Wolf-Rayet Stars
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A 2D view of Wolf-Rayet Galaxies

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The main objective of this work is to investigate the evolution of massive stars, and the interplay between them and the ionized gas for a sample of local metal-poor Wolf-Rayet galaxies. Optical integral field spectrocopy was used in combination with multi-wavelength radio data. Combining optical and radio data, we locate Wolf-Rayet stars and supernova remnants across the Wolf-Rayet galaxies to study the spatial correlation between them. This study will shed light on the massive star formation and its feedback, and will help us to better understand distant star-forming galaxies.

1 Introduction

The complex physics governing the interplay between massive star formation (SF) and the interstellar medium (ISM) is one of the key issues limiting our knowledge of galaxy formation and evolution. Galaxies whose spectra show broad emission lines attributed to Wolf-Rayet (WR) stars are called WR galaxies (Schaerer et al. 1999). Two main classes of WR stars are defined based on emission-line ratios: nitrogen-type (WN) and carbon-type (WO and WC) stars (e.g. Crowther et al. (1998). The blue and red WR bumps observed in galaxy spectra are centered at ~ 4680 and 5808 Å, respectively. While WN stars are mainly responsible for the formation of the blue bump, the carbon-type WR stars contribute the most for the red bump emission.

The WR phase is an evolutionary stage characterized by the ejection of the outer layers of evolved massive stars by stellar winds which supply mechanical energy to the ISM (Freyer et al. 2003, 2006). These WR stars are incredibly massive and luminous, and have very high rates of mass loss. The winds that they produce can collide with regions of gas and drive rapid star formation. WRs have a fundamental influence on the ISM and galaxy evolution and are responsible for the bulk of the ionization observed in H II regions. WR stars enrich the ISM at short time-scales (i.e. <100 Myr) by returning the processed nuclear material during their lifetime and at their end by going off as Supernovae (SN) (Maeder 1981). These stars are the likely progenitors of (at, least some) core-collapse SN, and of Gamma-Ray Bursts (GRBs; Woosley & Bloom (2006)) which are predicted to be optically dim and radio loud. The remnant will be similar to Cas A or the Supernova Remnant (SNR) in the galaxy NGC 4449 showing weak broad optical emission from [O III], [S II] and [Ne III] but no broad hydrogen lines.

The SN explosion energy of the most massive stars is only $\sim 10^{51}$ erg (Hamuy 2003) so their SNRs follow the σ-D relation (Preite-Martinez & Fusco-Femiano 1986) and account for the bulk of the non-thermal radio emission. Both thermal emission from H II regions and non-thermal radiation from cosmic ray electrons contribute to the total radio flux. By comparing the Far Infra-Red (FIR), thermal radio and non-thermal radio luminosities of the WR galaxies, we can search for an older, less massive stellar population underlying the young WR outburst. The youngest star-burst regions should have relatively flat spectra dominated by thermal emission from H II regions ionized by extremely massive ($M > 30M_{\odot}$) short-lived ($<5\times10^6$ yr) WR stars. Steep-spectrum non-thermal emission from cosmic rays accelerated by SNRs of relatively low mass (M$< 8M_{\odot}$) stars will eventually dominate the radio emission at centimeter wavelengths.

To carry out this project, we used low frequency radio observations, optical field spectroscopy (IFS) and multi-wavelength data. Many nearby galaxies have been surveyed in the radio for SNRs, usually using images obtained at 20 cm and 6 cm to constrain discrete sources spectral indices and separate non-thermal SNRs from H II regions. Some of the most successful searches of this kind have been in M33 (Gordon et al. 1999) and NGC 6946 (Lacey & Duric 1997, 2001). We can also study the radio luminosity function of SNRs by their radio emission. Radio bright SNRs typically have diameters of ∼10 - 100 pc (Gordon et al. 1999), corresponding to 0.7 - 7 arcsec at a distance of 3 Mpc. Therefore, for nearby galaxies, they will appear as discrete (point like or slightly resolved) sources when observed with most ground-based observatories.

It is well known that SNRs contribute significantly to the non-thermal radio emission which, owing to its steeper spectral index in comparison to that of the thermal emission, is expected to dominate at low (< 1 GHz) radio frequencies (e.g. Bogdan & Volk 1983; Biermann & Strom 1993; Srivastava et al. 2014).

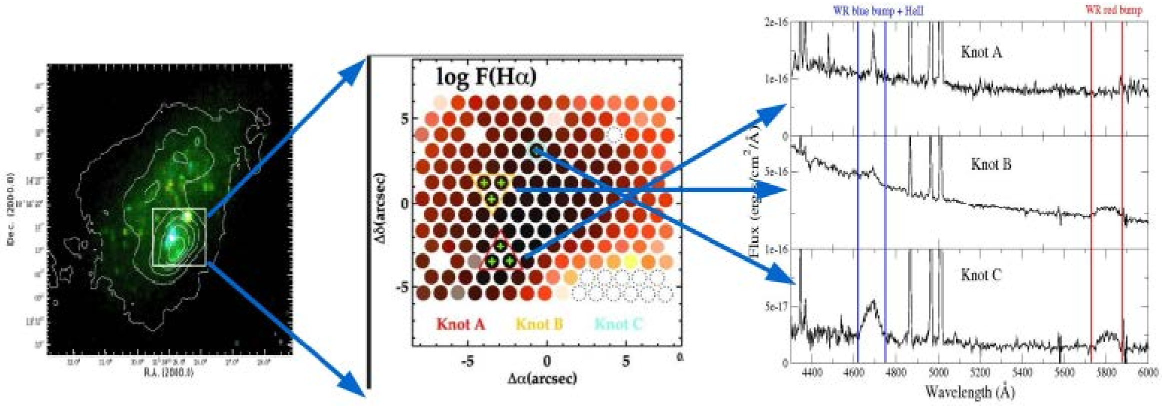

Fig. 1: From left to right:(a) Hα contours (Gil de Paz et al. 2003) drawn on the three-band (z,r,i) SDSS color-composite image of Mrk 178, (b) The three WR knots (A, B and C) are labelled on the Hα flux map, and green crosses mark the spaxels where WR features were detected, (c) Integrated spectrum, in units of erg s^{-1} cm^{-2} Å^{-1}, for the three knots in which the WR features are detected [Image credit: Kehrig et al. (2013)]

Tab. 1: General Properties of the Galaxies

Galaxy	Right Ascension$^{(1)}$ (J2000)	Declination$^{(1)}$ (J2000)	Morphology	Distance (Mpc)
MRK 178	$11^h33^m28.9^s$	$+49°14'14''.0$	Irr+Comp; WR	3.9
NGC 4449	$12^h28^m11.9^s$	$+44°05'40''.0$	IBm; H II	3.7

Source: https://ned.ipac.caltech.edu

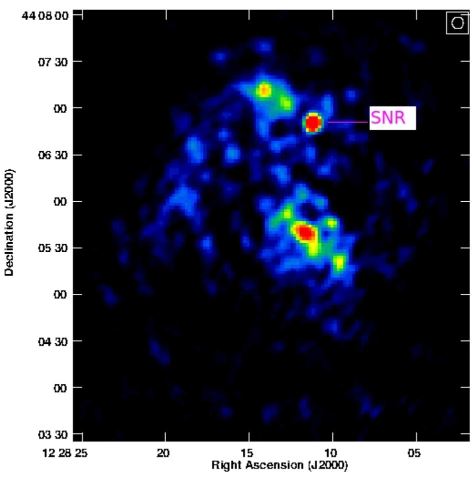

Fig. 2: SNR J1228+441 was detected in the GMRT radio image of NGC 4449 at 610 MHz [Image credit:Srivastava et al. (2014)]

It is worth mentioning that, we have observed NGC 4449 using GMRT (Srivastava et al. 2014). In this context, the main goal of the present project is to perform a comprehensive 2D investigation of the Wolf-Rayet (WR) population, supernovae remnants (SNRs) and the properties of the ionized gas (metallicity, temperature, ionizing sources, etc)for metal poor WR galaxies. In this paper we are presenting optical results of MRK 178 and radio results of NGC 4449. The paper is structured as follows. In §2 we describe the optical and radio observations, and a summary is presented in §3.

2 Observations

2.1 Optical Observation of MRK 178

The integral field spectroscopy (IFS) technique was used to present the optical study of the metal poor galaxy MRK 178 with the INTEGRAL fiber system (Arribas et al. 1998) in combination with the WYFFOS spectrograph (Bingham et al. 1994) at the 4.2 m William Herschel Telescope (WHT), Roque de los Muchachos observatory. This technique is used to collect spectra of many different regions of an extended object. Kehrig et al. (2013) probe the spatial correlation between massive stars and the properties of the surrounding ISM of MRK 178. They were able to locate and resolve star-forming knots hosting a few WR stars and also characterized the WR content.

2.2 Radio Observations of NGC 4449

The radio observations were done using the Giant Metrewave Radio Telescope (GMRT) (Swarup et al. 1991). The GMRT is an interferometric array of 30 antennas, each of 45 m in diameter. NGC 4449 a bright WR galaxy, lying at a distance of about 4 Mpc and has been known as irregular dwarf galaxy which in shape and size is similar to the Large Magellanic Cloud. This galaxy exhibits numerous signs of a recent merger (Annibali et al. 2008, 2011). The SNR J1228+441 was detected (Srivastava et al. 2014) (Fig. 1) in our radio images at 150, 325 and 610 MHz as the most intense feature in NGC 4449. The young SNR is located within a rich cluster of OB stars (along with some WR stars) only a few parsecs in size (Milisavljevic & Fesen 2008). The SNR was first discovered in the radio by (Seaquist & Bignell 1978) as a bright, unresolved non-thermal radio source ($\sim$ 10 mJy at 2.7 GHz) $\sim 1'$ north of the nucleus of the galaxy at a location nearly coincident with an HII region cataloged by Sabbadin & Bianchini (1979). This SNR is five times more luminous than Cas A at 20cm (Chomiuk & Wilcots 2009). It has been extensively monitored (e.g. Lacey et al. (2007) and references therein). Lacey et al. (2007) report steepening of the spectral index from $\alpha = -0.64\pm0.02$ in 1994 to $\alpha = -1.01\pm0.02$ in 2001–2002, showing rapid evolution. Reines et al. (2008) using high-resolution VLA data at several frequencies find that the SNR had a spectral index of -1.8 between 3.6 and 6 cm and an index of -0.9 between 1.3 and 3.6 cm between 2001 and 2002,indicating a break in the spectrum. From our observations at 325 and 610 MHz in 2008–2009, we estimate flux densities of 35.2$\pm$9.1 and 11.2$\pm$2.9 mJy, respectively giving radio spectral index to be -1.5.

3 Summary

In summary, by combining optical IFS and radio data we will be able to study the spatial correlation between WRs and SNRs across our sample of WR galaxies. To explore SNRs in MRK 178, observations at 20 and 50 cm using GMRT have been recently taken in the on-going observing cycle. Therefore, this galaxy is one of the best laboratories to study starburst; considered as a template system that helps us to understand distant star-forming galaxies.

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Dominik Bomans: Critical for radio spectra is thermal convection. Did you have a deep Hα map of the whole area, and reddening? Do you plan to add higher frequency observations to avoid the thermal estimate?

Shweta Srivastava: We used a Hα map from the NED. I think it covered the full galaxy. We are not planning any high frequency observations for substantiating the thermal estimates.