LEGO: Why is HCN unexpectedly bright in gas of low density?

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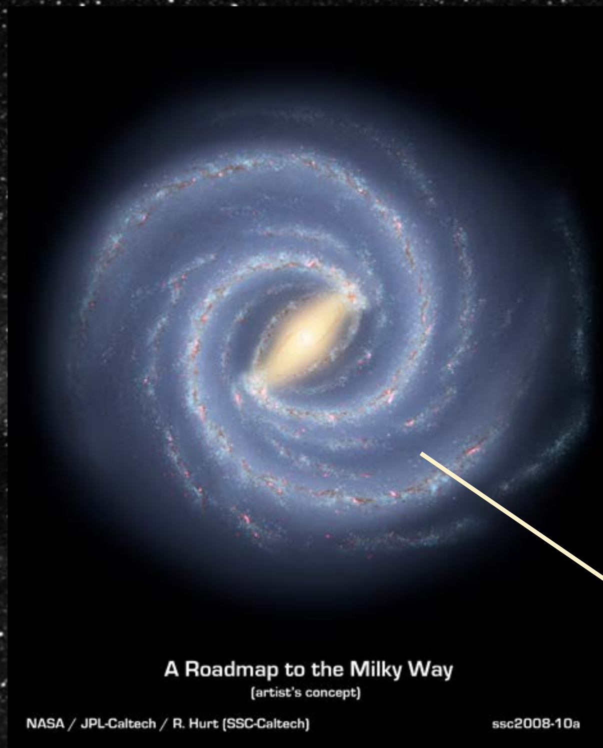
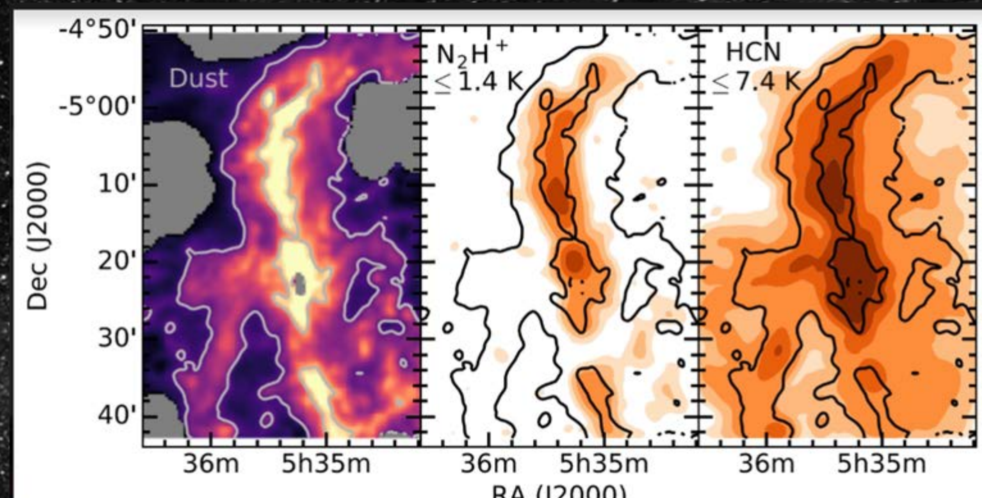
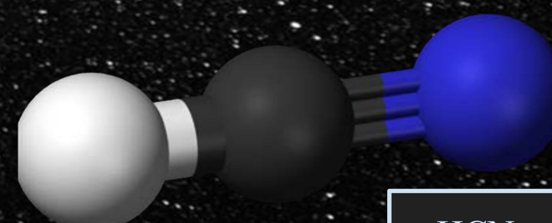
REU 2022

Motivation





molecular cloud



HCN

Motivation

General assumptions in star formation:

- $\dot{M}_{\star} \propto M_{\mathrm{dg}}$
- $\dot{M}_{\star} \propto L_{\mathrm{IR}}$
- $M_{\mathrm{dg}} \propto L_{\mathrm{HCN}}$ (Gao & Solomon 2004)
  - Due to assumption that HCN traces gas at densities $\gg 10^4\ \mathrm{cm}^{-3}$

$\rightarrow\ L_{\mathrm{IR}} \propto L_{\mathrm{HCN}}$

(Kauffmann et al. 2017) found that HCN traces gas 1-2 orders of magnitude below density assumed by Gao & Solomon

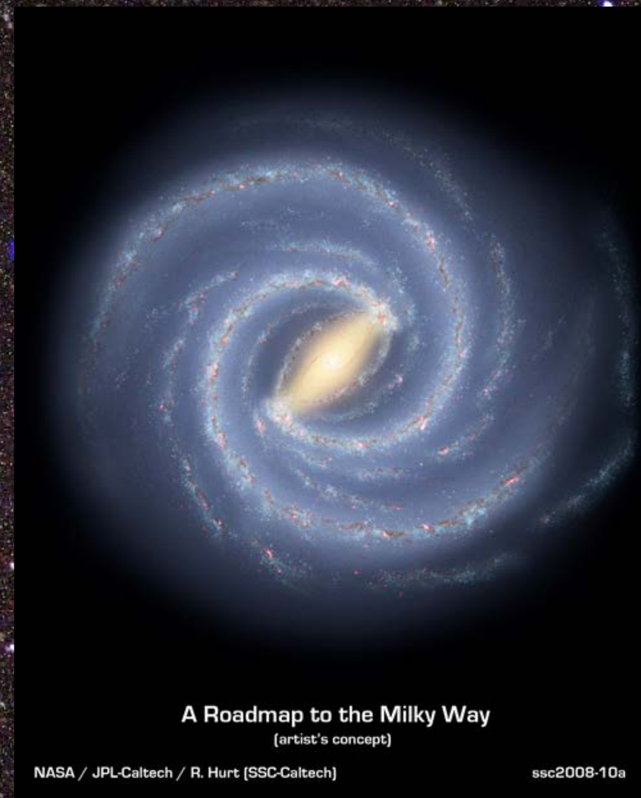
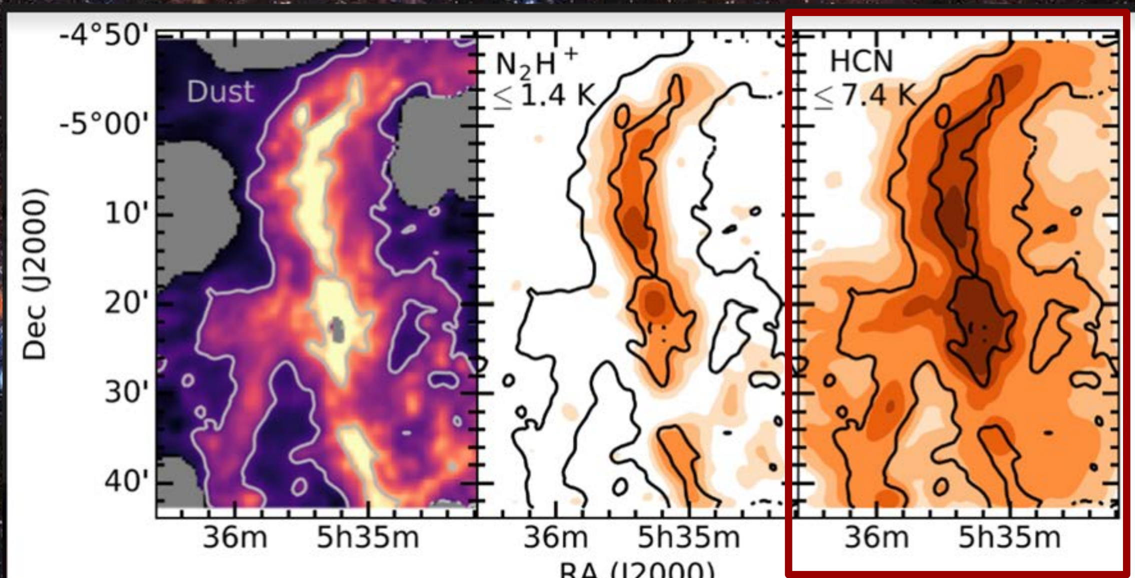


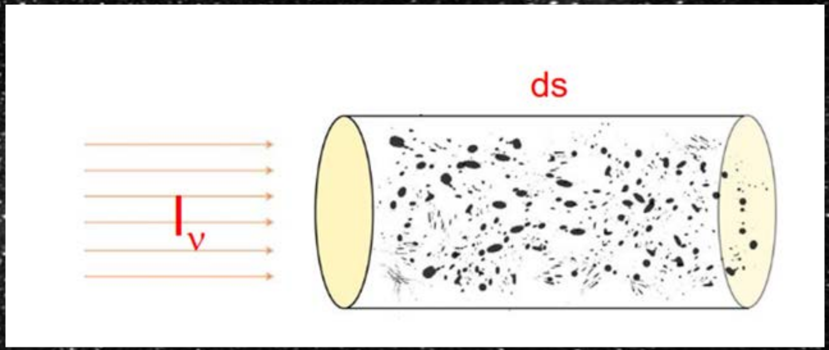
Image Credit ESO/ VISION SURVEY

- Why is HCN unexpectedly bright in low density gas?
  - High HCN abundance
  - Stronger excitation



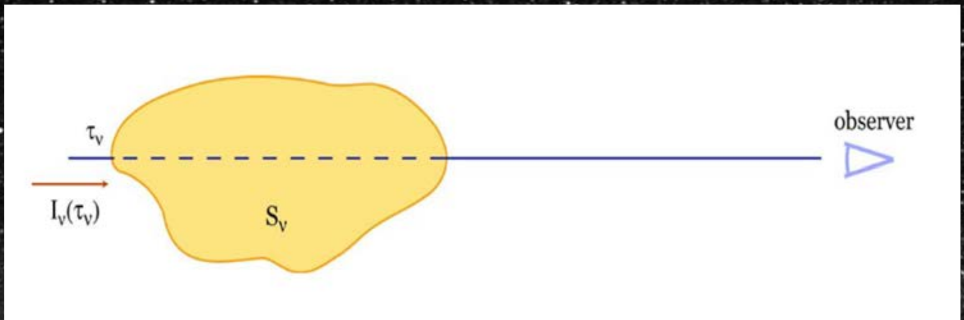
Background

visual extinction: absorption and scattering of radiation by dust and gas between an observer and an emitting object

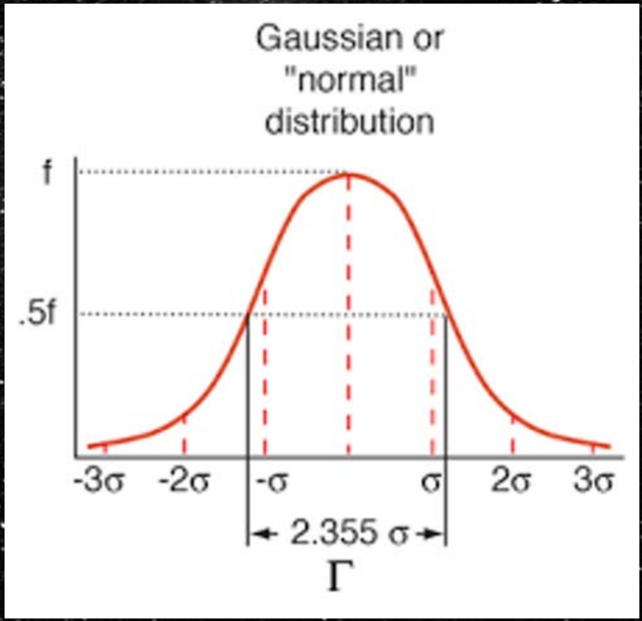


column density: number of molecules along a line of sight

Background



optical depth: measure of opacity.



line width: width of hyperfine structure

Methods Overview

- Radex (van der Tak et al. 2007)
  - non-LTE radiative transfer software that is executable in Python
  - *Input: line width, column density, kinetic gas temperature, gas density*
  - *Output: brightness temperature*
- Understanding input parameter relationships
- Corresponding the intensity with column density
- $X_{HCN} = N_{HCN}/N_{H2}$

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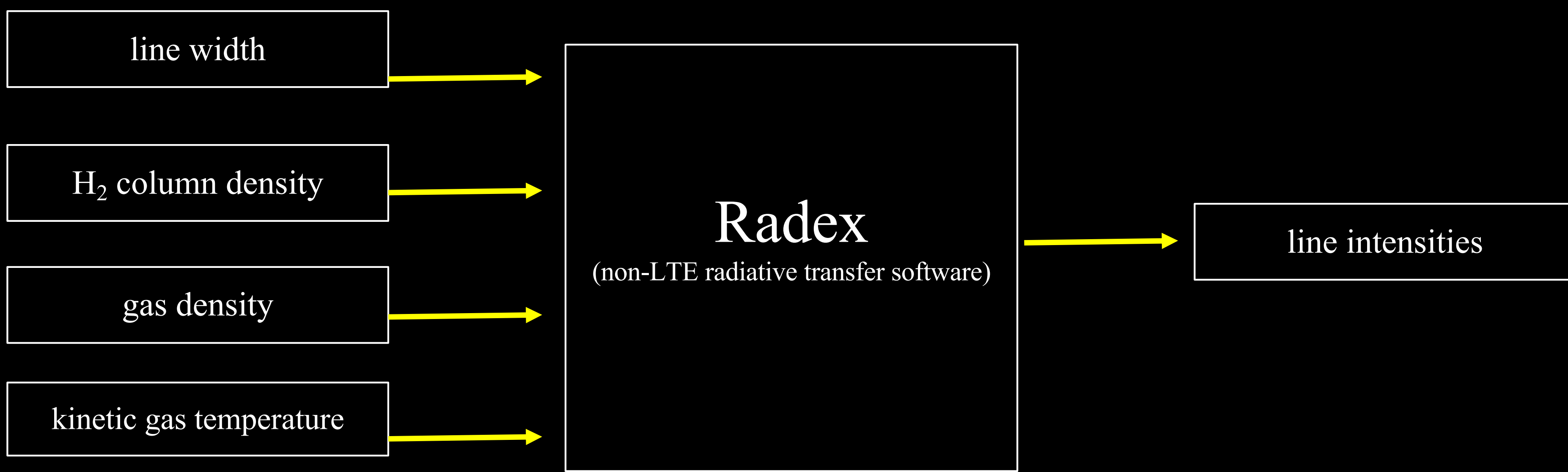
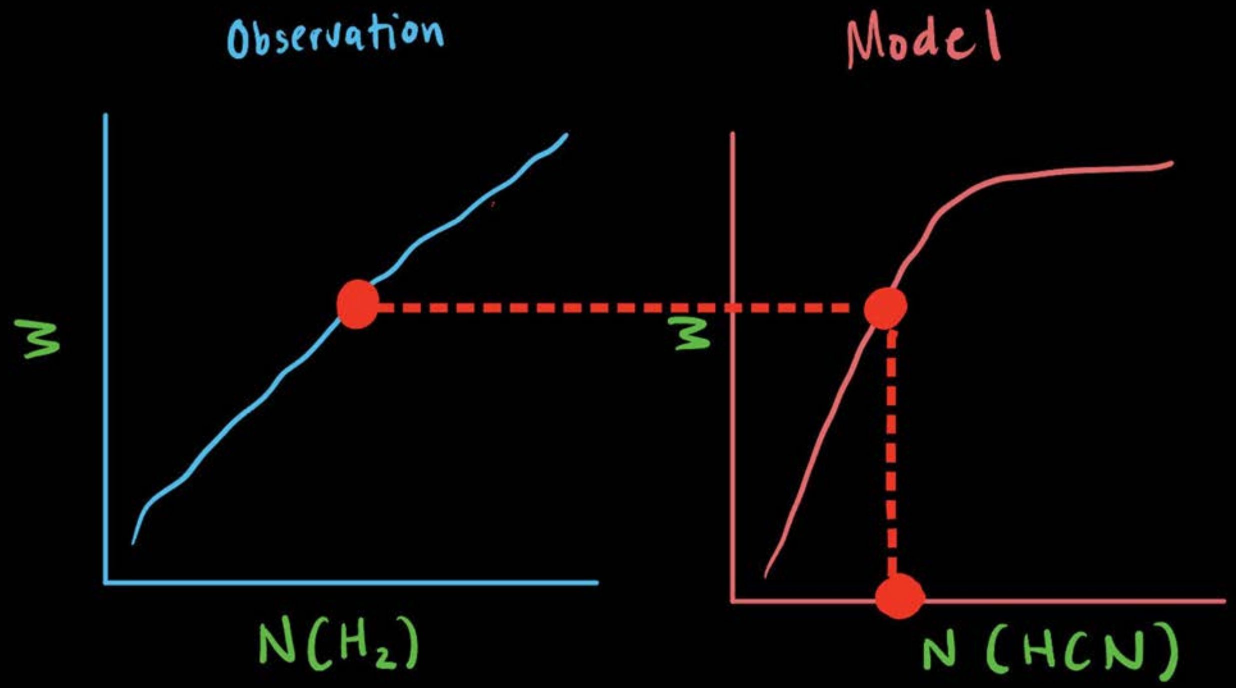
Methods


line width
H_2 column density
gas density
kinetic gas temperature
Radex
(non-LTE radiative transfer software)
line intensities

Methods



Radiative Transfer Equation

$$W = T_{ex}(1 - e^{-\tau})\,\Delta v$$

if $\tau \to 0$:

$$W = T_{ex}\,\tau\,\Delta v$$

if $\tau \gg 1$:

$$W = T_{ex}\,\Delta v$$

$$\tau \propto N / \Delta v$$

if $\tau \ll 1$:

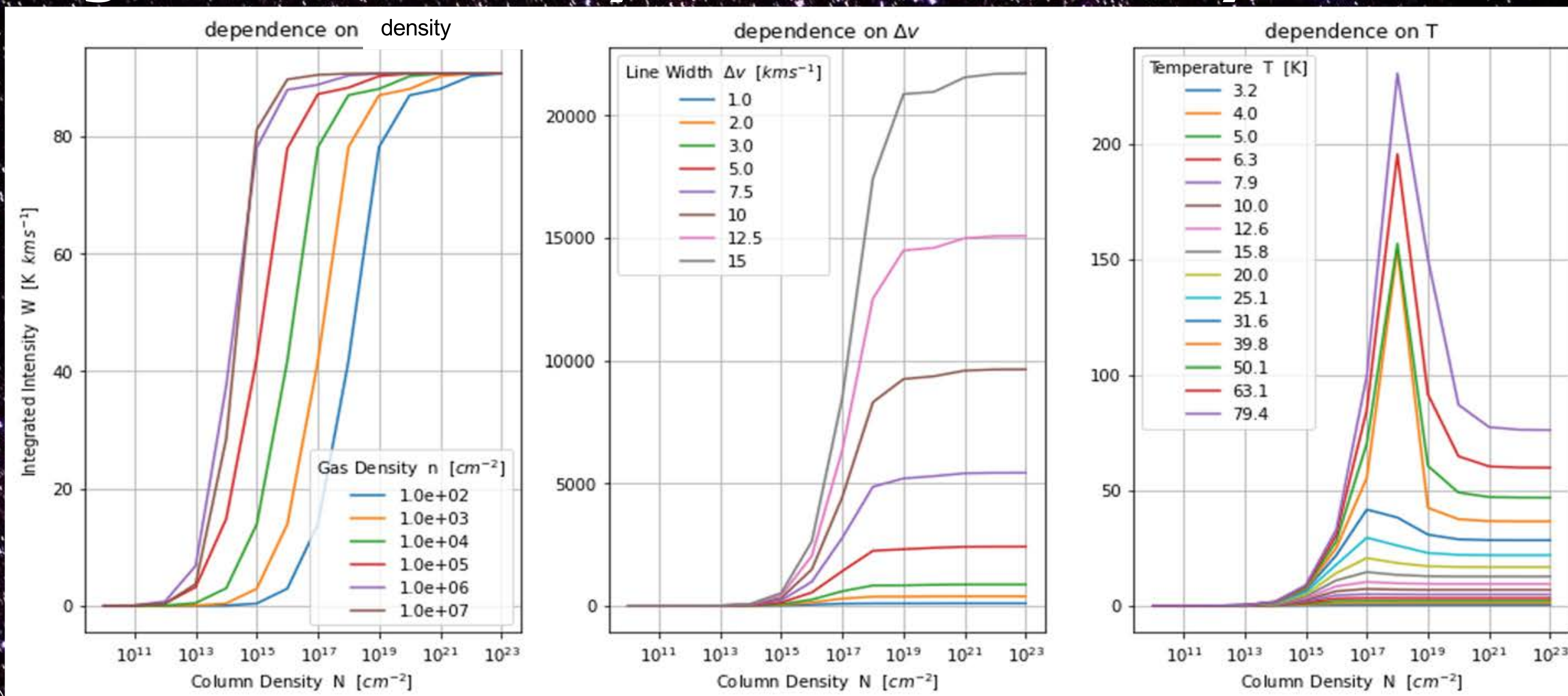
- ($n \gg n_{cr}$): $W = (T_{gas} - T_{CMB})\,N / \Delta v$
- ($n \ll n_{cr}$): $W = (T_{gas} - T_{CMB})\,n\,N / \Delta v$

if $\tau \gg 1$:

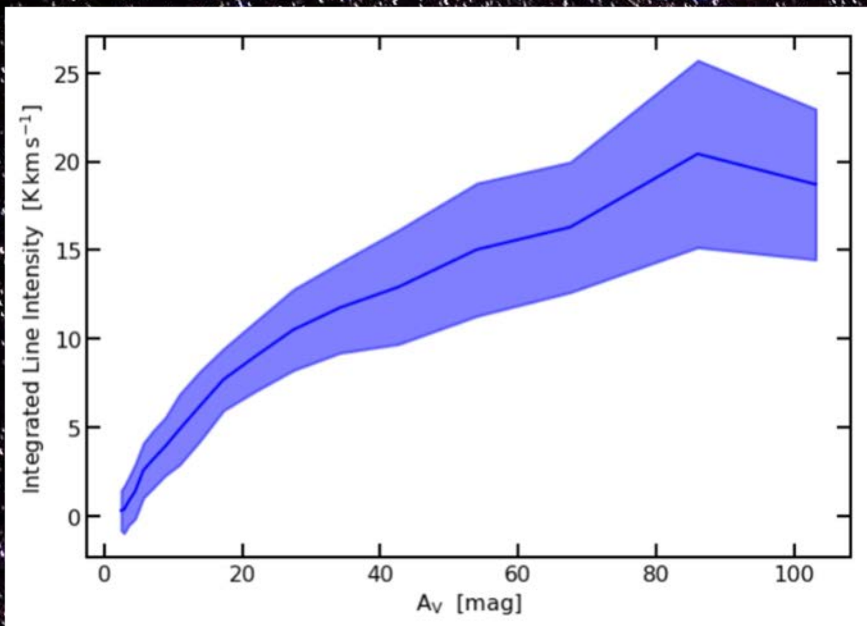
- ($n \gg n_{cr}$): $W = (T_{gas} - T_{CMB})$
- ($n \ll n_{cr}$): $W = (T_{gas} - T_{CMB})\,n$

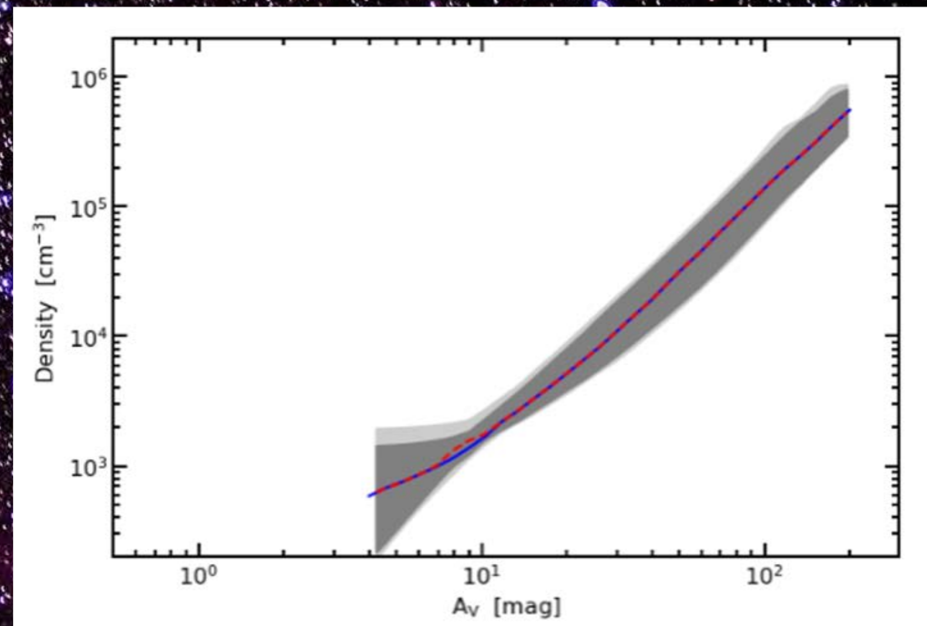
W = intensity
τ = optical depth
T_{ex} = excitation temperature
Δv = line width
T_{gas} = kinetic gas temperature
T_{CMB} = cosmic microwave background temperature
n = cloud gas density
n_{cr} = critical density
N = HCN column density

Integrated Intensity - Column Density Model

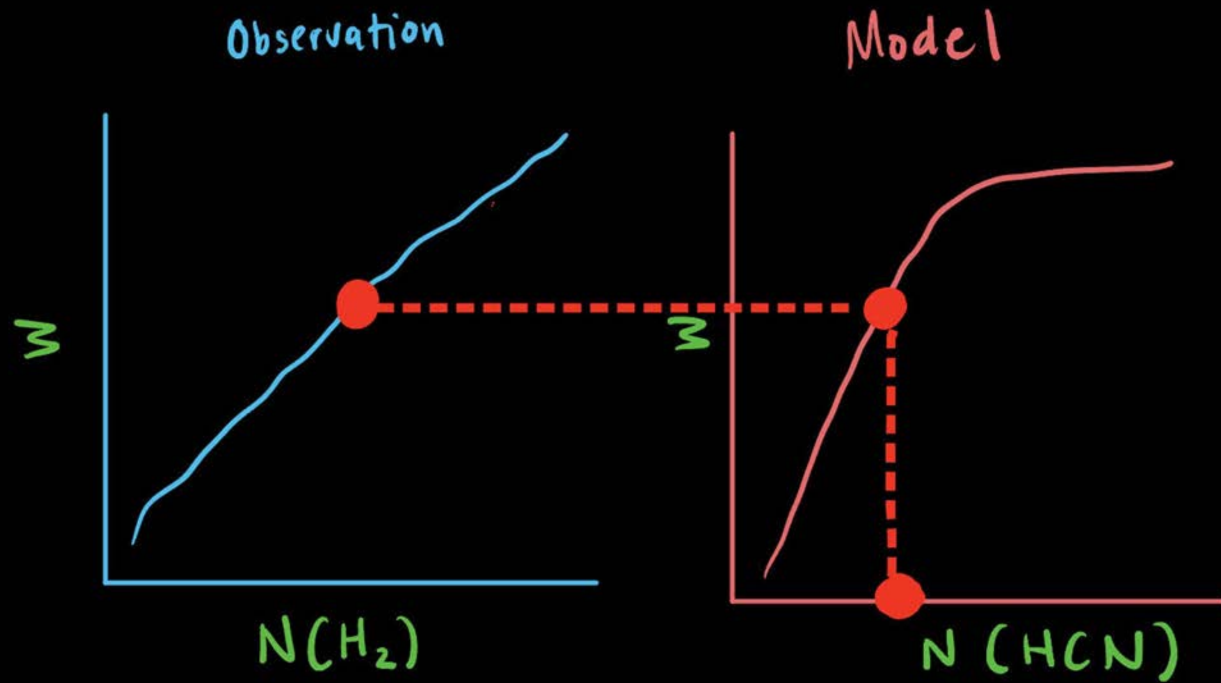


LEGO Observations

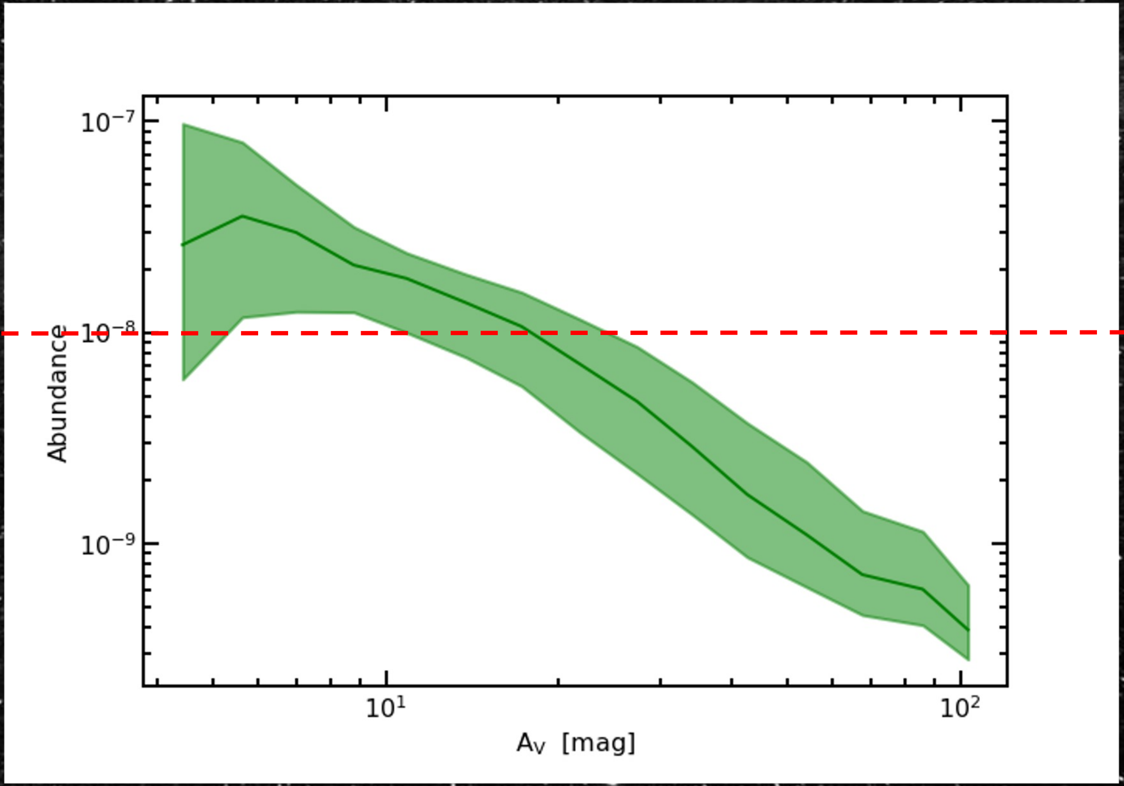




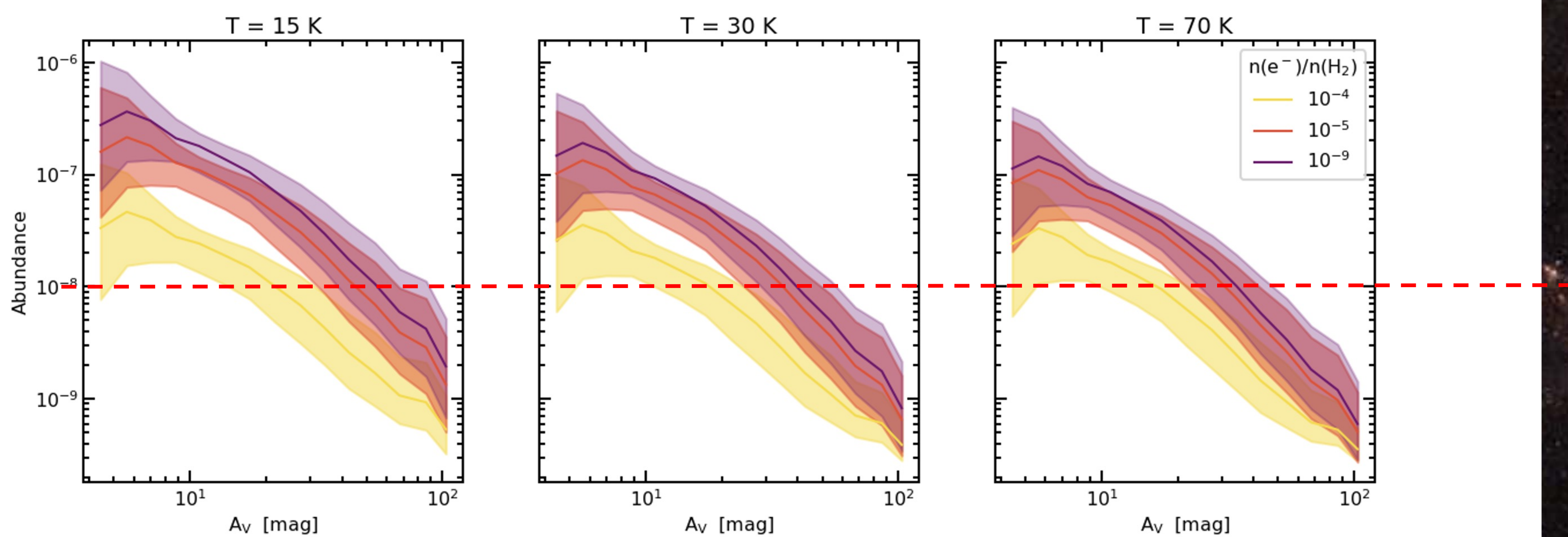
Methods



HCN Abundance



HCN Abundance Modeled



Summary

- Explored analytical equations behind radiative transfer software
- Calculated abundance using column density estimation
- HCN abundance in model is still relatively high, compared to typical value
- Abundance of the molecule or ionization fraction is high

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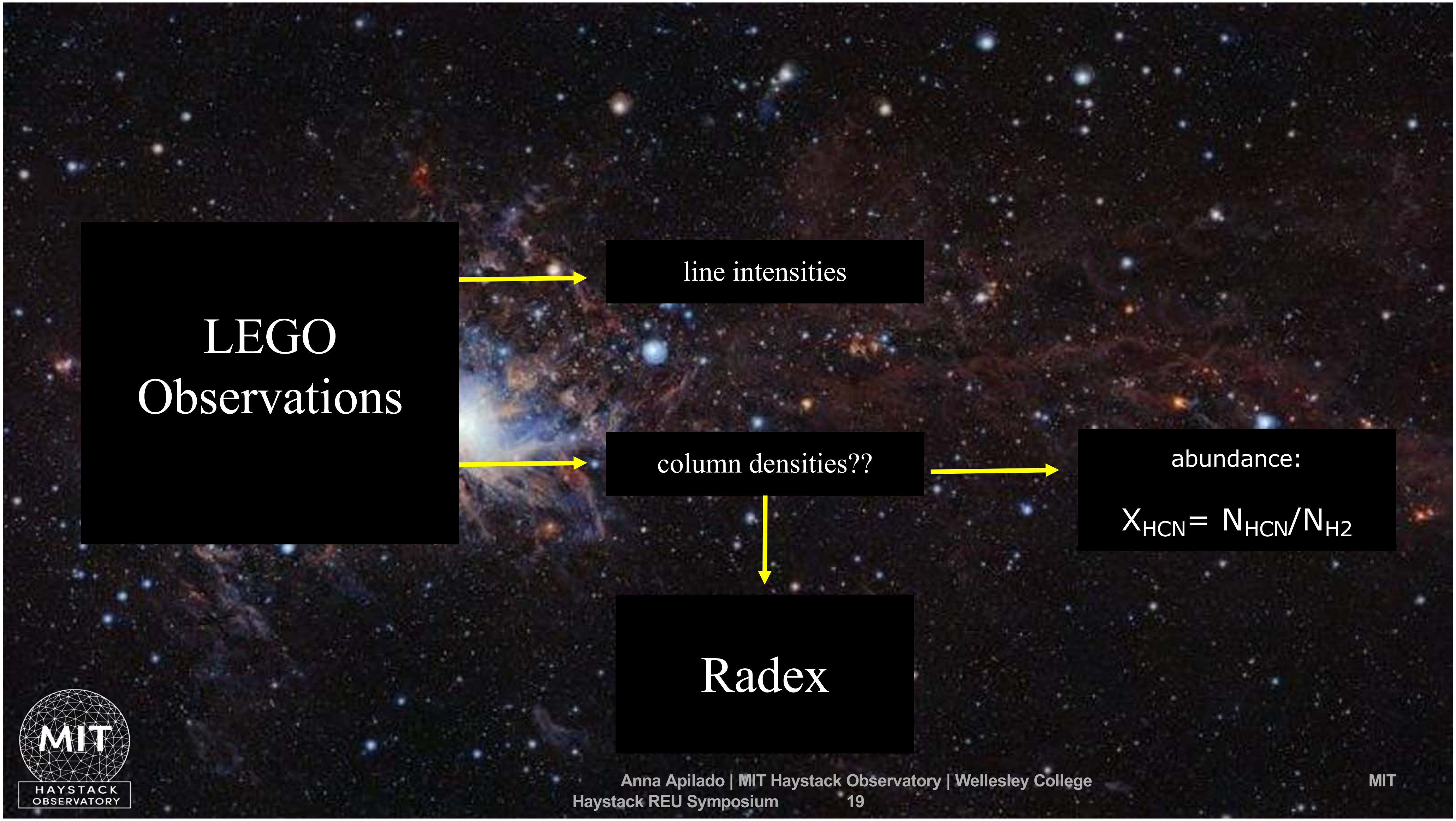
Questions?

Acknowledgements: Thank you to Dianne, Nancy, Vincent, and Phil for organizing the REU. Thanks to Drew, John, and IT for helping with all technical issues. Of course, thanks to Jens for the mentorship and patience throughout the project!

Extra Slides


LEGO Observations
line intensities
column densities??
abundance:
$X_{HCN} = N_{HCN}/N_{H2}$
Radex
MIT
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Optical Depth

$\tau \propto N / \Delta v$

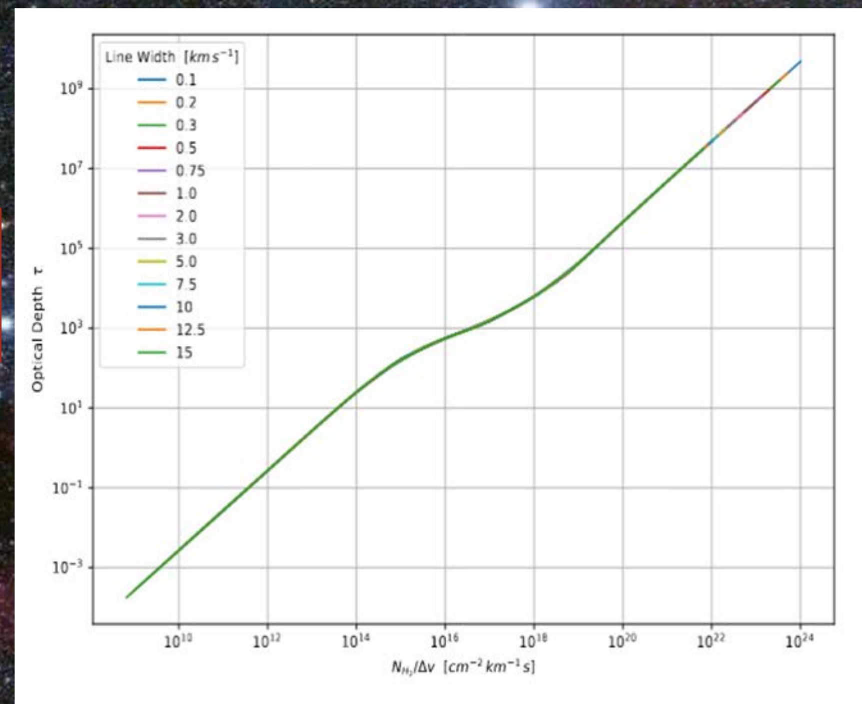
if $\tau \ll 1$

- $(n \gg n_{cr})$: $W = (T_{gas} - T_{CMB})\, N / \Delta v$
- $(n \ll n_{cr})$: $W = (T_{gas} - T_{CMB})\, n\, N / \Delta v$

if $\tau \gg 1$

- $(n \gg n_{cr})$: $W = (T_{gas} - T_{CMB})$
- $(n \ll n_{cr})$: $W = (T_{gas} - T_{CMB})\, n$

T_{gas} = kinetic gas temperature
T_{CMB} = cosmic microwave background temperature
n = cloud gas density
n_{cr} = critical density
N = HCN column density
Δv = line width



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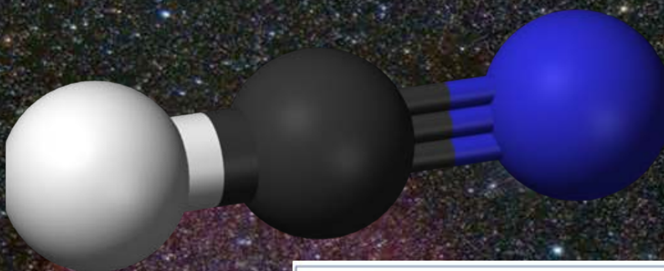
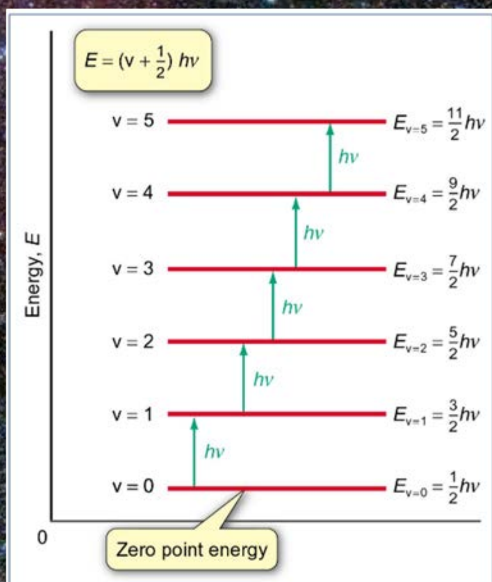
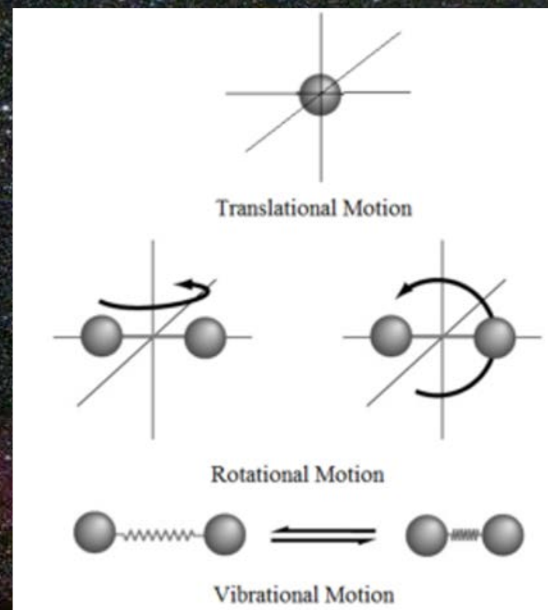
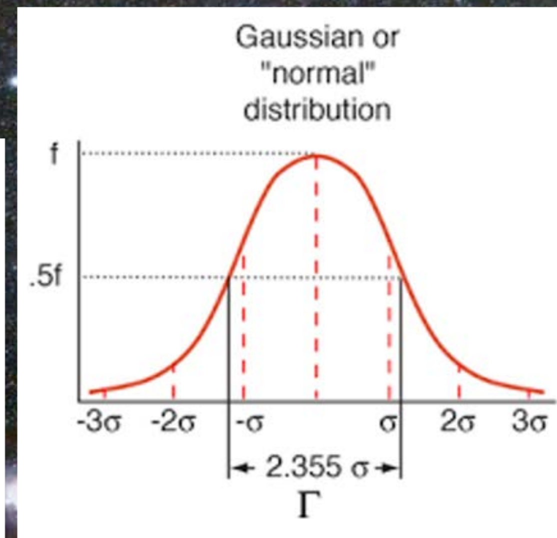
What is a line emission?









Radiative Transfer Equation

$$dI_\nu/ds = j_\nu - \alpha_\nu I_\nu + \alpha_\nu I_\nu e^{-\tau}$$

$$T_b = T_{ex}(1 - e^{-\tau})$$

$T_b = T_{ex}\,\tau$ if $\tau \rightarrow 0$

$T_b = T_{ex}$ if $\tau \gg 1$

I_ν = intensity at each point in line of sight

j_ν = emission term

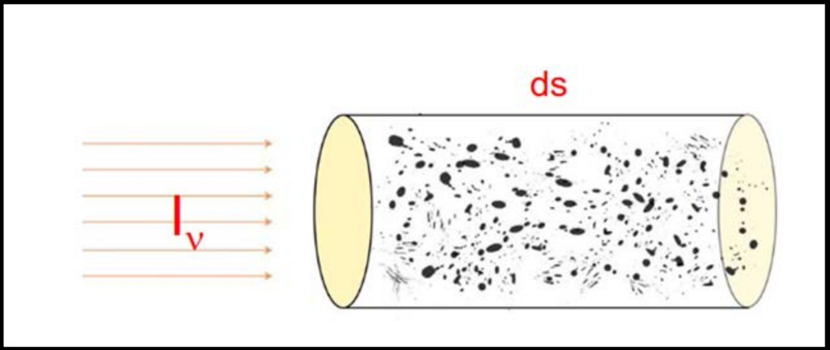
α_ν = extinction coefficient

τ = optical depth

dI_ν/ds = change in intensity with distance s along a line of sight

T_b = brightness temperature

T_{ex} = excitation temperature



High Optical Depth vs Low Optical Depth

$\tau \propto N / \delta_v$

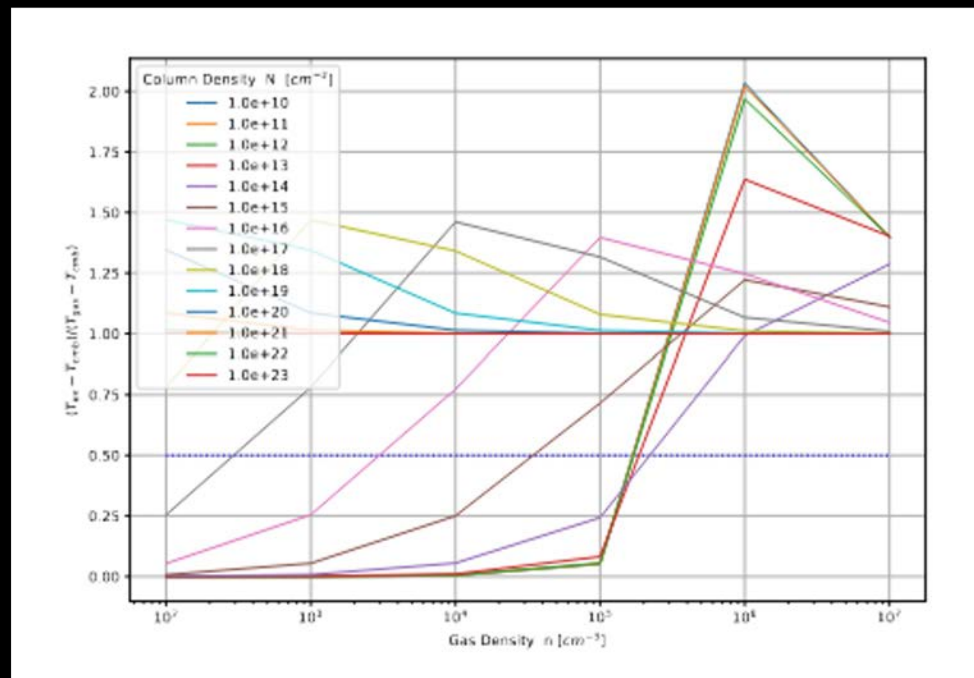
Low optical Depth

$T_b = (T_{ex} - T_{CMB})\ \tau$

$\propto (T_{ex} - T_{CMB})\ N / \Delta v$

$\rightarrow (T_{gas} - T_{CMB})\ N / \Delta v \qquad (n \gg n_{cr})$

$\rightarrow (T_{gas} - T_{CMB})\ n\ N / \Delta v \qquad (n \ll n_{cr})$



High Optical Depth vs Low Optical Depth

$\tau \propto N / \delta_v$

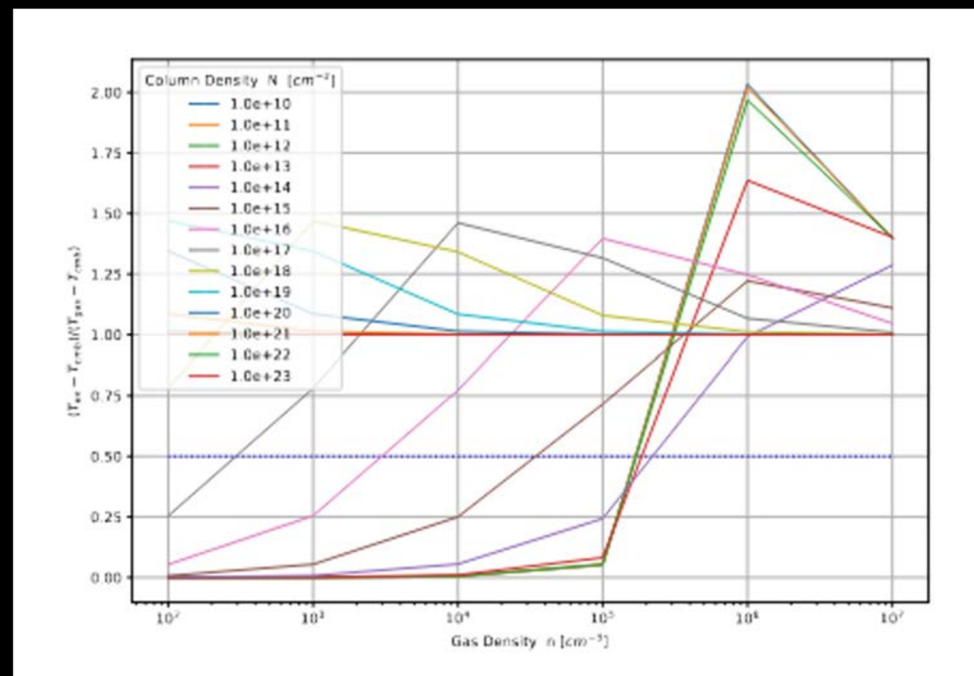
Low optical Depth

$W = (T_{ex} - T_{CMB})\, \tau$

$\propto (T_{ex} - T_{CMB})\, N / \Delta v$

$\rightarrow (T_{gas} - T_{CMB})\, N / \Delta v \qquad (n \gg n_{cr})$

$\rightarrow (T_{gas} - T_{CMB})\;\; n \;\; N / \Delta v \qquad (n \ll n_{cr})$



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Understanding input parameter relationships

- $W = T_{ex}(1 - e^{-\tau})\ \Delta v$

- $T_{ex} = T_{gas}$ $(n \ll n_{cr})$
  $T_{ex} = T_{CMB}$ $(n \gg n_{cr})$

- $\tau \propto N / \delta_v$

  for low optical depth:

  → $(Tgas - T_{CMB})\ N / \Delta v$ $(n \gg ncr)$

  → $(Tgas - T_{CMB})\ \ n\ \ N / \Delta v$ $(n \ll ncr)$

  for high optical depth:

  → $(Tgas - T_{CMB})$ $(n \gg ncr)$

  → $(Tgas - T_{CMB})\ \ n$ $(n \ll ncr)$

High Optical Depth vs Low Optical Depth

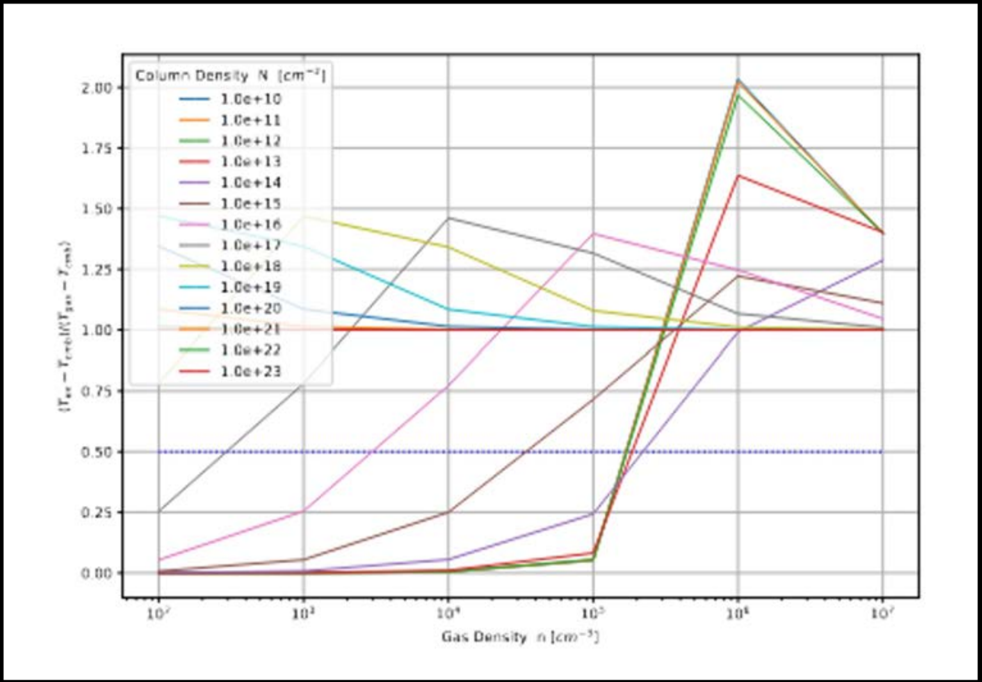
$\tau \propto N / \delta_v$

High Optical Depth

$T_b=(T_{ex}-T_{CMB})$

$\rightarrow (T_{gas}- T_{CMB})$ $(n \gg n_{cr})$

$\rightarrow (T_{gas}- T_{CMB})\ n$ $(n \ll n_{cr})$



Excitation Temperature

$(n \ll n_{cr})$ $T_{ex} = T_{gas}$

$(n \gg n_{cr})$ $T_{ex} = T_{CMB}$

T_{gas} = kinetic gas temperature
T_{ex} = excitation temperature
n = cloud gas density
n_{cr} = critical density