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Hα imaging for BeXRBs in the Small Magellanic Cloud

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Abstract. The Small Magellanic Cloud (SMC) hosts a large number of high-mass X-ray binaries, and in particular of Be/X-ray Binaries (BeXRBs; neutron stars orbiting OBe-type stars), offering a unique laboratory to address the effect of metalicity. One key property of their optical companion is Hα in emission, which makes them bright sources when observed through a narrow-band Hα filter. We performed a survey of the SMC Bar and Wing regions using wide-field cameras (WFI@MPG/ESO and MOSAIC@CTIO/Blanco) in order to identify the counterparts of the sources detected in our *XMM-Newton* survey of the same area. We obtained broad-band *R* and narrow-band Hα photometry, and identified ∼10000 Hα emission sources down to a sensitivity limit of 18.7 mag (equivalent to ∼B8 type Main Sequence stars). We find the fraction of OBe/OB stars to be 13% down to this limit, and by investigating this fraction as a function of the brightness of the stars we deduce that Hα excess peaks at the O9-B2 spectral range. Using the most up-to-date numbers of SMC BeXRBs we find their fraction over their parent population to be $\sim 0.002 - 0.025$ BeXRBs/OBe, a direct measurement of their formation rate.

Keywords. Magellanic Clouds, stars: early-type, stars: emission-line, Be, X-rays: binaries

1. Introduction

The Small Magellanic Cloud (SMC) has been a major target for X-ray surveys due to our ability to detect sources down to non-outbursting X-ray luminosities ($L_X \sim 10^{33}$ erg s^{-1}) and its impressive large number of High-Mass X-ray Binaries (HMXBs; Haberl & Sturm 2016). However, the X-ray properties alone cannot fully characterize the nature of each source. HMXBs consist of an early-type (OB) massive star and a compact object (neutron star or black hole), which accretes matter from the massive star either through strong stellar winds and/or Roche-lobe overflow in supergiant systems or through an equatorial decretion disk in, non-supergiant, OBe stars (Be/X-ray Binaries; BeXRBs). The compact object dominates the X-ray spectrum while the companion dominates the optical spectrum. Thus, to understand the nature of BeXRBs we need to study their optical counterparts, which should be consistent with OBe stars. These are massive stars that show Balmer lines in emission, of which Hα is typically the most prominent. Although the SMC is close enough to resolve its stellar population, we still lack the identification of the optical counterparts or their optical spectral classification for a large fraction (∼ 40% of the candidate HMXBs) of the most recent census (121 candidates in total; Haberl & Sturm 2016). To address this issue we take advantage of the fact that OBe stars display Hα in emission, making them easily discernible from other stars in Hα narrow-band images, and we performed a wide Hα imaging survey of the SMC to reveal prime candidates for BeXRB optical counterparts.

2. Observations and Data Reduction

We used the Wide Field Imager (WFI@MPG/ESO 2.2m, La Silla, on 16/17 November, 2011) and the MOSAIC camera (@CTIO/Blanco 4m, Cerro Tololo, on 15/16 December, 2011) to observe 6 and 7 fields in the SMC, respectively. Given their large field-of-views ($\sim 33' \times 33'$) we covered almost the whole galaxy. Each field was observed in the R broad-band (the continuum) and Hα narrow-band filters. A dithering approach was needed to cover camera chip gaps, and the exposure time was selected to achieve a similar depth ($R \sim 23$ mag) in both campaigns to allow for coverage of late B-type stars at the distance of the SMC. Additionally, a set of spectrophotometric standards was observed to flux calibrate the results. THELI† was used to reduce and produce the final mosaics from the WFI data. For the MOSAIC data we retrieved the reduced data products from the NOAO online pipeline‡ and then combined them using IRAF's `mscred` package. We finally re-sampled (with SWARP¶) the mosaic images for each field, using a common center and frame size (for details see Maravelias 2014).

Because of the high source density we performed PSF photometry with IRAF's `daophot` by properly selecting its parameters for each field. However, we ran the source detection on the broad-band R image only, as the same process in Hα would result to many spurious sources due to the HII regions of the SMC. This (R-selected) source list was used to perform photometry on Hα. We first screened the (flux-calibrated) `daophot` results to select stellar sources, according to their χ^2 (~ 1) and `sharpness` ($|\mathrm{sharp}| < 0.5$) values. Since we were interested in OB stars we kept sources brighter than $R = 18.7$ mag, which corresponds to B8 spectral-type stars at the distance of the SMC. We cross-correlated the two filters (R and Hα) to identify the common sources and then with the MCPS catalog (Zarithsly *et al.* 2002) to obtain their V, B photometry. Using the locus of OB stars (Antoniou *et al.* 2009) we selected the best OB candidate sources, for which we calculated their (H$\alpha - R$) index, its error, and SNR (following Zhao *et al.* 2005).

Since the R filter includes the Hα region the corresponding baseline for stars without any Hα excess would be equal to (H$\alpha - R$)= 0 mag. However, due to the differences between the two filters and the range of spectral types considered, this is not 0 (see Maravelias 2014). To overcome this we define the baseline (H$\alpha - R$) value for non-Hα excess stars individually for each field based on the mode ($\langle \mathrm{H}\alpha - R \rangle$) and standard deviation (σ) of the (H$\alpha - R$) distribution of all OB stars in each field. We consider as best Hα emitting candidates the sources with: $(\mathrm{H}\alpha - R) < \langle \mathrm{H}\alpha - R \rangle - 5 \times \sigma$, and SNR$> 5$.

3. Results and Discussion

Our survey reveals 9808 Hα emitting sources in the SMC. This is 2 to 4 times more sources from other previous surveys (1844 sources; Meyssonnier & Azzopardi 1993), mostly due to our deeper coverage down to $V = 18.5$mag instead of $R \sim$16.5 mag.

From our analysis we know the number of OB stars and the corresponding number of emission-line stars (i.e. OBe). This allows us to derive the OBe/OB fraction for each field. We find an average value of $\sim$13.3% across the SMC, consistent with previous studies (e.g. $\sim 5 - 11$% from Iqbal & Keller 2013). This fraction is only a lower limit of the actual population of the OBe stars since their activity is a transient phenomenon

† `http://www.astro.uni-bonn.de/~theli/`
‡ `http://portal-nvo.noao.edu/search/query`
¶ `http://www.astromatic.net/software/swarp`

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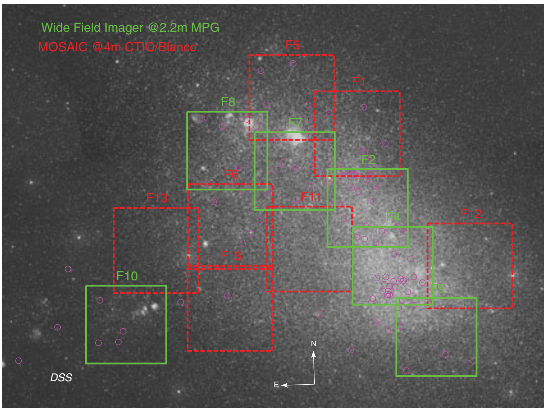

Field-ID	OBs	OBe/OBs	BeXRBs/OBe
1	6916	0.157	0.0184
2	9217	0.128	0.0246
4	9799	0.121	0.0218
5	5396	0.136	0.0136
6	6716	0.101	0.0088
7	8428	0.142	0.0133
8	7305	0.118	0.0081
9	3672	0.132	0.0145
10	1687	0.144	0.0165
11	5542	0.096	0.0019
12	3905	0.183	0.0
13	2693	0.129	0.0
16	3236	0.142	0.0022

Figure 1. *Left:* The fields observed with the WFI (green solid boxes) and the MOSAIC (red dashed boxes) wide-field cameras, overplotted on a DSS image of the SMC. BeXRBs (taken from Haberl & Sturm 2016) are shown as smaller purple circles. *Right:* For each field (col. 1) we show the number of OB stars identified (col. 2), the fraction of $H\alpha$ emitting stars of OBe/OBs (col. 3), and the formation rate BeXRBs/OBe (col. 4). (Not including fields 3 and 14/15 due to reduction issues and shallower exposures, respectively.)

and only a fraction of them is active in a certain epoch. Furthermore, if we examine the relation of this fraction with R magnitude (1 mag $\sim$ 3 spectral sub-types at the distance of the SMC), we notice a peak at $\sim$15 mag (corresponding to O9-B2) and a fast drop with magnitude (equal to later spectral types). This trend is consistent with previous observations, but we extend it to later B-type stars (from Martayan *et al.* 2010: peak at B2 but limited to $\sim$B3). Moreover, it confirms theoretical models that predict a peak of that ratio at B3, as a result of the critical rotational velocity (Maeder & Meynet 2000).

Given the numbers of OBe stars and BeXRBs we derive the BeXRBs/OBe fraction in the range $\sim 0.002 - 0.025$, which provides us with the formation efficiency of these systems with respect to their parent population. This is a direct measurement of their formation rate, which can place constraints on stellar population synthesis models (e.g. Belczynski *et al.* 2008). Currently, we are working on the cross-correlation of this catalog with the most recent list of candidate BeXRBs in the SMC (Haberl & Sturm 2016) in order to identify more optical counterparts.

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