The Inner Galaxy ALFA (I-GALFA) Low-Latitude H I Survey

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1 Survey Overview

The I-GALFA survey is mapping all of the H I in the inner Galactic disk visible to the Arecibo telescope within 10 degrees of the Galactic plane. The AO 305m sensitivity and ALFA’s mapping speed allow a detailed look at this key region of the Galaxy, including cold atomic gas in and outside molecular clouds, faint high-velocity H I emission associated with old, hidden supernovae, shells and chimneys associated with star formation and disk-halo energetics, and stochastic filamentary structure from energy turbulent cascades and magnetic fields. The full I-GALFA science case is given in the original proposal.

Figure 1. I-GALFA fields on low-resolution maps of H I 21cm line peak brightness (Leiden-Dwingeloo 26m survey; Hartmann & Burton 1997). Left: J2000 fields (red) and LST ranges (blue), which are 15" longer for spectral calibration; the ZE/ZW LSTs are 2 versions of the zenith field shifted 51" east or west of the meridian. Black lines mark $\ell = 30^\circ, 60^\circ, 90^\circ$, and $b = \pm 10^\circ, \pm 20^\circ, \pm 30^\circ$ and $-40^\circ$; $b = 0^\circ$ is gray. Right: Galactic coordinate plot showing I-GALFA coverage (red) vs. the Canadian and VLA Galactic plane synthesis surveys (CGPS, VGPS in green; Taylor et al. 2003; Stil et al. 2006).

The 5 survey fields, slightly modified from the proposal, are shown in Figure 1, and their parameters are listed in Table 1. The total field area of 1157 square degrees requires a minimum of 310 hours of observing spread over 130 nights. Dark time is essential for obtaining good spectral baselines. For an angular resolution of 3.35' with 0.184 km s$^{-1}$ raw velocity channels from the GALSPECT backend, we anticipate an I-GALFA empty-field sensitivity of $T_{\text{rms}} \sim 0.25$ K. This is 10 times better than the CGPS or VGPS, which have a 1' beam but 0.824 km s$^{-1}$ channels and less latitude coverage (Fig. 1).

Two projects are commensal with I-GALFA: the Zone of Avoidance (ZOA) H I survey for hidden external galaxies (A2144), and the GALFA Continuum Transit Survey (GALFACTS) to map full-Stokes 1400 MHz continuum emission (A2390). They have shared the WAPP spectrometers in a sub-optimal compromise configuration so far but will switch to the new Mock spectrometers as soon as they are available.
Table 1: I-GALFA Field Properties

<table>
<thead>
<tr>
<th>Field name</th>
<th>min α range$^{a,b}$</th>
<th>full δ range$^{b}$</th>
<th>$\ell_{b=0}$ range</th>
<th>min LST range</th>
<th>min hrs/day$^c$</th>
<th>days$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>18.0628 19.9022</td>
<td>-01.2667 +08.1167</td>
<td>31.51 42.03</td>
<td>17.8128 19.9022</td>
<td>1.8394+0.25</td>
<td>26+3</td>
</tr>
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<td>B</td>
<td>18.3713 20.2741</td>
<td>+07.7833 +17.1667</td>
<td>41.68 52.26</td>
<td>18.1213 20.2741</td>
<td>1.9028+0.25</td>
<td>26+3</td>
</tr>
<tr>
<td>ZW$^e$</td>
<td>18.6707 20.3967</td>
<td>+16.8333 +19.8333</td>
<td>51.92 55.30</td>
<td>19.2707 21.2467</td>
<td>1.7260+0.25</td>
<td>12+2</td>
</tr>
<tr>
<td>C</td>
<td>18.7597 20.8814</td>
<td>+19.5000 +28.8833</td>
<td>54.94 65.75</td>
<td>18.5097 20.8814</td>
<td>2.1217+0.25</td>
<td>26+3</td>
</tr>
<tr>
<td>D</td>
<td>19.0737 21.5435</td>
<td>+28.5500 +37.9333</td>
<td>65.40 76.56</td>
<td>18.8237 21.5435</td>
<td>2.4698+0.25</td>
<td>26+3</td>
</tr>
</tbody>
</table>

$^a$This RA range is the absolute minimum needed to cover $|b| \leq 10^\circ$.
$^b$RA+DEC are in current equinox for LST compatibility; observations use J2000.
$^c$Extra 0.25 hrs is for Least-Squares Frequency Switching calibration (LSFS; Heiles 2007).
$^d$Minimum days required to map field + 10% overhead for telescope problems, etc.
$^e$The version of the zenith field that is being observed; both versions are shown in Fig. 1.

2 Observing Status

I-GALFA observations began this spring. All instrumentation, techniques, and software were in place when the survey was proposed in 2005 (e.g., see the GALF A H I precursor paper by Stanimirović et al. 2006), so this long delay has been discouraging. However, since the start of Galactic plane dark time this year, I-GALFA has hit the ground running. As of this writing, we have completed one major field (A) and the zenith field (ZW), with the goal of finishing one other major field (D) before summer’s end. We are grateful to NAIC for finally scheduling this project and giving it sufficient priority to make significant headway. Table 2 summarizes major events in the I-GALFA timeline, including future expectations for completing the project in a timely fashion. The data release dates presume an 18-month proprietary period from the earliest possible creation of H I data cubes.

Table 2: I-GALFA Timeline

<table>
<thead>
<tr>
<th>Date(s)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 Oct 01</td>
<td>proposal submitted</td>
</tr>
<tr>
<td>2006 Jan 30</td>
<td>given “A” rating, with a mean referee score of 8/9</td>
</tr>
<tr>
<td>2006 Jul 14</td>
<td>skeptical review panel meets</td>
</tr>
<tr>
<td>2006 Sep 14</td>
<td>notified of skeptical approval, too late for 2006 observing</td>
</tr>
<tr>
<td>2007 Apr 17 - Dec 10</td>
<td>ALFA off telescope for painting; no 2007 Galactic dark time</td>
</tr>
<tr>
<td>2008 Apr 13 - May 02</td>
<td>11 pre-survey observing tests on new CIMA with M. Lerner</td>
</tr>
<tr>
<td>2008 May 03 - Jun 15</td>
<td>survey field A observed</td>
</tr>
<tr>
<td>2008 Jun 16 - Jul 29</td>
<td>survey field ZW observed</td>
</tr>
<tr>
<td>2008 Aug - Oct</td>
<td>anticipate field D observed</td>
</tr>
<tr>
<td>2009 Summer</td>
<td>anticipate survey completion (fields B and C observed)</td>
</tr>
<tr>
<td>2010 Winter</td>
<td>first public release of survey data (after 18 month period)</td>
</tr>
<tr>
<td>2011 Spring</td>
<td>full public release of survey data products through the NVO</td>
</tr>
</tbody>
</table>

Prior to the start of I-GALFA, extensive tests were carried out with Mikael Lerner to accommodate improvements to the CIMA control software and the complex needs of the dual-commensal program. Once the survey began, we also streamlined the generation of observing scripts and the daily data processing. Successful observations have been made at the console, remotely via VNC from Seoul and Arecibo, and in absentee mode with the telescope operator following prepared instructions. We wish to express our sincere gratitude to the operations staff for supporting our observations in this way.
3 Survey Method and Logistics

3.1 Scan Method

The major I-GALFA fields (A-D) are observed by “nodding” the telescope north and south, slewing 0.84′/sec along the meridian to trace out a zig-zag pattern on the sky as the Earth rotates, while the zenith field (ZW) is observed by “wagging” 0.59′/sec in azimuth 51′ (12.75° cos δ) west of the meridian. A map is made by “basket-weaving” many such tracks starting at different positions on different days, as Figure 2 illustrates.

Figure 2. Daily positional data plots for 2008 May 27 (day 18 of 26) observations of Field A to illustrate the survey mapping method. ALFA is rotated so that its 7 beam tracks are equally spaced on the sky. Only the central beam is shown here. Left: One day’s meridian nodding scan positions vs. local time. To get the most science out of the telescope, these observations deliberately come as close as possible to the Zenith Angle limit of 19.69° without overshooting it. Right: Scans on the sky for this date (red) and previous dates (blue), showing a map that is about 2/3 sampled. The prime target area is marked in green.

The standard CIMA procedure for these observations always starts at the minimum DEC of a particular scan cycle, or “lambda” (Λ). This leads to inefficiencies, since a good map requires scan intersections at all points; to ensure this, the scan pattern must begin at least 1 whole lambda before the field’s west edge. Scans in Fig. 2 generally start 1-2 lambdas early for this reason. The I-GALFA and GALFACTS teams have devised an improved “partial lambda” method that would allow starting scans at an arbitrary part of the cycle. This is now under development for CIMA by M. Lerner.

3.2 Data Taking and Pipeline

The current observations are taken in a dual GALSPECT + WAPPs mode, using a procedure adapted from the Perseus Molecular Cloud H I + continuum commensal mapping project (A2174 + A2293). A 3-sec hi-cal (10 K) is fired at the scan endpoints for H I gain calibration, and a 25 Hz lo-cal (1 K) is fired during the scans for continuum zero-point calibration. The WAPPs dump 1024 channels over 100 MHz every 4 ms to sample the cal signal adequately (the GALFACTS pipeline bins the 4 ms data to 1 s for ZOA). No doppler corrections are made, as these are handled in post-processing. The 1440 ± 60 MHz pulsar filter is
Figure 3. IRAS 100 µm dust thermal emission in the survey region (Miville-Deschênes & Lagache 2005), on a log-intensity scale from 1 to 10⁵ MJy sr⁻¹. The blank area was not observed by IRAS. Galactic coordinate grid lines and fields are marked as in Fig. 1. I-GALFA will see a similar amount of angular detail as IRAS but with an added velocity dimension; I-GALFA is sensitive enough to velocity-map every IRAS dust feature. The nodding scan track from one night’s observing in Field A (20080527, as in Fig. 2) illustrates how scan data taken outside the core science area probe higher latitude gas in the vicinity — in this case, including the H I edge of Loop I near 18h.

used to block airport radar RFI, which is sometimes strong enough to severely bias the continuum levels for several seconds while the system recovers. This problem is under investigation by Electronics and with luck will soon be eliminated, since it compromises ZOA’s redshift coverage for z ~ 0.035 and GALFACTS’ broadband Faraday rotation measuring ability. That improvement and the new Mock spectrometers are both eagerly awaited.

The GALSPECT backend records 8192 channels each second for I-GALFA along with detailed positional data like those shown in Fig. 2. Daily plots of this sort are put on the I-GALFA website¹, as are quick-look raw-spectrum plots generated by Peek’s IDL software. The GALFA H I data IDL pipeline developed by Heiles, Peek, Douglas, Krčo, and others is being used for the entire I-GALFA data stream from raw FITS files to final cubes. Our basic FITS image cubes will have 512 × 512 × 8192 pixels covering 8.53° × 8.53° × 1413 km s⁻¹, which can be subsetted or resampled as needed on the fly. An RA+DEC grid of such tiles covering the Arecibo sky has already been developed by Gibson for the TOGS (Turn On GALSPECT Survey; A2059 + A2124) project.

All raw I-GALFA data are archived at Arecibo, and data processing is currently done on-site as well. When production cubes are ready for public release (see Table 2), these will be distributed through one or more Virtual Observatory portals, including the Cornell Theory Center; Adam Brazier at NAIC in Cornell is our CTC VO contact. Peek has developed IDL code to assemble user-requested cubes on an arbitrary grid. Gibson attended the 2006 NVO Summer School to learn the basics of VO image serving and has also advised NVO architects on 3-D radio astronomy image serving needs.

¹http://www.naic.edu/~igalfa/
Figure 4. Quick-look preliminary map of I-GALFA H I emission in Field A in a single velocity channel near $v_{LSR} = 0$ km s$^{-1}$. Scan stripes will be excised in a more careful reduction. Despite these artifacts, diffuse H I clouds in the Solar neighborhood (within a few hundred pc) are clearly visible across most of the field. Many of these clouds may be associated with neutral atomic filaments on the edge of Radio Loop I, a nearby supernova shell of great interest to Galactic astronomers. The combined I-GALFA and GALFACTS data sets will provide an unprecedentedly rich view of this structure. Also visible are H I clouds concentrated near the Galactic plane (red line). These lie on the far side of the Galaxy, at which distance (13 kpc) their $\pm 1^\circ$ scatter corresponds to heights above the plane of $z \sim \pm 200$ pc.

4 Science and Publications

With data in hand, the I-GALFA team plans to move aggressively on all science fronts outlined in the 2005 proposal, plus any surprise discoveries that arise in the course of the survey. Figure 3 illustrates the dust and neutral gas structure that I-GALFA will map in H I at high velocity resolution, as has been demonstrated with other GALFA H I data (Gibson et al. 2008).

A very preliminary map of I-GALFA H I emission in Field A is shown in Figure 4. These data are only partially reduced as yet, and the effects of some bad ALFA Beam 0b data from early survey observations in May are clearly visible. Proper flagging of the bad scans should remove these artifacts. However, a variety of H I emission features are already visible from both the near and far sides of the Galaxy.

We plan to write an overview paper on the I-GALFA survey in the next year, accompanied by short science papers on early results that can be extracted from the first field(s). Systematic science papers on the whole survey will follow the completion of observations in 2009. A general technical paper on the GALFA H I data pipeline is in preparation by Peek et al.

5 Personnel

- Koo graduated 3 PhD students (including Kang) in June, but has more coming along that can participate in I-GALFA and maintains a keen interest in the survey science.
- Gibson is departing from NAIC this summer to a tenure-track position at the University of Western Kentucky, where he plans to involve undergraduates in all aspects of the survey.
- Kang successfully defended her PhD thesis in June. She will be moving to NAIC to begin a postdoc at Arecibo Observatory, where she will be closely involved in I-GALFA.
• Peek also defended his dissertation in June. He is moving to a postdoc in the Berkeley Space Sciences Lab, where he will continue his deep involvement in I-GALFA and related projects.

• Douglas moved this summer from a teaching position at the UBC - Okanagan to a Marie Curie fellowship at the University of Exeter, where he will resume his contributions to the project.

• Heiles, who has been instrumental in the entire GALFA H I enterprise, continues his own advisory role for I-GALFA at Berkeley.

• Korpela continues his I-GALFA participation at Berkeley - SSL, including GALFA H I infrastructure support at the San Diego Supercomputing Center.

• Bania, a pioneer of H I surveys with Arecibo, has an active interest in I-GALFA, having first discussed the idea with Gibson at the 2004 NAIC GALFA meeting.

References


