Astro 596/496 NPA
Lecture 38: The Final Frontier
May 1, 2019

Announcements:

- **Take-Home Final Problem Set** out today
  due Monday May 6, 10:00 pm as pdf post on Compass
  open book, open notes, open web, open instructor
  but please do not collaborate
- all homework solutions are posted

Solar Abundances Revisited

Solar Abundances Revisited

`www: A&G solar abundances`

Please list:

- the basic features
- their nulcear physics origin
- their astrophysical site

Don’t worry: not a quiz!

Solar Abundances Revisited

Nuclides/Feature	Major Astro Site	Nuke Physics Origin
H, D, He, Li	BBN	weak freeze, NSE freez
LiBeB	cosmic rays	spallation
C	post-MS He burning	3α
O–Ca	SN Type II	α-process
Fe peak	SN Ia, CCSN & core-coll	NSE
>Fe, esp. magic N peaks	AGB stars	s-process
>Fe, esp. peaks below magic N	NS-NS, CCSN?	r-process
Odd-even scatter	–	odd-even BE diff

A cosmic symphony!

We are stardust
Billion year old carbon
We are golden
Caught in the devil's bargain
And we've got to get ourselves
Back to the garden
Nuclear Astrophysicist J. Mitchell (1970)

recall: solar system composition is
a sum of all nucleosynthesis process
experienced over cosmic history until the Sun's birth
by the matter in the protosolar nebula

we would like to understand how this sum is made...

Abundance Evolution Warmup

recall stellar "age-metallicity" relation
Fe/H vs $\tau_\star$ in local neigborhood stars

Q: what is the trend?
Q: how can we understand it in terms of nucleosynthesis processes?

helium abundances: $Y = X(^4\text{He})$ vs $Z = \text{O/H}$ has

$$Y = mZ + b \tag{1}$$

Q: significance of fit parameters m*?* b*?*

age metallicity:

- large scatter, but
- *older stars have low* Fe/H

recall: iron made in supernova explosions
and ejected, mixed with interstellar matter
so as star formation proceeds, iron builds up with time
and is incorporated into later generations of new stars
so that younger stars have higher Fe/H

helium: made in big bang, and also in main sequence stars
oxygen: α element made in supernovae

so we expect $Y = Y_{\mathrm{BBN}} + Y_\star$
and since stars make both He and O, $Y_\star \propto Z$
so observed $Y = mZ + b$ gives:

- $m = (dY/dZ)_\star$ is helium production per unit metal production
- $b = Y_{\mathrm{BBN}}$ is the primordial helium abudance

Galactic Chemical Evolution

Basic idea simple: follow gas cycling

`www: chemical evolution cartoon`

$$\begin{array}{ccc} \text{gas} & \rightarrow & \text{stars} \\ \uparrow & \swarrow & \downarrow \\ \text{ejecta} & + & \text{remnant} \end{array} \tag{2}$$

Calculate cumulative effect of
nucleosynthesis processing of matter

Will consider 1-zone model:
"uniform galaxy approximation"
generalizations are straightforward

Key variables:
total gas mass $M_{\rm g}(t)$ (or surface density $\sigma_{\rm g}$)
(gas) mass fractions of species i: $X_i = M_i/M_{\rm g}$
star mass $M_\star$ (or $\sigma_\star$)

Q: how are these related?
Q: how do these change with time?
Q: what processes affect each quantity?
Q: what depends on present star formation?
Q: what depends on past star formation?

Basic Chemical Evolution Formalism

basic galactic chemical evolution equations:

for **total gas mass**

$$\begin{aligned}\frac{d}{dt}M_{\mathrm{g}} &= -\text{new stars} + \text{dying stars} - \text{outflow} + \text{infall}\\ &= -\psi + E - \vartheta + \mathcal{I}\end{aligned}$$

and for **gas mass in species** i

$$\frac{d}{dt}M_i = -X_i\psi + E_i - X_{\vartheta,i}\vartheta + X_{\mathcal{I},i}\mathcal{I} \tag{3}$$

where :

- $\psi = dM_{\text{new stars}}/dt$ is the star formation rate
- $E = dM_{\text{dying stars}}/dt$ is dying star mass ejection rate
- ϑ is the mass outflow rate
- $\mathcal{I}$ is the mass infall rate

These give abundance evolution:

$$\begin{aligned} M_{\mathrm{g}}\frac{d}{dt}X_i &= E_i - X_iE - (X_{\vartheta,i} - X_i)\vartheta + (X_{\mathcal{I},i} - X_i)\mathcal{I} \\ &= (X_{\mathrm{ej},i} - X_i)E - (X_{\vartheta,i} - X_i)\vartheta + (X_{\mathcal{I},i} - X_i)\mathcal{I} \end{aligned}$$

where $X_{\mathrm{ej},i} = E_i/E$ is mass fraction of i in ejected matter

Note struture: abudances X_i change due to
net changes in composition of stellar ejecta, infall, outflow

Q: What fundamental physical principle lies behind these eqs?
Q: what must be specified to actually do this calculation?

Chemical Evolution: Model Building

to model chemical evolution, need relevant rates

- must identify a region of interest:
  (proto)-Galaxy, galaxy cluster, the universe
- and specify processes which change mass/abundance content

At minimum, must include:

- star formation and death rates
- star mass distributions: initial mass function
- nucleosynthesis yields as a function of stellar mass
- prescriptions (or neglect) of infall, outflow

Then must compare with data:

- solar abundances
- Galactic disk, halo stellar populations
  abundances, number counts, mass distributions
- extragalactic abundances, e.g.,: stars, intracluster medium
  quasar absorption line systems

A sketch of some of these issues appears in
Director's Cut Extras

FINALE

Open Questions and the Future

job security:
Nuclear and Particle Astrophysics young and vigorous

Q: What key open questions in NPA?

Q: What are ways that NPA is a tool for astrophysics?

Q: What are possible/likely key advances in the next decade?

- *observational?*
- *experimental?*
- *theoretical?*

NPA Open Questions: A Sample

- What is the dark matter?
- How are the forces unified?
- How is the baryon asymmetry generated?
- What is the nature of neutrino masses?
- What was the nature and signatures of the quark-hadron transition?
- Where are the dark baryons?
- What is the astrophysical origin of the r-process?
- What is the nature of the first stars (Pop III)?
- How is the chemical evolution of the galaxy related to its merging history?
- What is the origin of ultra-high-energy cosmic rays?
- What is the origin of the bulk of the cosmic rays?
- ...

NPA as a Tool: A Sample

- BBN + CMB = probe of early universe
- abundance patterns as fossils of matter history
- Neutrinos as solar, terrestrial thermometers
- r-process in halo stars as tracers of inhomogeneous mixing
- Extinct radionuclides and a presolar "trigger"
- Live radionuclides as probes of prehistoric supernovae
- Pre-solar grains as tracers of diverse nucleosynthesis sites
- Gamma-ray lines as supernova diagnostics, calorimeters
- …

The Next Decade in NPA: Predictions

Thanks to: Richard Cyburt, Vasiliki Pavlidou, Tijana Prodanovic

Observations

- dark energy evolution probed by LSST, WFIRST, ...
- CMB T, polarization anisotropy to high precision
  precision Ω_{baryon}, ^{4}He, N_ν, $\sum m_\nu$ ...
- deuterium in QSO absorbers to $< 1\%$: probe early U.
- IceCUBE (high-E νs): more extragalactic sources
- JWST: Pop III supernovae imaged
- nearby SN in last 3 Myr seen in new radioisotopes
- gravity waves seen in on-axis GRB, many NS/NS binaries, and NS/BH binary
- Galactic supernova explodes!
  huge neutrino signal seen
  gravity wave signal seen (pulsar kick)
  detailed test of collapse, explosion mechanism
- completely unexpected result(s) makes some of the above look naive

Experiments

- ν oscillation matrix measured, ν CP violation tested
- Higgs boson probed in detail
- LHC at CERN finds signal beyond standard Model
- β-decay experiments detect ν mass
- completely unexpected result(s) makes some of the above look naive

Theory

- new particle detection leads to detailed inflation, baryogenesis theories
- dark energy motivates/constrains quantum gravity progress
- supernova models robustly explode, probe direct collapse scenarios
- chemical evolution models married with structure formation
  Galactic stellar abundances probe Galactic merger tree
- conventional models cannot explain e^+ annihilation in Galactic center
  requires exotic solution
- job security as unexpected new results challenge theorists

THANK YOU!

Director's Cut Extras: Chemical Evolution–Simple Model

Star Formation History

number of stars created in
- mass range $(m, m + dm)$
- time $(t, t + dt)$

given by the "creation function"

$$dN = C(m,t)\, dm\, dt \tag{4}$$

birthrate by mass for all stars in $m \in (m_{\mathrm{lo}}, m_{\mathrm{up}})$

$$\psi(t) = \int_{m_{\mathrm{lo}}}^{m_{\mathrm{up}}} dm\, m\, C(m,t) \tag{5}$$

"star formation rate"

Usually assume C is separable:

$C(m,t) = \psi(t)\phi(m)$

ψ = SFR

ϕ = initial mass function (IMF): time-indep.

Q: in words, what does the IMF describe?

Initial Mass Function

IMF: dist'n of $\star$ masses at birth
different normalizations in literature
Tinsley (& me): $\int dm\; m\; \phi(m) = 1$
(not how dist functs usually normed, but convenient if want SFR in terms of mass and not numbers)

IMF tells how to avg over $\star$ masses
Salpeter (high-mass): $\phi(m) \propto m^{-2.35}$
ex: the mean newborn mass is

$$\langle m \rangle = \frac{\int dm\; m\; \phi(m)}{\int dm\; \phi(m)} \simeq 0.35 M_\odot \text{ (Salp.)} \tag{6}$$

ex: the fraction by mass of stars $> 10 M_\odot$ is

$$f(> 10 M_\odot) = \frac{\int_{10 M_\odot}^{m_{\rm up}} dm\; m\; \phi(m)}{\int_{m_{\rm lo}}^{m_{\rm up}} dm\; m\; \phi(m)} \simeq 0.1 \text{ (Salp.)} \tag{7}$$

Chemical Evolution: Rates

Total mass ejection:
need star lifetime τ_m, a func of mass m
inverse: $m(t)$

present "turnoff mass" is $m(t_0) \equiv m_0 \simeq 0.9 M_\odot$

at time t, death of stars born at $t - \tau_m$
i.e., death rate is time-lag of birth rate
$\Rightarrow$ "death function" is $C_{\rm d}(m,t) = C(m, t - \tau_m)$

Mass ejection is ejecta-weighted death:

$$\begin{aligned} E(t) &= \int_{m(t)}^{m_{\rm up}} dm\, m_{\rm ej}\, C_{\rm d}(m,t) && (8) \\ &= \int dm\, m_{\rm ej}\, C(m, t-\tau_m) && (9) \\ &= \int dm\, m_{\rm ej}\, \phi(m)\psi(t-\tau_m) && (10) \end{aligned}$$

where $m_{\rm ej}(m) = m - m_{\rm rem}(m)$

That is total gas mass

Q: what about element/nuclide i?

For species i,
nuke cacl'ns give ejected mass $m_{\mathrm{ej},i}(m) = X_{\mathrm{ej},i} m_{\mathrm{ej}}$

$$E_i(t) = \int_{m(t)}^{m_{\mathrm{up}}} dm\, m_{\mathrm{ej},i}\, C(m, t - \tau_m) \tag{11}$$

$$= \int dm\, m_{\mathrm{ej},i}\, \phi(m) \psi(t - \tau_m) \tag{12}$$

note: $\sum_i E_i = E$
⇒ all hard-won nucleosynthesis info
lives in $\boxed{m_{\mathrm{ej},i}}$

note: full GCE eqs. integro-differential
no general analytic solution → have to use computer

The Simple Model

useful analytic approx.: "Simple Model"
$\Rightarrow$ use most drastic simplifications

- lifetimes: "instantaneous recycling approx." (IRA)

$$\tau_m = \begin{cases} \infty & m < m_0 \\ 0 & m > m_0 \end{cases} \tag{13}$$

and sometimes also

- infall = outflow = 0 $\Rightarrow M_{\mathrm{tot}} = const = M_0$; "closed box"

Then simple model gives

$$E(t) = \psi(t) \int_{m_0}^{m_{\mathrm{up}}} dm\, m_{\mathrm{ej}}\, \phi(m) \equiv R\, \psi(t) \qquad (14)$$

where the “return fraction” is

$$R = \int dm\ m_{\mathrm{ej}} \phi(m) = \langle m_{\mathrm{ej}} \rangle / \langle m \rangle \leq 1 \qquad (15)$$

Salpeter: $R \sim 0.35$

Q: what about yields? Simplest assumptions?

$$\begin{aligned}\text{For yields, put } m_{\mathrm{ej},i} &= \text{unprocessed} + \text{change}\\ &= X_{i,\mathrm{init}} m_{\mathrm{ej}} + \Delta m_i\end{aligned}$$

$$E_i(t) = \left[R X_i + (1-R) y_i\right] \psi \tag{16}$$

where mean "yield" of *new* material

$$(1-R) y_i = \int dm \; \Delta m_i \; \phi(m) \tag{17}$$

Note: $\sum_i \Delta m_i = 0$, so some $\Delta m_i < 0$!

Q: Can you think of an example?

Simple Model GCE gas eqns:

$$\dot{M} = -(1-R)\psi \tag{18}$$
$$M\dot{X}_i = (1-R)y_i\psi \tag{19}$$

can solve:

$$\dot{X}_i = -y_i\frac{\dot{M}}{M} \tag{20}$$
$$X_i = y_i \ln\frac{M_0}{M} = y_i \ln\frac{1}{\mu} \tag{21}$$

where $\mu = M/M_0$: "gas fraction"
Note: $X_i(\mu)$ indep of SFR!

MW today: $M_\star \simeq 10^{11} M_\odot$; $M_{\rm gas} \simeq 10^{10} M_\odot$
$\Rightarrow \mu_0 \sim 0.1$, $\ln \mu^{-1} \sim 2.3$

example: $\boxed{\text{“metals” } Z}$ massive stars: $y_Z \simeq Z_\odot/2$
(10× solar per SN, but 10% of mass goes into SNe)
$\Rightarrow$predict $Z_0 = 2.3(Z_\odot/2) \simeq Z_\odot$ in ISM

Age-Metallicity Relation

Time dependence $Z(t)$ ("age-metallicity")
$\rightarrow$ need to know $\psi(t)$

example: if $\psi = M_{\rm gas}/\tau_\star \propto M_{\rm gas}$
Then $M_{\rm gas} = M_0 e^{-(1-R)t/\tau_\star}$
$Z = (1-R) y_Z t/\tau_\star$ linear growth!
$[{\rm Fe/H}] \sim \log(Z/Z_\odot) \sim \log t + const$

`www: age-metallicity for solar neighborhood`

Elt vs elt:
$Z_i/Z_j(t) = y_i/y_j = const$ if const ys
removes GCE uncertainties
$\Rightarrow$ can learn about nuke!

G-Dwarfs

G-dwarfs: long-lived, $\tau_m \gtrsim t_0$
fossil of cumulative star form

Simple Model:

$$dN_G/dt = \int_{m_{\rm lo}}^{m_0} dm\ \phi(m)\psi(t) = -f_G \dot{M}_{\rm g} \tag{22}$$

where $f_G = (1-R)^{-1} \int^{m_0} dm\ \phi(m)$
$\Rightarrow$ cum. # $N_G = f_G M_0 (1-\mu) = N_0 (1 - e^{-Z/y_Z})$
$\Rightarrow$ metal dist'n

$$\frac{dN_G}{d\ln Z} = Z \frac{dN_G}{dZ} = N_0 \frac{Z}{y_Z} e^{-Z/y_Z} \tag{23}$$

sketch $dN/d\ln Z$

Observe:

`www: local disk G-dwarf distribution` Disk stars dN/d[Fe/H] cut off at [Fe/H] $= -1$

low [Fe/H] overpredicted in closed box

"G-dwarf problem"

Ideas?

Solutions to G-Dwarf Problem

(1) open the box: allow infall
e.g., if $\mathcal{I} = f\psi$, metal free $Z_{\mathcal{I}} = 0$, then

$$\frac{dN_G}{d \ln Z} = N_0 \frac{Z}{y_Z} e^{-Z/y'_Z} \tag{24}$$

where $y'_Z = (1 - R)/(1 - R - f)\, y_Z \geq y_Z$
⇒ shorter tail!
infall evidence: high-velocity clouds
`www:  HVC image`

(2) 1-zone model inadequate:
Pop I vs Pop II metal dis'ns diff't

Ultimately, will need to merge chemev analysis with galaxy, structure formation
⇒ consistent star formation rate, merging/gas-mixing events
big project, but must be done!