Astro 406
Lecture 9
Sept. 16, 2013

Announcements:

- **PS 3 available, due Friday**
  uses real online data: need internet connection
- ASTR 401: abstract due today
- Research opportunity: Prof. Ryan Foley `rfoley@cfa.harvard.edu`
  new Astronomy & Physics faculty member
  studies exploding stars and dark energy
  a chance to find targets for *Hubble* observations!

Last time: began study of Milky Way interstellar gas
Q: most abundant element?
Q: how do we observe it?
Q: pattern on 2-D sky? in 3-D space?

In Search of Interstellar Hydrogen: Molecular Form

molecular hydrogen: $H_2 = H - H$

identical atoms → symmetric quantum state

→ no dipole moment → no dipole radiation! Aargh!

but: **carbon monoxide = CO** molecule has dipole

excited by collisions, mostly with H_2

for experts: radiates via transitions between rotational states:

- $E_J = L_J^2/2I = J(J+1)\ \hbar^2/2I$
- $\Delta E = E_{J+1} - E_J = J\ \hbar^2/I$

→ for $J = 1 \to 0$: $\nu_{10} = \Delta E_{10}/h =$ 115 GHz: radio

Q: predictions for CO sky map? how compare to 21 cm map?

`www: CO map`

Molecular Hydrogen: H_2

on sky:

- most CO very concentrated in midplane
- most CO emission $\ell \lesssim \pm 90^\circ$
- some emission far outside of midplane
  especially at large $\ell \sim 180^\circ \rightarrow$ anticenter

in 3-D:

- CO mostly in very thin disk
- most CO in regions closer to center than we are
- emission beyond midplane $\rightarrow$ probably very nearby!

In Search of Intersellar Hydrogen: Ionized Form

ionized H II = free, unbound p, e: *"plasma"*

To ionize H (and/or other atoms)
need energetic environment:

- hot $\rightarrow$ violent collisions between atoms
- high-energy (UV, X-ray, γ-ray) photons

Q: why? – see Director's Cut Extras bonus track lecture

ionized gas made of free p, e
Q: how to detect?
Hint: atoms can and do form, but don't last long

The idea: in plasma atoms *do* re-form:

$p + e \rightarrow H(n > 1) + \gamma \rightarrow \cdots \rightarrow H(n = 1) + \gamma$

"recombination cascade" of photons

$\rightarrow$ can observe this radiation!

particularly useful: **Balmer line** "Hα" $n = 3 \rightarrow n = 2$

note: this is in optical band (red!)

Q: and so?

Note: have now created a neutral H atom

but plasma too violent: other p, e rapidly blast atom apart again

so gas is always $\gg 99\%$ ionized

Q: What will the Balmer sky look like?

`www: Hα sky`

Q: what does distribution tell us?

Ionized Hydrogen: H II

on sky:

- roughly concentrates in plane but very irregular
- large spherical blobs with filamentary structure

in 3-D:

- H II roughly planar but puffier distribution
  not smoothly distributed, very nonuniform
- blobs $\rightarrow$ "H II regions"
  localized sources of ionization *Q: like what?*
- caution: since Hα is optical, like starlight
  do *not* see whole Galaxy in H II
  but only local neighborhood

summing up:
Q: what are main messages from hydrogen sky?

Milky Way Hydrogen Executive Summary

Milky Way contains large amounts of H gas

- H is the dominant element, as expected
- significant components of H_2, H I, and H II
- interstellar medium has wide range of temperature, density
  phases co-exist in equilibrium (pressure balance)
- cooler components $\rightarrow$ more concentrated in disk
- more on this in Astronomy 405!

Interstellar Metallica: Heavy Element Mapping

heavy elements (i.e., $>$ He) found in interstellar space
- in gas phase (e.g., CO molecules)
- in solid phase: dust

in particular, can map dust
Q: guesses? `www: Far IR`
interstellar medium has $M_{\rm dust}/M_{\rm gas} \sim 1\%$
$\Rightarrow$ interstellar "metallicity"

$$Z_{\rm ism} = M_{\rm metal}/M_{\rm gas} \sim 10^{-2} \sim Z_{\odot} = 0.02 \tag{1}$$

Q: is this reasonable?

total Galactic gas mass: $M_{\rm gas} \sim (0.5-1) \times 10^{10} M_{\odot}$

Q: is this a lot of gas or a little?
Q: what to compare against?

Milky Way Mapping: Stars

We want to map the stars in the Milky Way
want map to be *complete*

to avoid dust obscuration, need to observe
at wavelengths $\lambda \gtrsim few\ \mu > r_{\rm dust}$

`www: Near IR sky`

What shapes, features do you see on the sky?
What could these correspond to in 3-D space?

Galactic stars: sky view

- most stars seen Galactic plane
  $\rightarrow$ most stars are in disk
- highest sky density near $\ell = 0$
  $\rightarrow$ disk stars concentrated towards Galactic center
- roughly spherical component in center, but somewhat flattened

Two stellar components: "populations"

⋆ *Population I*: *disk* geometry
the Sun is a Pop I star

⋆ *Population II*: *spheroidal* geometry

Population I: Disk Stars

- metal contents ≈ solar: **metallicity**

$$Z_{\odot} = \frac{M_{\text{metals}}}{M_{\text{total}}} = 0.02 = 2\% \text{ metals by mass} \tag{2}$$

- orbits ∼ circular

Pop I stellar (number) density in 3-D space:
tapers off exponentially in both R and z

$$\boxed{n_{*,\text{disk}}(R,z) = n_0 \; e^{-R/h_R} \; e^{-z/h_z}}$$

radial "scale length" $h_R = 3000 \text{ pc} = 3 \text{ kpc}$
vertical "scale height"

$$h_z \sim \begin{cases} 300 \text{ pc} & \text{short-lived stars} & \text{"thin disk"} \\ 1000 \text{ pc} & \text{long-lived stars} & \text{"thick disk"} \end{cases} \tag{3}$$

Population II: Spheroid Stars

- spherical distribution, most concentrated at center
- small or no net spin $\rightarrow$ radial orbits
- **central bulge**: metal-rich ($Z \sim Z_\odot$)
- **stellar halo**: metal poor (Z down to $10^{-5} Z_\odot$)
- globular clusters distributed throughout spheroid

Milky Way Stars: Census

would like to know properties of MW stars
i.e., distribution of mass, luminosity
and their contribution to the Galaxy's mass, luminosity
note: need *distances* to know this

for nearest stars, can get good distances
simplest + most direct: (trigonometric) *parallax*

other methods directly or indirectly tested and "calibrated"
by parallax measurements
Q: how would this work

Local stars: the Solar Neighborhood

Want to determine:
what is the number density of stars?
what is distribution of masses, luminosities?

Recall PS1:
Q: what biases enter in surveys of stars?
Q: how might you correct for these?

Director's Cut Extras

Tutorial on Hydrogen Atoms and their Demise

recall: H-atom energy levels

$$E_n = -\frac{1}{n^2}\frac{1}{[\pi\epsilon_0]}\frac{e^4 m}{2\hbar^2} = -\frac{13.6 \text{ eV}}{n^2} \tag{4}$$

where 1 eV = 1 electron Volt = energy 1 electron gains
when accelerated by 1 Volt potential

Note:

- quantized levels–no states in between
- ground state: $E_1 = -13.6$ eV – most stable
- to go to higher states, must jump by exact amount

Q: what if H-atom given energy > 13.6 eV

Q: what is significance of sign $E_n < 0$?

Q: astrophysical implications? signals from ionized regions?

to tear apart bound H atom $\rightarrow$ unbound p, e
must supply at least 13.6 eV
if supply less, can't free the e
$\rightarrow |E_1| = 13.6$ eV is H binding energy

Astrophysical implications: in very energetic environments
if H very hot (violent collisions),
and/or subject to ionizing radiation
$\rightarrow$ atoms torn apart: ionized to free e, p plasma