Dwarf Galaxies: From the Deep Universe to the Present
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Galactic Winds in Low-Mass Galaxies

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Abstract. Mass-loss via stellar-feedback driven outflows is predicted to play a critical role in the baryon cycle of low-mass galaxies. However, observational constraints on warm winds are limited as outflows are transient, intrinsically low-surface brightness events and, thus, difficult to detect. Here, we search for outflows in a sample of eleven nearby starburst dwarf galaxies which are strong candidates for outflows. Despite deep H? imaging on galaxies, only a fraction of the sample show evidence of winds. The spatial extent of all detected ionized gas is limited and would still be considered part of the ISM by simulations. These new observations indicate that the physical extent of warm phase outflows is modest and most of the mass will be recycled to the galaxy. The sample is part of the panchromatic STARBurst IRegular Dwarf Survey (STARBIRDS) designed to characterize the starburst phenomenon and its impact on the evolution of low-mass galaxies.

Keywords. galaxies: dwarf, galaxies: evolution, galaxies: halos

1. Introduction

In the shallow potential wells of low-mass galaxies, stellar feedback is thought to play an important role in shaping a galaxy's properties. This is borne out in hydrodynamical simulations which consistently predict that stellar feedback is a dominant driver in determining the internal structure, gas-phase metallicity, and to some degree, stellar mass build-up in low-mass systems (e.g., Brooks *et al.* 2007; Davé 2009; Christensen *et al.* 2016; Lu *et al.* 2017).

Quantifying stellar feedback and the impact feedback has on a host galaxy is difficult as feedback events are transient and multi-phase, requiring observations across the electromagnetic spectrum. Galactic winds are one measure of cumulative stellar feedback in a galaxy which can be linked directly to the recent star formation activity in a system. While expected to be ubiquitous in star-forming, low-mass galaxies, the main observational constraints on winds in the local Universe originate from a relatively small number of dwarf galaxies that occupy a narrow mass range (e.g., Marlowe *et al.* 1995; Martin 1998, 1999).

To deepen our understanding of the frequency and properties of galactic winds in low-mass systems, we have obtained Hα imaging designed to detected ionized gas at extremely low surface brightness on a sample of 11 nearby actively star-forming dwarf galaxies with stellar masses ranging from $10^7 - 10^{9.3}$ M$_\odot$. All galaxies are part of the STARBurst IRegular Dwarf Survey (STARBIRDS) and have previously derived star formation histories based on HST imaging of their resolved stellar populations (McQuinn *et al.* 2010, VLA imaging of their neutral hydrogen, and WIYN IFU spectroscopy of the

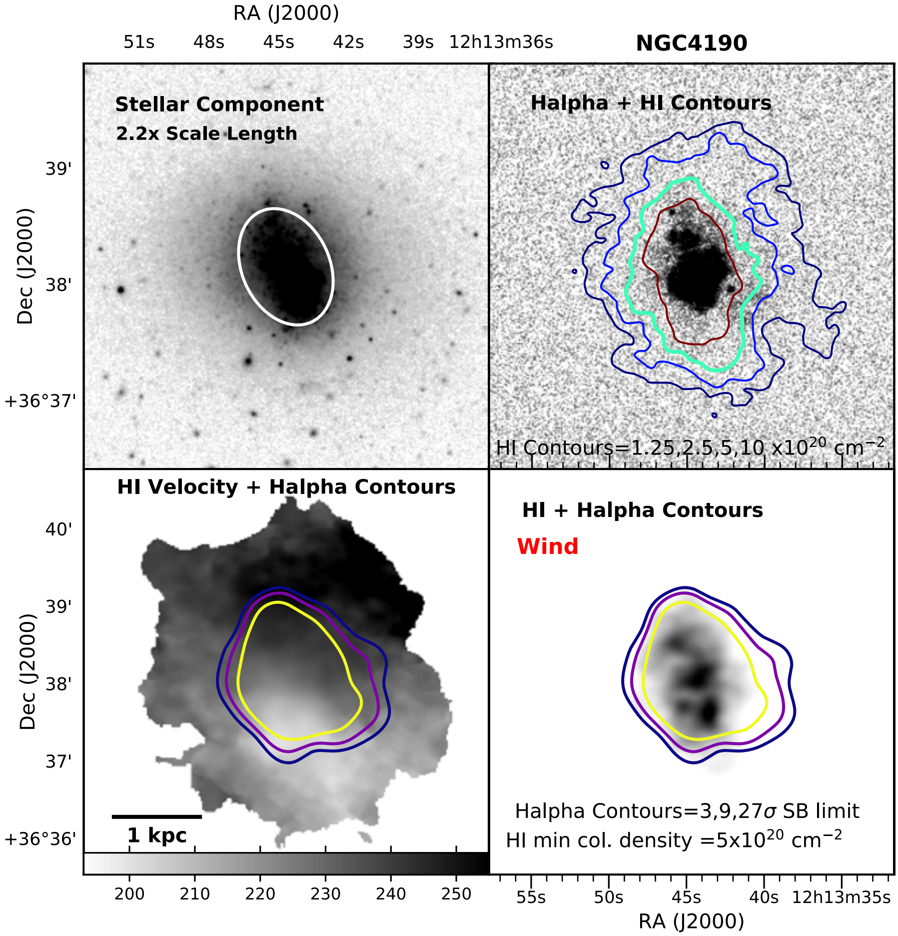

Figure 1. Montage of images for NGC 4190. Clockwise from the top left: optical R-band image with the main stellar disk outlined in a white ellipse, Hα image with HI contours overlaid to column densities of 1 $M_{\odot}pc^{-2}$, HI image truncated to the edge of the defined HI disk with smoothed Hα contours out to surface brightness limit of the sample, and the HI velocity field with Hα contours.

ionized gas (L. van Zee et al. in preparation). Combined with the new Hα imaging, these data provide a comprehensive view of the star formation, stellar feedback driven galactic winds, neutral gas properties, and ionized gas kinematics.

2. Detecting Galactic Winds and Outflows

We search for ionized gas outflows using new Hα imaging obtained from the KPNO Mayall 4m and the University of Arizona 2.3m Bok telescopes. We compare the morphology and extent of the Hα emission to the stellar component traced by broad-band optical imaging and neutral gas traced by VLA observations of the 21 cm line. The ionized gas is considered a wind if it is significantly extended beyond the stellar and gaseous discs. If Hα emission is detected in small regions reaching just outside the gas disk, we label these features small-scale, local outflows.

Figures 1 & 2 present montages of the stars, neutral, and ionized gas for two galaxies in the sample which show representative examples of a detected wind and small-scale outflow, respectively. The upper left panels show the stellar component of the galaxy

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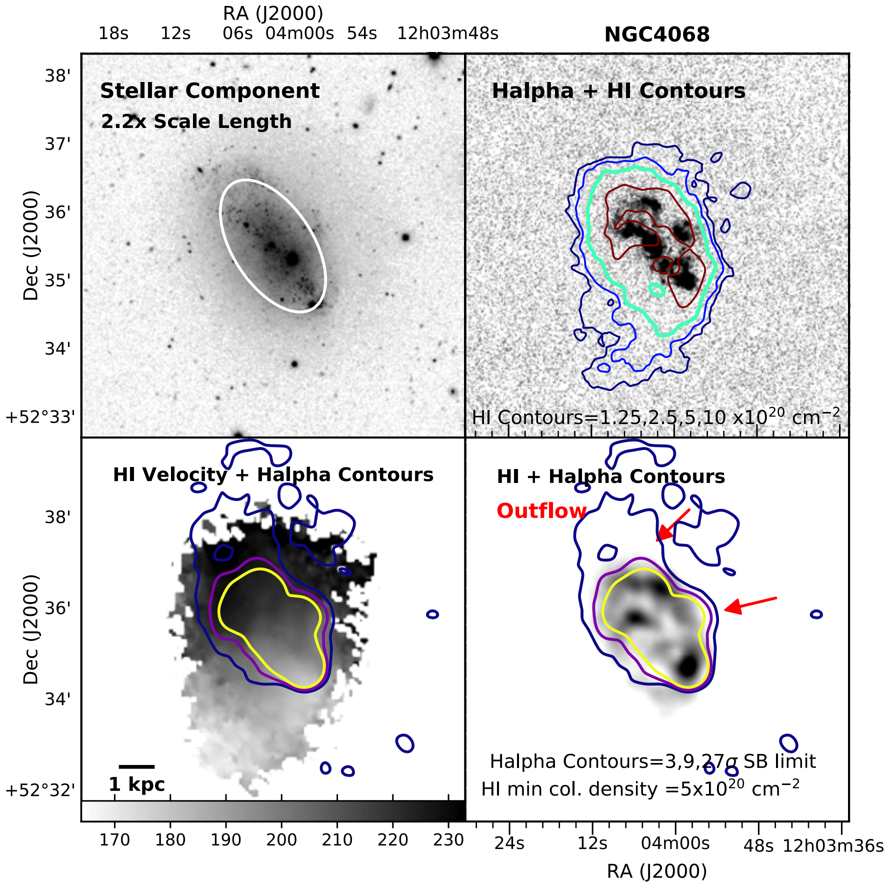

Figure 2. Montage of images for NGC 4068. Clockwise from the top left: optical R-band image with the main stellar disk outlined in a white ellipse, Hα image with HI contours overlaid to column densities of 1 $M_\odot pc^{-2}$, HI image truncated to the edge of the defined HI disk with smoothed Hα contours out to surface brightness limit of the sample, and the HI velocity field with Hα contours.

for reference with the main stellar disk outlined in white. However, as the gaseous disks in low-mass galaxies are often more extended than the stars and can more effectively impede an outflow, we mainly focus on comparing the extent of the ionized gas with neutral hydrogen presented in the remaining three panels of each figure. The Hα imaging is shown in the upper right, while smoothed Hα contours are overlaid in the bottom panels. The Hα contours were chosen uniformly for the sample and reach the surface brightness detection limit of the entire sample, achieved in the observations of NGC 4190 shown in Figure 1.

In the three panels, the ionized gas traced by Hα is compared with the neutral gas traced by HI. The HI data are shown as column density contours overlaid on the Hα imaging in the upper right, truncated at the traditionally used column density limit of 1.25×10^{20} cm^{-2}, an HI column density map in the lower right, truncated at a slightly higher column density corresponding to a level that would impede the escape of ionized gas (5×10^{20} cm^{-2}), and a velocity map in the lower left, truncated at the lower column density of 1.25×10^{20} cm^{-2}.

Focusing on the lower right panel in Figure 1, ionized gas is clearly extended outside the gaseous disc of NGC 4190, constituting a warm wind. In Figure 2, there are small

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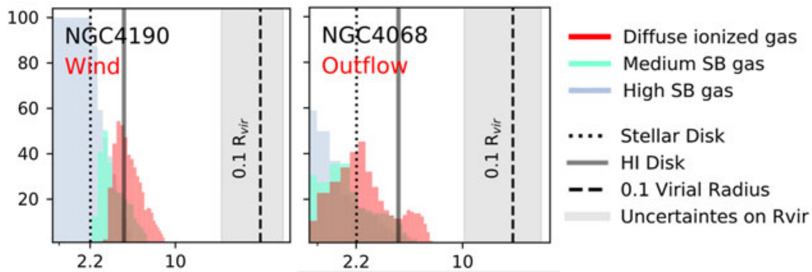

Figure 3. The low surface brightness ionized gas (red) extends past the HI disk (solid line) in each of the galaxies. However, the outflows and winds do not reach 0.1 of the virial radius (dashed line), which marks the end of the ISM and the beginning of the halo in simulations.

areas where the ionized gas breaks through the HI disk at high confidence in NGC 4068, constituting a small-scale local outflow denoted by the arrows. Note that the lowest Hα contour level is set by the detection limit of the sample from the observations of NGC 4190 shown in Figure 1. This low level of emission may be detecting very low column density ionized gas in the Northern halo of the galaxy but at a lower confidence level. We we restrict our interpretation of the Hα emission to the higher confidence contours.

The extent of the low-surface brightness warm winds and outflows are confirmed in radial profiles of the Hα emission shown Figure 3. The high and medium surface brightness gas (blue, green) are located at smaller radii while the low surface brightness gas (red) extends outside the stellar and gas disks (dotted and solid vertical lines) to several scale lengths. In all cases, the ionized gas lies well within 0.1 of the virial radius (dashed line) which defines the ends of the ISM and the beginning of the galaxy halo in simulations. Thus, these detections would not be classified as winds in simulations.

3. Summary of Results and On-going Work

Of the 11 galaxies studied, 4 (36%) have winds as defined by ionized gas beyond the optical radius, 4 (36%) have outflows as defined by ionized gas beyond the neutral gas radius, and 3 (27%) show Hα emission *only* within the optically defined extent of the galaxy. Our findings support the general result that star formation in dwarfs can drive mass-loss from galaxies. However, the observed spatial extent of the winds and outflows are limited and conflicts with the larger distances predicted by simulations. Rather than being expelled to the intergalactic medium, it is more likely that mass lost via these winds and outflows will be recycled into the host systems, which has important implications for the growth and global properties of low-mass galaxies. Our full analysis will include a calculation of the mass-loading factors of the winds based on the Hα emission, ionized gas velocities from the IFU spectroscopy, and star formation activity and timescales from the star formation histories (McQuinn et al. in preparation).

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