The VIRUS-P Exploration of Nearby Galaxies (VENGA): Survey Design and First Results

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Abstract.
VENGA is a large-scale extragalactic IFU survey, which maps the bulges, bars and large parts of the outer disks of 32 nearby normal spiral galaxies. The targets are chosen to span a wide range in Hubble types, star formation activities, morphologies, and inclinations, at the same time of having vast available multi-wavelength coverage from the far-UV to the mid-IR, and available CO and 21cm mapping. The VENGA dataset will provide 2D maps of the SFR, stellar and gas kinematics, chemical abundances, ISM density and ionization states, dust extinction and stellar populations for these 32 galaxies. The uniqueness of the VIRUS-P large field of view permits these large-scale mappings to be performed. VENGA will allow us to correlate all these important quantities throughout the different environments present in galactic disks, allowing the conduction of a large number of studies in star formation, structure assembly, galactic feedback and ISM in galaxies.

1. Introduction

In ΛCDM cosmology, the formation and evolution of galaxies takes place in gravitational potential wells in the dark matter distribution (DM halos). Gas accretion and merging processes ultimately trigger star formation giving rise to galaxies (Blumenthal et al 1984). Although consensus has been reached concerning this picture, the baryonic physics behind galaxy formation in the centers of DM halos are aggressively debated. The triggering of star formation and the variables that set the star formation rate (SFR) (Kennicutt 1998b; Leroy et al. 2008; Krumholz et al. 2009; Tai 2009), the contribution from different types of feedback processes (AGN, SN, stellar radiation) at regulating the gaseous budget, structure and kinematics of the ISM (Kauffmann et al. 1999; Croton et al.)
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Figure 1. DSS cutouts showing the VENGA sample of 32 nearby spirals ordered by RC3 morphological type from early (top left) to late (bottom left) types. White boxes show the VIRUS-P 1.7′ × 1.7′ FOV.

2006; Thompson 2009), and the role that major and minor mergers as well as secular evolution processes play at shaping galaxies (Kormendy & Kennicutt 2004; Weinzirl et al. 2009), are the main current areas of research. All these processes play a major role in determining how galaxies evolve throughout cosmic time, building up their stellar mass and shaping their present day structure.

The detailed manner in which the above physical phenomena (star formation, feedback, interactions, and secular evolution) proceed ultimately determines the morphology, kinematics, stellar populations, chemical structure, ISM structure, and star formation history (SFH) of a galaxy. We can put constraints on these processes by obtaining spatially resolved measurements of quantities like the SFR, stellar and gas kinematics, stellar populations, chemical abundances (both gas phase and photospheric), atomic and molecular gas surface densities, etc. and studying the correlations between them. Wide field optical
integral field spectroscopy allows the measurement of many of these quantities in nearby galaxies. IFU maps combined with multi-wavelength broad band photometry and sub-mm and radio maps of the same galaxies are powerful datasets to study galaxy evolution.

VENGA is a large-scale IFU survey of 32 nearby spiral galaxies (Figure 1) using the VIRUS-P spectrograph (Hill et al. 2008; Blanc et al. 2009) on the 2.7m Harlan J. Smith telescope at McDonald Observatory. The sample spans a wide range in Hubble types, SFR, and morphologies, including galaxies with classical and pseudo-bulges, as well as barred and unbarred objects. Ancillary multi-wavelength data including HST optical and NIR, Spitzer IRAC and MIPS, and far-UV GALEX imaging, as well as mid-IR IRS spectroscopy, CO maps and HI 21cm maps, are available for most of the sample. VENGA will allow a large number of researchers to conduct an extensive set of studies on star-formation, structure assembly, stellar populations, gas and stellar dynamics, chemical evolution, ISM structure, and galactic feedback. VENGA will also provide the best local universe control sample for IFU studies of high-z galaxies (e.g. Förster Schreiber et al. 2009).

2. Survey Design

VIRUS-P is currently the largest field-of-view (FOV) IFU in the world. It has 246 optical fibers (each 4.3" in diameter) which sample a 1.7′ × 1.7′ field with a 1/3 filling factor. Three dithers provide contiguous coverage of the FOV. Hence, for each VIRUS-P pointing we obtain spectra of 738 independent spatial resolution elements. Depending on the angular size of the targets we observe 1 to 3 pointings on each galaxy (see Figure 1) providing full coverage of the central parts of the galaxies and a typical sampling of the outer disks out to 2.5 $R_{\text{eff}}$. The spectra is obtained in both a blue and a red setup covering the 3600Å-5800Å and 4600Å-6800Å ranges respectively, and has a spectral resolution of 5Å FWHM ($\sigma_{\text{inst}} \sim 120$km s$^{-1}$). On total the survey is composed of 74 VIRUS-P pointings over the 32 galaxies, providing spectra for $\sim 55000$ independent regions across the disks of our targets.

VENGA also includes a secondary observing campaign using the upcoming wide field high resolution integral field spectrograph VIRUS-W (Fabricius et al. 2008), which will be conducted after the instrument is commissioned. VIRUS-W will provide spatially resolved spectroscopy of the VENGA sample with a spectral resolution of $\sigma_{\text{inst}} \sim 25$km s$^{-1}$, allowing the measurement of stellar velocity dispersions throughout the bulges, bars, and disks of the galaxies.

The VIRUS-P data reduction is being conducted using our custom pipeline VACCINE, and spectral analysis (measurement of stellar kinematics, gas kinematics, and fitting of emission lines) is being done using a modified version of the GANDALF software (Sarzi et al. 2006), which includes an implementation of the Penalized Pixel-Fitting method (pPXF Cappellari & Emsellem 2004). As an example of our data products Figure 2 presents four VENGA maps of NGC2903 showing the integrated stellar continuum in our red setup wavelength range, the observed Hα line flux, the stellar velocity, and the ionized gas velocity as measured from the centroid of the Hα line.
3. First Results: The Spatially Resolved Star Formation Law

Using the VENGA data on the central pointing of NGC5194 we investigate the relation between the star formation rate surface density ($\Sigma_{SFR}$) and the mass surface density of gas ($\Sigma_{HI+H_2}$), usually known as the Star Formation Law (SFL, a.k.a. Schmidt Law or Schmidt-Kennicutt Law, Schmidt 1959; Kennicutt 1998b). The method and results are reported in detail in Blanc et al. (2009).

From the VIRUS-P spectra we measured H$\alpha$, H$\beta$, [NII]$\lambda$6548,6584, and [SII]$\lambda$6717,6731 emission line fluxes for 735 regions $\sim$170 pc in diameter. We used the Balmer decrement to calculate nebular dust extinctions, and correct the observed H$\alpha$ fluxes in order to measure accurately $\Sigma_{SFR}$ in each region. The THINGS (Walter et al. 2008) HI 21cm and BIMA-SONG (Helfer et al. 2003) CO J=1-0 maps of NGC5194 were used to measure the HI and H$_2$ gas surface density for each region. We used a new Monte Carlo method for fitting the SFL which includes the intrinsic scatter in the relation as a free parameter, allows the inclusion of non-detections in both $\Sigma_{gas}$ and $\Sigma_{SFR}$, and is free of the systematics involved in performing linear correlations over incomplete data in logarithmic space. After rejecting regions whose nebular spectrum is affected by the central AGN in NGC5194, we use the [SII]/H$\alpha$ ratio to separate spectroscopically the contribution from the diffuse ionized gas (DIG) in the galaxy, which has a different temperature and ionization state from those of H II regions in the disk. The DIG only accounts for 11% of the total H$\alpha$ luminosity integrated over the whole central region, but on local scales it can account for up to a 100% of the H$\alpha$ emission, especially in the inter-arm regions. After removing the DIG contribution from the H$\alpha$ fluxes, we measure a slope $N = 0.85 \pm 0.05$, and an intrinsic scatter $\epsilon = 0.43 \pm 0.02$ dex for the total gas SFL, as shown in Figure 3. We also measure a typical depletion timescale $\tau = \Sigma_{HI+H_2}/\Sigma_{SFR} \approx 2$ Gyr, in
good agreement with recent measurements by Bigiel et al. (2008). The atomic gas density shows no correlation with the SFR, and the total gas SFL in the sampled density range closely follows the molecular gas SFL. Integral field spectroscopy allows a much cleaner measurement of Hα emission line fluxes than narrow-band imaging, since it is free of the systematics introduced by continuum subtraction, underlying photospheric absorption, and contamination by the [NII] doublet.

Figure 3 also shows that the disagreement with the previous measurement of a super-linear (N = 1.56) SFL in NGC5194 by Kennicutt et al. (2007) is due to differences in the fitting method, given the good agreement seen in the data. Applying our Monte Carlo fitting method to the Kennicutt et al. (2007) data yields a slope of N = 1.03 ± 0.08. Our results support the recent evidence for a low, and close to constant, star formation efficiency (SFE=τ^{-1}) in the molecular component of the ISM of normal spirals. The data shows an excellent agreement with the recently proposed model of the SFL by Krumholz et al. (2009). The large intrinsic scatter observed may imply the existence of other parameters, beyond the availability of gas, which are important at setting the SFR.

4. Conclusions

VENGA will provide SFR maps from Hα emission, which together with far-UV and 24µ imaging, and PAH features in the IRS mid-IR spectroscopy will be used to study systematics in different SFR estimators, revise their calibrations, and further understand dust reprocessed radiation. Measuring the star-formation efficiency (SFE=Σ_{SFR}/Σ_{gas}) throughout disks, and looking for correlations between SFE and properties like metallicity, orbital timescale, stellar and gaseous velocity dispersion, stellar mass density, and local ionization field, will test different theoretical models for star formation laws and thresholds, and GMC formation.

Also, VENGA produces metallicity, velocity and velocity dispersion maps for gas and stars from emission and stellar absorption line fits. It also yields stellar population (SP) mapping of bulges, bars and disks. SP fitting benefits from the UV and IR imaging to break age-metallicity-reddening degeneracies in the SED modeling. Modeling of the SP will yield the SFR histories constraining the stellar buildup of galaxies. Metallicity and abundance gradients can constrain the galaxy merger history. Alpha/Fe ratio gradients test how effective secular processes are at driving gas inflow and inducing star formation. If bulge assembly proceeds through reassembly of disk material, the alpha/Fe enhancement in the bulge should not differ much from that in the disk. Gas kinematics are being used to quantify non-circular motions along bars, such as azimuthal or radial streaming (Figure 2), to test the role that bar-driven inflow plays in building pseudo-bulges. We will also measure v/σ in the central regions to look for evidence of rotationally supported pseudo-bulges.

For edge-on galaxies, VENGA will vertically map the extra-planar diffuse ionized gas (EDIG). The origin of the EDIG is not yet clear. It may well come from internal feedback phenomena described by galactic fountain models, as well as it could be accreted from the surrounding IGM. The kinematics and chemical abundances of EDIG will be used to unveil its origin, which will translate
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Figure 3. Total gas SFL in the central pointing of NGC5194. The VENGA data (blue and red squares) shows an excellent agreement with the data of Kennicutt et al. (2007) (black circles). Lines of constant depletion time are shown (black dotted lines). Parameters for the Monte Carlo best-fit SFL to our data (black solid line) are reported. The Monte Carlo method best-fit to the Kennicutt et al. (2007) data is presented (green solid line) and has a slope of $N = 1.03 \pm 0.08$. Also shown is the theoretical model of Krumholz et al. (2009) (red solid line).

to a better understanding of feedback and accretion processes driving galaxy evolution.

In summary, over the next few seasons VENGA will build an unprecedented spectroscopic dataset on nearby spiral galaxies. This dataset, in combination with publicly available data at other wavelengths, will allow us to conduct a large number of studies regarding the principal processes involved in galaxy formation and evolution. The VENGA dataset will also become a valuable
public spectroscopic resource on nearby galaxies available to the astronomical community.

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