Master Course Astrophysics – Galaxies & Cosmology
SS 2018

Lecture 9: Chemical evolution of galaxies

12.6.2018 Lutz Wisotzki (page 1)

Introduction: Abundances of elements increase over cosmic time, irreversably!

(*) slide: cosmic history, 2 phases of nucleosynthesis

(*) slide: Elements created right after the Big Bang

(*) slide: Element abundances in the sun / solar system

(*) slide: The origin of Solar System Elements:
- big bang fusion
- cosmic ray fission
- dying low mass stars
- exploding massive stars
- exploding white dwarfs
- merging neutron stars

(*) slide: Cosmic cycle of matter → enrichment with heavy elements

Goals for today:
- theoretical framework to link enrichment to cosmic time
- compare "simple model" to observations

Measuring abundances

Recall notation: $[X/H] = \log_{10} \frac{N_X}{N_H} - \log_{10} \left(\frac{N_X}{N_H}\right)_{solar}$

where X can be

- any element → [Fe/H], [O/H] etc
- all "metals" together → [Z/H] or [M/H]
- group of metals → [α/H] = all α-process elements

similar notation for abundance patterns,
e.g. [O/Fe] = Oxygen/Iron relative to sun, in $\log_{10}$

An ideal SSP has the same metallicity and abundance pattern as the ISM cloud it formed from.

Abundances in observations:

1) spectral analysis of individual stars
   (only in Milky Way & nearby galaxies)
   ⊗ example slide: Extremely metal-poor star

2) spectral fitting of integrated starlight
   - comparison with SSPs or synthesis models
   ⊗ example slide: integrated spectra of early-type galaxies

3) Gas-phase abundances from <u>interstellar</u> absorption lines
   - needs sufficiently bright background continuum source
   ⊗ example slide: interstellar absorption lines

4) Gas-phase abundances from emission-line spectra
   - often only [O/H], multiple ionisation stages needed
   ⊗ example slide: Orion nebula vs. I Zw 18

Chemical evolution – the "Simple Model"

Goal: Obtain expression for metallicity as a function of time, $Z = Z(t)$

and/or Z in relation to other time-dependent quantities.

Initial & boundary conditions:

1. $t = 0 \rightarrow Z = Z_0$ (which may or may not be $Z_0 = 0$)
2. all mass is in gas; no stars yet.
3. $\psi(t)$ is given: star formation rate as function of time
4. IMF is given
5. Known: R = mass fraction returned to ISM per unit of time due to stellar evolution.
   (or assumed) Depends on IMF.
   $\Rightarrow$ $(1-R)$ = mass fraction staying in low-mass stars and compact stellar remnants (WD, NS, BHs)
6. Known: y = mass fraction of heavy elements (metals) returned to ISM = "stellar yields"
   (or assumed)

$Z(t)$ = mass fraction of metals in gas phase (= metallicity of new stars forming at t)

notation: $$\left.\begin{array}{l} M_{gas} := g(t) \\ M_{stars} := s(t) \end{array}\right\}$$ masses in the system

Equations for "Simple Closed Box" approximation:

$$g(t) + s(t) = \text{const} \quad \text{(closed box)}$$

$$g(t_0) = M_0 \quad \text{(total mass)}$$

$$s(t_0 = 0) = 0 \quad \text{no stars at beginning}$$

$s(t)$ changes because of

+ star formation
− mass loss to ISM, $\propto s$

$$\frac{ds}{dt} = \psi(t) - R \times s(t)$$

Gas mass accordingly changes as

$$\frac{dg}{dt} = -\frac{ds}{dt} \quad \text{(closed box)}$$

Mass of metals in gas phase:

$$\frac{d}{dt}(gZ) = \underbrace{-Z\frac{ds}{dt}}_{\text{stuff going into stars}} + \underbrace{y\frac{ds}{dt}}_{\text{enrichment}}$$

No generic solution, need further assumptions.

→ Instantaneous Recycling Approximation
enrichment of metals dominated by
short-lived stars (i.e. it happens "immediately")
⇒ y not explicitly time-dependent.

Then: $$\frac{d}{dt}(gZ) = (-Z+y)\frac{ds}{dt} = (Z-y)\frac{dg}{dt}$$

$$\cancel{Z\frac{dg}{dt}} + g\frac{dZ}{dt} = \cancel{Z\frac{dg}{dt}} - y\frac{dg}{dt}$$

$$\Rightarrow \quad \frac{dZ}{\cancel{dt}} = -\frac{y}{g}\frac{dg}{\cancel{dt}} \qquad (*)$$

! time derivative cancels out!
– strange, but we'll see soon
how to get time dependence back

Integration: $$\int_0^{Z(t)} dZ' = -y\int_0^t \frac{dg}{g(t')}$$

$$Z - Z_0 = -y \ln\left[\frac{g(t)}{g(0)}\right]$$
M_0

$$\boxed{Z = Z_0 - y\ln\left(\frac{g(t)}{M_0}\right)} \qquad (SCB)$$

Simple closed box with instantaneous
recycling

Connects metallicity to mass fraction converted
into stars → comparison with observations possible,
see below.

For explicit time dependence: two further approximations;

i) $\psi(t) \propto g(t)$

$$= p \times g(t) \quad p \text{ const.}$$

ii) since $R \ll 1$, let us set $R \approx 0$.

then $\frac{ds}{dt} \approx \psi(t) = -\frac{dg}{dt} = p \cdot g$

thus $\frac{dg}{g} = -p\, dt$

Back to Eq. (*): $\frac{dZ}{dt} = -y \frac{dg}{g\, dt} = +y \cdot p \cdot \frac{dt}{dt}$

$$\Rightarrow \quad Z(t) = Z_0 + y \cdot p \cdot t$$

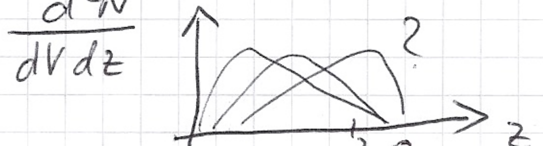
[very special solution, but instructive]

Confrontation with Observations

How? Neither (SCB) nor $Z(t)$ ~~die~~ contain direct observables!

possibility 1: use redshift as look-back-time
→ last lecture

possibility 2: compare predicted vs. observed fractions of stars with different metallicities. (Milky Way or nearby gal.)



No of stars per volume per Z interval.

⊛ slide: Observed metallicity distribution of stars in the solar neighbourhood.

How to predict this from SCB model?

We want: mass of stars with $Z' < Z(t)$

i.e. $s(Z(t)) = M_0 - g(Z(t))$ for given Z

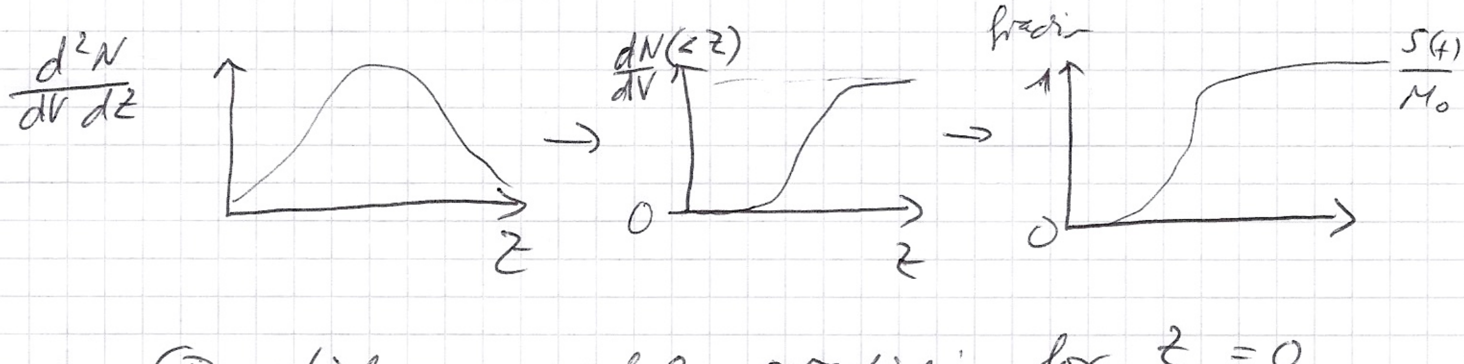
solution of (SCB) for $g(t)$:

$$g(t) = M_0 \, e^{-\frac{Z(t) - Z_0}{y}}$$

$$\boxed{\frac{s(t)}{M_0} = 1 - e^{-\frac{Z(t) - Z_0}{y}}}$$

exactly what we need!

to facilitate comparison: convert observed histogram into a normalised cumulative distribution:



⊛ slide: model prediction for $Z_0 = 0$

⊛ slide: + data points

Discussion

Prediction of SCB model clearly <u>not</u> in good agreement with the observations for Milky Way / solar neighbourhood!

→ predicted: many stars with low Z (= old stars)

→ observed: most stars have $Z \simeq Z_\odot$ (± 0.2 dex)

⇒ "G-Dwarf problem"

Possible solutions:

i) Observations are wrong (incomplete, biased, etc.)
- should always be considered, but probably not the case.

ii) solar neighbourhood is not representative [maybe, but not to this degree]

iii) maybe the assumed parameter values $y = 0.1$ and $Z_0 = 0$ are unrealistic?

→ Exercise: Try other values. Does it help?

iv) basic assumptions of closed-box model may be unrealistic.

Indeed that is the favoured explanation.
Galaxies are not closed boxes, but complex "eco systems",
- inflow of gas from intergalactic medium
- merging of galaxies
- outflow of gas (supernovae, other "feedback" mechanisms)

but there are still contexts for which the SBC model gives good results - not entirely dead!

New family of chemical evolution models:
"Accreting box"; main idea: continuous resupply of gas from IGM.

Special version: Assume that accretion rate $A(t)$ = loss of gas into stars, at all times,

i.e.: $$\frac{dg}{dt} = -\frac{ds}{dt} + A(t) = 0 \qquad \text{(EAB)}$$

"Extreme Accreting Box"

Further assumptions to simplify the problem:

* Accreted gas has $Z_A = 0$
* $R \simeq 0$
* $\psi(t) \approx p \cdot g(t) = \frac{ds}{dt}$ } as above

$\boxed{\text{Exercises:}}$
→ derive $Z(t)$
→ derive $Z\left(\frac{s}{g}\right)$
→ cumulative metallicity distribution
⇒ compare with solar neighborhood
→ compare with distribution for Galactic Halo

* slide: Observed metallicity distribution for stars in the Galactic Halo.