NOAO Observing Proposal *Survey proposal* **Panel:** *For office use.*
Date: March 15, 2000 **Category:** Resolved Galaxies

Star Formation in HI Selected Galaxies

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
Cosmological evolution is mapped using tracers of star formation. Usually the selection of tracers is biased by stellar luminosity. We propose to determine star formation properties of a sample selected free of the stellar bias: by gas content from the HIPASS survey. Since an interstellar medium is a prerequisite for star formation, our survey will uniformly sample all galaxies that could form stars, and hence provide a fair view of the local star formation demographics. The sample will consist of the 500 HIPASS galaxies, each of which will be imaged in Hα and the stellar continuum. Integrated, this yields the local star formation rate density, which will be used as benchmark to estimate the bias in other Hα samples. This survey will also provide high resolution images of the star formation morphology over a wide range of galaxies, particularly towards irregular dwarfs which are often missed in other studies. The HI content of galaxies combined with the SFR will be used to predict the evolution of the HI mass function and the epoch when the cosmological gas tank runs dry.

Scheduling constraints and non-usable dates *(up to four lines)*.

The moon must be within 10 days of new to reach our surface brightness limit. Two observing runs per semester of four to five nights each are requested.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

Introduction

Statistical studies of galaxies in the local universe are hampered by the existence of severe selection biases, which make it difficult to tell whether the quantities being measured pertain to all galaxies or simply those favored by the survey's selection criteria. The large uncertainties in the local density of low-surface-brightness galaxies (Impey & Bothun 1997), the failure to verify or disprove Stochastic-Self-Propagating Star Formation (SSPSF) models for dwarf galaxies (Gerola et al. 1980), and the missing evolutionary links between exotic objects such as luminous infrared galaxies or blue compact dwarf galaxies and the rest of the Hubble sequence are all examples of the difficulties brought on by selection effects. The selection biases are particularly severe for existing Hα surveys of galaxies often used to study both the physics of star formation and to estimate the integrated star formation density for cosmological studies. Previous Hα imaging surveys of local galaxies either covered a broad range of morphologies (e.g. Hodge & Kennicutt 1983; Young et al. 1996) or concentrated on a particular interesting type of galaxy (e.g. Seyfert galaxies: Mulchaey et al. 1996; edge-on starbursts: Lehnert & Heckman 1996; Early type spirals: Hameed & Devereux 1999). But in all cases the selection of targets was based on optical or infrared properties. Wide-field emission-line surveys have been used to detect star forming galaxies and estimate the local star formation rate density (e.g. Gallego et al. 1995) but are intrinsically biased toward galaxies with the highest star formation intensities and a proper treatment of these biases integrated over the Hα luminosity function could introduce substantial corrections (Schade & Ferguson 1994).

Selecting galaxies in a new way (e.g. via infrared radiation in the case of IRAS) can lead into new insights in the physics of galaxies, especially if those surveys are accompanied by detailed follow-up studies. The recently completed HI Parkes All-Sky Survey (HIPASS) in the southern hemisphere is the first large survey to select galaxies entirely by their HI 21-cm emission. Because hydrogen is the essential fuel for star formation, this is an ideal sample to use in star formation surveys. The HI survey is completely unbiased with respect to optical luminosity, surface brightness, or Hubble type and covers the entire sky south of $\delta = +2^\circ$ over a velocity range -1200 to 12,700 $\mathrm{km\,s^{-1}}$ with a detection limit $\sim 10^6 D^2 M_\odot$ where D is measured in Mpc. Hence it can offer a unique opportunity to study not only the intrinsic trends of Star Formation Rates (SFR) with galaxy properties (e.g. mass, surface brightness) but also the distribution about the mean trends.

We propose an Hα imaging survey of a large, unbiased subset of HIPASS selected to evenly sample the HI mass function (Fig. 1). The survey will address evolution issues (detailed below) ranging from how star formation is regulated within galaxies, to the star formation history of the universe as a whole. The size, completeness, and quality of the survey insures that it will be the reference Hα dataset of nearby galaxies for at least the next decade.

Science Drivers

Star Formation Density of the Local Universe. The redshift evolution of the SFR density, $\rho_{\rm SFR}(z)$, is fundamental to understanding cosmological evolution, and the local SFR, $\rho_{\rm SFR}(0)$, is a key datum in discriminating between various models. The $\rho_{\rm SFR}(z)$ plot of Madau et al. (1996) shows a factor of ≈ 10 decline in $\rho_{\rm SFR}$ from $z \approx 1$ to $z = 0$ which is difficult to reconcile with models of cosmological evolution (e.g. Baugh et al. 1998). Recent estimates of $\rho_{\rm SFR}(0)$ range over a factor of ~ 3 (0.03 to 0.08 $\mathcal{M}_\odot$ Mpc^{-3} yr^{-1} for $H_0 = 75$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$) with individual measurements not always agreeing within their quoted errors. This is in part due to the various sample biases. For example, Hα samples (e.g. Gallego et al. 1995) are biased towards high equivalent width (starburst) systems; the UV sample of Treyer et al. (1998) is biased against very dusty systems; conversely, FIR samples (e.g. Sanders & Mirabel 1996) are biased against low dust systems. No survey is completely free from selection biases (ours may be slightly biased towards high SFR galaxies if photodissocation of H_2 significantly increases HI content). However, our survey will be free from most of the selection biases that plague the optical and IR studies, providing an independent estimate of $\rho_{\rm SFR}(0)$. Strictly speaking, we will measure a lower limit to $\rho_{\rm SFR}(0)$, since our observations do not address extinction. Additional observations in the literature (e.g. $\rho_{\rm SFR}(0)$ from IRAS) can be used with our results to constrain the total SFR.

The Distribution of Star Formation Rates. A key aspect of our proposal is that it will allow a measurement of the distribution of star formation (rates and surface densities) as a function of other galaxy properties. The largest uncertainties in cosmological models of galaxy evolution are the prescriptions for star formation (quiescent and merger-induced) and feedback. These prescriptions are poorly tested by measurements of mean quantities such as the Tully-Fisher relation or the color–luminosity relation. Much more stringent tests are possible when the full distribution functions can be measured. A powerful aspect of the present generation of semi-analytic galaxy-formation models is that they predict such distribution functions (e.g. Sommerville & Primack 1999). The HIPASS Hα survey will provide a sample for testing the cosmological predictions for the distribution of SFR at fixed HI mass. The sample will also test more schematic models of self-propagating star formation in dwarf galaxies (Gerola et al. 1980; Tyson & Scalo 1988) and provide evidence for or against intermittent star formation in Milky-Way-like galaxies (Rocha-Pinto et al. 2000).

HII region luminosity functions. HIILFs are important diagnostics of current star formation. At the upper end, there may be a universal power-law in the number of stars per cluster, as suggested by the HIILF shape in most galaxies (Oey & Clarke 1998), the LF of open and globular clusters (Elmegreen & Efremov 1997), and super star clusters (Meurer et al. 1995). The HIILFs in our sample will be a crucial test to see whether this universal law is upheld. A turnover at the faint end of the HIILF sensitively probes the high mass end of the stellar IMF.

Census of star formation modes. Our observations will provide new demographics on how and where stars form in galaxies. We will catalog different star forming structures (i.e. spiral arms, bars, rings, and nuclei) and determine how frequently they occur. Of particular interest, central starbursts will be recognized by their high Hα effective surface brightness (μ_e(Hα)). Thus we will make an accurate estimate of the starburst incidence rate. When combined with estimates of starburst duration (Meurer 2000), the average number of bursts per galaxy can be determined.

Gas consumption timescales. While star formation occurs in molecular gas, to astronomical precision, the neutral mass, $1.3\mathcal{M}_{\rm HI}$, makes a good proxy for the total gas mass (the mean $\log(\mathcal{M}_{\rm HI}/\mathcal{M}_{\rm H_2}) \approx 0.0$ in the sample of Young et al. 1996) and is a lot easier to measure than $\mathcal{M}_{\rm H_2}$. Hence to first order the the gas consumption time $t_{\rm gas} \sim 1.3\mathcal{M}_{\rm HI}/{\rm SFR}$. On a galaxy by galaxy basis $t_{\rm gas}$ is an alternative for distinguishing between starburst ($t_{\rm gas} \ll 1/H_0$) and quiescent systems ($t_{\rm gas} \gtrsim 1/H_0$), which we will compare with the μ_e(Hα) method. On a sample wide scale we will measure the cosmological gas consumption timescale $t_{\rm gas,cosmo} \approx 1.3\rho_{\rm HI}/\rho_{\rm SFR}$, where $\rho_{\rm HI}$ is the local HI density in $\mathcal{M}_\odot$ Mpc^{-3}. This tells how long present day evolution can be maintained before the cosmic fuel tank starts to run dry. We will also estimate the gas consumption rate over each 0.5 dex bin of the HIMF which will indicate where evolution is occurring most quickly.

The Reference Hα sample for the local universe. An essential aspect of the survey will be the release to the community of high quality calibrated Hα and continuum images. This will enable comparative studies with other measurements of gas and star formation in galaxies. For example, UV observations with HST or GALEX (Martin et al. 1997) can be used to calibrate the extinction correction for UV star formation rates and constrain the high mass end of the IMF; The HII regions can be used to derive the true [O/H] distribution of galaxies, avoiding the current bias towards

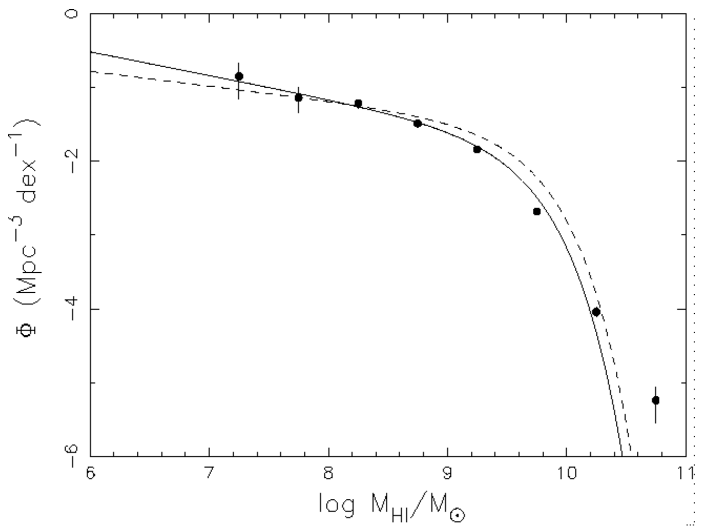

Figure 1: HIPASS HI mass function of Kilborn et al. (1999)

towards high excitation systems with [O/H] ≈ 0.1 (Kunth & Östlin 1999); and HI and ^{12}CO imaging will allow a detailed reexamination of the star formation law of Kennicutt (1989; 1998) without a bias toward optically prominent galaxies.

Sample Selection

HIPASS (Staveley-Smith et al. 1996) is a blind survey for 21 cm HI line emission of the entire sky with $\delta < +2^{\circ}$ using the Parkes 64m radio telescope and the multibeam receiver. It covers the velocity range $V_r = -1200$ to 12,700 km s^{-1} with a peak flux limit of ~ 40 mJy; survey observations have just been completed. Preliminary analysis of $\approx$10% of the survey reveals a relatively steep faint end slope ($\alpha \approx 1.3$) to the HIMF as shown in Fig. 1 (Kilborn et al. 1999). HIPASS is detecting many previously uncatalogued galaxies ($\sim$ 20% of detections). However, so far only one has not been detected in optical broadband follow-up observations.

We will select 500 HIPASS sources from the whole high galactic latitude ($|b| > 30^{\circ}$) southern sky. The survey will include galaxies in the HI mass range $10^7 < \mathcal{M}_{\rm HI} < 10^{11}$, with 150 galaxies chosen per decade of HI mass in the range $10^8 < \mathcal{M}_{\rm HI} < 10^{10}$, and the remaining 50 from the extreme high- and low-mass ends of the sample (this will include virtually all HIPASS galaxies at the extremes). Except for the high-mass extreme, $\mathcal{M}_{\rm HI} \gtrsim 10^{9.75}$, the sample will have radial velocities $V_r \lesssim 1800$ km/s, with selection of specific galaxies guided by their velocity relative the the center of the bandpasses of the Hα filters.

A sample of this size is the minimum necessary to accomplish the essential goal of this proposal: to measure not only the mean but also the *distribution about the mean* of star formation rates among galaxies of different HI masses, Hubble types, surface brightnesses, and in different environments. A sample of 150 galaxies per decade of HI mass in the core sample allows the mean SFR per decade to be measured to better than 10% accuracy, the mean SFR per magnitude central surface brightness $21.6 < \mu_c < 24.6$ within each decade of HI-mass to be measured to 15% accuracy, and the mean SFR per decade local density $10^{-2} < \rho < 10^2$ Galaxies/Mpc^3 to be measured to better than 20% accuracy. Within each decade of $\mathcal{M}_{\rm HI}$, the rms width of the Hα luminosity distribution can be determined to $\sim$ 10% (SSPSF models predict that the width should increase with decreasing galaxy mass; Gerola et al. 1980), and sensitive tests for non-Gaussianity can be performed. This sample will allow a search for extremely rare objects: galaxies with significant HI masses but no star formation (such as transition dI/dSph systems), and galaxies with low HI masses but very high star formation rates.

Summary: Advancement of Astronomy

The HIPASS Hα survey will be the first to measure the star formation properties of galaxies in a sample free from optical or IR selection biases. The data set will provide an independent and more precise estimate of the local star formation density $\rho_{\rm SFR}(0)$, and a measurement of which galaxies contribute the most to that star formation. By measuring the *distribution* of $L({\rm H}\alpha)/\mathcal{M}_{\rm HI}$ the survey will provide a definitive test of stochastic star formation models for low mass galaxies, and a sensitive test for sporadic variations of the star formation rate in more massive galaxies along the traditional Hubble sequence. The sample will provide a new set of demographics on the morphology of star formation and vast improvement in the constraints on HII region luminosity functions. We intend this sample to provide *the reference Hα data set* for nearby galaxies for the next decade. The public release of uniform high-quality data from a large sample with well-defined selection criteria will provide an ideal basis for complementary studies at other wavelengths and with other techniques, advancing our general understanding of star formation in galaxies.

References

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Management Plan *Describe the overall plan for conducting the proposed survey, including the experimental design, survey deliverables, staffing requirements, and a list of observing runs. See the Survey Program instructions for details.*

The observations. For each source we will obtain images with a narrowband filter whose passband encompasses redshifted Hα and the broad band R "continuum". We will use FWHM $\approx$ 35Å Hα filters for this study. This width provides a good compromise between low widths which minimize sky contribution on the one hand, and broader widths which allow the full velocity width of galaxies to be image, and keep costs reasonable. Our team has one such filter available (Smith's 6573/30). We will purchase additional $3''$ filters to cover the V_r range of our sample. The data will be obtained in three frames per band with small offsets between frames for cosmic-ray and bad-pixel removal. Southern spectro-photometric standards will be observed to flux-calibrate the data.

As detailed in the technical section, a total of fifty nights on the 1.5m with CFIM8 + T2K are required to obtain high-quality observations of all 500 galaxies in our sample. The observations will be spread over six semesters (2000B to 2003A) to insure enough time for the HiPASS team to extract sources to its full depth. Two runs per semester are requested to evenly sample the sky.

Accuracy. Previous studies (e.g. Young et al. 1996) demonstrate that continuum subtraction with R band images will be adequate for our purposes, producing Hα fluxes accurate to $\sim$ 20%. The satellite [NII]6548,6584Å lines also limit the accuracy of Hα flux determinations. From typical HII region spectra and the pass band of the filter we estimate that the Hα fluxes will typically be boosted $\lesssim$ 20% by [NII] contamination. We will correct for this effect statistically, using published HII region spectra. The correction factor will be tuned to the HI velocity profile of each galaxy.

Products. For each galaxy, the products that we will make available to the community are:

(1) Flux calibrated continuum subtracted Hα image (with error array).
(2) Flux calibrated continuum image (with error array).
(3) Hα and continuum radial surface brightness profiles (with error arrays).
(4) Catalog of HII region positions and their Hα fluxes.

The final manufacture of these products will be done in a pipeline consisting of a series of *IRAF* scripts. Error arrays are important for determining which sources are real. The error arrays will include Poissonian and read noise terms, and the Hα error array will include the properly propagated continuum errors and a term for the uncertainty in the Hα/continuum ratio. The radial profiles will be extracted in elliptical annuli with constant center and axial ratio. These orientation parameters will be determined from the continuum image using a moment analysis technique. Code to perform the surface photometry has been developed by Meurer and will be encorporated into the pipeline. HII region detection and photometry will be done within the DAOPHOT package, or a specialized HII region photometry package (we are currently assessing the options).

Labor. The initial breakdown of responsibilities is listed in Table 1. We expect to also attract one or two graduate students. They will assist in all aspects of the project. These include observing, pipeline development, pipeline runs, scientific analysis and paper writing.

Project support. The initial observations will be made with funds available to the individual observers and team members. Full financial support for the USA based investigators will be requested from the NSF. These funds will support graduate students, buy computer resources, and archive resources, and support observing runs. We expect enough funds from JHU's Center for Astrophysical Sciences general research funds, STScI's Director's Discretionary Research Fund, and Hubble Fellowship grants (Putman) to allow at least five observing trips from the USA per year until our own grant is obtained. Note, one of our team members (Smith) is on the CTIO staff and can cover some of the runs with little cost.

Table 1: Responsibilities

Member	Responsibilities
Gerhardt Meurer	PI, observer, pipeline construction and overview
Harry Ferguson	co-PI, observer, science overview
Rachel Webster	Australian-PI, coordination with full HIPASS team
Michael Drinkwater	Pipeline development
Ken Freeman	Science advisor
Rob Kennicutt	Science and technical advisor
Virginia Kilborn	Sample selection, pipeline development
Patricia Knezek	Observer, source positions
Sally Oey	Observer, HII region photometry specialist
Mary Putman	Observer
Chris Smith	Observer, filter specialist, local CTIO contact
Lister Staveley-Smith	Source positions

Release of Data *Describe the timeline and mechanism for the release of data subsets, the complete dataset, and catalogs to the astronomical community.*

Our intention is to make the pipeline as fully automated as possible. We expect that much of the effort expended in the first year will be spent in constructing scripts of sufficient robustness to accomplish this goal. We will also construct tools to efficiently examine the output products so as to insure that the pipeline is behaving. Appropriate flags and comments will be placed in the image/product headers if human intervention is required. The final check on quality will be comparison of the derived fluxes with previously published Hα imaging (e.g. Ryder & Dopita 1993; Young et al. 1996)

The raw data will be archived on CDROM in Baltimore and Melbourne and will be available upon request. Project web pages will be established at JHU. The pipeline software will be available on these pages, as will ASCII observing logs, and logs of the pipeline runs. The final data products listed above will be archived in STScI's Multi-Mission archive, and hence will be available to the community via the web (http://archive.stsci.edu/mast.html). The images will be stored in fits format, while the radial profiles and HII region catalogs will be ASCII tables. The first data delivery will occur a year after the observations commence, with semesterly data ingestions there after.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the Principal Investigator during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal.*

Why CTIO? *(For CTIO proposals only.) Explain why access to the southern hemisphere is needed to achieve your scientific goals.*

HIPASS is primarily a southern sample: it results from observations made with the 64m Parkes Radio Telescope in Australia. It can only be efficiently accessed from a southern site.

Observing Run Details for Run 1: CT-1.5m/CFIM8 + T2K

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

Our scientific goals require fairly deep Hα images, especially to probe the HIILFs, but also to measure the integrated Hα fluxes for the galaxies, including the contribution from diffuse emission. While useful Hα images could be obtained on the 0.9m, the gain in efficiency of using the 1.5m (3$\times$ the collecting area) and the associated improvement in image quality (3$\times$ fewer cosmic rays, less susceptibility to guiding errors) make it the preferred telescope. The equal sensitivity at given surface brightness often associated with small telescopes is not relevant to the 0.9m because it has the same *focal length* as the 1.5m (the pixel scale of the Schmidt is too large for distinguishing HII regions). With the exposure times detailed below and about 11 minutes of overhead per galaxy (filter changes, telescope offsets, and readouts) we require 47 minutes per galaxy, and can observe about 10 galaxies a night. The entire survey can be completed in 50 nights. In contrast, with the 0.9m two hours per galaxy would be required, only four galaxies a night can be observed, and we would require 125 nights to complete the survey.

The primary goal of the HIILF work is to test the models of Oey & Clarke (1998). This requires that we reach the turn-over in the LF, which typically occurs at $L_{\mathrm{H}\alpha} \approx 10^{37}$ erg s^{-1}. Tracing the HIILF this deep also insures that the total Hα flux from HII regions is recovered. This turn-over corresponds to $F_{\mathrm{H}\alpha} \approx 2 \times 10^{-16}$ erg cm^{-2} s^{-1} at $D = 20$ Mpc. Beyond this distance crowding makes it difficult to probe the peak of the HIILF. For the 1.5m, this flux corresponds to a count rate of $\approx 0.2\, e\, s^{-1}$, compared to the sky count rate of $\approx 1.6\, e\, s^{-1}$ through a 35Å wide filter and a $2''$ aperture at 10 days lunation. This flux can be measured with 20% random errors in 30 minutes of exposure with the 1.5m. As noted earlier, the flux error from continuum subtraction is also $\sim 20\%$ so there is no need to go deeper.

For diffuse emission detection, a limiting surface brightness $\gtrsim 1\%$ of sky is usually set by flatfielding uncertainties. The observations are easily sky limited even in dark time. One percent of sky corresponds to $S_{\mathrm{H}\alpha} \approx 10^{-17}$ erg cm^{-2} s^{-1} arcsec^{-2} for 10 days lunation and a 35Å wide filter. This is about the state of the art in simple narrow-band Hα surface photometry (e.g. Ferguson et al. 1998). Hence 10 days lunation is the most we can tolerate for these observations. The R band continuum image will be obtained in 3×2 minutes, and will easily have high enough S/N that its subtraction will not add significant Poissonian or readnoise to the Hα image.

A complete list of targets is not yet available. However, $\approx$ 3000 HIPASS detections spread over the whole southern sky will be available for selection, so we will have sufficient targets for any time allocations we are assigned. Ideally, each observing run will last 4-5 nights and will occur every three months or so.

Instrument Configuration

Filters: R band and our own Hα filters.	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.2.