Chemical Evol'n of Galaxies (The Disk)

Would like to know the time evol'n of the composition of I.S. gas in galaxies, and the resultant time evol'n of stellar abundances

In reality, this is an enormously complicated question – let's see how far we can get with some simplifying assumptions

1. Region under study has ISM of uniform composition
2. Gains or loses mass only through gas flows

For more complicated situations (e.g., abundance gradients in galactic disks or halos) we divide the galaxy into zones.

[Assumption ② is, e.g., known <u>not</u> to be true for early phase of the Galactic halo]

Total mass M changes:

$$\frac{dM}{dt} = f \equiv \text{net rate of infall or accretion of gas}$$

Mass of stars changes as a result of star formation and mass loss from evolved stars

$$\frac{dM_s}{dt} = \psi - E$$

ψ = star formation rate; E = total ejection rate for stars of all masses and ages

Gas mass changes via SF, ejection, and net inflow or outflow,

$$\frac{dM_G}{dt} = -\Psi + E + f \quad ; \quad \text{note } M(t) = M_S(t) + M_G(t)$$

Gas fraction in a region:

$$\mu \equiv \frac{M_G}{M} \quad ; \quad M_S = (1-\mu)M$$

Now, E depends on IMF and SFR. We'll assume that each star undergoes all mass loss after a time τ_m that it lives on the M.S. If a star dies at time t, it was born at $(t-\tau_m)$. Let w_m be the remnant mass (as a function of m).

$$E(t) = \int_{m_t}^{\infty} (m - w_m)\,\Psi(t-\tau_m)\,\phi(m)\,dm$$

where m_t is the mass at the top of the M.S. at time t and $\phi(m)$ is the IMF at time $t-\tau_m$ (not time now)

Generally we lump all heavy elements other than H, He into "metals". Assume:

① Production of metals is only a fn. of stellar initial mass and not of initial metallicity

② Metals are mixed "instantaneously" into the ISM [not too bad an approximation, since most metals are produced by very short-lived massive stars]

⇒ "Instantaneous Recycling Approximation"

Mass of metals ZM_g in ISM (gas phase)
↑ fraction of mass in metals, by mass

$$\frac{d}{dt}(ZM_g) = -Z\Psi + E_Z + Z_f f$$

[solar abund ⇒ $Z = 0.02$]

- $\frac{d}{dt}(ZM_g)$: rate of change of gas-phase metallicity
- $-Z\Psi$: mass locked in stars
- E_Z: total ejection rate of metals from stars
- Z_f: mean metal abundance of infalling gas (metal fraction by mass)

Now, let p_{Zm} be the mass fraction of a star of mass m that is converted to metals and ejected — rate of new metals from stars at time t is

$$\int_{m_t}^{\infty} m\, p_{Zm}\, \Psi(t-\tau_m)\, \phi(m)\, dm$$

↑ star formation rate τ_m "ago"

Unprocessed material occupies a mass $(m - w_m - m p_{Zm})$ of the ejected part of a star of mass m and the metal abundance in the unprocessed ejected gas is $Z(t-\tau_m)$

(w_m: mass of remnant for star of initial mass m)

So, the total ejection rate of old and new metals is

$$E_Z(t) = \int_{m_t}^{\infty} \left[(m - w_m - m p_{Zm})\, Z(t-\tau_m) + m p_{Zm} \right] \Psi(t-\tau_m) \cdot \phi(m)\, dm$$

The mean metallicity of stars ever formed Z_s is

$$M_s Z_s + Z_s M_G = \int_0^t \int_{m_{t'}}^{\infty} m p_{Zm}\, \Psi(t'-\tau_m)\, \phi(m)\, dt'\, dm$$

- $M_s Z_s$: metals locked in stars
- $Z_s M_G$: in gas

Some quantities depend only on stellar evolution, not on $\Psi(t)$:

Stellar Evol'n - Dependent

① The "returned fraction" R. The turnoff mass at t=now can be taken to be $\sim 1\,M_\odot$. R is the fraction of the mass put into stars at a given time in the past, that is returned to the ISM by now

$$R \equiv \int_{m_t \approx 1 M_\odot}^{\infty} (m - w_m)\, \phi(m)\, dm$$

e.g. if all stars in a galaxy formed in a rapid initial burst at $t=0$, 10^{10} yrs later the total mass in stars would be $M_s(1-R)$

② The "yield" of heavy elements y — the mass of new metals ejected (eventually) when $1\,M_\odot$ is turned into stars

$$y \equiv \frac{1}{(1-R)} \int_{m_t = 1 M_\odot}^{\infty} m\, p_{zm}\, \phi(m)\, dm$$

e.g., if a mass M_s formed in a single initial burst, then by now (10^{10} yrs later) the mass of new metals ejected would be $y(1-R)M_s$.

MOST HEAVY ELEMENTS ARE PRODUCED BY MASSIVE STARS, so R and y don't depend strongly on m_t at the present epoch.

Some approximations are now possible:

1/23/14

$R \equiv$ returned fraction $\quad R \equiv \int_{m_t = 1 M_\odot}^{\infty} (m - w_m)\, \phi(m)\, dm$

e.g. || if all stars (M_s) formed in a burst at $t=0$, 10^{10} yrs later

$$\boxed{M_{s,0}\,(1-R)}$$

↑ ~30% of mass was returned to ISM

$y \equiv$ "yield" $\equiv$ mass of new metals ejected (eventually) when $1\ M_\odot$ is turned into stars

$$y \equiv \frac{1}{(1-R)} \int_{m_t = 1 M_\odot}^{\infty} m\, p_{zm}\, \phi(m)\, dm$$

e.g., if M_s formed at $t=0$, by 10^{10} yrs later mass of new metals ejected would be

$$\boxed{y\left[(1-R) M_{s,0}\right]} \quad (y \approx 1.5 \text{ solar})$$

Consider "Instantaneous Recycling" again:

Stars are divided into 2 classes

① Those that never eject material ($m < m_1$), $\tau_m = \infty$

② Those that eject mass as soon as they are born: $\tau_m \to 0$

So, lower mass limit in integrals now taken to be

$m_1(t)$ and $t - \tau_m \to t$

$$\Rightarrow \quad E(t) = R\,\Psi(t)$$

$$E_Z(t) = R\,Z(t)\,\Psi(t) + y(1-R)[1 - Z(t)]\,\Psi(t)$$

where t = current time, e.g. now

In practice, $Z \ll 1$ (~ 0.02 now) so

$$E_Z(t) \approx R\,Z(t)\,\Psi(t) + y(1-R)\,\Psi(t)$$

simply removed this factor

$\Rightarrow$ w/ these simplifications,

$$\frac{dM_S}{dt} = (1-R)\Psi$$

$$\frac{dM_G}{dt} = -(1-R)\Psi + f$$

net infall/outflow (f)

$$\frac{d(ZM_g)}{dt} = -Z(1-R)\Psi + y(1-R)\Psi + Z_f f$$

$= M_g \frac{dZ}{dt} + Z \frac{dM_g}{dt}$, then substitute

An eqn. for $Z(t)$ is obtained from the above:

$$M_G \frac{dZ}{dt} = y(1-R) + (Z_f - Z) f$$

$(Z_f - Z)$: difference in metallicity between infalling gas and ISM

Constant IMF

In the case that R, y are constants, but not f(t)

so, $$M_s(t) = (1-R)\int_0^t \Psi(t')\,dt' \equiv (1-R)\,\overline{\Psi}\,t$$

↑ avg SFR

w/ instant recycling and constant IMF,

$$Z_s M_s + Z M_G = y\, M_s$$

so, $$Z_s = y - \frac{\mu}{1-\mu} Z \qquad \left(\mu \equiv \frac{M_g}{M}\right)$$

"Gas Fraction"

$\Rightarrow$ $Z_s \to y$ as $\mu \to 0$

i.e., when no gas left, all the metals ever made and ejected (yM_s) are incorporated into later generations of stars. An estimate of the yield for the solar neighborhood where $\mu = 0.05$ is $y \approx 0.02 \approx 1.5\, Z_\odot$ $(Z_\odot \approx 0.015)$

CLOSED BOX SYSTEM

Assume there is no inflow or outflow, f=0, M=const.

$$M_g^0 = M_{TOT} \quad M_s^0 = 0, \quad Z_0 = Z_s^0 = 0$$

$$\frac{d(ZM_G)}{dM_G} = Z - y \qquad \text{(combine 2 eqn's to eliminate } t\text{)}$$

$$M_G \frac{dZ}{dM_G} + Z = Z - y \Rightarrow M_G \frac{dZ}{dM_G} = -y$$

$\Rightarrow$ i.e., $$\boxed{Z = y \ln\left(\frac{M_{TOT}}{M_G}\right)}$$ "Simple Closed Box Model"

Infall Balanced by Star Formation

Assume SF just keeps up w/ rate of infall plus mass ejection from stars:

$$\Psi = f + R\Psi$$

$$\text{so, } M_G = \text{const} = M_0 \; ; \; M_s^0 = 0, \; Z_0 = 0$$

Assume $Z_f = 0$ (not necessarily true!)

Can show that $M_G \frac{dZ}{dM} = y - Z$.

We solve this in terms of ν, the ratio of the accreted mass to the initial mass

$$\nu \equiv \frac{(M - M_0)}{M_0} = \frac{(M - M_G)}{M_G} = \mu^{-1} - 1$$

$$\text{and} \quad Z = y\,(1 - e^{-\nu})$$

Since $Z_s = y - \frac{\mu}{1-\mu} Z = y - \frac{\mu}{1-\mu}\, y\,(1 - e^{-\nu})$

In this case, as $\mu \to 0$, $Z \to y$, whereas in closed box model $Z \to 1$

Represents an equilibrium between infall and rate of enrichment by evolved stars.

General Statements

For instantaneous recycling and constant IMF,

① $Z \propto y$. True for "primary" elements whose production in stars independent of initial composition

② $\frac{Z}{y}$ depends mostly on current properties of the system

③ $\frac{Z}{y}$ does not depend strongly on y, Ψ/f $\Rightarrow$ regions of galaxies w/ very different $\frac{M_G}{M}$ may have similar Z.

Comparison w/ Observations

The Age-metallicity relation for disk stars (Edvardsson et al 1993 A+A 275 101)

— Over ~10 × 10^9 yrs, the abundances in the Galactic disk have only changed from ~ $\frac{Z_\odot}{4}$ to $Z_\odot$

[V.G.]

"The G-Dwarf Problem"

Basically, there are far too few metal-poor (disk) stars compared to expectation of simple models (first realized in 1962!)

Under a closed box model (or, any other simple model), one can work out the cumulative metallicity distribution of stars still on the M.S. (e.g. G, K, M class)

We saw previously that

$$M_s = (1-\mu) M_{TOT} \qquad \mu \equiv \frac{M_g}{M}$$

The fraction of all stars made while gas fraction was $\geq \mu$ is

$$\frac{M_s}{M_{s,t}'} = \frac{1-\mu}{1-\mu'} \qquad M_s', \mu' \text{ are } \underline{\text{present}} \text{ values}$$

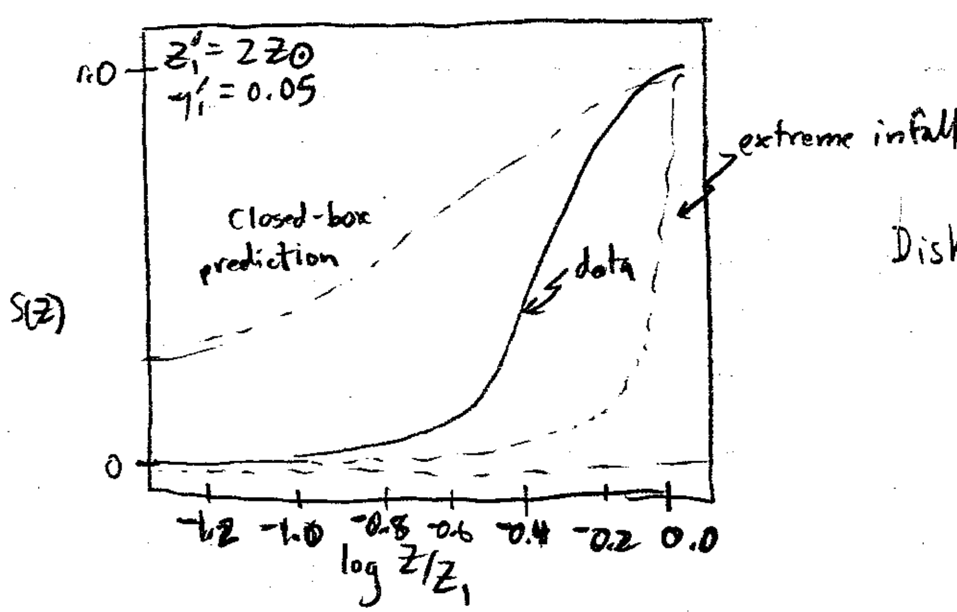
These stars formed when gas metallicity was $Z \leq y \ln(\mu^{-1})$

$\Rightarrow$ fraction of stars w/ metallicity $\leq Z$ is

$$S(Z) = \frac{M_s}{M_s'} = \frac{1-\exp(-Z/y)}{1-\mu'}$$

We can eliminate the yield y using $y = Z_t / \ln(\mu_t^{-1})$ and the assumption that the IMF (and $\therefore y$) have been constant

So, $$S(Z) = \frac{1-\mu_1'^{Z/Z_1'}}{1-\mu_1'}$$ (Subscripts " ' " indicate present values.)



Disk Star Metallicity Histogram

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

Possible Solutions to G-Dwarf Problem

① extreme infall – disk grows by accretion, slowly, beginning w/ small amount of gas

⇒ distribution strongly peaked @ $Z = y$

⇒ too few stars with $Z < Z_1$!

② pre-enrichment of disk gas → Can explain radial abundance gradients

Gas that formed disk had been enriched prior to infall – can reduce to

$$Z = Z_0 + y \ln(\mu^{-1})$$

$Z_0 \equiv$ initial metallicity of infalling gas

and $$S(Z) = \frac{1 - \mu_1^{(Z - Z_0)/(Z_1 - Z_0)}}{1 - \mu_1}$$

$Z_1 \Rightarrow$ present metals

This actually works quite well w/ $Z_0 = 0.2\, Z_1$!

Cf. HVC recent data !!

③ Variable IMF – "top-heavy" IMF at early times ⇒ rapid enrichment w/o producing low mass stars

not a crazy sol'n

④ "Metal Enhanced" S.F.

Suppose stars form preferentially in regions w/ higher Z (e.g., more efficient cooling?) NOT A CRAZY IDEA

AGE DATING – The AGE of the Milky Way

- nuclear cosmochronology
- stellar evol'n MS timescales (GC's)
- W.D. Cooling curve

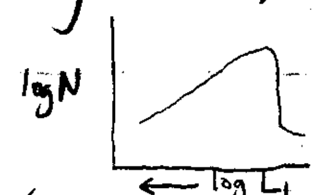
Stellar Age-Dating of the Galaxy

① The White Dwarf Cooling curve

Search for a cutoff in the W.D. luminosity function at the cool (faint end). This cutoff indicates, when combined with evolutionary models, that

$$t_{DISK} \approx 9.3 \pm 2.0 \text{ Gyr}$$

↳ NOTE SOLAR NBHD!



$L \propto T_{eff}^4$
$M_V \propto -10 \log T$
R = const. for degenerate matter

This is very difficult in practice, because cool W.D.'s are intrinsically very faint (the cutoff in the LF occurs at $M_V \sim 16-17$, i.e. $\log\left(\frac{L_{WD}}{L_\odot}\right) \approx -4.5$!

$D_{max} \approx 250\text{pc}$ for $m-M=7$

Cool W.D.s are also redder than hot W.D.s and therefore more difficult to distinguish from disk dwarfs. Depends also on models for cooling - systematics?

② Nuclear Cosmochronology

Examine abundances of radioactive isotopes with $\tau^{1/2}$ on the order of the age of the Universe. Best numbers are for Th/Eu (date solar system at ~4.5 Gyr).

↳ both r-process, should have well-known initial abundance ratios

1997 Cowan et al ApJ 480, 246

CS 22892-052 extremely metal poor star

Th/Eu = 0.219 as compared to S.S. value 0.463

→ $\tau(CS) \gg \tau(SS)$ ⟹ Radioactive decay age 15.2 ± 3.7 Gyr (a lower limit)