where $F_{\text{max}}$ and $F_{\text{min}}$ are the maximum and minimum points of the folded light curve for each energy band. $PF_S = 34 \pm 9$ per cent and $PF_H = 43 \pm 6$ per cent. The values are both consistent within errors and with the value in McGowan et al. (2007). This is probably due to the lack of soft counts.

**Figure 7.** Hα spectra of SXP65.8. Spectra dates top to bottom: 2006 August 31, 2006 November 13 (this spectrum was scaled to allow the comparison of the Hα profile).

**Figure 8.** Pulse profile for SXP65.8 in the energy range 0.5–8.0 keV.
4 DISCUSSION

4.1 SXP101

The identification of the correct counterpart to SXP101 has finally enabled its identification as a Be/X-ray binary. The Hα and Hβ line profiles provide strong evidence to suggest that the circumstellar disc is an extremely variable component of the system. The most recent observations made at the end of 2006 suggest that the circumstellar disc has recently grown in size. Interestingly the Hβ line has shown some considerable variation over the course of a few months. Fig. 2 clearly shows all the Balmer lines to be deep and well defined including Hβ; 14 d later the Hβ line has considerably changed and is almost totally filled in with the remaining Balmer lines showing no change (Fig. 3). This would agree with the Hα observations which show that over approximately the same time-scale the Hα line has gone from being filled in completely to slightly in emission. These recent observations provide strong evidence to suggest that the circumstellar disc is an extremely variable object. The apparent lag of the Hβ line with respect to Hα could be evidence of the emission originating from a different part of the circumstellar disc than the Hα. This could be due to temperature or density changes. Further modelling of the circumstellar disc structure would be needed to confirm this.

The classification of B3–B5 is also potentially very interesting since it would make this Be/X-ray binary one of the latest types to have been found. Comparing the spectral type of SXP101 with the spectral distribution found in the Galaxy (Negueruela 1998) clearly shows that SXP101 would lie on its own, becoming the latest spectral type found. McBride et al. (in preparation) will present full spectral classifications and analysis of all the Be/X-ray binaries in the SMC where the counterparts are known. This work will help in understanding any potential differences between the spectral distribution in the SMC and the Galaxy.

4.2 SXP700

The presence of a strong Hα emission line and a classification of B0–B0.5 clearly places this Be/X-ray binary right in the centre of the Galactic spectral distribution (Negueruela 1998). The unchanging EWs of the Hα line (Table 2) suggests that the circumstellar disc was in a fairly stable state. An orbital period of 267.38 ± 15.10 d was found in OGLE III data (McGowan et al. 2007). This period is entirely consistent with that predicted from the Corbet diagram (Corbet 1986) for a 700-s pulsar. Assuming SXP700 only goes into outburst every time the neutron star passes through periastron then we would only expect outbursts approximately every 9 months. For such long intervals where no accretion is taking place the circumstellar disc has remained stable. This could be indicative of a stable truncated circumstellar disc at its maximum EW, similar to the stable circumstellar disc observed in GRO J1008-57 (Coe et al. 2007). Reig (2007) presents an up to date version of the $P_{\text{orb}}$–EW(Hα) diagram containing all the known Galactic and Magellanic Be/X-ray binaries where the orbital periods are known. The measured Hα value is assumed to be representative of a circumstellar disc at maximum size. The measured values for SXP700 are not consistent with this plot. However, we also note that the values for GRO J1008–57 (Coe et al. 2007) where the circumstellar disc is in a stable state are also not consistent with the plot. In order to properly place SXP700 on this diagram we would need many more observations at varying times to evaluate the changes that take place in the circumstellar disc.

4.3 SXP348

This source was first detected by BeppoSAX in 1998 (Israel et al. 1998) with a pulse period of 345.2 ± 0.1 s. After its discovery a previous ASCA observation from 1996 was found to have the same source present at a slightly slower spin period of 348.9 ± 0.3 s (Yokogawa & Koyama 1998). Several later observations reveal that SXP348 has continued its spin-up at an almost constant rate, detections by Chandra in 1999 of 343.5 ± 0.3 s pulsations (Israel et al. 2000) and then XMM–Newton observations in 2000 at 341.21 ± 0.5 s (Haberl & Pietsch 2004). An XMM–Newton observation in 2001 showed a slight spin-down of the pulsar to 341.7 ± 0.4 s (Sasaki, Pietsch & Haberl 2003). The recent Chandra observation at 339.56 ± 0.58 s supports this trend of continued spin-up. Fig. 9 shows how SXP348 has been spinning up (McGowan et al. 2007) over the last 10 yr. The recent Chandra observation suggests that the constant spin-up rate has slowed down.

It appears that SXP348 has transitioned at some point into a different state where the spin period is now changing more slowly. We have divided the observations into two epochs, with the transition point being the average of the two XMM–Newton observations that fall around MJD 52000. Epoch 1 yields $P_1 = (5.1 \pm 0.4) \times 10^{-8}$ s$^{-1}$, which is consistent with the value found in Haberl & Pietsch (2004); this implies $L_{\text{rot}} = (4.5 \pm 0.4) \times 10^{35}$ erg s$^{-1}$. Epoch 2 yields $P_2 = (1.2 \pm 0.5) \times 10^{-8}$ s$^{-1}$, which implies $L_{\text{rot}} = (1.1 \pm 0.4) \times 10^{35}$ erg s$^{-1}$. We have derived an estimate on the magnetic field strength using equation (6.24) of Frank, King & Raine (2002). The luminosity value of epoch 1 yields a field strength of $B_1 = (4.3 \pm 1.6) \times 10^{13}$ G. The field strength derived from epoch 2 is consistent with this value but has significantly larger errors. The change in luminosity is as expected and would indicate that SXP348 has had significant changes to its accretion rate, possibly implying that the pulsar is nearing a spin period where the accretion flow will be cut off due to the propeller effect caused by the magnetosphere. The estimated value of the magnetic field is higher than expected; this is probably a reflection of the estimation method used when only a handful of points are known.

The classification of B0–B0.5 agrees with the spectral type of O9–B1 (V–III) determined by Hughes & Smith (1994), and places this source in the middle of the Galactic spectral distribution. The
variation of the H\(_\alpha\) profile shows that the circumstellar disc is variable on time-scales of around a year; this is twice the expected orbital period as predicted from the Corbet diagram (Corbet 1986). Since the state of the circumstellar disc is intricately linked to the spin period changes we would require many more observations to fully understand the dynamics of the system.

### 4.4 SXP65.8

Observations of a varying H\(_\alpha\) emission line and a classification of B1–B1.5 confirm SXP65.8 as a Be/X-ray binary. Since the H\(_\alpha\) emission is arising from the circumstellar disc we deduce that the reduction in EW is due to the circumstellar disc reducing in size over the course of a few months.

The phase-resolved spectroscopy would appear to suggest that as the X-ray beam passes through the line of sight the X-ray emission becomes harder. This would indicate that the soft emission is originating in a different location to the magnetically collimated beam and is probably more representative of thermal emission from either the surface of the neutron star or the accretion disc.

### 5 CONCLUSIONS

Four pulsars were detected in the SMC Chandra wing survey, SXP101, SXP700, SXP348 and SXP65.8. Follow-up optical observations have enabled spectroscopic classifications of all the counterparts. All the counterparts are classified within the range B0–B5. Red spectra covering the H\(_\alpha\) atomic line has revealed that all the sources have at some point in time exhibited H\(_\alpha\) emission, resulting in their classification as emission-line stars. Three of the Be/X-ray binaries fall within the known Galactic spectral distribution for Be/X-ray binaries (Negueruela 1998). SXP101 falls outside this distribution and hence becomes the latest spectral type known for a Be/X-ray binary. Currently there is not enough evidence to suggest that there is a different population in the wing compared to the bar. The work by McBride et al. (in preparation) will shed some light on the spectral distribution of Be/X-ray binaries in the SMC. From the H\(_\alpha\) monitoring it would appear that SXP700 has a stable circumstellar disc, unlike the three other sources where variations in the profile would suggest a more dynamic circumstellar disc. This is likely to be due to the differences in the length of the orbital periods and hence the influence of the neutron star on the circumstellar disc geometry.

McGowan et al. (2007) suggest that the wing pulsars could be coming from a different population to the bar pulsars due to the pulsars exhibiting harder X-ray spectra; however, our findings are unable to clarify this matter any further.

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