PROCEEDINGS OF SCIENCE

The VIRUS-P Investigation of the eXtreme Environments of Starbursts (VIXENS): Survey and First Results

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The VIXENS project is an integral field unit (IFU) survey of 15 nearby infrared bright ($L_{IR} > 3 \times 10^{10} L_{\odot}$) starburst/interacting galaxies, chosen to cover a range of interaction stages (from early to late phase mergers), star formation rates, and gas surface densities. The main goal of VIXENS is to investigate the relation between the star formation rate (SFR) and gas surface densities on spatially resolved scales of 0.2-0.9 kpc by comparing various tracers of star formation and gas content. More specifically, we use the Hα from our IFU data, 24μm, and far-UV data to investigate star formation and archival CO and HI maps, as well as maps of dense gas as traced by HCN(1–0). VIXENS will provide 2D maps of ionized gas, SFRs, stellar and gas kinematics, and metallicities. This unique data set will enable us to test theoretical predictions at the high star formation rate and gas surface density regime of the Kennicutt-Schmidt relation.

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1. Introduction

A detailed understanding of the rate at which molecular gas is converted into stars is an essential prerequisite for models of galaxy formation and evolution. In fact, this rate, and the parameters that cause it to vary, are currently ill constrained, leading to large uncertainties in theoretical models of galaxy formation. This presents an observational need for a robust determination of the relation between star formation rate (SFR) and the amount of available dense molecular gas. Our focus is to explore the evolution of the rate at which molecular gas is converted into stars through detailed IFU spatially resolved observations of gas-rich nearby interacting galaxies.

Measuring the spatially resolved star formation efficiency in nearby starburst/ interacting galaxies has direct implication at high-z, where such galaxies play and increasing role in the total SFR density e.g., [13]. Recent work by [9] and [7] found a bi–modal relationship between the SFR and gas surface densities for high-z merging galaxies and normal disk galaxies (Figure 3). The high-z mergers [9] lie along the same relation as Galactic low- and high-mass star-forming regions [11], suggesting that the bulk of gas in merging systems traces star forming gas. While starburst and interacting galaxies are relatively rare in the low-z universe, they are the dominant mode of star formation in the distant universe. Understanding the physics of star formation in nearby interacting/starburst systems is therefore paramount and will provide key insight to the physical processes of star formation in high-z interacting galaxies.

Observations of many galaxies on global or disk-averaged scales have been fit to a power law of N = 1.4 [15]. Recently, this proposed SFR-gas relation has been studied on ∼kpc scales in nearby spiral galaxies where a deviation from the N = 1.4 Kennicutt power law is found e.g., [4, 17]. While some work has been done on the integrated emission SFR-gas relation in extreme star-forming environments [10], such as those in local (ultra)luminous infrared (IR) galaxies, ((U)LIRGs) [18], there has been little work done studying the spatially-resolved relation between the SFR and gas surface densities in extreme environments such as the triggered starbursts in interacting galaxies. The VIXENS observational program will provide the required constraints on theoretical models for galaxy evolution as well as a comparison sample for multiwavelength observational studies of high-z interacting galaxies.

2. The Survey

The VIRUS-P Investigation of the eXtreme Environments of Starbursts (VIXENS)[1] project is a large IFU survey of 15 nearby IR bright ($L_{IR} > 3\times10^{10}L_{\odot}$) interacting/starburst galaxies selected on carefully chosen criteria: (1) IRAS IR derived SFRs $\sim 5-280\ M_{\odot}\ \mathrm{yr}^{-1}$, and molecular hydrogen gas surface densities, $\Sigma_{\mathrm{H_2}} \sim 200-10^4\ M_{\odot}\ \mathrm{pc}^{-2}$ from ^{12}CO maps, (2) because star formation is crucially affected by the state of galaxy interactions [16], the sample is selected to include the full range of interaction stages with morphological signatures that range from early stage (close pairs) to late stage mergers (single system with multiple nuclei) and implied mass ratios $1/3 < M_1/M_2 \leq 1/1$ estimated from optical luminosity ratios. The latter requirement is justified because simulations suggest that the interaction stage significantly impacts the galaxies' evolution as seen in optical and HI imaging [3,14 and references therein], and (3) the availability of ancillary data sets, which include: archival *Spitzer* 24 μm, GALEX far-UV, and existing ^{12}CO(1–0) and HI maps. In

[1] http://www.as.utexas.edu/~alh/vixens.html

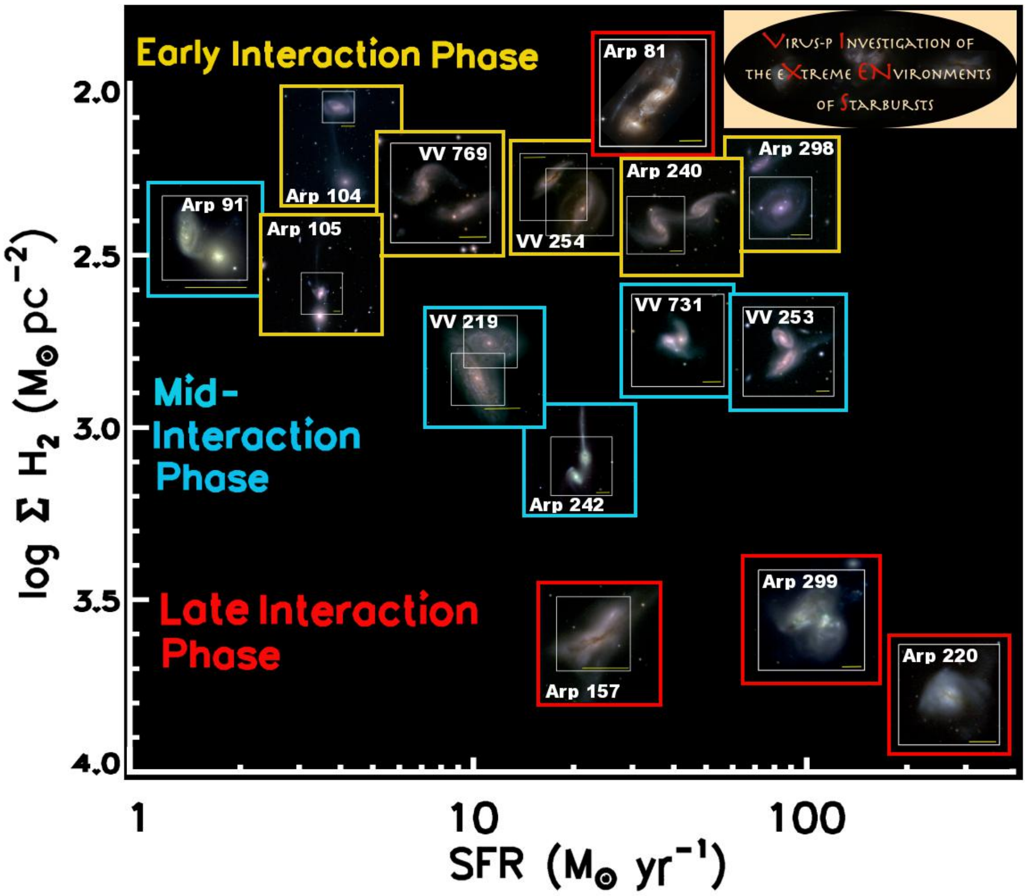

Figure 1: SDSS RGB (i,r,g) images of the VIXENS interacting galaxy sample. The white boxes show the VIRUS-P IFU field of view ($1.7' \times 1.7'$) and the yellow lines indicate a scale of 10 kpc. The range of total molecular hydrogen gas surface densities estimated from CO maps and SFRs from IRAS are shown.

addition to these archival data sets, we are also obtaining single-dish dense gas tracers (HCN(1–0), HCO^+(1–0), HNC(1–0)) from Nobeyama 45-m and IRAM 30-m telescopes for our whole sample, as well as HCN(1–0) maps for a subset of our sample from CARMA. Figure 1 shows SDSS RGB (i,r,g) images of the VIXENS sample with the exception of Arp 81, which instead shows an *HST* color image as this galaxy is not covered by the SDSS.

VIXENS uses the VIRUS-P spectrograph on the 2.7-m Harlan J. Smith telescope at McDonald Observatory. VIRUS-P has a field of view of $1.7' \times 1.7'$, and has 246 $4.3''$ optical fibers and a 1/3 filling factor for which three dithers provide contiguous coverage. One VIRUS-P pointing covers each system with the exception of VV 219 and VV 254 in which two pointings were necessary (Figure 1). The spectra cover each object in the wavelength range 4600 Å-6800 Å and have a spectral resolution of 5 Å FWHM ($\sigma_{\rm inst} \sim$120 km s^{-1}). The VIXENS IFU data will provide 2D maps of ionized gas, SFRs, stellar and gas kinematics, and metallicities.

VIRUS-P data reduction is done using VACCINE [2]. Spectral analysis, including measurement of gas and stellar kinematics as well as emission line fitting, is performed using PARADA, a modified version of the GANDALF software [19], which includes an implementation of the Penalized Pixel-Fitting method (pPXF) [6]. Figure 2 shows VIXENS data products linearly interpolated based on the discrete values at each fiber position, including integrated 4600 Å-6800 Å stellar flux, stellar velocity field, Hα flux, and Hα velocity field, for the late interaction phase galaxy merger Arp 299.

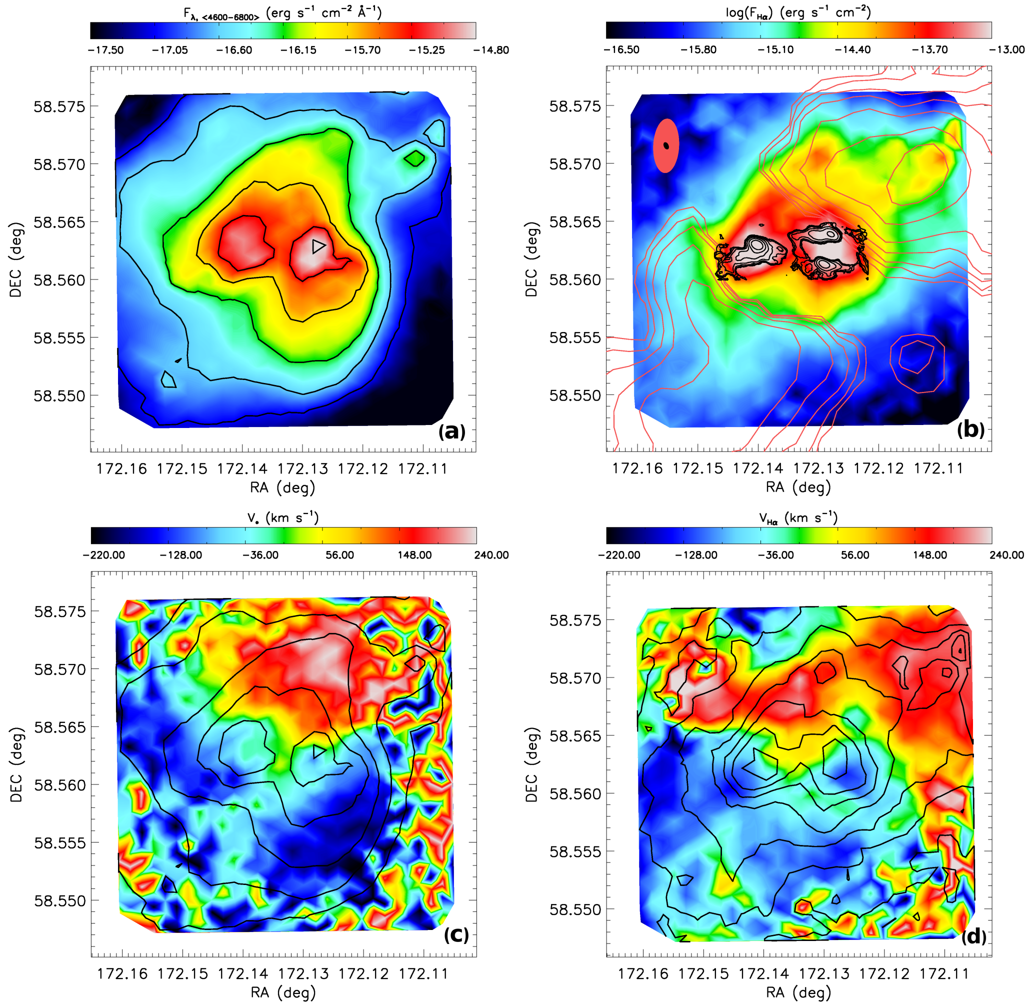

Figure 2: Late interaction phase galaxy merger Arp 299 VIRUS-P linearly interpolated IFU maps based on the discrete values at each fiber position of **(a)** 4600Å-6800Å integrated stellar flux, **(b)** Hα flux overlaid with CO(2-1) and HI integrated intensity map contours in intervals of 1–σ_{rms} and beam sizes from the CO(2-1) (black) and HI (red) maps, **(c)** stellar velocity field, and **(d)** Hα velocity field.

3. First Results: The Star Formation Rate and Gas Surface Density Relation in Galaxy Merger Arp 299

The main goal of VIXENS is to investigate the relation between star formation and gas content on spatially-resolved scales of 0.2-0.9 kpc in the extreme environments of IR bright interacting galaxy pairs and mergers. The VIXENS sample will allow us to study a wide range of SFRs and molecular gas surface densities (Figure 1). Figure 3 shows the first results from the VIXENS survey for late interaction phase galaxy merger Arp 299 [12]. We plot the spatially resolved SFR-gas surface density relation in Arp 299 on IFU fiber size scales of ~900 pc at our adopted distance of 44 Mpc. We use extinction-corrected Hα measurements from our IFU data to derive SFRs and a CO(2–1) gas map from [21] with a CO(2–1) to CO(1–0) ratio from [1] to derive H_2 surface densities. Two sets of points are shown, one using a Galactic CO–to–H_2 (X_{CO}) conversion factor [5] and the other using a starburst conversion factor [8]. Since Arp 299 has a high global IRAS IR SFR (94 $M_\odot$ yr^{-1}), this system is likely closer to starburst phase. It is unclear whether all the regions sampled by our IFU are starburst regions. However, since most of the fibers covered by the CO(2–1) gas map lie in the range of starburst galaxies [15], and SFRs based on Hα are likely lower limits, a starburst conversion factor may be more appropriate. Another caveat, however, is that X_{CO} likely varies as a function of interaction phase based on if the system is in starburst mode and therefore a bimodal X_{CO} is highly unlikely e.g., [20].

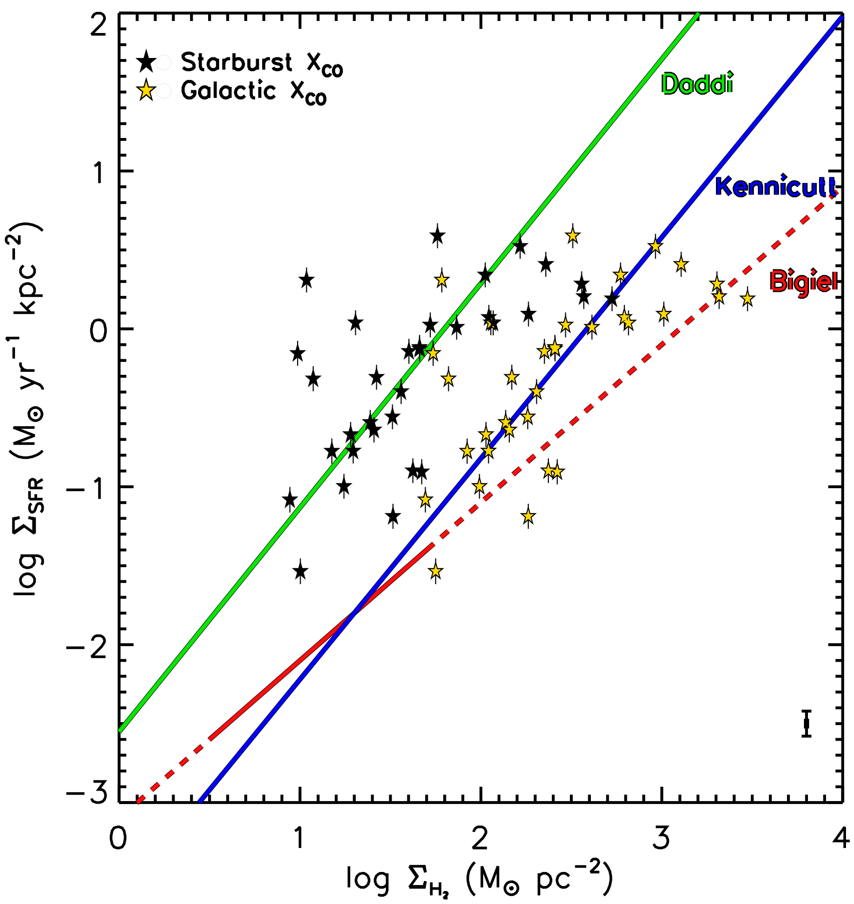

Figure 3: Spatially resolved SFR-H_2 surface density relation from measurements at each IFU fiber position with CO coverage (Figure 2) in late interaction phase galaxy merger Arp 299. Points are shown using a Galactic (yellow stars) and starburst (black stars) X_{CO} conversion factor. Lines indicate extragalactic relations on disk-averaged scales for spirals and starbursts (blue line) [15] and high-z mergers (green line) [7], as well as in 750 pc regions in spirals and dwarf galaxies (red line) [4].

Assuming a Galactic X_{CO} factor, spatially-resolved 900-pc regions in Arp 299 lie close to the Schmidt-Kennicutt relation (blue line), with slight deviations at the high gas surface density end (Figure 3). Since this late phase merger is likely closer to starburst phase, using a starburst X_{CO} factor would shift these points to the left, where they would lie in agreement with the relation (green line) found in high-z mergers [7,9]. If we assume that the X_{CO} starburst conversion factor [8] is correct for Arp 299, this implies there may be two regimes of star formation between normal disk galaxies and mergers at both low-z (this work) and at high-z [7,9]. However, this idea requires further testing on how the X_{CO} conversion factor varies on $\sim$kpc scales with interaction phase in interacting/starburst galaxies.

Acknowledgments

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