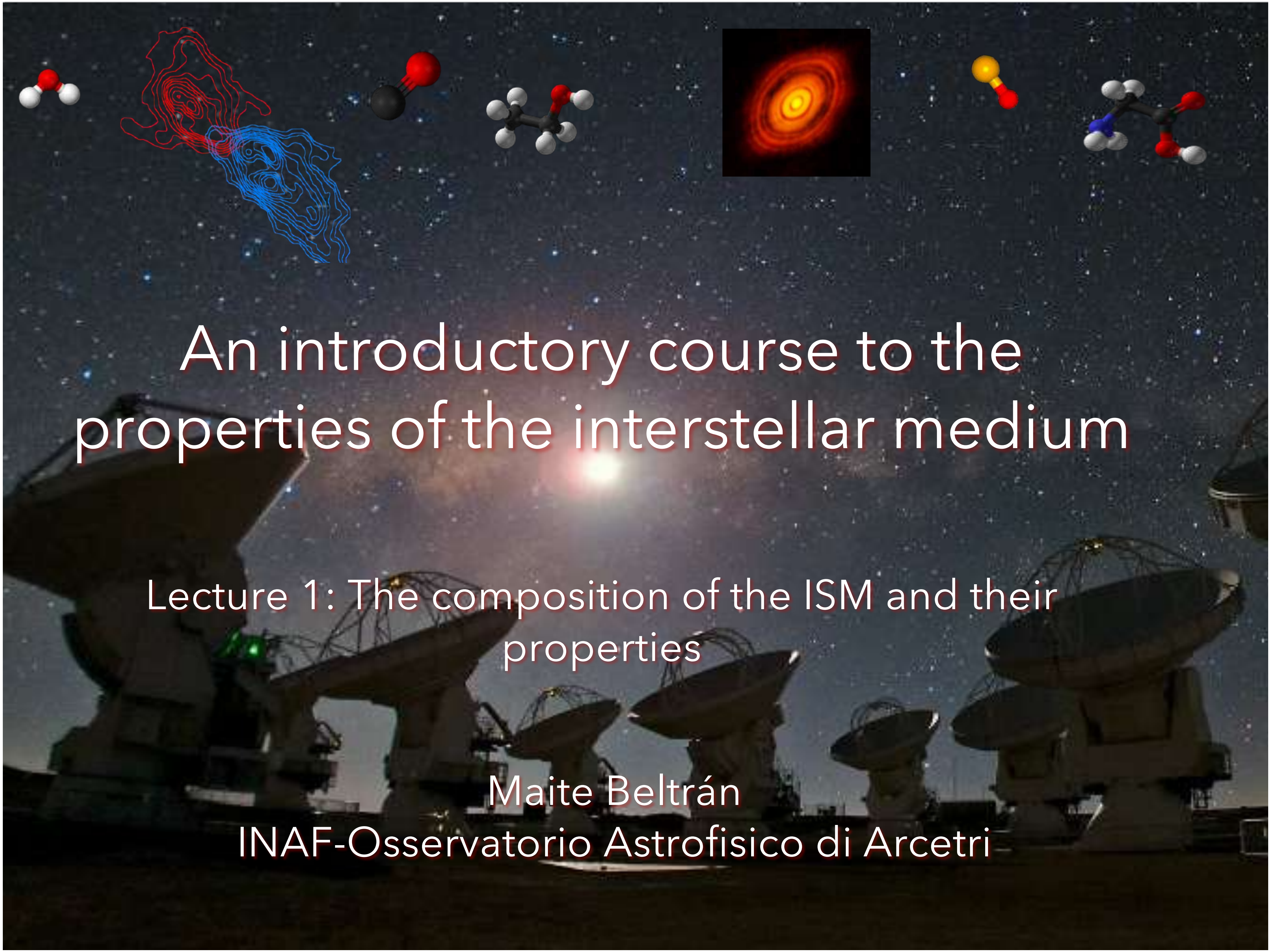

An introductory course to the properties of the interstellar medium

Lecture 1: The composition of the ISM and their properties

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Summary

1. Definition of interstellar medium
2. Brief historical overview
3. Components of the ISM
4. Detection of molecules
5. Molecular clouds

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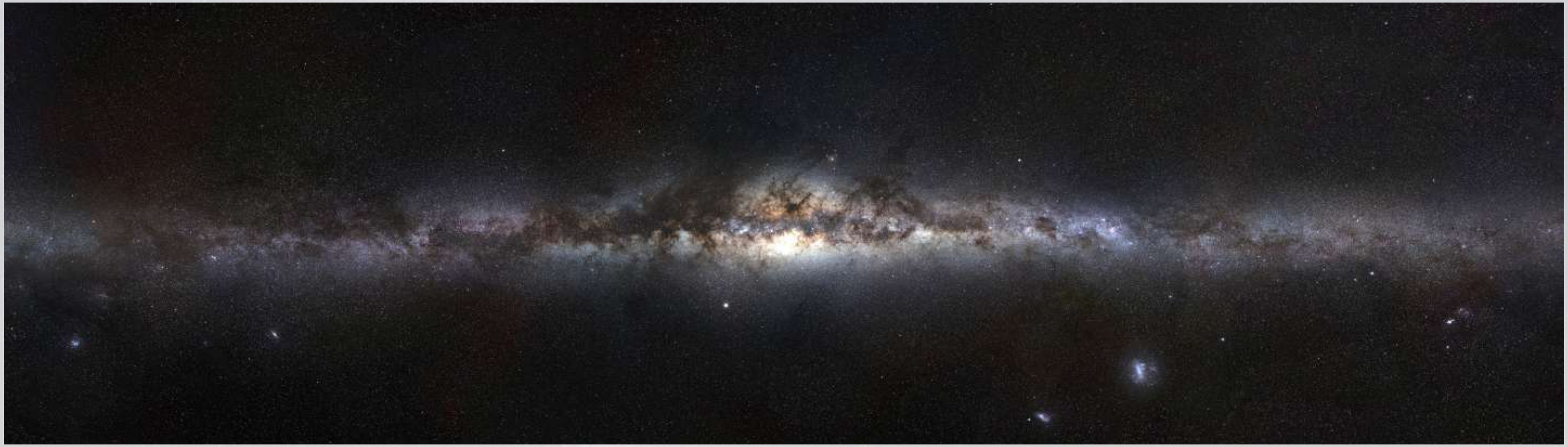
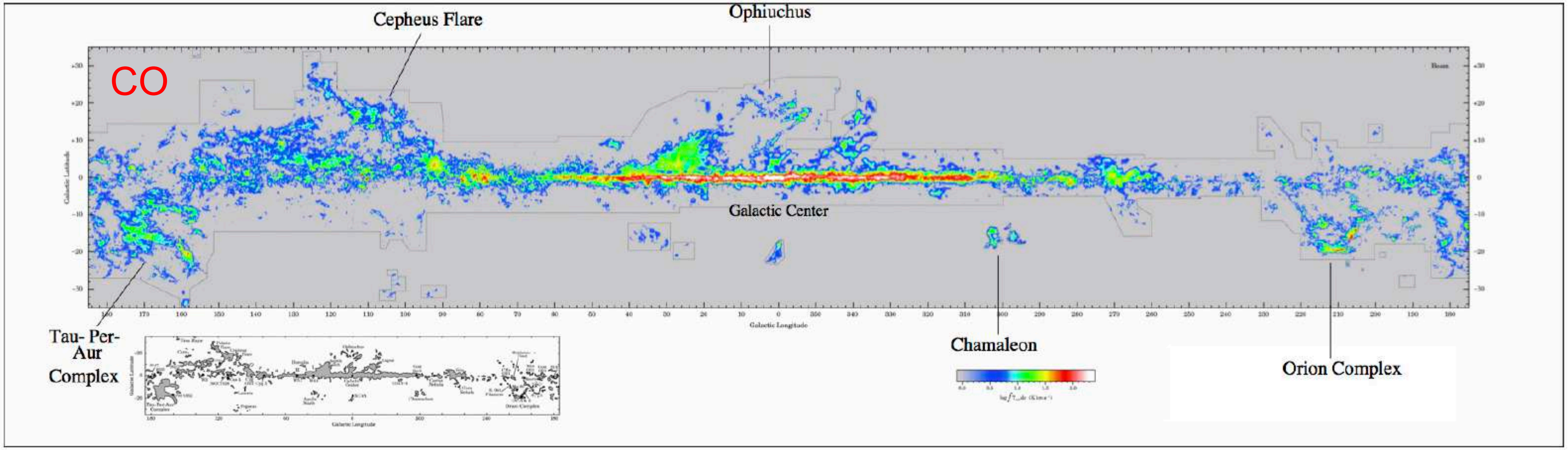
Stars, dust and gas

1. Definition of interstellar medium





1. Definition of interstellar medium

- The Milky Way is composed of 100 billion stars that are quite distant from each other and occupy a small volume.
- The space between stars is called interstellar medium (ISM)

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- The space between stars is called interstellar medium (ISM)

    - Mass: 10-20%
    - it hosts two main components: gas (99%) and dust (1%)
    - **gas composition**: H, He (98% of the mass of the ISM)

      metals (C, O + others; 2%)
    - **gas phases**: atomic, ionized, molecular: H_2 + other molecules (CO, NH_3, H_2O, CH_3OH, ...)
    - **dust**: half of the heavier elements form dust (relatively large grains composed of carbon-containing molecules, e.g., PAHs)
    - **magnetic field** and **cosmic rays**

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2. Brief historical overview

- The first indication of its existence was obtained by Hartmann in 1904 by observing a stationary Ca II absorption line in a spectroscopic binary, δ Orionis. The line appeared stationary in the star's spectrum, meaning that**: *the calcium line does not share in the periodic displacements of the lines caused by the orbital motion of the star*** (binary star)

- Several hypothesis for the origin were proposed and discarded:
    - Earth's atmosphere
    - Binary second component

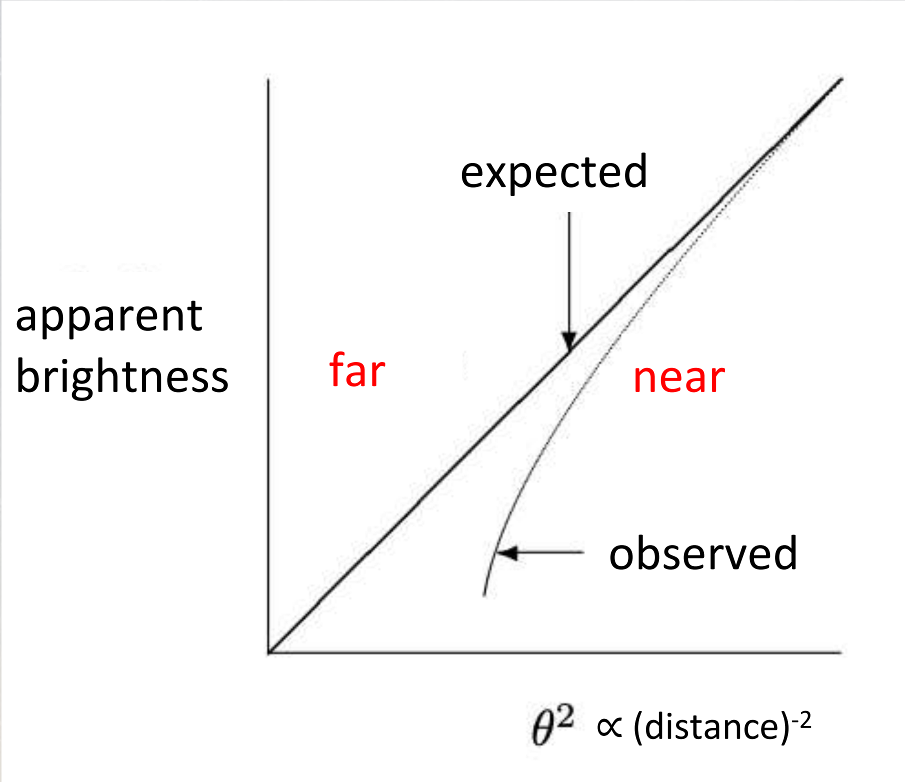
- Final hypothesis: an interstellar *cloud of calcium vapor* located between the Sun and δ Orionis produces the absorption

2. Brief historical overview

- Interstellar dust was observationally discovered by Trumpler in 1930 by studying the relationship between apparent brightness and the angular diameter (θ) of open clusters.

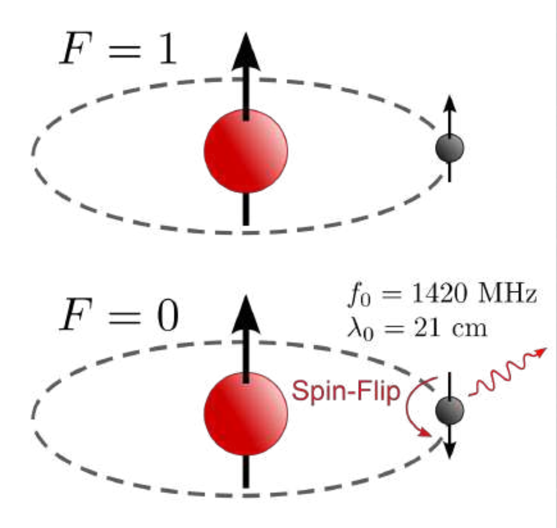
- A linear dependence between brightness and the square of the angular diameter (proportional to 1/distance^2) was expected if the dimensions of open clusters do not depend on their heliocentric distance (clusters of similar constitution have on an average everywhere the same dimensions).

- However, Trumpler found that the most distant clusters were less bright than expected: their light was absorbed by interstellar dust.



2. Brief historical overview

- The modern study of the ISM started when the observational techniques allowed observation at long wavelengths (radioastronomy and FIR astronomy): interstellar dust extinction is not significant and the types of processes characteristic of very cold regions can be studied naturally.
- HI at 21 cm (1420 MHz) was detected in 1951 by Ewen & Purcell at Harvard University.
- In the 60s, the first molecules were detected: OH (1963), NH_3 and H_2O (1968).
- CO, the most important tool to study the H_2 clouds, was detected in 1970.
- CH_3OH, the first complex organic molecule (COM), was detected in 1970.



Hyperfine transition lines for H I are produced when a hydrogen atom with proton and electron spins aligned (top) undergoes a flip of the electron spin

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3. Components of the ISM

- **Gas**
  - Cold atomic medium (H I)
  - Cold molecular medium (H_2)
  - Warm atomic medium (intercloud gas)
  - Photoionized regions (H II)
  - Collisionally/hot ionized medium (coronal gas)

- **Cold/difuse atomic/neutral medium (H I)**

  - Diffuse H I regions are composed of neutral atomic hydrogen (H I), with the presence of some low-excitation ions (C II, Ca II).
  - $T \simeq 50–150$ K, with a typical value of 80 K.
  - Detected by means of the 21 cm line of H I, although the absorption lines of Ca II are also detected against the stellar background.
  - The morphology of diffuse H I regions is cloud-like, with a characteristic size $L \simeq 5$ pc, a density $n(\mathrm{HI}) \simeq 1–100\ \mathrm{cm}^{-3}$, and a mass $M \simeq 50–500\ M_{\odot}$. The internal (turbulent) velocity of the clouds is 1–4 km s^{-1}.
  - The distribution of the clouds has a characteristic height above the Galactic plane $2H \simeq 250$ pc and occupies a small fraction, 2–3%, of the Galactic volume.
  - Their mass is about half the mass of the ISM.

- **Cold molecular medium (H_2)**

  - Molecular clouds are mainly composed of molecular hydrogen (H_2), with traces of other molecules (CO, NH_3, H_2O,….).
  - $T \simeq 10–30$ K. They are mainly detected from the emission of CO rotational transitions, which have an energy of the order of the thermal energy of the region ($\Delta E \simeq kT$).
  - Typical sizes $L \simeq 5$ pc, $n(H_2) \simeq 10^3–10^5$ cm^{-3} and $M \simeq 1000$ up to 10^6 $M_\odot$. The turbulent velocity of molecular clouds is typically ~ 1–5 km s−*1*.
  - Distribution of molecular clouds close to the Galactic plane, $2H \simeq 120$ pc, and they occupy a small fraction ~ 2% of the Galactic volume.
  - Their mass is about half the mass of the ISM.
  - Molecular clouds are the sites of star formation.

3. Components of the ISM

- **Warm atomic/neutral medium (intercloud gas)**

  - The intercloud gas is composed of hot atomic hydrogen (H I), with an ionization fraction of 10–20%.
  - $T \simeq 5000–6000$ K and it is detected by the 21 cm line of H I.
  - Its density is more or less uniform, with a low value of $n(\mathrm{HI}) \simeq 0.1–1$ cm^{-3}.
  - It is distributed at a great height above the Galactic plane, $2H \simeq 400$ pc, and occupies approximately half of the Galactic volume.

- **Photoionized regions (H II)**
  - H II regions are formed by photoionized hydrogen around young stars. They are found within molecular clouds and are regions created and maintained by stellar ultraviolet photons. They are detected from free-free emission in the continuous spectrum and from recombination lines.
  - $T \simeq 5000$–10000 K, with a typical value of 8000 K.
  - $M \simeq$ few 100s to $10^5\ M_\odot$.
  - Typical densities are $n \simeq 10^2$–10^4 cm^{-3} and their sizes are $L \simeq 1$ pc
  - Distribution of H II regions close to the Galactic plane

- **Collisionally/hot ionized medium (coronal gas)**

  - Coronal gas is formed by collisional ionization of hydrogen due to the extremely high temperatures ($T \simeq 10^5$–10^6 K) in the region. It is detected based on its soft X-ray emission (0.1–2 keV).

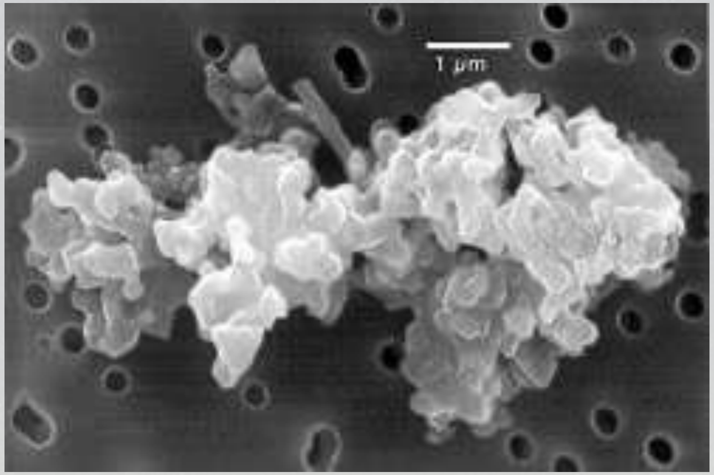
  - Coronal gas is produced by supernova explosions. The shock wave heats the gas as it passes through to temperatures of 10^6–10^7 K, and the gas takes a long time to cool down.

  - Its characteristic height above the Galactic plane is $2H \simeq 700$ pc. Coronal gas occupies approximately 50% of the Galactic volume.

3. Components of the ISM

Component	Fractional Volume (%)	Temperature (K)	Mass ($M_\odot$)	Density (cm^{-3})	Scale height, 2H (pc)	State of Hydrogen	Observational techniques
Diffuse H I region	2-3	50-150	50-500	1-100	250	neutral atomic	H I line absorption
Molecular clouds	~2	10-30	$1000\text{-}10^6$	$10^3\text{-}10^5$	120	molecular	CO and molecular lines
Intercloud gas	50%	5000-6000	50%	0.1-1	400	neutral atomic	H I line emission
H II regions	negligible	$5000\text{-}10^4$	$100\text{-}10^5$	$10^2\text{-}10^4$	80-100	ionized	free-free, radio recombination lines, Hα
Coronal gas	50%	$10^5\text{-}10^6$	0.1%	$10^{-4}\text{–}10^{-2}$	700	ionized	X-ray, absorption lines of highly ionized metals

- **Dust**



  - Interstellar dust consists of grains with a characteristic size of 0.1µm, which is on the order of the wavelength of visible light.
  - Its effects are: **extinction** of starlight, **reddening** due to differential extinction (blue light undergoes more extinction than red light), and **interstellar polarization**.

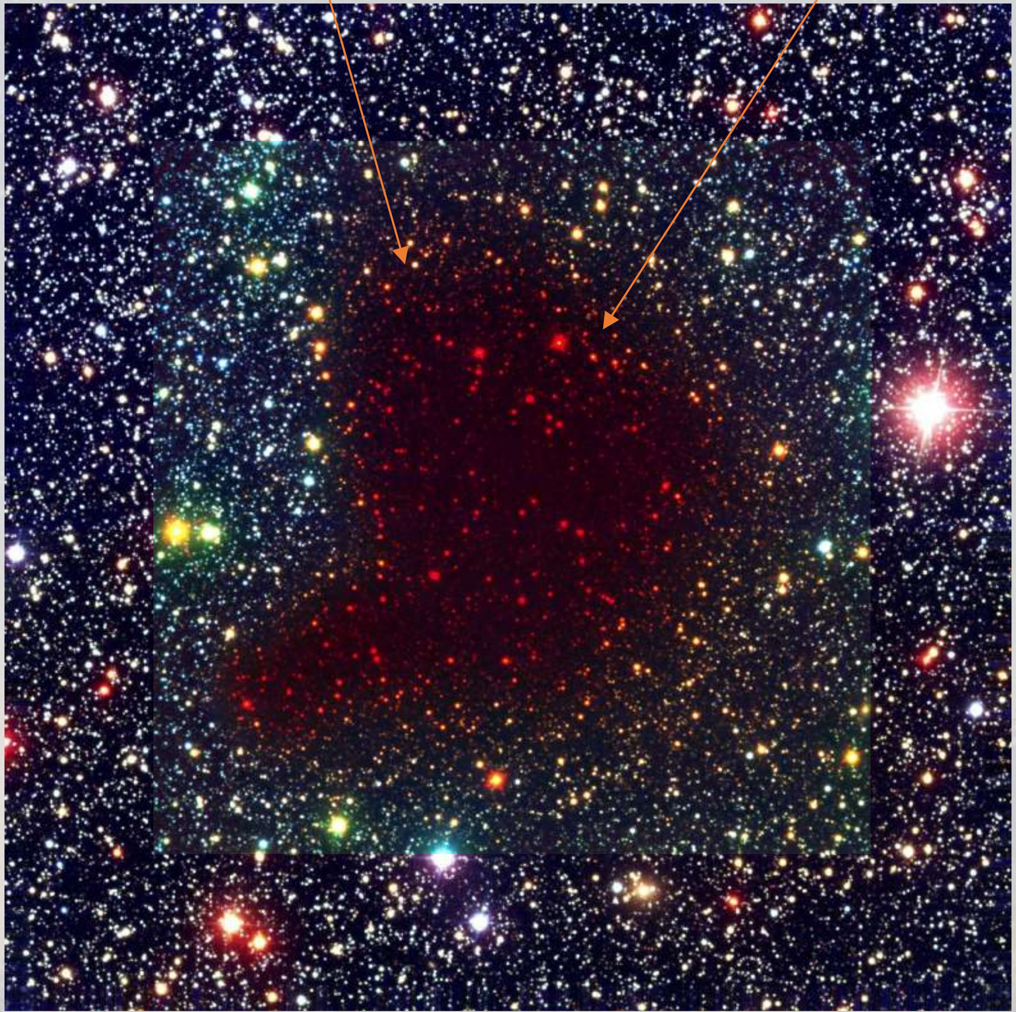
- **Dust**

    - Dust only makes up about 1% of the ISM but is very good at absorbing visible light, particularly toward the blue end of the spectrum. As a result, starlight shining through a cloud of dust appears redder, and sometimes can be blocked entirely.

    - Dust clouds are studied at radio and infrared wavelengths, because the emission is optically thinner at those wavelengths and light passes through dust clouds more easily.

Gas and dust absorb almost all the visible light from the background stars

The dust produces reddening



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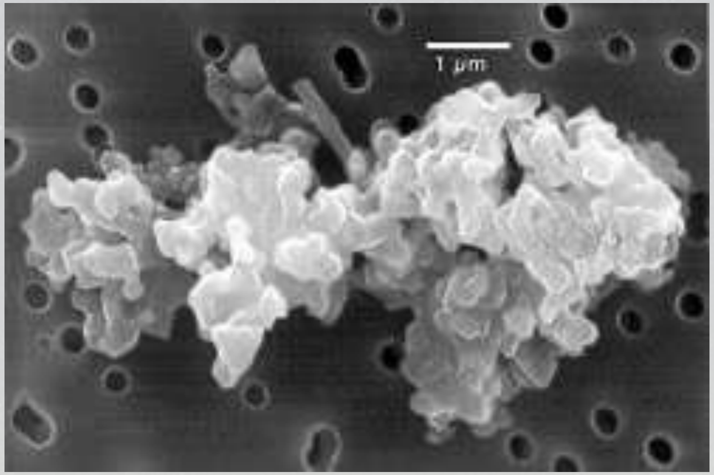
- Its effects are: **extinction** of starlight, **reddening** due to differential extinction (blue light undergoes more extinction than red light), and **interstellar polarization**.
- Extinction is ∝ 1/λ in the visible region of the spectrum, with a peak in the UV at 2200 Å. A typical value for extinction in the Galaxy is ~ 1 mag/kpc.
- There is a good correlation between the column density of molecular gas and the visible extinction produced by interstellar dust, A_v

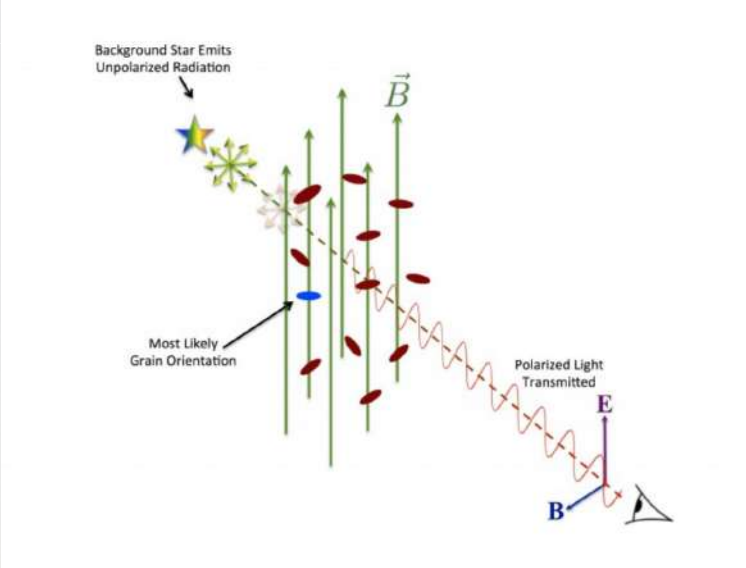


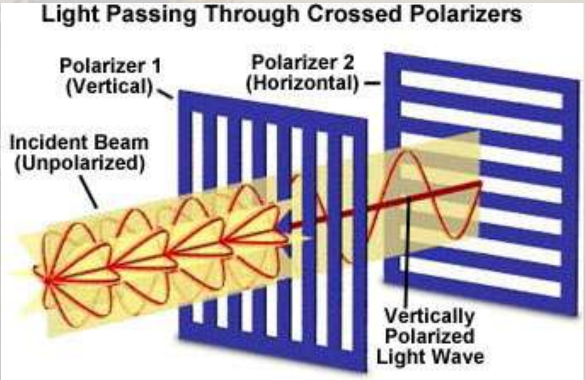
$$\left[\frac{N(H_2)}{cm^{-2}}\right] \simeq 10^{21} \left[\frac{A_v}{mag}\right]$$

- **Dust**

  - To explain **interstellar polarization**, we assume that dust grains are elongated and partially aligned. The latter is explained by the rotation of the grains, which tends to occur around an axis in the direction of the local magnetic field (dust grains aligned with their minor axes parallel to the local magnetic field.)

  - As starlight interacts with the interstellar dust, part of it becomes absorbed by the dust grains, which preferentially absorb light along their long axis. This causes the light to become polarized along the short axis of the grain. As dust grains are aligned with their short axis along the direction of the local magnetic field, the starlight's polarization is also parallel to the magnetic field.



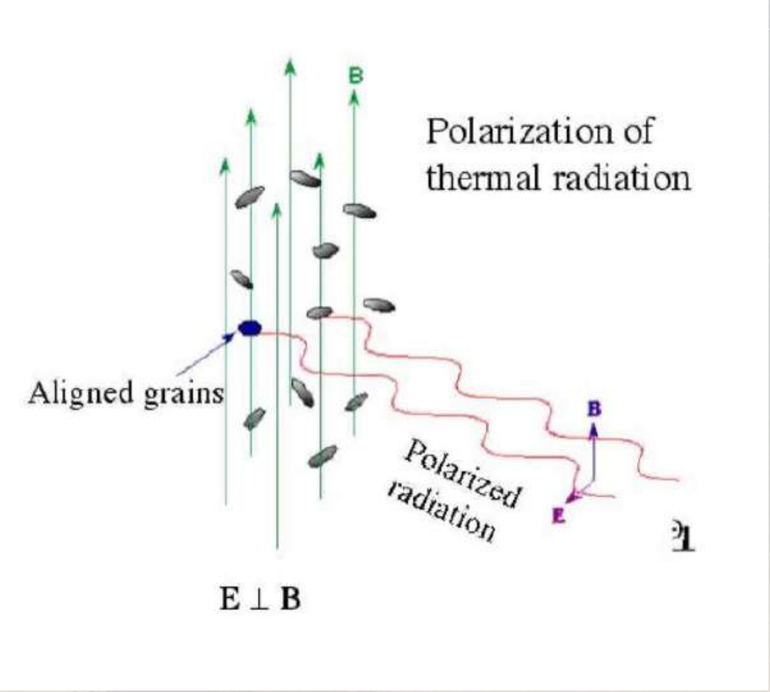


3. Components of the ISM

- **Dust**

  - The light that is absorbed by the dust grains is not lost: it heats the grains and is re-emitted as thermal (black-body) radiation.

  - In emission, light emerges preferentially along the long axis of the dust grains. So the polarization of the thermal dust emission is perpendicular to the magnetic field.



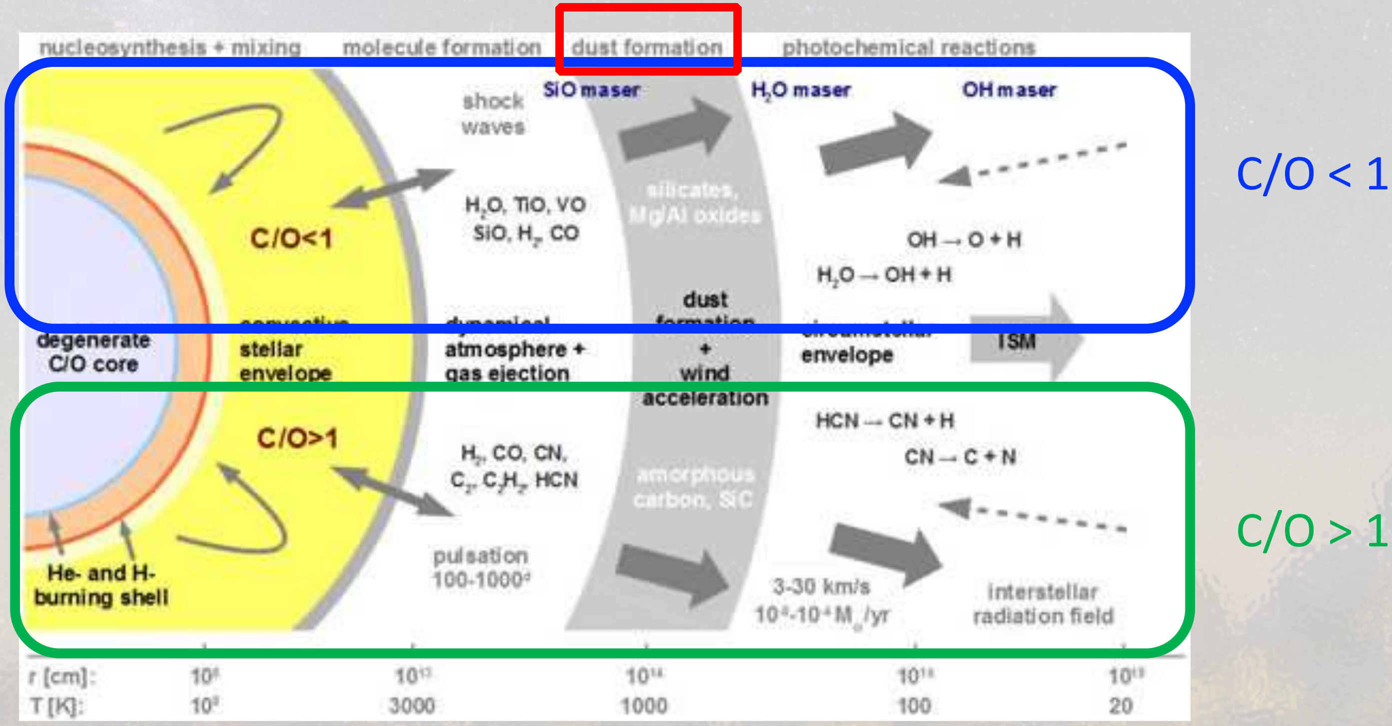
3. Components of the ISM

- **Dust**

  - Cosmic dust originates primarily in the envelopes of cool evolved stars (AGBs) and supernovae (SNe) explosions. These stars eject material, including elements like carbon, oxygen, silicon, and iron, into space. As this gas cools, these elements condense and form molecules, which then clump together to create dust particles.

The stellar winds from AGB stars are sites of cosmic dust formation, and are believed to be the main production sites of dust in the universe.

In the dust formation zone, refractory elements and compounds (Fe, Si, MgO, etc.) are removed from the gas phase and end up in dust grains.



- **Dust**

  - Interstellar dust is associated with molecular gas and is therefore found in molecular clouds.
  - Dust grains play an important role in the formation of some molecules (among them, the most abundant, H_2) and in their preservation once formed by protecting them from ultraviolet radiation.

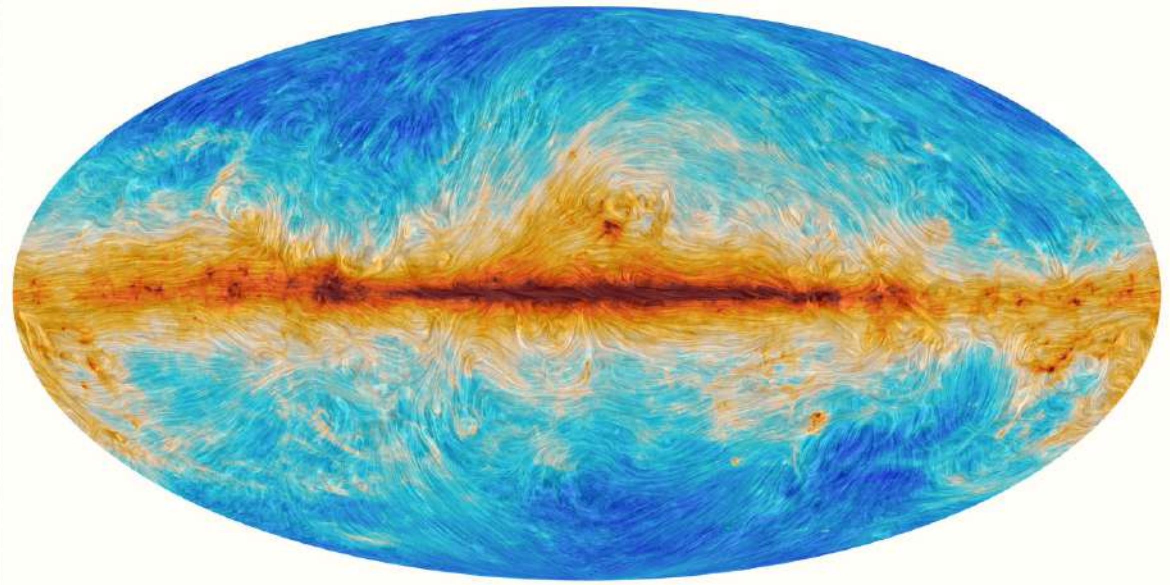
Continuum emission from dust a different temperatures

Blue PACS 70 micron
Green 160 micron
Red SPIRE 250 micron

3. Components of the ISM

- **Magnetic field**

  - Magnetic fields are everywhere and influence the ISM in many different ways.
  - The physical conditions in the ISM are significantly affected by the coupling of charged particles to the magnetic field.
  - Their role in many astrophysical processes is usually neglected because it is difficult to take into account/quantify.

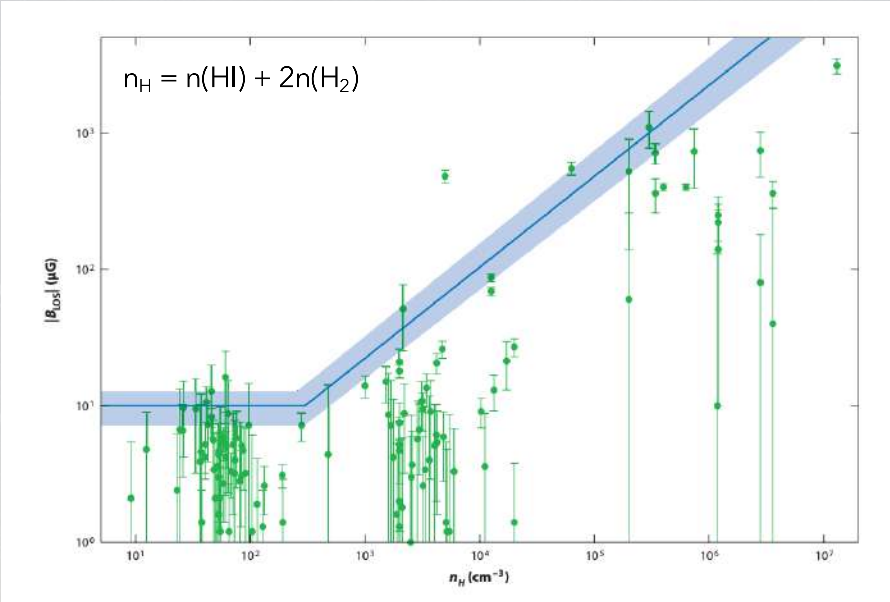


Planck Collaboration (2014)

- **Magnetic field**

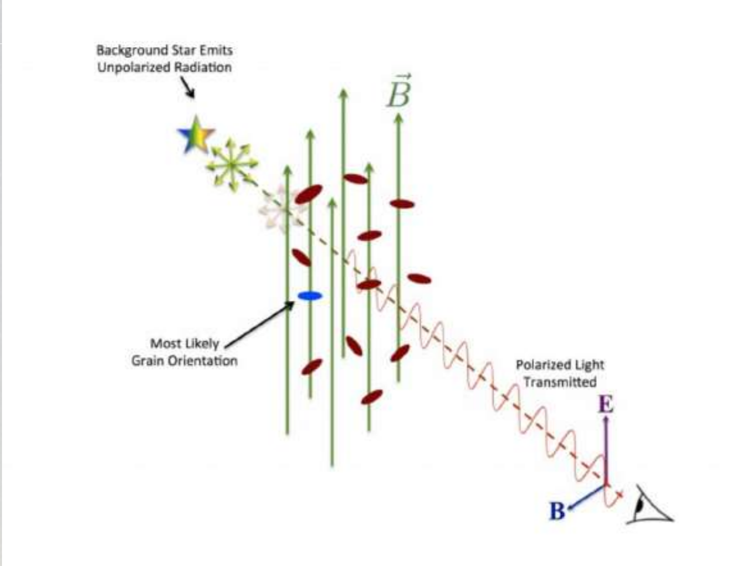
  - The Galactic magnetic field strength varies cross different regions, but on average, it is of the order a few μG (2-3 μG), quite weak compared to Earth's magnetic field (0.2-0.6 G).
  - Its strength depends on the density of the interstellar medium, $B \propto n^{\alpha}$, with α = 1/3–2/3, although there are significant local variations.
  - In star-forming regions, *B* can can reach 1 mG in filamentary structures and ~ 10 mG in massive star-forming cores (e.g G31.41+0.31: Beltrán et al. 2024)

B vs. n_H for diffuse and molecular clouds



Crutcher (2012)

- **Tools to measure the magnetic field**



- <u>Dust linear polarization observations</u>:
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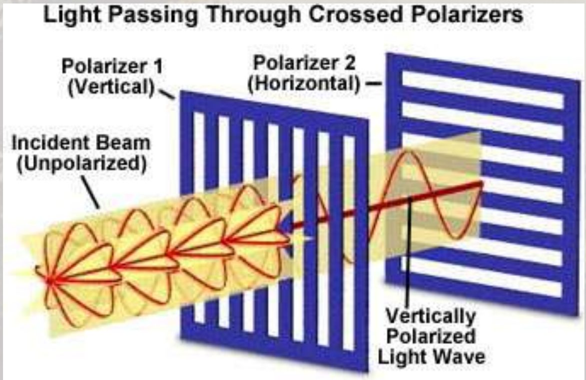

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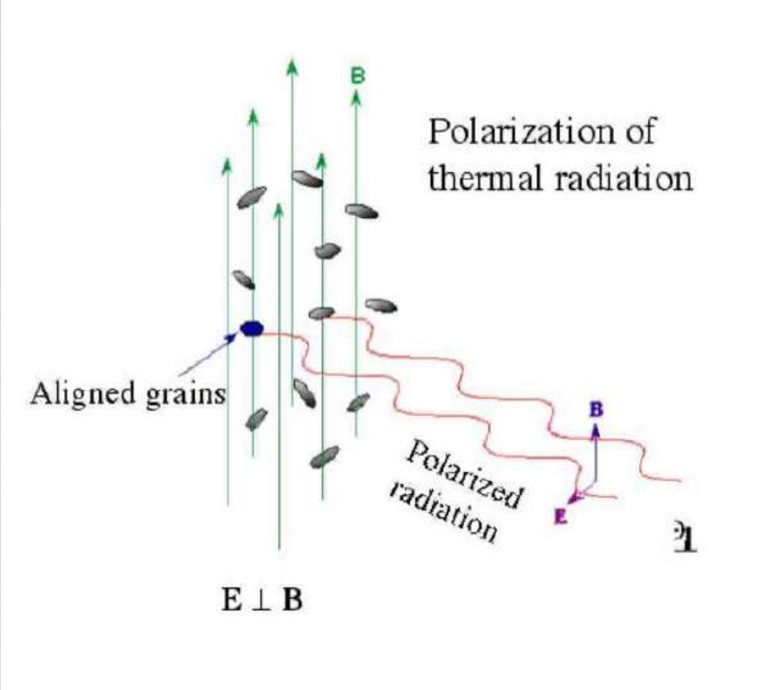

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- **Tools to measure the magnetic field**

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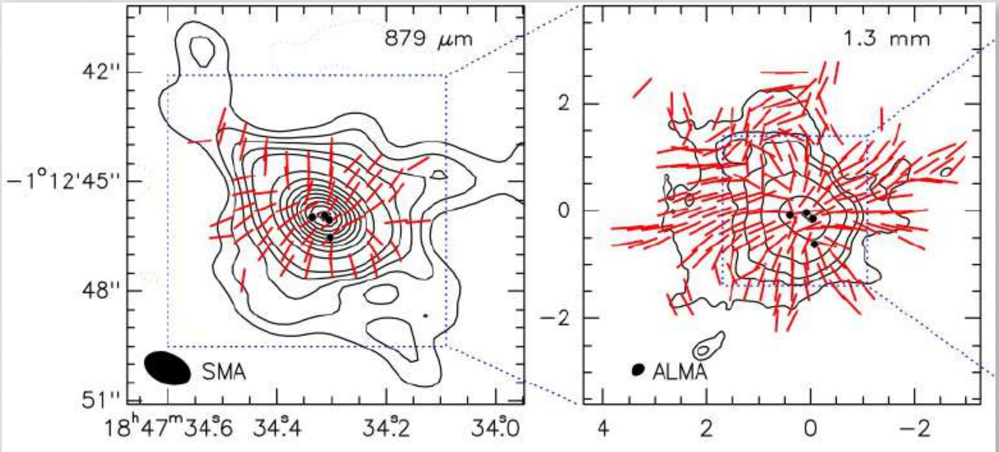
  - In emission, light emerges preferentially along the long axis of the dust grains. So the polarization of the thermal dust emission is perpendicular to the magnetic field.
  - Linearly polarized dust emission observations at (sub)mm λ's are the most used technique to probe the magnetic field morphology in star-forming regions.

G31.41+0.31

Beltrán+ (2019)



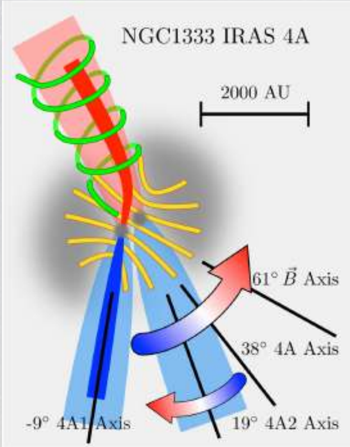
SMA @ 1" (3750 au) ALMA @ 0.24" (900 au)

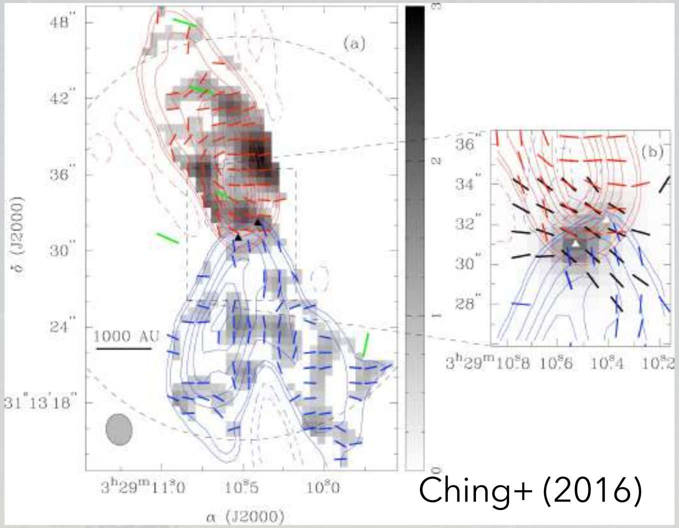
* Dust polarization can also be produced by scattering (in very high dense regions with large dust grains) → polarization ≠ magnetic field

- **Tools to measure the magnetic field**

NGC1333 IRAS4A

  - <u>Linear polarization of thermal lines</u>: Goldreich-Kylafis effect. Linear polarization of spectral line radiation (CO, CS) under anisotropic conditions (Goldreich & Kylafis 1981) trace the magnetic field direction. Ambiguous interpretation (polarization can be ∥ or ⊥ or perpendicular to the magnetic field)





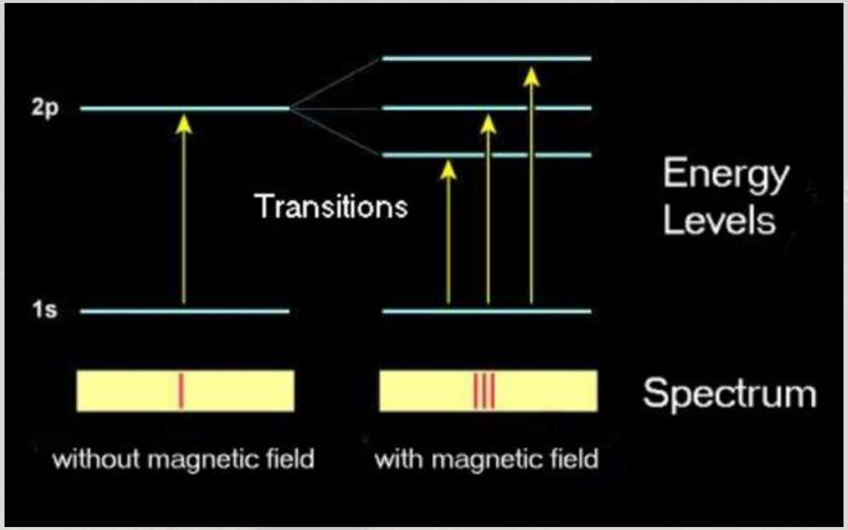
Ching+ (2016)

CO linear polarization in a low-mass core

- **Tools to measure the magnetic field**

  - Circular polarization of thermal (maser) lines: the only direct way to estimate the B-field strength is through Zeeman splitting of spectral lines of paramagnetic species (CN, SO, C_2H) in the presence of a magnetic field (observed either in absorption or emission).

  - This splitting occurs because the magnetic field interacts with the magnetic dipole moment of the atom, causing their atomic energy levels to shift and split and resulting in distinct spectral lines.



3. Components of the ISM

- **Tools to measure the magnetic field**

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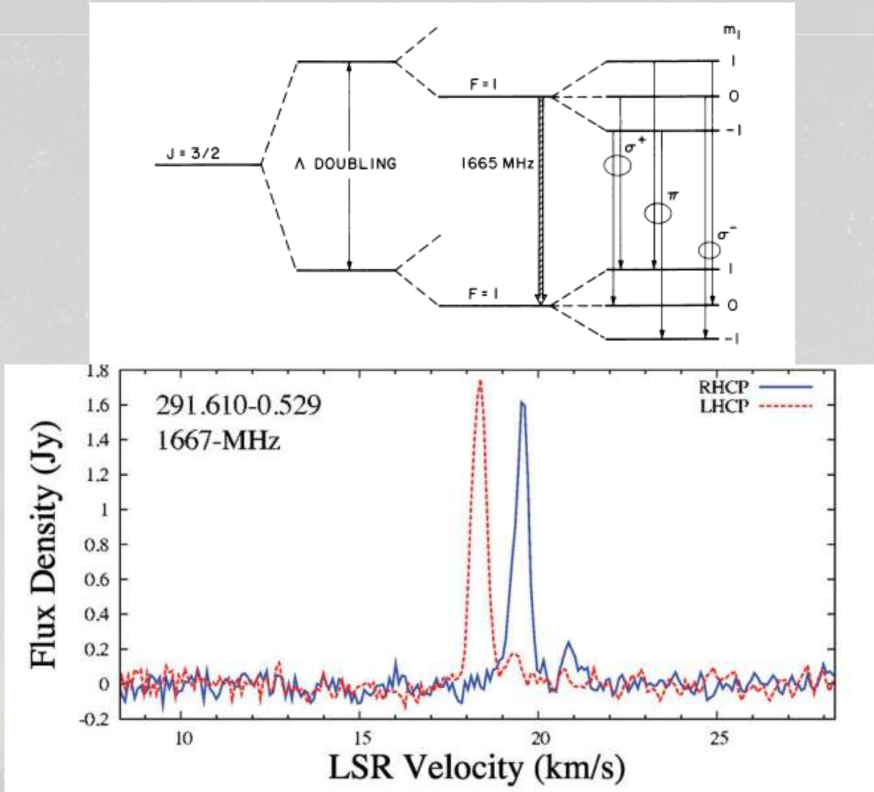
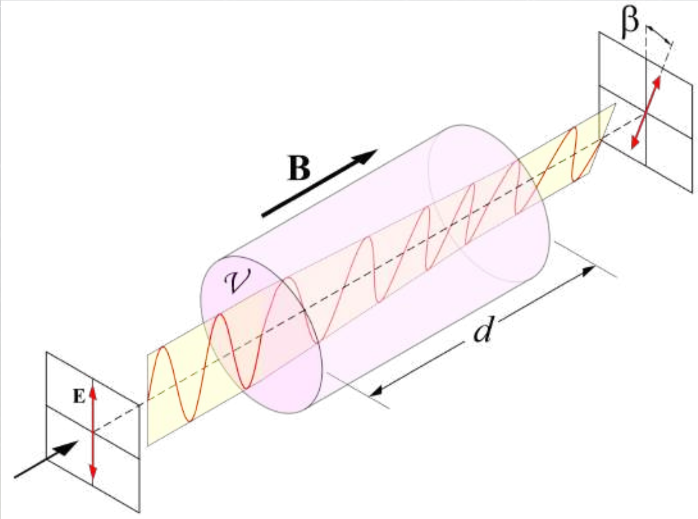
  - Clearly observed in masers (H_2O, OH), also for linear polarization



Zeeman effect splitting the 1665 MHz line in the OH 2 Π 3/2 ground state with different transitions possible

- **Tools to measure the magnetic field**

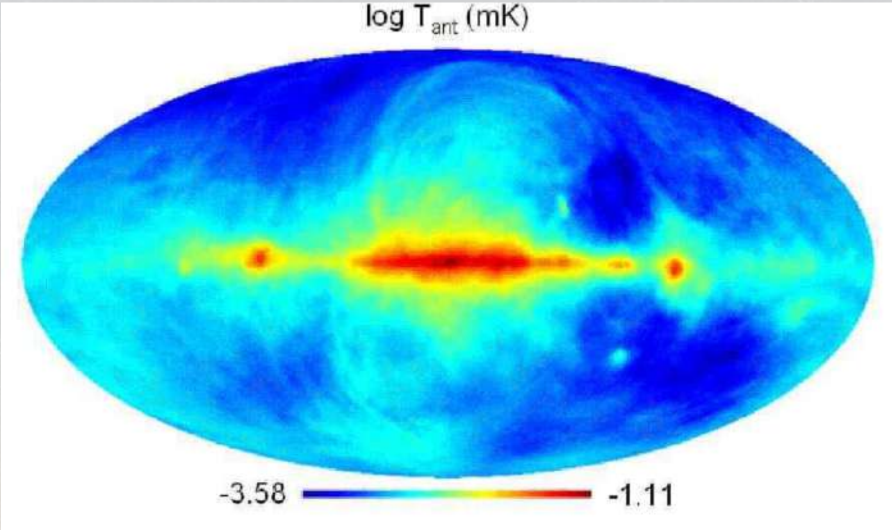
- <u>On Galactic scales: Faraday rotation</u>
- The Faraday effect is caused by left and right circularly polarized waves propagating at slightly different speeds.
- It causes a polarization rotation which is proportional to the projection of the magnetic field along the direction of the light propagation.
- The magnetic field can be estimated from rotation measures (RM) if the electron number density in the ISM is known.
- The rotation angle β is directly proportional to the parallel component of the field as well as to the square of wavelength



$$\beta = RM \cdot \lambda^2$$

- **Tools to measure the magnetic field**

  - <u>On Galactic scales: polarization of diffuse synchrotron radiation</u>
  - Diffuse synchrotron radiation is polarized due to the emission from relativistic electrons spinning around Galactic magnetic field lines.
  - Significant tracer of magnetic field strength and orientation by measuring the total radio intensity and polarization respectively.



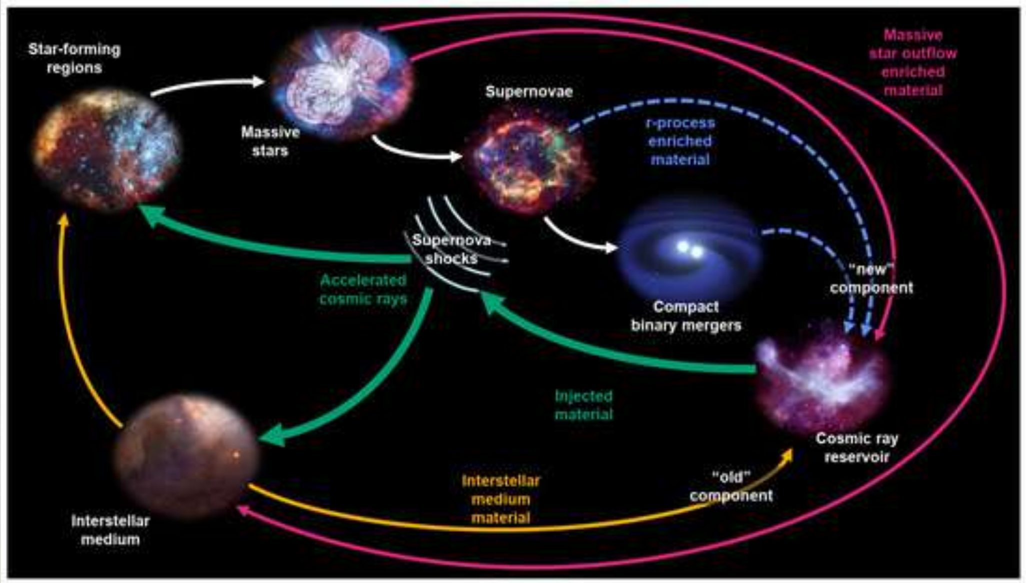
Map of the Galactic diffuse synchrotron emission

- **Cosmic rays**

  - The entire galaxy is traversed by relativistic particles, especially high-energy electrons, protons, and atomic nuclei (can also contain high-energy photons such as gamma rays, and neutrinos) primarily originating from supernovae.

  - The acceleration of electrons in the Galactic magnetic field produces Galactic synchrotron background radiation, concentrated in the Galactic plane, with a maximum in the direction of the Galactic center.

  - Their interactions with the ISM are crucial for understanding Galactic evolution. These high-energy particles influence the dynamics, turbulence, and evolution of the ISM, affecting chemistry, star formation, and other Galactic processes.



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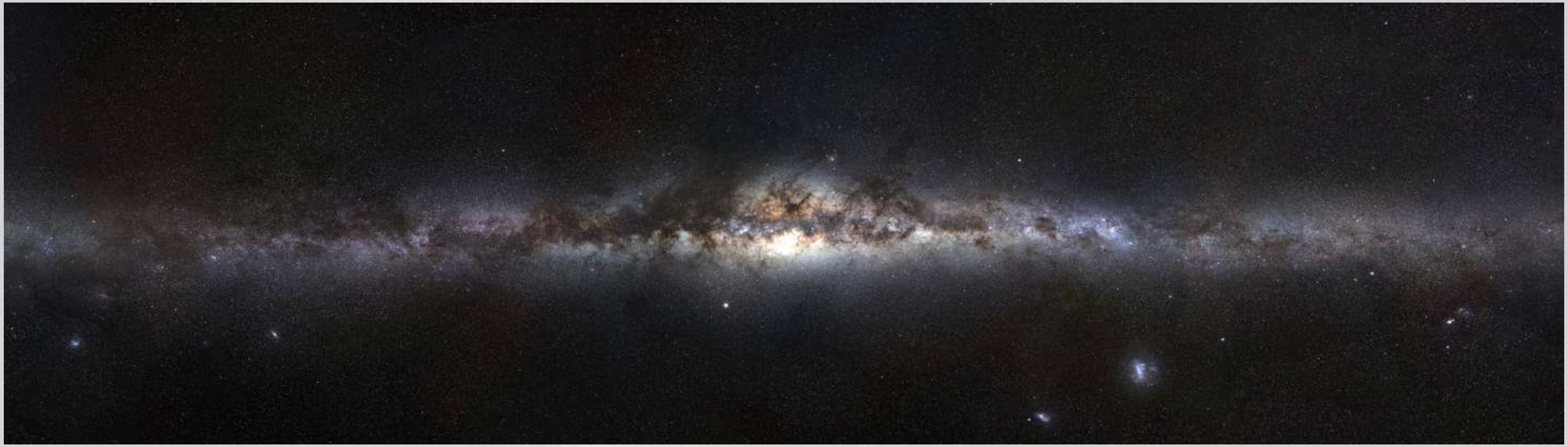
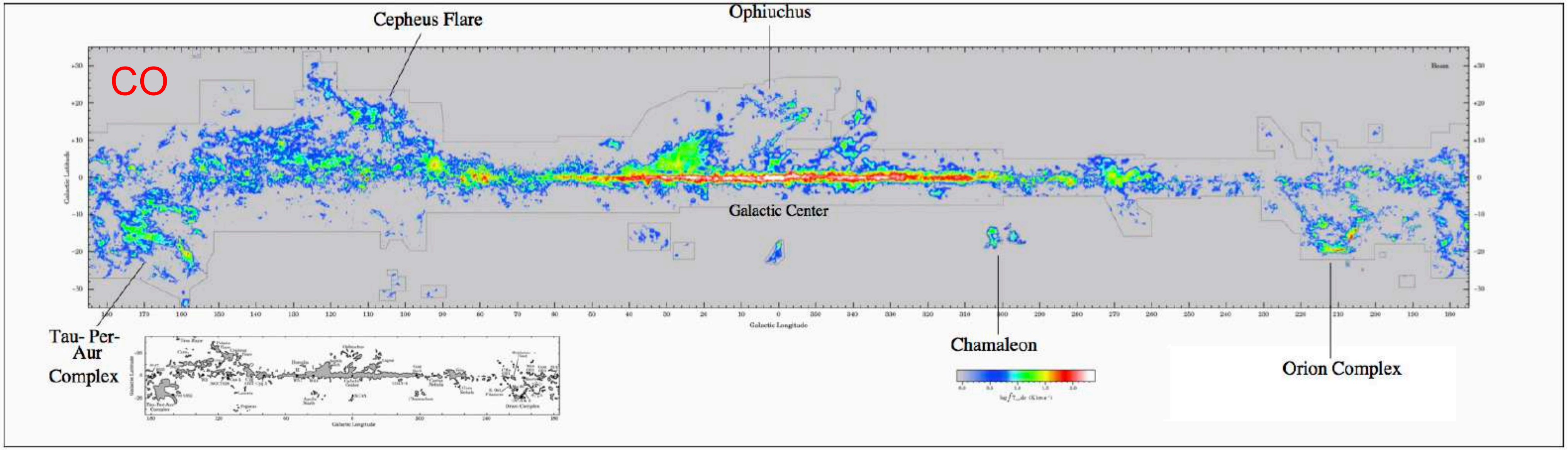
4. Detection of molecules



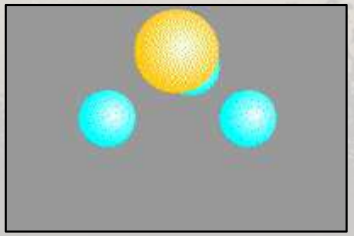


4. Detection of molecules

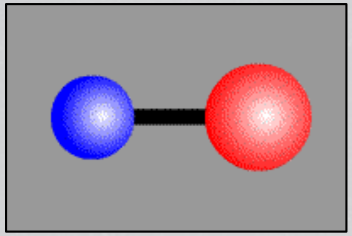
- The atoms in molecules can vibrate or rotate around an axis, emitting or absorbing pulses of energy known as photons at a certain frequency (radio, sub-millimeter, IR)

- We study interstellar molecules by observing the spectral lines they emit due to their **rotational** and **vibrational** transitions.

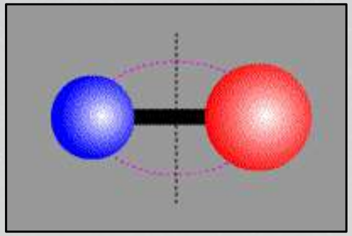
- A three-dimensional molecule such as NH_3 emits electromagnetic radiation by reversing its configuration (inverse transition).



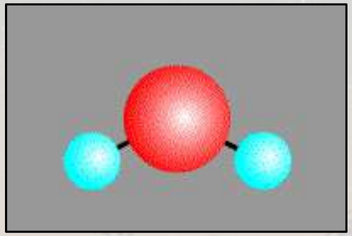
vibrational transition on CO

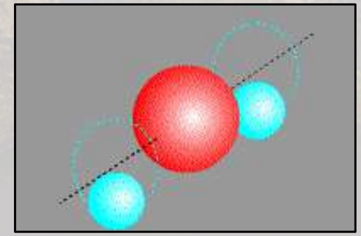


rotational transition o CO



rotational transition of H_2O





4. Detection of molecules

- A molecule can also present electronic transitions (which involve a change in the distribution of the electron cloud). This type of transition also occurs in atoms, while the other two are exclusive to molecules.

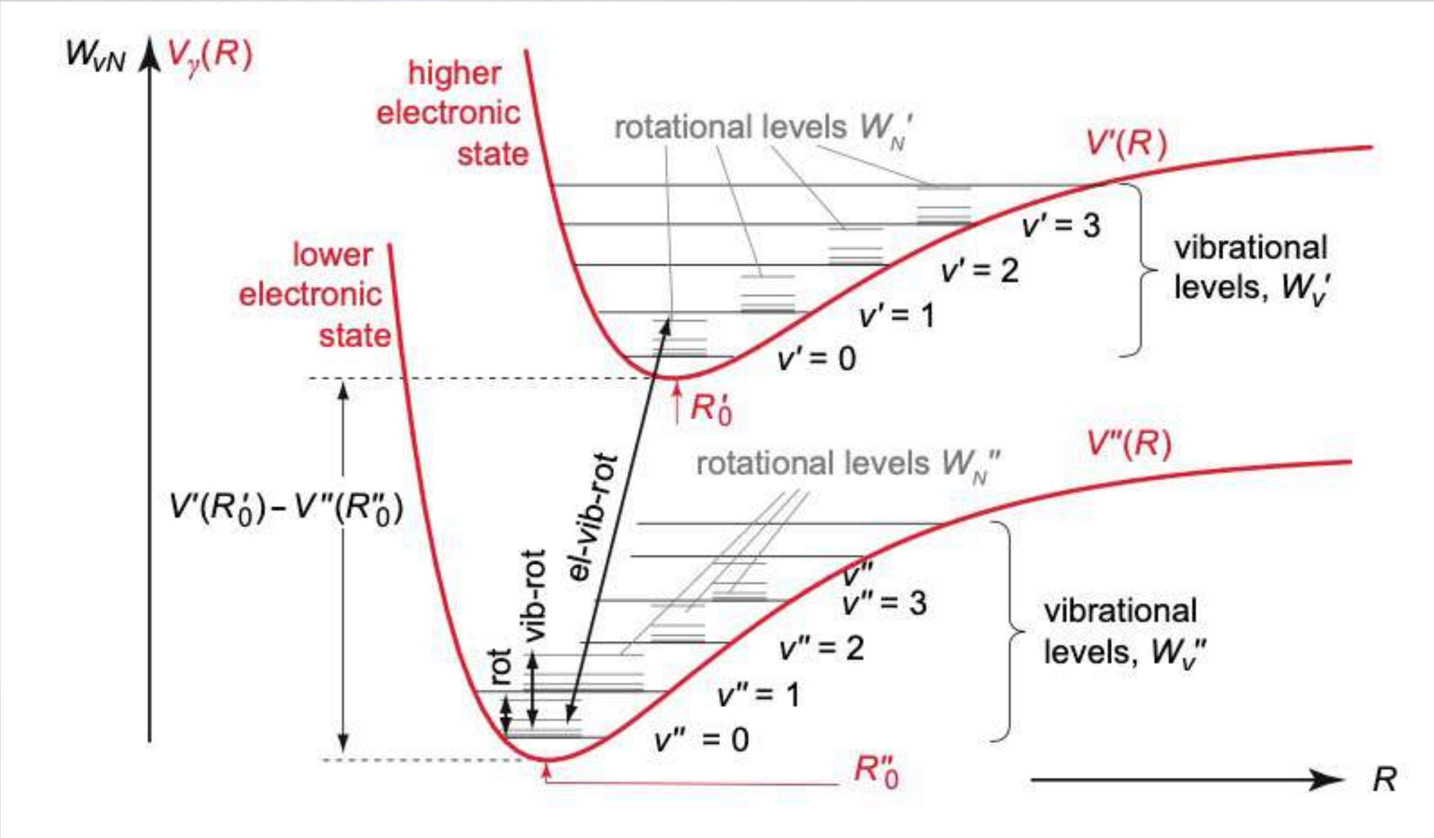
$$E_{tot} = E_{\mathrm{rot}} + E_{\mathrm{vib}} + E_{\mathrm{el}}$$

  - rotational transitions: $T_{\mathrm{rot}} = E_{\mathrm{rot}}/\kappa_B \sim 5$ K
  - vibrational transitions: $T_{\mathrm{vib}} = E_{\mathrm{vib}}/\kappa_B \sim 600$ K
  - electronic transitions: $T_{\mathrm{el}} = E_{\mathrm{el}}/\kappa_B \sim 9 \times 10^4$K

$$E = k_B T = h\nu = \frac{hc}{\lambda}$$

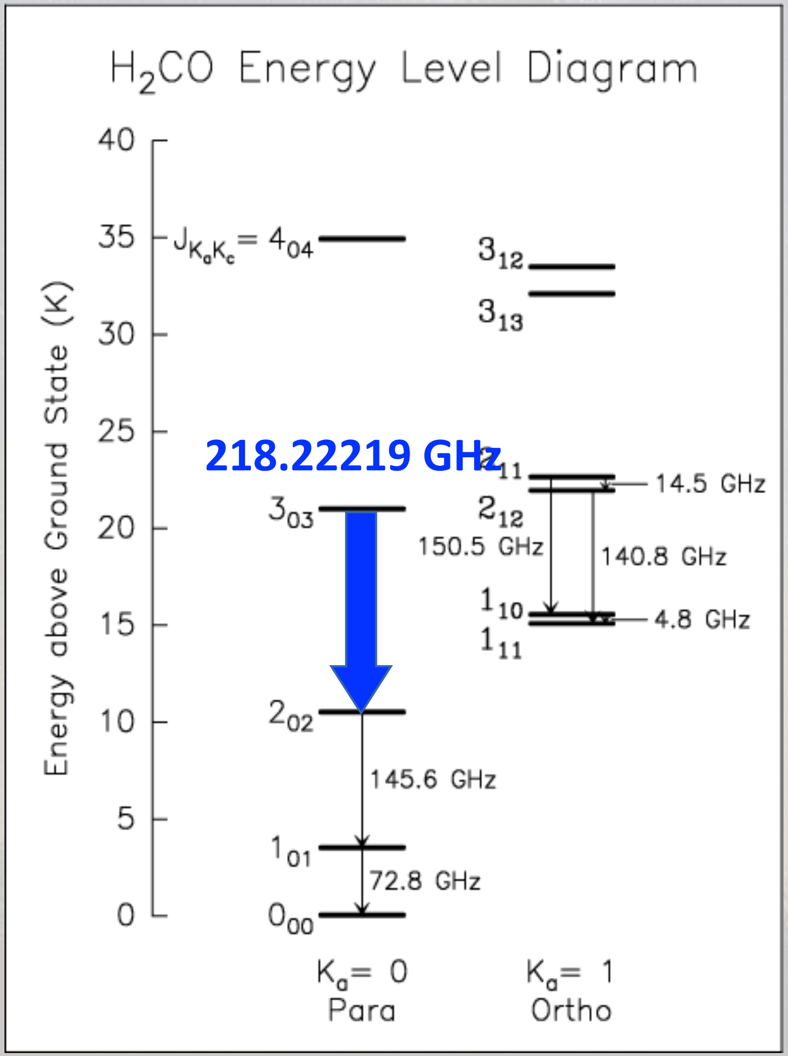
- A molecule can also present electronic transitions (which involve a change in the distribution of the electron cloud). This type of transition also occurs in atoms, while the other two are exclusive to molecules.

$$E_{tot} = E_{\text{rot}} + E_{\text{vib}} + E_{\text{el}}$$



4. Detection of molecules

When the vibrational or rotational state of a certain molecule changes discretely, obeying quantum dynamics, they emit or absorb photons at a certain frequency, producing molecular lines.



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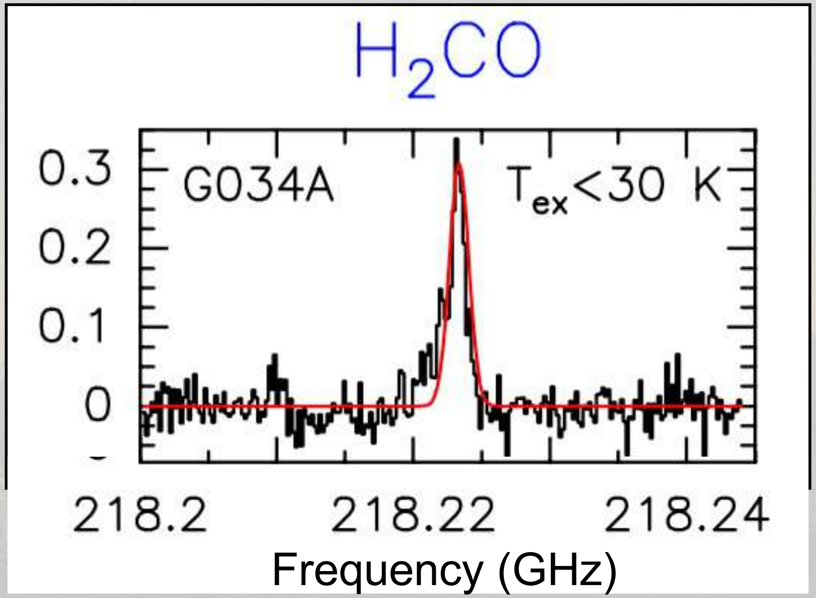
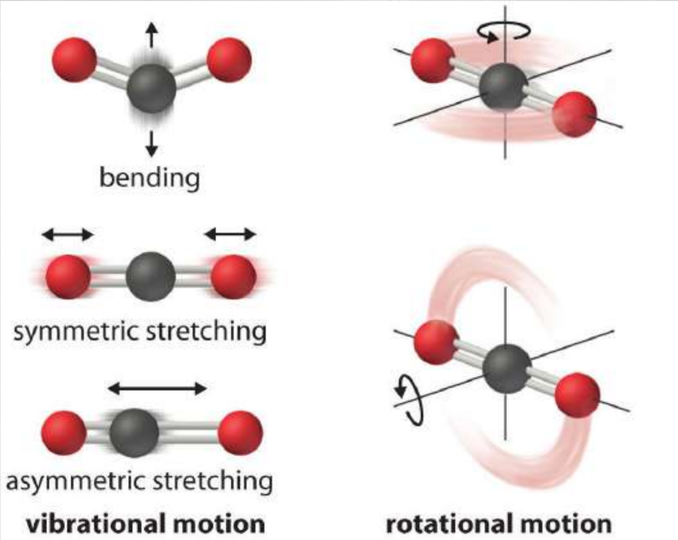
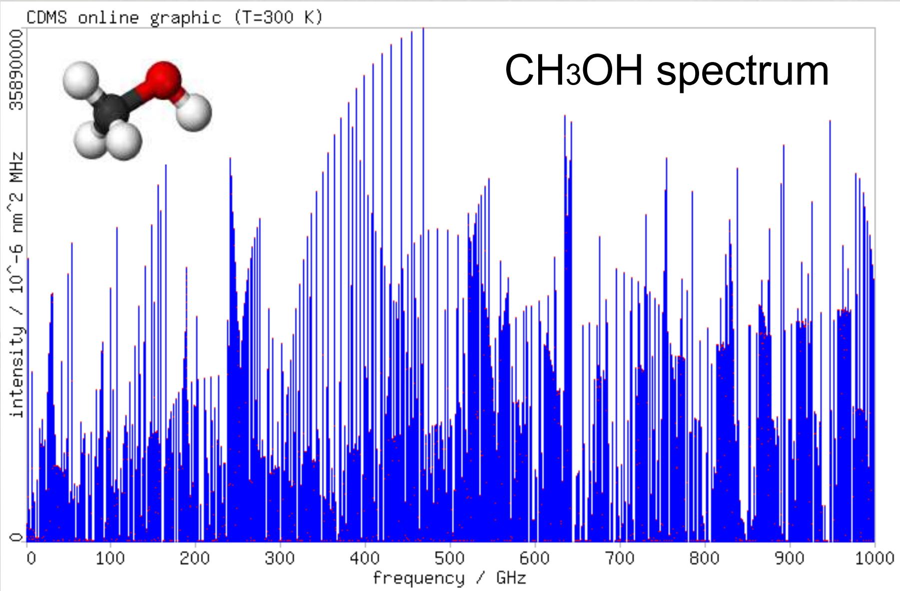
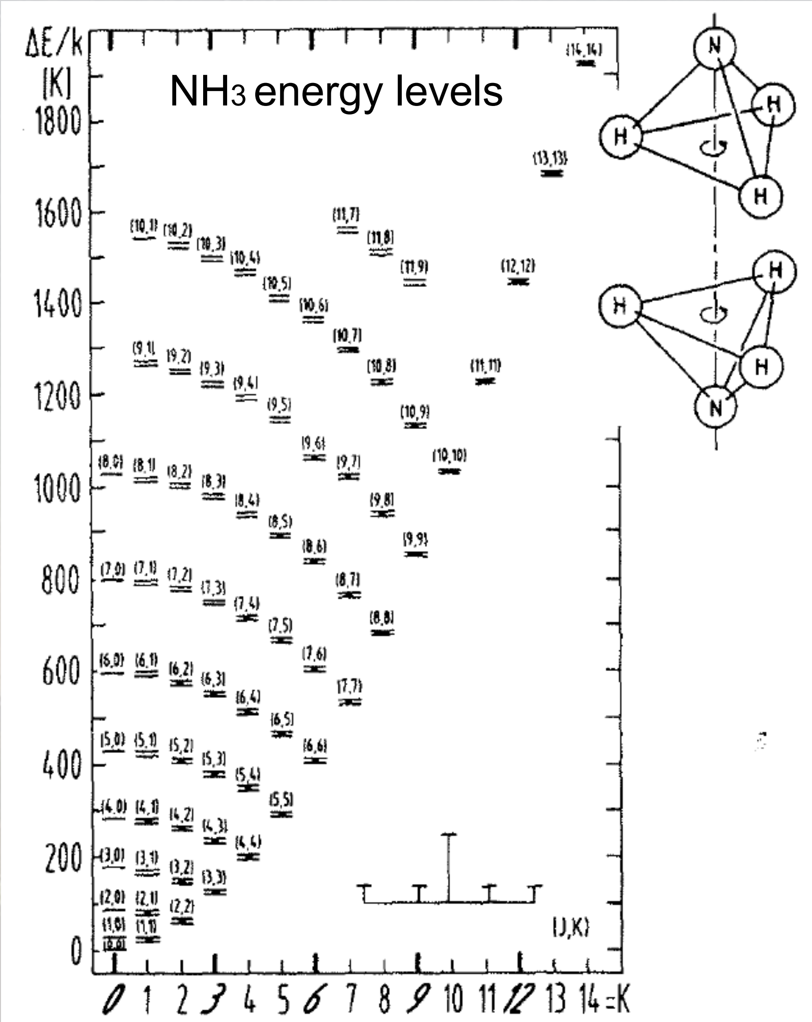


4. Detection of molecules

Each molecule produces a unique spectrum.

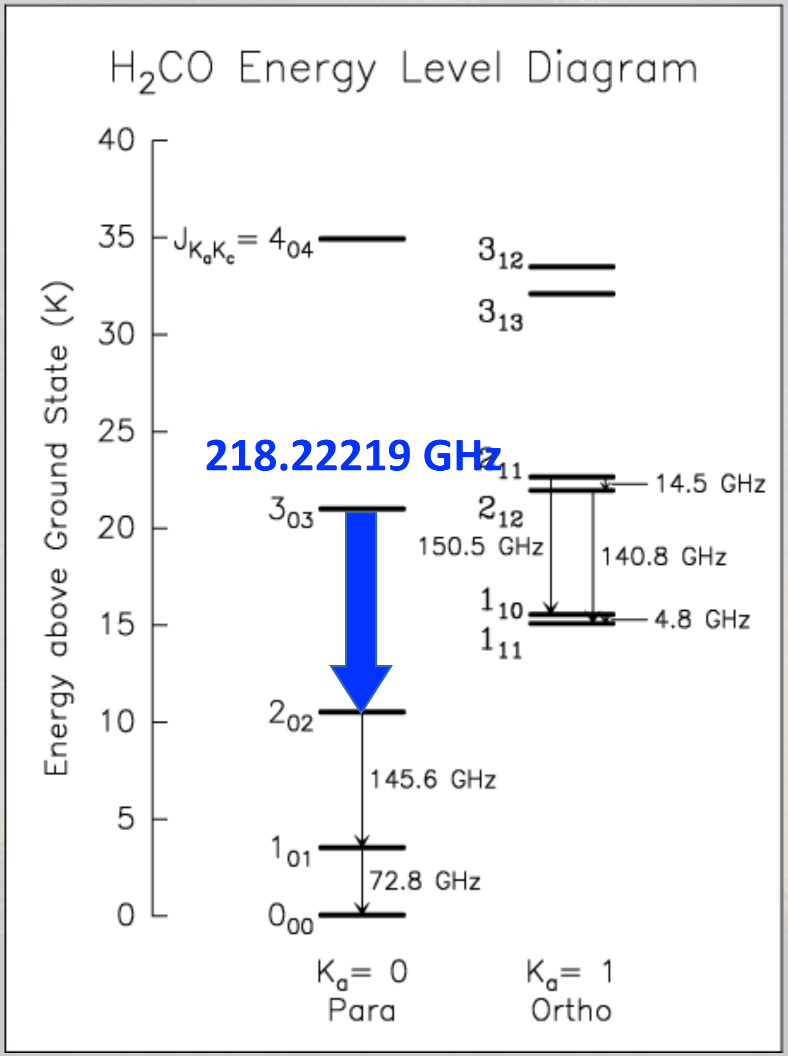






4. Detection of molecules

When the vibrational or rotational state of a certain molecule changes discretely, obeying quantum dynamics, they emit or absorb photons at a certain frequency, producing molecular lines.



$$E = h\nu = \frac{hc}{\lambda}$$

Linear molecule

$E_J = hB_{rot}\, J(J+1)$

$E_{J+1} - E_J = h\nu = h(2J+1)B_{rot}$

where B_{rot} is the rotational constant of a molecule that represents the spacing between its rotational energy levels and it's a function of the moment of inertia I: $B_{rot} = \frac{h}{8\pi^2 I}$

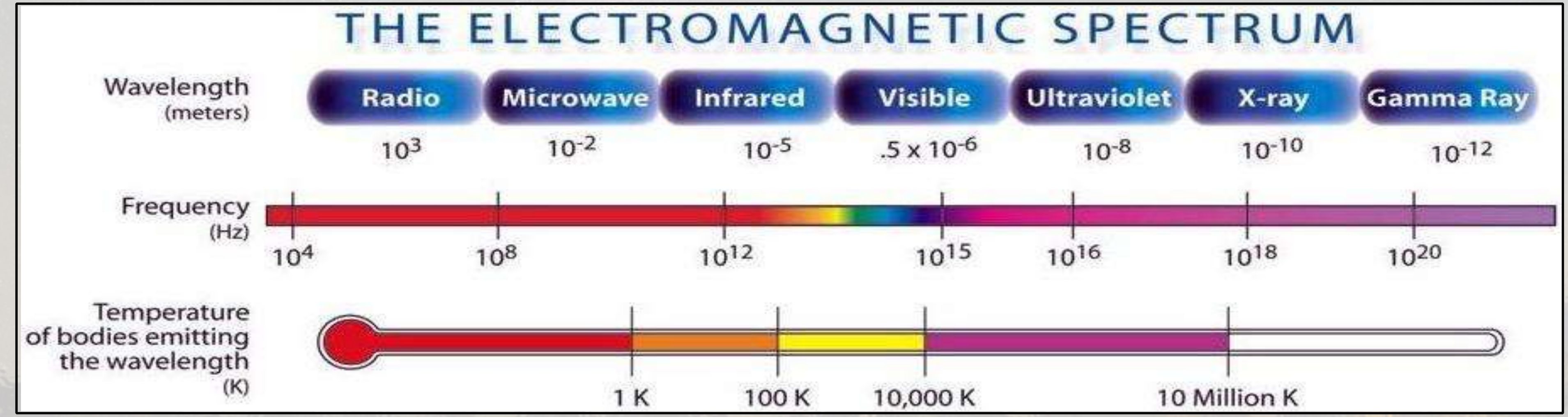
B_{rot} ~ 1 – 200 GHz
→ ν ~ 1 – 200 GHz (for J=0)
→ ν ~ 3 – 600 GHz (for J=1)

4. Detection of molecules

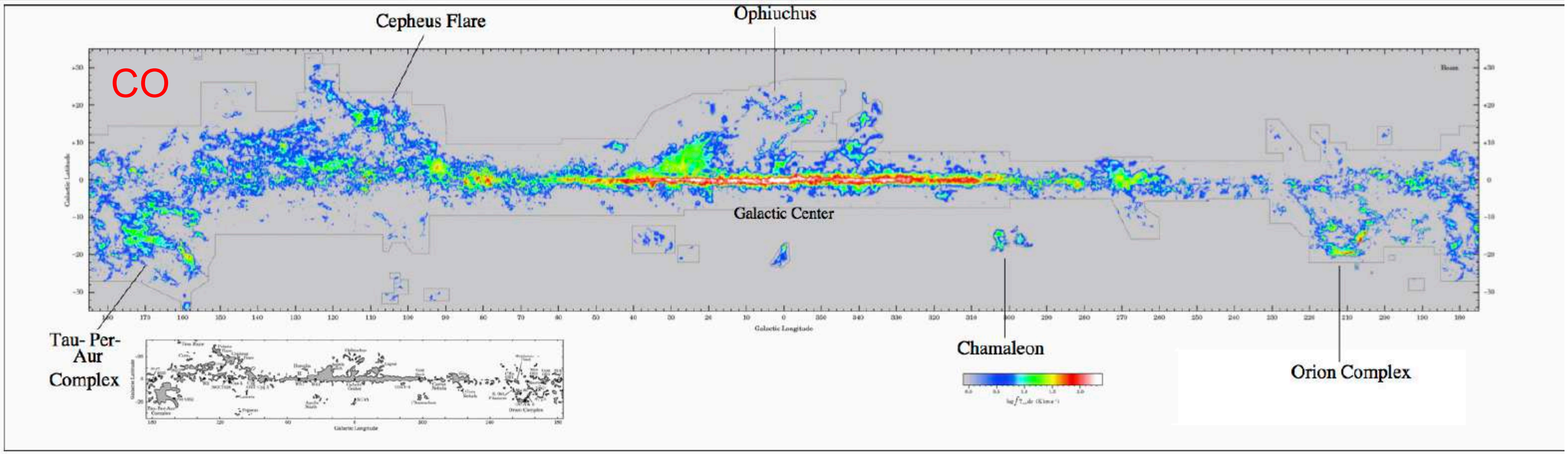
The vibrational and rotational transitions produce photons with energies (with frequencies) in the radio, microwave (sub-millimeter), and IR regime.

- rotational transitions: $T_{rot} = E_{rot}/\kappa_B \sim 5$ K
- vibrational transitions: $T_{vib} = E_{vib}/\kappa_B \sim 600$ K
- electronic transitions: $T_{el} = E_{el}/\kappa_B \sim 9 \times 10^4$ K

$$E = k_B T = h\nu = \frac{hc}{\lambda}$$



4. Detection of molecules

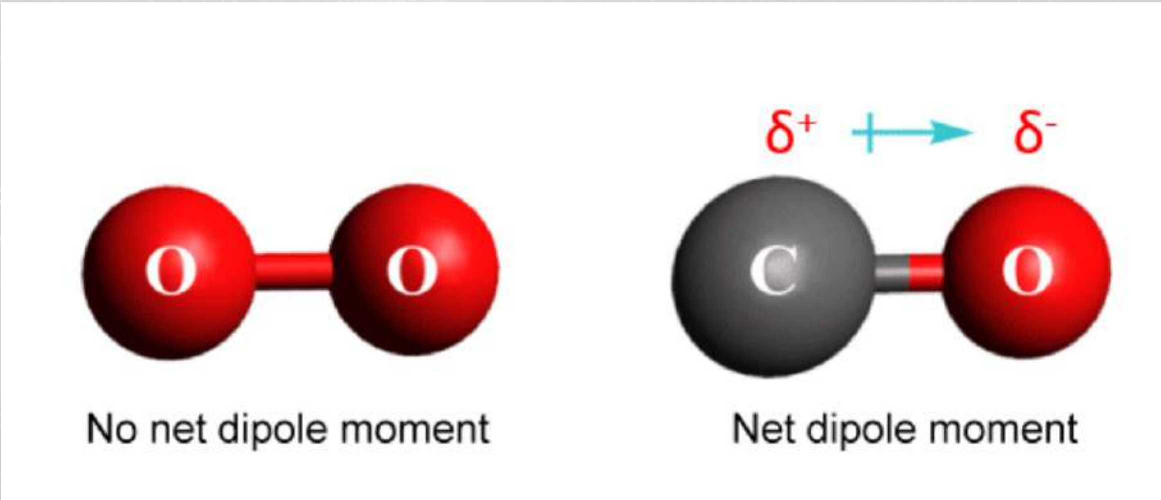


Dame+ (2001)

4. Detection of molecules

- H_2, like other diatomic homonuclear molecules (C_2, N_2, O_2 …), is highly symmetric and will always have a linear geometry. Due to this symmetry, the molecule has no dipole moment and all ro-vibrational transitions within the electronic ground state are forbidden for electric dipole transitions and instead occur through electric quadrupole transitions with low spontaneous coefficient values (A_{ij}).

- A molecule whose dipole moment is zero cannot emit radiation through rotational transitions: for electromagnetic energy to be emitted, there must be a change in the dipole moment vector, and rotation does not produce a change in the dipole moment vector if it is zero.



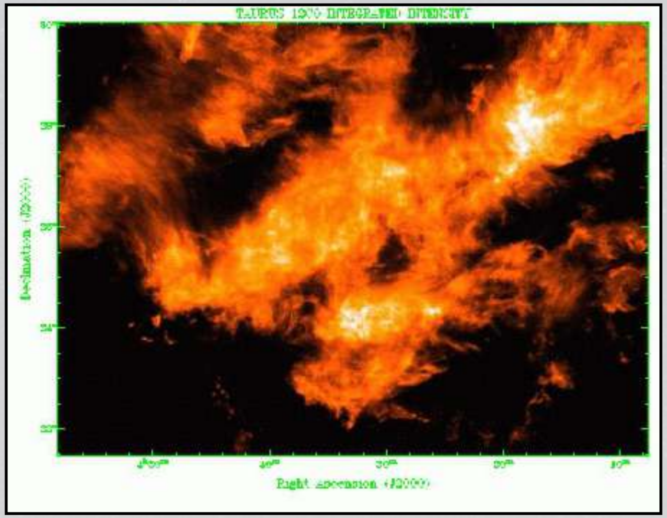
Summary

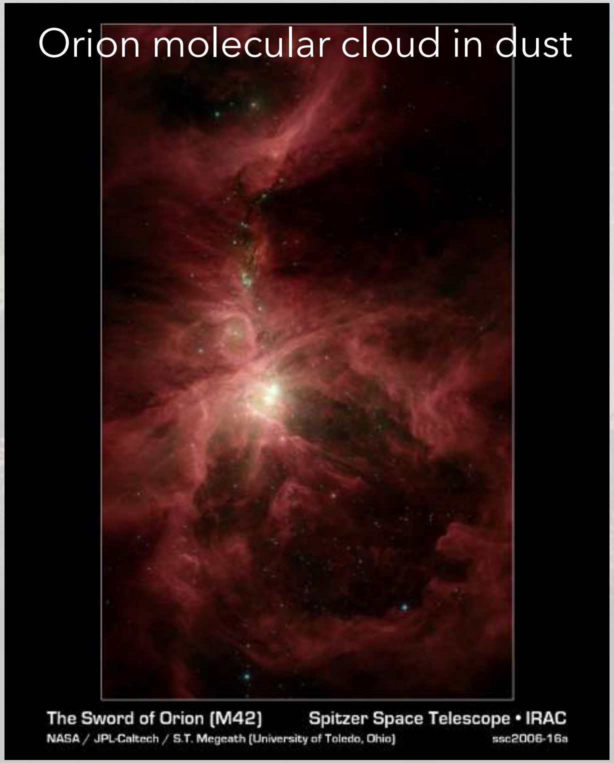
1. Definition of interstellar medium
2. Brief historical overview
3. Components of the ISM
4. Detection of molecules
5. Molecular clouds

5. Molecular clouds

- Half of interstellar gas is compressed into 2% of the volume, and forms interstellar clouds.
- The densest interstellar clouds are the molecular clouds.
- Molecular clouds are very dense by ISM standards, and very cold.
- Molecular clouds are formed of dust and gas with the most common component of these clouds being molecular hydrogen (H_2).

Taurus molecular cloud in CO

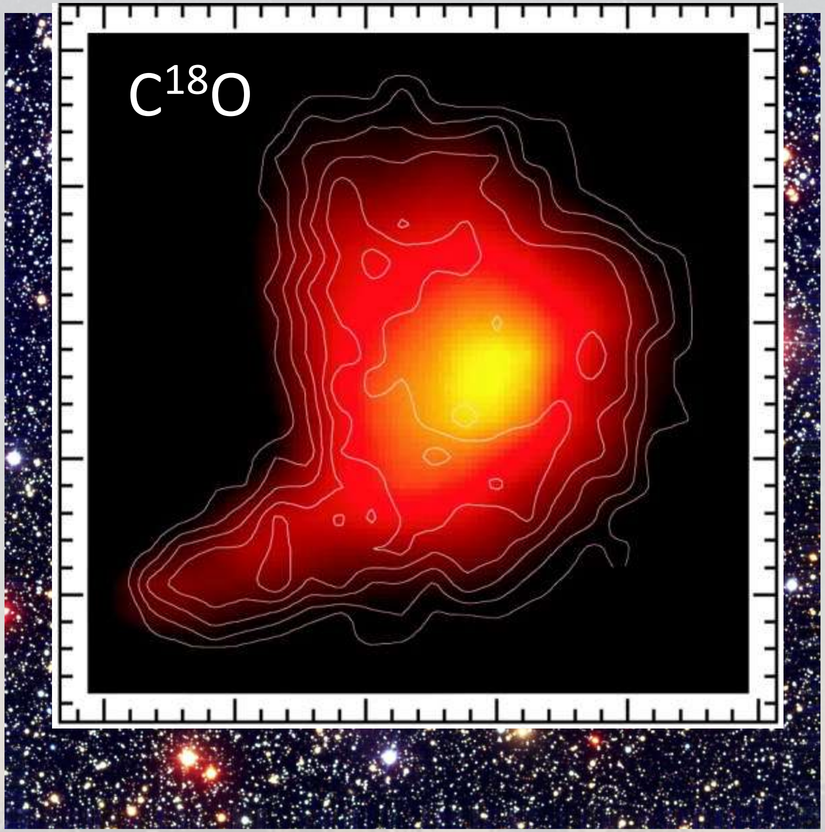




5. Molecular clouds

- Molecular clouds are not homogeneous and range greatly in size and density, from small dense cores with densities > 10^4 cm^{-3} , up to giant molecular clouds (GMCs).

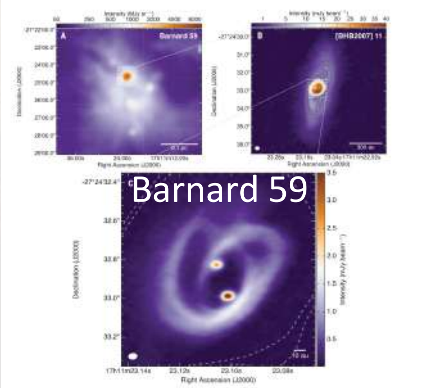
- Star formation occurs in the densest regions of molecular clouds: **dense cores** or **dark clouds**



5. Molecular clouds

- **Properties**

	Low-mass	High-mass
	Dark clouds	**Cores in GMCs**
Mass ($M_\odot$)	0.3-10	$10\text{-}10^3$
Diameter (pc)	0.05-0.5	0.1-3
Density (cm^{-3})	$10^4\text{-}10^5$	$10^4\text{-}10^7$
Temperature	10	20-100
Associations	Single/binaries	OB clusters



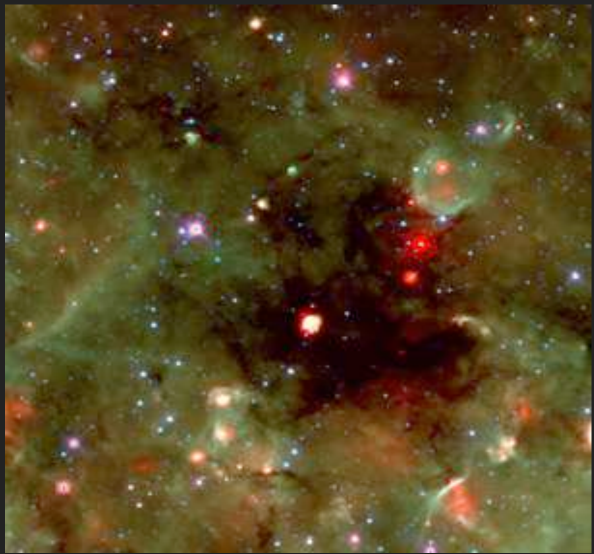
5. Molecular clouds: composition

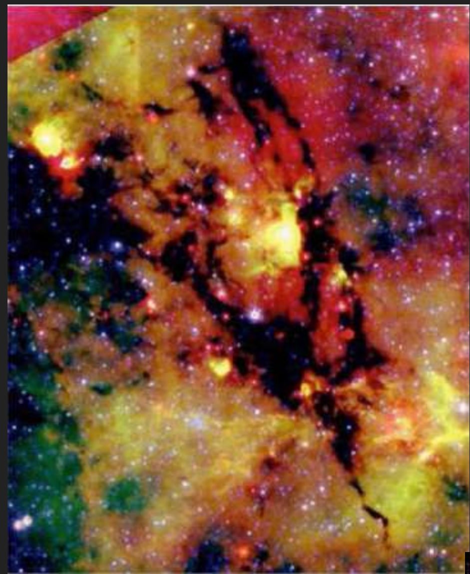
- H_2
- He (25% in mass)
- dust (1% in mass)
- CO (10^{-4} by number)
- CS ($\sim 10^{-9}$ by number)
- NH_3 (10^{-9} by number)
- N_2H^+ (10^{-10} by number)

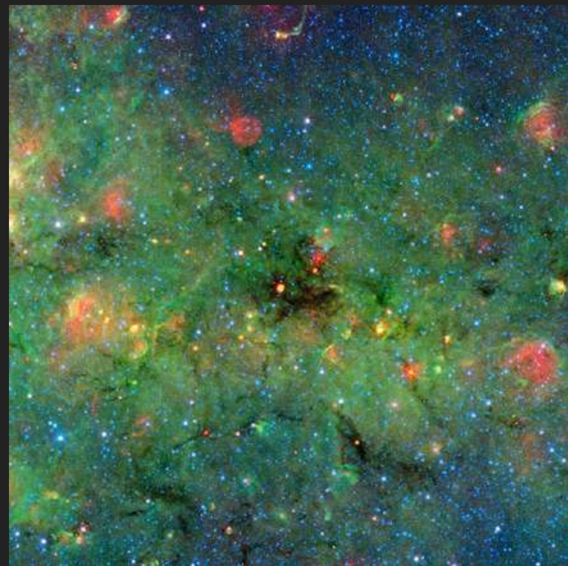
and many other molecules with low abundances.

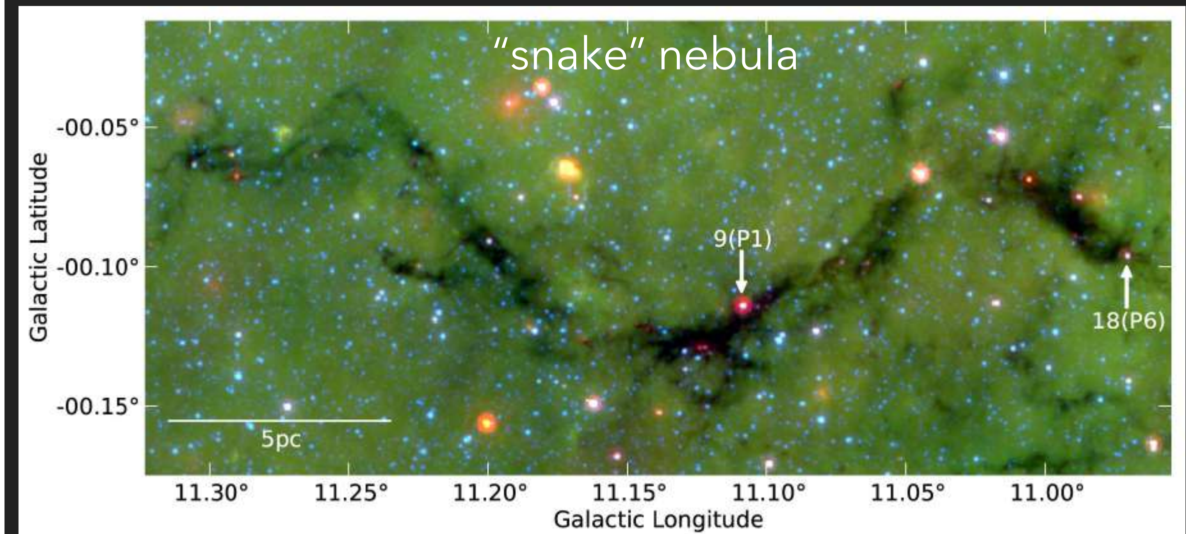
5. Molecular clouds

- **Morphology**







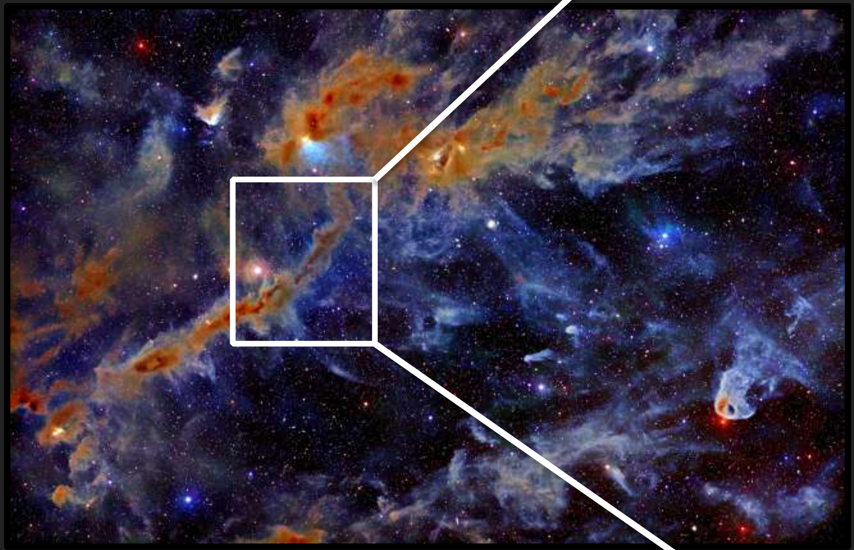


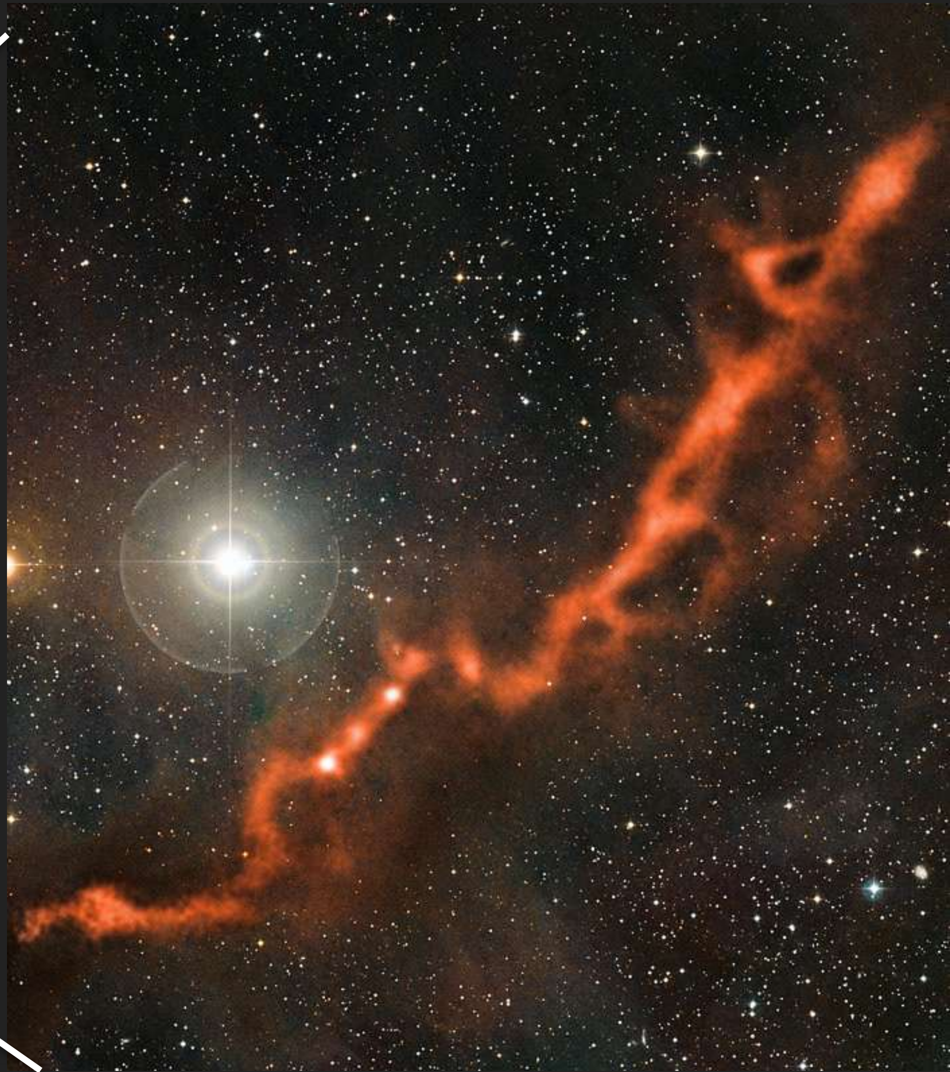
Taurus molecular cloud

5. Molecular clouds: filaments

- **Filamentary structure**

Taurus molecular cloud





Adapted from J. Jackson

5. Molecular clouds: filaments

- **Filamentary structure**

Spitzer 4.5/8/24 μm

100 pc x 0.5 pc

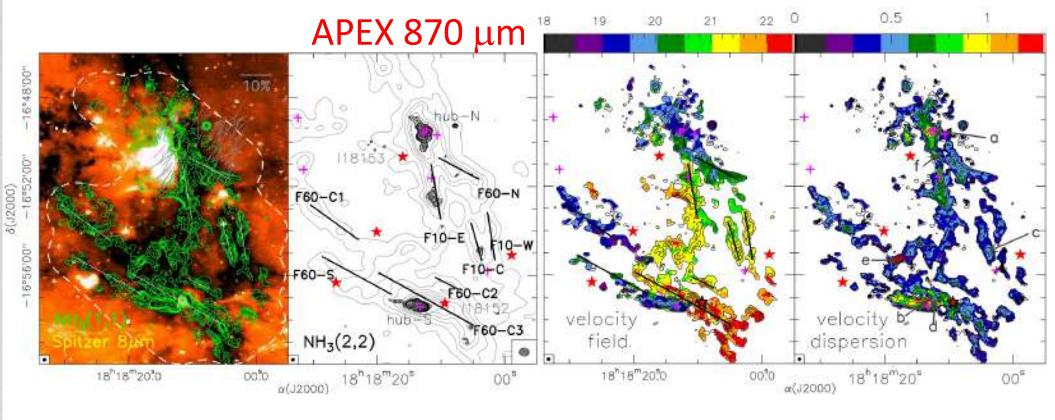
Adapted from J. Jackson

5. Molecular clouds: filaments

- **Morphology**

  - Network of filaments intersecting in high-density hubs (Myers+ 2009; Liu+ 2012), where compact cores are found.
  - Filaments velocity maps indicate velocity gradients along them.

G14.225−0.506

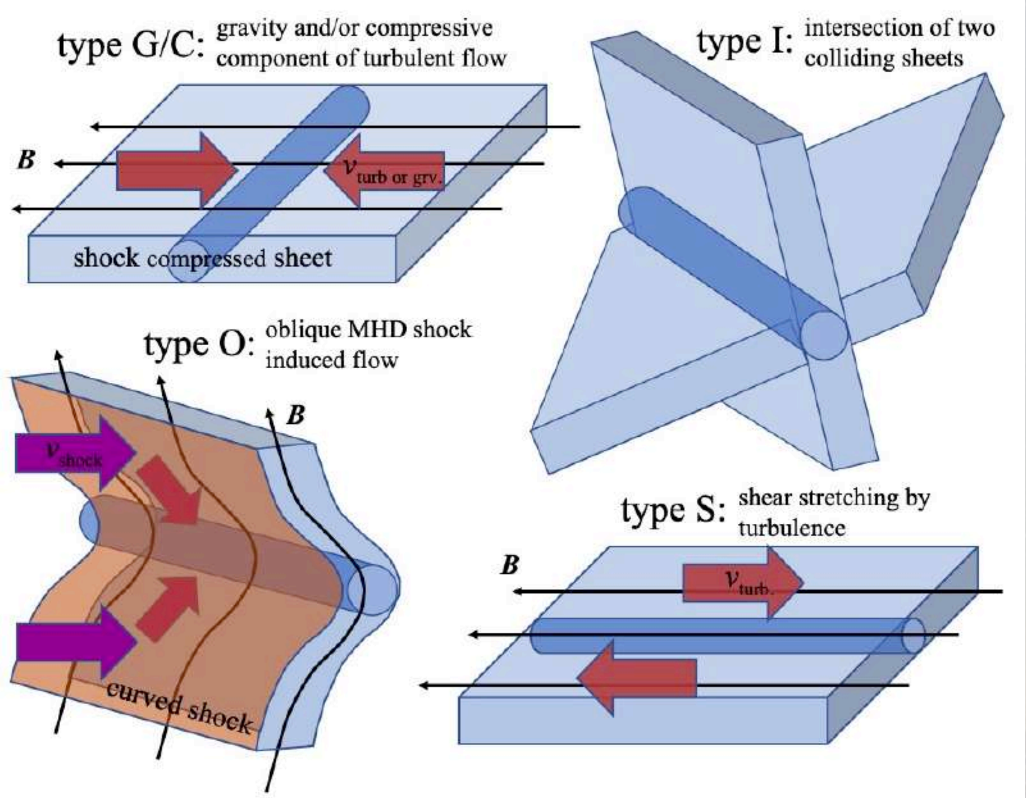


Busquet+ (2013)

5. Molecular clouds: filaments

- **Formation**

  - Formation of filaments: large-scale turbulence (Arzoumanian+ 2011); convergence of flows or filament-filament collisions (e.g., Heitsch+ 2008; Jiménez-Serra+ 2010; Henshaw+ 2013); Nakamura+ 2012); magnetic fields (e.g., Nagai+ 1998; Nakamura & Li 2008).



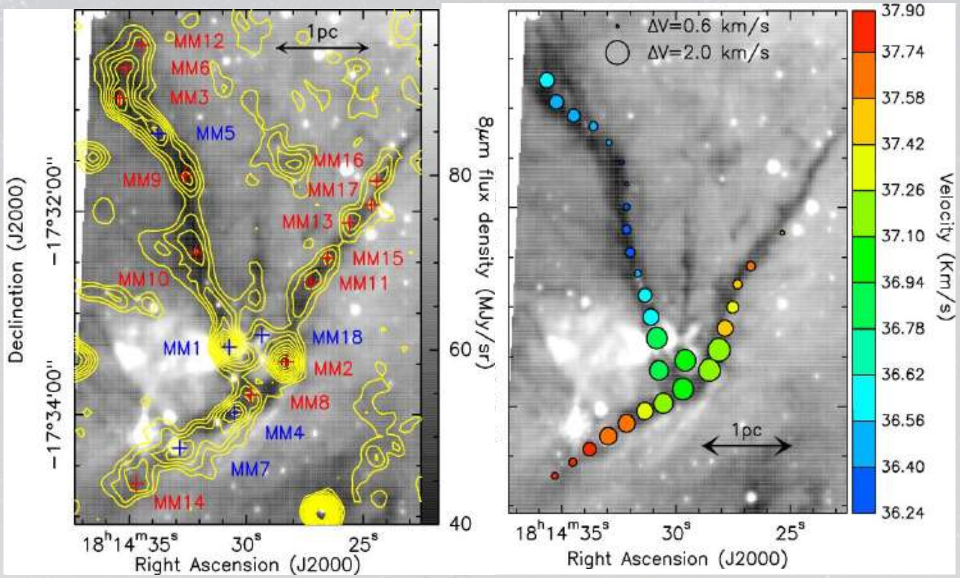
Pineda+ (2023)

Schematics of the filament formation mechanisms, where the blue sheets are shock compressed layers in which filaments are formed, the black thin arrows represent the magnetic fields, and the thick a rrows show the gas flow orientations.

- **Dynamics**

- Filaments present either subsonic or supersonic non-thermal motions (e.g. Hacar & Tafalla 2011; Pineda+ 2011).
- Coherent velocity along the filaments (e.g. Jackson+ 2010; Busquet+ 2010) that suggests longitudinal collapse (e.g. Peretto+ 2014) towards the center of the system.
- Velocity dispersion increases in the hubs, where star formation occurs.

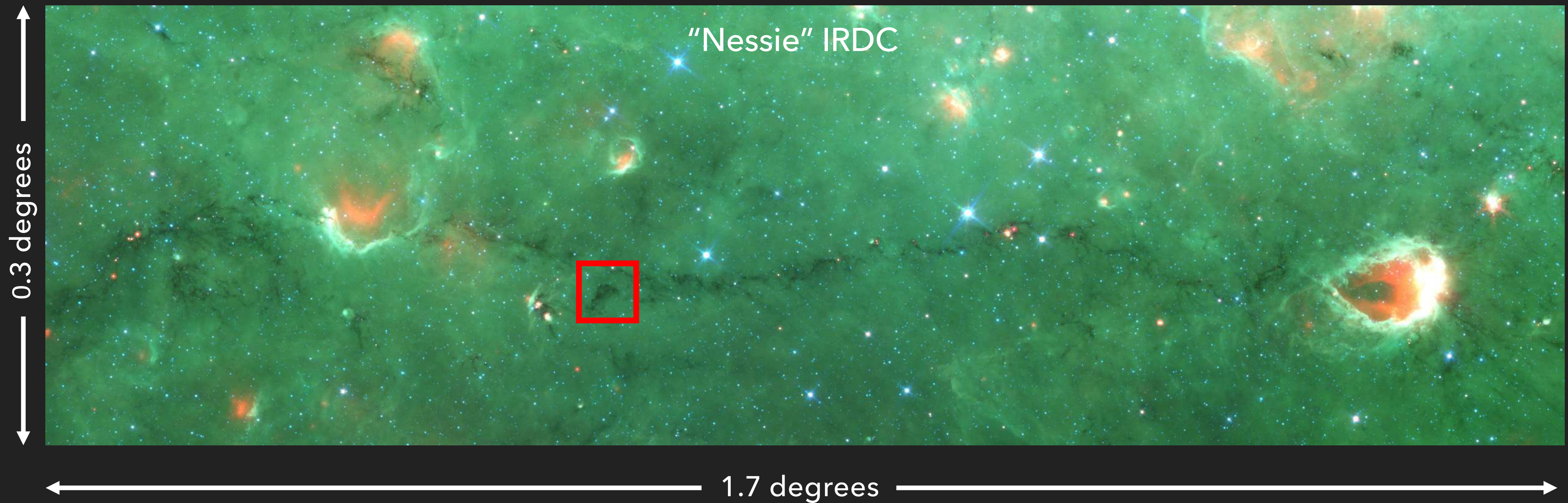
SDC13



Peretto+ (2014)

5. Molecular clouds

- **Different evolutionary phases**



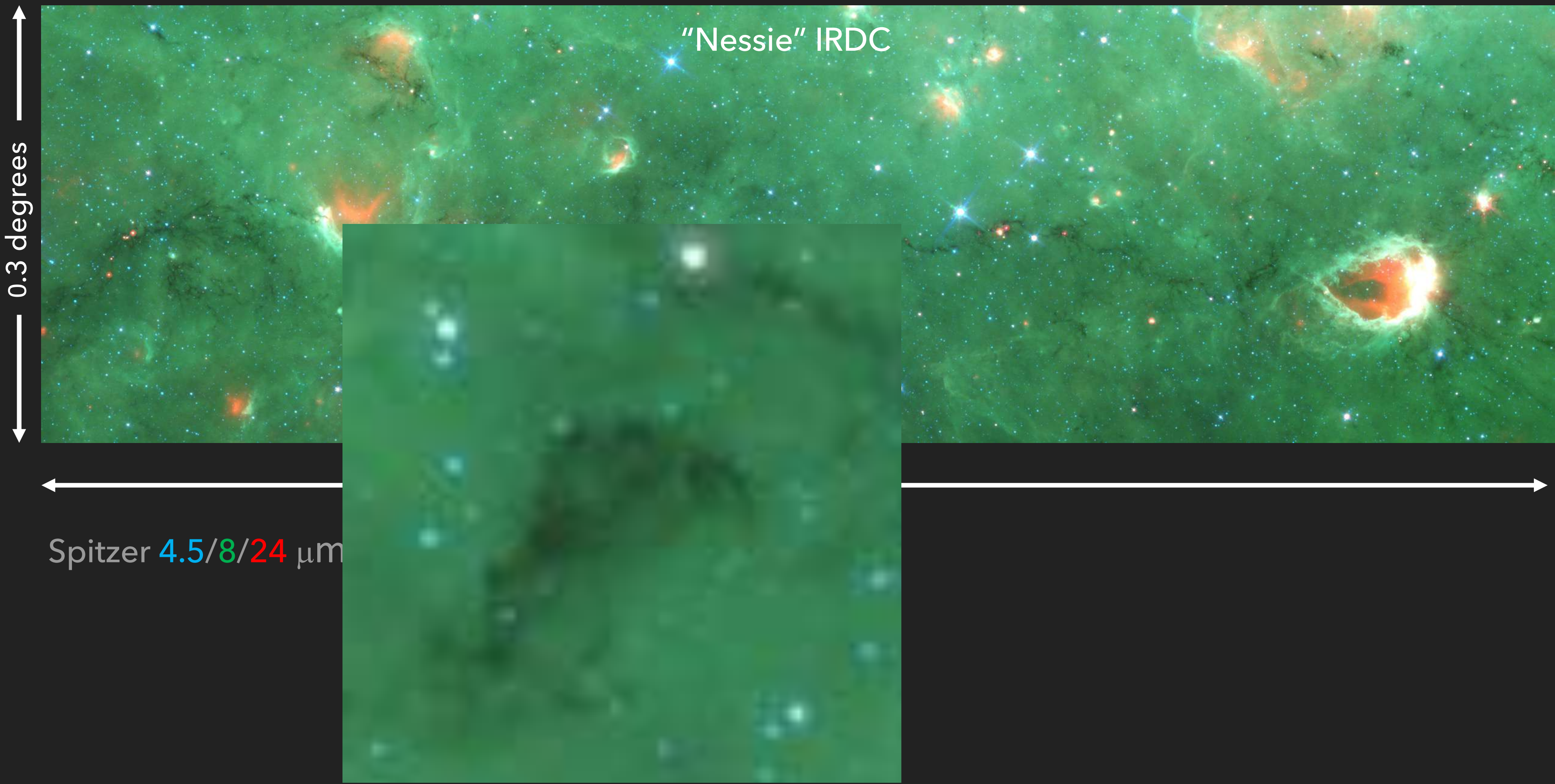
Spitzer 4.5/8/24 μm

pre-stellar core candidate

Adapted from J. Jackson

5. Molecular clouds

- **Different evolutionary phases**



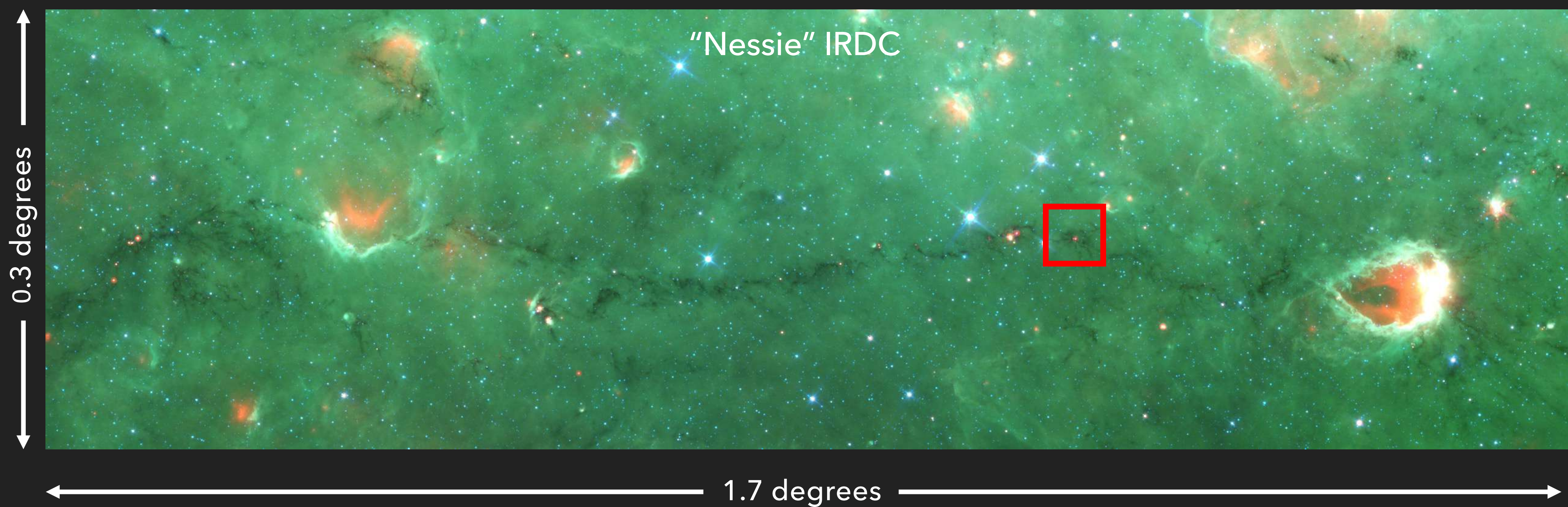
Spitzer 4.5/8/24 µm

pre-stellar core candidate

Adapted from J. Jackson

5. Molecular clouds

- **Different evolutionary phases**



Spitzer 4.5/8/24 μm

Proto-stellar object

Adapted from J. Jackson

5. Molecular clouds

- **Different evolutionary phases**

0.3 degrees

1.7 de

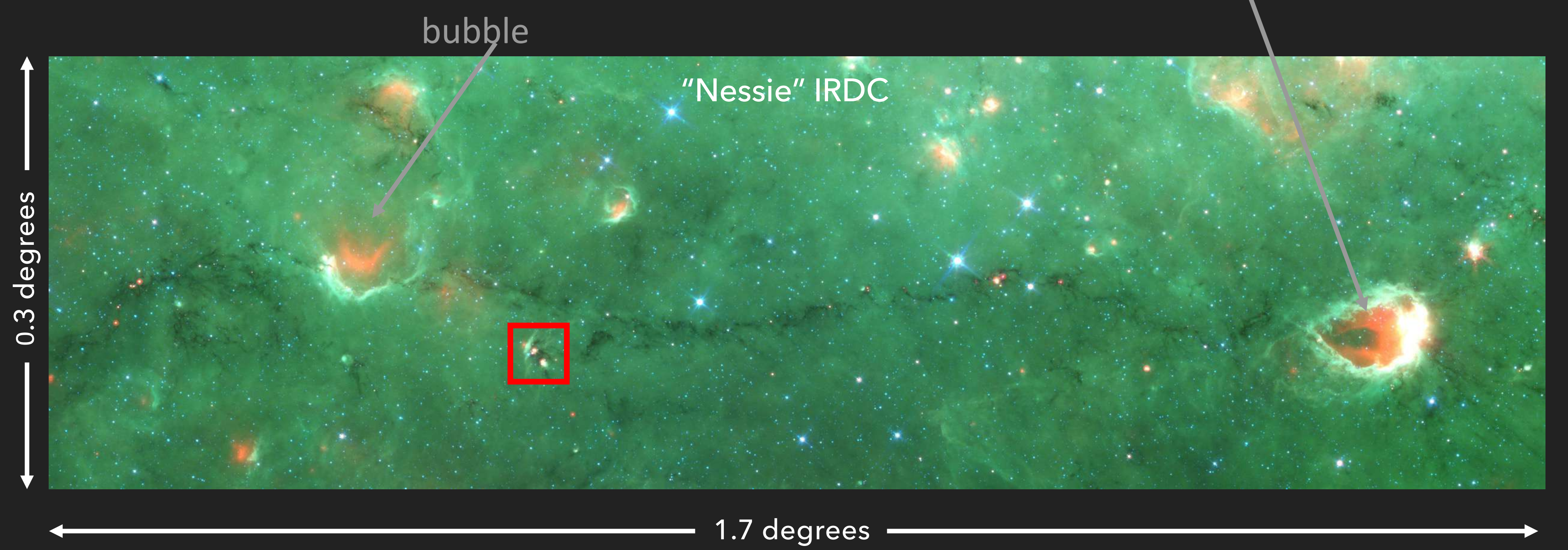
Spitzer 4.5/8/24 μm

Proto-stellar object

Adapted from J. Jackson

5. Molecular clouds

- **Different evolutionary phases**



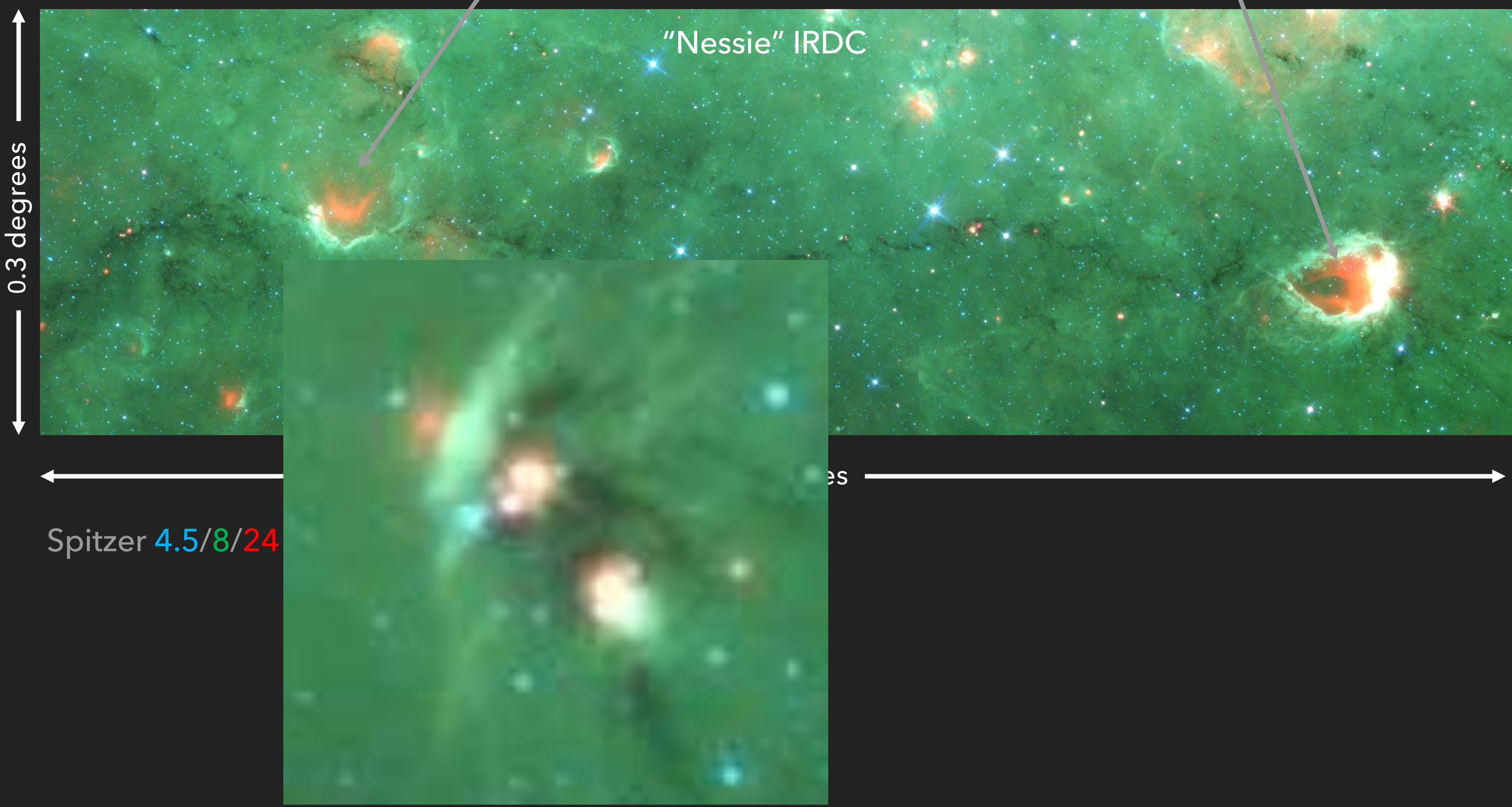
Spitzer 4.5/8/24 μm

HII region

Adapted from J. Jackson

5. Molecular clouds

- **Different evolutionary phases**



Adapted from J. Jackson

5. Molecular clouds: cloud properties

The standard CO analysis to estimate the physical parameters of a cloud from CO observations consists in observing the same transition e.g. J=1→0 or 2→1 for ^{12}CO and one isotopologue, usually ^{13}CO or C^{18}O.

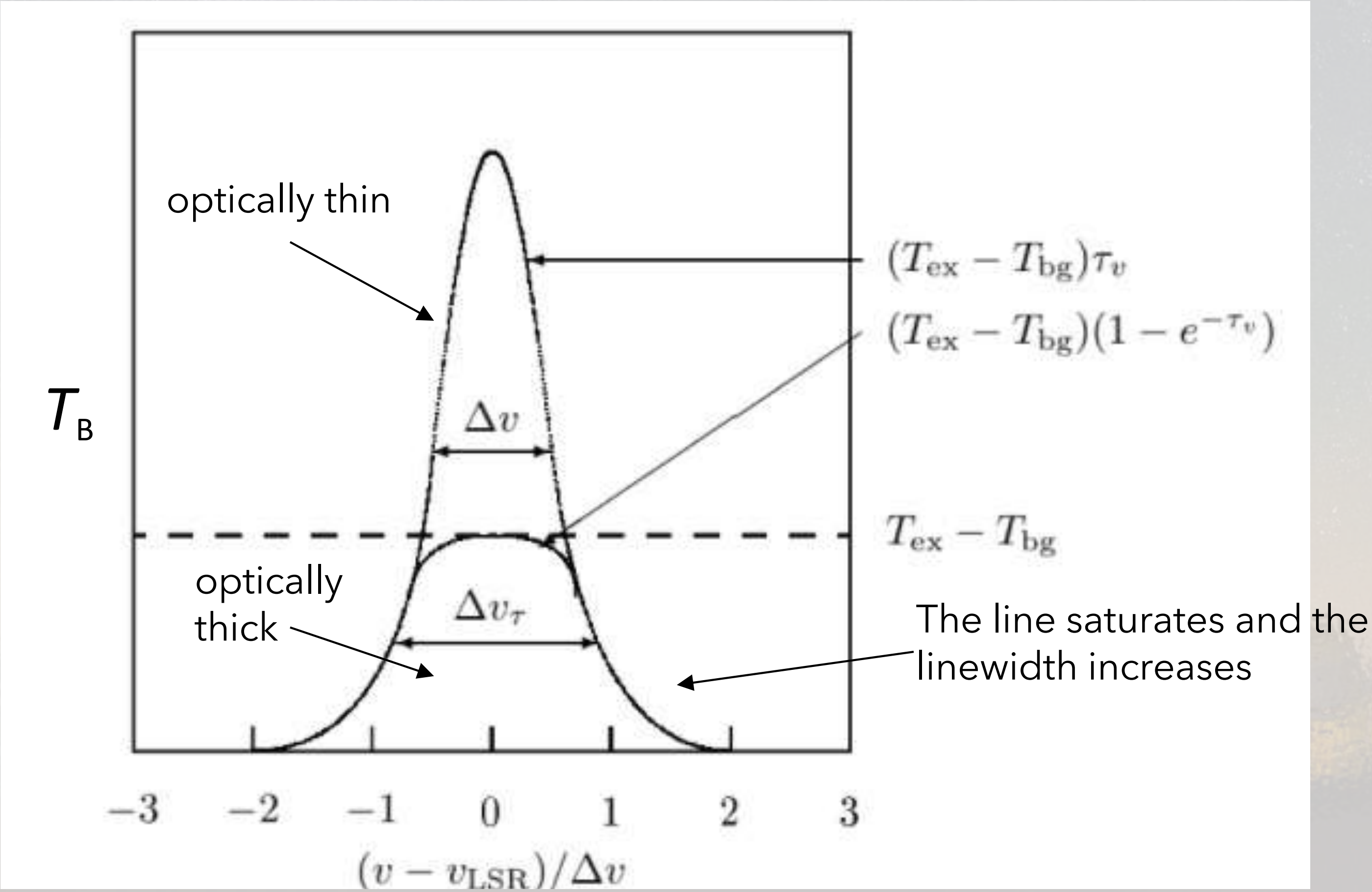
1. Thermalized emission = LTE ⇒ $T_k = T_{ex}(^{12}CO) = T_{ex}(^{13}CO) = T_{ex}$
2. ^{12}CO optically thick: $\tau^{12} \gg 1$
3. ^{13}CO optically thin: $\tau^{13} \ll 1$
4. $[^{13}CO/^{12}CO] \approx 1/90$
5. Not in R-J because high frequency ⇒ $T_B = [J_\nu(T_{ex}) - J_\nu(T_{bg})](1 - e^{-\tau_0})$

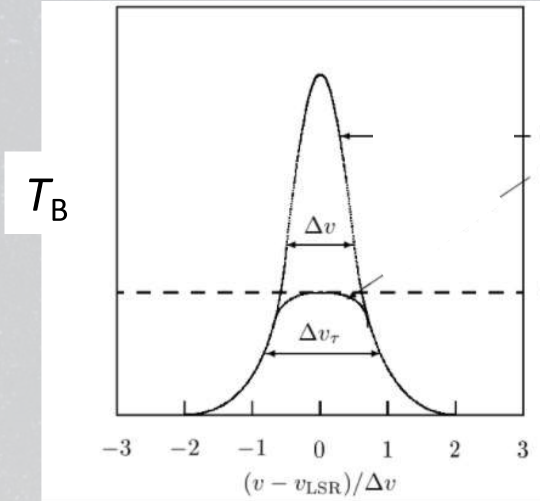
where $J_\nu(T) = \frac{h\nu/k}{e^{h\nu/kT} - 1}$

5. Molecular clouds: temperature diagnostics

From radiative transfer equation ↓   LTE ↓

- If $\tau_0 \gg 1$ (optically thick) $\Longrightarrow T_B \simeq T_{ex} - T_{bg} \Longrightarrow T_{ex} = T_k$
- If $\tau_0 \ll 1$ (optically thin) $\Longrightarrow T_B = (T_{ex} - T_{bg})\,\tau_0 \Longrightarrow$ knowing $T_{ex} \Longrightarrow \tau_0$





Obtaining T_{ex}

In the limit of large optical depth for the ^{12}CO line,

$$T_B^{12} = J^{12}(T_{ex}) - J^{12}(T_{bg})$$

where T_{ex} (= T_k because LTE) is

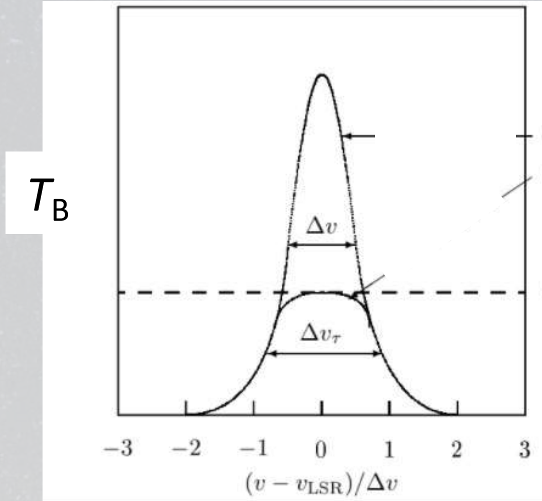
$$T_{ex} = \frac{h\nu/k}{\ln\left[1 + \frac{h\nu/k}{T_B^{12} + J^{12}(2.7)}\right]}$$

T_{bg} = 2.7 K

For J=1→0: $T_{ex} = \frac{5.53}{\ln\left[1+\frac{5.53}{T_B^{12}+0.82}\right]}$

for J=2→1: $T_{ex} = \frac{11.06}{\ln\left[1+\frac{11.06}{T_B^{12}+0.19}\right]}$

<u>Obtaining τ</u>



In the limit of small optical depth for the ^{13}CO line, and for $T_{ex}(^{12}CO) = T_{ex}(^{13}CO)$

$$T_B^{13} = [J^{13}(T_{ex}) - J^{13}(T_{bg})]\left(1 - e^{-\tau_0^{13}}\right)$$

$$T_B^{13} = [J^{13}(T_{ex}) - J^{13}(T_{bg})]\tau_0^{13}$$

where τ_0^{13} is

$$\tau_0^{13} = -\ln\left[1 - \frac{T_B^{13}}{J^{13}(T_{ex}) - J^{13}(T_{bg})}\right]$$

For J=1→0: $\tau_0^{13} = -\ln\left[1 - \frac{T_B^{13}}{\frac{5.29}{e^{5.29/T_{ex-1}}} - 0.87}\right]$

for J=2→1: $\tau_0^{13} = -\ln\left[1 - \frac{T_B^{13}}{\frac{10.58}{e^{10.58/T_{ex-1}}} - 0.21}\right]$

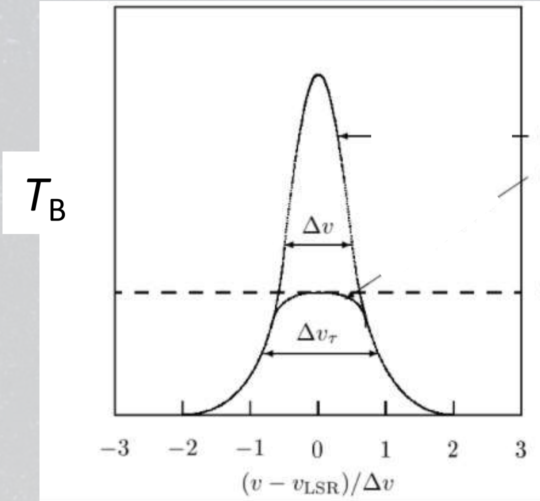
5. Molecular clouds: optical depth

<u>Obtaining τ</u>

Assuming that the frequencies of the two isotopologues are similar, the optical depth can also be obtained:

$$\tau_0^{13} \cong -\ln\left[1 - \frac{T_B^{13}}{T_B^{12}}\right]$$

If $\tau_0^{13} \ll 1$, then $\tau_0^{13} = \frac{T_B^{13}}{T_B^{12}}$



Obtaining N^{13}

The optical depth in ^{13}CO is then converted into a column density as follow

$$\tau_0 = \frac{(2J+1)h\,c^3 A_{J,J-1}}{16\pi J \nu_{J,J-1}^2 \Delta V T_{ex}} N \left(e^{h\nu_{J,J-1}/kT_{ex}} - 1\right) e^{-(J+1)h\nu_{J,J-1}/2kT_{ex}}$$

For ^{13}CO J=1→0, A_{10}= 6.29x10^{-8} s^{-1}

$$\left[\frac{N^{13}}{cm^{-2}}\right] = 3\times10^{14} \left[\frac{\Delta V}{km\ s^{-1}}\right]\left[\frac{T_{ex}}{K}\right]\frac{\tau_0^{13}}{1-e^{-5..29/T_{ex}}}$$

Obtaining N_{H2}

If the abundance of ^{13}CO [H_2/^{13}CO] is known, then:

$$N(H_2) = \left[\frac{H_2}{^{13}CO}\right] N^{13}$$

5. Molecular clouds: mass

<u>Obtaining $M(H_2)$</u>

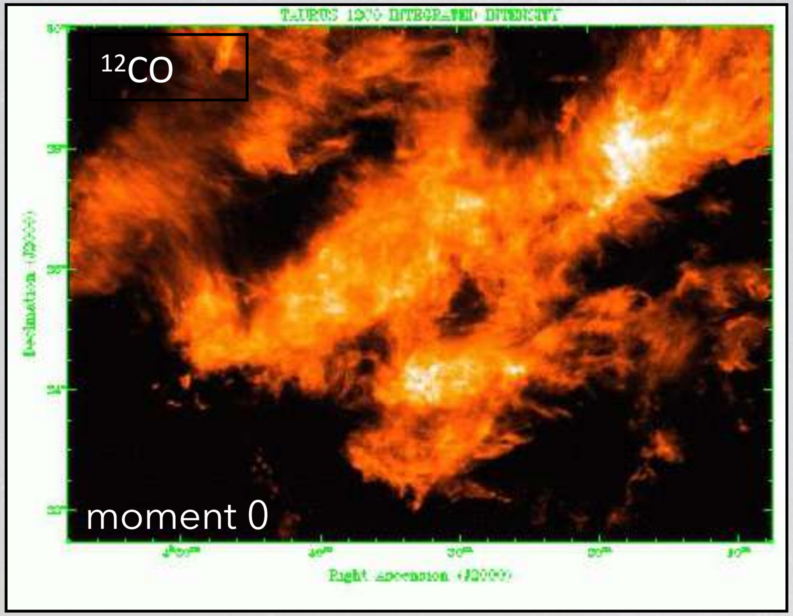
$$N(H_2) = \left[\frac{H_2}{^{13}CO}\right] N^{13}$$

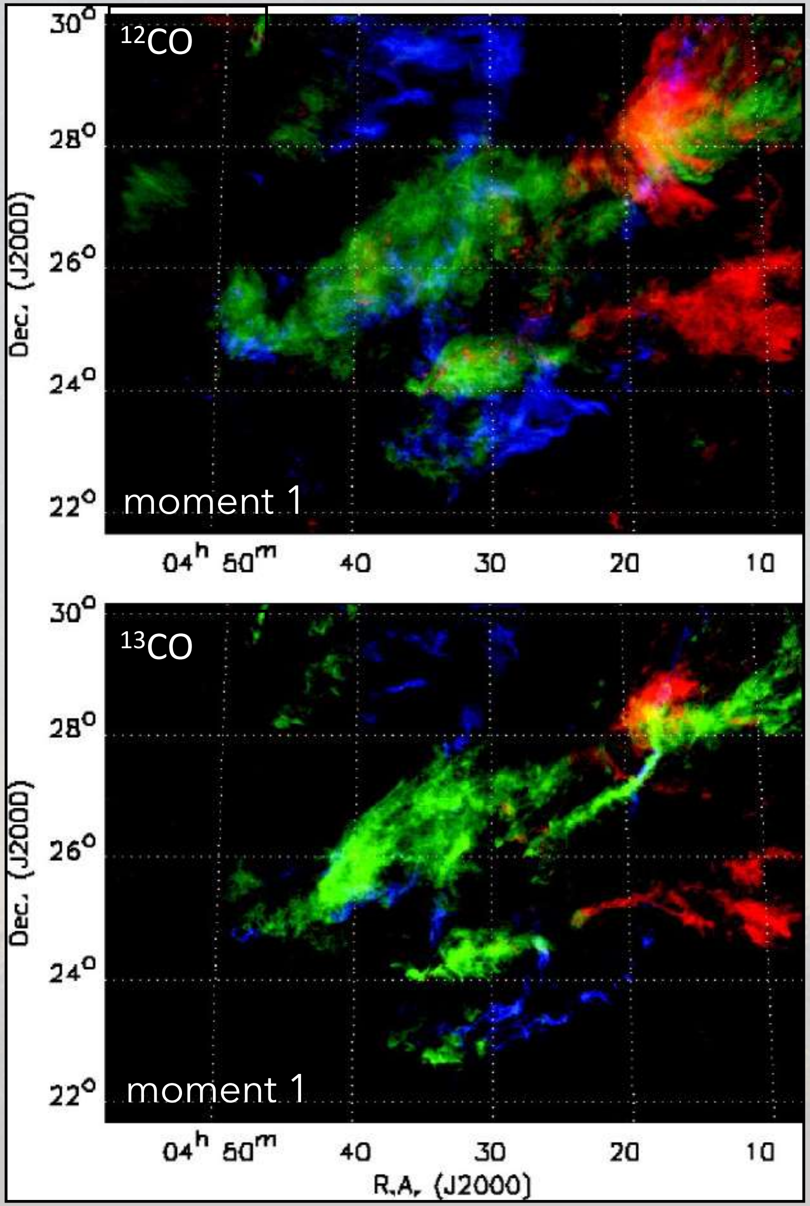
If R is the radius or the cloud, then:

$$M(H_2) = \pi R^2 N(H^2)\, m_{H2}$$

5. Molecular clouds: kinematics

Taurus molecular cloud



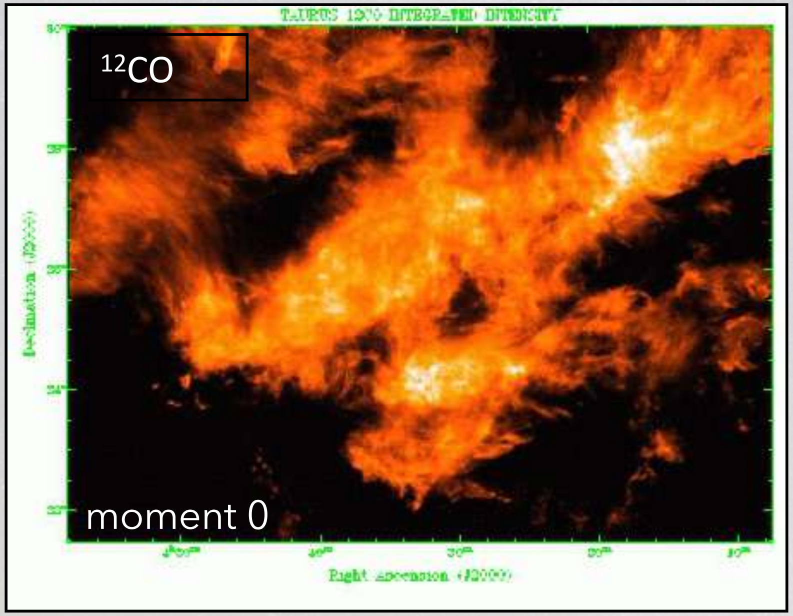


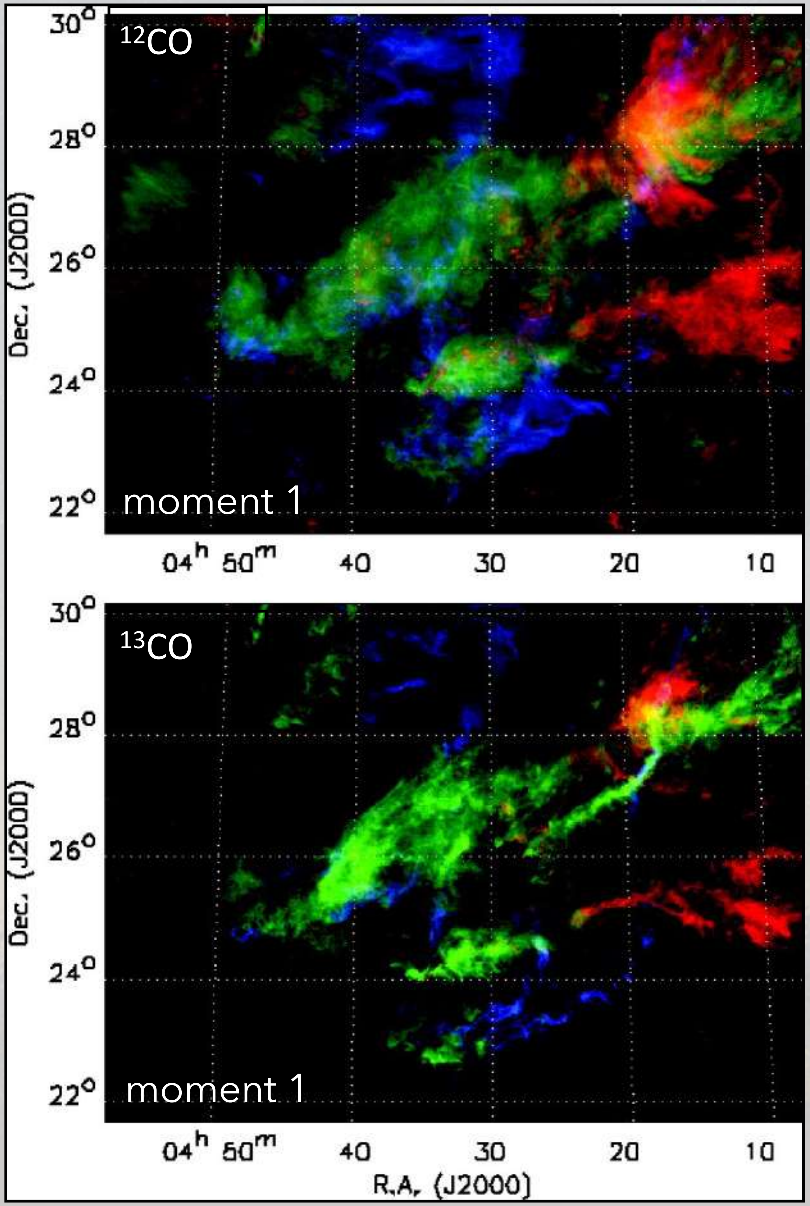
Moment maps

- moment 0 map: integrated intensity over the spectral line (in K km/s or Jy/beam km/s)
- moment 1 map: intensity-weighted velocity of the spectral line (in km/s)
- moment 2 map: velocity dispersion or width of the spectral line (in km/s)

5. Molecular clouds: kinematics

Taurus molecular cloud





Moment maps

- moment 8 map: peak intensity over the spec tral line (in K or Jy/beam)
- moment 9 map: peak velocity of the spectral line (velocity where the peak intensity is locat ed) (in km/s)

Serpens South molecular cloud: moment 0 + moment 1