A. Research Objectives and Program Overview

Understanding how galaxies – the building blocks of the Universe – form and evolve constitutes a central problem in astronomy. In the framework of contemporary galaxy formation paradigms, the evolution of galaxies is determined by the merging history of dark matter halos and the behavior of baryons (gas and stars) in the gravitational potential wells of these halos (e.g., Cole et al. 2000; Steinmetz & Navarro 2002). While there is broad consensus on the behavior of dark matter on large scales and on the overall qualitative picture, our understanding of how galaxies evolve is severely limited by uncertainties in the baryonic models. How do dark matter halos acquire cold gas? How do new stars form from this cold gas and make small proto-galaxies ? How do stars and black holes shape galaxy evolution through the energetic feedback they exert on surrounding gas? How do these proto-galaxies subsequently assemble into more massive systems resembling present-day galaxies, such as our own Milky Way? Ultimately, are galaxies and their key structural components (bulges, bars, and outer disks) built mainly through violent processes called galaxy mergers, or via more quiescent modes involving secular (internal) processes (e.g., Kormendy & Kennicutt 2004; Jogee et al. 2005; Elmegreen et al. 2008), and smooth accretion (Dekel et al. 2009)?

This proposal requests support for the VIRUS-P Exploration of Nearby Galaxies (VENGA), an unprecedented 2D spectroscopic survey of the inner and outer regions of a large sample of 32 nearby spiral galaxies with the VIRUS-P Integral Field Unit (IFU) on the 2.7m telescope at McDonald Observatory. VENGA will allow breakthroughs on many of the above critical questions by allowing a systematic exploration of the distribution and velocities of gas and stars over wide areas of a large number of spiral galaxies (see § B for details).

While conventional so-called “long-slit” or 1D spectroscopic surveys typically obtain spectra at a few aligned positions in a galaxy over a few hours, a so-called 2D spectroscopic survey conducted with an IFU unit is much more powerful. In the same amount of time, it can obtain independent spectra from a *very large* number of contiguous positions in a galaxy using fibers. A strong advantage of VENGA is that VIRUS-P has large sensitive fibers and the largest field-of-view (3.36 arcmin^2) among existing IFUs. As a result, VENGA is the most efficient survey worldwide currently acquiring 2D spectra over large areas of spiral galaxies, from the bright inner parts out to the faint outer disk. VENGA supersedes the past survey of the central parts of 18 nearby spirals (Ganda et al. 2006) using the SAURON IFU (Bacon et al. 2001) with a 0.37 arcmin^2 field of view, and the ongoing PINGS survey of 11 spirals using the PMASS IFU with a 1.3 arcmin^2 field-of-view (Rosales-Ortega et al., submitted).

Another remarkable feature of VENGA is that it is a project initiated and led by graduate students, with secondary oversight from faculty. Such a large graduate-student-led project is rare and it provides unique leadership and research opportunities for students (§ D). VENGA data are being used in the Ph.D. theses of at 4 UT graduate students (§ B and § D). We request NHARP funding primarily to support graduate and undergraduate students involved in VENGA, and complement the significant institutional resources already made available to the project (§ E).

VENGA is poised to have a far-reaching impact. To date, large samples of thousands of nearby spiral galaxies have been studied via imaging surveys (e.g., with SDSS, 2MASS, the *Hubble Space Telescope*, *Spitzer*). The next decadal frontier is to secure 2D spectroscopic data of comparably large samples of galaxies. VENGA paves the way for next-generation IFU surveys by acting as a prototype for large IFU surveys of nearby galaxies, and by generating the largest and best comparison dataset for IFU studies of distant galaxies. In the medium term, VENGA also provides an important synergy with other near-future surveys, such as the Calar Alto Integral Field Area Survey (CALIFA) with the PMAS/PPAK IFU. The sample and observing strategy of VENGA and CALIFA are being coordinated to optimize their scientific return to the astronomical community at large.

B. Methodology

We describe below the sample selection for VENGA, the observational setup, the status of the survey, the data reduction, and the ongoing scientific analyses.

Sample: The VENGA sample of 32 nearby spiral galaxies spans a wide range in properties, such as star formation rates, morphologies (Hubble types Sa-Sd), bulges (e.g., classical bulges and pseudo-bulges; Kormendy & Kennicutt 2004; Weinzirl et al. 2009), and bar types (Marinova & Jogee 2007). This ensures that the samples covers the parameter space relevant for answering the science questions posed by the 4 main UT Ph.D. theses using the VENGA survey (see "Science Analysis" section below for details). We also required that a large fraction (60% to 97%) of the sample galaxies have complementary data at ultraviolet, optical, infrared, radio, and X-ray wavelengths, taken with other facilities (the *Hubble Space Telescope*, *Spitzer*, GALEX, CARMA, etc). The 2D optical spectra of VENGA show the distribution and kinematics of young-and-intermediate-age stars, and of warm ionized gas heated by the energy of stars and black holes. The complementary data provide information on the extremely young and old stars, the cold and hot gas, and dust at different temperatures.

Observational Setup and Survey Status: Taking advantage of the large field-of-view (3.36 arcmin^2) and large ($4''$) fibers of VIRUS-P, VENGA data can probe even the faint outer parts of galaxies, reaching down to 0.7 of the R_{25} isophotal radius in most cases. Two or three pointings are made for each galaxy, with an average exposure of 60 minutes per pointing, and three dithers per pointing. Each pointing is observed in two spectral modes: a low-resolution red setup (4550-6800 Å coverage and $\sigma_{inst} = 120$ kms^{-1}), and a high-resolution blue setup (3650-4400 Å and $\sigma_{inst} = 50$ kms^{-1}). The combined coverage allows the mapping of emission lines from warm ionized gas (e.g., [O III] 4959 and 5007 Å, $H\alpha$, $H\beta$, and $H\delta$), and absorption features from stars (e.g., Mg b 5140 Å, Fe 5015 Å, $H\beta$, and $H\delta$).

The McDonald Observatory telescope allocation committee (TAC) has strongly supported VENGA through the allocation of $\sim$ 60 nights over the 2009-2010 trimesters. 50 nights have already been observed, completing 75% of the red observations. We expect another 70 nights to be allocated over 2011-2012 to complete VENGA.

Data Reduction: We have already developed an extensive suite of software to reduce the VIRUS-P data. Basic reduction is carried with our VACCINE software (Blanc at al. 2008) and includes bias subtraction, flat fielding, wavelength calibration, and flux calibration of the extracted spectra. Using a modified version of the GANDALF software (Sarzi et al. 2006), stellar and gas kinematics are then derived by separating the stellar and nebular gas contributions to the spectra. For each spectrum acquired by a VIRUS-P fiber, we ultimately obtain a stellar absorption spectrum cleaned of nebular emission, stellar kinematics and absorption line-strength indices, as well as the kinematics and flux of ionized gas. For data of low signal-to-noise, Voronoi binning (Cappellari & Copin 2003) or other forms of binning will be employed to ensure a suitable minimum signal-to-noise in each final spatial bin. Figure. 1 depicts some of the reduced unbinned VIRUS-P data for the barred spiral NGC 2903. Similar high quality maps are available for other emission and absorption features.

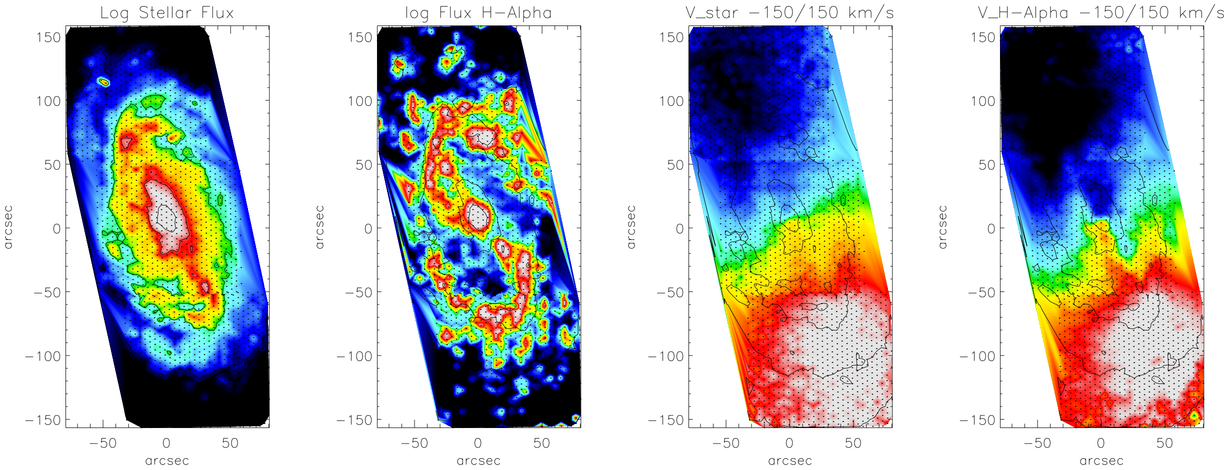

Figure 1: Some of the reduced VIRUS-P data are shown for the barred spiral NGC 2903. From left to right: a) Stellar continuum map showing the central bulge, elongated bar, and outer disk; b) Distribution of ionized gas traced by the Hα emission line. Note the pattern of star formation along the spiral arms and bar; c) Stellar velocity field; d) Ionized gas velocity field showing non-circular motions along the bar.

Science Analysis: At least 4 graduate students (Blanc, Marinova, Weinzirl, Heiderman) at UT are using the VENGA data in their Ph.D theses in order to explore important questions on galaxy evolution What sets the rate and efficiency at which stars form from cold gas in galaxies? Do the star formation laws vary within different regions of a galaxy and across different types of galaxies? While galaxies grow in mass, how do stars arrange themselves into the main structural components (bulges, bars, and outer disks) of spiral galaxies? What is the relative importance in galaxy evolution of violent galaxy merger events versus more quiescent modes involving secular (internal) processes and smooth accretion of gas from cosmological filaments? What role does feedback (the process whereby the energy and momentum transported by stellar winds and jets from black holes is deposited into the surrounding gas) play in galaxy evolution? We describe below the ongoing analysis of the VENGA data to address these questions.

The Hα flux from VENGA are used to measure the star formation rate. Corrections for extinction from dust are applied using the Balmer decrement $H\alpha/H\beta$ (Brand et al. 2007).

By combining the VENGA Hα data with complementary data at ultra-violet and infrared wavelengths, we can get a better handle on the total star formation rate. We are investigating the relationship between the local star formation rate density ($\Sigma_{\rm SFR}$) and the local molecular and atomic gas surface density ($\Sigma_{\rm gas}$) in order to characterize the spatially resolved Schmidt law, in both normal galaxies and interacting galaxies. The first VENGA paper on this topic has just been published (Blanc et al. 2008). We are exploring how the star formation efficiency (defined as $\Sigma_{\rm SFR}/\Sigma_{\rm gas}$) depends on local parameters, such as metallicity, orbital timescale, and local ionization field in order to test different theoretical models of star formation.

We are also comparing the star formation efficiency across three regions of a spiral galaxy: the circumnuclear region involving the central 1-2 kiloparsec, the stellar bar, and the outer disk. These regions define different star formation environments as they exhibit widely different dynamical timescales and cold gas properties (density, kinematics, shear, velocity dispersion, level of rotational support). We will investigate whether the star formation efficiency along strong stellar bars is very low due to the large non-circular motions and shear in the inflowing cold gas (e.g., Jogee et al. 2005). Such a low star formation efficiency is central to the untested idea that strong bars efficiently channel cold gas into the circumnuclear region without consuming much of it, thereby driving mass buildup and secular evolution of the circumnuclear region.

The metallicity, velocity, and velocity dispersion maps for gas and stars produced by VENGA can constrain the galaxy assembly history. The abundance ratios between the α-elements and iron ([α/Fe]) are tied to star formation timescale. High [α/Fe] enrichment is expected to result from rapid star formation episodes, such as those induced in major mergers. We will look for gradients in [α/Fe] across the bulge, bar, and outer disk. We will measure the rotational and random stellar velocities in order to separate classical bulges and certain type of disky bulges called pseudo-bulges (Kormendy & Kennicutt 2004). We will use the $H\alpha$ ionized gas velocity field to quantify non-circular motions along bars, and the strength of shocks along bars. This will help to test the role that bar-driven gas inflow plays in building pseudo-bulges.

Finally full-spectrum fitting in pixel space of the emission-line-cleaned spectra from VENGA will be used to analyze the underlying stellar populations and test different star formation histories (e.g., multiple bursts versus exponentially declining histories).

C. Research personnel

VENGA is run by a core team of UT graduate students (Blanc, Marinova, Weinzirl, Heiderman, and Fisher) working closely with a faculty oversight committee (Jogee, Evans and Gebhardt), and several independently-funded postdocs (Joachim, van den Bosch, and Hao). This NHARP proposal primarily requests funding (§ F) for the graduate and undergraduate students involved in VENGA.

Under the leadership of Guillermo Blanc, the graduate students initiated the VENGA survey and lead the core operations, including writing the observing proposals, conducting the observations, developing the data reduction pipeline, conducting the scientific analyses, and planning the public data release. The postdocs, some of whom have extensive prior IFU experience, help with the data reduction and are collaborating on science projects. UT undergrads are getting first-hand research experience by observing and reducing date for VENGA (§ D), under the mentorship of faculty, postdocs, and graduate students.

The faculty members provide scientific guidance, ensure the timely publication of papers planned for the survey, and coordinate the science outputs from the survey, resolving potential conflicts of interest. The first refereed VENGA paper is already published (Blanc et al. 2008). Faculty also oversee the public data release and ensure continuity as new graduate students join the VENGA team and current ones graduate. The VENGA collaboration is working very well and the first highly productive team meeting was held in December 2009 at UT Austin.

D. Student involvement and research opportunities

VENGA is a project initiated, led, and run by graduate students. While the faculty provides oversight (§ C), the inception and vision for VENGA stemmed from the UT graduate students. This type of large graduate-student-led project is rare. VENGA provides an excellent training platform where graduate students learn all aspects of a large survey, from writing observing proposals, optimizing observing strategies, developing data reduction pipelines, leading cutting-edge science, and conducting a timely public data release with accompanying documentation. The experience thus gained by the graduate students positions them to lead future large science programs. This is especially valuable as the field of astronomy is now increasingly driven by such large programs and collaborations.

The VENGA data are being used in the Ph.D theses of at least 4 UT graduate students (Blanc, Marinova, Weinzirl, Heiderman), as well as a graduate student (Fabricius) from the University of Munich. For new entering graduate students, numerous other research projects are planned on the properties of black holes, measurements of the pattern speed and dynamical mass-to-light ratios of stellar bars, modeling the dark matter halos of galaxies, etc.

The mentorship and involvement of UT undergrads in research is an integral part of VENGA. Undergrads accompany graduate students on observing runs to McDonald observatory when classes are not in session, and they are extremely enthusiastic about their hands-on learning experience. Undergrads also help with aspects of the data reduction. Among the 72 astronomy majors, we have a large number of undergrads who want to get involved with VENGA, but we need funds to support them.

VENGA will also benefit researchers beyond the boundaries of UT. By 2012,VENGA science products (e.g., calibrated spectral data cubes with their associated error maps and astrometry, stellar kinematics maps, and gas kinematics maps) will be made available to the community at large and offer the potential for extensive data mining.

E. Institutional commitment and sources of additional support

The VENGA observations are taken at McDonald Observatory, a research unit of the University of Texas at Austin. The observatory time allocation committee has shown strong support of VENGA: $\sim$ 60 nights were allocated over the 2009-2010 trimesters and a similar allocation is expected over the next 2 years. There are adequate computer resources within the department for the main data reduction and analysis. We will use the TACC supercomputing resources for more involved modeling.

To date, VENGA has received financial support from a mix of sources : \$3,100 from McDonald observatory to cover some of the expenses for observing runs; \$5,000 from a Sigma Xi foundation award to graduate student Blanc; \$5,000 from faculty member Jogee through grants addressing science questions, which will laterally benefit from the VENGA data; and $\sim$ \$2,000 through various departmental funds to support undergrad travel. This seed funding has enabled the impressive groundwork to date (§B), but we now urgently need a large dedicated source of funding for graduate and undergraduate students involved in VENGA in order to ensure the long-range success of VENGA. As the first proposal with a main focus on VENGA submitted to an external funding agency, this NHARP proposal would provide the core student funding for VENGA. We expect to leverage this grant with funding proposals to the National Science Foundation next year, as well as partial support from the Astronomy Department Cox Excellence funds and the Walton Funds to cover undergraduate stipend and travel.

F. Budget justification

We request $110,50 of salary support (research assistantships) over 2010-2012 for 5 UT graduate students (Blanc, Marinova, Weinzirl, Heiderman, and a new incoming student) whose research projects make a significant use of the VENGA data. We request $4,200 of travel support (car rental, lodging, meals) for graduate students taking part in 5 one-week-long VENGA observing runs. An additional $2,240 is requested to cover the board and lodging of 4 undergrads accompanying them. We anticipate at least 5 important graduate-student-led papers from VENGA and request $11,000 to cover the publication cost ($110 per page ×20 pages ×5). In order to maximize the impact of VENGA and foster collaborative synergy, we need to disseminate the results through national and international conferences. We therefore request funds to support 1 domestic conference for 5 graduate students ($1,640 ×5 or $8,200), 1 domestic conference for 2 undergrads ($3,280), and 1 international conference for the PI, Co-PI, and 1 graduate student ($2,330 ×3 or $6,990). Finally, a modest summer salary of $3000 is requested for the PI.

G. Bibliography

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