ALFALFA and the Hunt for Dark Galaxies

Kristine Spekkens

ALFALFA Undergrad Workshop – July 13th, 2006

$V < 500 \text{ km/s}$

$600 < V < 1300$

$1400 < V < 2000$

$V > 2000$

Chung et al 2005,
Bohringer et al. 1994
ALFALFA and the Hunt for Dark Galaxies

Outline:

- Why we expect them, how we detect them
- Hunting for HI-rich, low-mass galaxies with ALFALFA
- Case studies: VirgoHI21 and a new HI cloud complex in the Virgo Cluster

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“Dim” and “Dark” Galaxies

• Most of our galaxy catalogs stem from optical surveys…

• Is there a significant population of “dim” or “dark” galaxies that have been missed?
Do We Expect Dark Galaxies?

What’s in the Universe (today):

- 74% Dark Energy
- 22% Dark Matter
- 4% Atoms

Galaxy and cluster growth:

“cold dark matter” drives galaxy formation and evolution
The Cold Dark Matter Paradigm

Galaxy evolution is driven by “Cold Dark Matter”
Do We Expect Dark Galaxies?

cold dark matter predicts large numbers of low-mass dark galaxies

Number density of “cold dark matter” halos

Low mass

High mass

Marinoni & Hudson 2002
Detecting Dark Galaxies

Gravitational lensing

RESULT:
- Strong and weak lensing models constrain satellite distribution in clusters (Natarajan & Springel 2004)
- Good agreement with theory at higher masses

Natarajan & Springel 2004
Detecting Dark Galaxies

Gravitational lensing
Isolated interacting galaxies

RESULT:
- Very few (0.5%) optically isolated galaxies are disturbed (Karachentsev et al. 2005)
- BUT: can’t always see small companions…
Detecting Dark Galaxies

Gravitational lensing
Isolated interacting galaxies
Brown dwarfs/white dwarfs

- Isn’t feasible yet (need ~2 days on-source!)
Detecting Dark Galaxies

Gravitational lensing
Isolated interacting galaxies
Brown dwarfs/white dwarfs
Neutral hydrogen
Hunting for Dark Galaxies in HI

WHY?
1. Low surface brightness galaxies are gas-rich
2. Feasible to go to low halo masses

Zwaan et al. 2003
## Comparison of Blind HI Surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Beam</th>
<th>Area</th>
<th>rms</th>
<th>min $M_{\text{HI}}$ @ 10 Mpc</th>
<th>$N_{\text{det}}$</th>
<th>$t_s$</th>
<th>$N_{\text{los}}$</th>
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</thead>
<tbody>
<tr>
<td>AHISS</td>
<td>3.3</td>
<td>13</td>
<td>0.7</td>
<td>$2.0 \times 10^6$</td>
<td>65</td>
<td>var</td>
<td>17,000</td>
</tr>
<tr>
<td>ADRS</td>
<td>3.3</td>
<td>430</td>
<td>3.3</td>
<td>$9.6 \times 10^6$</td>
<td>265</td>
<td>12</td>
<td>500,000</td>
</tr>
<tr>
<td>HIPASS</td>
<td>15</td>
<td>30,000</td>
<td>13</td>
<td>$3.6 \times 10^7$</td>
<td>4315</td>
<td>460</td>
<td>1.9$ \times 10^6$</td>
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<tr>
<td>HIJASS</td>
<td>12</td>
<td>(TBD)</td>
<td>13</td>
<td>(?)</td>
<td>3500</td>
<td>(TBD)</td>
<td></td>
</tr>
<tr>
<td>J-Virgo</td>
<td>12</td>
<td>32</td>
<td>4</td>
<td>$1.1 \times 10^7$</td>
<td>31</td>
<td>3500</td>
<td>3200</td>
</tr>
<tr>
<td>HIDEEP</td>
<td>15</td>
<td>32</td>
<td>3.2</td>
<td>$8.8 \times 10^6$</td>
<td>129</td>
<td>9000</td>
<td>2000</td>
</tr>
<tr>
<td>ALFALFA</td>
<td>3.5</td>
<td>7,000</td>
<td>1.7</td>
<td>$4.4 \times 10^6$</td>
<td>20,000?</td>
<td>40</td>
<td>7$ \times 10^6$</td>
</tr>
</tbody>
</table>

**ALFALFA** is ~ 1 order of magnitude better than HIPASS in both sensitivity and areal resolution.

slide from R. Giovanelli
Searching for HI clouds in Virgo

High concentration of galaxies $\rightarrow$ better chance of finding a dark one

BUT: Virgo is a rough place for HI clouds!

Worry about:
- Tidal interactions
- Mergers
- Ram pressure stripping
- "Harassment" (lots of little, fast interactions)
Hunting for dark galaxies: VirgoHI21
Hunting for dark galaxies: VirgoHI21

VIRGO HI 21

NGC 4254

Slide from B. Kent
Hunting for dark galaxies: VirgoHI21

Combined ALFALFA data around NGC 4254
cz = 2243 to 2557 km/s

Single dish detection VIRGOHI21: dark galaxy?

Minchin et al. 2005

Slide from B. Kent
Hunting for dark galaxies: VirgoHI21

Image at higher resolution... part dark galaxy, part tidal feature?

Minchin et al. 2005 (preprint)

Slide from B. Kent
ALFALFA detects VIRGOHI21

Overlayed datasets

Slide from B. Kent
ALFALFA detects a huge stream connecting VIRGOHI21 and NGC 4254
A New HI Complex in Virgo

You are here
A New HI Complex in Virgo

ALFALFA Spring 2005 run:

Giovanelli et al 2006

150 kpc

30’
A New HI Complex in Virgo

ALFALFA Spring 2005 run:

OPTICAL

Uncatalogued

Giovanelli et al 2006
A New HI Complex in Virgo

ALFALFA Spring 2005 run:

VCC 1357
Faint!
A New HI Complex in Virgo

ALFALFA Spring 2005 run:

A6 = NGC 4424

- Disturbed stellar and gaseous morphologies
- Need both a merger and a cluster “wind” to explain this

HI

optical

Chung 2005

Cortes et al. 2006

Giovanelli et al. 2006

Cortese et al. 2006
A New HI Complex in Virgo

Follow up with higher resolution observations...

Two detections: A1 and A2
Disordered morphology, kinematics
HI Morphology – A1
HI Morphology – A2

Coherent motion across A2?
HI Morphology – A2

7 kpc
What could it be?
A New HI Complex in Virgo

Gas stripped from NGC 4424?
Group of dwarf galaxies?
Dark galaxies?

Giovanelli et al 2006

A4
A3
A2
A5
A1
A6

150 kpc
30’
Conclusions

• The “cold dark matter paradigm” predicts many dark, low mass galaxies
• They might be detectable in HI with ALFALFA
• ALFALFA is finding many interesting low-mass clouds…

The hunt for dark galaxies is underway!
What is it?

- Clumpy emission on scales >2 kpc (> resolution limit)
- HI, CO in N4424 → ram pressure stripping at work (Cortes et al. 2006)
- 2 potential optical counterparts to VLA detections. In one, HI + optical separated by ~7 kpc: ram pressure?
- BUT: hard to explain morphologies with ram pressure alone
- Galaxy harassment scenario preferred
Ram Pressure Stripping Geometry

Chung 2005
What is it?

- Complex HI mass exceeds that of any galaxy within few 100 kpc
- Clumpy emission, (mostly) disordered velocities on scales >2 kpc (> resolution limit)
- No clear connection with N4424 + disordered velocity structure = tidal int. unlikely
- HI, Hα, CO in N4424 → int. mass merger + ram pressure stripping (Cortes et al. 2006)
- 2 potential optical counterparts to VLA detections. In one, HI + optical separated by ~7 kpc
- Hard to consistently explain properties of all clumps via ram pressure
- Galaxy harassment scenario preferred
HI Follow-up: Lessons Learned

1. Arecibo is sensitive
   - Huge collecting area
   - Scales > few arcmin resolved out by VLA

2. Virgo is big
   - Multiple pointings + configurations necessary

Coherent, large follow-up VLA proposal might maximize telescope time/science returns
Uncertainty at lower HI masses...

Zwaan et al. 2003 (HIPASS)
Detections

Contours at (-3, -2, 2, 3, 4, 5, 6) σ
Global Properties

- Non-detections of A4, A5 expected if AO flux distributed over ~1.5 arcmin

### Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>cz, km/s</td>
<td>494 (AO)</td>
<td>602 (AO)</td>
</tr>
<tr>
<td></td>
<td>496 (VLA)</td>
<td>597 (VLA)</td>
</tr>
<tr>
<td>$W_{50}$, km/s</td>
<td>66 ± 2 (AO)</td>
<td>45 ± 9 (AO)</td>
</tr>
<tr>
<td></td>
<td>72 ± 13 (VLA)</td>
<td>33 ± 7 (VLA)</td>
</tr>
<tr>
<td>SdV, Jy km/s</td>
<td>3.9 ± 0.4 (AO)</td>
<td>0.7 ± 0.1 (AO)</td>
</tr>
<tr>
<td></td>
<td>2.8 ± 0.2 (VLA)</td>
<td>0.6 ± 0.1 (VLA)</td>
</tr>
</tbody>
</table>