HI in galaxies

- major mass component of ISM (there is also hotter and colder gas)
- large part of gaseous reservoir of material for star formation (also H$_2$)
- Can detect it far from galaxy centers -- good for tracing orbital motions and measuring total masses of galaxies -- leading to evidence for dark matter in galaxies
- in gas we see clear evidence for interactions -- both gravitational and ram pressure stripping
why is HI emission a good tracer of the mass of atomic hydrogen gas?
Measuring HI mass from 21cm line

HI is major mass component of ISM: How can we measure the mass in this phase? What assumptions does this rely on? How well does this work?

\[
\left( \frac{M_{\text{HI}}}{M_\odot} \right) \approx 2.36 \times 10^5 \left( \frac{D}{\text{Mpc}} \right)^2 \int \left[ \frac{S(\nu)}{\text{Jy}} \right] \left( \frac{dv}{\text{km s}^{-1}} \right)
\]

This equation derives from the quantum mechanics of the hyperfine transition and the assumption that the HI gas is optically thin.

Mass depends on Distance squared

Line flux is observed (integral over all velocities)

Flux density

\[ S(\nu) \text{ or } F_\nu \text{ (janskys)} \]

1 jansky = \(10^{-26} \text{ W m}^{-2} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2}\)
Detecting atomic hydrogen with spectral line of HI

\( H \) is most abundant element in universe (\(~74\% \) by mass)

\( I \) in HI means atom has all its electrons (only 1 in case of H)
Neutral Hydrogen (HI): $\lambda=21$cm spectral line from “spin-flip transition”

An H atom in upper energy state (parallel spins)

will *spontaneously* change to

lower energy state (anti-parallel spins), emitting a photon with $\lambda=21$cm in the process
21cm HI spectral line from spin-flip transition of neutral Hydrogen

*Electron in ground state orbital level is split into 2 hyperfine levels*

*Hydrogen energy level diagram*

- $F = 1$
- $F = 0$

- $f_0 = 1420 \text{ MHz}$
- $\lambda_0 = 21 \text{ cm}$

- Electron in 2nd orbital level
- Electron in ground state orbital level
Why 21cm HI line is important

1. It is easy to excite upper energy level

- Upper energy level is only $E = 5.9 \times 10^{-6}$ eV or $T = E/k = 0.07$ K above ground state!
- Tiny amount of energy required to excite upper state – it is easy to do this with low energy collisions, which happen almost anywhere in universe!
- 21cm HI line is excellent probe of neutral hydrogen gas throughout universe
Why 21cm HI line is important

2. Intensity is good measure of amount of gas

- Intensity depends (mostly) on number of H atoms along the line of sight – so it’s a good measure of the mass of neutral Hydrogen along the line of sight
compare ...

H$\alpha$ “recombination line” from HII regions with 21cm line (= HI line) from HI regions...
Hα emission

n=3→2 “recombination” line

In optical, \( \lambda=0.6563 \, \mu m \)

typically occurs where gas has \( T\sim10^4 \, \text{K} \) and atoms can be ionized

- Suppose H atom somehow gets excited and its electron is in a higher energy level (\( n>1 \)) (e.g., by collision with another atom, or if it previously absorbed a photon)
- After a while the electron will spontaneously fall to a lower energy level, and the atom emits a photon as it does
how well does $\text{H}\alpha$ emission trace the mass of hydrogen gas?

A. the number of $\text{H}\alpha$ photons is proportional to the *total* gas mass

B. the number of $\text{H}\alpha$ photons is proportional to the *ionized* gas mass

C. the number of $\text{H}\alpha$ photons depends on the *ionized* gas mass and the gas density

D. the number of $\text{H}\alpha$ photons depends on the *ionized* gas mass and the gas density and the temperature
Why is the 21cm HI line a good tracer of neutral hydrogen gas mass, but the Hα line is a poor tracer of ionized hydrogen gas mass?
Hα: collision time vs. spontaneous emission time

\[ t_{\text{coll}} (=t_{\text{rec}}) \sim 10^4 \text{ yr} \]
\[ t_{\text{em}} (=A^{-1}) \sim 10^{-8} \text{ sec} \]

\[ t_{\text{em}} \ll t_{\text{coll}} \]

since \( t_{\text{em}} \ll t_{\text{coll}} \), atom in excited state will emit Hα photon before it has another collision

fraction of atoms that produce photons = fraction of atoms in excited state, which depends on density and temperature

more collisions (recombinations) \( \rightarrow \) more Hα photons
HI : collision time vs. spontaneous emission time

\[ t_{\text{coll}} \sim 10^3 \text{ yr} \]
\[ t_{\text{em}} (=A^{-1}) \sim 10^7 \text{ yr} \]

since \( t_{\text{em}} \gg t_{\text{coll}} \), the vast majority of atoms in excited state will have another collision before it emits HI photon

fraction of atoms that produce photons = fraction of atoms in excited state, which is already a ~maximum since atoms are in collisional equilibrium, so doesn’t depend on density or temperature

more collisions \( \rightarrow \) same # HI photons
Why 21cm HI line is important

2. Intensity is good measure of amount of gas

- Intensity depends (mostly) on number of H atoms along the line of sight – so it’s a good measure of the mass of neutral Hydrogen along the line of sight

- **Intensity doesn’t depend on gas density** (collision time much shorter than time it takes to emit 21cm photon) (very different from Hα spectral line (WIM) or X-Ray continuum emission (HIM), whose intensity depends on density squared)
The 21cm HI line is forbidden

forbidden: collision time $\ll$ spontaneous emission time

- Average ‘excited’ H atom takes $\sim 11$ Myr to (spontaneously) make hyperfine transition which produces 21cm photon. (This is average time – for any 1 atom, the time will be different -- statistical process)

$$A_{10} \approx 2.85 \times 10^{-15} \text{ s}^{-1}$$

Einstein A coefficient for spontaneous emission of 21cm photon

- Collision time for H atoms in ISM is $\sim 1000$ yrs – much shorter than 11 Myr. So collisions determine population of energy levels.

- Most H atoms in upper energy level are collisionally de-excited before they can emit a photon. But a small fraction of the ‘excited’ H atoms manage to emit a photon before they have a collision. And this is enough to produce a 21cm emission line from a gas cloud that is strong enough to detect, since there are so many atoms in the gas cloud

- the number of HI photons produced is proportional to the number of H atoms in excited state $= \frac{3}{4}$ total number of H atoms
equation of radiative transfer

\[ I_\nu (\tau_\nu) = I_\nu (0) e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu}) \]

\( \tau_\nu = \text{optical depth} \)

\( I_\nu (0) \) = background intensity

\( S_\nu \) = source function

\( I_\nu (\tau_\nu) \) = observed intensity
equation of radiative transfer

\[ I_\nu (\tau_\nu) = I_\nu(0) e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu}) \]

\[
S_\nu(T) = B_\nu(T) = \frac{2\nu^3}{c^2} \frac{1}{e^{\frac{\nu}{k_B T}} - 1} \approx \frac{2\nu^3}{c^2} \cdot \frac{k_B T}{\nu} = \frac{2\nu^2 k_B T}{c^2}.
\]

in thermodynamic equilibrium, the source function = Planck intensity

radio astronomers often express surface brightness \( I_\nu \) in terms of brightness temperature \( T_b \)

\[
T_b(\tau_\nu) = T_b(0) e^{-\tau_\nu} + T_s (1 - e^{-\tau_\nu})
\]

for low frequencies \( \nu \ll kT \), use Rayleigh-Jeans limit of Planck intensity
• what is temperature $T_s$ in this equation?

• relevant fact is the number of particles in the upper and lower states

• this can be expressed in terms of an “excitation temperature $T_{\text{ex}}$” or “spin temperature $T_s$” even if gas not in local thermodynamic equilibrium (LTE)
• The **Excitation Temperature** \((T_{ex})\) or “spin temperature” \((T_s)\) is defined for a population of particles via the Boltzmann factor. It satisfies
\[
\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{h\nu}{kT_s}\right) = 3 \exp\left(-\frac{h\nu}{kT_s}\right)
\]

• where \(n_1\) and \(n_0\) represent the number of particles in an upper (e.g. excited) and lower (e.g. ground) state, and \(g_1\) and \(g_0\) their statistical weights respectively.

• Thus the excitation temperature is the temperature at which we would expect to find a system with this ratio of level populations. However it has no actual physical meaning except when in local thermodynamical equilibrium. The excitation temperature can even be negative for a system with inverted levels (such as a maser).

• In observations of the 21 cm line, the apparent value of the excitation temperature is often called the "spin temperature".
if optically thin i.e., $\tau << 1$ and no background emission, i.e. $T_b(0) = 0$

$\rightarrow T_b(\tau_\nu) = \tau_\nu \ T_s$

but!

$s = \text{path length}$

$\tau_\nu \equiv \int_{s_{\text{out}}}^{s_{\text{in}}} -\kappa_\nu(s')ds'$

$\kappa_\nu = \text{absorption coefficient}$

so.... $T_s$ dependence cancels out and $T_b$ depends only on $N_H = \int n_H \ ds$ !!

$n_H = n_1 + n_0$
Measuring HI column densities from 21cm line

the HI column density $N_H$ (in atoms cm$^{-2}$) can be determined directly from the integrated line brightness when $\tau << 1$.

\[
\left( \frac{N_H}{\text{cm}^{-2}} \right) \approx 1.82 \times 10^{18} \int \left[ \frac{T_b(v)}{K} \right] d\left( \frac{v}{\text{km s}^{-1}} \right)
\]
Measuring HI mass from 21cm line

\[ M_H = m_H \int N_H \, dA \]

\( m_H \) = mass of H atom

\( A \) = area on sky, which depends on...

\( D \) = distance to galaxy
Measuring HI mass from 21cm line

the HI mass (in $M_{\text{sun}}$) $M_{\text{HI}}$ can be determined directly from the integrated line flux \textbf{when} $\tau \ll 1$

\[
\left( \frac{M_{\text{HI}}}{M_{\odot}} \right) \approx 2.36 \times 10^5 \left( \frac{D}{\text{Mpc}} \right)^2 \int \left[ \frac{S(v)}{\text{Jy}} \right] \left( \frac{dv}{\text{km s}^{-1}} \right)
\]

This equation derives from the quantum mechanics of the hyperfine transition and the assumption that the HI gas is optically thin.

\textbf{Mass depends on Distance squared}

\textbf{Line flux is observed (integral over all velocities)}

\textbf{Flux density $S(v)$ or $F_{\nu}$ (janskys)}

\textbf{NOTE: Some HI is optically thick (especially cold clouds – the CNM) so the true total HI mass is higher than this formula predicts!}

1 jansky = $10^{-26}$ W m$^{-2}$ = $10^{-23}$ erg s$^{-1}$ cm$^{-2}$
cold vs. optically thin HI revealed by comparing HI absorption vs. emission spectra

HI absorption spectra are very sensitive to temperature (shows more cold HI)

HI emission spectra are ~uniformly sensitive to optically thin HI at all temps (not temp sensitive)

HI absorption + emission spectra toward/ right next to source 1714-397

Dickey+83

some peaks seen in both abs + em – optically thin HI

some peaks only in absorption – cold HI
2 different phases of HI

- **Cold Neutral Medium (CNM)** $T \sim 100-200$ K, $n \sim 50$ cm$^{-3}$, optically thick, small filling factor – small cold clouds (undercounted in emission)
- **Warm Neutral Medium (WNM)** $T \sim 7000$ K, $n \sim 0.5$ cm$^{-3}$, optically thin, large filling factor – intercloud medium

Relation between HI emission intensity and HI column density & mass assume optically thin HI… but some HI (esp CNM) is optically thick so we are undercounting it!
# Major Phases of ISM in Milky Way

<table>
<thead>
<tr>
<th>Phase of ISM</th>
<th>T(K)</th>
<th>n (cm(^{-3}))</th>
<th>h (pc)</th>
<th>(f_{vol})</th>
<th>(f_{mass})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot ionized medium (HIM)</td>
<td>10^6</td>
<td>10^{-3}</td>
<td>3000</td>
<td>0.5</td>
<td>0.04</td>
</tr>
<tr>
<td>Warm ionized medium (WIM)</td>
<td>8000</td>
<td>0.3</td>
<td>900</td>
<td>0.2</td>
<td>0.10</td>
</tr>
<tr>
<td>Warm neutral medium (WNM)</td>
<td>6000</td>
<td>0.3</td>
<td>400</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Cold neutral medium (CNM)</td>
<td>100</td>
<td>20</td>
<td>140</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td>Molecular medium (MM)</td>
<td>10</td>
<td>10^2-10^3</td>
<td>70</td>
<td>0.001</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\(T\) = temperature  
\(N\) = volume density  
\(h\) = vertical scale height  
\(f_{vol}\) = volume filling factor  
\(f_{mass}\) = ISM mass fraction  

* HI phases

Values given are representative values for Milky Way.  
h and \(f_{vol}\) are values within a few kpc of solar neighborhood;  
the inner \(\sim\)kpc and outer galaxy are different.

Ref: Brinks 1990; Boulanger & Cox 1990; Kulkarni & Heiles 1988
# MAJOR PHASES OF ISM IN MILKY WAY

<table>
<thead>
<tr>
<th>PHASE OF ISM</th>
<th>description</th>
<th>Traced by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot ionized medium (HIM)</td>
<td>Coronal gas produced by supernovae</td>
<td>X-Ray continuum emission</td>
</tr>
<tr>
<td>Warm ionized medium (WIM)</td>
<td>HII regions around massive stars &amp; throughout ISM</td>
<td>H(\alpha)+other recombination lines;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>radio continuum emission</td>
</tr>
<tr>
<td>Warm neutral medium (WNM)</td>
<td>Diffuse clouds &amp; envelopes around molecular clouds</td>
<td>HI in emission</td>
</tr>
<tr>
<td>Cold neutral medium (CNM)</td>
<td>Dense sheets &amp; filaments; envelopes around molecular clouds</td>
<td>HI in emission &amp; absorption</td>
</tr>
<tr>
<td>Molecular medium (MM)</td>
<td>Cold, dense, gravitationally bound clouds</td>
<td>CO and other emission lines</td>
</tr>
</tbody>
</table>

Ref: Brinks 1990; Boulanger & Cox 1990; Kulkarni & Heiles 1988
Key ISM facts

• Muhc of molecular medium in self-gravitating discrete clouds (but also some diffuse non-self-gravitating molecular gas)

• Rest of phases in global pressure equilibrium \( (P=knT; \text{ compare product of n and T}) \)

• Most of gas mass in disk galaxies in MM+CNM+WNM \( \rightarrow \) observe with HI, CO

• Most of gas mass in luminous E’s in HIM \( \rightarrow \) observe with X-Rays

• WIM – not much gas mass, but good tracer of ongoing star formation
2 most important radio telescopes for HI studies of galaxies

**Very Large Array (VLA)**
New Mexico, US
27 dishes with 25m diameter interferometer

**Arecibo Telescope**
Puerto Rico
305m diameter
Single dish
Milky Way in stars (NIR) and neutral gas (HI)

A disk component (not bulge) but some HI clouds extend up into the halo
HI gas vs. optical in NGC 3521

HI associated with disk, not with bulge

H I intensity = HI surface density

Optical – starlight

HI velocity

HI velocity dispersion

Walter etal 2008

THINGS

VLA
HI vs. optical in NGC 2403

HI more extended than stars

Walter et al. 2008 THINGS
HI vs. optical in NGC 2841

- HI more extended than stars
- HI distribution in outer disk, beyond most of stars, is often warped
Warped HI disk in Sb NGC 4013

- Outer disk highly warped
- Warped part of galaxy is almost all gas, very few stars
- -> star formation inefficient in part of disk that is warped

Warps: not well understood, may result from gas accretion or tidal interaction
Sc galaxy M101

M101 is one of largest nearby spirals
Optical vs. HI in Sc M101 to same scale

- HI much more extended than optical

Kamphuis et al 1991

Fig. 1. Grey-scale picture of the total HI column density distribution of M 101. The column densities range from $1 \times 10^{20}$ (white) to $3.8 \times 10^{21}$ cm$^{-2}$ (dark). The resolution is $13'' \times 16''$ ($\sim$ 500 pc). The arrow indicates the position of the superbubble.
Optical vs. HI in Sc M101 to same scale

- HI much more extended than optical
  -> Gas inefficient in forming stars in outer parts of galaxy
Optical vs. HI in Sc M101 to same scale

- HI much more extended than optical
  - Gas inefficient in forming stars in outer parts of galaxy
- Strong spiral structure in gas -> need gas to form spiral structure

Kamphuis et al. 1991

HI (gas)

optical (stars)
Optical vs. HI in Sc M101 to same scale

- HI much more extended than optical
  -> Gas inefficient in forming stars in outer parts of galaxy
- Strong spiral structure in gas  -> need gas to form spiral structure
- Outer disk lopsided  -> probably due to recent accretion

HI (gas)  Kamphuis et al 1991
Holes in HI disks

NGC 5457 (M 101)

Walter et al. 2008 THINGS
• Holes in HI distributions in some galaxies
• Due to energy from star formation (supernovae and OB stellar winds) or accretion/minor mergers – gas punching through disk
HI holes in M101 disk: 2-sided superbubble

expanding HI shell associated with HI hole in spiral arm (2-sided kinematically)

$d \sim 1.5$ kpc, $M \sim 3 \times 10^7 \, M_{\odot}$, $v_{\text{exp}} \sim 50$ km/s

$KE \sim 10^{53}$ erg $\sim 1$ core collapse SN/ hypernova
due to energy from star formation (supernovae and OB stellar winds)
Milky Way superbubble

- 7 kpc away
- 3 kpc high

HI GBT, NRAO website
HI holes in M101 disk: large 1-sided hole

\[ M \approx 10^8 \, M_{\odot}, \, v_{\text{out}} \approx 150 \, \text{km/s}, \, KE \approx 10^{54} \, \text{erg} \sim 10 \, \text{hypernovae} \]

high-velocity HI associated with disturbed part of spiral arm (disturbed HI is kinematically 1-sided)
due to accretion/minor merger?

van der Hulst & Sancisi 1988

PV diagram along red line but not caused by hypernovae...
Intensity of most things increase toward galaxy center but not HI
Central HI “hole” or depression or plateau filled in with molecular
gas in many (but not all) galaxies

Kenney & Young 1989
Kenney et al 1991
HI radial distributions

- HI much more extended than stars (& nearly all other baryonic things) in non-cluster spirals
- Central HI “hole” or depression or plateau filled in with molecular gas (H$_2$) in many (but not all) galaxies

Kenney & Young 1989
HI radial distributions

- HI much more extended than stars (& nearly all other baryonic things) in non-cluster spirals
- Central HI “hole” or depression or plateau filled in with molecular gas in many (but not all) galaxies

Log Gas Mass Density in $M_{\text{sun}}/pc^2$
or Intensity

Radius (arcmin)

Kenney & Young 1989
Kenney et al 1991

Sb spiral NGC 4192

Sc spiral M101
HI in Magellanic Clouds

Evidence of tidal interactions much clearer in HI than stars because of larger extent of HI

Figure 1. The Large and Small Magellanic Clouds and the Magellanic Stream.
HI: Parkes Multibeam All-Sky Survey (see Staveley-Smith et al., these proceedings, p. ??), 15.5' resolution, contours $1 \times 10^{18}$ cm$^{-2}$ x 2$^\circ$.
Optical: Image from the color imaging team at Mt. Stromlo Observatory (see Bessell, M. 2000, PASA, 17, 179).
Nearby M51 system is classic grand design spiral galaxy M51 (=NGC 5194) interacting with another galaxy NGC 5195.
Evidence of tidal interactions much clearer in HI than stars because of larger extent of HI

**Figure 1.** M51: The Whirlpool Galaxy.

*HI*: VLA C+D-array, 34" resolution, contours=4 x 10^{18} \text{ cm}^{-2} \times 2".

*Optical*: DSS, FOV=26" \times 29".

Leo Triplet
nearby small galaxy group
HI in Loose groups

Evidence of tidal interactions much clearer in HI than stars because of larger extent of HI

Arecoibo telescope observations