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SUPERNOVA REMNANTS IN THE MAGELLANIC CLOUDS

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ABSTRACT

We present an ongoing study of the complete sample of supernova remnants (SNRs) and candidates in the Magellanic Clouds. 108 objects in both Clouds are considered to be either SNR or reliable candidates. This represents the most complete sample of all known SNRs in any galaxy. It therefore allows us to study SNR population properties such as the age-diameter (Age–D) relation. Here, we show that this Age–D relation is strongly dependant on the local environment in which SNRs are residing.

Key words: supernova remnants – Magellanic Clouds

1. INTRODUCTION

At known distances of 50 kpc and 60 kpc (di Benedetto, 2008), the Large and Small Magellanic Clouds (SMC) are well known laboratories for studying objects such as supernova remnants (SNRs). The line of sight to both Magellanic Clouds (MCs) lies well away from the Galactic plane, minimising the obscuration and confusion from the foreground gas, dust and stars.

A distinguishing characteristic of SNRs at radio frequencies is their well-established, predominantly non-thermal continuum emission. Collectively, SNRs have a radio spectral index of $\alpha \sim -0.5$ (defined by $S \propto \nu^{\alpha}$), although α may vary quite a lot due to the wide variety of SNRs, differing environments and stages of evolution (Filipović et al., 1998). On one side, younger and very old remnants can have a spectral index of $\alpha \sim -0.8$, while mid-to-late-age and Pulsar Wind Nebulae (PWN) tend to have flatter radio spectra with $\alpha \sim -0.2$. As one of the most energetic class of sources in the Universe, these objects do have a great impact on the structure, physical properties and evolution of the interstellar medium (ISM). Conversely, the interstellar environments in which SNRs reside will heavily affect the remnants' evolution. Here, we report on radio-continuum, X-ray, and optical observations of the most up-to-date sample of MCs SNRs and SNR candidates, consisting of 82 objects in the Large Magellanic Cloud (LMC) and 26 in the SMC.

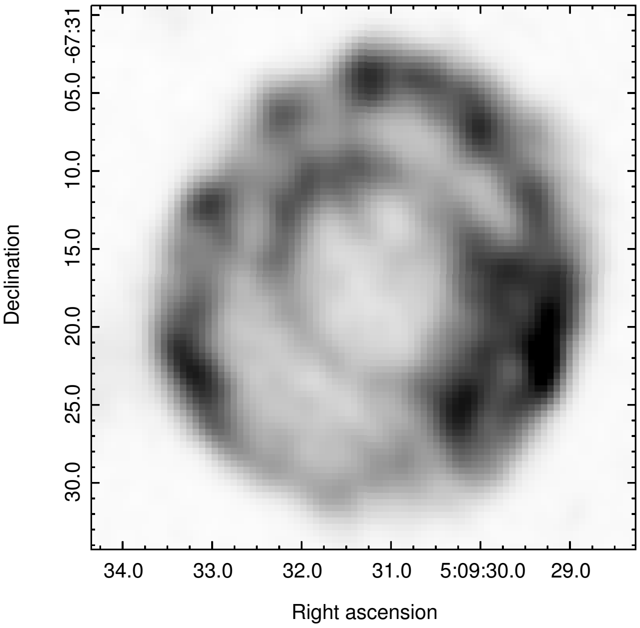

Figure 1. Radio-continuum image of J0509−6731, a young (∼400 yr) Type Ia SNR in the LMC, from the observations described in Bozzetto et al. (2014a).

2. MAGELLANIC CLOUDS SURVEYS

There are several present-generation multi-wavelength surveys used in this study. Radio-continuum surveys were predominately based on observations from the Australian Telescope Compact Array (ATCA), including the 20 cm mosaics by Filipović et al. (2002); Payne et al. (2004); Hughes et al. (2007); Wong et al. (2011a,b)

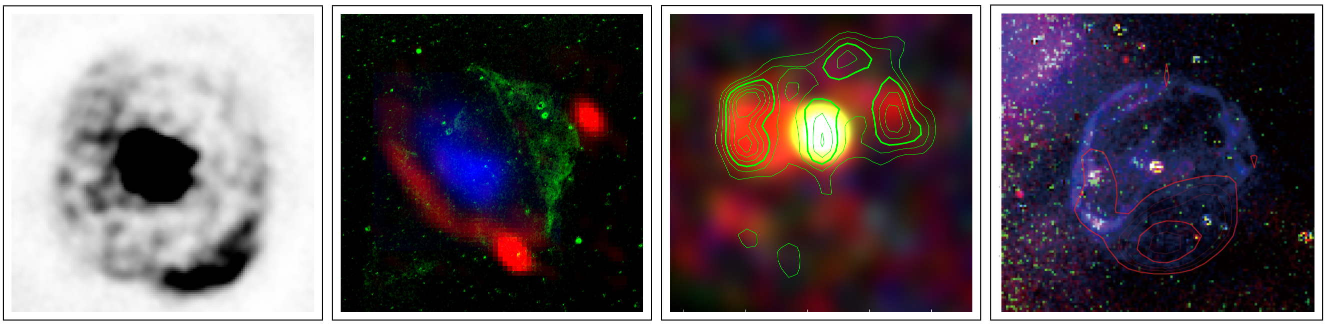

Figure 2. *Left:* Radio-continuum image of J0453−6829, a SNR/PWN in the LMC, from the observations described in Haberl et al. (2012). *Mid-left:* The image shows the multi-wavelength emission from MCSNR J0508−6902, from radio (red) optical (green) and X-ray (blue) observations. Image from Bozzetto et al. (2014b). *Mid-right:* The SMC SNR HFPK 443 (Crawford et al., 2014). Chandra three colour composite image (red: 0.3–1.0 keV (soft), green: 1.0–2.0 keV (medium), blue: 2.0–6.0 keV (hard)) smoothed with a Gaussian width to match the 20 cm radio image. The radio contours are 0.6–1.6 mJy/beam in 0.2 mJy/beam steps. *Right:* The SMC SNR J0127-7332 (Haberl et al., 2014). The MCELS image is dominated by the [O III] line (blue). The MOST survey radio contours are 1.5–3.5 mJy/beam in 0.5 mJy/beam steps.

as well as the 6 cm and 3 cm mosaics published by Dickel et al. (2005); Crawford et al. (2011); Wong et al. (2012). In addition, a 36 cm Molonglo Synthesis Telescope (MOST) mosaic image (as described in Mills et al. 1984) was used. We note that the former surveys (i.e., those from the ATCA) included a zero-spacing measurement from the single 64-m Parkes dish (Filipović et al., 1995, 1997), while the latter MOST image did not. This resulted in missing short spacings at $\lambda = 36$ cm, and therefore, the potential for missing flux may be an issue, especially for larger remnants.

Over the past decade we have performed X-ray surveys of both Clouds using the *XMM-Newton* observatory Haberl et al. (2012); Haberl (2014). The *XMM-Newton* LMC large project comprises 25 ks observations of 70 fields, which together with archival data cover an area of about 10 square degrees. The *XMM-Newton* surveys provide a unique data set to investigate the X-ray source populations of the MCs including SNRs and candidates. For example, our latest search for new LMC SNRs resulted in the discovery of 4 such objects Maggi et al. (2014). A comprehensive review of the SMC X-ray sample can be found in Filipović et al. (2008) and Owen et al. (2011). Additional X-ray data were sourced from the *Chandra* Supernova Remnant Catalog[1].

Optical data came from the Magellanic Cloud Emission Line Survey (MCELS)[2] which was carried out at the 0.6 m University of Michigan/CTIO Curtis Schmidt telescope (Smith et al., 2006). Both Clouds were mapped in narrow bands corresponding to Hα, [O III] (λ=5007 Å), and [S II] ($\lambda = 6716, 6731$ Å), plus matched red and green continuum bands. Our own spectroscopic surveys of the LMC (Payne et al., 2008) and SMC (Filipović et al., 2005; Payne et al., 2007) SNR sample were mainly taken with the SAAO 1.9-m telescope.

Infrared data came from the *Spitzer* Space Telescope and *Herschel* surveys (Lakićević et al., 2014) of the MCs using the Multiband Imaging Photometer for *Spitzer* (MIPS) (24, 70 and 160 μm) and with SPIRE (Spectral and Photometric Imaging Receiver) at 250, 350 and 500 μm and with Photodetector Array Camera and Spectrometer at 100 and 160 μm for *Herschel*.

3. RESULTS

Sixty-one SNRs currently exist in the LMC with approximately 21 candidates, while in the SMC, 19 SNRs have been confirmed and 6 are currently under investigation as candidates. A multi-frequency approach was taken in measuring the extent of the remnants to get the best overall view of their emission. An example of the effectiveness of such an approach can be seen in Figs. 1 and 2, where the X-ray, optical and radio emission can be seen complementing each other.

Ages for the remnants were all taken from various other studies. However, all the extents (with the exception of SN1987A) were measured in this study. As the LMC contains the larger sample of the two MCs, it was used to investigate whether a relationship exists between the evolutionary size of an SNR and its SN type. This was further broken down into those core-collapse SNRs (including ones which contained a central PWN) and also those Type Ia SNRs that were part of the classification suggested in Borkowski et al. (e.g., 2006); Bozzetto et al. (e.g., 2014b); Maggi et al. (e.g., 2014). However, we did not find a strong connection between the type of SN from which the remnant came and the rate at which it expanded.

Following this, the SMC data were added, as well as data from seven young/historic Galactic remnants. The results are shown in Fig. 3. All three galaxies' data appear to follow a somewhat similar trend, though, moreso for the SMC than the Galaxy. The Galactic SNRs seem to fall below the trend of the LMC and SMC data, which may be due to various selection effects or something intrinsically different in the SNR and the environment in which they are expanding.

We explore the potential effect of the density of the ISM in which the remnants reside. To approximate this, the ellipse annotation formed when measuring the remnants extent was used to delineate the area in which

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[1] http://hea-www.harvard.edu/ChandraSNR/snrcat_lmc.html

[2] http://www.ctio.noao.edu/mcels/

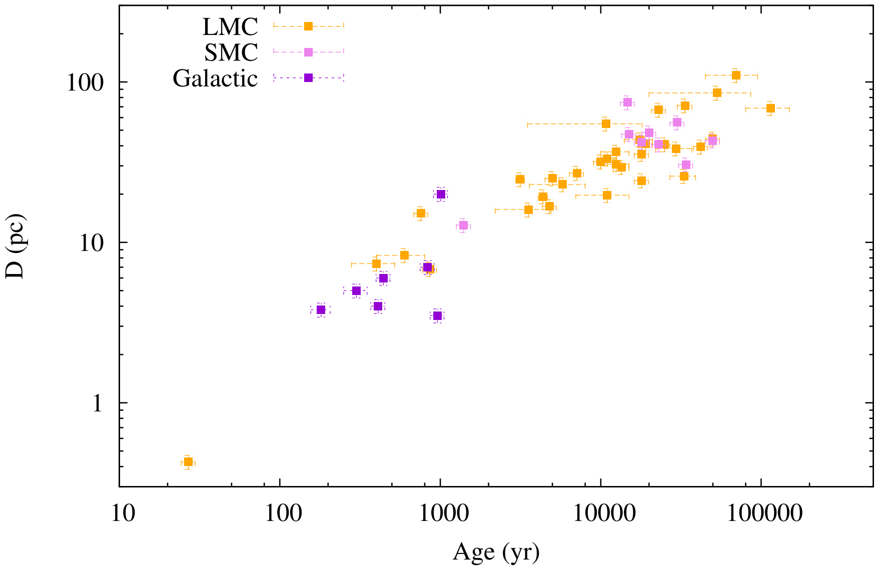

Figure 3. Age–D graph for all MCs SNRs with the addition of data from the literature for seven young Galactic SNRs.

an average density measurement was taken from the H I data (from Kim et al., 2003; Staveley-Smith et al., 2003). This resulted in a tricolour scale between low, medium and high density environments. Using the same LMC data-points from Fig. 3, the SNRs were plotted with their respective density-colour (Fig. 4). These preliminary results are in line with expected results, as SNRs expanding in a low density environment exhibit a steeper slope ($\alpha = 0.47$) than those in a medium density environment ($\alpha = 0.38$), and those in the high density environment show the flattest slope ($\alpha = 0.31$). Therefore, the more rarified the environment, the faster an SNR will expand.

To probe into the previous issue pertaining to the Galactic SNRs falling below the general trend line of the graph, the results of a study by Xu et al. (2005) which looked into the Age–D relation of 80 Galactic SNRs were compared. They found a slope of $\alpha = 0.34$ (which is shown as a solid blue line in Fig. 4), a value falling roughy between the slopes found for medium and high density environments in the LMC. This would add evidence for the idea that Galactic SNRs are expanding into a denser environment than their MCs SNR counterparts.

Moreover, one may suspect that SNRs expanding in a higher than average density environment are more likely to encounter high density regions (e.g. molecular clouds). If they are in such an inhomogeneous environment, then the "pure Sedov" relation cannot be applied. The size evolution will be slowed by the higher density region, resulting in a flatter Age–D relation. Splitting the sample between SNRs close to molecular clouds and SNRs far away from may shed some lights on this question.

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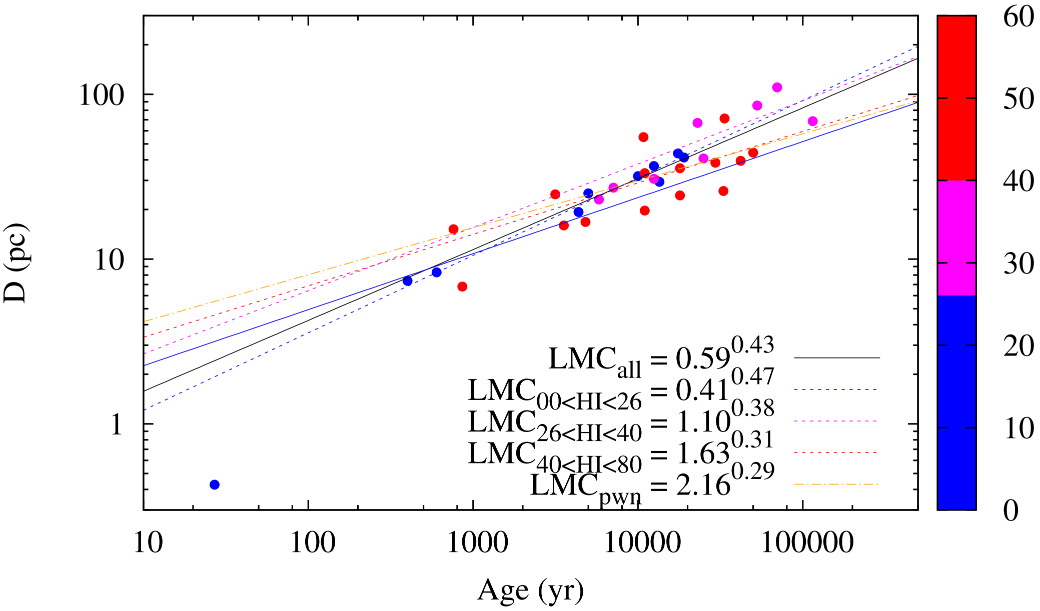

Figure 4. Age–D graph for all LMC SNRs, with the tricolour palette representing the different H I densities (units are 10^{21} cm^{-2}).

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