

# GALFA Proposal for ALFA Precursor Observations of Atomic Hydrogen and Radio Recombination Lines

The GALFA Consortium

## Abstract

We request **89 hours** of Arecibo observing time for a variety of tests related to the commissioning of ALFA, the GALFA-dedicated spectrometer, data acquisition techniques, and data reduction software. The requested time is allocated as: 53 hours for HI test observations, 10 hours of Radio Recombination Line test observations, and 26 hours of test observations specifically dedicated to evaluating observing techniques and software.

## 1 Introduction

The Galactic ALFA (GALFA) consortium brings together astronomers interested in studying the Milky Way by undertaking observations of HI emission and absorption, radio continuum emission, and radio recombination line emission. The scientific case for GALFA covers a wide and very diverse range of questions. The full scientific case can be found in the White Paper ([http://alfa.naic.edu/galactic/alfa\\_galactic.html](http://alfa.naic.edu/galactic/alfa_galactic.html)). The GALFA consortium plans numerous ambitious surveys for mapping of large areas of the sky.

The purpose of this proposal is to request observing time for a number of tests related to the commissioning of the system. We will undertake these tests by observing several small test regions, representative of GALFA's diverse spectrum of scientific projects. The GALFA subgroup for continuum studies will be proposing a separate request for observing time, hence this proposal includes only atomic hydrogen (HI) and Radio Recombination Line (RRL) projects. Another motivation for observing several test regions is the hope to attract many people with different interests and expertise to participate in the test observations and development of data reduction tools. Having real data in hand is the best motivation for joining the efforts to make the proposed GALFA surveys as successful as possible. In addition, different types of projects have different data reduction needs, and hence these test observations will initiate efforts on a wide data processing front. While providing ideal test data sets for numerous tests listed below, by sampling very different observing 'conditions' (e.g. weak vs strong lines, broad vs narrow lines, day vs night-time observing, being close vs far away from continuum sources, compact vs diffuse), the selected test regions also have scientific importance in their own right, which should further encourage commitment from a wide range of individuals who will contribute to obtaining and exploiting GALFA data.

## 2 Description and Justification for Regions for HI Test Observations

### (1) Quiescent Dark Cloud L1544

As a well studied starless cloud, L1544 is good target for GALFA test observations. The main component of the HI emission is at  $V_{lsr} = 3 \text{ km s}^{-1}$  with FWHM line width of about  $20 \text{ km s}^{-1}$ . There is also a second component at  $-30 \text{ km s}^{-1}$  with FWHM line width of about  $14 \text{ km s}^{-1}$ . These separate components will be used to test the broad baseline stability of the system. Another valuable feature of L1544 is a very narrow absorption feature at  $6 \text{ km s}^{-1}$  with FWHM around  $0.6 \text{ km s}^{-1}$ . This feature, known as HI narrow

self-absorption (HINSA) is produced by cold HI present within the well-shielded interiors of molecular clouds absorbing the background radiation. The existence of such features makes the high resolution mode provided by the GALFA spectrometer essential. HI emission in this direction is, not surprisingly, is very extended. We propose to limit the area mapped to a 1 square degree region, which encloses the molecular cloud as seen in  $^{13}\text{CO}$ . A Nyquist sampled and highly sensitive map of L1544 would be very valuable for understanding the atomic component of star forming clouds in addition to providing important test data. This will require approximately 2 hr of telescope time.

### (2) High Latitude Cloud MBM40

MBM40 is an isolated high-latitude molecular cloud projected near the North Polar Spur. The cloud is a low-extinction translucent cloud of 20-40 solar masses that has not formed stars. It consists of two principal molecular ridges surrounded by a much larger envelope of atomic hydrogen (Shore et al. 2003). A 4 deg x 2 deg region was mapped using the single-pixel HI receiver at Arecibo in 2000. In addition to the Arecibo 21 cm data, 3/4 of the above region was also mapped at the GBT (10' resolution vs. 3'.5 at Arecibo) in order to check the Arecibo data for stray radiation (there was virtually no stray radiation in the Arecibo data). Because both Arecibo and GBT 21 cm data are available for the region around MBM40, it is important to map the identical region with the 7-pixel ALFA feed in order to test the performance of the feed on a well-studied area. A test of this type is critical if we are going to properly understand the response of the feed and devise data reduction strategies for HI mapping (such as how to correct for the sidelobe response of the individual horns). We thus propose to map the region twice. This test observation will require 6 hours of telescope time.

### (3) Compact HVC CHVC218+29+145 (RA(2000)=8h44m20s, Dec(2000)=+8d41)

Compact high-velocity clouds are thought to represent the missing dark matter mini halos predicted by current  $\Lambda$ CDM cosmology (Braun & Burton 1999). CHVC218+29+145 is a compact, elongated cloud (50' in RA, 15' in dec) with a symmetric column density distribution comparable to an edge-on galaxy, having a major axis that is aligned to right ascension. In contrast to a galaxy, this cloud shows almost no velocity gradient ( $\Delta v_{LSR} = 4 \text{ km s}^{-1}$  from east to west). Effelsberg HI observations show that this cloud has cold gas embedded in a warmer medium that is not resolved by the Effelsberg beam. The cold gas shows a regular gradient of the line widths from FWHM = 4  $\text{km s}^{-1}$  to FWHM = 10  $\text{km s}^{-1}$  from east to west. The cloud has relatively high brightness temperatures of about 3 K observed with Effelsberg, making this cloud easy to observe with ALFA. This cloud has the advantage of being isolated on sky (in position and in velocity), minimizing the side lobe effects that are not related to the cloud itself.

We propose to observe CHVC218+29+145 in a 70' by 40' region. A fully sampled map with a single beam takes about 2 hours including overhead for driving. If all 7 beams are connected to a spectrometer, 7 fully sampled maps of this cloud – one for each beam – will be available after 2 hours. These maps allow to derive the quality of each individual beam, especially the influence of the coma lobes.

### (4) Forbidden Velocity Wing Source 40.0+0.5 (RA 19 03 00, Dec+06 35 00)

One of the key science goals of the GALFA survey will be to reveal the nature of wispy, faint high-velocity wings seen in low-resolution large-scale ( $\ell, v$ ) diagrams in the Galactic plane. These “forbidden-velocity (FV)” wings constitute a hitherto unrecognized, potentially important new class of objects. They must be associated with some dynamical processes such as SN explosions, stellar winds, collision of high-velocity clouds, etc. Prior to the ALFA survey, it is important to check technical issues related to observing faint extended wings, and to provide scientific results on a small scale to justify future large requests for GALFA time. We selected one source in our list of FV wings which shows well-defined FV wings in an ( $\ell, v$ )

diagram and is spatially confined to a small region. There is no indication at all in other wavelengths that some dynamical phenomenon occurred in this region. We will map this region repetitively for testing purposes. The total time we request for this subproject is 8 hours.

#### **(5) Tip of the Magellanic Stream & OVI Absorber (RA 23, Dec 8)**

One of the important science drivers for the all-sky HI survey that GALFA is proposing is the study of HI clouds in the Galactic Halo. Recent FUSE observations have revealed many detections of high-velocity OVI gas seen in absorption against background sources, with numerous detections being in the direction of the Magellanic Stream (MS). The important question that still needs to be answered is whether or not the high-velocity OVI absorbers are related to the MS HI clouds. One possible explanation is that the OVI absorption arises at the boundaries between the gaseous clouds and the surrounding hot Galactic corona, or even an extensive hot Local Group medium (Sembach et al. 2003). We will test this with GALFA. We propose to observe a  $2^\circ \times 2^\circ$  region around one of OVI absorbers, NGC7469. We need deep observations of this region, so a minimum of 4 passes are essential. The observing time request of 6 hours will thus provide an important test of ability to do deeper than usual maps with GALFA for special purposes.

#### **(6) Observing the Galactic Anticenter with GALFA in HI**

We propose observing the Galactic anti-center with GALFA in HI. These observations will be used as the first in “next step up” to a modest scale survey (approx. 25 square degrees) to look for any features in maps, etc., and also to determine the suitability of an interferometric search for deuterium with the Allen Telescope Array. A high-resolution HI map will be necessary to calibrate the deuterium to hydrogen ratio. The highest resolution observations currently available are from the Leiden-Dwingeloo Survey with a resolution of 30'. The 32 element ATA will have a resolution approximately 10' at 327 MHz, the frequency of the DI transition. Thus, the GALFA resolution of a 3 arcmin oversamples the ATA beam by a factor of 3. While the ideal area to be surveyed would be the 11 degree 327-MHz primary beam FWHM of the ATA centered at  $l=183.5$ ,  $b=0.5$ , important information can be gained by mapping only the central half of this region. Frequency resolution of 3 km/s and frequency coverage of  $\pm 100$  km/s are required, and can readily be achieved with the WAPP system. Since deuterium is very weak, we will only detect the brightest components of HI. Thus, only modest sensitivity is necessary, especially given that we can smooth the Arecibo data by approximately a factor of 2 (in solid angle). We thus request 10 hours to carry out this pilot moderate-scale mapping project.

#### **(7) An Expanding shell at $(l, b) = (192, 6)$**

The interstellar medium is permeated with large-scale structures including bubbles and shells. One of the goals of large-scale GALFA surveys is elucidating the origin of these regions and their connection with key processes including star birth and star death. To evaluate the system's ability to study regions of this type, we have chosen a shell at  $(l, b) = (192, 6)$ . This shell, which is about  $4^\circ$  in diameter, was first identified by Korpela et al. (2004 in press) in the Arecibo SETHI survey ( $\sim 0.1^\circ$  resolution). The shell is interesting, in part, because it shows an interior X-ray deficit which could indicate that the interior of the shell has cooled to below X-ray emitting temperatures. Low resolution spatial resolution H $\alpha$  observations by WHAM show some evidence that this shell is limb brightened. Evidence of aged shells has been lacking, and confirmation that this region is an old shell could give us insight into the overall state of the ISM and the timescales over which such objects persist. Recent high spatial resolution H $\alpha$  images (Sallmen & Korpela, in prep.) show that the structure of this emission varies greatly on arcminute scales. The low spectral resolution of the H $\alpha$  images, combined with the proximity to the galactic plane indicate that some of the features seen are likely to be foreground features. High spatial and velocity resolution would allow us to identify those H- $\alpha$  features which are correlated with shell structures. These observations should also allow us to measure

the shell expansion velocity and, given the higher sensitivity, potentially map the interior structure of the shell. We request 12 hours of telescope time to make two passes over this interesting region, which will also provide a consistency test for the moderate-size map that should result.

### (8) GALFA Observations of the Galactic Plane

The GALFA consortium proposes to survey the HI distribution and kinematics in the part of the Galactic Plane visible from Arecibo. As described in detail in the GALFA white paper, these first and third quadrant zones contain a myriad of important classes of astrophysical objects. Perhaps the greatest value of this GALFA survey will be its synergy with other Galactic plane surveys, including CGPS, VGPS, and SGPS in HI, GRS in CO, and MSX and GLIMPSE (with Spitzer) in the infrared. The GALFA survey will allow a detailed study of HI self-absorption (HISA) and provide, using HISA, a resolution of the first quadrant kinematic distance ambiguity toward star forming regions and molecular clouds. We therefore propose a pilot program to map HI toward a sample of 7 objects chosen to span this range of observational challenges. The sample has three classes of objects: (1) infrared dark clouds (IRDCs), (2) HII regions, and (3) a massive young stellar cluster recently discovered by Spitzer during on-orbit checkout of the GLIMPSE survey protocols.

The 4 IRDCs in the sample are the darkest objects seen in MSX Band A (8 micron) that are visible from Arecibo. The HII regions, W51 and Sharpless 88, span a large range of source thermal continuum intensity and hence will allow us to probe how well we can hold calibration over a large dynamic range of input power. The final object is a massive star cluster recently discovered by Spitzer during on-orbit check-out of the GLIMPSE data acquisition algorithms. This cluster has a known CO velocity from GRS. Its small ( $\sim 1.5'$ ) angular size will make it challenging to see with ALFA maps.

We will map a 1.5 square degree field about each object. Each field will take  $\sim 30$  minutes, so that making two passes over each field in the sample will require  $\sim 7$  hours of observing. The sources all lie close to the Arecibo “magic” longitude of  $42^\circ$  which transits at zenith. This means that one can observe 2 maps per day. Being able to complete the maps in a single day will enhance our ability to test for repeatability and to compare different observing techniques.

Darkest IRDCs present in the first quadrant visible from Arecibo							
l	b	$V_{lsr}$ <sup>1</sup>	$\Delta V$	$R_{GC}$	$D_{near}$	$D_{far}$	Approx. Size
35.48	-0.29	44.71 km/s	3.56 km/s	6.30 kpc	3.01 kpc	10.83 kpc	3 x 7 arcmin
38.96	-0.47	41.59 km/s	3.09 km/s	6.53 kpc	2.84 kpc	10.36 kpc	2 x 2 arcmin
35.61	-0.25	44.74 km/s	4.30 km/s	6.29 kpc	3.01 kpc	10.80 kpc	2 x 2 arcmin
36.66	-0.11	54.39 km/s	3.56 km/s	6.01 kpc	3.59 kpc	10.03 kpc	6 x 6 arcmin

1 The LSR velocities are  $^{13}\text{CO}$  velocities.

HII Regions		
Name	$\alpha$	$\delta$
W51	19:21:24.4	+14:24:48
S88	19:44:41.0	+25:05:31

Spitzer-discovered massive star cluster

Table 1: Source List

source	$\alpha(1950)$	$\delta(1950)$
W48	18 59 14.0	+01 08 29
W49	19 07 54.0	+08 59 08
S88	19 44 41.0	+25 05 31
K3-50	19 59 50.0	+33 24 33

l	b	$\alpha$	$\delta$	$V_{lsr}$ (km/s)	Approx. Size
41.88	0.495	19:06:5.5	08:11:04.1	22 km/s	2 x 1 arcmin

### 3 Radio Recombination Lines

The observational strategy for the RRL survey proposed for ALFA requires careful design. Because RRLs are weak, significant integration times are required. Pointed observations of 5 minutes per position are needed in a broad spectrum to include several RRL transitions so they can be observed simultaneously and then averaged together. In order to get the highest signal-to-noise and the best quality data, a number of tests are proposed here to verify the data taking process.

We propose to observe with the ALFA receiver 4 Galactic HII regions in RRLs using the 7 beams of ALFA with the WAPPS operating at bandwidths of 50 and 100 MHz. The 50 MHz bandwidth provides a spectral resolution of  $1.3 \text{ km s}^{-1}$  (8k lags) while the 100 MHz bandwidth provides a maximum resolution of  $2.6 \text{ km s}^{-1}$ . In the 50 MHz bandwidth we will be able to observe 2 RRL transitions simultaneously, while in the 100 MHz band 4 transitions can be observed. This will provide enough information as a starting point to check data acquisition, data reduction, and observational strategy for the RRL survey.

In the first phase of test observations, we propose to observe four sources: 1 compact source and 3 extended sources that are well studied in the RRLs. For each source we need 5 minutes of integration time, observed in 5 one minute scans. The compact source is S88 and has a strong continuum. For the extended sources we choose two sources with angular extend smaller than ALFA but larger than a single beam, (K3-50 and W48), and one source with an angular extend larger than the total ALFA footprint (W49). In addition, we wish to observe a relatively *empty* region of the sky where no RRLs have been detected before to test problems with the background.

We require about 10 minutes of observing time for each source, for a total of 40 minutes, and 10 minutes for the *empty* sky observations. The sources do not need to be observed the same day (though that would be preferred). Then, for each correlator setup (50 MHz and 100 MHz bandwidths) we need a total of about 2 hours of observing time. We propose to observe each region twice for a basic consistency (stability) check. Including two hours of overhead time, a total of six hours of observing time will provide valuable information on RRL observing strategies.

The second phase of observations will be to use the GALFA prototype spectrometer to verify proper operation in high resolution observing mode. We propose to do a relatively deep integration on a weak, narrow carbon recombination line to verify that the system performs as expected. This test will require

four hours of telescope time.

The basic data reduction pipeline will be very similar to that for the HI data, (with different lines present rather than different velocity components). We would expect the RRL data to flow through the same pipeline, while the branch point will be at the relatively late stage when we need to combine the data for various lines. Given the long integration times per point and the necessarily (relatively) slow rate of obtaining data, we do not feel it is necessary at this time to have separate test for the RRL data reduction software.

## 4 An Update on recent GALFA activities

Recent activities of the GALFA consortium have been focused on two fronts: development of the GALFA-dedicated spectrometer and an investigation of the best survey strategies.

### (i) GALFA-dedicated spectrometer:

The GALFA-dedicated spectrometer, based on the FPGA technology, is under development by Dan Werthimer and his group at the Space Sciences Laboratory (UC Berkeley). This spectrometer will be able to provide simultaneously both high (10 MHz bandwidth with 8k channels) and low (100 MHz bandwidth with 256 channels) resolution spectra, with a superb RFI rejection. It is expected that a prototype spectrometer, capable of handling one ALFA beam (2 polarizations), will be ready by June 2004. After necessary testing, this system will be replicated to cover all 7 ALFA beams.

### (ii) Survey Strategies that minimize instrumental effects:

The GALFA consortium recognizes that one of the major limitations for HI surveys with ALFA could be baseline ripples resulting from standing waves due to continuum sources. This problem has been known for a very long time at Arecibo. Heiles et al. (2003, Arecibo memo) showed that by using a wide bandwidth, of order of 100 MHz, it is possible to model and subtract the baseline ripple from the data. This motivated the current spectrometer specifications, whereby it will be possible to almost simultaneously take spectra in both high and low-velocity resolution modes: the broadband, low resolution spectra will be used to model and remove the standing waves.

In addition to the standing wave problem we are investigating mapping techniques which will minimize temporary and spatial variation of instrumental effects, such as zero level offsets, gain dependence on azimuth and zenith angle, stray radiation picked up by sidelobes etc. For the October 2003 Arecibo proposal deadline, GALFA's group for testing observing techniques, led by Carl Heiles, proposed test (pilot) observations with the current single-pixel receiver using a so-called "basket-weaving" observing technique. This mode of observing is less affected by day-to-day variability associated with equipment, and also influence of standing waves caused by continuum sources. This project was granted grade "A" and should be scheduled in the near future. However, it is still not known when exactly. For logistical reasons we may choose to defer these observations until June 2004.

## 5 Proposed Observations for Evaluation of Spectrometer Performance and Observing Strategies

We request observing time for the following three categories of tests.

### 1. Testing of the GALFA-dedicated Spectrometer:

We expect that the prototype GALFA spectrometer will be ready during the later part of the proposal period (August to October 2004). The prototype will cover one ALFA beam in both polarizations. *We request 2 hours of day-time observing for 5 (consecutive) days.* This way we will be able to analyze the data and modify things before the next day's run. We will use the requested observing time to conduct several tests of the prototype spectrometer, including:

1. Usefulness of the wide band spectrometer mode? Using it, will we be able to measure and reject standing waves adequately?
2. Bandpass stability tests - can we remove the baseline well?
3. Adequacy of the image rejection.
4. Level setting - what is optimum noise level into the ADC? How critical is it?
5. Tests of dynamic range and interference rejection.
6. Channel-to-channel isolation.
7. Stokes parameter testing (this may not be feasible right away)
8. Adequacy of the control, data-taking, and basic analysis software for our needs.

The prototype GALFA spectrometer will only handle one beam; but one beam should be sufficient for all of the above tests; this will enable us to do complete acceptance testing before the full seven beam spectrometer construction proceeds. If we are very lucky, the seven beam spectrometer will be available for the last of the proposed observing runs, and we will be able to test the entire system.

### 2. Testing of survey strategies and ALFA performance with WAPP units:

2.1. By the time potential observing time is awarded, it will be possible to use the WAPP system, with between 4 and 7 pixels, in high-resolution mode, along with availability of 100 MHz bandwidth. To simulate observing with the GALFA-dedicated spectrometer, we propose to use the "4+4 on 4" configuration for observations of our test regions. This means that we will use 4 ALFA beams only for mapping, and for each beam we will use 2 WAPP units simultaneously, one in high resolution mode, and another one in low resolution mode. The low resolution data will be used to model and remove bandpass ripples from the high resolution data.

For each of three test regions we will obtain approximately a  $2^\circ \times 2^\circ$  map. With 8 secs of integration time per sample, this requires about 2 hr per map. We will investigate both drift scanning and basket-weaving observing techniques. We plan to observe each region 1–3 times to investigate the repeatability of results and sensitivity issues. We request 12 hours of telescope time for this portion of the test program.

2.2. As well as investigating the standing-wave removal and different scanning techniques, our observations will provide important tests of the representative variation in beam shape and gain for ALFA.

2.3. As the third test in this category, we would like to characterize performance of WAPP units in the narrow resolution mode. We are concerned that the WAPP units have not been thoroughly tested in this mode. Therefore, we would like to run the interim correlator with the 4 segments being allocated to 4 pixels. We understand this cannot be done simultaneously with the WAPP observations due to a difference in input center frequencies. Thus, separate telescope time allocation of 4 hours for one of our test regions is needed to double check the WAPP performance.

### 3. Testing of data acquisition and reduction programs:

While doing tests under categories 1. and 2. we will be also testing data acquisition and reduction programs. Hence we request additional factor of two of observing time to allow for proper software testing and fixing all the bugs encountered in this process.

This task will include:

- testing of data taking routines, for different observing schemes, including the basket-weaving technique
- handling ALFA data, reading into IDL, examining data headers
- data monitoring tool
- off-line data reduction

We are initiating development of data reduction programs following the layout of the data pipeline as described in the White Paper.

## Additional Notes

Results of all performed tests will be made publicly available within 6 months and will be documented in the Arecibo Memo Series. We will be in contact with other groups for comparing and sharing results, data, ideas. For the initial period we are spectrometer limited so there is no obvious possibility for commensal observing, however we are happy to accommodate this observing mode in when it becomes feasible.

## References

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