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MULTI-WAVELENGTH OBSERVATIONS OF GALACTIC WINDS

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RESUMEN

En este texto presentaré algunos ejemplos recientes de análisis de múltiples longitudes de onda de enanas con estallidos estelares, con especial énfasis en observaciones del continuo de radio de baja frecuencia y algunos con algunas reminiscencias de mi época de trabajo con You-Hua en UIUC.

ABSTRACT

In this text I will present a few recent examples of multiwavelength analyses of starburst dwarfs with special emphasis of low frequency radio continuum observations and some with some reminiscenses from my time working with You-Hua at UIUC.

Key Words: Galaxies: irregular — Galaxies: ISM — Galaxies: magnetic fields — Galaxies: starburst — Galaxies: evolution — radio continuum: galaxies

1. BACKGROUND

Galactic scale outflows (when the material stays inside the gravitational well of the galaxies) and galactic winds (when the material escapes into the intergalactic medium) driven by stellar feedback are well established as important processes for the evolution of galaxies (Rupke 2018; Zhang 2018). There is a lot of progress in simulations and observation over the last years, but many questions remain unanswered. Multi-wavelength (or even multi-messenger) observations on galactic winds are critical for the understanding of the complex physics, e.g. when looking at the different situations: stellar wind driven and supernova driven galactic winds, radiation pressure driven winds (AGN or near maximum starbursts), cosmic ray driven winds (with several possible CR transport mechanisms), and intercombination of all the processes. Multi-wavelength observations provide data on structure and kinematics of different gas phases, the relative importance of magnetic fields and dust, as well as the energetic, driving sources, and also the transport mechanisms prevalent for the cosmic rays.

2. NGC 4449

While working with You-Hua on the X-ray and Hα data of NGC 4449 (Bomans et al. 1997), the possible importance of ordered magnetic fields and cosmic ray feedback in NGC 4449 also became clear (Klein et al. 1996). The creation of strong, ordered magnetic fields is well explained in spiral galaxies by the workings of the $\alpha\omega$ dynamo (e.g. Beck 2015), ordered magnetic fields in low mass galaxies require different processes, especially a working turbulent dynamo (e.g. Siejkowski et al. 2014). Over the last 20 years more and more observations showed not only ordered magnetic fields inside low mass star forming galaxies, but also in their outflows and winds (e.g. Chyży et al. 2016). With the installation of the LOFAR (LOw Frequency Array) in the Netherlands and several other European countries (notably Germany with 6 stations, and Poland with 3 stations) observations of galaxies at low frequencies ($\sim$ 30 to $\sim$ 200

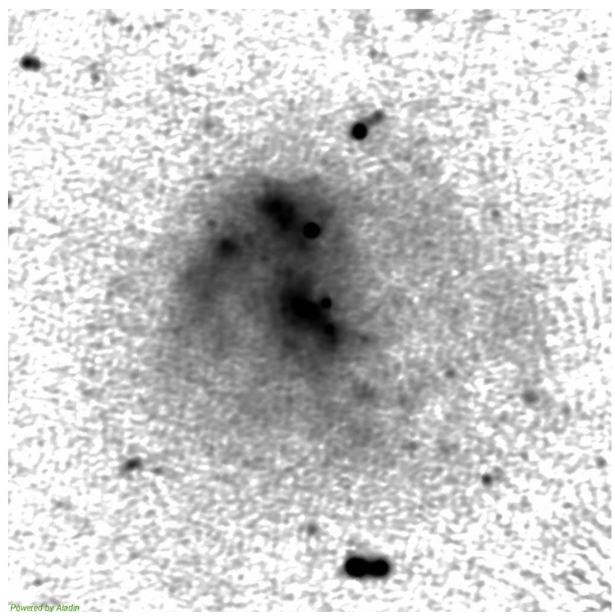

Fig. 1. High resolution (6″) LOFAR 150 MHz image ($9' \times 9'$) of NGC 4449, displayed with logarithmic stretch to show the very extended synchrotron halo of this starbursting irregular galaxy.

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MHz) with high sensitivity, and high spatial resolution (20″ and 6″ at a frequency of 150 MHz) became possible (Heesen et al. 2022). At 150 MHz, the observed emission is dominated by synchrotron emission and is therefore tracing magnetic fields frozen in a thermal plasma and relativistic electrons. In the case of NGC 4449, the LOFAR image (Fig. 1) shows the starforming regions filling the main body of the galaxy (the sites of the freshly accelerated relativistic electrons by supernovae and large scale shocks). Still, it also shows the galactic scale outflow, we previously analyzed at UIUC. The 150 MHz emission correlates well with the large shells and filaments (Bomans et al. 1997; Bomans & Weis 2014), but also show faint, diffuse radio continuum emission well beyond the faintest Hα filmenents detected in NGC 4449 (Bomans & Weis 2014).

3. MRK 1434

Going from the large irregular galaxy NGC 4449 to a lower mass starbursts, Mrk 1434, is one of the very promising relatively nearby ($\sim$ 35 Mpc distance) laboratories for low metallicity, compact starbursts showing particularly highly ionized emission lines. Based on SDSS data, (Shirazi & Brinchmann 2012) conducted a search for He II emitting galaxies, which resulted in a catalog of 3164 objects, of which 84 star forming galaxies showed nebular He II emission, but no stellar features typical of Wolf-Rayet stars, which are (besides the presence of an AGN) the natural explanation for a hard radiation field in galaxies. So one could speculate that these objects contain very massive, low metallicity stars, making them good proxies for highest redshift galaxies, which recent JWST results on z $\sim$ 12 galaxies seem to support (Topping et al. 2024). We did searches which provided more highly ionized dwarf galaxies and we could show for a new sample, that these galaxies are good candidates for Lyman continuum leakers (Enders et al. 2023), which would make these galaxies also important drivers of reionzation. Mrk 1434 is such a proxy galaxy, where we can study the feedback processes in details unobtainable even with JWST. We took a deep spectrum of Mrk 1434 with the LBT MODS spectrograph. Fig. 2 shows an archival HST F606W image which not only shows the red stellar continuum, but clearly the filamentary, bubbly ionized gas emission all over the galaxy and several kpc into the halo, the slit runs through the central region with a position angle of 45 deg. The HST image is presented at hard contrast with an inset showing the structure of the brightest emission. A central superbubble and large diffuse filaments are visible. Fig. 3 show a small section of the MODS spectrum (the Hβ line). Two velocity components are needed for an satisfactory fit of the line, implying an outflow with an expansion velocity of 150 km s^{-1}. This pattern is also visible in other strong lines. The galaxy also shows soft X-ray emission centerend on the superbubble and is detected with LOFAR, implying a complex magnetized superbubble and galactic outflow/wind in the galaxy. Our analysis is still ongoing.

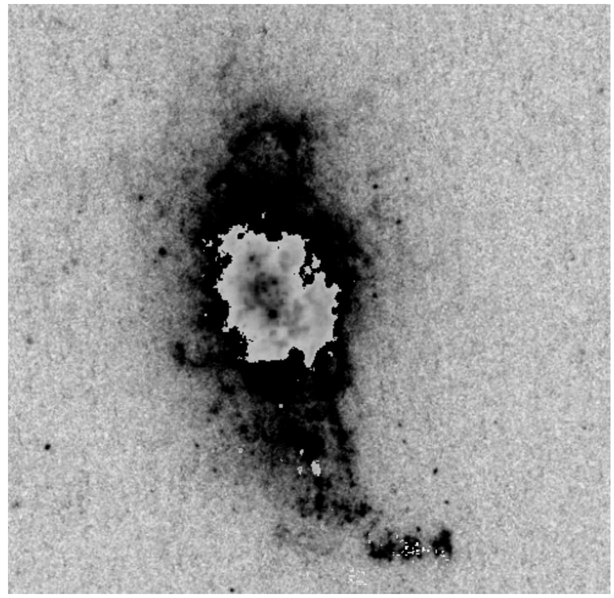

Fig. 2. Section of an archival HST F606W image of Mrk 1434 (20″ × 20″). Together with a hard contrast image to show the faint filamentary emission in the halo, a soft stretch image of the brightest central part of the galaxy is put it to show the central superbubble.

4. LARS 14

Making another step into more distant and extreme dwarf starbursts, I picked LARS 14. This member of the “green pea” galaxy class (Cardamone et al. 2009) is the most distant and lowest mass object of the LARS (Lyman Alpha Reference Survey) (Hayes et al. 2013), which used HST to analyze the nature the Lyα emission of a sample of nearby galaxies. It is also the second strongest Lyα leaker in the sample. Fig. 4 shows an archival HST F390W image of LARS 14 with contours of the LOFAR 150 Mhz emission overlayed. LARS 14 is clearly detected and its synchrotron emission appears extended with similar shape and size as the Lyα emission shown in Hayes et al. (2013). Clearly, high resolution radio data are needed, but it is tempting to speculate that LARS 14 is hosting a magnetized outflow. We

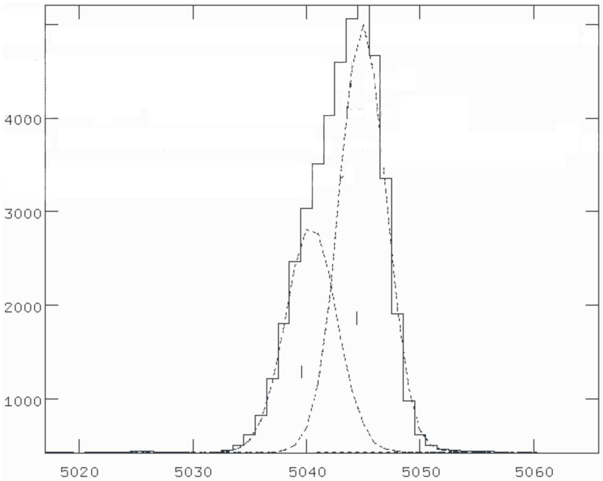

Fig. 3. Section of the MODS spectrum of Mrk 1434 around the Hβ lines with the two component fit shown. The line split of 300 km. s^{-1} together with superbubble seen in the HST image.

currently conducting a larger survey of Green Pea Galaxies with LOFAR and LBT/MODS.

5. CONCLUSIONS

The multi-wavelength analysis of low mass galaxies using UV, optical, X-ray and radio-continuum data hold a lot of promise for the understanding of the complex, interwoven processes driving and shaping galactic outflows, Lyα and Ly continuum leaking, and chemical evolution. Magnetic fields apparently play a significant role for the structure and dynamics of outflows and galactic winds even for these low and very low mass galaxies. This implies also, that the processes during galaxy formation are even harder to decipher with the current (already beautiful) data of the current generation of telescopes. Even SKA will not change this significantly, so the use of the relatively local, extreme objects as proxies to get detailed physics insights is still highly rewarding.

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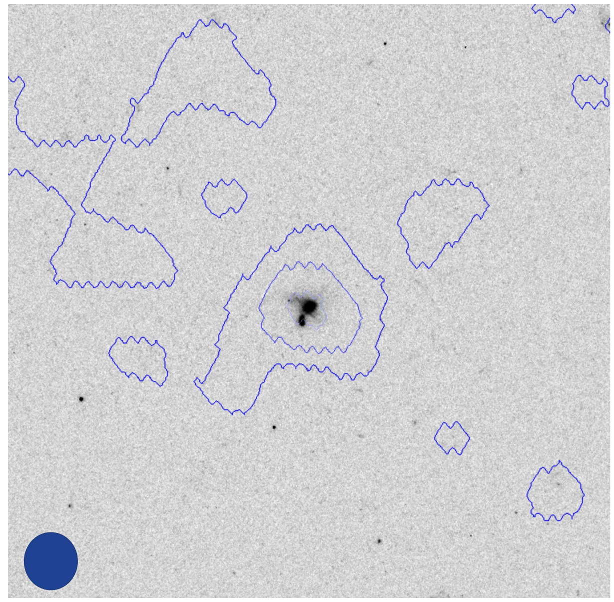

Fig. 4. Archival HST F390W image section (45″ × 45″) of the Green Pea galaxy LARS 14 with the LOFAR 150 MHz contours overlayed. The synchrotron emission is extended (see beam in lower left) and closely resembles the Lyman α emission of LARS 14.

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