Astro 596/496 NPA
Lecture 42: Course Finale
Dec. 9, 2009

Announcements:

- Final Problem Set due Monday at 5pm
  open book+notes+web, but please do not collaborate

Last time: atmospheric neutrinos and neutrino finale
Q: how are atmospheric neutrinos created?
Q: what are their flavors at birth?
Q: what is the evidence for atmospheric oscillations?

Oscillation mass constraints summarized

$$\Delta m^2_\odot \equiv \Delta m^2_{12} = m_2^2 - m_1^2 = (7.59 \pm 0.20) \times 10^{-5}\ \text{eV}^2$$
$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{23} = m_3^2 - m_2^2 = (2.43 \pm 0.13) \times 10^{-3}\ \text{eV}^2$$

Q: what does this say about the m_i*?*
Q: possible (m_1, m_2, m_3) *mass schemes?*

Neutrino Masses

will show in Final PS that:

None of m_i fixed, but :

- *all* mass-square differences Δm^2 fixed
- beta decay experiments add info ν_e mass components

Cosmological implications:

- oscillations alone set *lower limit* to Ω_ν
- oscillations+β decays sets *upper limit* to Ω_ν

In particular, upper limit gives: $\boxed{\Omega_\nu < \Omega_{\rm matter}}$

$\Rightarrow$ Last question on Final:

Q: why is this result centrally important to cosmology and particle physics?

Solar Abundances Revisited

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`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 freeze
LiBeB	cosmic rays	spallation
C	post-MS He burning	3α
O–Ca	SN Type II	α-process
Fe peak	SN Ia & II	NSE
$>$Fe, esp. magic N peaks	AGB stars	s-process
$>$Fe, esp. peaks below magic N	SN II? NS-NS?	r-process
Odd-even scatter	–	odd-even BE diff

We are stardust, we are golden
We are billion-year-old carbon
Nuclear Astrophysicist J. Mitchell (1969)

Note:
solar matter *sums over nuke process*
would like to understand how sum made...

Galactic Chemical Evolution

Basic idea simple: follow gas cycling

`www: GCE sketch`

$$\begin{array}{ccc} \text{gas} & \longrightarrow & \text{stars} \\ \uparrow & \swarrow & \downarrow \\ \text{ejecta} & + & \text{remnant} \end{array} \tag{1}$$

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 GCE eqs:

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

$$\frac{d}{dt}M_i = -X_i\psi + E_i - X_{\vartheta,i}\vartheta + X_{\mathcal{I},i}\mathcal{I} \quad (2)$$

where :

- ψ is star formation rate
- E is "ejection rate"
- ϑ is outflow rate
- $\mathcal{I}$ is infall rate

These give abundance evolution:

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

where $X_{\mathrm{ej},i} = E_i/E =$ 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 origin of ultra-high-energy cosmic rays?
- What is the origin of the bulk of the cosmic rays?
- What is the astrophysical origin of the r-process?
- What is the nature of Pop III stars?
- How is the chemical evolution of the galaxy related to its merging history?
- ...

NPA as a Tool: A Sample

- BBN + CMB = probe of early universe
- Extraglactic gamma-rays as probes of extragalactic cosmic rays
- LiBeB as cosmic ray fossils
- Neutrinos as solar, terrestrial thermometers
- r-process in halo stars as tracers of inhomogeneous mixing
- Extinct radionuclides and a presolar "trigger"
- 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 DES, SNAP, ...
- CMB T, polarization anisotropy to high precision
  precision $\Omega_{\rm baryon}$, ^{4}He, N_ν, $\sum m_\nu$ ...
- deuterium in QSO absorbers to $< 1\%$: probe early U.
- *Fermi* (high-E γs):
  structure formation γs seen
  π^0 emission seen in SNRs $\rightarrow p$ accel confirmed
- IceCUBE (high-E νs): extragalactic sources seen (AGN?)
- X-ray observations probe structure, state of intergalactic baryons
- Webb (NGST): Pop III supernovae imaged
- WIMP annihilation confirmed in Galactic center
- geological radioisotope anomalies confirm nearby SN in last 3 Myr
- gravity waves detected from NS/NS merger, associated with γ burst
- 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 osciallation matrix measured, ν CP violation tested
- Higgs boson discovered (origin of electroweak mass)
- WIMP detectors confirm signal
- LHC at CERN finds supersymmetric partners consistent with WIMP evidence
- β-decay experiments detect ν mass
- completely unexpected result(s) makes some of the above look naive

Theory

- supersymmetry detection leads to detailed inflation, baryogenesis theories
- dark energy motivates/constrains quantum gravity progress
- supernova models achieve successful explosions
- 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"

$$d\mathcal{N} = C(m,t)\, dm\, dt \tag{3}$$

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

$$\psi(t) = \int_{m_{\rm lo}}^{m_{\rm up}} dm\; m\; C(m,t) \tag{4}$$

"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

$$\langle m \rangle = \frac{\int dm\, m\, \phi(m)}{\int dm\, \phi(m)} \simeq 0.35 M_\odot \text{ (Salp.)} \tag{5}$$

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

$$f(> 10M_\odot) = \frac{\int_{10M_\odot}^{m_{\rm up}} dm\, m\, \phi(m)}{\int_{m_{\rm lo}}^{m_{\rm up}} dm\, m\, \phi(m)} \simeq 0.1 \text{ (Salp.)} \tag{6}$$

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 $C_\mathrm{d}(m,t) = C(m, t - \tau_m)$

Mass ejection is ejecta-weighted death:

$$E(t) = \int_{m(t)}^{m_{\mathrm{up}}} dm\, m_{\mathrm{ej}}\, C_{\mathrm{d}}(m,t) \tag{7}$$

$$= \int dm\, m_{\mathrm{ej}}\, C(m, t-\tau_m) \tag{8}$$

$$= \int dm\, m_{\mathrm{ej}}\, \phi(m)\psi(t-\tau_m) \tag{9}$$

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

That is total gas mass

Q: what about element/nuclide i?

For species i,

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

$$E_i(t) = \int_{m(t)}^{m_{\mathrm{up}}} dm\, m_{\mathrm{ej},i}\, C(m, t - \tau_m) \quad (10)$$

$$= \int dm\, m_{\mathrm{ej},i}\, \phi(m)\psi(t - \tau_m) \quad (11)$$

note: $\sum_i E_i = E$

$\Rightarrow$ all hard-won nucleosynthesis info

lives in $m_{\mathrm{ej},i}$

note: full GCE eqs. integro-differential

no general analytic solution $\rightarrow$ have to use computer

The Simple Model

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

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

$$\tau_m = \begin{cases} \infty & m < m_0 \\ 0 & m > m_0 \end{cases} \tag{12}$$

and sometimes also

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

Then simple model gives

$$E(t) = \psi(t) \int_{m_0}^{m_{\text{up}}} dm\, m_{\text{ej}}\, \phi(m) \equiv R\, \psi(t) \tag{13}$$

where the "return fraction" is

$$R = \int dm\, m_{\text{ej}} \phi(m) = \langle m_{\text{ej}} \rangle / \langle m \rangle \leq 1 \tag{14}$$

Salpeter: $R \sim 0.35$

Q: what about yields? Simplest assumptions?

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

$$E_i(t) = [RX_i + (1 - R)y_i]\, \psi \tag{15}$$

where mean "yield" of *new* material

$$(1 - R)y_i = \int dm\, \Delta m_i\, \phi(m) \tag{16}$$

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:

$$\dot{M} = -(1-R)\psi \tag{17}$$

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

can solve:

$$\dot{X}_i = -y_i \frac{\dot{M}}{M} \tag{19}$$

$$X_i = y_i \ln \frac{M_0}{M} = y_i \ln \frac{1}{\mu} \tag{20}$$

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

`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:

$$dN_G/dt = \int_{m_{\rm lo}}^{m_0} dm\, \phi(m)\psi(t) = -f_G \dot{M}_{\rm g} \qquad (21)$$

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

$$\frac{dN_G}{d\ln Z} = Z\frac{dN_G}{dZ} = N_0 \frac{Z}{y_Z} e^{-Z/y_Z} \qquad (22)$$

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

$$\frac{dN_G}{d\ln Z} = N_0 \frac{Z}{y_Z} e^{-Z/y'_Z} \quad (23)$$

where $y'_Z = (1-R)/(1-R-f)\, y_Z \geq y_Z$
$\Rightarrow$ 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
$\Rightarrow$ consistent star formation rate, merging/gas-mixing events
big project, but must be done!