Discovery of SXP 265, a Be/X-ray binary pulsar in the Wing of the Small Magellanic Cloud

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ABSTRACT
We identify a new candidate for a Be/X-ray binary in the XMM–Newton slew survey and archival Swift observations that is located in the transition region of the Wing of the Small Magellanic Cloud and the Magellanic Bridge. We investigated and classified this source with follow-up XMM–Newton and optical observations. We model the X-ray spectra and search for periodicities and variability in the X-ray observations and the Optical Gravitational Lensing Experiment I-band light curve. The optical counterpart has been classified spectroscopically, with data obtained at the South African Astronomical Observatory 1.9 m telescope, and photometrically, with data obtained using the Gamma-ray Burst Optical Near-ir Detector at the MPG 2.2 m telescope. The X-ray spectrum is typical of a high-mass X-ray binary with an accreting neutron star. We detect X-ray pulsations, which reveal a neutron-star spin period of $P_X = (264.516 \pm 0.014)$ s. The source likely shows a persistent X-ray luminosity of a few $10^{35}$ erg s$^{-1}$ and in addition type-I outbursts that indicate an orbital period of $\sim$146 d. A periodicity of 0.867 d, found in the optical light curve, can be explained by non-radial pulsations of the Be star. We identify the optical counterpart and classify it as a B1-2II-IVe star. This confirms SXP 265 as a new Be/X-ray binary pulsar originating in the tidal structure between the Magellanic Clouds.

Key words: stars: emission-line, Be – stars: neutron – pulsars: individual: SXP 265 – galaxies: individual: Small Magellanic Cloud – galaxies: stellar content – X-rays: binaries.

1 INTRODUCTION

Besides supergiant high-mass X-ray binaries, Be/X-ray binaries (BeXRBs, for a review see Reig 2011) are the dominant subclass of high-mass X-ray binaries (HMXBs). They consist of a Be star orbited by a compact object, usually a neutron star (NS). Be stars primarily eject material in the equatorial plane, building up a decretion disc, which leads to observable emission lines (e.g. Hα) in the optical spectrum and an excess emission in the near-infrared (NIR). Both are potentially variable due to instabilities in the disc and interaction with the NS. X-ray outbursts are observed when the NS accretes enhanced amount of material from this decretion disc, particularly during periastron passage (type-I, $L_X \gtrsim 10^{36}$ erg s$^{-1}$) or decretion disc instabilities (type-II, $L_X \gtrsim 10^{37}$ erg s$^{-1}$), but persistent X-ray emission is also observed in some systems ($L_X \sim 10^{35}$ erg s$^{-1}$).

Because of recent star formation, the Magellanic Clouds harbour a large population of BeXRBs that is well observable with today’s X-ray observatories owing to the short distance of 50–60 kpc and a relatively small absorbing foreground column density of a few $10^{20}$ cm$^{-2}$. These systems enable a wealth of possible physical studies. Prominent examples are the recently discovered pulsar LXP 169 (Maggi et al. 2013), which shows optical transits likely caused by material captured by the NS, and SXP 1062 (Haberl et al. 2012; Hénault-Brunet et al. 2012; Sturm et al. 2013b), which is associated to a supernova remnant allowing a robust age determination. Both systems can be used to constrain accretion physics. In addition to individually interesting sources, the known population of the Magellanic Clouds is as comprehensive as the Galactic sample and ideally suited for statistical studies, e.g. to determine the NS spin distribution (Knigge, Coe & Podsiałowski 2011; Cheng, Shao & Li 2014), the relation to the star formation history (Antoniou et al. 2010), and the faint end of the X-ray luminosity function (Shtykovskiy & Gilfanov 2005; Sturm et al. 2013c).

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and to find and constrain the population of Be/white dwarf systems (Kahabka et al. 2006; Li et al. 2012; Sturm et al. 2012; Morii et al. 2013).

We have been granted two triggered XMM–Newton observations in AO 12 to follow up hard X-ray transients in the Magellanic Clouds and to get a more complete sample of pulsars in these galaxies. The first source observed was RX J0520.5—6932 in the Large Magellanic Cloud (LMC) leading to the discovery of the pulse period and a characterization of the X-ray spectrum during a type-I outburst as presented by Vasilopoulos et al. (2014). Here, we present the results from the second observation, that led to the discovery of a new pulsar, SXP 265, located in the intersection of the Wing of the Small Magellanic Cloud (SMC) and the Magellanic Bridge, a tidal structure connecting the LMC and SMC with a continuous stream of gas and young stars (Skowron et al. 2014). This region has a different star formation history (Harris & Zaritsky 2004; Harris 2007) and metallicity (Dufton et al. 2008) to the Bar of the SMC, which harbours most of the known SMC BeXRBs, and so it is particularly interesting to find more BeXRBs in this region.

This paper is structured as follows. In Section 2, we describe the observations and reduction of the data, followed by the analysis in Section 3, the discussion of the results in Section 4, and a summary in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

2.1 XMM–Newton

XMM–Newton (Jansen et al. 2001) carries three X-ray telescopes with the European Photon Imaging Camera (EPIC; Strüder et al. 2001; Turner et al. 2001) instrument at the focal point of each. Between observations, the EPIC-pn operates with the medium filter whilst slewing, allowing for detections of sources with flux $F > 1.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the (0.2–12.0) keV band. These sources are included in the XMM–Newton slew-survey catalogue (Saxton et al. 2008).

We found SXP 265 in an investigation of XMM–Newton slew surveys in the field of the Magellanic Clouds. The source is listed as XMMSL1 J013250.6—742544 and was initially detected on 2007 June 4, followed by a second slew detection on 2007 October 28. A third slew detection on 2011 October 17 is listed as XMMSL1 J013251.0—742549 in the 1.6 release of the slew-survey catalogue. Using a Swift observations on 2013 October 23 (see Section 2.2), we found the source in a bright outburst allowing us to trigger a pointed XMM–Newton observation performed 4 d later (MJD 56592.7—56593.1). The observation log is presented in Table 1.

The data of the pointed observation of all three EPIC instruments were processed with SAS 13.0.0.1 Time intervals of high background have been rejected by selecting background rates in the $7.0–15.0$ keV band below 8 cts ks$^{-1}$ arcmin$^{-2}$ for EPIC-pn and below 2.5 cts ks$^{-1}$ arcmin$^{-2}$ for both EPIC-MOS. Events were extracted within a circular region around the source the radii of which was determined with the SAS task REGIONANALYSE to optimize the signal-to-noise ratio. For the selection of background events, we used a circular extraction region of a source-free area on the same CCDs as the source. For the creation of spectra and response matrices with ESPECGET, we used single- and double-pixel events of EPIC-pn and single- to quadruple-pixel events of EPIC-MOS with FLAG=0. All spectra were binned for a signal-to-noise ratio of at least 5 in each bin. Time series were extracted with the same pattern selection but using all events independent of flags. The photon arrival times were randomized within the CCD frame time and recalculated for the Solar system barycentre. A merged time series for all three instruments was created, using only simultaneous good-time intervals for all instruments.

2.2 Swift

SXP 265 was observed independently with the Swift satellite. The source is listed as SWIFT J0132.5—7425, an unidentified X-ray source, in the Swift/BAT 58-month hard X-ray survey catalogue, but is not included in the 70-month BAT catalogue (Baumgartner et al. 2013). SWIFT J0132.5—7425 was observed with two Swift/XRT exposures in 2010, also listed in Table 1. The corresponding X-ray source in the seven-year Swift-XRT point-source catalogue (D’Elia et al. 2013) is 1SWXRT J013251.3—742545. We requested further Swift observations in 2013, after identifying the source as a BeXRB candidate. Swift/XRT spectra were extracted from the cleaned level-3 event files with the ftool2 xselect using circular extraction regions for the source and background. The spectra were not binned due to the low statistics. Ancillary response files were created using XRTMKarf.

2.3 GROND

On 2013 October 28 03:29 UT, close to the time of the XMM–Newton observation, we observed SXP 265 with the Gamma-ray Burst Optical Near-infrared Detector (GROND; Greiner et al. 2008) at the MPG 2.2 m telescope in La Silla, Chile. 141 s of integration were obtained in $g'$, $r'$, $i'$ and $z'$ and 240 s in $J$, $H$ and $K_s$. The data were reduced and analysed with the standard tools and methods described in Krühler et al. (2008). The $g'$, $r'$, $i'$ and $z'$ photometric calibration was obtained relative to an observation of the Sloan Digital Sky Survey (SDSS) standard star field obtained ~1 h earlier. The $J$, $H$ and $K_s$ photometry was calibrated against selected 2MASS stars (Skrutskie et al. 2006). The derived AB magnitudes including systematic uncertainties, but not corrected for foreground reddening, are: $g' = 14.87 \pm 0.02$, $r' = 15.20 \pm 0.03$, $i' = 15.44 \pm 0.04$, $z' = 15.59 \pm 0.07$, $J = 15.92 \pm 0.07$, $H = 16.12 \pm 0.08$ and $K_s = 16.70 \pm 0.11$ mag.

2.4 OGLE

SXP 265 has been monitored regularly in the $I$ and $V$ band during the phase IV of the Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 2008) since 2010 August 6 (MJD 55414). The OGLE source identification is SMC739.11.1265. In this study, we use data until 2014 January 12 (MJD 56669), containing 341 $I$-band and 29 $V$-band measurements collected in four seasons. Ongoing observations are accessible with the X-ray variables OGLE Monitoring (XROM; Udalski 2008) system.

2.5 SAAO 1.9 m

The optical spectra were taken with the 1.9 m Radcliffe telescope at the South African Astronomical Observatory (SAAO) on the night of 2013 November 5 (MJD 56601) with an exposure time

1 Science Analysis Software (SAS), http://xmm.esa.int/sas/

2 http://heasarc.nasa.gov/f tools/
of 1500 s. A 600 lines mm\(^{-1}\) reflection grating was used, blazed at 4600 Å, along with the SITe CCD. A slit width of 1.5 arcsec was employed. This resulted in a wavelength range of λ\(\lambda\)3500–5500 Å and a resolution of \(\sim\)3.0 Å, determined from the full width half-maximum of the arc lines in the comparison spectra. This corresponds to 2.7 pixels on the CCD. The median signal-to-noise ratio in the λ\(\lambda\)4000–5000 Å region is \(\sim\)33, ranging from \(\sim\)17 to 74.

The data were reduced using the standard packages available in the Image Reduction and Analysis Facility (IRAF). Wavelength calibration was implemented using comparison spectra of copper and argon lamps taken immediately before and after the observation with the same instrument configuration. The spectrum was normalized and a redshift correction applied corresponding to a recession velocity of the SMC of 158 km s\(^{-1}\) (Richter, Tammann & Huchtmeier 1987).

### 3 ANALYSES AND RESULTS

#### 3.1 X-ray spectrum

The three EPIC spectra were fit simultaneously using XSPEC (Arnaud 1996) version 12.7.0. A constant factor was included and allowed to vary for instrumental differences. We find \(C_{\text{MOS1}} = 1.07 \pm 0.04\) and \(C_{\text{MOS2}} = 1.04 \pm 0.03\) relative to EPIC-pn (\(C_{\text{pn}} = 1\)), consistent with the current cross-calibration discrepancy. All other parameters for various models were forced to be the same for all instruments and are listed in Table 2 with 90 per cent confidence uncertainties (\(\Delta \chi^2 = 2.71\)). The photoelectric absorption within the Galaxy was calculated assuming a column density of \(N_{\text{H}, \text{Gal}} = 4 \times 10^{20}\) cm\(^{-2}\) (Dickey & Lockman 1990) with solar abundances (according to Wilms, Allen & McCray 2000). Additional absorption by material within the interstellar medium of the SMC or intrinsic to the source was determined by the fit with abundances set to \(Z_{\odot} = 0.2\) (Russell & Dopita 1992). The spectra are described satisfactorily by an absorbed power law with \(\chi^2 = 1.15\) (with \(v = 583\) degrees of freedom), but this fit exhibits systematic residuals in all instruments (second panel from Fig. 1).

We found a disc blackbody model to be a better fit to the data, but this requires physically implausible parameters. Alternatively, we can account for a steeper spectral shape at higher energies with a broken power-law model, which results in \(\chi^2 = 1.00\), \(\Gamma_1 = 0.60\), \(\Gamma_2 = 1.1\), and a break energy of \(E_b = 3.19\) keV, or with a power-law model containing an additional high-energy cut-off, which results in \(\chi^2 = 1.00\), \(\Gamma = 0.56 \pm 0.08\), a cut-off energy of \(E_{\text{cut}} = 2.32 \pm 0.03\) keV and a folding energy of \(E_{\text{fold}} = 10.5_{-2.4}^{+2.4}\) keV. We note, that a simultaneous fit to the Swift/BAT spectrum with this cut-off model (with free model normalization, \(C_{\text{BAT}} = 1.4 \pm 0.4\)) does not show systematic offsets in the BAT data residuals.

### Table 2. Spectral-fitting results for SXP 265.

| Observation | Mode\(^{ab}\) | \(N_{\text{H}, \text{SMC}}\) \(10^{22}\) cm\(^{-2}\) | \(\Gamma\) | \(kT\) (keV) | \(R\) keV | \(F\) (10\(^{-14}\) erg cm\(^{-2}\) s\(^{-1}\)) | \(L_{\odot}\) (10\(^{33}\) erg s\(^{-1}\)) | \(z^2\) | \(v\) |
|-------------|----------------|------------------|---|---|---|---|---|---|
| XMM 2013    | PL             | 1.07\(^{+0.21}_{-0.20}\) | 0.820\(^{+0.022}_{-0.021}\) | – | – | 3.836 ± 0.077 | 1.83\(^{+0.03}_{-0.03}\) | 1.16 | 583 |
|             | DiskBB         | 0.71\(^{+0.15}_{-0.14}\) | – | 6100\(^{+540}_{-450}\) | 0.101\(^{+0.012}_{-0.012}\) | 3.716 ± 0.080 | 1.77\(^{+0.03}_{-0.03}\) | 1.03 | 583 |
|             | PL + BB        | 4.58\(^{+0.98}_{-0.88}\) | 0.914\(^{+0.034}_{-0.029}\) | 63.7\(^{+5.4}_{-5.8}\) | 0.88\(^{+0.10}_{-0.09}\) | 3.786 ± 0.076 | 2.88\(^{+0.32}_{-0.30}\) | 1.07 | 581 |
|             | PL + BB 2      | 4.93\(^{+0.23}_{-0.17}\) | 0.825\(^{+0.055}_{-0.052}\) | 1280\(^{+142}_{-142}\) | 1.26\(^{+0.19}_{-0.16}\) | 3.790 ± 0.050 | 1.70\(^{+0.02}_{-0.02}\) | 0.99 | 581 |
|             | PL + DiskBB    | 4.60\(^{+0.95}_{-0.93}\) | 0.926\(^{+0.032}_{-0.030}\) | 73.4\(^{+7.0}_{-7.4}\) | 0.80\(^{+0.012}_{-0.012}\) | 3.785 ± 0.078 | 3.37\(^{+1.43}_{-1.41}\) | 0.69 | 1.07 | 581 |
| Swift 2010 a| PL             | <1.6             | 0.82 ± 0.34 | – | – | 0.69 ± 0.17 | 0.33\(^{+0.08}_{-0.07}\) | – | – |
| Swift 2010 b| PL             | 0.89 ± 0.41      | 0.43\(^{+0.19}_{-0.14}\) | – | – | 0.14          | 0.14          | – | – |
| Swift 2013 a| PL             | 2.02 ± 0.56      | 0.96\(^{+0.25}_{-0.21}\) | – | – | 0.43          | 0.43          | – | – |
| Swift 2013 b| PL             | <3.4             | 0.75\(^{+0.15}_{-0.20}\) | – | – | 7.06 ± 0.96  | 3.37\(^{+0.43}_{-0.39}\) | – | – |
| Swift 2013 c| PL             | 2.87 ± 0.63      | 1.37\(^{+0.28}_{-0.25}\) | – | – | 0.14          | 0.14          | – | – |

\(^{ab}\)For definition of spectral models see Section 3.1. \(^{c}\)Column density within the interstellar medium of the SMC or intrinsic to the source in 10\(^{19}\) cm\(^{-2}\). \(^{d}\)Temperature in keV. \(^{e}\)Radius of the emitting area (for BB) or inner-disc radius for an inclination of θ = 0 (for DiskBB) in km. \(^{f}\)Observed flux in the (0.2–10.0) keV band in 10\(^{-12}\) erg cm\(^{-2}\) s\(^{-1}\).
3.2 X-ray pulsations

Using a fast Fourier transformation, we find a clear signal at a frequency of $f = 0.00378$ Hz in the merged EPIC time series in the (0.2–10.0) keV band (Fig. 2). This period is independently seen in all three EPIC instruments. The pulse period and its 1σ uncertainty are determined as $P = (264.516 \pm 0.014)$ s using a Bayesian detection method (see Haberl, Eger & Pietsch 2008). The folded background-subtracted EPIC light curves are presented for the total (0.2–10.0) keV band and the standard subbands (0.2–0.5), (0.5–1.0), (1.0–2.0), (2.0–4.5) and (4.5–10.0) keV in Fig. 3. The first two bands have been merged to increase the statistics. Variations in the hardness ratio, defined by $HR_i = (R_{i+1} - R_i)/(R_{i+1} + R_i)$ with $R_i$ denoting the background-subtracted count rate in the standard energy band $i$ (with $i$ from 1 to 4), are also shown. We estimate the pulsed fraction in the total energy band to be $R_{\text{pulsed}}/R_{\text{total}} = 0.21 \pm 0.03$, assuming a sinusoidal pulse profile.

Figure 1. The X-ray spectra of SXP 265 as observed with XMM–Newton together with the folded best-fitting model (solid lines) of a power-law (dotted lines) and a multitemperature disc (dashed lines) are plotted in the upper panel. EPIC-pn/MOS1/MOS2 data are plotted in black/red/green. The residuals for a simple power law, a power law and disc, power law with high-energy cut, and power law and hot blackbody model are plotted in the lower panels (from top to bottom). For clarity, the residuals have been rebinned by a factor of 5.

However, since this spectrum has only eight data bins, the fit statistics is dominated by the XMM–Newton spectra.

A soft emission component (e.g. Hickox, Narayan & Kallman 2004; Eger & Haberl 2008) might be expected to contribute to the X-ray emission of HMXBs. We tested a possible contribution by adding a blackbody or a multitemperature disc blackbody model. These models give significantly better fits with $f$-test probabilities of $2 \times 10^{-8}$ and $1 \times 10^{-8}$. We found a second, even better, solution for a higher blackbody temperature, as listed by the PL+BB 2 model in Table 2.

Another possible spectral feature of BeXRBs is Fe Kα line emission. By adding a Gaussian line profile with fixed central energy $E_c = 6.4$ keV and width of $\sigma = 0$, we obtain a 3σ upper limit for the line flux of $F_{\text{FeK}\alpha} \leq 2 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$, which corresponds to an equivalent width of $EW \geq -54$ eV.

The low statistics of the Swift spectra mean the data can be described sufficiently with the best-fitting power-law model derived from the XMM–Newton data. When fit to the Swift spectra independently, the absorption and photon index are consistent with the XMM–Newton values within uncertainties (see Table 2). We therefore used the parameter values from the best-fitting power-law model and fitted only the normalization to the unbinned spectra with C statistics, to derive the fluxes and luminosities listed in Table 2.

Figure 2. Power-density spectrum of the merged EPIC time series in the (0.2–10.0) keV band.

Figure 3. Left: X-ray pulse profile of SXP 265 in various energy bands of the merged time series. The pulse profiles are background-subtracted and normalized to the average net count rate of 0.14, 0.26, 0.30, 0.19 and 0.89 cts s$^{-1}$ from top to bottom. Right: hardness ratios as a function of pulse phase derived from the pulse profiles in two neighbouring standard energy bands.
3.3 Long-term X-ray light curve

SXP 265 is listed three times in the XMM–Newton slew-survey catalogue (Saxton et al. 2008) as XMMSL1 J013250.6−742544 and XMMSL1 J013251.0−742549 with count rates (1.52 ± 0.57) s−1 on 2007 June 4 (MJD 54255), (0.70 ± 0.25) s−1 on 2007 October 28 (MJD 54401), and (0.85 ± 0.41) s−1 on 2011 October 17 (MJD 55851), respectively.

Assuming the best-fitting power-law model from above, this corresponds to (0.2–10.0) keV fluxes of (13.7 ± 5.1) × 10−12, (6.3 ± 2.3) × 10−12, and (7.7 ± 3.7) × 10−12 erg cm−2 s−1 for an EPIC-pn exposure with medium filter.

All X-ray fluxes from pointed observations are listed in Table 2. These flux measurements reveal a variability by a factor of 10. If the XMM–Newton slew detections are included, variability of at least a factor of 20 becomes evident.

The long-term X-ray light curve of SXP 265 is presented in Fig. 4. Included are the upper limits from XMM–Newton slews without a detection of SXP 265 that were obtained from the XMM–Newton upper-limit server.3

Assuming a conservative detection limit of 7 cts in the ROSAT all sky survey, we obtain an upper limit of 0.012 cts s−1 (0.1–2.0 keV) for 1990 October. For the best-fitting power-law model, this translates to a (0.2–10.0) keV flux of 1.4 × 10−12 erg cm−2 s−1 and thus does not exclude X-ray emission at the low-level, as seen with Swift in 2010.

By assuming a distance of the SMC of 62.1 kpc (Graczyk et al. 2014) throughout the paper, these fluxes translate to X-ray luminosities exceeding 1036 erg s−1 for the three XMM–Newton slew detections and the outburst observed in 2013 October. This would be atypical for a persistent X-ray emitting state and points to X-ray outbursts. The first two slew detections are separated by 146 d and therefore unlikely to be caused by the same type-I outburst, as these last typically up to ∼30 per cent of the orbit (Galache et al. 2008). Interestingly, the third slew detection and the maximum of the 2013 outburst (Swift observation 2013 b), were 1451 d and 2187 d later, i.e. ∼10 times and ∼15 times the above separation. This might indicate the orbital period of the system, but needs further confirmation. We note that the X-ray light curve folded with the 146 d period includes all detections with LX > 1036 erg s−1 within ∼10 per cent of the tentative orbital period as expected for type-I outbursts (Galache et al. 2008).

3.4 X-ray coordinates

The pointed XMM–Newton observation provides the most precise X-ray position of SXP 265. Source detection was performed on the X-ray images of all three EPIC instruments simultaneously (for details see Sturm et al. 2013c). We identified seven other X-ray sources in the field of view, to derive an astrometric correction of ΔRA = −0.53 arcsec and ΔDec. = −0.46 arcsec. This yields X-ray coordinates of SXP 265 of RA = 01h32m51.39 and Dec = −74°25′45″ (J2000). Using astrometric corrections, the expected systematic uncertainty reduces from σsys = 1 arcsec to σsys = 0.35 arcsec (Watson et al. 2009) resulting in a 1σ position uncertainty for SXP 265 of σ = 0.36 arcsec, where the statistical error is added quadratically.

This position is in agreement with the XMM–Newton slew detections, with angular separations of 15.3 arcsec (due to the high position uncertainty this is equivalent to 1.7σ), 3.9 arcsec (0.66σ), and 4.0 arcsec (0.76σ), respectively. All Swift/XRT detections have angular separations <3.3 arcsec (<1.1σ) and are therefore also in agreement with the XMM–Newton coordinates.

The XMM–Newton position allows us to identify 2MASS J01325144−7425453 as the optical counterpart with an angular separation of 0.26 arcsec. The X-ray position is indicated in the GROND r′-band finding chart (Fig. 5). The small circle indicates the improved and the large circle the uncorrected XMM–Newton position. The star is also listed in the Spitzer SMC survey (Gordon et al. 2011) as SSTISAGEMA J013251.49−742545.2. No other object is found to be in positional agreement with the X-ray source.

Figure 4. Long-term X-ray light curve including XMM–Newton (black diamonds) and Swift (red squares) detections. Upper limits from the XMM–Newton slew survey are marked by arrows. Dashed vertical lines indicate a 146 d period.

Figure 5. GROND r′-band finding chart. The cross marks the optical counterpart of SXP 265. In the 8 arcsec × 8 arcsec zoom-in, the corrected and uncorrected 1σ XMM–Newton positions are indicated by a small and large circle, respectively.

3 http://xmm.esac.esa.int/external/xmm_products/slew_survey/upper_limit/uls.shtml
3.5 Optical spectrum

Spectrally classifying early-type stars in the SMC is difficult due to the low-metallicity environment. The metal lines required for classification using the traditional Morgan–Keenan (MK; Morgan, Keenan & Kellman 1943) system are either much weaker or are not present. As such, the optical counterpart of SXP 265 was classified using the system developed by Lennon (1997) for B-type supergiants in the SMC, and implemented for the SMC and LMC by Evans et al. (2004, 2006). This system has been normalized to the MK system such that the classification criteria follow the same trends in line strengths. Fig. 6 shows the normalized spectrum of SXP 265 smoothed with a boxcar average\(^4\) with width 3.

Be stars are characterized by their rapid rotation. This behaviour replenishes the decretion disc where the emission lines originate, which, in turn, leads to the ‘e’ designation. It is therefore unsurprising that the optical spectrum of SXP 265 is dominated by the rotationally broadened hydrogen Balmer series. The H\(\beta\) line in particular shows evidence of ‘infilling’ – i.e. an emission feature superimposed on an absorption line.

The spectrum does not show any evidence for the He \(\lambda\lambda 4200, 4541\) or 4686 lines above the noise level of the data, suggesting a spectral type B1 or later. There does, however, appear to be some evidence for the Si \(\lambda\lambda 4088\) and 4116 lines, which, if real, would constrain the spectral type to B1. The proximity of these lines to the broadened H\(\gamma\) line makes it hard to determine whether they are genuine. The Si \(\lambda\lambda 4553\) line is stronger than the Mg \(\lambda\lambda 4481\) line constraining the spectral type to B2 or earlier.

The luminosity class of the counterpart was determined using the ratios of He \(\lambda\lambda 4121/He \lambda 4143\) and Si \(\lambda\lambda 4553/He \lambda 4387\) (Walborn & Fitzpatrick 1990). The former decreases with increasing luminosity class (i.e. decreasing luminosity) the latter increases with increasing luminosity class. The signal-to-noise ratio and resolution of the spectrum, along with its proximity to the Doppler broadened H\(\alpha\) line, make it difficult to draw any conclusions based on the He \(\lambda\lambda 4121\) line but the Si \(\lambda\lambda 4553/He \lambda 4387\) ratio suggests a luminosity class II–IV. This is supported by the strength of the O \(\lambda\) spectrum, which also increases with increasing luminosity, however the low-metallicity environment make this an unreliable luminosity-class indicator.

The well-known distance to the SMC means we can calculate the absolute magnitude of the optical counterpart of SXP 265 accurately and precisely. This value can then be compared to those predicted for a B1-2II-IVe star to confirm the luminosity classification. Using the GROND \(r^\prime\) and \(i^\prime\) magnitudes, as well as equation (5) of Krühler et al. (2011), we get an uncorrected \(V = (15.06 \pm 0.04)\) mag. For comparison, the OGLE \(V\)-band measurements cover the range from \(V = 14.986\) to 15.084 mag and the one on 2013 November 4 (closest to the GROND observation) yielded \(V = (15.040 \pm 0.003)\) mag. Assuming the column density from the best-fitting model to the X-ray spectrum of \(N_{H, \text{SMC}} = (5 \pm 2) \times 10^{20} \text{cm}^{-2}\), along with the \(N_{H, \text{Gal}}\) from Dickey & Lockman (1990, \(4 \times 10^{20} \text{cm}^{-2}\)) and equation (1) from Güver & Özel (2009), we derive an optical extinction of \(A_V = (0.407 \pm 0.092)\) mag. Along with a distance modulus of \(m - M = (18.95 \pm 0.07)\) mag (Graczyk et al. 2014), this implies \(M_V = (-4.3 \pm 0.1)\) mag. This value is consistent with a B1He star (Wegner 2006); however, we note that it falls within the range of a B1-1.5Sbe star all the way down to a B1-1.5IV-Ve star. As such, we classify the optical counterpart of SXP 265 as a B1-2II-IVe star.

3.6 Spectral energy distribution

The simultaneously measured GROND data and the \(uvw1\) measurement from the optical monitor of XMM–Newton were used to construct the spectral energy distribution of the source. The boxes in Fig. 7 give flux densities, corrected for the Galactic foreground redening (squares) and for additional redening within the SMC (diamonds). The red and blue lines represent stellar atmosphere models at \(T_{eff} = 25\,000\) and 30\,000 K, respectively, both for a stellar radius of \(R = 10.5\ R_\odot\).

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\(^4\) http://northstar-www.dartmouth.edu/doc/idl/html_6.2/SMOOTH.html

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Figure 6. Spectrum of SXP 265 in the wavelength range \(\lambda\lambda 3900–5000\ \text{Å}\) taken with the Radcliffe 1.9 m telescope at SAAO on 2013 November 5. The spectrum has been normalized and redshift corrected by 158 km s\(^{-1}\). Atomic transitions relevant to spectral classification have been marked.

Figure 7. Spectral energy distribution of the optical counterpart of SXP 265 corrected for Galactic foreground redening (squares) and for additional maximum redening within the SMC (diamonds). The red and blue lines represent stellar atmosphere models at \(T_{eff} = 25\,000\) and 30\,000 K, respectively, both for a stellar radius of \(R = 10.5\ R_\odot\).
reddening of $E(B - V) = 0.044$ mag (Schlafly & Finkbeiner 2011), which we assume as the lower limit for the reddening. We assume an upper limit of the reddening within the SMC of $E(B - V) = 0.11$ mag, which corresponds to the total line-of-sight $\text{HI}$ column density of $N_{\text{HI,SMC}} = 6 \times 10^{20}$ cm$^{-2}$ (Stanimirovic et al. 1999) when using the relation of Predehl & Schmitt (1995).

We compare both spectral energy distributions with the stellar atmosphere models of Lanz & Hubeny (2007) with $Z = 0.2 Z_\odot$ and $\log (g) = 4$. The model with effective temperature $T_{\text{eff}} = 25,000$ K and radius $R = 10.5 R_\odot$ (blue line) well describes the data at shorter wavelengths in the low-extinction case. This temperature is typical for a B1 star. The radius is somewhat larger than that expected for a main-sequence star. In the high-extinction case, a $T_{\text{eff}} = 30,000$ K (red line) is needed to compensate for the high extinction in the UV, this temperature is more typical of a B0 star.

The uncertainty in the proper extinction correction has the greatest effect towards the UV. However, towards the NIR, the reprocessing of the UV radiation from the star by the decretion disc is expected to cause an additional emission component. For both extinction scenarios, we find a clear indication for such an excess in the $H$ and $K_s$ band.

### 3.7 Optical light curve

The OGLE-IV $I$-band light curve, presented in the middle panel of Fig. 8, reveals long-term variability, e.g. by a systematic increase of $\sim 0.2$ mag in the $I$ band between 2010 August and 2011 July (MJD 55414–55745). Another, even stronger, brightening of the source is found between 2MASS (1998 October 8, MJD 51094) and 2MASS6X (2000 December 8, MJD 51886) observations (Skrutskie et al. 2006) by (0.922 $\pm$ 0.072) mag in the $J$ band, (1.07 $\pm$ 0.19) mag in the $H$ band, and $>0.5$ mag in the $K$ band.

We obtained $V - I$ colours using the OGLE V-band observations closest in time to the $I$-band observations, with a maximal separation of one day. This resulted in 9 and 18 colour measurements in the first and second OGLE season, respectively, as plotted in Fig. 9. A clear correlation is seen between the parameters. The source becomes redder with increasing brightness. This is expected if the inclination of the decretion disc is $\lesssim 80^\circ$ with respect to the observer (Rajoelimanana, Charles & Udalski 2011).

The Lomb–Scargle periodogram (Scargle 1982) of the detrended OGLE light curve, between 2011 May and 2014 January (season 2–4, MJD 55699–56669), is presented in Fig. 10. The significant peaks are found at 6.532, 1.177, 0.867, 0.541, 0.464, 0.351 and 0.317 d as labelled in Fig. 10. These are 1-d aliases of each other caused by the sampling. Whereas the strongest power is found for the 6.532 d period when using the seasons 2–4, the 0.867 d period has a similar power to the 6.532 d period, if only season 2 is used (22.00 versus 22.02). No significant detections are seen when the other seasons are independently investigated. The folded light curves for both periods are sinusoidal (Fig. 11) and have small amplitudes of (0.00699 $\pm$ 0.00028) and (0.00754 $\pm$ 0.00028) mag, respectively.

To estimate the uncertainties in both periods, we use the bootstrap method (Efron 1982). We created random light curves from the original OGLE measurements by sampling with replacement (i.e. one epoch can be drawn multiple times) and searched for periodicities. We repeated the above procedure 1000 times allowing the
\( d, \) however this needs further confirmation. We determine uncertainties to be determined from the resulting distribution as shown in the lower panel, the sine function has a period of 6.532 d.

\( \sigma \) uncertainties to be determined from the resulting distribution as \((6.532 \pm 0.012) \) and \((0.867 \pm 0.010) \) d.

In Fig. 11, we also show the light curve convolved at 26.13 d, i.e. four times the 6.532 d period. In this case, we see a stronger dip and increase at phase \( \sim 0.5 \) than at the other expected minima. These phases are also marked in the detrended light curve with vertical lines in Fig. 8. We note that these dips are not present in the first season, when the source was brightening but still in a fainter state. The total OGLE light curve covers 1254 d allowing periods up to \( \sim 600 \) d to be resolved. The Lomb–Scargle periodogram of the unaltered light curve (i.e. without detrending) shows strong power at \( \sim 241 \) and \( \sim 643 \) d (in addition to the 1 and 6.532 d periods) and the \( \sim 346 \) d that is seen when the first season is not used. Due to the limited statistics and additional long-term variability, a longer coverage of the source is needed to establish the orbital period of the NS from optical variability.

4 DISCUSSION

The X-ray spectrum, X-ray pulsations and the identification of the optical counterpart as a Be star allow us to clearly identify SXP 265 as a NS BeXRB. Its properties are discussed in the following.

4.1 Spectra

The precise XMM–Newton coordinates allow us to clearly identify 2MASS J01325144–7425453 as the optical counterpart. Our spectral classification of a B1-Ive star is typical for a BeXRB in the SMC, as these are primarily found between O9.5 and B1.5 (McBride et al. 2008). Irregular long-term optical variability and excess emission in the NIR are observed. This is typical for Be stars and likely caused by a varying amount of reprocessing material in the decretion disc around the Be star.

The overall X-ray spectrum follows a power-law model with a typical photon index for BeXRBs in the SMC (Haberl & Pietsch 2004). Evidence for a moderate deviation from this model is seen in the residuals. This could be due to the contribution of a low temperature (\( kT \sim 100 \) eV) soft excess. The inferred values are typical of those found in other BeXRBs (e.g. Haberl & Pietsch 2008; Sturm et al. 2011) and allow for a soft excess with bolometric luminosity up to \( L_{\text{bol}} = 1.6^{+1.9}_{-0.8} \times 10^{36} \text{ erg s}^{-1} \). However, these models require a high absorbing column. The derived radius of the emission region, estimated according to Hickox et al. (2004), is \( R = (L_{\text{bol}}/4\pi\sigma T^4)^{1/2} = 756 \) km; too large for an NS. We attribute this excess to an accretion disc or X-ray reprocessing material around the NS.

A contribution by a thermal component with higher temperature (\( kT > 1 \) keV) is also possible (Bartlett, Coe & Ho 2013; La Palombara et al. 2013). For some sources, this solution results in a physically questionable scenario, with the power-law component dominating the spectrum at lower energies and the blackbody component contributing most of emission at higher energies. In this case, however, the blackbody component contributes 20 per cent to the measured (0.2–10.0) keV flux and the flux density of the blackbody is below that of the power-law component at all energies. A possible interpretation for the origin of this component is emission from the heated polar caps of the NS. The radius is at the upper limit of what is usually reported, but a slowly spinning NS with a rather constant X-ray luminosity is in agreement with this picture. An indication of spectral variability at higher energies is seen in the HR variations (Fig. 3), but the statistics is insufficient for a detailed phase-resolved spectral analysis.

We also derived good fits using a power-law model with a high-energy cut-off. In other HMXBs, such a cut-off is observed at higher energies, \( \gtrsim 10 \) keV (Townsend et al. 2011), and so we do not favour this model.

For all the models, the absorption of the X-ray spectrum is in agreement with or above the total line-of-sight SMC column density of \( N_{\text{H,SMC}} = 6 \times 10^{20} \) cm\(^{-2} \) (Stanimirovic et al. 1999). This suggests the system is behind the absorbing interstellar medium in the SMC or there is some intrinsic absorbing material in close proximity to the NS. Comparing the spectrum and the spectral energy distribution of the optical counterpart suggests a rather low extinction, placing the absorbing material close to the NS.

4.2 Periodicities

The X-ray pulsations establish the compact object as an NS. The spin period of \( P_s = (264.516 \pm 0.014) \) s puts the system in the population of slowly rotating pulsars (Knigge et al. 2011), which typically show wide and circular orbits with only moderate X-ray outbursts (Cheng et al. 2014). SXP 265 was consistently detected above \( F_X \sim 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \) when observed with sufficient sensitivity, suggesting the source exhibits a rather persistent X-ray emission at this lower level. We also observe what appears to be moderate type-I outbursts, where the X-ray luminosity increases by a factor of \( \sim 10–20 \); these are only expected during periastron. The temporal separation of these outbursts suggests an orbital period of \( P_o \sim (146 \pm 2) \) d, however this needs further confirmation. We note that this orbital period is in agreement with the spin period, according to the Corbet relation (Corbet 1984; Laycock et al. 2005; Corbet et al. 2009).

A 6.53 d period is found in the OGLE light curve with a small amplitude of \((0.00754 \pm 0.00028) \) mag. There is also an indication of a feature at four times this period. Given the long spin period of...
4.3 Population comparison

The location of SXP 265 is compared with the H I column density and the distribution of the other HMXBs in Fig. 12. SXP 265 is located in the transition region between the SMC Wing and the Magellanic Bridge. The bulk of known HMXBs are found in the SMC Bar, which is known to have had an enhancement in its recent star formation. A population of sources following the tidal feature towards the LMC, i.e. the Wing and high-density western part of the Bridge, is also evident. The HMXB population appears to be less dense in the Wing (McGowan et al. 2008; Sturm et al. 2013c), but the low X-ray coverage in the outer regions of the SMC Wing and the Bridge makes it difficult to currently estimate the population of HMXB. Only three confirmed BeXRBs are currently known to be located in the Magellanic Bridge, the first was found with ROSAT by Kahabka & Hilker (2005) and two further systems were reported by McBride et al. (2010).

It is worth noting that no BeXRBs have been found elsewhere around the SMC, despite the similar coverage of the INTEGRAL and XMM–Newton slew surveys. This suggests that the BeXRBs in the Magellanic Bridge do not originate in the SMC Bar, as noted by McBride et al. (2010). The Bridge formed ~200 Myr ago, i.e. much longer than the lifetime of an HMXB, and so these BeXRBs cannot have been tidally stripped from the SMC Bar population. The tidally triggered episode of star formation in the Bridge ended ~40 Myr ago (Harris 2007). This is the expected evolution time of BeXRBs (Antoniou et al. 2010), and it is therefore likely that the observed BeXRBs in the Bridge were formed in this event.

Future eROSITA survey observations (Merloni et al. 2012) will reveal the population in the outer regions of the SMC with a sensitivity down to $L_X > 10^{35}$ erg s$^{-1}$. This will allow us to further study the population of BeXRBs in a tidal structure, and might put further constraints on supernova kick velocities when the surrounding regions of the SMC have a deeper homogeneous X-ray coverage.

5 SUMMARY AND CONCLUSIONS

We discovered a variable X-ray source, named SXP 265, in archival XMM–Newton and Swift observations. We classified this source as a BeXRB candidate based on its correlation with a blue star in the SMC and investigated it in detail with additional follow-up observations with XMM–Newton, Swift, GROND at the MPG 2.2 m telescope, and spectroscopy at the 1.9 m Radcliffe telescope at the SAAO in addition to the analysis of OGLE light-curve data.

The X-ray spectrum is typical for a HMXB with an NS compact object. The spin period of the NS is $P_s = (264.516 \pm 0.014)$ s. The source appears to show persistent X-ray luminosity at a few $10^{35}$ erg s$^{-1}$ as well as type-I outbursts, of luminosity of a few $10^{36}$ erg s$^{-1}$, indicating a possible orbital period of 146 d.

We identify the optical counterpart at RA $= 01^h32^m51^s47$ and Dec. $= -74^\circ25'45''2$ (J2000, 2MASS6X coordinates) and classify it as a B1-2II-IVe star, which has long-term variability and an excess in the NIR. An optical period is found at 0.867 d (or one of its 1-d aliases) and might be explained by NRPs of the Be star. SXP 265 is located in the transition region of the SMC Wing and the Magellanic Bridge where only a few systems are known and is the second most eastern pulsar associated with the SMC.

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