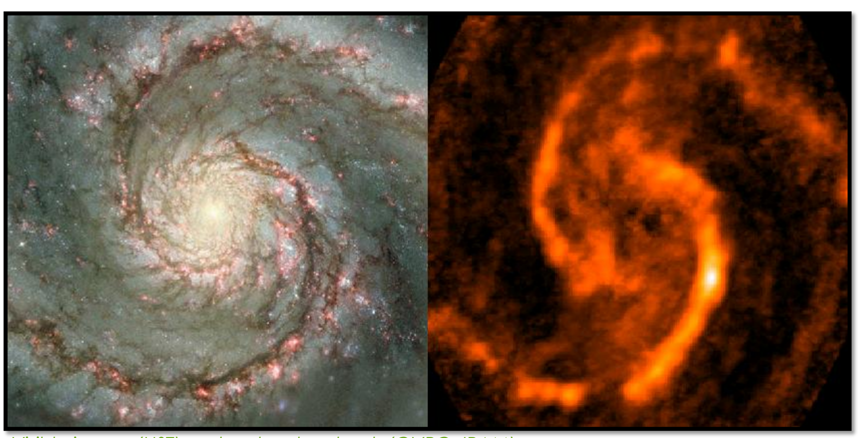
17 September
2019

FROM MOLECULES TO MOLECULAR CLOUDS TO STARS

Homework #2 on WeBWorK due tomorrow by 7pm



Visible image (HST) and molecular clouds (OVRO, IRAM)

From molecules to molecular clouds to stars

Aromatic (benzene-ring) molecules in space

Formation of molecules on dust-grain surfaces and in the gas phase

Interstellar molecular clouds

Gravitational collapse of molecular clouds

The formation of stars and protoplanetary disks

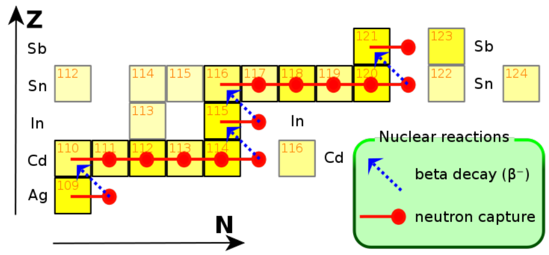
Slow fusion processes in stars: s-process

Fusion in stars near death, starting with Pop II: the **s-process** (slow neutron-capture)

- Some of the lighter-nucleus fusion processes have neutrons as a byproduct; for instance,

  $^{13}C + {}^{4}He \rightarrow {}^{16}O + n$

- These neutrons tend to be gobbled up by heavier nuclei, especially those heavier than Fe.
- Add beta decay, and this process fills in many of the gaps between the "alpha" elements made in explosions.



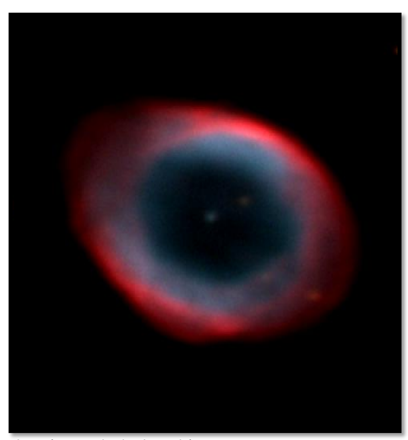
Example: s-process from Ag to Sb (Wikimedia Commons)

Stellar death: white dwarfs

The star begins to shed its outer layers, sending the heavy-element enriched material back out to the ISM.

After a few million years, when helium and carbon fusion have ceased, only the dead core, as a **white dwarf**, and surrounding shells of expanding material are left.

The last gasp of ejected material is called a **planetary nebula**; it decorates the scene for a few thousand years as its contents merge into the interstellar medium.



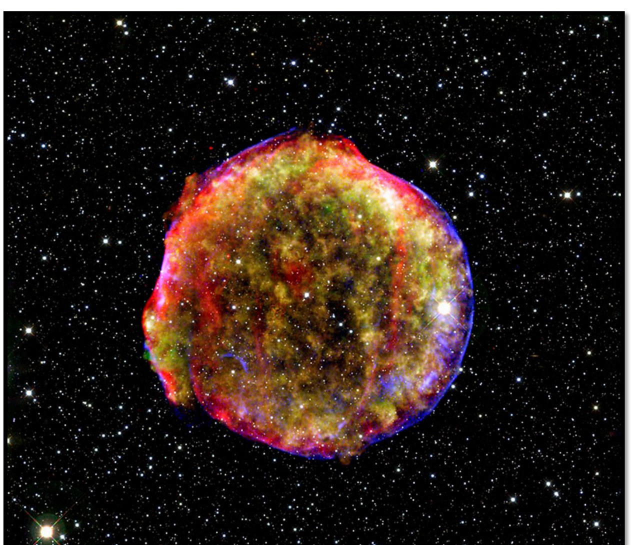
The Ring Nebula (M57) in Lyra near Vega (UR/Mees Observatory)

Stellar death: Type Ia supernovae

Some of the white dwarfs can die again, as **Type Ia supernovae (SN Ia)**

- Many stars live in close multiple systems. The death of one does not disturb the others much.
- White dwarfs can wind up close to ordinary or giant stars, close enough to **accrete** matter from them.
- White dwarfs have a maximum mass of $1.4M_{\odot}$. If accretion tips a white dwarf over the maximum, rapid collapse and the ignition of C and O fusion explode it with great violence, spewing highly-concentrated heavy elements into space.

European Southern Observatory



Remnant of Tycho's Supernova (1572), which was a SNIa. Blue = X-ray (Chandra, NASA/CXC/SAO), green = visible light (MPIA, Calar Alto), red = mid-infrared (Spitzer, SSC/NASA). By Olivier Krause.

SN Ia nucleosynthesis

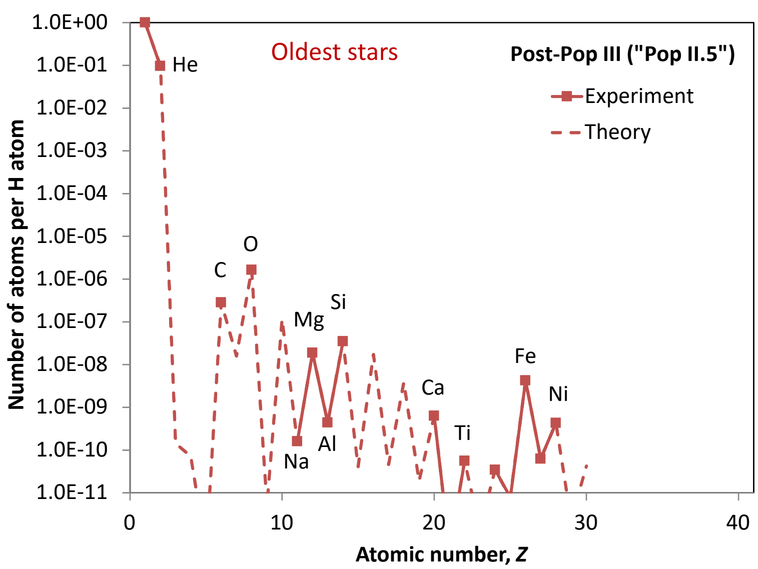
SN Ia are particularly productive of iron-peak elements. Though the events are rare, they are thought to have produced about half of the iron in the present-day ISM.

Population I

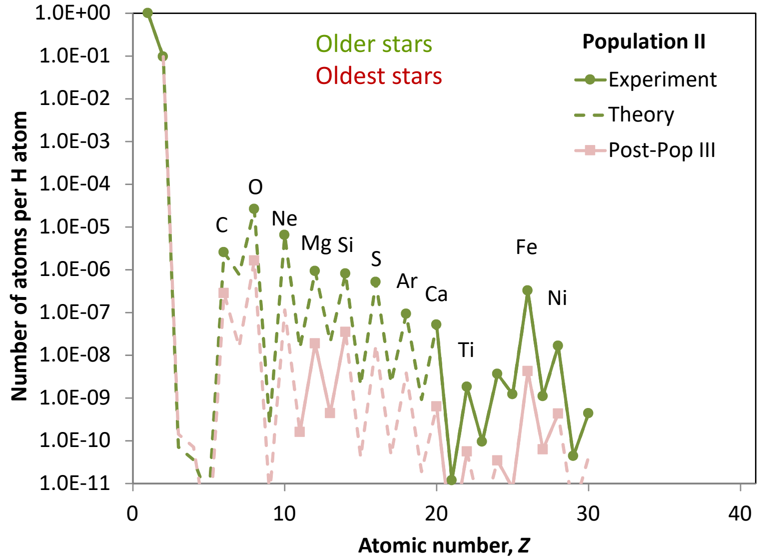
There is a population of stars with higher abundances of heavy elements than Pop II, in accordance with the combination of explosive and stellar-core nucleosynthesis in Pop III and Pop II:

- Much smaller random motions than Pop II and confined much more tightly to the plane of the Milky Way where most of the ISM also resides
- Absent from globular clusters
- Can belong to clusters, but these **open clusters** are smaller, less organized, and rarely older than 1 Gyr
- The Sun is one of these stars.

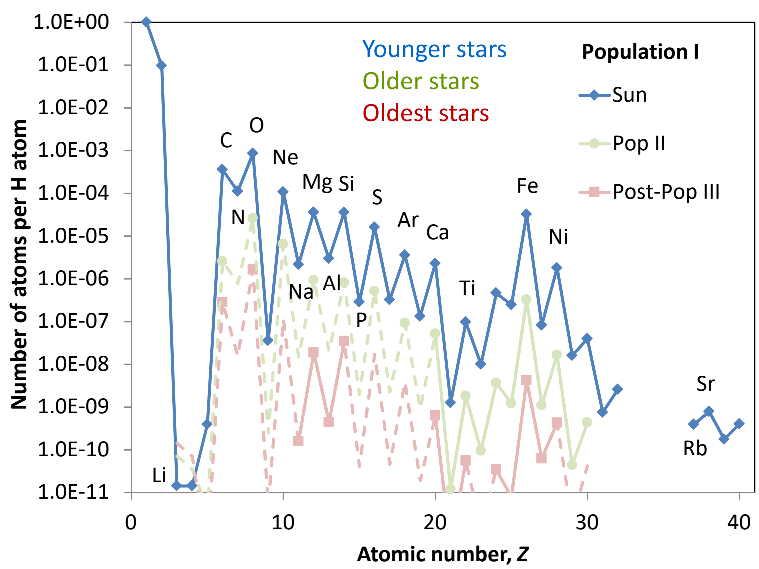
We call these stars **Population I**.



The nuclear-chemical evolution of the Milky Way

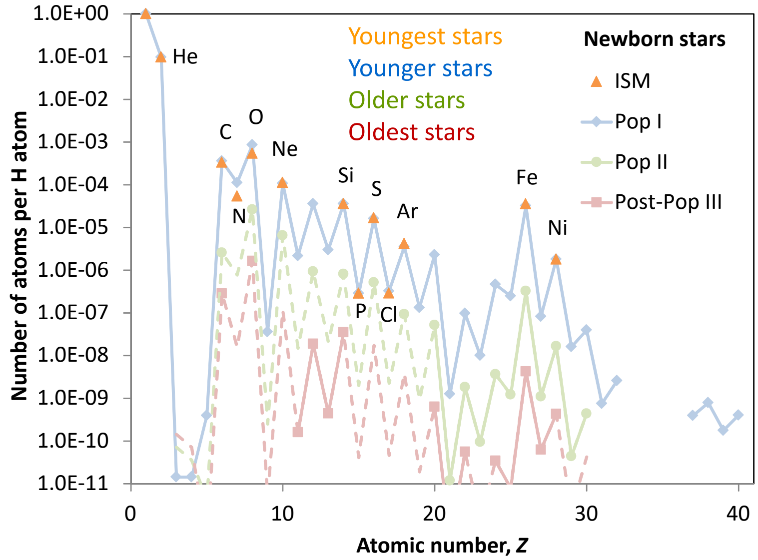


The nuclear-chemical evolution of the Milky Way



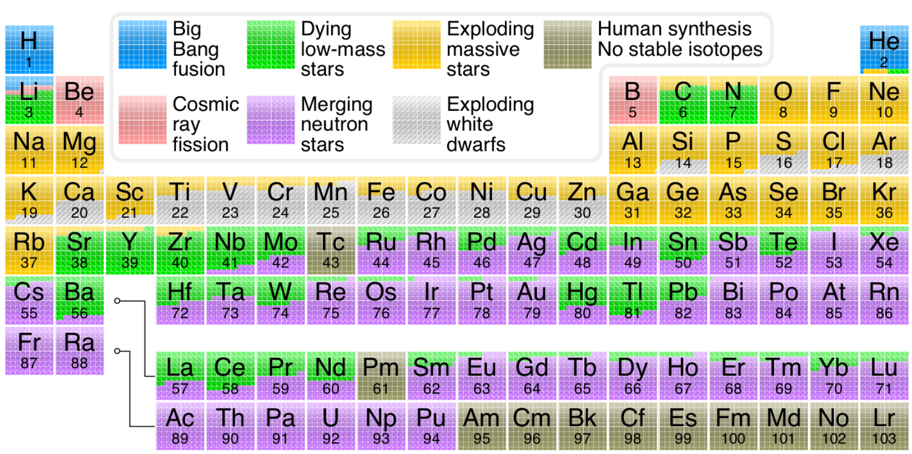
The nuclear-chemical evolution of the Milky Way

Smaller factor between odd and even Z: CNO, s-process more important as time goes on.



The nuclear-chemical evolution of the Milky Way

Origin of the elements



The nuclear-chemical evolution of the Universe

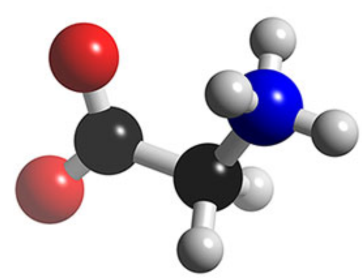
As time has elapsed since the Big Bang,

- Many successive generations of stars have enriched the interstellar medium with elements heavier than those made in the Big Bang.
  - At first via explosive nucleosynthesis
  - Later with the star's own internal fusion products
- The composition change is small between consecutive generations but adds up steadily over time: a form of **evolution**
- As the composition changes, the structure of galaxies and their interstellar medium drastically change, along with the mechanisms of star formation and death.

The evolution of interstellar matter: emergence of molecules

The heavy-element enriched material from normal stellar death via mass loss / planetary nebula / white dwarf comes out in two forms:

- Gas, mostly (99% by mass)
- **Dust**: initially partly-crystalline (mineral!) clumps containing high-melting-point (a.k.a. **refractory**) materials like Si, Mg, and Fe. Small: 100-100,000,000 atoms



The heavy-element enriched gas and dust mixes into the existing ISM and **profoundly** affects the nature of the ISM, as the presence of dust and the higher concentration of heavy elements lead to the formation of lots of molecules.

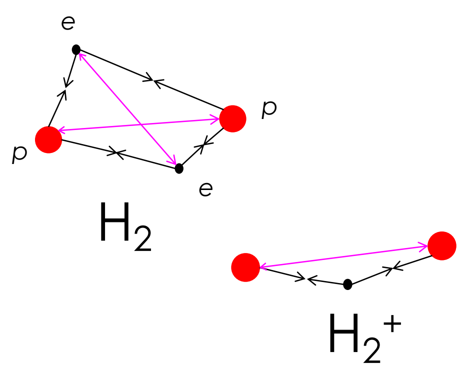
Molecular binding

Like atoms, molecules are held together by the **electrostatic force**, with the nuclei of the participating atoms typically about 10^{-8} cm apart.

Binding is a result of the balance between the attraction of the nuclei for each other's electrons, and the repulsion of the nuclei and the electrons. Bond = electron sharing

Thus, molecules tend to be fragile, but they can have complex structure.

Nothing obliges them to be neutral (not ionized).

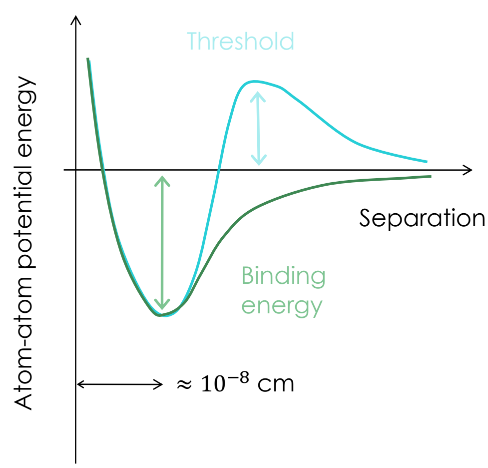


Molecular binding

Atoms bind into molecules if the potential energy is less than that of the separated atoms.

Two neutral atoms or similarly-charged ions exhibit thresholds at separations larger than that for minimum binding energy.

Ion-neutral pairs, or oppositely-charged ions, have zero threshold.



Quantum behavior of molecules

On the distance scale of molecular bonds (about 10^{-8} cm), electrons behave as (probability density) waves instead of particles.

Waves can **interfere** with one another either constructively or destructively (particles cannot).

As a result, electrons in molecules cannot have any energy they want: only certain energies are allowed (quantization of molecular electronic energy levels).

But nuclear position influences the electron structure and vice versa.

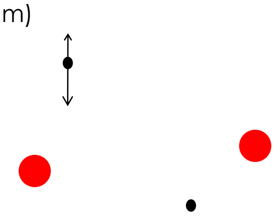
Thus, energies of molecular **vibration** and **rotation** are quantized, too.

Energies of different bound states of molecules

Electronic energies

Different states correspond to electrons in different configurations

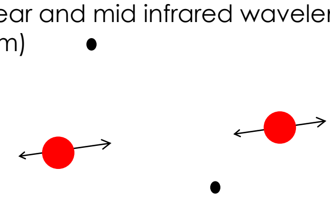
Energy differences typically correspond to visible and ultraviolet wavelengths (0.1-1 μm)



Vibrational energies

Different states: different modes of vibration of the nuclei, either along or transverse to the bonds: like different notes on a guitar string.

Energy differences typically correspond to near and mid infrared wavelengths (1-50 μm)

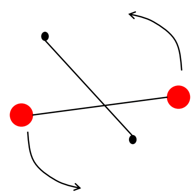


Energies of different bound states of molecules

Rotational energies

Different states: rotation of the molecules by quantized amounts about various different axes

Energy differences typically correspond to far-infrared and millimeter wavelengths (50 μm – 10 mm)



Linear and symmetrical molecules have **fewer vibrational and rotational states than complex, bent ones**.

Thus, they have fewer, and stronger, spectral lines and are easier to detect and identify.

By the same token, complex and misshapen molecules can be quite difficult to detect and identify, even if they are relatively abundant.

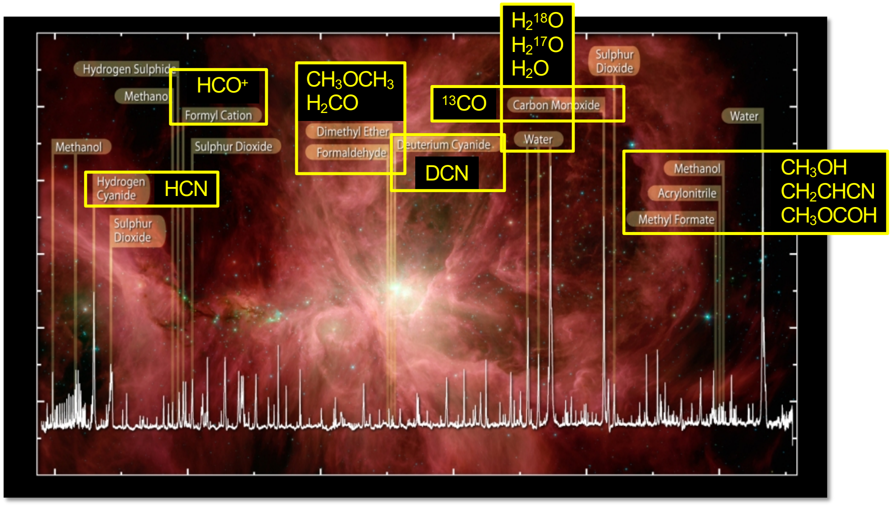
Identifying molecules in interstellar clouds & measuring their abundances

Every molecule has a distinctive set of electronic, vibrational, and rotational energy levels, and thus a distinctive spectrum: molecules can be positively identified.

The wavelengths and strengths of the spectral lines can be measured in the laboratory, usually to very high precision and accuracy.

The relative brightness of lines of a given species can be used to determine density, temperature, and pressure of the emitting region.

Thus, the relative brightness of lines of different species can be used to determine relative abundances.



Example rotational molecular-line spectrum

By Ted Bergin et al., with the HIFI instrument on the ESA Herschel Space Observatory

Question

Which molecule do you suppose would be the most abundant in the cold interstellar medium?

A. CO
B. O_2
C. CaO
D. SiO
E. FeO

Review question

What molecular process gives rise to the difference in energy between the *lowest*-energy states of a molecule?

A. Rotation
B. Vibration
C. Electronic displacement

Question

Which element necessary for human life is absent from the current inventory of interstellar molecules?

A. Carbon
B. Hydrogen
C. Oxygen
D. Nitrogen
E. Sulfur
F. Phosphorus
G. These are all present.

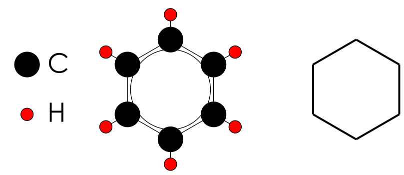
Aromatic molecules in space

In addition to the molecules listed earlier, there is also a well-known and abundant class of **aromatic ring molecules** in interstellar clouds.

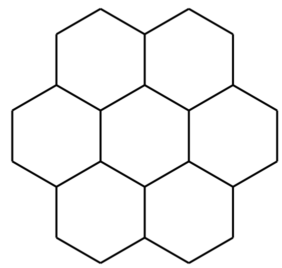
Archetype of aromatic rings: **benzene**, C_6H_6. **Lots of the molecules of life contain aromatic rings.**

In space are "polycyclic aromatic hydrocarbons" (**PAH**s) with 20-50 carbon atoms in a ring and hydrogen around the edge.

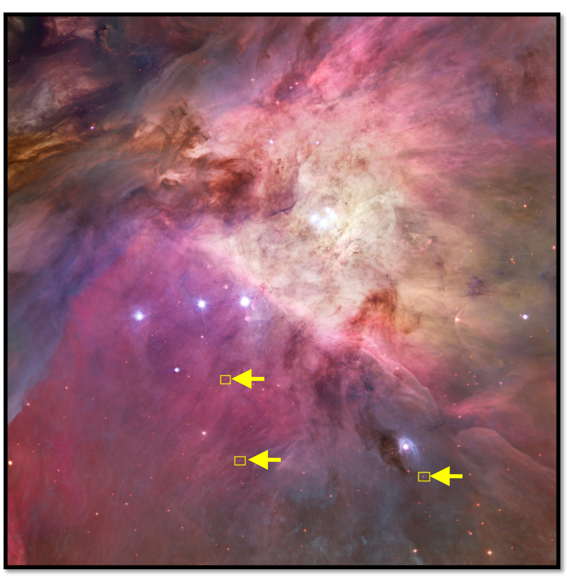
We know them from their vibrational spectra, which blend together the signatures of different-size PAHs.

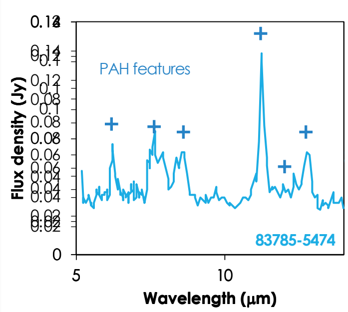


Benzene, C_6H_6



Coronene, $C_{24}H_{12}$





PAH emission from protoplanetary disks in the Orion Nebula.

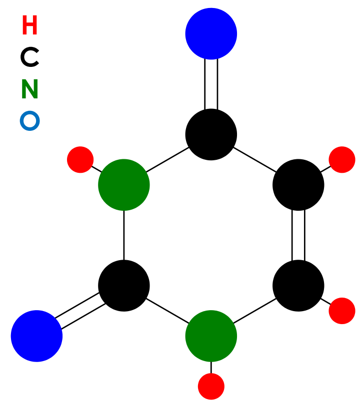
Spectra: Kyoung Hee Kim's PhD dissertation, 2013. Image: HST/STScI/NASA

Aromatic molecules in space

So far, no rotational transitions of PAH molecules have been seen, so molecules with specific numbers of C atoms have not been identified.

No five- or six-member rings containing nitrogen – which also frequently occur in biomolecules – have been identified yet either.

Still, the complex PAHs are more easily excited (by UV light) and detected than the simpler ring molecules like the organic bases that make up DNA and RNA, so we expect these other molecules to also exist in interstellar space, and to be detectable in the near future.

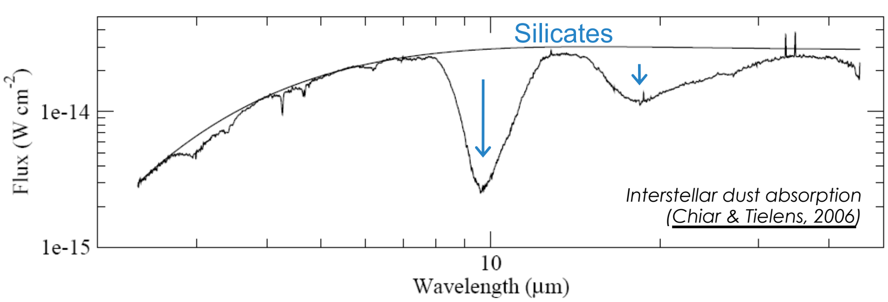


Uracil (simplest component of RNA)

Dust grains in interstellar space

Some dust grains are made of **amorphous** (randomly oriented, non-crystalline) **carbon** – these are the larger end of the particles whose smaller end are the PAHs.

Most are made of the ingredients of silicate minerals – e.g. Si, O, Mg, and Fe – in the proportions found in common **silicate** minerals (e.g. $MgFeSiO_4$) and are also amorphous.



The origin of molecules

Interstellar molecules can get quite complex, and many abundant species are based upon carbon.

- Molecular complexity is extraterrestrial.
- Carbon-based chemistry is not peculiar to Earth. (Recall also that Earth is rather poorly supplied with C.)

How do molecules form from atoms in the ISM? Three ways:

- Dust grain catalysts
- Ion-molecule reactions
- Neutral-neutral reactions in shocked material

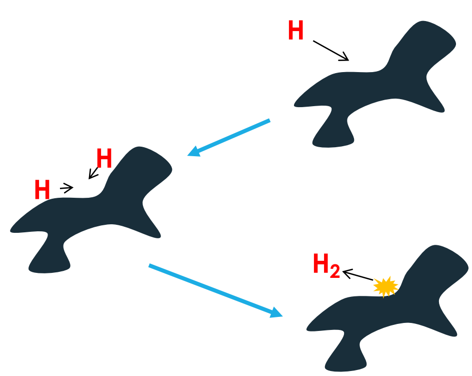
Why is not all the ISM in molecular form?

- Ultraviolet starlight destroys molecules when they are unprotected by lots of gas and dust.

Dust grain catalysis

Perhaps surprisingly, the most abundant molecule, H_2, cannot form by combining two H atoms in gas. Instead, its formation is **catalyzed** by dust grains.

- Colliding with a dust grain, an H atom is likely to lightly stick to the surface.
- Stuck lightly, it moves on the surface in response to surface charges and fields.
- If it finds another H atom, it can combine to form H_2.
  - The energy released in binding can kick the new molecule off the surface.
  - The grain goes away with the recoil momentum.

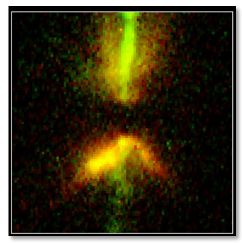


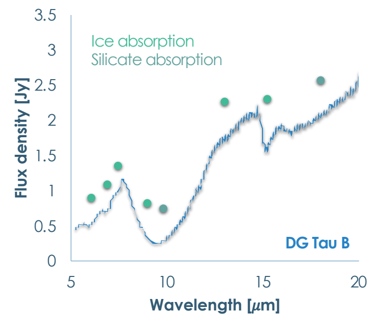
More chemistry on grain surfaces

In very cold regions, molecules can freeze onto the surfaces of dust grains forming "ice mantles."

Eventually, if enough energy (e.g. UV light) is added, the dense concentration of molecules can react to produce even more complex molecules that froze out in the first place.

Interstellar ethanol, for example, is thought to be made this way.





DG Tau B image by Hubble (STScI/NASA), spectrum by Spitzer (Watson et al. 2004)

Ion-molecule reactions

Neutral-neutral reactions can have a high threshold, but ion-molecule reactions have zero threshold.

There are always ions around, as ultraviolet light and high-energy cosmic rays (CRs; mostly high-energy photons) ionize atoms and molecules.

UV photon + C → $C^+ + e^-$

$C^+ + H \rightarrow CH^+$ + photon

$CH^+ + O \rightarrow \boxed{CO} + H^+$

$CR + H_2 \rightarrow H_2^+ + e^- + CR$

$H_2^+ + H_2 \rightarrow H_3^+ + H$

$H_3^+ + CO \rightarrow \boxed{HCO^+} + H_2$

$\Downarrow$

Increasingly complex molecules

Neutral-neutral reactions

When molecular matter is heated, as when a shock wave (supersonic disturbance, like a sonic boom) passes through, neutral-neutral reactions that have high thresholds or are even endothermic (cost energy) can produce species abundantly that are difficult to produce in large quantities otherwise:

$$O + H_2 \rightarrow OH + H$$

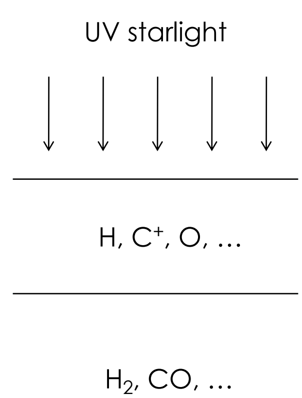
$$OH + H_2 \rightarrow H_2O + H$$

Dissociation of molecules

Molecules can be dissociated by UV starlight. But dust grains can absorb UV and simply warm up a little.

A dusty layer of gas with about 10^{21} H/cm^2 attenuates the general interstellar UV radiation field sufficiently for molecules to form behind it.

This layer, in which matter is mostly atomic, is called the **photodissociation** region.



The interstellar medium (ISM)

The ISM of the Milky Way has a mass of about $2 \times 10^{10} M_{\odot}$ ($M_{\odot} = 2 \times 10^{33}$ g = Sun's mass).

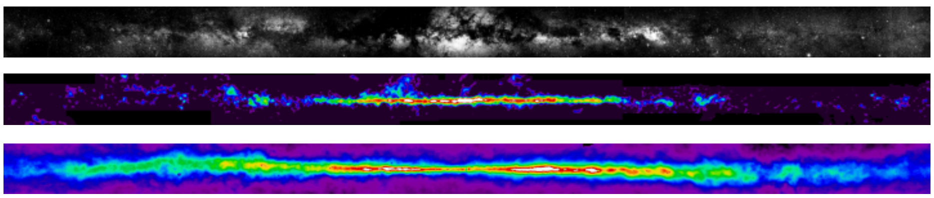
90% of it is matter in the form of **diffuse clouds**, mostly atomic in composition, and filling 40-80% of the Galaxy's volume.

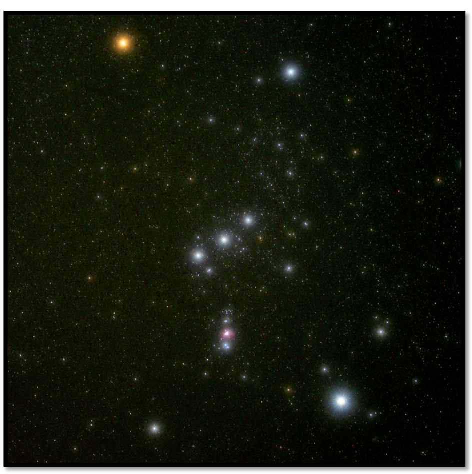
10% is in **molecular cloud complexes**, shielded from starlight by surrounding diffuse clouds and filling a tiny fraction of the Galaxy's volume.

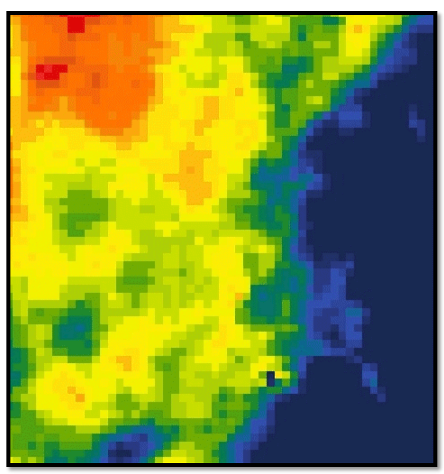
Starlight, dust extinction — *0.54 μm*

Molecular gas — *CO J = 1 → 0 2.6 mm*

Neutral atomic gas — *HI 21.1 cm*



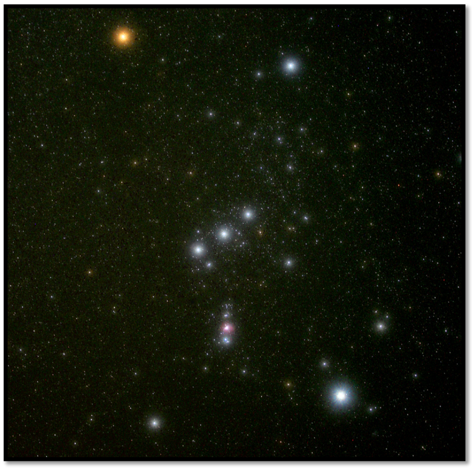


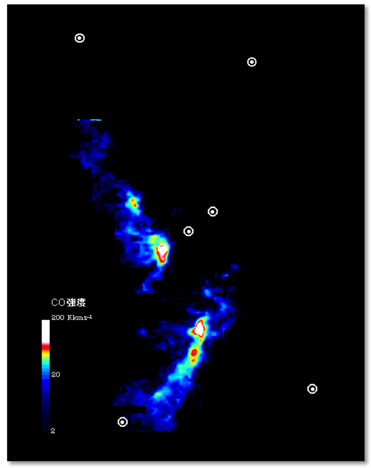


Orion and its diffuse clouds

Left: Visible John Gauvreau

Right: HI content Ron Maddalena, NRAO





Orion and its dense molecular clouds

Left: John Gauvreau

Right: Sakamoto et al. (1994)

Molecular clouds can gravitationally collapse

The molecules in molecular clouds have importance in addition to their potential biological role.

Molecular clouds are gravitationally bound and supported against their weight by pressure and turbulence.

If the clouds cool inefficiently (through emission of light), their pressure can hold them up for a long time.

Molecules radiate efficiently even at very low temperatures because of **collisional excitation** of their rotational transitions.

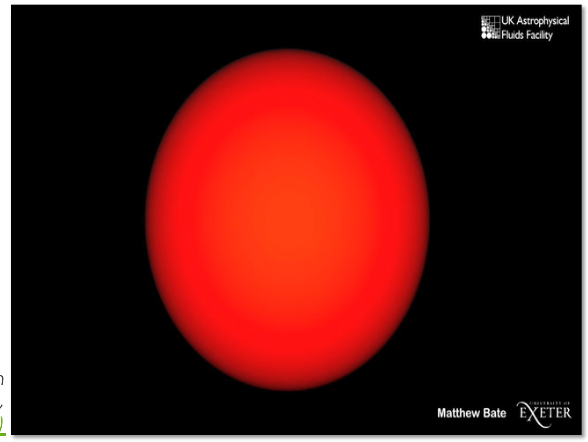
- Two molecules collide; some of the energy of their motion goes into exciting one of them to a higher-energy rotational state.
- The excited molecule returns to its ground state by radiating photons.
- The photons escape the cloud, carrying their energy with them.

Collapsing molecular clouds

While atomic clouds are typically $T = 70 - 100$ K, molecular clouds are typically 10-20 K.

Molecular cooling can rob a molecule clump of internal heat and pressure and cause it to collapse to a (much) smaller size.

It turns out that this is how stars form.

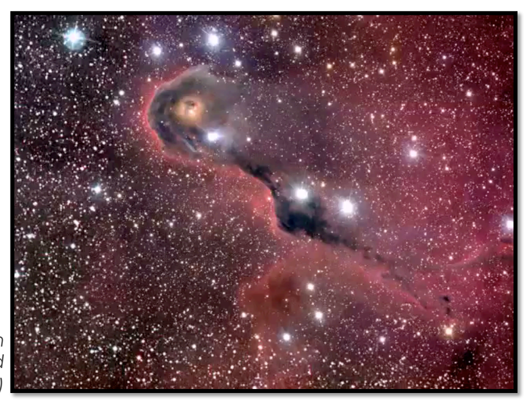


Simulation of star-cluster formation in an initially $500M_{\odot}$ spherical cloud, by Matt Bate (2009)

Quick summary of star formation

The Milky Way is not unusual: most spiral galaxies have a large fraction of their gas (0.1-0.5) taken up by molecular clouds.

Much of this fraction is in the form of giant complexes of molecular clouds: massive ($10^4 - 10^6 M_{\odot}$) very dense (by interstellar standards) as well as fairly cold.



IC 1396: zoom to smaller scales and in wavelength from visible to mid-infrared (R. Hurt, SSC/JPL/Caltech/NASA)

Star formation

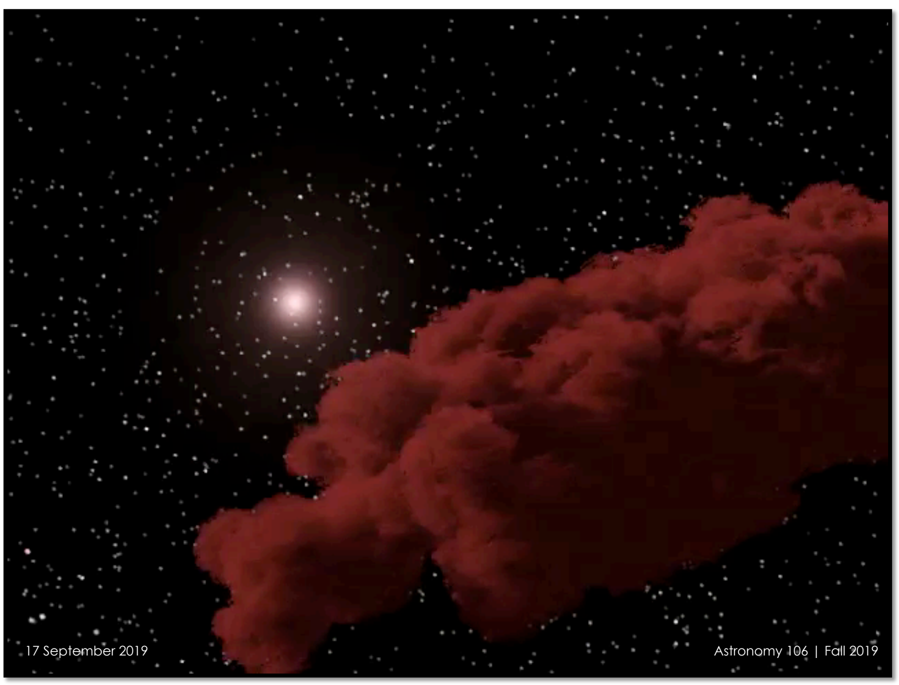
The molecular material can be seen directly with very long wavelength light ($\lambda = 30\ \mu$m – 3 mm) emitted by molecules and dust.

- Molecules are seen by being "heated" into higher rotational energy states by collisions with other molecules. The longer the wavelength, the smaller the energy difference between rotational states.
- Dust grains are seen by their thermal (blackbody) radiation; they are also heated by collisions with molecules and, on cloud edges, by UV light.

As fragments of molecular clouds emit the light we see, they cool down even more.

If a molecular cloud fragment cools enough so that its internal pressure is insufficient to support its weight and any external pressure, it will collapse and its density will rise.

Physical conditions in molecular clouds are often such that the density increase leads to an even greater light-emission (i.e. cooling) rate than before, which causes the fragment to collapse further, thus cooling even faster, thus collapsing even further, etc. This sort of runaway is called **gravitational instability**.



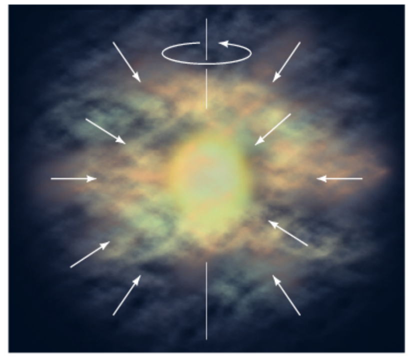
Supernova-induced star formation

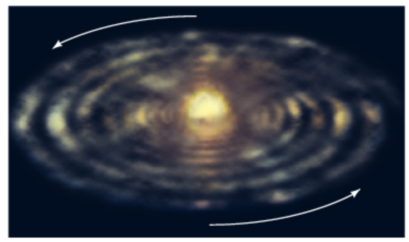
R. Hurt, SSC/JPL/Caltech/NASA

Star formation

In general, the fragment was slowly tumbling before the collapse started. But it has to obey the conservation of angular momentum (spin), and now that it is somewhat disconnected from its surroundings, it spins up as it collapses.

Along the rotation axis, the collapse can proceed freely. In the perpendicular directions, the collapse is stopped by centrifugal support: a protostar and a surrounding **disk** have formed.

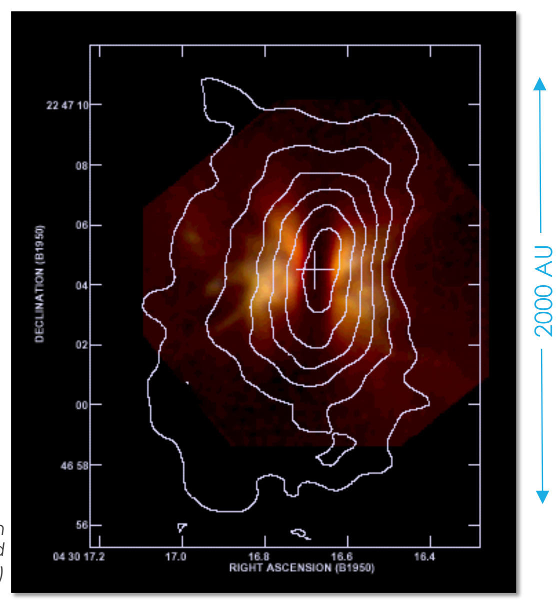




Star formation

For typical molecular-cloud fragments with $M = 1M_{\odot}$, the size of the disk would be expected to be a few thousand AU. Sure enough, we see flattened structures of similar mass and size in molecular clouds.

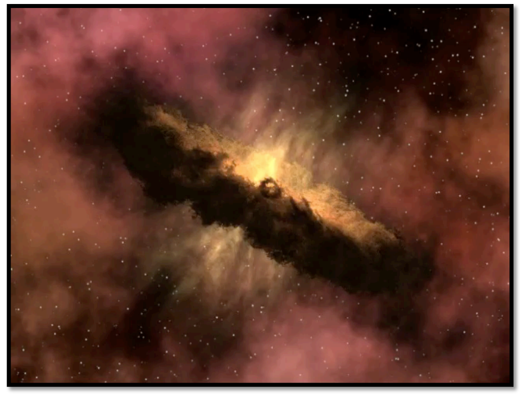
(1 AU = distance between Earth and Sun = $1.5{\times}10^{13}$ cm)



IRAS 04302+2247 in ^{13}CO emission (OVRO) and scattered near-infrared light (HST). From D. Padgett et al. (1999)

Star formation

The disk continues to "collapse" in its radial direction, but much more slowly: collisions among molecules and dust grains at slightly different radii (and orbital speeds) slowly convert the angular momentum to heat and allow material to slowly progress toward the center. Soon, a central **protostar** builds up from this **accretion disk**.

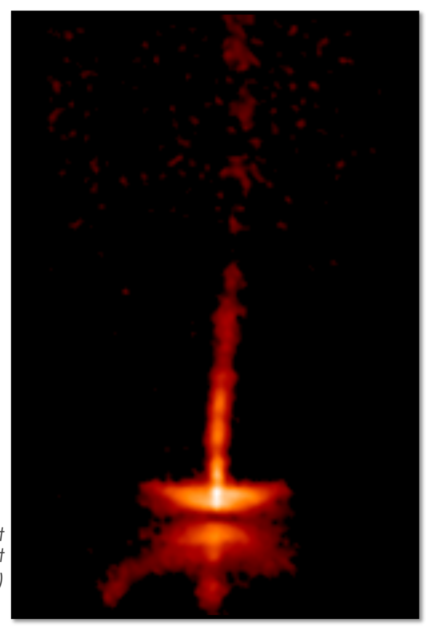


Protostar with accretion disk (R. Hurt, SSC/JPL/Caltech/NASA)

Star formation

For awhile, the central object accretes gas and dust from the disk and drives a bipolar outflow into its surroundings, which is thought to carry off the accreted material's spin.

The star cannot inherit all the spin of the disk without breaking up.



Several HST-WFPC2 images of the jet in the edge-on young stellar object HH30 by Alan Watson et al. (2000)

Star formation

Over time, the disks dissipate due to numerous processes that use up or drive away the surrounding dust and gas. We can see this evolution by looking at the **spectra** of the disks or **images** of the structure of the disk at **infrared** (and longer) wavelengths, because their temperatures are ~100 K.

After 3-5 million years, not much (micron-size) dust or gas remains around the star.

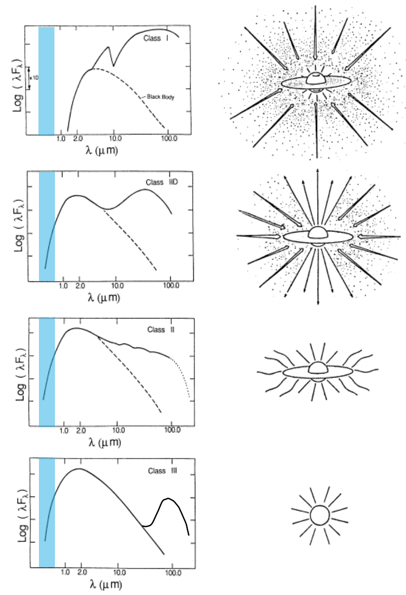


Figure adapted from Wilking (1989)

= visible wavelengths