Large-Scale Surveys with the ARECIBO L-BAND FEED ARRAY (ALFA):
Scientific Potential and Link to the Next Generation of Radio Telescopes

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Gregorian Upgrade

Transforms the Arecibo line-focus to a point-focus

Allows use of focal plane receivers, including a focal plane array receiver

Radio Camera
ALFA is a 7 pixel spectroscopic radio camera

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Horns</td>
<td>7</td>
</tr>
<tr>
<td>Polarization</td>
<td>Dual linear</td>
</tr>
<tr>
<td>Polarization Isolation</td>
<td>&gt; 20dB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>~300MHz</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1225 - 1525MHz</td>
</tr>
<tr>
<td>Gain variation over band</td>
<td>+1/-2 dB</td>
</tr>
<tr>
<td>Dewar flange input noise temp</td>
<td>6 – 8 K average</td>
</tr>
<tr>
<td>Calibration noise source</td>
<td>Correlated between polarizations</td>
</tr>
<tr>
<td>Dewar rotation</td>
<td>+/- 110 °</td>
</tr>
<tr>
<td>weight</td>
<td>~900kg (2000 lbs)</td>
</tr>
<tr>
<td>horns</td>
<td>Stepped TE_{11} horns, ( \varnothing 25\text{cm} )</td>
</tr>
<tr>
<td>Backend processors</td>
<td>Direct FFT, and correlators</td>
</tr>
</tbody>
</table>

7 times faster mapping!
Total Incoherent Multi Beam Pattern

$\text{TE}_{11}$ Mode Horn $25.0 \text{ cm} \times 26.0 \text{ cm}$

Sky Area $25' \times 25'$ at 1.375 GHz
SCIENTIFIC FOCUS OF ALFA

• Galactic Astronomy
  21cm Line of Atomic Hydrogen
  Radio Recombination Lines
  Continuum
• Pulsar Astronomy
• Extragalactic Astronomy
  HI
  OH Megamasers
## Multiple Backends for Different Scientific Tasks

<table>
<thead>
<tr>
<th></th>
<th>Bandwidth</th>
<th>Channels per polarization</th>
<th>Input Levels</th>
<th>Output Levels</th>
<th>Dump Time</th>
<th>Misc.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P-ALFA</strong></td>
<td>300 MHz</td>
<td>1000 (res. 300 kHz)</td>
<td>8 bits min</td>
<td>4 bits max (flexible)</td>
<td>64 usec</td>
<td>output after long-term mean removed in SW</td>
</tr>
<tr>
<td><strong>E-ALFA</strong></td>
<td>200 MHz</td>
<td>8192 (res. 25 kHz)</td>
<td>8 bits min (12 desired)</td>
<td>16 bits max at 1 sec dumps</td>
<td>1 sec</td>
<td>flexible blanking in hardware</td>
</tr>
<tr>
<td><strong>G-ALFA HI</strong></td>
<td>1415-1425 MHz</td>
<td>10k, 20k desired (res. 1 kHz min)</td>
<td>10 desired (few ok if little rfi)</td>
<td>10 bits</td>
<td>1 sec</td>
<td>blanking not needed*</td>
</tr>
<tr>
<td><strong>G-ALFA recombination lines</strong></td>
<td>One 6 MHz band + eleven 3 MHz bands (all fixed)</td>
<td>~40k channels (res. 0.5 kHz, 1kHz min)</td>
<td>8 bits min</td>
<td>10 bits</td>
<td>&lt;1 sec</td>
<td>blanking not needed*</td>
</tr>
<tr>
<td><strong>G-ALFA continuum</strong></td>
<td>300 MHz</td>
<td>1000 (res. 300 kHz)</td>
<td>8 bits min</td>
<td>16 bits</td>
<td>0.1 sec</td>
<td>blanking not needed* full Stokes required</td>
</tr>
</tbody>
</table>

*rfi excised in software
CURRENT STATUS OF ALFA

- Front end installed on telescope April 2004
- 7 x 100 MHz bandwidth WAPP systems available for spectroscopy & pulsar search
- Downconverter & fiber optics IF system installed and tested
- Test observations underway May 2004
- 2 additional processors (300 MHz BW & High Resolution) under construction – 2004/5
- Software under development by NAIC & scientific consortia
GALFA-HI

Galactic Astronomy Using the 21cm Line of Atomic Hydrogen
GALFA HI SUB-CONSORTIUM

THE MAJOR THEMES

• What are the critical physical processes that determine the structure and evolution of the interstellar medium?
• What are the CONNECTIONS -- between atomic and molecular ISM, between the “cold” and “normal” neutral medium, and between the Disk and the Halo?
• What are high latitude clouds and clouds in the Galactic Halo?
Galactic HI

• Neutral Hydrogen as Probe of the Origin & Evolution of Molecular Clouds
• Interstellar Turbulence (low & high – b)
• Cold Neutral Medium
• The Disk-Halo Connection
• HI Clouds in the Galactic Halo
• High-Latitude Line Wings & Turbulence
• High-Latitude Clouds
• HI Self-Absorption & Kinematics
• Line Wings at Forbidden Velocities
GALFA HI – High Latitude Surveys: Interstellar Turbulence

Critical mechanism for determining structure of ISM

- Intermittency
- Energy Injection
- Relationship with Theory

Require l-b-v cubes for which you can calculate velocity-density correlations
The Disk-Halo Connection

“Spurs” & “Chimneys” imply energy input from Plane
GALFA HI – High Latitude Surveys: HI Clouds in the Galactic Halo

Gas at high latitudes not consistent with Galactic rotation models – clouds are clearly outside the Galactic disk

– Intermediate Velocity Clouds (IVCs): distances few hundred pc - 2 kpc; solar metallicities; final stage of a Galactic fountain (?)

– High Velocity Clouds (HVCs): deviate by > 50 km from Galactic rotation; metallicity = 0.1 solar; two-phase structure with cold cores embedded in warm envelope; DISTANCE UNCERTAIN

– Magellanic Stream: only HVC complex with known origin, namely that they are tidal debris of Magellanic Clouds; HI mass almost 5x10^8 solar masses;

– Compact High Velocity Clouds (CHVCs): separate class spatially and kinematically; visible counterparts of Dark Matter Halos (?)
HI Clouds in the Galactic Halo (cont’d.)
GALFA HI – Low Latitude Surveys: Survey of the Galactic Plane at |b| < 5 deg

SCIENTIFIC OBJECTIVES:

(2) Use HI self-absorption to map spiral arms in first quadrant (resolve distance ambiguities)

(3) Study atomic and molecular gas in Giant Molecular Clouds (sites of formation of massive stars)

(4) Infrared Luminosity Function of the Inner Galaxy – correlations with MSX and other surveys

Area to be mapped is approximately 800 deg²
GALFA HI – Low Latitude Surveys:
FV Line Wings – undiscovered supernovae?
ALFA PULSAR SURVEYS -
Pulsar Science Highlights

– Neutron star physics
– Magnetospheric physics (emission mechanisms)
– Probing the interstellar medium
– Orbital elements of binary pulsars and tests of gravitation theories
– Pulsars as gravitational wave detectors
Why more pulsars?

Extreme Pulsars:
- \( P < 1 \text{ ms} \)  \( P > 5 \text{ sec} \)
- \( P_{\text{orb}} < \text{hours} \)  \( B > 10^{13} \text{ G} \) (link to magnetars?)
- \( V > 1000 \text{ km s}^{-1} \)
- Population & Stellar Evolution Issues
- NS-NS & NS-BH binaries
- The high-energy connection (e.g. GLAST)
- Physics payoff (GR, LIGO, GRBs…)
- Serendipity (strange stars, transient sources)
- Mapping the Galactic magnetoionic medium

New instruments (AO-ALFA, GBT, SKA) can dramatically increase the volume searched (galactic & extragalactic).
Pulsars are Extreme -

- 10x nuclear density
- High-temperature superfluid & superconductor
- \( B \sim B_q = 4.4 \times 10^{13} \) Gauss
- Voltage drops \( \sim 10^{12} \) volts
- \( F_{EM} = 10^9 F_g = 10^9 \times 10^{11} F_{gEarth} \)
Pulsar Populations

**Canonical (1700+):**
- $P \sim 0.01 - 1.5 \text{s}$
- $\frac{dP}{dt} \sim 10^{-14} \text{s/s}$
- $B \sim 10^{12} - 10^{13} \text{ G}$
- 1% of known have companions
- Age $\sim 10^5 - 10^8 \text{ yr}$

**Millisecond (~80):**
- $P \sim 1.5 - 30 \text{ ms}$
- $\frac{dP}{dt} \sim 10^{-20} \text{ s/s}$
- 80% of known have companions
- $B \sim 10^8 - 10^9 \text{ G}$
- Age $\sim 10^9 - 10^{10} \text{ yr}$
Fast and Faster Pulsars

- Recently recycled: PSR J1740-5340, with $P = 3.6$ ms
- "Black Widow" PSR 1957+20, with $P = 1.6$ ms — companion will evaporate in about $10^9$ yr
- Fastest known rotator: PSR 1937+21, with $P = 1.5578$ ms
- Sub-millisecond pulsars — ?
Motivation for Sub-MSP Searches

• Limits on pulsar periods and masses
• Equation of state of exotic matter
• Phase transitions in neutron stars
• Ground state of matter in the Universe
  – Hadronic (no strangeness)?
  – Hyperonic (strangeness)?
  – Quark deconfined?
  – Strange deconfined?
Pulsars as Probes of the Galaxy

Electron density projected onto the Galactic plane:

Two disk components, spiral arms, Galactic center, clumps and voids

Paper I = the model (astro-ph/0207156)

Paper II = methodology &
particular lines of sight
(astro-ph/0301598)

Code + driver files + papers:
www.astro.cornell.edu/~cordes/NE2001
Cosmological Gravitational Wave Background

Millisecond pulsars act as arms of huge detector:

Pulsar Timing Array: Look for global spatial pattern in timing residuals
P-ALFA Science Goals Require Massive Surveys

– Drift scan surveys
  (14 sec across 3.5 arcmin)

– Deep Galactic plane survey (GPS)
  (5-10min, |b| < 5 deg, 30 < l < 80 + anticenter)

– Medium latitude surveys
  (5 < |b| < 25 deg)

– Targeted searches: globular clusters, high EM/DM HII regions, SNRs, Galactic chimneys, M33, X/γ -ray selected objects
  (long dwell times, up to 2.5 hr)

1 PETABYTE TOTAL DATA VOLUME
ALFA Galactic Plane Survey

- $|b| < 5$ deg, $32$ deg $< l < 80$ deg + anticenter?
- 1.225-1.525 GHz bandwidth = 300 MHz
- digital backends (<0.3 MHz channels)
  - FPGA-FFT or Polyphase filter approach (300 MHz)
- $\sim300$ s integrations, **2000-3000 hours total**
- Can see 2.5 to 5 times further than Parkes MB
  - period dependent
  - from AO sensitivity + narrower channels (larger DM)
- Expect $\sim1000$ new pulsars (modulo pulsar scale height $\Leftrightarrow$ velocity distribution, birth sites, etc.)
Surveys with Parkes, Arecibo & GBT

Simulated & actual

Yield ~ 1000 pulsars

ONLY A HINT OF PROBABLE RESULTS FROM SKA
E-ALFA: Extragalactic HI Surveys using ALFA at Arecibo
Scientific Goals of E-ALFA Surveys:

- Determine the local density dependence of the HIMF
- Map the distribution of luminous and dark matter
- Investigate the faint end of the HI mass function (HIMF) in the local ($z < 0.1$) Universe
- Determine the gas-rich membership of nearby groups of galaxies
- Determine the population of gas-rich systems in the Local Group and the periphery of the MW (HVCs)
- Investigate connection with Ly α absorbers via 21cm absorption
- Find (rare) OH Megamasers near $z=0.25$
- Be surprised !!

A STEP TOWARDS SURVEYS POSSIBLE WITH SKA
Planned Major E-ALFA Surveys

All-Arecibo sky Fast ALFA Survey (ALFALFA)
~ 2000 hours, 12,000 square degrees, one-pass (?)
in drift mode, 50-100 MHz coverage

Very Deep Survey
~ 1100 hours, 0.4 square degrees, 200 MHz coverage,
50-100 hours integration per beam

Medium-Deep (Virgo and other groups) Survey
Virgo-anti Virgo (VAVA) will require ~900 hours,
drift mode, 5 passes (60 sec per beam)

ZOA survey – probably piggyback on Pulsar galactic
plane survey: ~300 sec per beam, stare mode,
+/- 5 deg gal latitude of plane visible from AO
<table>
<thead>
<tr>
<th>Survey</th>
<th>Beam</th>
<th>Area</th>
<th>rms (mJy)</th>
<th>min $M_{HI}$</th>
<th>$N_{det}$</th>
<th>$t_s$</th>
<th>$N_{los}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALFALFA</td>
<td>3.5</td>
<td>12,000</td>
<td>3.0</td>
<td>$4.0 \times 10^5$</td>
<td>12,000?</td>
<td>12</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>VAVA</td>
<td>3.5</td>
<td>900</td>
<td>1.0</td>
<td>$1.3 \times 10^5$</td>
<td>3,000?</td>
<td>60</td>
<td>$300,000$</td>
</tr>
<tr>
<td>ZOA</td>
<td>3.5</td>
<td>1000</td>
<td>0.5</td>
<td>$0.7 \times 10^5$</td>
<td>8,000?</td>
<td>300</td>
<td>$330,000$</td>
</tr>
<tr>
<td>AO-DEEP</td>
<td>3.5</td>
<td>0.4</td>
<td>0.05</td>
<td>$0.7 \times 10^4$</td>
<td>40?</td>
<td>252,000</td>
<td>105</td>
</tr>
</tbody>
</table>

ALFALFA and VAVA’ will be run in drift mode
ALFALFA in one or perhaps two passes,
VAVA’ probably in 5 passes
ZOA will dwell 3-5 minutes per beam
DEEP will dwell ~70 hrs per beam