SOAR 2018: Galaxies

Aileen A. O’Donoghue
Priest Associate Professor of Physics
Galaxies

★ 9/4/18

Milky Way Galaxy Contents & Motions

★ 9/11/18

Milky Way Environment & the Local Group

★ 9/18/18

Other Galaxies & Clusters of Galaxies

★ 9/30/18

Expansion, History & Evolution of the Universe
SOAR: Galaxies
The Milky Way Environment & the Local Group

Aileen A. O’Donoghue
Priest Associate Professor of Physics
The Local Group

☆ The Milky Way's Galaxy Cluster

> 54 galaxies within 5 million light years

An Atlas of

The Universe

Andromeda (M31) & Satellites M32 & M33

Triangulum (M110)

Sextans A, Sextans B

Antlia Dwarf

NGC 3109

Leo A

Leo I, Leo II

NGC 6822

Phoenix Dwarf

Tucana Dwarf

Cetus Dwarf

WLM

IC 1613

Triangulum Dwarf

Sagittarius Dwarf Irregular

Andromeda I, II, III and LGS 3

Aquarius Dwarf

Pegasus Dwarf
OUR GALAXY AND ITS NEIGHBORHOOD

The 'Hood

GALACTIC CORONA
Hot gas surrounding the Milky Way

HIGH-VELOCITY CLOUD (HVC)
Infalling clump of relatively fresh hydrogen gas

GALACTIC DISK
Flattened system of stars, gas and dust

SUPERBUBBLE
Gas pushed out by supernovae, outward leg of "Fountain"

INTERMEDIATE-VELOCITY CLOUD (IVC)
Clump of recondensed gas, return leg of "Fountain"

LARGE MAGELLANIC CLOUD
Satellite galaxy of the Milky Way

SMALL MAGELLANIC CLOUD
Satellite galaxy of the Milky Way

SAGITTARIUS STREAM
Trail of stars torn off Sagittarius dwarf galaxy

SAGITTARIUS DWARF SPHEROIDAL GALAXY
Satellite galaxy of the Milky Way

ANDROMEDA GALAXY
Nearest major spiral galaxy

TRIANGULUM GALAXY
Nearby midsized spiral galaxy

MAGELLANIC STREAM
Gaseous filament torn off Magellanic Clouds
Milky Way's Environment

IntraCluster Medium (ICM)

Did galaxies form from this gas?
Galaxies emit and absorb gas

**Galactic Fountain**: Intermediate-velocity clouds are probably the return leg of a vast cycle of gas. Clusters of supernova explosions generate bubbles of hot gas (blue) that break through the surrounding cold gas (yellow) and feed a hot corona. Chunks of the gas cool and fall back to the disk.

**Gas Infall**: Many of the high-velocity clouds (yellow) are gas raining onto the Milky Way, continuing its formation nearly 12 billion years after it started. Such gas could provide fresh fuel for star formation. Observationally, they are easily confused with the intermediate-velocity clouds (orange).
Milky Way’s Environment

Milky Way’s Lumpy Halo

Stars, Globular Clusters, Gas, Dwarf Galaxies

Being studied by RAdial Velocity Experiment by Institutions from 11 nations
Galactic Cannibalism

- Galaxies grow by eating their neighbors
- MW has 9 dwarf companion galaxies
- Halo stars from disrupted dwarfs

GALACTIC CANNIBALIZATION: The Milky Way is ripping gas from two of its satellite galaxies, the Large and Small Magellanic Clouds. Along their orbits, astronomers see the Magellanic Stream (orange). Other, unrelated high-velocity clouds (yellow), possibly condensing out of a hot corona, float in the same space.
The Milky Way Growing?

★ Galaxies merge with other galaxies
  "Galactic Cannibalism"

★ Milky Way has two known merging galaxies
  ● Dwarf Elliptical Galaxy in Sagittarius
  ● Dwarf Galaxy in Canis Minor
    ▷ Closest galaxy in process of merging

★ Researchers expect to find more!
Sagittarius Dwarf Elliptical

Part of the “Sagittarius Stream” of gas & stars

52 kly from galactic center

Has passed through MW 10 times

Dark Matter indicted by lack of disruption!

Stars of SgrDEG have different speeds than MW stars

SgrDEG on far side of galactic center
Sagittarius Stream

☆ Stars & gas stripped from SgrDEG

APOD image of Sagittarius Stream

“Flyaround” of Milky Way with Sagittarius Stream

Photo by Marc Staves 2011
Sagittarius Stream

Simulations of tidal stripping of SgrDEG

~ 2 billion BCE to 500 million CE

Color indicates time of tidal stripping

Color indicates stellar density

Simulations by Kathryn V. Johnston, Wesleyan University
Canis Minor Dwarf

Discovered in 2003, 25 kly from MW center
CMi Dwarf
- Discovered in 2003
- 42 kly from MW center
- Merging with MW
Milky Way Ring

★ Thick ring of stars beyond disk

A Ring around the Milky Way

The Sun

Ghostly Ring
Milky Way Ring

★ Due to past galactic collision?

Star formation in ring of shocked gas

Which of these galaxies passed through one to left?

Cartwheel Galaxy

Photo by: K. Borne (ST ScI), NASA
The Local Group

- More than 54 galaxies
- Mostly dwarfs, including those merging with the Milky Way
- 3 Major spiral galaxies
  - Milky Way, Andromeda & Triangulum

http://www.atlasoftheuniverse.com/
The Sky Tonight

Looking NE from Canton at 9:30 pm

Polaris

Alpheratz

Scheat

Almach

Little Dipper

Little Dipper

Polaris

Big Dipper

Pegasis

Enif

Cepheus

δ Cephei

Scheat

Markab

Algenib

Triangulum Galaxy

Great Square of Pegasus

Capella

Algol

δ Cephei

Andromeda

Andromeda Galaxy

Perseus

Almaph

Rasalmothallah

Triangulum

Aries

Algol

Capella
Finding Galaxies

Andromeda Galaxy

Alpheratz

Almach

Triangulum Galaxy

Rasalmothallah

Andromeda

Triangulum
Andromeda Galaxy

★ Local Group’s Largest Galaxy

❖ One Trillion Stars ($10^{12}$)
❖ 2.5 million light-years away
   ➢ $1.5 \times 10^{19}$ mi ($1 \text{ ly} = 5.88 \times 10^{12}$ miles $\sim 6 \text{ trillioin}$)
❖ 200,000,000 $M_\odot$ black hole in center
❖ Approaching us at 300 km/s (190 miles/sec)
   ➢ Should collide with Milky Way in $\sim 4$ billion years
Triangulum Galaxy

☆ Pinwheel Galaxy (M 101)

🌍 40 Billion Stars \((10^{10})\)

🌍 3 million light-years away
  ➞ 1.5 \(\times\) \(10^{19}\) mi \((1\ \text{ly} = 5.88 \times 10^{12}\ \text{miles} \sim 6\ \text{trillion})\)

🌍 Linked to Andromeda by streams of stars and neutral hydrogen

⇒ interacted with Andromeda 2-8 by ago

⇒ will have more violent interaction in 2.5 my

⇒ may participate in collision with MW

Photo by Marc Staves 2011
The Coming Collision

Collision Scenario for Milky Way and Andromeda Galaxy Encounter

Triangulum (M33)

Andromeda (M31)

Collision in 4 billion years

Milky Way

Sun

Clusters of Galaxies

☆ Gravitationally bound galaxy groups
  ⊗ Require dark matter
    ⊰ galaxies move too fast for glowing matter
    ⇒ map the distribution of dark matter!

☆ Range in size and Richness
  ⊗ Local Group = 54 members
  ⊗ Virgo Cluster (nearest) = 1,300 – 2,000 mem.
  ⊗ El Gordo (largest) = 1,000,000 members
Clusters of Galaxies

Gravitationally bound galaxy groups require dark matter, as galaxies move too fast for glowing matter. This enables the map of dark matter distribution.

Range in size and richness:
- Local Group = 54 members
- Virgo Cluster (nearest) = 1,300 – 2,000 members
- El Gordo (largest) = 1,000,000 members

Virgo Cluster of Galaxies seen from Kitt Peak, Arizona

https://commons.wikimedia.org/wiki/File:ESO-M87.jpg
Clusters of Galaxies

Gravitationally bound galaxy groups Require dark matter galaxies move too fast for glowing matter map the distribution of dark matter!

Range in size and Richness

Local Group = 54 members

Virgo Cluster (nearest) = 1,300 – 2,000 mem.

El Gordo (largest) = 1,000,000 members

El Gordo Cluster of Galaxies image from Hubble Space Telescope

Clustering of Galaxies

★ Galaxies emit gas, dust, cosmic rays
  ◇ stellar explosions, collisions, etc.
★ Galaxy clusters have atmospheres
  ◇ Intracluster Medium (ICM)
    ▶ Glows in X-Rays due to electrons zipping by protons

X-ray emission

Thermal Bremsstrahlung Radiation
Clusters of Galaxies

Galaxies emit gas, dust, cosmic rays, stellar explosions, collisions, etc.

Galaxy clusters have atmospheres

**Intracluster Medium (ICM)**

Glows in X-Rays due to electrons zipping by protons

\[ e^- + p^+ \rightarrow \text{X-ray emission} \]

Thermal Bremsstrahlung Radiation

Chandra X-Ray Image of Virgo

Clusters of Galaxies

★ Galaxies emit gas, dust, cosmic rays
★ stellar explosions, collisions, etc.
★ Galaxy clusters have atmospheres
★ Glows in Radio due to electrons zipping along magnetic field lines.

Synchrotron Radiation

\[ f_{\text{radiation}} \propto E_{\text{electron}} \]
Clusters of Galaxies

- Galaxies emit gas, dust, cosmic rays from stellar explosions, collisions, etc.
- Galaxy clusters have atmospheres that glow in radio due to electrons zipping along magnetic field lines.

Synchrotron Radiation is a type of radiation produced by high-energy electrons.

Perseus A in the Perseus Cluster of Galaxies

Visible Hubble images with violet shells of X-ray gas and pink jets and lobes of radio-luminous plasma.
Seeing Dark Galaxies: The ALFALFA Survey

Aileen O'Donoghue
Priest Associate Professor of Physics
St. Lawrence University, Canton, NY
ALFALFA

- Arecibo Fast ALFA Survey
  - Arecibo
  - ALFA
  - L-Band
  - Radio Galaxies
    - Continuum Sources
    - Spectral Line Sources
  - ALFALFA Observations
  - Some ALFALFA Results
Arecibo Observatory

National Astronomy & Ionosphere Center
Funded by NSF, administered by Cornell University

Arecibo, Puerto Rico

Karst Topography
Subsurface limestone ⇒ sink holes
Like Gulin, China

Li River near Gulin, China
Arecibo Observatory

- Largest Single-dish radio telescope
  - diameter = 305 m = 1000 ft
  - depth = 167 ft (870 ft sphere)
  - 40,000 3 x 5 aluminum panels
Arecibo Observatory

Largest Single-dish radio telescope

Cables shape spherical dish

Tie-downs keep platform steady
Arecibo Observatory

- **Instrument Platform**
  - weight = 900 tons, 18 supporting cables
  - height = 450 ft above dish
  - azimuth arm length = 328 ft

Gregorian Dome

430 MHz line feed
On The Platform

Up via cable car

Jamie on the azimuth arm

Down via catwalk
Arecibo Observatory

Instruments

Line feed counters spherical aberration

Different parts of dish focus to different heights

430 MHz line feed (70 cm)
Arecibo Observatory

Instruments

- Gregorian dome houses instruments
- “gregorian” → secondary behind primary focus

Odd Puerto Rican berry!

Gregorian Dome
Inside the Gregorian Dome

Inside of dome is secondary reflector

Main dish

Tertiary reflector
ALFA

- Arecibo L-Band Feed Array
- Seven feeds in hexagonal array
- ALFA receivers

Made in Australia

... and SLU student
**ALFA**

- Point Spread Function

- Multiple beams & asymmetries alias sources

- Combining beams into one image requires careful processing
L Band

1200 - 1800 MHz

National Telecommunications and Information Administration
ALFALFA Observing band 1335 - 1435 MHz
ALFALFA

- 1335 - 1435 MHz
- 100 MHz, 4096 channels
  ⇒ 24.4 kHz/channel

Recessional Velocities

\[
v_{\text{channel}} = \frac{0.0244}{(1435 + 1335)/2} \times 2.998 \times 10^5 = 5.3 \text{ km/s}
\]

\[
v_{\text{max}} = \frac{1420 - 1335}{1335} \times 2.998 \times 10^5 = 19,200 \text{ km/s}
\]

\[
v_{\text{min}} = \frac{1420 - 1485}{1485} \times 2.998 \times 10^5 = -3050 \text{ km/s}
\]
Distances

**Hubble Constant**
Currently 72 km/s/Mpc = $2.33 \times 10^{18}$ s$^{-1}$

Gives the age of the universe as 13.6 By

**Cosmological Distances (local)**

\[
\rho = \frac{\nu}{H_0}
\]

\[
H_0 \frac{\nu}{\rho} \text{ km/s Mpc}
\]

**ALFALFA's far view**

\[
r_{\text{max}} = \frac{\nu_{\text{max}}}{H_0} = \frac{19,179 \text{ km/s}}{72 \text{ km/s/Mpc}} = 266 \text{ Mpc} = 870 \text{ million ly}
\]
Radio Sources

Continuum Sources
- Thermal radiation
- Synchrotron radiation

Spectral Line Sources
- Cool H
- Some molecules
**Continuum Radio Emission**

Thermal emission minimal

**Planck Curve for 2.725K**

**Wein’s Law:**

for $\lambda_{\text{max}} = 21$ cm

$T = 13.8$ mK

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Blackbody Radiation Intensity (mW/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>
Continuum Radio Emission

- **Continuum Radiation: Synchrotron**
  - e- spiral along magnetic fields

  \[ f_{\text{radiation}} \propto E_{\text{electron}} \]

  Radiate due to acceleration (centripetal acceleration) “beamed” in forward direction (relativistic motion)

Spectrum shows particle energy distribution (ie. Power Law)

Radiated Power

<table>
<thead>
<tr>
<th>L Band</th>
<th>C Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 GHz</td>
<td>5 GHz</td>
</tr>
</tbody>
</table>
Continuum Radio Galaxies

- **Wide Angle Tailed Radio Galaxies**
  - C-shaped radio emissions
  - shaped by "winds" due to smaller clusters of galaxies merging together ...
  - Even galaxies clusters are still evolving!

\[\sim 500,000\ \text{ly}\]
Continuum Radio Galaxies

- Attached to cD galaxies
- Cluster Dominant galaxies
- Huge ellipticals in centers of galaxy clusters
  - Got big by eating neighbors
  - Some not done ... multiple nuclei

~ 500 kly
Radio Galaxies

3C 75

- Dual radio galaxies
- Two radio sources from same galaxy
- Two nuclei
Radio Galaxies

3C 75

Cluster in X-ray emission shows two nuclei.
Spectral Radio Emission

- Spectral Line Radiation
  - Hydrogen hyperfine structure

- Spin-flip transition
  - Emits radiation at 1.420405 GHz
  - 21.106 cm
  - Spontaneous flip ~ 11 million years
  - Collisional flip ~ 400 years
Cool HI in the Milky Way

- **GALACTIC CORONA**: Hot gas surrounding the Milky Way.
- **HIGH-VELOCITY CLOUD (HVC)**: Infalling clump of relatively fresh hydrogen gas.
- **GALACTIC DISK**: Flattened system of stars, gas, and dust.
- **SUPERBUBBLE**: Gas pushed out by supernovae, outward leg of “Fountain”.
- **INTERMEDIATE-VELOCITY CLOUD (IVC)**: Clump of recondensed gas, return leg of “Fountain”.
- **LARGE MAGELLANIC CLOUD**: Satellite galaxy of the Milky Way.
- **SMALL MAGELLANIC CLOUD**: Satellite galaxy of the Milky Way.
- **SAGITTARIUS STREAM**: Trail of stars torn off Sagittarius dwarf galaxy.
- **SAGITTARIUS DWARF SPHEROIDAL GALAXY**: Satellite galaxy of the Milky Way.
- **SUN AND PLANETS**.
- **ANDROMEDA GALAXY**: Nearest major spiral galaxy.
- **TRIANGULUM GALAXY**: Nearby midsize spiral galaxy.
- **MAGELLANIC STREAM**: Gaseous filament torn off Magellanic Clouds.
Cool HI in the Milky Way

GALFA - Galactic ALFA
- Galactic HI in star-forming complexes
- Small-scale structure of Galactic HI
- Disk-Halo interferences
- Halo clouds and cloud-halo interactions

Surveys in the International Galactic Plane Survey
Extragalactic Cool HI

ALFALFA Science

- Expected to detect 25,000 objects
  - Local low-mass HI dwarfs ($\geq 10^6 \, M_\odot$)
  - Gas-rich massive galaxies ($\leq 10^{10.8} \, M_\odot$)

- HI spectra provide
  - Redshifts
  - HI cloud masses
  - HI disk populations & rotation rates
  - History of tidal events
  - Potential for future star formation

- Blind survey not prejudiced toward bright or interesting objects ... offers surprises!
ALFALFA Data

- Raw Data
- 14 Spectra per second (7 feeds, 2 polarizations)
ALFALFA Data

- Raw Data
- 14 Spectra per second (7 feeds, 2 polarizations)

Time (RA)

Increasing z

Galactic HI (\(z = 0\))
ALFALFA Data

- Raw Data
- RFI: Radar

Galactic HI (z = 0)

San Juan Airport Radar

... and harmonics

Time (RA)
ALFALFA Data

- Raw Data
- RFI: Radar ... and GPS bursts

Time (RA)

San Juan Airport Radar ... and harmonics

Galactic HI (z = 0)
ALFALFA Data

- Raw Data
- Galaxies: Known

Time (RA)

San Juan Airport Radar
AGC galaxies
Galactic HI (z = 0)
ALFALFA Data

Raw Data

Galaxies: Known and Unknown

Time (RA)

San Juan Airport Radar

New radio galaxy

Galactic HI (z = 0)
ALFALFA Data

- Cubes
- Spectra “gridded” into spatial images at increasing red shifts

Red shift 4096 channels!
Arecibo Sky …

3 am in April

ALFALFA data cube at
11h 48m +13°

The SLU cube
1148+13 Optical Images and Spectra

Double humped spectrum for edge-on

Single humped spectrum for face-on
1148+13

3-D plot of galaxies in the SLU cube

Bit of a clump …
1148+13

Distribution of Galaxies

Hickson Compact Group

Number of Galaxies vs. Redshift

Hickson Compact Group 59
Other ALFALFA Results

- **Tidal Stream in Virgo Cluster**
  - ~500 kpc, ~7 x 10^7 M_☉ (~10% of system mass)
  - Seems to be remnant of a NGC 4532 and DDO 137 interaction


Other ALFALFA Results

Virgo HI21 near Pinwheel galaxy (M99)

Rotating HI cloud ... First Dark Galaxy?

http://arxiv.org/abs/0706.1586

University of Alabama
http://www.astr.ua.edu/Galleries.html
Other ALFALFA Results

- Debunking the Dark Galaxy
- "An Act of Harassment"
- Part of a larger tidal stream from NGC 4254

The adventure continues...