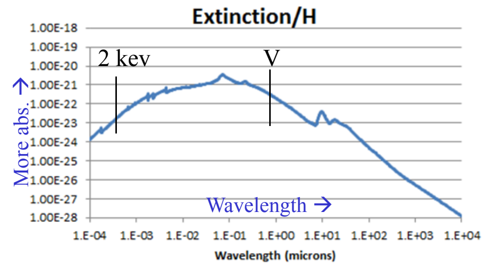
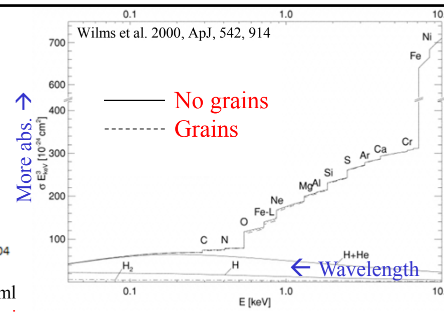
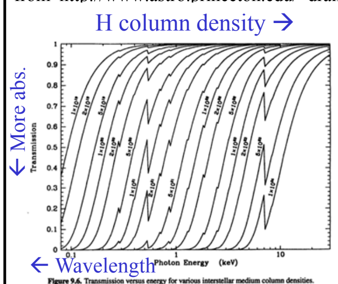
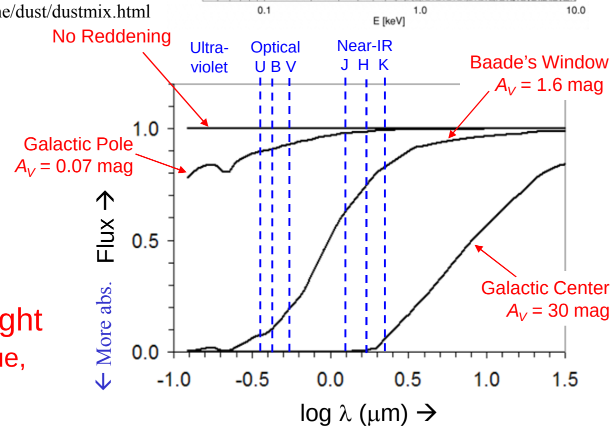


from http://www.astro.princeton.edu/~draine/dust/dustmix.html

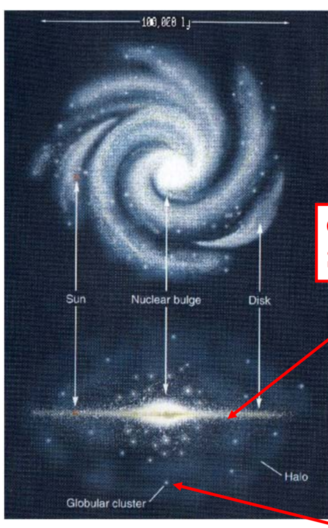




- Absorb and scatter light
  - Effect strongest in blue,
  - less in red,
  - zero in radio.



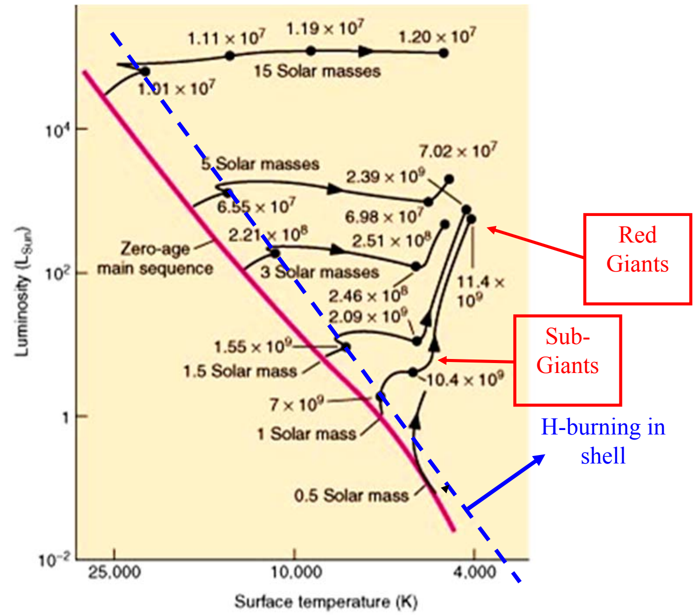
Star clusters



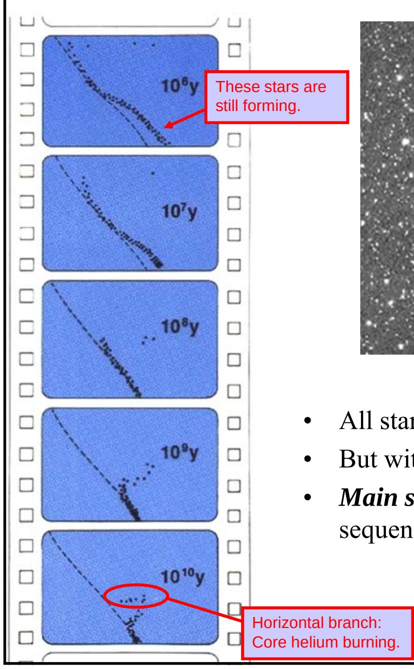
Open Clusters: formed in disk of Galaxy.
Some recently-formed, some middle-aged.

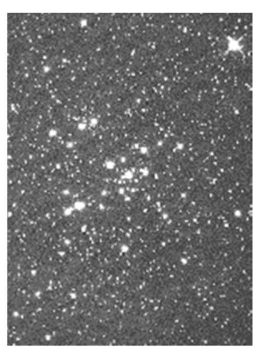
Globular Clusters: ~ 150 in spherical distribution in our Galaxy. All are very old.

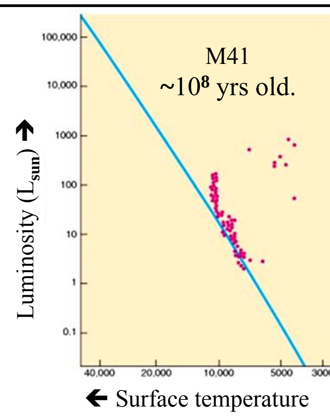
Predicted paths of stars on HR diagram



Star cluster H-R diagrams

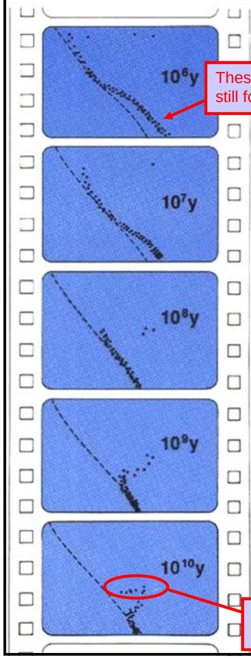


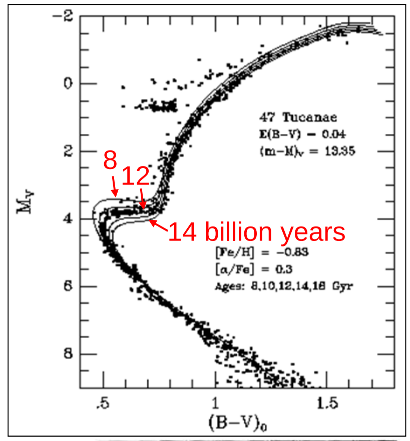


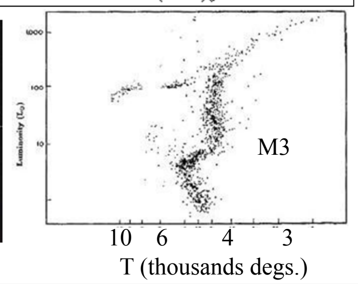


- All stars in a given cluster formed at same time.
- But with a wide range in masses.
- ***Main sequence turnoff*** = stars just finishing main sequence evolution.

Globular cluster H-R diagrams.







Baade (1944)

Stellar Populations

X,Y,Z = mass fractions
- X ~ 0.73 (H)
- Y ~ 0.25 (He)
- Z ~ 0.02 (metals)

- Abundances
- Kinematics
- Ages

- Pop I : Metal rich (Z ~ 0.02), disk, younger
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  - Open clusters
  - Gas
  - Star formation regions
- Pop II: Metal poor (Z ~ 0.001), halo, older
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  - Bulge??? ….but includes metal rich stars.
- Abundance Determinations
  - Stellar spectroscopy
    - [Fe/H], etc. ➔ log(N_{Fe}/N_H) – log(solar)
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    - Iron often used as tracer of *all* metals.
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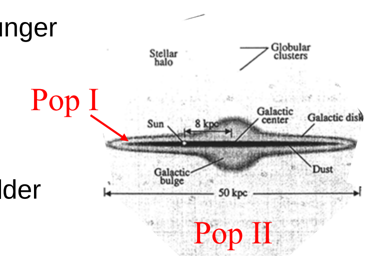
  - HII regions



	[Fe/H]
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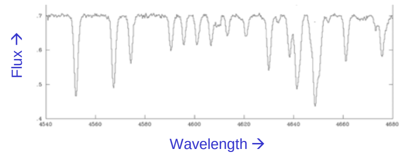
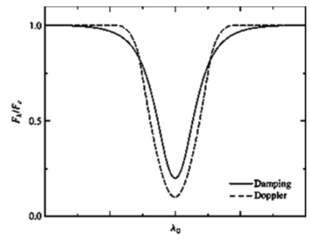
Thick Disk	-2.2➔ -0.5
Halo	-5.4➔ -0.5
Bulge	-2.0➔+0.5

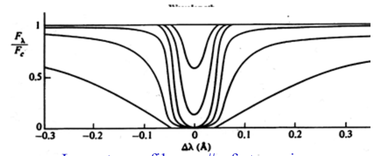
Measuring abundances from absorption lines

(see [9.5] for gory details)



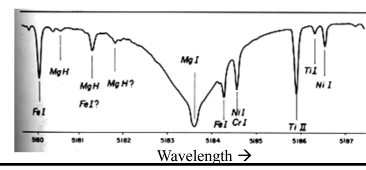


- Lorentz profile
  - Natural profile of stationary absorber.
    - wings due to finite lifetime of excited state in QM model..
    - Or to "damping" in classical oscillator mode.



Lorentz profiles as # of atoms increases

- Voigt profile
  - Lorentz profile convolved with Gaussian velocity distribution.
  - Line shape increases in funny way.



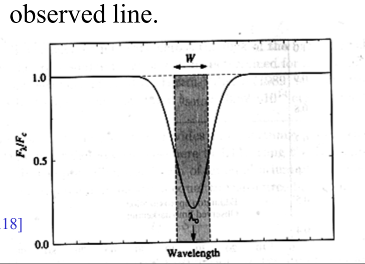
EQUIVALENT WIDTH

- Often, wavelength resolution and/or signal:noise too low to measure details of line profile.
- Can still measure fraction of continuum light that is absorbed
- then convert to *column density* of absorbing atoms.

$$W_\lambda = \int \left[1 - \frac{I_\lambda}{I_\lambda(0)}\right] d\lambda = \frac{\lambda^2}{c} \int \left[1 - e^{-\tau_\lambda}\right] d\lambda$$

in units of Å

- same as width of square profile going to zero and having same W_λ as observed line.



[CO fig. 9.18]

Optical depth:

$$\tau_\lambda = \int \alpha_\lambda \, n \, ds$$

← Abs.cross section/atom

$$I_\lambda = I_\lambda(0) e^{-\tau_\lambda}$$

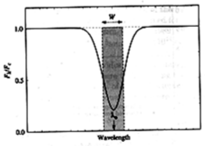
Column density:

(atoms/cm^2 along line of sight)

$$N = \int n \, ds$$

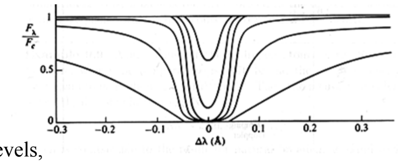
CONVERTING W_λ TO COLUMN DENSITY OF ABSORBING ATOMS:

$$W_\lambda = \int \left[1 - \frac{I_\lambda}{I_\lambda(0)} \right] d\lambda = \frac{\lambda^2}{c} \int \left[1 - e^{-\tau_\lambda} \right] d\lambda$$



CURVE OF GROWTH shows how W_λ depends on N

- **For small column density:**



$$W_\lambda = \lambda^2 \tau_\lambda$$

$$\frac{W_\lambda}{\lambda} \propto N_j f_{jk} \lambda$$

where j,k are lower, upper levels,

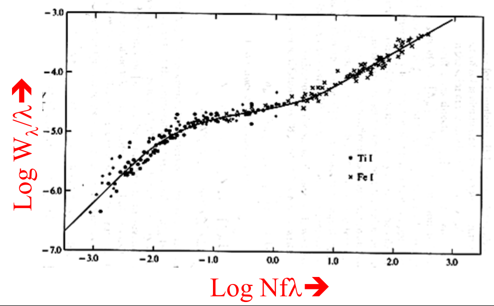
f_{jk} is oscillator strength = effective number of oscillators participating in transition.

- **For intermediate column density:**
  where $b = \text{sqrt}(v_o^2 + v_{turbulent}^2)$:

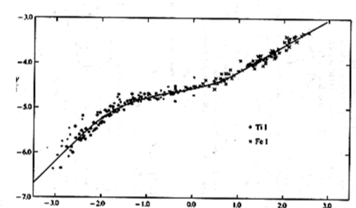
$$\frac{W_\lambda}{\lambda} \propto b \left[\ln \left(\frac{.015 N f \lambda}{b} \right) \right]^{1/2}$$

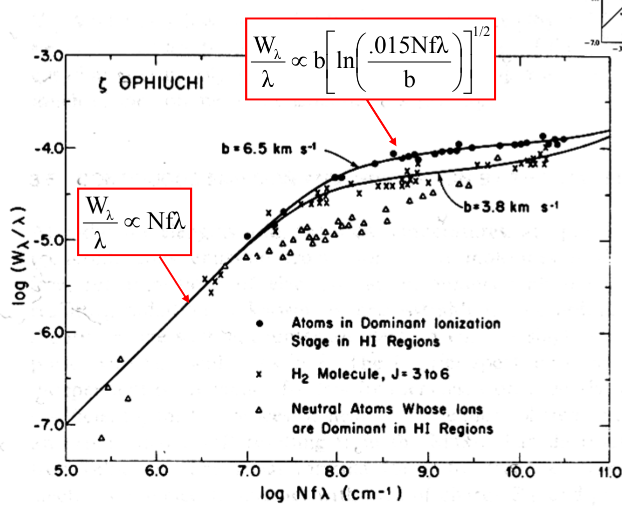
- **For large column density:**

$$\frac{W_\lambda}{\lambda} \propto \left(\lambda^2 N f \right)^{1/2}$$



Sliding observed c.o.g. over theoretical c.o.g in both x and y ➔ N, b

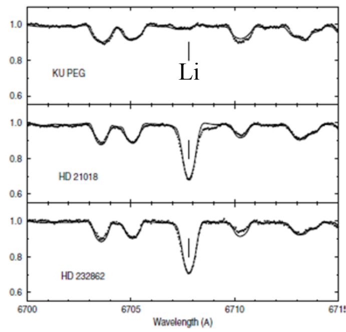


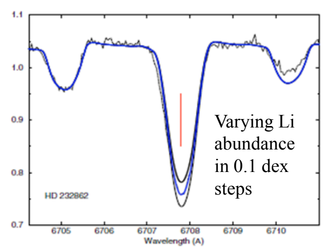


Works OK for interstellar gas.

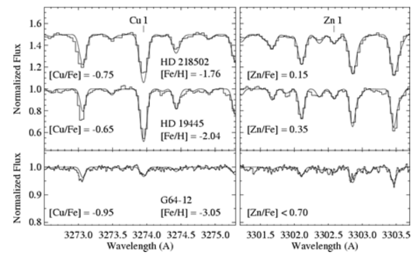
But for stars, must take account of structure of atmosphere.

Nowadays… for stars: Spectral synthesis

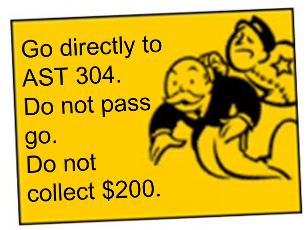




Compute expected spectrum.
Compare to observations.
Adjust abundances until they match.



Lebre et al. 2009, A&A, 504, 1011



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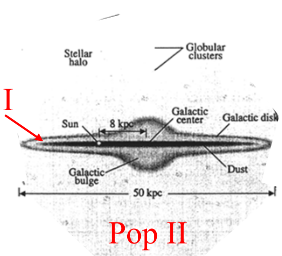

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Closed Box Model

(and friends and relatives)

Metallicity
$Z = M/G$
$Z_{\odot} \sim 0.02$

Gas ➔ stars ➔ enriched gas

S = mass of stars
M = mass of metals (heavy elements) in ISM
G = total mass of gas in ISM

Assume instantaneous recycling.

From each new generation of stars:

dS = mass of low mass stars added to S

$p\,dS$ = mass of heavy elements added to M from massive stars in this generation. ← Instantaneous recycling

where p = *yield*.

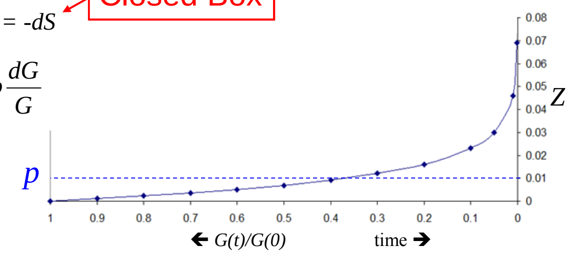
$dM = p\,dS - Z\,dS$

$= -p\,dG + Z\,dG$ since $dG = -dS$ ← Closed Box

$$dZ = d\left(\frac{M}{G}\right) = \frac{dM}{G} - \frac{M}{G^2}dG = -p\frac{dG}{G}$$

$Z(t) = -p \ln [G(t)/G(0)]$

$G(t) = G(0)\, e^{-Z(t)/p}$



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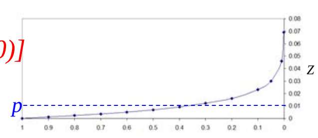


G dwarf problem

$S[Z<Z(t)] = S(t) = G(0) - G(t)$

$= G(0)\,\{1 - e^{-Z(t)/p}\}$

where $Z(t)$ = gas metallicity at time t

Compare to case when gas had some arbitrary fraction α of that metallicity:

$$\frac{S[Z<\alpha Z(t)]}{S[Z<Z(t)]} = \frac{1-X^{\alpha}}{1-X}$$

where $X = e^{-Z(t)/p} = \frac{G(t)}{G(0)} \sim 0.1 - 0.2$

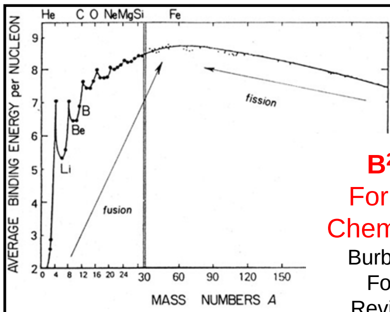
Predicts broad distribution in metallicity of stars. For x=0.1:

➔ $S[Z<1/4\, Z_{\odot}] = 0.4\, S[Z<Z_{\odot}]$

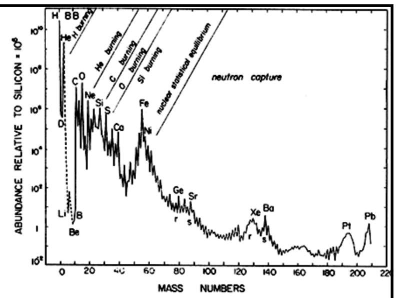
Very different than what is observed in solar neighborhood:

$S[Z<1/4\, Z_{\odot}] = 0.02\, S[Z<Z_{\odot}]$

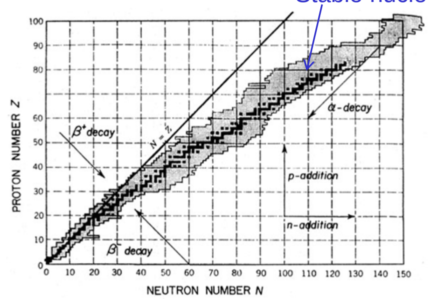
It's *NOT* a closed box
Infall? Outflow?



B^2FH (1957)
Formation of the Chemical Elements
Burbidge, Burbidge, Fowler & Hoyle.
Reviews of Modern Physics, 29, 547.



Stable nuclei



Gradual processes in Interiors of Stars

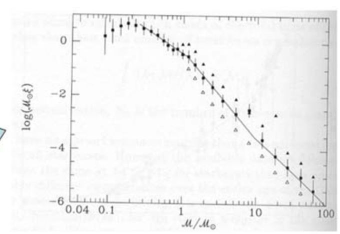
- H burning (4H ➔ He)
- α process (C,O,Ne,Mg,Si,S…)
- s process
  - slow neutron capture, relative to beta-decay timescale

Supernovae

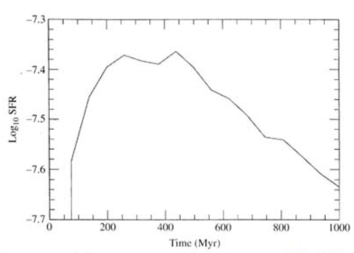
- e process
  - nuclear statistical equilibrium
  - iron peak elements
- r process
  - rapid neutron capture

The Initial Mass Function (IMF)

- $dN = N_o \xi(M) dM$ = number of stars born with masses in range $M, M+dM$
- Salpeter (1955) IMF: $\xi(M) \propto M^{-2.35}$
- Scalo (1986) IMF:
  - $\xi(M) \propto M^{-2.45}$ for $M > 10M_\odot$
  - $\xi(M) \propto M^{-3.27}$ for $1 < M < 10M_\odot$
  - $\xi(M) \propto M^{-1.83}$ for $0.2 < M < 1M_\odot$



- Others as well.
- Star Formation rate = $\psi(t)$



[CO Fig. 26.18]

- Stellar birthrate function

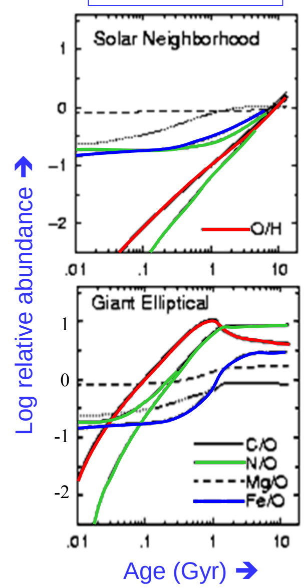
$B(M,t) = \psi(t)\xi(M)\, dM\, dt$

= number of stars born per unit volume with masses in range $M, M+dM$ in time interval $t, t+dt$. [CO eqn. 26.4]

Modeling chemical enrichment

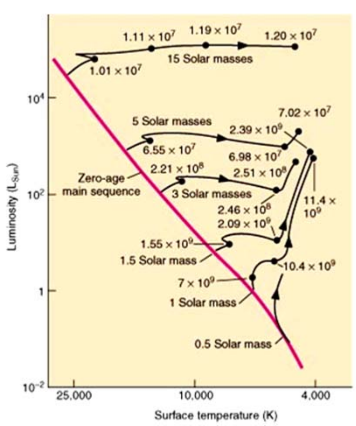
- One zone, accreting box model.
  - Start with pure H, He mix.
  - Further H, He falls in at specified rate.
- Follow evolution of individual elements H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca and Fe.
- Subdivide stellar population into three classes of stars:
  - $< 1M_\odot$ nothing recycled
  - $1.0 – 8.0\ M_\odot$ fraction give white dwarf supernovae
  - $> 8M_\odot$ Core collapse supernovae.
- Assume that each class of stars spews specified % of its mass of each element back into ISM at end of a specified lifetime.
- Must provide IMF to specify mix of star masses.
- Two extreme models:
  - "Solar neighborhood": conventional IMF, slow stellar birthrate, slow infall (15% gas at 10 Gyr) .
  - "Giant Elliptical": flatter IMF, 100x higher birthrate, fast infall (15% gas at 0.5 Gyr).

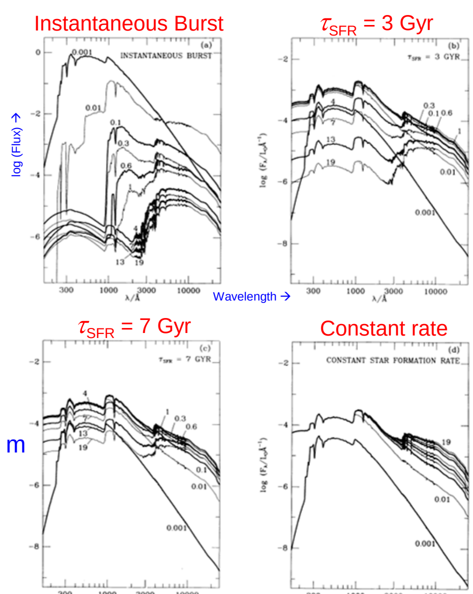
Hamann & Ferland 1992



Population Synthesis Models

Bruzual & Charlot (1993); Worthey et al (1994)

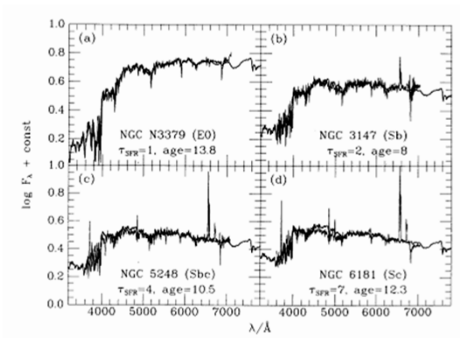




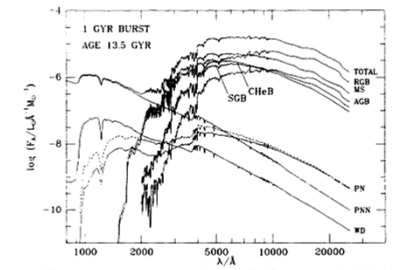
Ingredients:

- Evolution of star of mass m
- IMF = number of stars formed with each m
- ➔ evolving composite spectrum $f_\lambda(\tau)$
- Star formation rate $\Psi(t) = \tau^{-1} \exp(-t/\tau)$
- $F_\lambda(t) = \int \Psi(t-\tau) f_\lambda(\tau) d\tau$

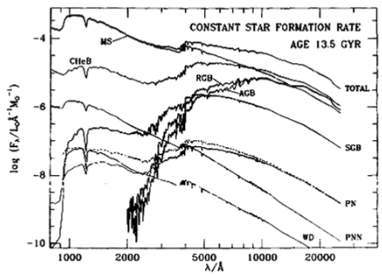
Some Bruzual & Charlot results



Models fitted to real spectra for different galaxy types.



Components of E galaxy spectrum



Components of late-type spiral galaxy spectrum