The 3-Helium Problem: Constraining the Chemical Evolution of the Milky Way

TOM BANIA
Institute for Astrophysical Research
Department of Astronomy
Boston University
Light Elements as Baryometers

![Graph showing the element abundances of Helium 4, Deuterium, Helium, and Lithium relative to hydrogen and density of ordinary matter (relative to photons).]
Primordial Nucleosynthesis: BBNS

Burles et al. (2001)
$^4$He: Optical recombination lines

Metal poor blue compact galaxies

Izotov et al. (1999)
$^4$He Abundances

<table>
<thead>
<tr>
<th>Yp [mass]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2421 (0.0021)</td>
<td>Izotov &amp; Thuan (2004)</td>
</tr>
<tr>
<td>0.249 (0.009)</td>
<td>Olive &amp; Skillman (2004)</td>
</tr>
<tr>
<td>0.2371 (0.0015)</td>
<td>Peimbert &amp; Peimbert (2002)</td>
</tr>
</tbody>
</table>
Li: Resonance Line

Metal poor Halo stars

Boesgaard et al. (2005)
$^7\text{Li: The Spite Plateau}$

![Graph showing Li abundance vs. Fe/H ratio](chart.png)

**Log($^7\text{Li}/H$) + 12**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan et al. (2000)</td>
<td>2.09 (+0.19,-0.13)</td>
</tr>
<tr>
<td>Melendez &amp; Ramirez (2004)</td>
<td>2.37 (0.1)</td>
</tr>
<tr>
<td>Boesgaard et al. (2005)</td>
<td>2.44 (0.18)</td>
</tr>
</tbody>
</table>
Deuterium: Lyman series

Q1243+3047

HS 0105+1619

Kirkman et al. (2003)

O’Meara et al. (2001)
Deuterium Abundances

Kirkman et al. (2003)
Steigman (2005)

\[ \frac{D}{H} = 2.78 \pm 0.44 \times 10^{-5} \]
The 327 MHz Deuterium Line

Rogers, Dudevoir, Carter, Fanous, Kratzenberg, and Bania
“Deuterium Abundance in the Interstellar Gas of the Galactic Anticenter from the 327 MHz Line” 92 cm wavelength
Array: 24 stations
Station: 24 crossed Yagis
Station Area: 12 m²
Station Beam: 14°
Beam Steering: +/- 40°
Frequency: 327.4 MHz
Bandwidth: 250 kHz
Channels: 1024
Resolution: 244 Hz
Polarization: Dual Linear
System Temperature: 40 K + sky
# Rx Ports: 48 x 24 = 1152
D I Beam

Continuum

H I

Model D I Spectra
Mar 2006

L = 183°

L = 171°

Blank Fields
ANTICENTER D/H ABUNDANCE

* Spin Temperature Range: 100-150 K
* Continuum Uniformly Distributed Along Line of Sight
* 1 Sigma measurement errors

=> $<D/H> = (2.0+/-0.5) \times 10^{-5} \leq$

for $R_{gal} = (10+/-1) \text{kpc}$
I ♥ ³He
Stalking the Cosmic $^3$He Abundance

Tom Bania (BU),
Bob Rood (UVa),
Dana Balser (NRAO),
Miller Goss (NRAO),
Cintia Quireza (ON, Brazil),
Tom Wilson (MPIfR)
$^3$He: Stellar Evolution

$^1$H + $^1$H $\rightarrow$ $^2$H + e$^+$ + $\nu$  Production  
$^2$H + $^1$H $\rightarrow$ $^3$He + $\gamma$  $T > 6 \times 10^5$ K

$^3$He + $^3$He $\rightarrow$ $^4$He + 2 p  Destruction  
$^3$He + $^4$He $\rightarrow$ $^7$Be + $\gamma$  $T > 7 \times 10^6$ K

Daniele Galli
\textbf{\(^3\text{He}: \text{Observations}}\)

\textbf{Solar System:}

Meteorites (protosolar)—\(^3\text{He}/\text{H} = 1.5 \pm 0.3 \times 10^{-5}\) (Bochslr & Geiss 1974)
Jupiter (Galileo Probe)—\(^3\text{He}/^4\text{He} = 1.66 \pm 0.05 \times 10^{-4}\) (Mahaffy et al. 1998)

\textbf{Local Interstellar Medium (LISM):}

Ulysses Probe—\(^3\text{He}/^4\text{He} = 2.2^{+0.7}_{-0.6}\) (stat) \pm 0.2(sys) \times 10^{-4}\) (Gloeckler & Geiss 1996)
Mir—\(^3\text{He}/^4\text{He} = 1.71^{+0.50}_{-0.42} \times 10^{-4}\) (Salerno et al. 2003)

\textbf{Galactic:}

\(^3\text{He} \text{ Recombination Lines?}\)
\(^3\text{He}^+ \text{ Hyperfine Line?}\)
$^{3}\text{He}^+$ Hyperfine Transition

$|N=3\rangle$    $^{2}S_{1/2}$  $F=0 \rightarrow 1$

$|N=2\rangle$    F=0 Singlet

$|N=1\rangle$    F=1 Triplet

$\nu_{01} = 8665.65$ MHz ($3.46$ cm)

$A_{01} = 1.950 \times 10^{-12}$ s$^{-1}$ ($16,300$ years)
NRAO 140 Foot: HII Regions

Galactic HII Regions
(1982 – 1999)
(~50)

Orion nebula (M42)
Eagle nebula (M16)
Rosette nebula
W49
S209
G0.60+0.32

HPBW = 3.5 arcmin
G93.06+2.8  45.8 hr integration
HII Region $^3\text{He}^+$ Spectra

Bania et al. (1997)
Radio Recombination Lines

W43 Recombination Lines

Bania et al. (1997)
200 Day Integration: 27 microKelvin RMS
$T_{\text{sys}} = 50 \text{ K}$
For a uniform, isothermal, ionized nebula composed solely of hydrogen and helium the $^{3}\text{He}^{+}/H^{+}$ column density ratio is

$$\frac{N(^{3}\text{He}^{+})}{N(H^{+})} = 3.873 \times 10^{-3} \frac{T_{L}^{A}(^{3}\text{He}^{+})\Delta v(^{3}\text{He}^{+})[\ln(5.717 \times 10^{-3} T_{e}^{3/2})]^{1/2} \theta_{\text{obs}}}{A(\eta_{b} T_{C}^{A} D)^{1/2} T_{e}^{1/4} (\theta_{\text{obs}}^{2} - \theta_{a}^{2})^{3/4}}$$

(1)

where

$$A^{2} = \left\{ \left(1 + \frac{n(\text{He}^{+})}{n(H^{+})} + 2 \frac{n(\text{He}^{++})}{n(H^{+})} \right) \right.$$ \[1 + \frac{n(\text{He}^{+})}{n(H^{+})} + 4 \frac{n(\text{He}^{++})}{n(H^{+})} \left[ 1 - \frac{\ln(2)}{\ln(5.717 \times 10^{-3} T_{e}^{3/2})} \right] \] \left\}^{-1}.$$

(2)
H II Region Continuum
“The $^3\text{He}$ Problem”

Galli et al. (1995)

$\frac{(^3\text{He}/\text{H}) \times 10^5}{\eta_{10} = 2 \rightarrow \eta_{10} = 4 \rightarrow}$

WMAP

Time (Gyr)

Meteorites $\neq$ Jupiter

Local ISM

HII regions

Meteorites: Geiss (1993)
Jupiter: Mahaffy et al. (1998)
HII regions: Bania, Rood & Balser (2000)
Local ISM: Gloecker & Geiss (1998)
“Simple” H II Regions
For D highest observed value is a lower limit for cosmological D

For $^3$He lowest observed $^3$He/H is an upper limit for cosmological $^3$He
$^{3}\text{He} \text{ Abundance in H II Regions} \quad \text{--}\quad \text{“The}^{3}\text{He Plateau”} \quad \text{Bania, Rood & Balser (2002)}$

$^{3}\text{He/H)}_p = 1.1 \times 10^{-5}$
BBNS CONSTRAINTS

Izotov & Thuan (2004)
Peimbert & Peimbert (2002)

Kirkman et al. (2003)

Bania, Rood, & Balser (2002)

Ryan et al. (2003)
Boesgaard et al. (2006)

Burles et al. (2001)
Spergel et al. (2006)
MPIfR 100 m: PNe


NGC 3242 (Eye)
NGC 6543 (Cat’s Eye)
NGC 6720 (Ring)
NGC 7009 (Saturn)
NGC 7662 (Blue Snowball)

HPBW = 80 arcsec
NGC 3242: Eye Nebula

Balick et al.
MPIfR 100 m PNe Survey


Composite: NGC 6543 + NGC 6720 + NGC 7009 + NGC 7662 + IC 289

NGC 3242

1987-1997

$^3\text{He}^+$
NGC 3242 Confirmation


NRAO 140 ft spectrum is a 270 hour integration
Abundance versus [O/H]

Bania, Rood & Balser (2002)
Abundance versus $R_{\text{gal}}$

Bania, Rood & Balser (2002)
$^3\text{He}$ evolution with extra-mixing

$^3\text{He}/\text{H} \times 10^5$

Tosi (1996)

protosolar
HII regions

Time (Gyr)
Extra-Mixing Hypothesis

- Charbonnel 1995 (see also Hogan 1995): an extra-mixing mechanism acting during the RGB and/or AGB phases of stars with mass $M \rightarrow 2 M_\odot$ can reduce the surface $^3$He abundance.

- Extra-mixing decreases the surface $^{12}\text{C}/^{13}\text{C}$: the $^3$He problem is linked to other isotopic anomalies in RGB and AGB stars.
Mixing on the RGB

- Surface $^3\text{He}$ destroyed
- $^{13}\text{C}$ dredged-up

- Convective envelope
- H-burning shell
- He core
Extra-mixing Process

96% of low-mass stars
Charbonnel &
do Nascimento (1998)

Charbonnel (1995)
No Mixing in NGC 3242

Balser et al. (1999)

Palla et al. (2002)
The rescue of the standard model

- Rood, Bania & Wilson (1992)
- Balser, Rood & Bania (1999)
- Palla et al. (2002)

$^3$He yes!

$^{13}$C no!

NGC 3242 (HST)

Palla et al. (2002)
3He abundance is a good test for cosmology, stellar evolution (standard and non-standard), and Galactic chemical evolution

Solving the 3-He Problem requires extra-mixing in ~ 90% of stars with $M \sim 2 \, M_\odot$
One is not enough!

Except in cosmology
The PN sample:

PNe progenitor stars with no extra mixing:

\[ \frac{^4\text{He}}{\text{H}} < 0.125 \]

\[ \frac{\text{N}}{\text{O}} < -0.3 \]

\[ \frac{^13\text{C}}{^12\text{C}} \text{ as low as possible} \]

Oldest possible stellar population has highest 3-He:

Peimbert Class IIb, III, and IV

Helium is singly ionized
Jonckheere 320 – PN G190.3-17.7

J320

Planetary Neb J 320
R : G : B = [N II] 400s : [O III] 60s : He II 300s
KPNO 2.1m, Ref: Balick 1987 AJ 94 671
VLA Planetary Nebula J320

$^3\text{He} / \text{H} \text{ abundance} = 1.9 \times 10^{-3} \text{ by number}$
J320 $^3\text{He}^+$

Flux Density [mJy/Beam]

$\Theta_b = 30''$

$V_{LSR}$ [km s$^{-1}$]
J320 Halo: 30 arcsec

Balser et al. (2006)
NGC 6543

HST

ACS
NGC 6543: The Rings Around the Cat's Eye

NGC 6543
WFPC2/F502N
1200s

15"
N

"Cat's Eye Nebula" = Core

Rings [O III]

Halo Ha+[N II]

NGC 6720: Rings around the Ring

Planetary Neb NGC 6720 = "Ring Nebula"
R : G : B = [N II] 100s : [O III] 100s : He II 100s
KPNO 2.1m, Ref: Balick 1987 AJ 94 671

The grey scales are used twice in this deep image: once for the core or "Ring", and again to show the very faint outer halos.
Rings in the Haloes of Planetary Nebulae

GREEN BANK TELESCOPE
Conventional Blocked Aperture Is a very Bad Design
Standing Waves and Multipath
GBT: Clear Aperture Optics
S 209  H II Region

140 ft  March 1995

GBT June 2004

33.1 hr

3.2 hr
GBT S 209 H II Region

Calibrated Raw Spectrum 14.5 hour integration
DC Level Subtracted 15.1 hr integration
S 209 H II Region

14.5 hour integration  5 km/sec resolution

H171 eta  $^3$He$^+$
GBT PNe Composite Spectrum
NGC 3242 + NGC 6543 + NGC 6826 + NGC 7009

H171 eta

$^{3}\text{He}^+$

125.7 hour integration
NGC 7009 + NGC 6543 + NGC 6826

Composite PNe Spectrum  180.3 hr integration

Antenna Temperature (mK)

CHALLENGES

Tom Bania 2005-05-21T14:27:17.00
NGC 7009  H 114beta  62.1 hrs

817 NGC7009
21 04 10.8  -11 21 57
LST=  +17 21 32.6
HA=  -5.71   ZA=  71.3
Vsrc=  -45.60  L+R
Fsky=  8667.2115
Frest=  8665.3000
Tcal=  3.3
Tsys=  33.5
Tintg=  3724.1

Antenna Temperature (mK)

CHANNELS

2004-06-24T04:30:14.00
NGC 7009  H130gamma  62.1 hrs

817 NGC7009
21 04 10.8  -11 21 57
LST= +17 21 32.6
HA= -5.71  ZA= 71.3

Vsrc= -45.60  L+R  HE3g  RAY_MA05
Fsky= 8667.2115  Frest= 8665.3000  Bw= 50.0000
Tcal= 3.3  Tsys= 33.5  Tintg= 3724.1

Antenna Temperature (mK)

0.575  679.678  100.215
5.820  997.812  109.850

Rood-Bania-Balsor  2004-06-24T04:30:14.00
Conclude reliability level for NGC7009 $\sim 0.5$ mK
This looks as real as He3 but is much too strong.
NAIC Arecibo Observatory 305 m
3-Helium Experiment Status

- VLA $^3$He detection for PN J 320. It has a substantial halo, just as NGC 3242 does.
- Composite GBT PNe spectrum consistent with MPIfR 100 m survey result.
- Probable GBT $^3$He detection for NGC 7009. A second detection in NGC 6543 is likely.
- First epoch Arecibo observations complete.
3-Helium Experiment Status

• 25% of all planetary nebulae meet our selection criteria. To be consistent with Galactic Chemical Evolution models, only 1/5 of these should show detectible $^3$He.

• The EVLA (10 times more sensitive than the VLA) has great potential.

• LMC/SMC campaign using Parkes planned. (Surprising perhaps, but feasible.)
It had been a very long experiment.

They considered this in silence.

Finally, Bania spoke, very slowly and carefully. For a change.

“\textquote{I look at it all like this,}” he said. “\textquote{Before I did this damn experiment, I was like everyone else. You know what I mean? I was confused and uncertain about all the little details of life.}” \textquote{But now,} he brightened up, “\textquote{while I’m still confused and uncertain it’s on a much higher plane, d’you see, and at least I know I’m bewildered about the really fundamental and important facts of the Universe.”}

Rood nodded. “\textquote{I hadn’t looked at it like that,}” he said, “\textquote{but you’re absolutely right. The 3-He experiment has really pushed back the boundaries of ignorance. There’s so much about the Universe we don’t know.”}

The both savoured the strange warm glow of being much more ignorant than ordinary people, who were ignorant of only ordinary things.
GBT Conclusions

• Standing waves are not a problem

• There is still baseline structure (BS) probably resulting from the broadband feed, the polarizer, and or mismatches in the IF system.
  
  ▪ BS varies with frequency sometimes almost invisible other times very problematic
  
  ▪ BS amplitude is proportional to source continuum and moves with sky frequency

• At the mK level there are pseudo-lines

• In some AC bands there are short duration spikes in the ACF at seemingly random times, lags, and amplitudes
Helium-3 Conclusions

- We have found helium-3 in another PN, J320, using the VLA.
- We probably have found helium-3 in NGC7009 using the GBT and may have a second detection in NGC6543.
- Roughly 25% of PNe meet our selection criteria. To avoid conflict with Monica we should detect 3He in only 1/5.
- The scheduling mode and proposal pressure on the GBT may not allow us to solidify these results in the near future.
- The EVLA (10 x more sensitive than the VLA) has great potential.
NGC 7009

Planetary Neb NGC 7009 = “Saturn Neb”
R : G : B = [N II] 300s : [O III] 20s : He II 500s
KPN 2.1m, Ref: Balick 1987 AJ 94 671

NGC 7354

Planetary Neb NGC 7354
R : G : B = [N II] 400s : [O III] 400s : He II 400s
KPN 2.1m, Ref: Balick 1987 AJ 94 671
3-Helium Experiment Status

- GBT now fully operational for 3-He
- Two GBT 3-He epochs complete
- Spectral baselines of excellent quality
- Composite PNe spectrum consistent with MPIfR survey results
- VLA 3-He 4-sigma detection' for PN J320 (see Balser et al. poster)
- First epoch NAIC Arecibo Observatory observations complete
1035 S209

04 11 6.7 +51 09 44
LST= +22 38 30.5
HA= -5.54 ZA= 56.6

Vsrc= -49.30 L+R
Fsky= 8686.6011
Frest= 8665.3000
Tcal= 3.3
Tsys= 31.0
Tintg= 908.9

Antenna Temperature (mK)

1000 2000 3000
CHANNLES

2003-12-07T22:52:42.00

Rood-Bania-Balse
Some days it’s chicken; some days it’s feathers
PNe: J320

Balser et al. (2006)
Bania, Rood, & Balser 2002
\[ \eta_{10} = 5.4^{+2.2}_{-1.2} \]
\[ \Omega_B = 0.04 \]

Spergel et al. 2003, WMAP
\[ \eta_{10} = 6.5^{+0.4}_{-0.3} \]
\[ \Omega_B = 0.047 \pm 0.006 \]

For D highest observed value is a lower limit for cosmological D

For $^3$He lowest observed $^3$He/H is an upper limit for cosmological $^3$He
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For D highest observed value is a lower limit for cosmological D

For \(^3\)He lowest observed \(^3\)He/H is an upper limit for cosmological \(^3\)He
Mixing and the $^3$He problem

- Daniele Galli (INAF-Arcetri)
- Francesco Palla (INAF-Arcetri)
- Monica Tosi (INAF-Bologna)
- Federico Ferrini (Univ. Pisa)
- Letizia Stanghellini (HST)
- Oscar Straniero (INAF-Teramo)
A long standing problem

*Rood, Steigman & Tinsley (1976)*

- Low-mass stars produce substantial amounts of $^3\text{He}$, enriching the ISM: $X_{^3\text{He}} \uparrow 10^{-3}$

- But the measured protosolar value is much lower: $X_{^3\text{He}} \uparrow 10^{-5} \Rightarrow \text{problem!}$
$^3$He profile in a 1.25 M$_\odot$ PopII star

Weiss, Wagenhuber & Denissenkov (1996)
The “standard” $^3$He yields

$^3$He yields  
(Weiss et al. 1996)

$^3$He/H

stellar mass ($M_\odot$)
Theorists at work…

- Wrong extrapolation of the $^3\text{He} - ^3\text{He}$ nuclear cross section at low energies?

- Pollution of winds from massive stars in $\text{HII}$ regions?

- Continuous infall of primordial gas?
Mixing takes over

- *Charbonnel 1995* (see also *Hogan 1995*): an extra-mixing mechanism acting during the RGB and/or AGB phases of stars with mass $M \rightarrow 2 M_\odot$ can reduce the surface $^3$He abundance.

- Extra-mixing decreases the surface $^{12}\text{C}/^{13}\text{C}$: the $^3$He problem is linked to other isotopic anomalies in RGB and AGB stars.
Mixing on the RGB

- convective envelope
- H-burning shell
- He core

surface $^3\text{He}$ destroyed

$^{13}\text{C}$ dredged-up
NGC7009
NGC6826
NGC6548
Sum

Rood-Bania-Baier
2004-06-22T02:14:34.00
He3 in S209 in only 7.5hr!
A bonus: He$^{++}$ or O$^{++}$ RRL (a first?)

822 NGC7009
Vsrc = -45.60 L+R
HE$^{++}$
RAY_MA05
Fsky = 8371.91
Frest = 8665.30
Tcal = 3.5
Tsys = 36.4
Tintg = 3597.1

Antenna Temperature (mK)

CHANELS
0 1600 1800 2000 2200 2400
2.5 2.0 1.5 1.0 0.5 0.0 -0.5

2004-06-24T04:30:14.00
Rood-Bania-Baer
Calibrating the mixing on the RGB

Charbonnel (1995)

0.8
$M_\odot$
$Z=10^{-4}$

extra-mixing
The “new” $^3$He yields

- Extra-mixing $^3$He yields:
  - Charbonnel (1995)
  - Sackmann & Boothroyd (1996)

![Graph showing $^3$He/H ratio as a function of stellar mass (M$_\odot$).]
NGC 3242

$^3\text{He}$ data from Balser et al. (1997, 1999)

stellar masses from Galli et al. (1997)

one more detection in a PN! (see poster by Balser et al.)
Palla, Galli, Marconi, Stanghellini & Tosi (2002)
Palla et al. (2000)
Standard yields
$^3\text{He}$ abundance in HII regions

$(^3\text{He}/\text{H})_p \rightarrow 1.1 \pm 10^{-5}$

Bania, Rood & Balser (2002)
Bania, Rood, & Balser 2002

$\eta_{10} = 5.4^{+2.2}_{-1.2}$
$\Omega_B = 0.04$

Spergel et al. 2003, WMAP

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NGC 6543
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1200s

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"Cat's Eye Nebula" = Core

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Halo Ha+[N II]
