

Physics 343 Lecture # 6:
Lab # 3; the Interstellar Medium

This week's schedule

Thursday, 3/1 at 8:00pm in Physics Lecture Hall:

Prof. Tad Pryor (Rutgers): “Observing Satellite Galaxies of the Milky Way with the *Hubble Space Telescope*”

Lab sections will meet at regular times this week.

Lab 3 data will be taken on Friday (Saturday/Sunday in case of glitches) and emailed to you.

Lab # 3: spectral line observations!

So far all of our observations with the SRT have been with receiver mode 1, and we've simply averaged over (most) channels since we've only been interested in **continuum** emission from the Sun.

For **line** observations, we care about individual channels!

mode 1 = 500 kHz bandwidth ← all data so far

mode 2 = 250 kHz bandwidth

mode 3 = 125 kHz bandwidth

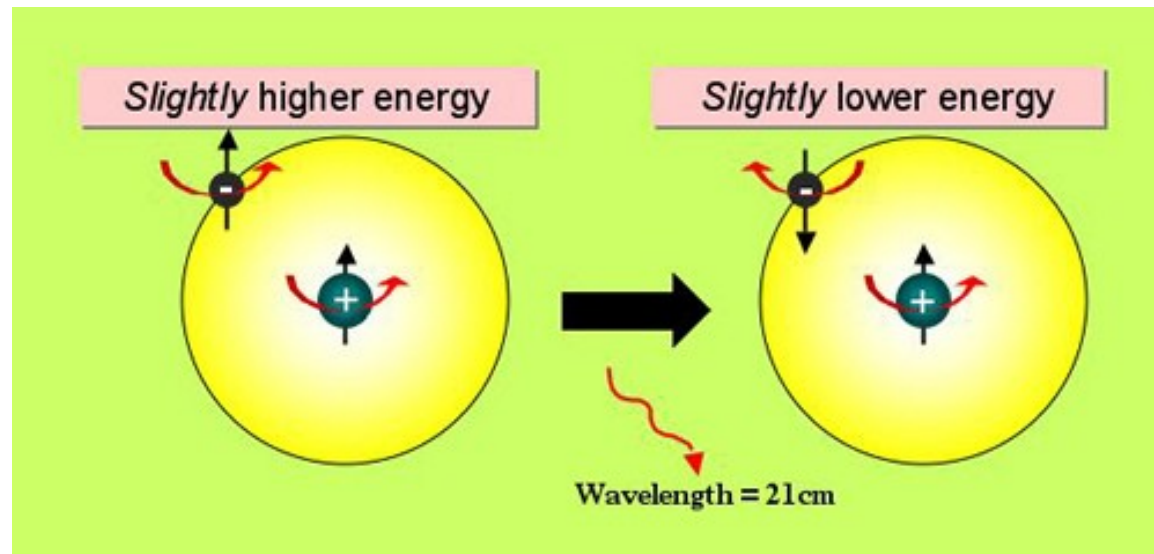
mode 4 = 3 x 500 kHz bandwidth (with overlaps:

1218.75 kHz bandwidth with 156 channels)

The key “spin flip” transition: 21cm H line

In a H atom, when the electron and the proton switch from having parallel spins to having antiparallel spins, a photon is emitted at

$$\lambda = 21\text{cm} \leftrightarrow \nu = 1420.4 \text{ MHz.}$$



Doesn't trace ionized or molecular gas – just neutral atomic gas!

Courtesy of Swinburne University.

Velocities in astronomy

Observed frequency and wavelength are related to **rest** (emitted) frequency and wavelength by a velocity (or redshift).

Exact relation = Doppler shift:

$$\nu_0/\nu = \lambda/\lambda_0 = 1 + z = \gamma (1 + v/c) \text{ for } \gamma = (1 - v^2/c^2)^{-1/2}$$

and for relative velocities, $\Delta\nu/\nu = \Delta\lambda/\lambda = \Delta z/(1 + z) = \Delta v/c$.

However, astronomers also make different approximations...

$$\text{radio: } \nu \simeq \nu_0 (1 - v_{\text{rad}}/c)$$

$$\text{optical: } \lambda \simeq \lambda_0 (1 + v_{\text{opt}}/c)$$

Distances in astronomy

Nearest stars can have distances measured by **parallax**:

the apparent shift in position relative to the background pattern of more distant stars caused by the earth's motion around the Sun.

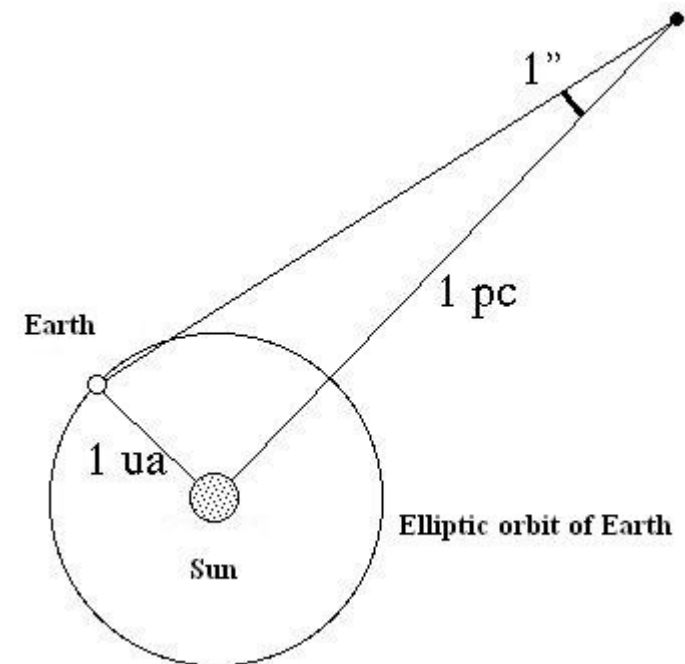
1 parsec = 1 pc:

3.089×10^{18} cm

~ 3.3 light years

Distances **inside** galaxies ~ kpc.

Distance **between** galaxies ~ Mpc.



Stellar components of spiral galaxies

Spiral galaxies have two principal components: **disk** and **bulge**.

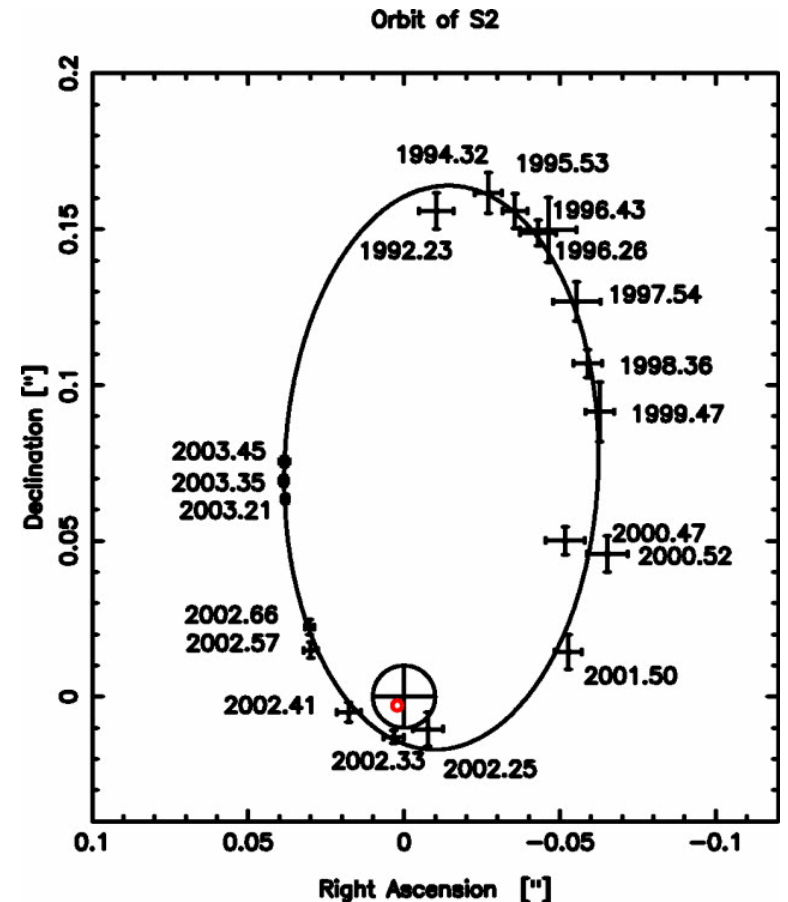


Where is the Sun within the Galaxy?

Note on terminology: Milky Way = “the Galaxy”; other “galaxies” are not capitalized.

Sun and solar system lie at a distance of **7.94 kpc** from the Galactic Center, where a supermassive black hole lies.

Eisenhauer et al. (2003)

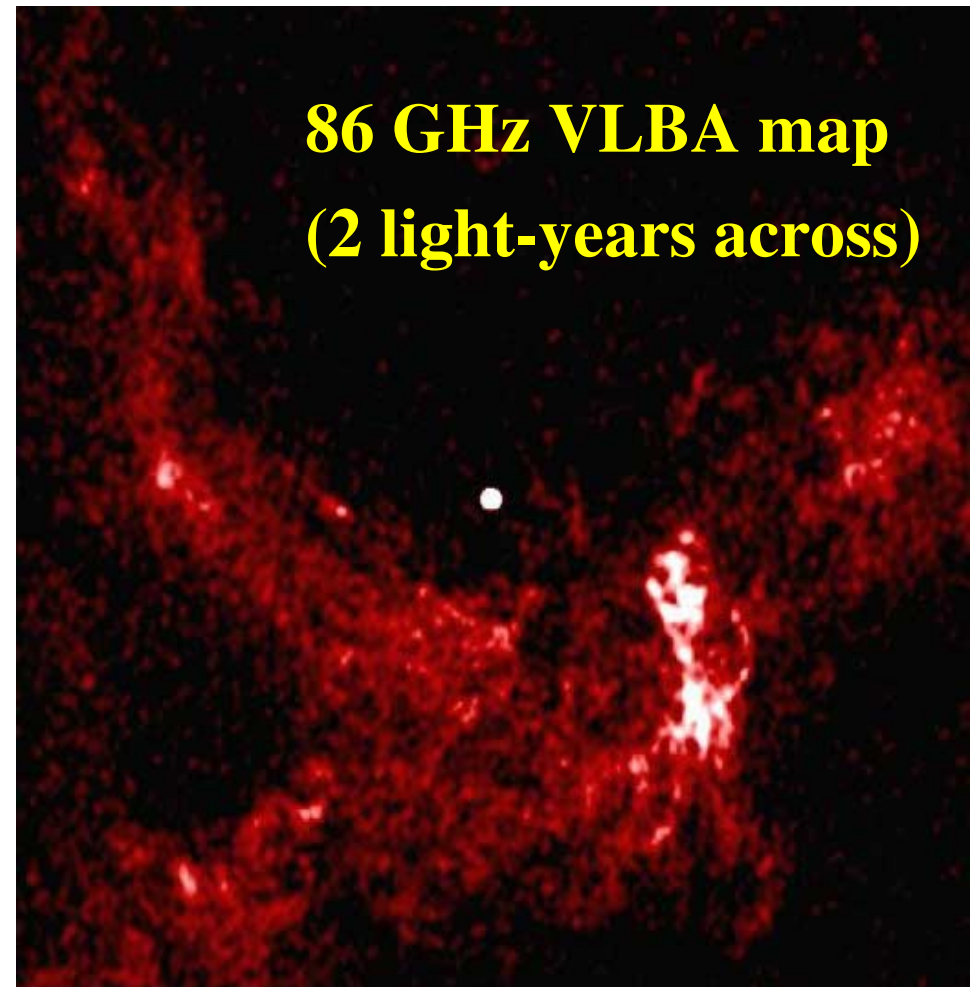


Central black hole is a radio source!

Motions of stars imply a large central mass – but from low proper motion of **Sgr A*** (“Sagittarius A–star”), we know that *it* must be massive.

Observations with the Very Long Baseline Array reveal a proper motion only due to the Sun's motion around the Galaxy.

Shen et al. (2005)

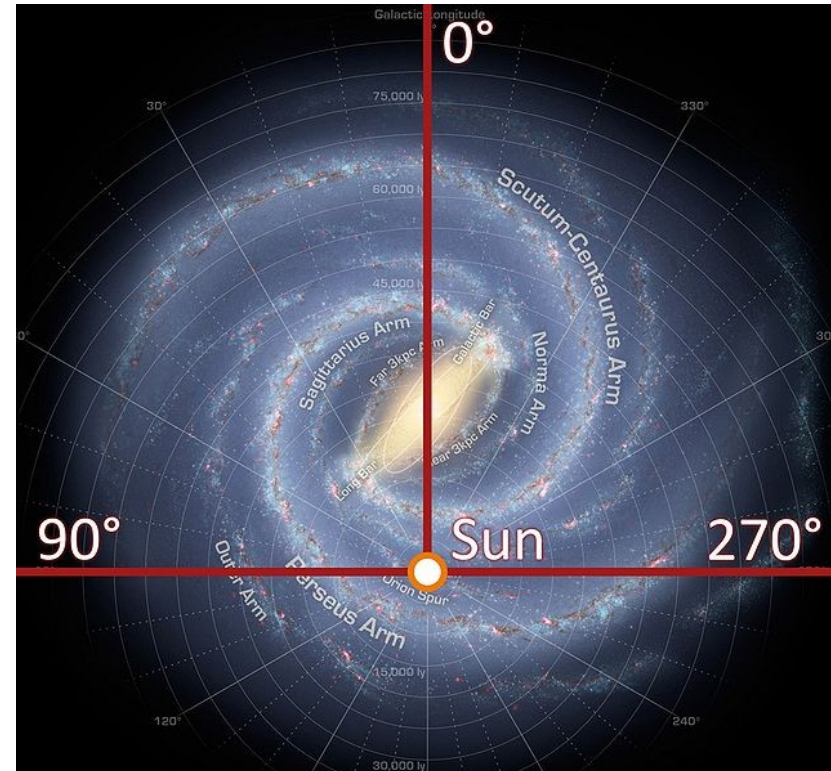
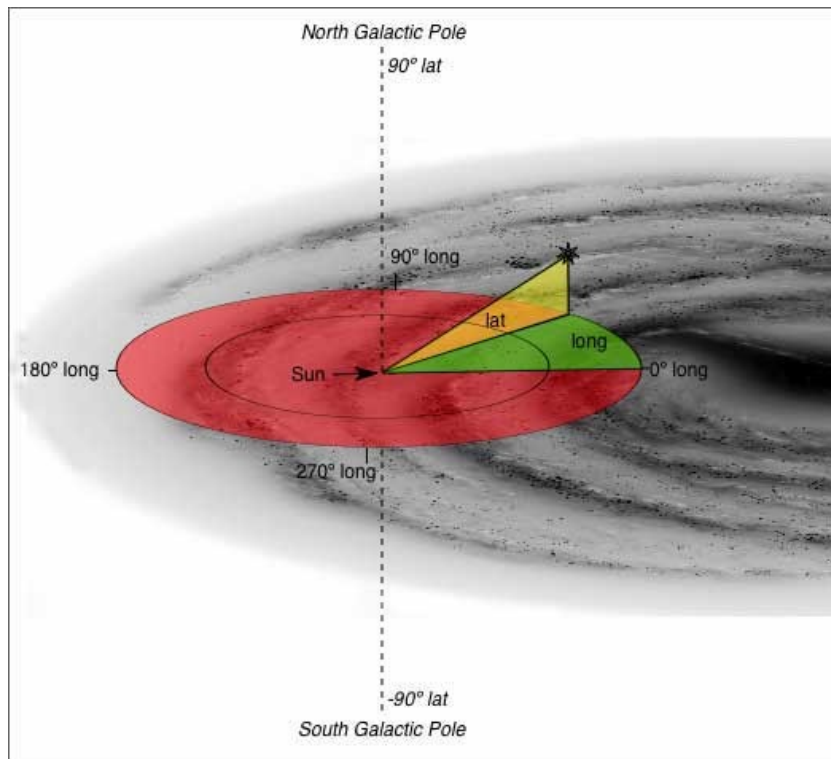


Galactic coordinates

The Sun is also located within the disk.

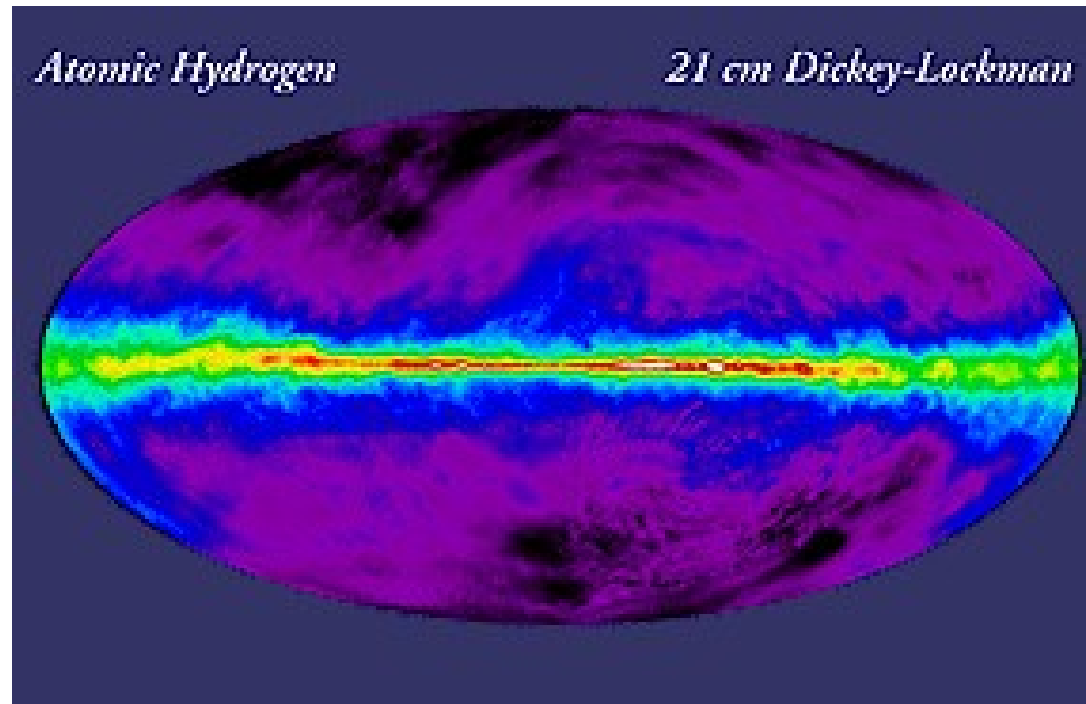
b = Galactic latitude (above/below plane)

l = Galactic longitude (0 towards Galactic Center; 90 in direction of Sun's motion = clockwise from “above”)



HI in the Milky Way

**Nearly all the HI (neutral H) in the Galaxy is located in the disk.
Observed velocities governed by (a) rotation (b) random motions.**



(plotted in Galactic coordinates)

Quiz

The interstellar medium and its variants

ISM = interstellar medium = whatever gas and dust exists in the space between a galaxy's stars.

ICM = intracluster medium = hot gas filling the volume between galaxies in a group or cluster

IGM = intergalactic medium = material that has been ejected from galaxies or never made it into a galaxy in the first place

Why should we care about the ISM?

Tongue in cheek answer: every astronomy talk can be followed by one of three (ISM-related) questions:

(1) What about **dust?**

(2) What about **magnetic fields?**

(3) What about the **initial mass function (i.e., relative numbers of newborn stars of different masses that result when a large gas cloud turns into stars all at once)?**

Why should we care about the ISM?

Serious answer: the ISM serves as the raw material for star formation and the dumping ground for the products of stellar nucleosynthesis (notably, all elements heavier than helium).

Moreover, the ISM affects nearly all observations we make by absorbing, scattering, or swamping the radiation from other sources of interest.

(for dust, absorption + scattering = extinction)

Key property of the ISM: composition

Gas mass fractions X (hydrogen) + Y (helium) + Z (“metals”) = 1:

Shortly after the Big Bang: no stars yet

$$X = 0.75$$

$$Y = 0.25$$

$$Z = 0.00$$

In the Sun (and surrounding ISM):

$$X = 0.739$$

$$Y = 0.248$$

$$Z = 0.012 \text{ (of which oxygen contributes 0.005)}$$

Key property of the ISM: phase

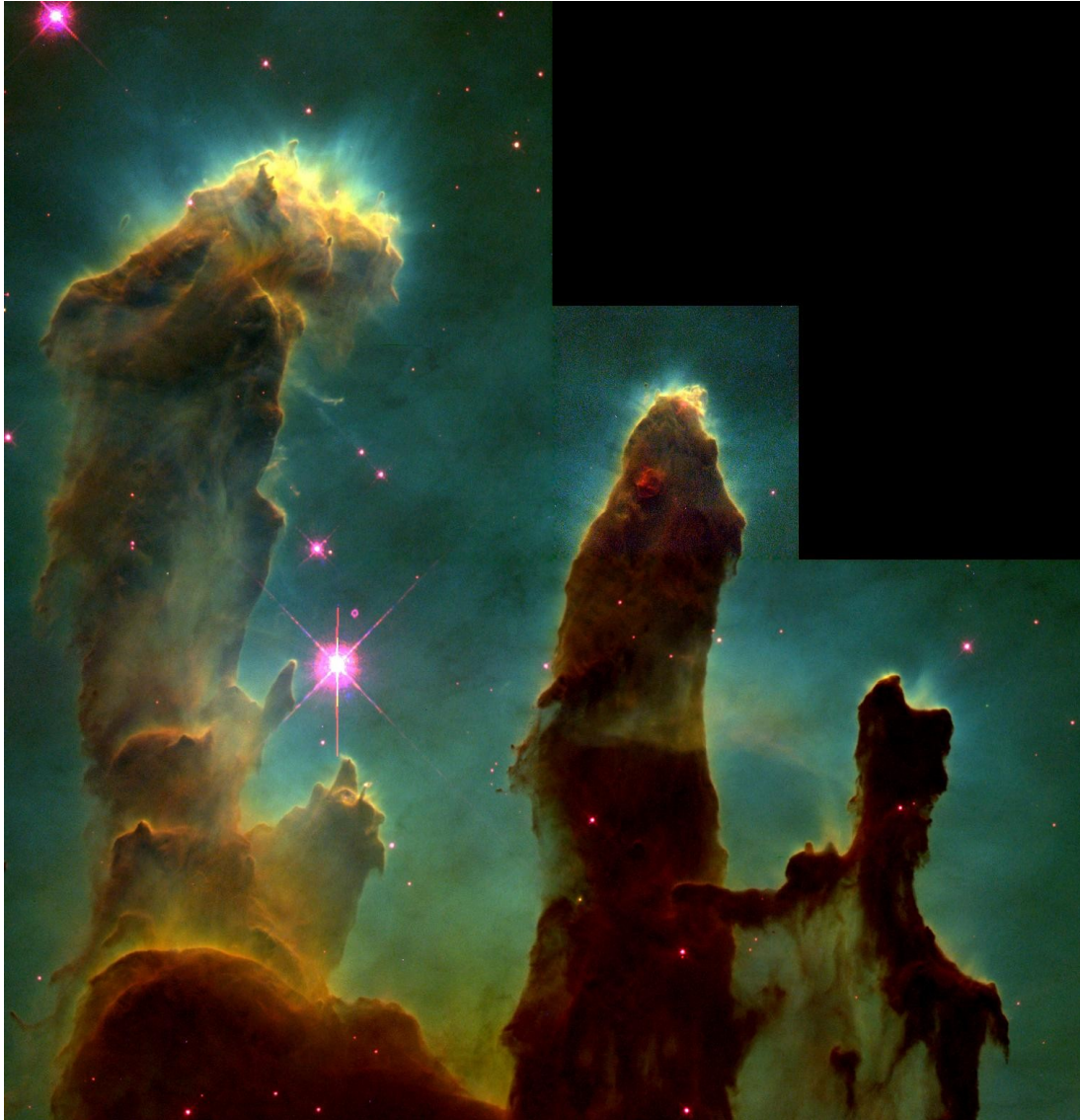
Two parcels of gas with the same composition can have very different physical states. We characterize the **phase** of interstellar gas with our answers to two questions:

- (1) In what form is the **hydrogen** predominantly found (ionized HII, neutral HI, and/or molecular H₂)?
- (2) What are the **temperature** and **density** of the gas?

Observed phases of the ISM

<u>Phase</u>	<u>n (cm⁻³)</u>	<u>T (K)</u>	<u>nT (K cm⁻³)</u>	<u>% V</u>	<u>% M</u>
hot ionized	0.003	10 ⁶	3000	50	4
warm ionized	0.1	8000	800	25	14
warm neutral	0.5	8000	4000	30	38
cold neutral	50	80	4000	1	30
molecular clouds	> 2000	10	> 20000	0.5	13

Molecular gas: birthplace of stars



**Eagle Nebula, imaged with
the *Hubble Space Telescope*:**

**young stars that have
emerged from their
dusty birth clouds
+ still younger stars that
are still enshrouded**

Star-forming regions

Carina Nebula imaged with the *Hubble Space Telescope*:



A mixture of still-forming and young stars, some so massive that they are on the verge of exploding (e.g., η Car).

Don't mess with the interstellar medium!



The “**defiant finger**” in the Carina Nebula (NASA/HST).

Molecular gas: birthplace of stars

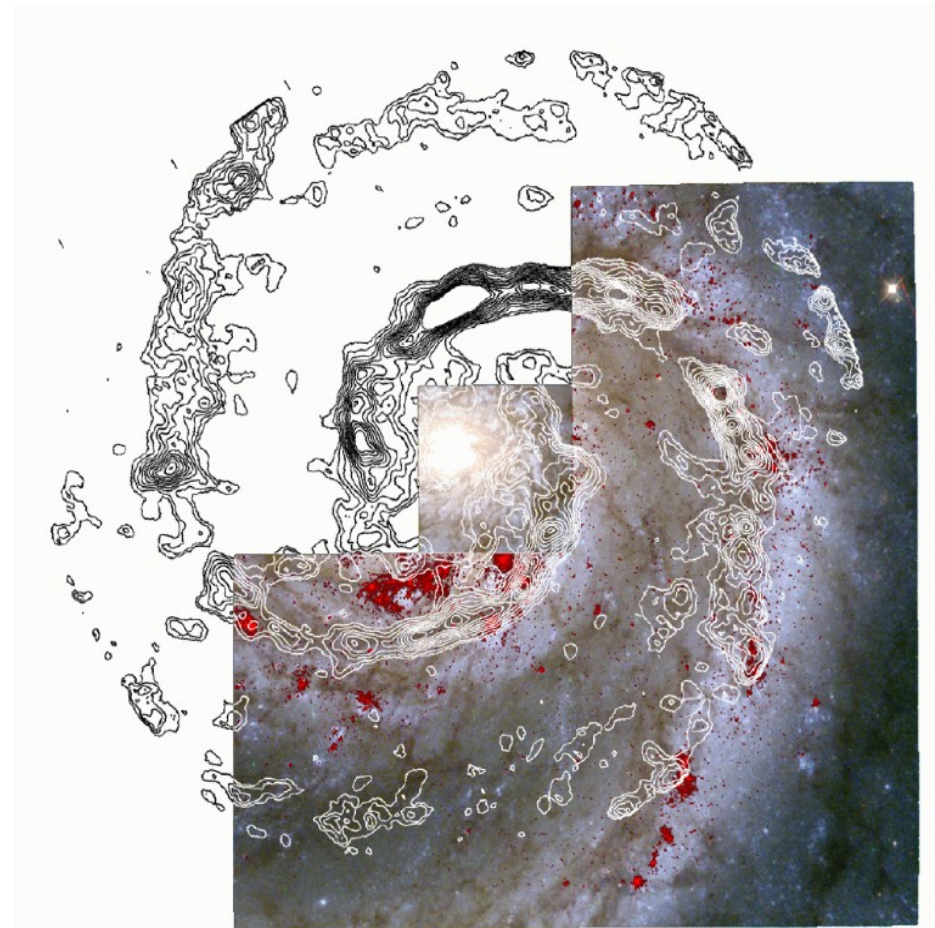
Whirlpool Galaxy • M51



Hubble
Heritage

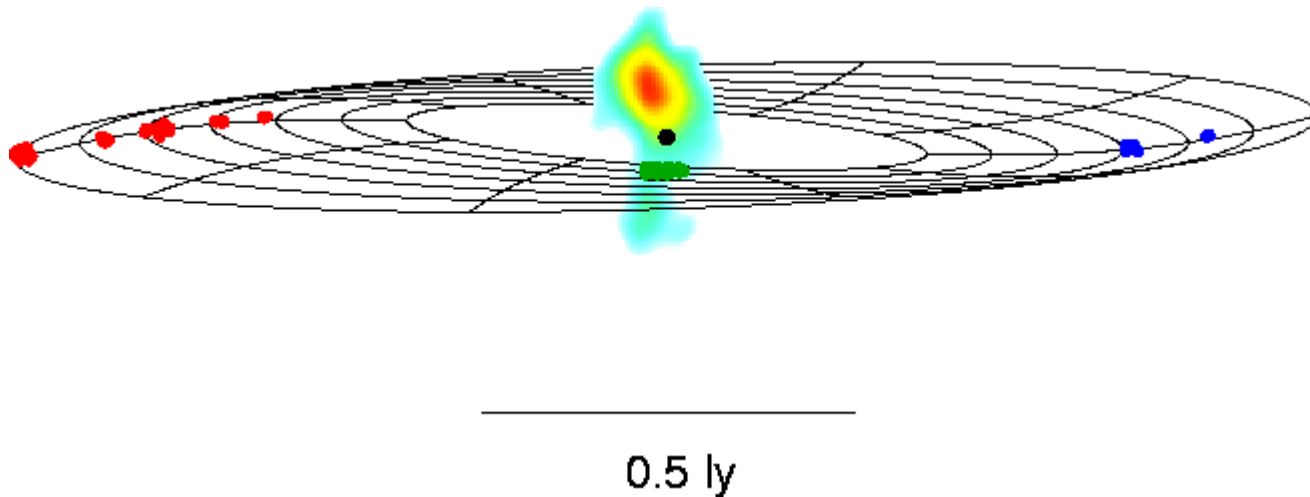
NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

**M51: CO contours overlaid on
Pa α emission + optical light**



Molecular gas: fuel for black holes

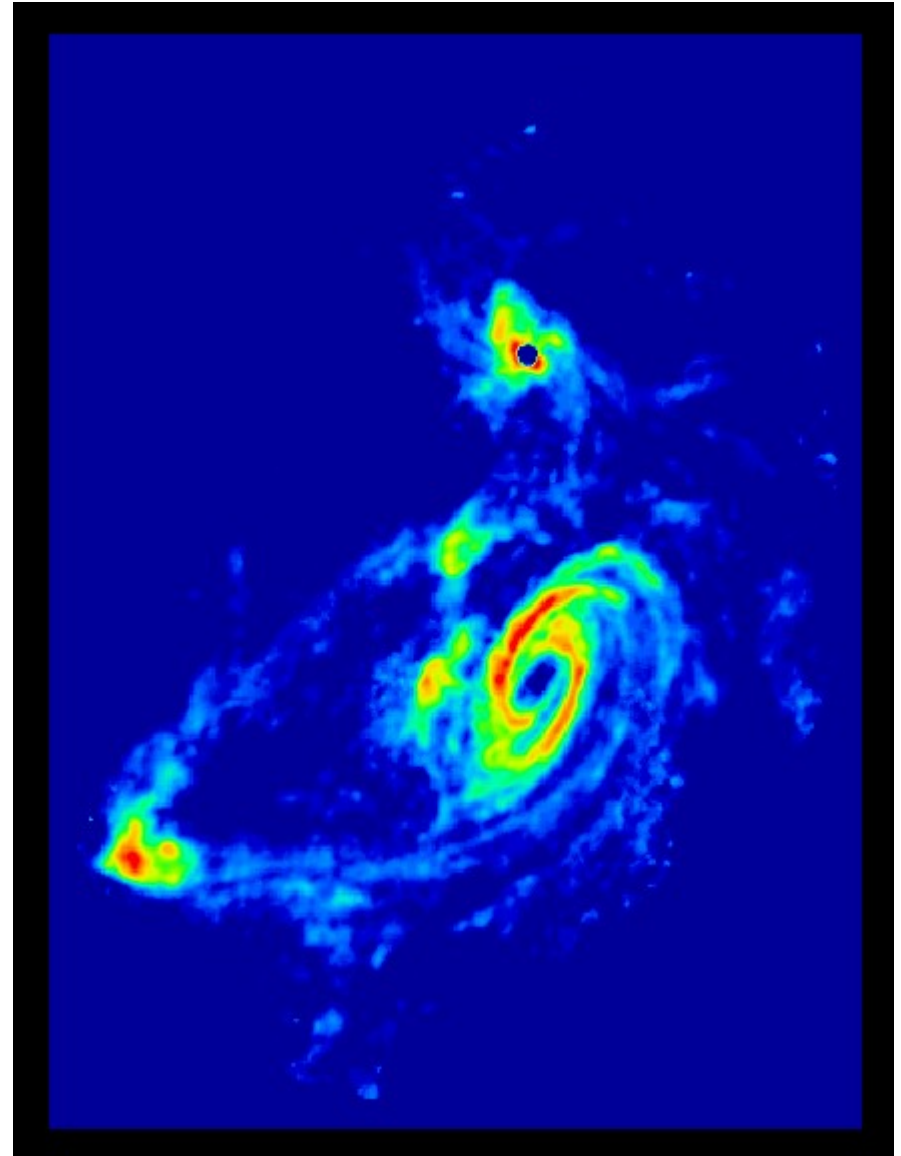
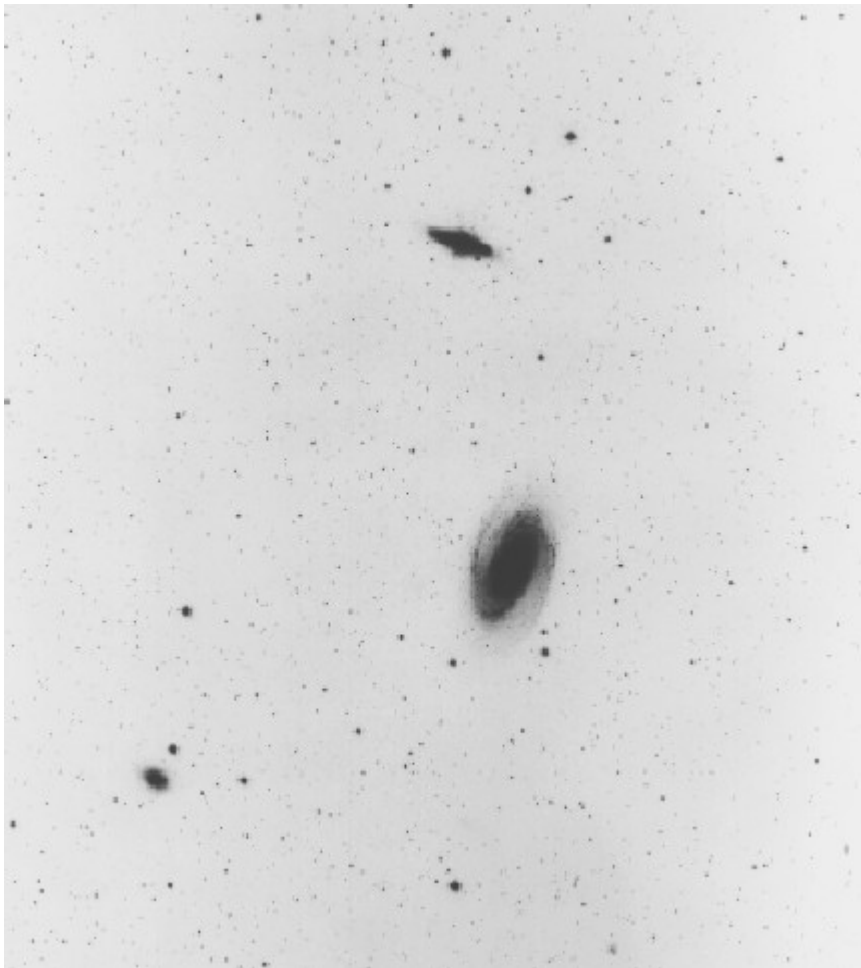
NGC4258: H₂O maser emission from dense, warm gas in clumps that are moving **towards us, **away from us**, and **in the plane of the sky** (Herrnstein et al. 1997).**



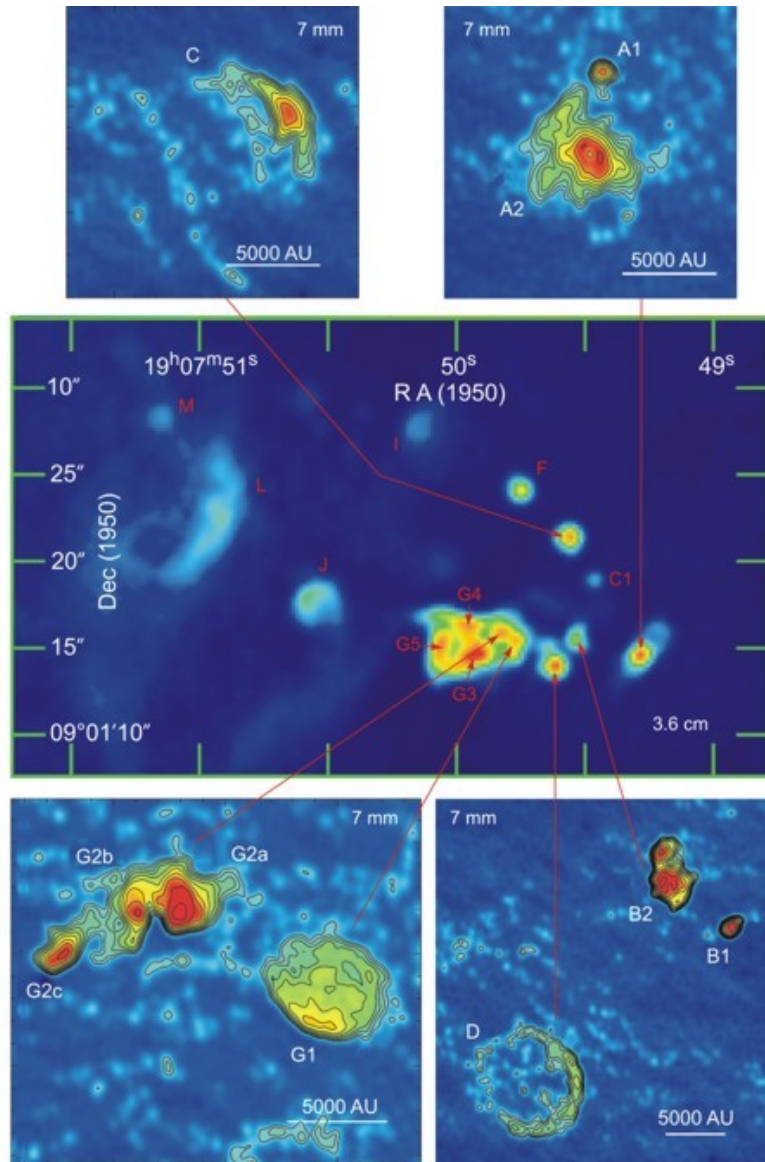
This gas fuels the black hole, which drives a jet perpendicular to the disk.

Atomic gas: a major gas reservoir

**M81 group: optical starlight
(left) + VLA HI (right)**



Ionized gas: HII regions...



**Free-free emission from young,
“ultracompact” (high- n_e)**

HII regions in Milky Way:

middle = 3.6cm, insets = 7mm

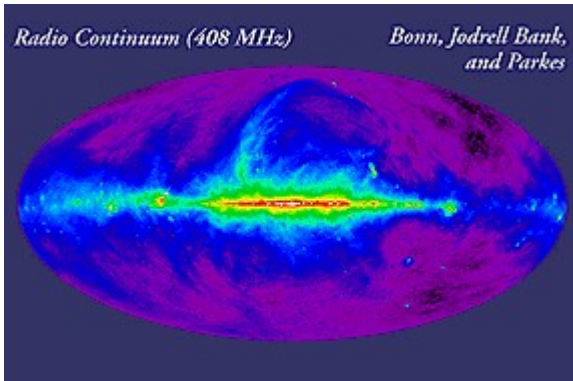
**C. DePree, M. Goss, J. Welch,
& D. Wilner**

...and superwinds

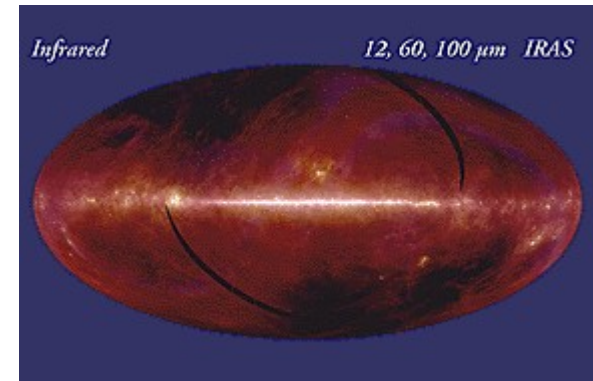


Starburst galaxy M82: X-ray emitting hot gas and H α emission from ionized gas trace ejection of material along minor axis

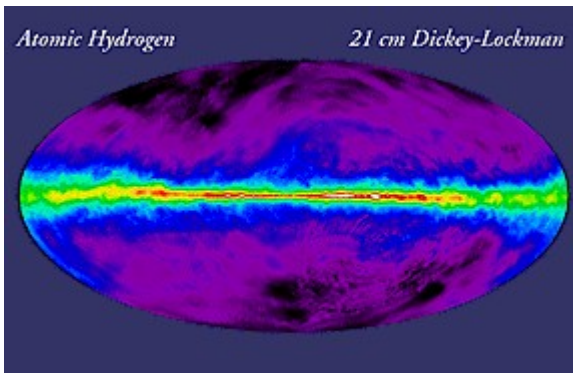
A multiwavelength view of the Milky Way



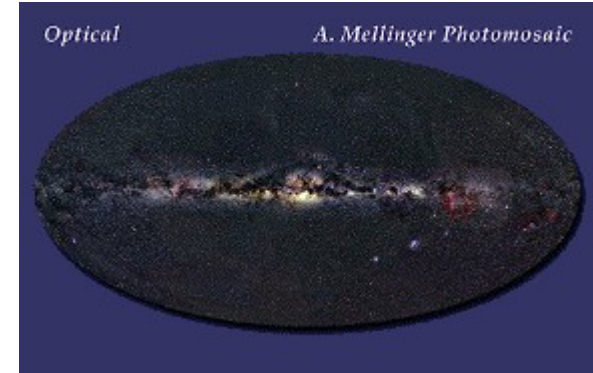
radio continuum



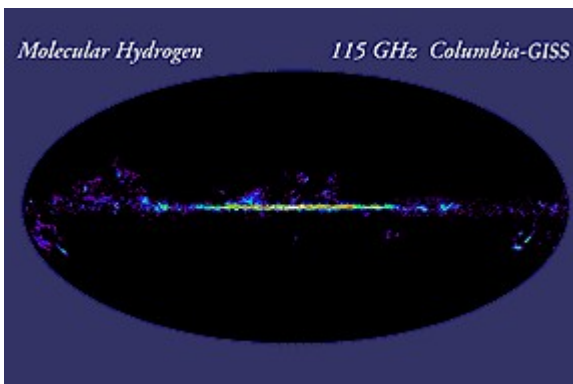
infrared (dust)



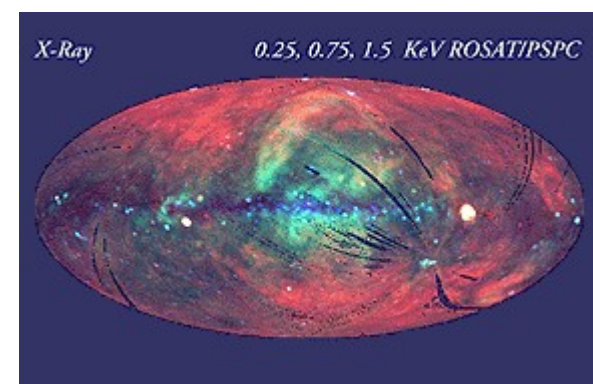
HI



optical



CO (H₂)



X-ray

Pressure equilibrium

<u>Phase</u>	<u>nT (K cm⁻³)</u>	
hot ionized	3000	Several phases of the ISM have the same thermal pressure as each other (nkT). This makes sense: a hot, dense bubble of gas will tend to expand until it reaches pressure equilibrium with its surroundings.
warm ionized	800	
warm neutral	4000	
cold neutral	4000	
molecular clouds	> 20000	Molecular clouds do not follow this pattern: they are bound by self-gravity!