Nucleosynthesis in Supernovae and the Big-Bang (I)

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Solar System Abundance

BIG-BANG

Constrains $\Omega_B$ and Cosmological Theories of $\Omega_{CDM}$ & $\Omega_\Lambda$!

STARS

R-process elements, SUPERNOVAE?

AGB STARS

COSMIC-RAYS

Actinide

$^{232}$Th (14.05 Gy)

$^{238}$U (4.47 Gy)

Supernova-\textgamma Process?
Universe is likely flat and accelerating!
\[ \Omega_B + \Omega_{CDM} + \Omega_{\Lambda} = 1 \]

Six (eleven) Parameters!

- **Is BARYON**, \( \Omega_B = 0.04 \), consistent with Big-Bang Cosmology and Nucleosynthesis (as a CANDLE of dark side of the Universe)?

  BBN constrains Brane Cosmology!

- **What is the nature of CDM**, \( \Omega_{CDM} = 0.26 \)?
  Disappearing CDM Model in Brane World Cosmology!
  Ichiki, Garnavich, Kajino, Mathews & Yahirow, PRD 68 (2003) 083518

- **What is DARK ENERGY**, \( \Omega_{\Lambda} = 0.7 \)?
  Growing CDM Model in Brane World Cosmology!

- **COSMIC AGE (13.7 \( \pm \) 0.2 Gy)**, strongly model-dependent?
  Supernova R-Process & Origin of \(^{232}\text{Th}, ^{235,238}\text{U} \) --- Model independent!
The Universe is homogeneous and isotropic in a large enough scale.

- $T = 2.728 \text{ K}$
- $\delta T < 18 \mu \text{K}$

2dF Quasar (Matter) Distribution: Homogeneous

Cobe Sky Maps of CMB; Isotropic
Birkoff’s Theorem: Gravity due to mass interior to an arbitrary sphere.

$$E = \frac{1}{2} m \dot{r}^2 - \frac{G m M}{r}$$

$$\frac{1}{2} m \dot{r}^2 = \frac{G m [(4 / 3) \pi \rho r^3]}{r} + E$$

$$\times \frac{1}{2} m r^2$$

$$\left(\frac{\dot{r}}{r}\right)^2 = \frac{8}{3} \pi G \rho + \frac{2E}{mr^2}$$

$$M = \frac{4}{3} \pi \rho r^3$$
General Relativity

\[ G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} R g^{\mu\nu} = 8\pi G T^{\mu\nu} + \Lambda g^{\mu\nu} \]

\[ R_{\mu\nu} = R^\lambda_{\mu\lambda\nu} = \partial_\lambda \Gamma^\lambda_{\mu\nu} - \partial_\nu \Gamma^\lambda_{\mu\lambda} + \Gamma^\lambda_{\eta\lambda} \Gamma^\eta_{\mu\nu} - \Gamma^\lambda_{\eta\nu} \Gamma^\eta_{\mu\lambda} \]

\[ \Gamma^\lambda_{\mu\nu} = \frac{1}{2} g^{\lambda\beta} \left\{ \partial_\nu g_{\beta\mu} + \partial_\mu g_{\beta\nu} - \partial_\beta g_{\mu\nu} \right\} \]

\[
g_{\mu\nu} = \begin{bmatrix} -1 & \frac{a^2(t)}{1-kr^2} & a^2(t)r^2 \\ \frac{a^2(t)}{1-kr^2} & - \frac{a^2(t)r^2}{1-kr^2} & a^2(t)r^2 \sin^2 \theta \\ a^2(t)r^2 \sin^2 \theta & a^2(t)r^2 \sin^2 \theta & - \frac{a^2(t)r^2}{1-kr^2} \end{bmatrix} \]

\[
T^\mu_{\nu} = \begin{bmatrix} -\rho & p & p \\ p & -\rho & p \\ p & p & -\rho \end{bmatrix} \]
**Einstein Equation**

**Space-space component**

\[ G^{00} = 8\pi G T^{00} + \Lambda g^{00} \]

**Friedmann Eq.**

\[ H^2 = \frac{8}{3}\pi G \rho - \frac{k}{a^2} + \frac{\Lambda}{3} \]

\[ H^2 = H_0^2 \left( \frac{\Omega_{\gamma}}{a^4} + \frac{\Omega_M}{a^3} - \frac{\Omega_k}{a^2} + \Omega_\Lambda \right) \]

**Deceleration parameter**

\[ q_0 = -\frac{(d^2r/dt^2)}{rH^2} = \left[ \Omega_{CDM}/2 - \Omega_\Lambda \right] \]

**Newtonian Equation**

\[ \frac{d^2r}{dt^2} = -k = \frac{E}{mr^2} \]

\[ H^2 = (v/r)^2 \]

\[ \Omega_\alpha = \frac{\rho_\alpha}{\rho_C} \]

\[ \rho_C = \frac{3H_0^2}{8\pi G} \]

\[ a = a(t) = \text{scale factor} = r \]

\[ \Omega_{CDM}/2 < \Omega_\Lambda \text{ acceleration !} \]
Cosmic Expansion History

Dark Matter + Dark Energy effect the expansion of the universe

- $\Omega_{\text{MCM}}$ = 0.3, $\Omega_{\Lambda}$ = 0.7 (accelerating)
- $\Omega_{\text{MCM}}$ = 0.3, $\Omega_{\Lambda}$ = 0.0 (decelerating)
- $\Omega_{\text{MCM}}$ = 1.0, $\Omega_{\Lambda}$ = 0.0 (critical)
- $\Omega_{\text{MCM}}$ = 5.0, $\Omega_{\Lambda}$ = 0.0 (closed)
\[ \frac{\delta T}{T} = \sum_l \sum_m a_{lm} Y_{lm}(\theta, \phi) \]

\[ C_l \equiv \left\langle |a_{lm}|^2 \right\rangle \]

\[ C_l = \left\langle \frac{\delta T}{T}(n) \cdot \frac{\delta T}{T}(n+\theta) \right\rangle \]
Cosmological Parameter Dependence

Larger $\Omega_\Lambda$

Larger $\Omega_{\text{CDM}}$

Larger $\Omega_B$

Multipole $l$

Dark Matter potential $\Omega_{\text{CDM}}$

Baryon Mass $\Omega_B$

Baryon Drag

$T_\gamma$
Pie Chart of Cosmic Mystery

Ordinary matter makes up a small fraction of mass/energy.

Dark matter and dark energy dominate.

$\Omega_\Lambda$

$\Omega_B$

$\Omega_{CDM}$

$t = 3 \times 10^5 \text{ yr}$
The Power of BBN is that the Physics is Accessible

Thermodynamic Equilibrium of Particles and Nuclei

\[ n_i(p)dp = \frac{1}{2\pi^2} g_i p^2 \left[ \exp \left( \frac{E_i(p) - \mu_i}{kT} \right) \pm 1 \right]^{-1} dp \]

\[ \rho_i = \int p \left[ n_i(p) + n_\bar{i}(p) \right] dp \]

\[ \rho_\gamma = \frac{\pi^2}{15} (kT_\gamma)^4, \quad \rho_\nu = \frac{7}{8} \frac{\pi^2}{15} (kT_\nu)^4 \]

\[ \rho = \rho_\gamma + \rho_\nu + \rho_i = \frac{\pi^2}{30} g_{\text{eff}}(kT)^4 \]

\[ g_{\text{eff}}(T) = \sum_{\text{bose}} g_{\text{bose}} + \frac{7}{8} \sum_{\text{fermi}} g_{\text{fermi}} \]

Cosmic Expansion

\[ H^2(t) = \left( \frac{1}{R} \frac{dR}{dt} \right)^2 = \frac{8\pi G}{3} \rho + \frac{\Lambda}{3} - \frac{k}{R^2} \]

Nuclear Reactions

\[ \frac{dY_i}{dt} = \sum_{ijk} N_i \left( \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_k!} \langle n_k \sigma_{ik} v \rangle - \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_k!} \langle n_j \sigma_{ij} v \rangle \right) \]
Supernova R-Process

NSE

$\alpha$-process

$R$-process

(neutron-rich)
Evolution of Abundances

Mass Fraction

Temperature (MeV)

NSE

Dynamical Nucleosynthesis

$^4\text{He}$

$^3\text{He}$

$^7\text{Li}$

$^7\text{Be}$

$^6\text{Li}$

$p$

$n$

d

t
Big-Bang Nucleosynthesis (BBN) Diagram

$t = 3 \text{ min}$

Big-Bang Nucleosynthesis Constraints

$\Omega_B$’s from BBN and CMB are inconsistent!
NEW MEASUREMENT OF NEUTRON LIFE

Serevlov et al., Phys. Lett. B605 (2005), 72

ULTRA-COLD NEUTRON

$$\delta \tau_n / \tau_n = -1 \%$$

STANDARD QUARK MODEL

KMS (Kobayashi-Masukawa-Cabbibo) MATRIX

$$N \rightarrow P$$

$$d \rightarrow u : V_{ud}$$
Effect of Neutro-Life on BBN-$^4$He: $2p + 2n \longrightarrow ^4$He

1st effect: $\delta \tau_n \rightarrow \delta T_d \rightarrow \delta (n/p) \rightarrow \delta (^4\text{He})$

\[
\delta \tau_n = \frac{\alpha m_\text{p}}{\tau_d} \delta T_d = \frac{\alpha m_\text{p}}{\tau_d} \delta \tau_d
\]

\[
\delta \tau_n = \frac{\alpha m_\text{p}}{2\pi^2} \delta (\text{He}) = \frac{\alpha m_\text{p}}{2\pi^2} \delta \tau_d
\]

\[
\delta \tau_n = \frac{\alpha m_\text{p}}{2\pi^2} \delta (\text{He}) \rightarrow \frac{\alpha m_\text{p}}{2\pi^2} \delta \tau_d
\]

2nd effect: $\delta \tau_n \rightarrow \delta n \rightarrow \delta (^4\text{He})$

\[
\delta \tau_n = \frac{\alpha m_\text{p}}{2\pi^2} \delta (\text{He}) \rightarrow \frac{\alpha m_\text{p}}{2\pi^2} \delta \tau_d
\]

\[
\delta \tau_n < 0 \rightarrow \delta (^4\text{He}) < 0
\]
Big-Bang Nucleosynthesis vs. CMB

Mathews, Kajino & Shima, PRD71 (2005) 021302 (R)

CMB - WMAP

CONSISTENT!

7Li PROBLEM!? 
7Li Abundance in Halo Dwarf Stars

SN II Nucleosynthesis contributes!

Is this plateau really Big-Bang origin?

Affected by SN ν-process?

SNe II Nucleosynthesis can produce $^7\text{Li}$ and $^{11}\text{B}$ as the BBN does in the early Universe!

Supernova $\nu$ - process!

*Supernova 1987A. These two photographs show the same star field in the Large Magellanic Cloud, near the Tarantula Nebula (30 Doradus), before and after the explosion. The star Sanduleak-69 202 is marked by an arrow. (D. Malin, Anglo-Australian Telescope Board).*

Calibrate $\nu$-Temperature!
Constrain $\nu$-Oscillation?

$^4\text{He}(\nu, \nu' p)^3\text{H}$, $^4\text{He}(\nu, \nu' n)^3\text{He}$, $^{12}\text{C}(\nu, \nu' p)^{11}\text{B}$

$^4\text{He}(\nu_e, e^- p)^3\text{He}$, $^4\text{He}(\bar{\nu}_e, e^+ n)^3\text{H}$, $^{12}\text{C}(\nu_e, e^- p)^{11}\text{C}$, $^{12}\text{C}(\bar{\nu}_e, e^+ n)^{11}\text{B}$
Primordial $^7$Li Abundance, observed?


Primordial $^7$Li is NOT affected by the SN $\nu$-PROCESS.

GCR + STARS

Nuclear Physics can solve $^7$Li PROBLEM?
BBN Nuclear Uncertainties are Improving


If cross section were EXTREMELY larger, then, $^7\text{Be}$ would be destroyed!

PRPROSAL of Coc et al. (2003)
Big-Bang Nucleosynthesis

If $^7\text{Be}$ would be destroyed, then $\Omega_B$'s from BBN and WMAP could be consistent!

New neutron life!

Mathews, Kajino and Shima, PRD71 (2005) 021302 (R)

Lyman-$\alpha$!
\[ ^{7}\text{Be} \ (d, p) \ 2\alpha \]

Angulo et al. (2005) EXPERIMENT

Data from Kavanagh (1960)

Not very largely enhancement!

Primordial \(^{7}\text{Li}\) should be high!!

Big-Bang Energy
PRIMARY PROCESSES

Big-Bang Nucleosynthesis

Initially \( p \& n \)

Supernova R-Process

NSE

\[ \alpha \text{-process} \]

\[ \text{R-process} \]

(neutron-rich)
INHOMOGENEOUS BIG-BANG NUCLEOSYNTHESIS


\[ ^{9}\text{Be} \]

\[ ^{7}\text{Li}(n,\gamma)^{8}\text{Li} (n,\gamma)^{9}\text{Li}(e^{-}\nu)^{9}\text{Be} , \]

\[ ^{7}\text{Li}(t,n)^{9}\text{Be} , ^{7}\text{Li}(^{3}\text{He},p)^{9}\text{Be} \]

\[ ^{7}\text{Li}(n,\gamma)^{8}\text{Li}(\alpha,n)^{11}\text{B} \]

\[ ^{7}\text{Li}(\alpha,\gamma)^{11}\text{B} \]
Universe is likely flat and accelerating!
\[ \Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1 \]

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  * Growing CDM Model in Brane World Cosmology!
  * Umezu, Ichiki, Kajino, Mathews Nakamura & Yahiro (2005)
    (astro-ph/0507227)

- COSMIC AGE (13.7 +- 0.2 Gy), strongly model-dependent?
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Brane World Cosmology

Motivated by the D-brane solution in 10 dim STRING THEORY
Randall-Sundrum II; PRL 83 (1999)

The Universe is embedded in a 5 dim spacetime AdS5.

Brane || 4D-Einstein Universe

Quantized matter fields in AdS5 leads to quasilocalized eigenstates on the 4 dim brane.

CDM Particle SUSY !?

5-th dimension, compactified.

Massive particle can tunnel into z!

Dubovsky, Rubakov, & Tinyakov (2000)
Disappearing LSP (Lightest SUSY Particle) CDM Model
Is a likely possibility!

LSP = Lightest Supersymmetric Particle

\[ m_0 \sim 1 \text{ TeV} \quad \text{vs.} \quad m_B \sim 1 \text{ GeV} \]

Fermion:

\[ \Gamma = m_0 (m_0/2k)^{2gv/k-1} \pi/\Gamma_f (gv/k+1/2)^2 \]

\( v = \text{vacuum expectation value} \)

\( g = \text{coupling const.} \)

Scalar Particles (Bosons):

\[ \Gamma = (\pi/16) m_0^3/k^2 \]

\( k = (-\Lambda_5/6)^{-1/2} \)

Largest \( \Gamma \) for largest \( m_0 \)

LSPs (CDM) disappear at cosmological time!

BARYONS do not!
Modified Friedmann Equation

\[ H^2 = \frac{8\pi G N}{3} \rho - \frac{k}{a^2} + \frac{\Lambda}{3} + \frac{K}{36} \rho^2 + E \]

\[ \rho = \rho_M + \rho_R + \rho_{DM} \]

\[ \rho_{DM} = Ce^{-\Gamma t} / a^3 \]

\[ \frac{dE}{dt} + 4HE = \Gamma \rho_{DM} \]

E = Dark Radiation or Electric part of the bulk
Weyle tensor

Ichiki, Garnavich, Kajino, Mathews & Yahiroyo
PRD 68 (2003), 083518
Thermal History of the Universe

INFLATION: (GW)

BBN (Big-Bang Nucleosynthesis)

Type Ia SNe, CLUSTER M/L

$10^{-43}$ sec  3 min  $10^5$ y  1-10 Gy

QCD phase tr $\nu$-dec, $e^+e^-$-annihi

CMB Anisotropies

Matter-Dom Era

Rad-Dom Era

Observables at different cosmic time!
Constraints on SUSY-Brane Cosmology (Disappearing CDM) Model

Dark Energy is still needed!

Our Model is as good as the standard model.

Ichiki, Garnavich, Kajino, Mathews & Yahiroy, PRD 68 (2003) 083518
Brane World Cosmology

CDM particles can exist in the bulk. Then, they can FLOW IN from the bulk!

5-th dimension, compactified.

The Universe is embedded in a 5 dim spacetime

Brane

\[ H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho + \rho + \rho_{\chi} + \frac{k}{a^2}) \]

Dark Enerfy term:

\[ \dot{\rho}_{\chi} + 4H\rho_{\chi} = -\alpha/a^q \times \rho_{\text{cr}}H. \]

\[ q = \text{adjustable parameter} \]

We propose Growing-CDM Model for DARK ENERGY! \( \Omega_{\Lambda} = 0 \) model!
Supernova $z$ vs. $m-M$ Relation

- Standard $\Lambda$CDM model
  \[ \Omega_\Lambda = 0.71 \]

- Our best-fit model
  \[ \Omega_\Lambda = 0 \]

- $t = 1-10$ Gy
CMB Anisotropies

Our best-fit model
\( \Omega_\Lambda = 0 \)

Only OUR MODEL can explain this quenching!

Standard \( \Lambda \)CDM model \( \Omega_\Lambda = 0.71 \)

Cosmic Variance?

\( t = 3 \times 10^5 \) y
Cosmic Microwave Background

WMAP shows evidence for suppression of quadrupole and octopole moments.

- This could suggest a compact cosmology
- Use axis to guide search (l,b) ~ (-80°,60°)
Matter Power Spectrum $P(k)$

- **Standard $\Lambda$CDM model**
  - $\Omega_\Lambda = 0.71$

- **Our best-fit model**
  - $\Omega_\Lambda = 0$

$t = 1-10$ Gy
Conclusion

Big-Bang Nucleosynthesis is one of the Pillars of very precise Particle-Nuclear Theory and Modern Cosmology.

- **Standard Quark Model** --- KMC Matrix!
- **Dark Matter** --- SUSY Particles in Brane Cosmology
- **Dark Energy** --- Flowing in of CDM in Brane Cosmology

  Acceleration, due to CDM inflow without $\Omega_\Lambda$!
  Quenching of low multipoles in CMB, due to late ISW effect!

  $^7$Li problem still remains ??

Core-Collapse Supernovae are Viable Astrophysical Sites for R-Process.

- **New Role of R-Process Elements** $^{232}$Th & $^{235,238}$U
  --- Cosmochronology for Metal-Deficient Stars, hopeful but needs more precision?
  --- Sensitivity of Neutrino Cutoff to BH vs. NS Formation!