The Interstellar Medium (ISM)

The radio view, what radio astronomy can measure

Main research fields

A number of open questions

- Fanti & Fanti § 13
- Tools of Radio Astronomy § 13
The Interstellar Medium (ISM)

- **What is it?** Composition, Observations, Parameters
  - HII
  - HI
  - Masers & Stars (circum – stellar envelopes)
  - H$_2$ (CO & al.)

- **Where is it?** Distribution, kinematics, origin and fate
  Spillars .vs. Ellipticals (& Irregulars)
Composition: ~99% gas
- 90% H, 10% other elements (mostly He)

Molecules, Atoms, Ions (including cosmic rays)

1% dust
- (grains, sub-um size)

+ Magnetic Field

Roto–vibrational transitions in mm, sub-mm (mostly CO) and infrared bands

Hyperfine transition at 1.42 GHz

Bremsstrahlung from thermal plasma (WIM & HIM) +

Synchrotron (electrons in cosmic rays + individual objects)

Gamma rays from CR-partner collisions

Extinction, absorption & IR Emission
The Interstellar Medium (ISM)

What is it? Composition, Observations, Parameters

Dust emission as observed with Planck
What is it? Composition, Observations, Parameters

Average density 0.1-1 cm$^{-3}$, inhomogeneous distribution

<table>
<thead>
<tr>
<th>Name</th>
<th>N (cm$^{-3}$)</th>
<th>T (K)</th>
<th>M ($10^9 M_{\odot}$)</th>
<th>Fraction of Total Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>molecular</em></td>
<td>&gt; $10^2$</td>
<td>10</td>
<td>2</td>
<td>1%</td>
</tr>
<tr>
<td>CNM</td>
<td>50</td>
<td>&lt; $10^2$</td>
<td>3</td>
<td>4%</td>
</tr>
<tr>
<td>WNM</td>
<td>0.5</td>
<td>$10^3$</td>
<td>4</td>
<td>30%</td>
</tr>
<tr>
<td>WIM</td>
<td>0.3</td>
<td>$10^4$</td>
<td>1</td>
<td>15%</td>
</tr>
<tr>
<td>HIM</td>
<td>0.003</td>
<td>&gt;$10^6$</td>
<td>0.1</td>
<td>50%</td>
</tr>
</tbody>
</table>

Typical values for a spiral galaxy

Dust is generally associated with CNM, i.e. dense and cold environments
Learning from other spirals: M 31 aka Andromeda Galaxy, $\sim 3.2^\circ \times 1.0^\circ$ in size
Learning from other spirals: X-rays captured by XMM-Newton (30' FoV)
Learning from other spirals:
Learning from other spirals:

Herschel view of M31: cold dust (bluish) and warm dust (reddish)
Learning from other spirals:

Comparison of emission observed at different wavelengths
Learning from other spirals:

NGC 2403
Learning from other spirals:

Composite image of spiral galaxy M106 (NGC 4258):
optical data from the Digitized Sky Survey is shown as yellow
radio data from the Very Large Array appears as purple
X-ray data from Chandra is coded blue,
infrared data from the Spitzer Space Telescope appears red.
Neutral Hydrogen

➢ Hyperfine structure: $\Delta E \sim 5.9 \mu$eV
➢ Natural width of 21 cm line = $10^{-16}$ m/s
➢ Collisions $10^4$ time more frequent than radiative transition, then thermal equilibrium
➢ Excited level : Ground level = 3 : 1

The brightness temperature derived from line photons:

$$T_{B(H)} = T_s \left(1 - e^{-\tau_H}\right) \text{ where } \tau_H \text{ is the optical depth}$$

If $\tau_H \ll 1 \rightarrow T_{B(H)} = T_s \tau_H$

$T_{B(H)}$ is in K if $N_H$ is in cm$^{-2}$

$n_H l = N_H \text{ column density}$

$$T_{B(H)} = \int_{\text{line}} T_{B(H)}(\nu) d\nu = \int_{\text{line}} T_s \tau_H(\nu) d\nu =$$

$$= 2.58 \cdot 10^{-15} N_H = T_s \tau_H$$

$$\tau_H = 2.58 \cdot 10^{-15} \frac{n_H l}{T_s} = 2.58 \cdot 10^{-15} \frac{N_H}{T_S}$$

Observed 1.4 GHz radio image of the edge-on spiral galaxy NGC 891. All the continuum emission seen in the image comes from relativistic electrons (synchrotron continuum emission).
Neutral Hydrogen

- Hyperfine structure: $\Delta E \sim 5.9 \, \mu\text{eV}$
- Natural width of 21 cm line $= 10^{-16} \, \text{m/s}$

- Observed width $\sim 100 \, \text{km/s}$, up to 500 km/s in the Galactic centre
  a) Broadening due to the thermal motions of the gas
  b) Systematic shift due to radial velocity along the l.o.s:

Thermal/turbulent and/or systematic motions are studied using the 21 cm line, which has a gaussian profile (or superposition of clouds with Gaussian profiles)
Neutral Hydrogen

- Hyperfine structure: $\Delta E \sim 5.9 \, \mu eV$
- Natural width of 21 cm line = $10^{-16} \, m/s$
- The photons of the line are a direct measure of the total amount of HI in the volume explored by the radio telescope
- In case of an optically thin emission

$$\frac{M}{M_{\odot}} \approx 2.36 \cdot 10^5 \left( \frac{D}{\text{Mpc}} \right)^2 \int_{\text{line}} \left( \frac{S(\nu)}{\text{Jy}} \right) \left( \frac{d\nu}{\text{km} \cdot \text{s}^{-1}} \right)$$
Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation?

◊ Let's assume circular orbits & same velocity

Inner regions have higher angular velocity (faster mix)

Other options:

➢ Solid body rotation: constant angular velocity

➢ Keplerian view: once the mass of the galaxy increases marginally with radius, such circular velocity should go with \( r^{-0.5} \).
Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation

Time lapse 1: green points were aligned, purple points are not aligned anymore
Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation

Time lapse 2: red dots appear uncorrelated
Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation: summary
Motions in the MW

A has greatest angular speed and moving fastest away from sun. A has higher density of H, B & C moving at about same angular speed > sun’s angular speed. D is outside solar distance—slower angular speed and has less material (density).

Everything rotating in same direction.

Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.
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Motions in the MW

Also the Sun moves, and has a component of the velocity along the line of sight!

A has greatest angular speed and moving fastest away from sun. A has higher density of H, B & C moving at about same angular speed > sun’s angular speed. D is outside solar distance—slower angular speed and has less material (density).

Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.
Oort constants

Velocities in the MW

\( v_r \) must be computed along a given line of sight and has components from both \( \Omega_o R_o \) and \( \Omega R \)

\[
v_r = \Omega R \cos\left(\frac{\pi}{2} - L - \theta\right) - \Omega_o R_o \cos\left(\frac{\pi}{2} - L\right)
\]

\[
= \Omega R \left( \sin \theta \cos L + \cos \theta \sin L \right) - \Omega_o R_o \sin L
\]

\( L \) is the galactic longitude (\( b \) is taken 0)

\( \theta \) is the galactocentric azimuth

\[
\frac{r}{\sin \theta} = \frac{R}{\sin L} \quad \text{i.e.} \quad r \sin L = R \sin \theta
\]

\[
R \cos \theta = R_o - r \cos L
\]

\[
v_r = R_o \left( \Omega(R) - \Omega_o \right) \sin L
\]
Fundamental equation to determine the rotation curve (measuring the radial velocity)

\[
\begin{align*}
  v(R,L)_r &= R_o \left( \Omega(R) - \Omega_o \right) \sin L \\
  v(R,L)_t &= R_o \left( \Omega(R) - \Omega_o \right) \cos L - r \Omega(R)
\end{align*}
\]

radial velocity
tangential velocity

For a measured \( v_r \) in a given direction \( L \), we can obtain \( \Omega(R) \), from which the local circular velocity can be derived: \( v(R) = \Omega(R) \cdot R \)

How to measure \( R \): stars, HII regions, PN, ...? any distance indicator

In case \( R \) is not known and motions are axially symmetric to the GC differential rotation

Velocity has a maximum at the “sub-central” / “tangential” point
Oort constants: \( (\Omega(R) - \Omega_o) \)

Can be expanded in Taylor series to the first order and at the end we get

\[
(\Omega(R) - \Omega_o) = \left( \frac{d\Omega}{dR} \right)_{R_o} (R - R_o) + \ldots \quad \text{where} \quad (R - R_o) \quad \text{is small}
\]

\[
\frac{d\Omega(R)}{dR} = \frac{d(v/R)}{dR} = \frac{1}{R} \frac{dv}{dR} - \frac{v}{R^2}
\]

The radial velocity can be rewritten as

\[
v_r = \left[ \left( \frac{dv}{dR} \right)_{R_o} - \frac{v_o}{R_o} \right] (R - R_o) \sin L = \left[ \frac{v_o}{R_o} - \left( \frac{dv}{dR} \right)_{R_o} \right] r \cos L \sin L
\]

since in the solar neighborhood \( (R - R_o) \approx r \cos L \)
The tangential velocity is

\[ v_t = \frac{v}{R} (R \cos L - r) - v_o \cos L = \left[ \Omega(R) - \Omega_o \right] R \cos L - \Omega(R) r \]

using the same Taylor expansion

\[ v_t = \left[ \frac{v_o}{R_o} - \left( \frac{dv}{dR} \right)_{R_o} \right] r \cos^2 L - \frac{v_o}{R_o} r = \left[ \frac{v_o}{R_o} - \left( \frac{dv}{dR} \right)_{R_o} \right] r \left(1 \cos 2L\right) - \frac{v_o}{R_o} r \]

\[ v_t = A r \cos 2L - \left[ \frac{v_o}{R_o} + \left( \frac{dv}{dR} \right)_{R_o} \right] \frac{r}{2} \]
Oort constants

The velocity of a given point at a distance $r$ can be written as

\[ v_r = A \cdot r \cdot \sin(2L) \]
\[ v_t = A \cdot r \cdot \cos(2L) + B \cdot r \]

with

\[ A = \frac{1}{2} \left[ \frac{v_o}{R_o} - \left( \frac{dv}{dR} \right)_{R_o} \right] \]
\[ B = -\frac{1}{2} \left[ \frac{v_o}{R_o} + \left( \frac{dv}{dR} \right)_{R_o} \right] \]
**Oort constants**

A and B are two coefficients dependent on \( R_o \) and \( (d\Omega / dR)_o \), known as Oort constants (1927)

\[
A = \frac{1}{2} \left[ \frac{v_o}{R_o} - \left( \frac{dv}{dR} \right)_{R_o} \right]
\]

\[
B = - \frac{1}{2} \left[ \frac{v_o}{R_o} + \left( \frac{dv}{dR} \right)_{R_o} \right]
\]

they can be computed by observations in the solar neighborhood.

- In case of a solid body rotation: \( A = 0, \quad B = -\Omega_o \)
- In case of a Keplerian regime: \( A = 3/4 \frac{v_o}{R_o}, \quad B = -1/4 \frac{v_o}{R_o} \)
- Observed values

\[
A = 14.82 \pm 0.84 \quad \text{km s}^{-1} \text{kpc}^{-1}
\]

\[
B = -12.37 \pm 0.64 \quad \text{km s}^{-1} \text{kpc}^{-1}
\]

Once known \( R_o \sim 8.5 \text{ kpc} \), the two constants allow to determine the velocity of the sun wrt the Galactic centre, \( v_o \sim 220 \text{ km s}^{-1} \)
In case of a flat rotation curve: \( A = \frac{1}{2} \frac{v_0}{R_0} \), \( B = -\frac{1}{2} \frac{v_0}{R_0} \)

\[
\begin{align*}
A &= \frac{1}{2} \left[ \frac{v_0}{R_0} - \left(0\right)_{R_0} \right] = \frac{1}{2} \frac{v_0}{R_0} \\
B &= -\frac{1}{2} \left[ \frac{v_0}{R_0} + \left(0\right)_{R_0} \right] = -\frac{1}{2} \frac{v_0}{R_0}
\end{align*}
\]

\[
\left( \frac{dv}{dr} \right)_{R_0} = -A - B = -3.4 \text{ km s}^{-1}
\]

\[
\frac{v_0}{R_0} = \Omega = A - B = 27.2 \text{ km s}^{-1} \text{ kpc}^{-1}
\]

\[
A = 14.82 \pm 0.84 \text{ km s}^{-1} \text{ kpc}^{-1}
\]

\[
B = -12.37 \pm 0.64 \text{ km s}^{-1} \text{ kpc}^{-1}
\]
➢ In case of a solid body rotation: \[ A = 0, \quad B = -\Omega \]

\[
\frac{dv}{dR} = \frac{v}{r} = \Omega
\]

\[
A = \frac{1}{2} \left[ \frac{v_o}{R_o} - (\Omega)_{R_o} \right] = \frac{1}{2} \left[ \frac{\Omega_o R_o}{R_o} - (\Omega)_{R_o} \right] = 0
\]

\[
B = -\frac{1}{2} \left[ \frac{v_o}{R_o} + (\Omega)_{R_o} \right] = -\frac{1}{2} \left[ \frac{\Omega_o R_o}{R_o} + (\Omega)_{R_o} \right] = -\Omega_o
\]
In case of a Keplerian regime: \[ A = \frac{3}{4} \frac{v_0}{R_o}, \quad B = -\frac{1}{4} \frac{v_0}{R_o} \]

\[ v = \sqrt{\frac{GM}{r}} \quad \rightarrow \quad \frac{dv}{dr} = -\frac{1}{2} \frac{\sqrt{GM}}{r^3} = -\frac{1}{2} \frac{v}{r} \]

\[ A = \frac{1}{2} \left[ \frac{v_o}{R_o} - \left( -\frac{v}{2r} \right)_{R_o} \right] = \frac{3}{4} \frac{v_o}{R_o} \]

\[ B = -\frac{1}{2} \left[ \frac{v_o}{R_o} + \left( -\frac{v}{2r} \right)_{R_o} \right] = -\frac{1}{4} \frac{v_o}{R_o} \]
Rotation curve: going out to external galaxies

Messier 101, the Pinwheel Galaxy (NGC 5457). Left: at visual frequencies by the HST. Centre: atomic hydrogen gas detected by the VLA as part of The HI Near Galaxy Survey (THINGS).
CO: also the molecular gas can be used to trace both distribution and dynamics. Located in different regions, it is an independent tracer of the galactic dynamics. In particular, very important in SFG and SBG. Complete analogy to HI line analysis.
Different regions contribute to different portions of the spectrum

Images are 2D and organized as a DATACUBE
Moment 0 – total intensity
Moment 1 – relative (radial) velocity
Moment 2 – velocity dispersion
The Interstellar Medium (ISM)

Learning from other spirals:
Neutral Hydrogen: the extraction of the Position – Velocity (PV) diagrams

Integrated emission over the line

NGC 5953

Casasola +, 2009
The PV diagram: interpretation

- PV diagram

Simulations of beam-smearing on a major-axis PV diagram.

**Top:** Assumed “true” rotation curve (thick) with a central core, bulge, disk, and halo

**Middle:** “Observed” CO PV diagram

**Bottom:** “Observed” HI PV diagram

*High resolution & high sensitivity necessary to detect central high velocities and steep rise*

(Sofue & Rubin 2001)
PV diagram

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(Sofue & Rubin 2001)
Contours: total HI emission;
Top: optical from SDSS
Middle: Hα, from Huang+, 2014
Bottom: HI velocity field from ALFAALFA
Hallenbeck +, 2014
HI in external galaxies Galaxies

Contours: total HI emission;
Top: optical from SDSS
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Hallenbeck +, 2014

Turquoise points define the rotation curve (on both sides!)
Learning from other spirals:

**The Interstellar Medium (ISM)**

- **Circinus**

- **Total Intensity**
- **Relative velocity**
Learning from other spirals:

The Interstellar Medium (ISM)
Observations:
Observations:

DISTRIBUTION OF DARK MATTER IN NGC 3198

$V_{\text{ar}}$ (km/s) vs. Radius (kpc)
The Interstellar Medium (ISM)

Constraints on Dark Matter:

- **Baryonic**
  - electrons, protons,..

- **Stellar endproducts**
  - WD, NS, BH

- **Brown Dwarves**

- **MACHOs**
  - Massive Astrophysical Compact Halo Objects

- **Non Baryonic**

- **Cold Dark Matter (CDM)**
  - particles with $v \ll c$

- **Hot Dark Matter (HDM)**
  - particles with $v \sim c$

- **WIMPs?**

- **Neutrinos + ?**

- $\sim 20\%$

- $> 70\%$

- $\sim < 3\%$
The story is not over... extra-planar clouds

Heald et al. 2011
The Interstellar Medium (ISM)

The story is not over...

Fraternali +, 2001

Battaglia +, 2006
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Bubbles (holes) in HI distribution

Messier 101, the Pinwheel Galaxy (NGC 5457). Left: at visual frequencies by the HST. Centre: atomic hydrogen gas detected by the VLA as part of The HI Near Galaxy Survey (THINGS)

NGC 2403
The Interstellar Medium (ISM)
Groups

Interaction triggers starburst and outflow in M82

- Tidal interaction (physical link)
- Different dynamical times: gas/stars
- Induced star formation
- Gas concentrations also in “empty parts of the sky”
Lopesidedness

- Environment weather
- Galaxy motion
Galaxy clusters

- HI deficiency
- Morphological segregation

Fig. 23. Integrated neutral hydrogen maps of the brightest spirals in the Virgo Cluster center. Each map has been drawn at the galaxy position indicated by a cross and magnified by a factor of 5 compared with the scale in right ascension and declination. The first contour in each map corresponds approximately to a column density of $10^{20}$ atoms cm$^{-2}$ (even if it is not the case in the maps published in Figs. 1-22 especially for NGC 4518, 4450, 4548, 4694).
Summary

- In spirals HI is distributed on a large fraction of the volume
- HI traces the neutral & warm ISM
- Line emission (absorption) very effective kinematic tool

- Rotation curve & Oort constants
- Dark matter
- External spirals
- Neutral gas effects (e.g. Lopesidedness, extra-planar gas, bubbles, etc)

Suggested readings:
- Fanti & Fanti, § 13