Stellar Populations

The evolution of individual stars is well understood.
The light produced by a composite population of $\sim 10^{11}$ stars can get a bit complicated.

We measure light.
For dynamics, we need to know the mass.

For a single burst of star formation (SSP), much depends on the IMF (especially the composite mass-to-light ratio $\Upsilon_* = \frac{M_*}{L_*}$

IMF = Initial Mass Function
The number of stars that form as a fcn of mass

Initial attempt a power law due to Salpeter (1955)

$$\xi(M) = \frac{dN}{dM} = \xi_0 M^{-\Gamma} \qquad \Gamma = -2.35$$

"Salpeter slope"

# of stars $N = \int \xi \, dM$ — integral performed over a finite range from the minimum to maximum stellar mass.

total mass $M = \int M \xi \, dM$

total luminosity $L = \int L \xi \, dM$ — L is a strong fcn of M; $L \sim M^{3.5}$ for main sequence stars. L goes way up during giant phase.

Most of the light is produced by massive stars while most of the mass is contained in low mass stars.
Nevertheless,

$$\Upsilon_* = \frac{M_*}{L} = \frac{\int M \xi \, dM}{\int L \xi \, dM} \simeq 1 \frac{M_\odot}{L_\odot}$$

Υ_* varies with bandpass and age, but is almost always $0.5 < \Upsilon_* < 5 \frac{M_\odot}{L_\odot}$

Note that the Salpeter IMF blows up when integrated to a lower limit $M_\ell \to 0$. Usually truncate at $M_\ell \sim 0.1 M_\odot$ (brown dwarf limit)

Subsequent observations
show that the power law is broken
(as it must be: Kroupa IMF)
so integral is finite.
Numbers of stars peaks somewhere around $M \approx \frac{1}{3} - \frac{1}{2} M_\odot$

Thats just for a simple population in which all the stars form at once.
In spiral galaxies, of must also consider the star formation history (SFH)
The SFH can be viewed as the sum of many individual star forming events. In principle, each event might have its own unique IMF.
Fortunately, galaxies appear to be consistent with a single universal IMF (Kroupa; Chabrier) which may simply result from averaging over many events.

Elaborate models can be made to estimate M_*/L.
These are good to a factor of ~ 2.
Hard to do much better (the IMF being the biggest uncertainty, esp. the low mass end.)

Typical values for spiral galaxies

Band	B	V	I	K	[3.6]	
$\Upsilon_* =$	1.5	1.4	1.2	0.6	0.5	$M_\odot/L_\odot$

The Υ_* in the near-infrared (K & [3.6]) is fairly stable and apparently universal.
Fluctuations around the mean get larger as one goes to bluer bands.

In practice, build detailed models that incorporate known spectra of stars

Major uncertainties

- IMF
- Star formation history

usually modeled as $SFR \propto e^{-t/\tau}$ *

E galaxies old: short τ: all SF over early on

S galaxies young: $\tau \to \infty$, rought constant SFR

nagging minor uncertainties

- effect of Z-distribution
- contribution of poorly modeled late stages of stellar evolution (TP-AGB stars)

Nevertheless, get decent models like Bell & de Jong (2001)
Portinari et al (2004)
Schombert & McGaugh (2014)

* In addition to smooth, continuous star formation rates like

$$SFR \sim e^{-t/\tau}$$

one can also impose sporadic bursts of star formation

$$SFR \sim \delta(t - t_{burst})$$

to construct model SFH of arbitrary complexity. Old PSPS fade, & massive stars fade fast, so most of the details of early SFH get washed out.

The ISM

The Interstellar Medium contains gas in all phases – molecular, atomic, and ionized (plasma) as well as dust.

In the Milky Way, all of these are largely confined to the plane of the disk, though there probably exists a tenuous quasi-spherical corona of hot, ionized gas at radii far beyond the edge of the stellar disk, ~~[illegible]~~ extending to ~ 300 kpc (very roughly).
This corona contains relatively little mass, though it might integrate up to $\sim 10^{10} M_\odot$ all the way out.

IN the disk of the Milky Way, in order of mass:

Atomic gas	HI	~ 60-70% of ISM mass
Molecular gas	H_2	~ 30% " " "
Ionized gas	HII	< 10% " " "
Dust		≪ 1%

Total gas mass in MW $\sim 10^{10} M_\odot$
dust mass maybe $\sim 10^{8} M_\odot$

HI extends to ~ 20 kpc
(The stellar $R_d \approx 2.2$ kpc, so almost all stellar mass is interior to 10 kpc)

$M_* \simeq 5$ or $6 \times 10^{10} M_\odot$

so the Milky Way has a gas fraction $f_g \lesssim 20\%$ which is typical for bright spirals.

HI Atomic gas

detected by spin-flip transition of H

$\overset{\uparrow}{\oplus}\ \overset{\uparrow}{\ominus} \longrightarrow \oplus\ \ominus\downarrow$

transition frequency very low energy

$$\nu_{10} = \frac{8}{3} g_I \left(\frac{m_e}{m_p}\right) \alpha^2 (cR_M) = 1420.4 \text{ MHz}$$

the <u>21cm</u> line

nuclear gyromagnetic factor $g_I = 5.6$ for proton

fine structure constant $\alpha = \frac{1}{137}$

Rydberg frequency

Emission coefficient

$$A_{ul} = \frac{64\pi^4}{3hc^3} \nu_{ul}^3 \left|\mu_{10}^*\right|^2$$

Bohr magneton (dipole moment of e^-)

$$\left|\mu_{10}^*\right| = \frac{\hbar}{2}\frac{e}{m_e c}$$

numerically

$$A_{10} = 2.85 \times 10^{-15}\ s^{-1}$$

radiative half-life $\tau_{1/2} = \frac{1}{A_{10}} \approx 11 \times 10^6$ yr

$(3.5 \times 10^{14}$ s $= 11$ Myr$) = \frac{1}{\tau_{1/2}}$

Very low critical density ($\ll 1\ cm^{-3}$) so almost always in LTE through collisional excitation

Can also define "spin temperature"

$$\frac{N_1}{N_0} = \frac{g_1}{g_0} e^{-\frac{\nu h_{10}}{kT_S}}$$

$g_1 = 3$ upper states

$g_0 = 1$ ground state

Note $\frac{h\nu}{k} \lessapprox 1K$ very small, so $e^{\frac{-\nu h_{10}}{kT}} = 1$ if $T_S \approx T$ anywhere near equilibrium

so $\frac{N_1}{N_0} = \frac{3}{1}$ & $N_H = N_0 + N_1 = 4N_0$ good for counting atoms counting 21 cm photons → counting HI atoms

$$M_{HI} = \frac{16\pi m_H}{3A_{ul}hc} D^2 \int F_\nu \, dv$$

(flux integral in Jy · km/s)

Numerically (1 Jansky = 10^{-26} W m^{-2} Hz^{-1})

$$M_{HI} = \left(2.34 \times 10^5 M_\odot\right) D^2 \int F_\nu \, dv$$

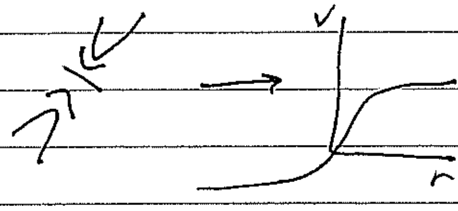
(D in Mpc (luminosity distance $(1+z) \times D_L$ in cosmology))

$M_{atomic\,gas} = \frac{1}{X} M_{HI}$ (X: Hydrogen mass fraction)

Can measure HI masses accurately to a few % IF care is taken. (because it's a line)

HI emission ALSO gives velocity field from Doppler effect – important tracer of the gravitational potential

Fit velocity field with tilted ring model to obtain rotation curve



Molecular ISM

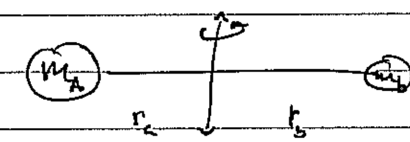
cold ~30 K
"dense" ~100 cm^{-3}

very clumpy; need to be to self-shield against interstellar radiation field (mild UV can photodissociate many molecules)

most mass in GMCs: Giant Molecular Clouds ~$10^6 M_\odot$
... this is where stars are born

Diatomic molecules boring - or at least hard to excite
↳ H_2, O_2, N_2 because symmetry prevent them from having a dipole moment.
Hence no radiation if they rotate. (Vibrational states much higher energy)

Polar molecules (like CO) have permanent dipole moment thanks to asymmetry leading to rich rotational spectrum (often at mm & cm wavelengths)



Angular momentum

$$L = \left(\frac{m_a m_b}{m_a + m_b}\right)(r_a + r_b)\,\omega \quad \text{is quantized}$$

rotational energy

$$E = \frac{J(J+1)\hbar^2}{2I}$$

moment of inertia

$$I = m_a r_a^2 + m_b r_b^2$$

need I to be large to generate detectable emission in cold molecular gas quantum mechanics requires $\Delta J = \pm 1$ so

$$\nu = \frac{hJ}{4\pi m_e r_e^2} \qquad m_e = \frac{m_a m_b}{m_a + m_b}$$

$$r_e = r_a + r_b$$

Rotational transitions lead to ladder spectrum

gets more complicated for multi-atom molecules

Can play same tricks as with HI.

$$M_{H_2} = 1.1 \times 10^4 \, D^2 \, F_{co} \qquad X_{co} = 2.8 \times 10^{20} \, cm^{-2} (K \, km/s)$$