Galaxies  Astro 530
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Chemical Evolution in Galaxies  PART 1
Gas is the raw material for star formation, but *where does the gas in galaxies come from?*

1. “primordial” (from Big Bang)
2. reprocessed & recycled, through stars

Figuring out how much the raw material in stars has been recycled through previous generations of stars offers powerful evidence on galaxy evolution!
Elemental abundances

• Heavy elements are produced in stars, and elemental ("chemical") abundances offer a record through which we can trace star formation histories & galaxy evolution.

• Abundances of elements heavier than helium ("metals") vary among stars and galaxies; abundances vary strongly with galaxy mass.

• In most small systems (star clusters and dwarf galaxies), abundances are relatively uniform, but in larger galaxies there are systematic variations with radius and large dispersions at any location.
Q: Why does the amount of elements heavier than Helium indicate the amount of processing thru stars?
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*Why elements heavier than Helium rather than heavier than Boron?*
Solar system elemental abundances

Made mostly in Big Bang (A=1-5)

Made mostly in stars & supernovae A=6-100+

Solar abundances:
Hydrogen: \( \frac{M_H}{M_{\text{gas}}} = 0.74 \)
Helium: \( \frac{M_{\text{He}}}{M_{\text{gas}}} = 0.24 \)
Heavies (Everything else): \( \frac{M_h}{M_{\text{gas}}} = 0.02 = Z_{\text{sun}} \)
("metals")
Astronomy definition of abundance ratio:

\[
[A/B] \equiv \log_{10}\left\{ \frac{\text{(number of A atoms/number of B atoms)}_\star}{\text{(number of A atoms/number of B atoms)}_\odot} \right\}
\]

[Fe/H] is logarithmic ratio of Fe/H in star relative to sun

*Fe is pretty good indicator of overall heavy element abundance.*

*Sometimes [Fe/H] represents average heavy-element abundance not just Iron.*

\[
\begin{align*}
[\text{Fe/H}] &= 0 \quad \text{solar abundance} \\
[\text{Fe/H}] &= -1 \quad \text{1/10}^{\text{th}} \text{ solar abundance} \\
[\text{Fe/H}] &= -2 \quad \text{1/100}^{\text{th}} \text{ solar abundance} \\
[\text{Fe/H}] &= -3 \quad \text{1/1000}^{\text{th}} \text{ solar abundance}
\end{align*}
\]
Q: What is special about iron?  
*Iron is the most tightly bound nucleus*

Iron $^{56}\text{Fe}$  
26 protons  
30 neutrons

Nuclear reactions involving Fe *require energy* rather than *release energy* once core makes iron it can’t generate any more fusion energy to support star
Range of heavy element abundances in Milky Way stars:

\[ Z = 10^{-5.5} \rightarrow 3 \, Z_{\text{sun}} \]

\[ [\text{Fe/H}] = -5.5 \rightarrow 0.5 \]
Stars with different elemental abundances

Stars with fewer heavy elements have:

Weaker absorption lines of heavy elements

Bluer continuum (fewer absorption lines in UV-blue part of spectrum)
Spectrum of extremely metal-poor halo star with $[\text{Fe/H}]=-5.5$
(heavy element content $1/300,000 \times$ solar)
Range of heavy element abundances in Milky Way:

\[ Z = 10^{-5.5} \rightarrow 3 \, Z_{\text{sun}} \quad \text{SUN: } 1 \, Z_{\text{sun}} = 0.02 = M_h/M_{\text{gas}} \]

\[ [\text{Fe/H}] = -5.5 \rightarrow 0.5 \quad \text{SUN: } [\text{Fe/H}] = 0.0 \]

There are **no stars in Milky Way** with “primordial” = Big Bang abundances,
i.e. \( Z \approx 0 \),
i.e. “Population III stars”.

All stars in Milky Way formed from gas that was polluted at least a bit by previous generation(s) of stars!
Q: Stars make new elements but not all the new elements get out of the stars. What stellar material has not been returned to space?
not all mass in stars get returned to ISM …

• Cores of stars
• Low mass stars
not all mass in stars get returned to ISM ...

- Cores of stars
- Low mass stars

Q: Why haven’t low mass stars returned much gas to ISM?
Some matter does not get returned to ISM: Low mass stars

MS lifetime for 0.7 $M_{\text{sun}}$ star =

$$\tau_{\text{MS}} = 14 \text{ Gyr}^* \text{ > age of universe = 13.8 Gyr}$$

*MS lifetime depends on metallicity for 0.7$M_{\text{sun}}$: $t_{\text{MS}} = 13$ Gyr $[Fe/H]=-2.5$; $t_{\text{MS}} = 15$ Gyr $[Fe/H]=-1.5$
Some matter does not get returned to ISM:

Low mass stars

MS lifetime for $0.7 \, M_{\text{sun}}$ star =

$$\tau_{\text{MS}} = 14 \, \text{Gyr}^* > \text{age of universe} = 13.8 \, \text{Gyr}$$

$\rightarrow$ so no low mass stars have ever evolved off the MS or returned much mass to the ISM anywhere in the universe!

* MS lifetime depends on metallicity for $0.7M_{\text{sun}}$: $t_{\text{MS}} = 13 \, \text{Gyr} \, [\text{Fe/H}] = -2.5$ ; $t_{\text{MS}} = 15 \, \text{Gyr} \, [\text{Fe/H}] = -1.5$
Some matter does not get returned to ISM

- **Cores of stars**

  White dwarf
  made by stars with $M<1.4M_{\text{sun}}$

  Neutron star
  made by stars with $\sim1.4<M<\sim8M_{\text{sun}}$

  Black Hole
  made by stars with $M<\sim8M_{\text{sun}}$
Close-up of core region for a $1 \, M_\odot$ Asymptotic Giant Branch star

- AGB star (radius $\sim 1\text{-}1.5 \, \text{AU}$)
- Hydrogen-burning shell
- Helium layer
- Helium-burning shell
- Carbon-oxygen core (no fusion)

Graph:
- Luminosity (solar units)
- Surface temperature (K)
- Spectral classification

- Asymptotic giant branch
- Horizontal branch
- Helium flash
- Red-giant branch
- Subgiant branch
- Zero-age main sequence

(not to scale)
This stuff gets out into ISM

This stuff doesn’t
One-Zone / Closed Box Model of chemical evolution

- Simplest possible chemical evolution model
- Nothing enters or leaves box
Simplest possible chemical evolution model: One-Zone / Closed Box

Nothing enters or leaves box, gas well mixed

$t = 0$
- no stars
- 100% H+He gas
- no heavy el. gas
- gas metallicity=0

$t = \text{later}$
- some stars
- lots H+He gas
- some heavy el. gas
- gas metallicity=low

$t = \text{much later}$
- mostly stars
- little H+He gas
- little heavy el. gas
- gas metallicity=high
One-Zone / Closed Box Model

- Simplest possible chemical evolution model
- Nothing enters or leaves box
- Initially mass in box is 100% gas, no heavy elements, no stars
- As time goes on, stars form from gas, massive stars explode and return H, He, and heavies to ISM; gas in ISM is gradually consumed and remaining gas becomes increasingly polluted by heavy elements
- Gas is always well-mixed within box

Some stellar systems are roughly consistent with CBM, but many are not, and are instead more consistent with a leaky or accreting box
$M_g = \text{mass of interstellar gas}$

$M_h = \text{mass of heavy elements in interstellar gas}$

$Z = \frac{M_h}{M_g} = \text{metallicity} \quad (Z_{\text{sun}} = 0.02)$

$M_s = \text{total mass in stars}$
\( M_g \) = mass of interstellar gas
\( M_h \) = mass of heavy elements in interstellar gas
\[ Z = \frac{M_h}{M_g} = \text{metallicity} \quad (Z_{\text{sun}} = 0.02) \]
\( M_s \) total mass in stars

Consider a suitably short time interval \( \Delta \).
What are net changes in this short time?

\( \Delta' M_s \) mass of new stars formed in time interval \( \Delta \)
\( \Delta M_s \) mass of new stars \textit{locked up} in
compact remnants & long-lived stars (in \( \Delta \))
\( \Delta' M_s - \Delta M_s \) mass of new stars \textit{returned to ISM} (in \( \Delta \))
This stuff gets out into ISM

Part of $\Delta M'_s - \Delta M_s$

This stuff doesn't

Part of $\Delta M_s$
This stuff gets out into ISM

Part of $\Delta M'_s - \Delta M_s$

This stuff doesn’t

Part of $\Delta M_s$

what contributes to other parts of $\Delta M_s$ and $\Delta M'_s - \Delta M_s$?
Consider a suitably short time interval $\Delta$

- What is net change in heavy element content (mass) of ISM in a short time interval?

- Net change = GAIN – LOSS

- This is complex in general, but becomes much simpler with assumption of instantaneous recycling
Instantaneous recycling!

approximation

- Neglect delay between formation of generation of stars and the ejection of elements by those stars as they evolve

(ignoring the change in ISM metallicity that happens between star formation & later stages of stellar evolution that return gas to ISM)
Instantaneous recycling!
approximation

- Neglect delay between formation of generation of stars and the ejection of elements by those stars as they evolve
  (ignore the change in ISM metallicity that happens between star formation & later stages of stellar evolution that return gas to ISM)

- OK for elements produced by core collapse SN (Type II, Ib) since these happen in massive stars which explode <100 Myr << $T_H (=14$ Gyr) after formation

- less OK for elements produced by less massive stars (Type Ia SN, PN, binary NS) since these occur >1 Gyr after formation (so more correct models take this time delay into account)
• LOSS = ??

• write an expression for the mass of heavy elements locked up in newly-formed low mass stars and compact remnants, in a short time interval
LOSS

• LOSS = ZΔM_s (in IR appx)
• Mass of heavy elements locked up in newly-formed low mass stars and compact remnants
• Massive stars blow up so fast that we ignore their temporary capture of heavy elements

ΔM_s mass of new stars locked up in compact remnants & long-lived stars (in Δ)
GAIN

- GAIN = ??
- write an expression for the Mass of heavy elements produced by newly-formed high-mass stars and returned to ISM in a short time interval
GAIN

- GAIN = $p'(\Delta'M_s - \Delta M_s)$ (in IR appx)
- Mass of heavy elements produced by newly-formed high-mass stars and returned to ISM
- $p' = \text{fraction of mass returned to ISM by massive stars which are metals produced by those stars}$

$\Delta'M_s - \Delta M_s$ mass of new stars returned to ISM (in $\Delta$)
GAIN

\[ \Delta'M_s - \Delta M_s \text{ mass of new stars returned to ISM (in } \Delta) \]

- **GAIN** = \( p' (\Delta'M_s - \Delta M_s) \) (in IR appx)

- Mass of heavy elements produced by newly-formed high-mass stars and returned to ISM

- \( p' \) = fraction of mass returned to ISM by massive stars which are metals produced by those stars

**We can also express:**

- **GAIN** = \( p \Delta M_s \)

- Even though the low mass stars & compact remnants aren’t creating the metals which pollute the ISM, we can write it this way because it’s mathematically convenient & easier to measure \( \Delta M_s \) than \( \Delta'M_s - \Delta M_s \)
follow the fate of gas which forms a bunch of stars

• for example, start with $100 \, M_{\odot}$ which forms stars.
follow the fate of gas which forms a bunch of stars

- for example, start with $100 \, M_{\text{sun}}$ which forms stars.
- some fraction (typically $\sim 60\%$) is mass locked up in long-lived stars and compact remnants ($\sim 60 \, M_{\text{sun}}$).
follow the fate of gas which forms a bunch of stars

- for example, start with $100 \, M_{\text{sun}}$ which forms stars.
- some fraction (typically $\sim60\%$) is mass locked up in long-lived stars and compact remnants ($\sim60 \, M_{\text{sun}}$).
- some fraction (typically $\sim40\%$) is returned to ISM ($\sim40 \, M_{\text{sun}}$).
follow the fate of gas which forms a bunch of stars

- for example, start with $100 \, M_{\text{sun}}$ which forms stars.
- some fraction (typically $\sim 60\%$) is mass locked up in long-lived stars and compact remnants ( $\sim 60 \, M_{\text{sun}}$).
- some fraction (typically $\sim 40\%$) is returned to ISM ( $\sim 40 \, M_{\text{sun}}$).
- some fraction of the mass returned to ISM are metals made by stars ( $\sim 1.2 \, M_{\text{sun}}$).
follow the fate of gas which forms a bunch of stars

- for example, start with $100 \ M_{\text{sun}}$ which forms stars.
- some fraction (typically ~60%) is mass locked up in long-lived stars and compact remnants ($\sim 60 \ M_{\text{sun}}$).
- some fraction (typically ~40%) is returned to ISM ($\sim 40 \ M_{\text{sun}}$).
- some fraction of the mass returned to ISM are metals made by stars ($\sim 1.2 \ M_{\text{sun}}$).

\[ p' = \frac{1.2M_{\text{sun}}}{40M_{\text{sun}}} = 0.03 \]

\[ \text{but yield } p = \frac{1.2M_{\text{sun}}}{60M_{\text{sun}}} = 0.02 \]
Meaning of yield $p$

- “Yield” of heavy elements by particular stellar generation
- Yield $p = \text{ratio of mass in metals produced by stars and returned to ISM to mass locked up in long-lived stars and compact remnants}$
- Dimensionless number, ratio of masses, like metallicity
- Normal yield $p \sim \text{solar metallicity} \sim 0.02$
- If stars are made from gas that is initially free of metals, so that $Z(0) = 0$, the closed box model predicts that, when all the gas is gone, the mean metal abundance of stars is exactly $p$. 
Loss & gain  (with IR appx)

• LOSS = \( Z\Delta M_s \)
• GAIN = \( p\Delta M_s \)
• on board: derive Z(t)
Metallicity of ISM gas in One-Zone / Closed Box Model:

\[ Z(t) = -p \ln \left( \frac{M_g(t)}{M_g(0)} \right) + Z(0) \]

at \( t=0 \) start

\[ \frac{M_g(t)}{M_g(0)} = 1, \ Z(t) = Z(0) \ \ [ = 0 \text{ if no pre-enrichment} \] \]
evolution in closed box model

\( \mathcal{M}_{\text{gas}} \)

\( M_{\text{stars}} \)

\( Z_{\text{gas}} \)
Metallicity of ISM gas in One-Zone / Closed Box Model:

\[ Z(t) = -p \ln \left( \frac{M_g(t)}{M_g(0)} \right) + Z(0) \]

at t=0 start

\[ \frac{M_g(t)}{M_g(0)} = 1, \quad Z(t) = Z(0) \quad [ = 0 \text{ if no pre-enrichment}] \]

at t = later (=t₁)

e.g. \( M_g(t) = 0.37 \ M_g(0) \) and assume \( Z(0) = 0 \)

so \( \ln \left( \frac{M_g(t)}{M_g(0)} \right) \approx \ln [0.37] = -1 \) so \( Z(t) = p \)
Metallicity of ISM gas in One-Zone / Closed Box Model:

\[ Z(t) = -p \ln \left( \frac{M_g(t)}{M_g(0)} \right) + Z(0) \]

at \( t=0 \) start

\[ \frac{M_g(t)}{M_g(0)} = 1, \quad Z(t) = Z(0) \quad [ = 0 \text{ if no pre-enrichment}] \]

at \( t = \text{later} = t_1 \)

e.g. \( M_g(t) = 0.37 \ M_g(0) \) and assume \( Z(0) = 0 \)

so \( \ln \left( \frac{M_g(t)}{M_g(0)} \right) \sim \ln [0.37] = -1 \) so \( Z(t) = p \)

at \( t = \text{much later}, \ M_g(t) \ll M_g(0) \)

e.g. \( M_g(t) = 0.05 \ M_g(0) \) and assume \( Z(0) = 0 \)

so \( \ln \left( \frac{M_g(t)}{M_g(0)} \right) \sim \ln [0.05] = -3 \) so \( Z(t) = 3p \)

so can get very metal rich stars but not many

(since available gas mass is really low for such stars)
evolution in closed box model

when gas supply is 37% of original, gas metallicity = p

Gas metallicity can get to high values but only once most of gas is gone!
we can predict number of stars with different metallicities in closed box model
we can write \( M_s(t) = M_s[<Z(t)] \)

since all the stars which exist at any time \( t \) have metallicity of \( Z(t) \) or less than \( Z(t) \)

- in CBM, gas metallicity increases smoothly with time
- at time \( t \), gas has metallicity \( Z(t) \), and a star formed at this time has metallicity \( Z(t) \)
- but stars formed at earlier times have metallicity \(<Z(t)\)
- so all the stars which exist at any time \( t \) have metallicity of \( Z(t) \) or less than \( Z(t) \).
derive $M_s[<Z(t)>]$ expression on board
One-Zone / Closed Box Model

with Instantaneous Recycling (IR) approximation
(best for elements produced by massive stars, e.g. O, Mg, Si)

metallicity of ISM gas

\[ Z(t) = -p \ln \left( \frac{M_g(t)}{M_g(0)} \right) + Z(0) \]

mass in stars as function of metallicity

\[ M_s[<Z(t)] = M_g(0) \left[ 1 - \exp \left\{ -(Z(t) - Z(0))/p \right\} \right] \]

mean metallicity of stars after gas gone

\[ \bar{Z}_s = p \sim Z_{\text{sun}} \]

Yield \( p \) = Ratio of:
mass in metals made by stars & returned to ISM to
mass locked up in long-lived stars and compact remnants
(normal yield \( \sim \) solar metallicity \( \sim 0.02 \))
$[\text{Fe/H}]$ in bulge of MW $\sim$ fits **closed box model**

Fe/H distr. **roughly** matches **closed box model** with $p_{\text{eff}}=Z_{\text{sun}}=0.02$

*[although the bulge has fewer very low mass stars than this model predicts! and detailed abundances ratios don’t match this model! So CBM gives decent 1st-order fit to bulge abundances, but not to 2nd order]*
Where does the Closed Box Model work?

Bulge of Milky Way

OK fit (to 1st order) with Closed Box model with IR and reasonable yield $p=2\times10^{-2}$
Where does the Closed Box Model work?

Bulge of Milky Way
OK fit (to 1st order) with Closed Box model with IR and reasonable yield $p=2 \times 10^{-2}$

BUT Disk of Milky Way is NOT well fit by CBM (not enough low Z stars -- “G-dwarf problem”)
Fe/H of nearby (disk) MW F & G stars vs. age

very few disk stars with $Z<0.25Z_{\text{sun}} \rightarrow \text{“G dwarf problem”}$

closed box model predicts $\sim50\%$ of stars should have $Z < 0.25 Z_{\text{sun}}$

so CBM is wrong for disk!