

^3He in the Cosmos

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18 February 2021



Bania



Rood

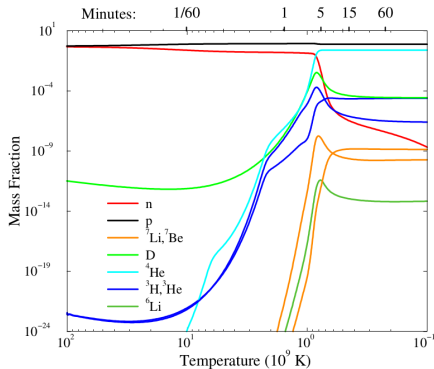


Wilson

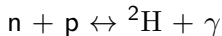


Goss

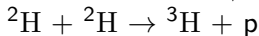
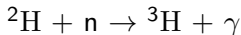
Primordial Nucleosynthesis—The Light Elements



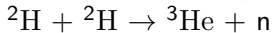
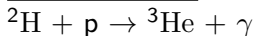
Deuterium Bottleneck



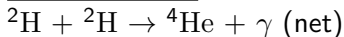
Tritium Production



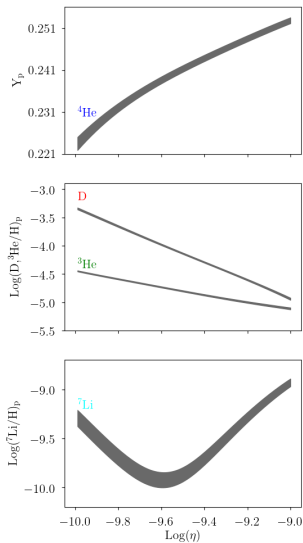
3 He Production



4 He Production

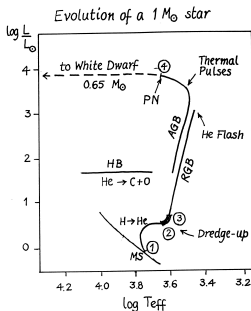
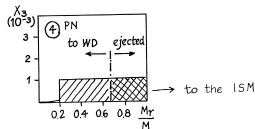
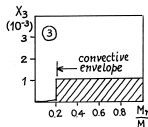
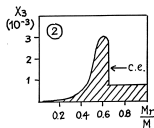
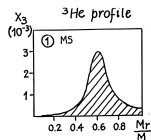


Primordial Nucleosynthesis—Abundances

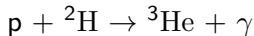


Burles et al. (2001)

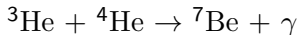
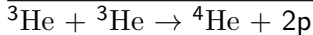
Stellar Nucleosynthesis— ^3He



Production $T > 6 \times 10^5$ K



Destruction $T > 7 \times 10^6$ K



“The present interstellar ^3He is more of stellar than primordial origin.”

Rood, Steigman, & Tinsley (1976)

Observations of ^3He

• Solar System:

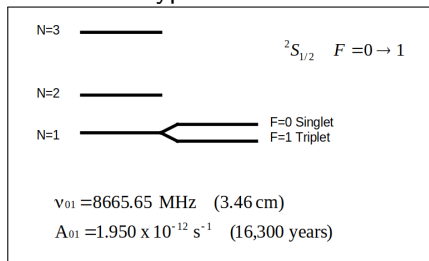
- Meteorites (protosolar): $^3\text{He}/\text{H} = 1.5 \pm 0.3 \times 10^{-5}$
- Jupiter (Galileo Probe): $^3\text{He}/^4\text{He} = 1.66 \pm 0.05 \times 10^{-4}$

• Local Interstellar Medium:

- Ulysses Probe: $^3\text{He}/^4\text{He} = 2.2_{-0.6}^{+0.7}(\text{stat}) \pm 0.2(\text{sys}) \times 10^{-4}$
- Mir: $^3\text{He}/^4\text{He} = 1.71_{-0.42}^{+0.5} \times 10^{-4}$

• Galactic:

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

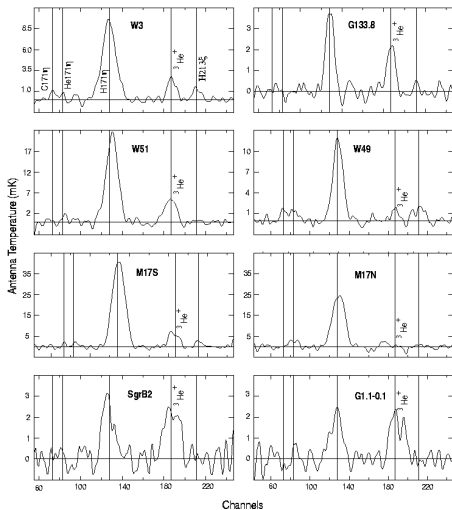


Bochsler & Geiss (1974), Mahaffy et al. (1998), Gloeckler & Geiss (1996), Salerno et al. (2003), Townes (1957), Sunyaev (1966), Goldwire & Goss (1967)

$^3\text{He}^+$ Observations—H II Regions



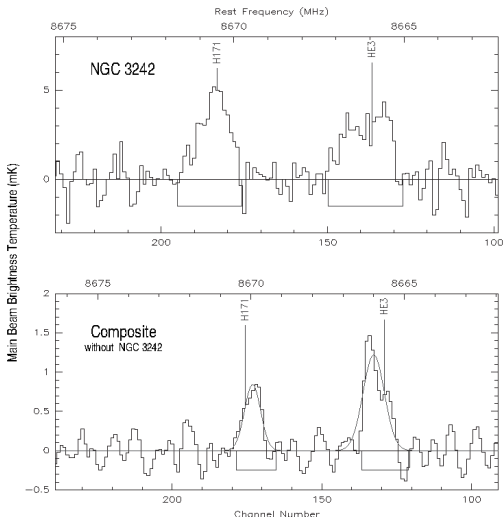
NRAO 140 Foot Telescope
(1982–1999): ~ 50 H II regions



$^3\text{He}^+$ Observations—Planetary Nebulae (PNe)

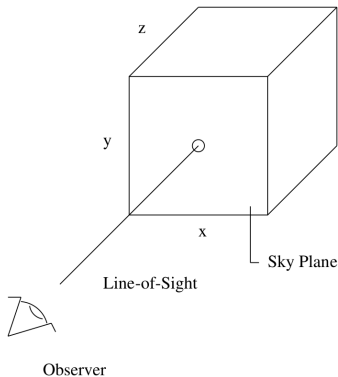


MPIfR 100 m Telescope
(1991–1995): 5 PNe



Balser et al. (1997)

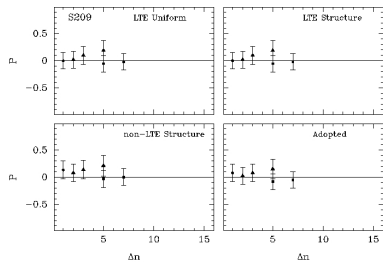
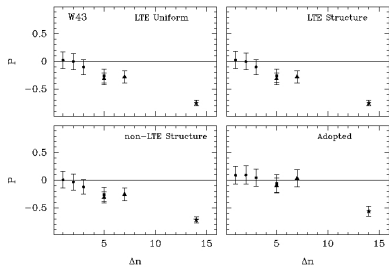
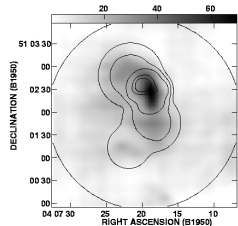
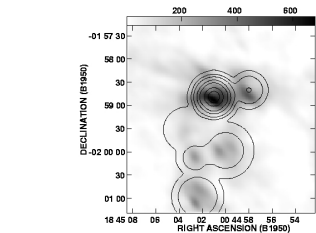
Calculating $^3\text{He}/\text{H}$ Abundance Ratio—NEBULA Program



- Density Structure
 - $^3\text{He}^+$ hyperfine: $\int n_e d\ell$
 - RRL/free-free: $\int n_e^2 d\ell$
- Ionization Structure
 - Hydrogen: 13.6 eV
 - Helium: 24.6 eV
- NEBULA Program
 - n_e, T_e
 - $^4\text{He}^+/\text{H}^+; ^4\text{He}^{++}/\text{H}^+;$
 $^3\text{He}^+/\text{H}^+$

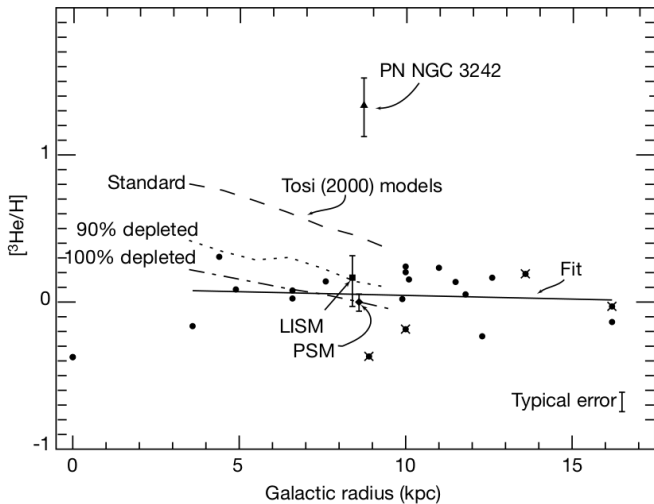
Balser (1995), Balser et al. (1999), Bania et al. (2007)

Calculating $^3\text{He}/\text{H}$ Abundance Ratio—Simple Sources



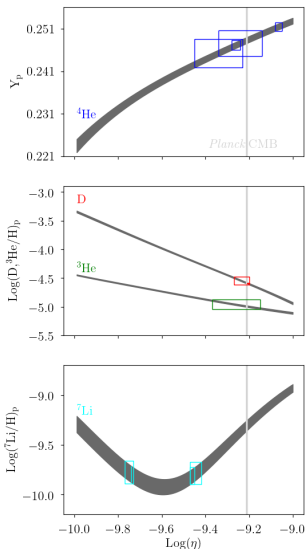
Balser et al. (1999)

$^3\text{He}/\text{H}$ Abundances—“The ^3He Plateau”



Bania, Rood, & Balser (2002)

Primordial ^3He Abundance



Planck:

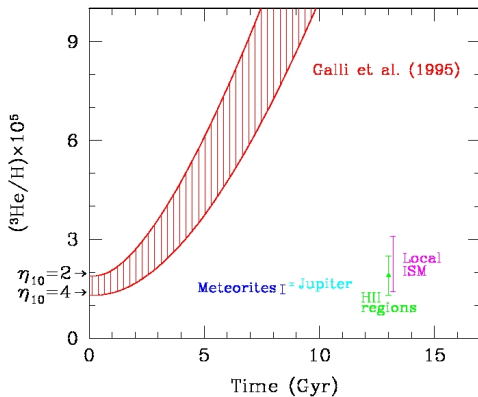
$$\eta = 6.129 \pm 0.039 \times 10^{-10}$$

Planck + SBBN:

$$(^3\text{He}/\text{H})_p = 1.003 \pm 0.090 \times 10^{-5}$$

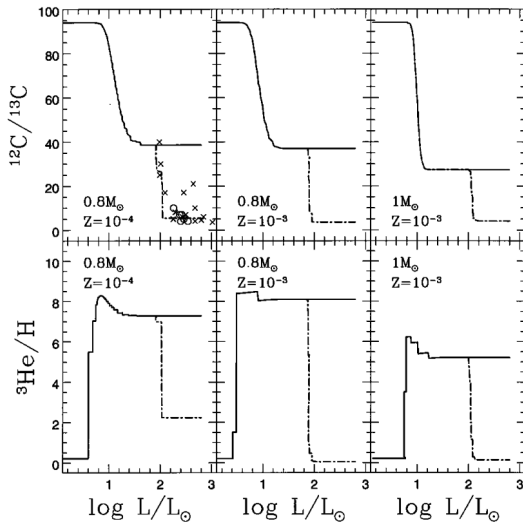
Burles et al. (2001), Fields et al. (2020); Izotov et al. (2007), Peimbert et al. (2007), Aver et al. (2020); Kirkman et al. (2003), Cooke et al. (2018); Bania et al. (2002); Boesgaard et al. (2005), Sbordone et al. (2010).

$^3\text{He}/\text{H}$ Abundances—“The ^3He Problem”



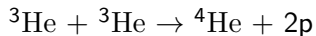
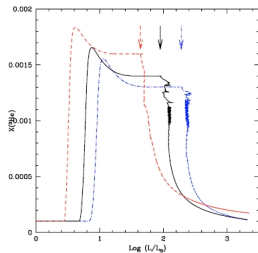
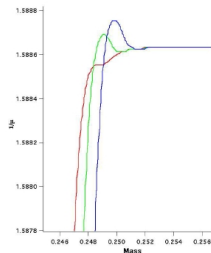
Meteorites: Geiss (1993)
Jupiter: Mahaffy et al. (1998)
HII regions: Bania, Rood & Balser (2002)
Local ISM: Gloecker & Geiss (1998)

Stellar Mixing—Rotation



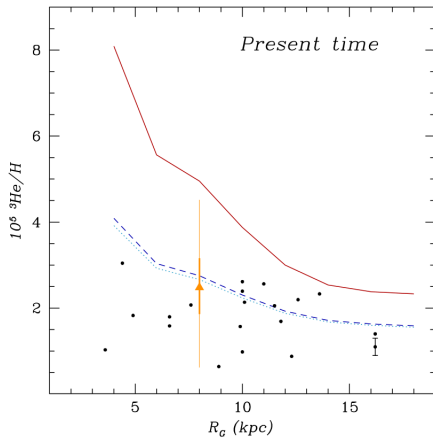
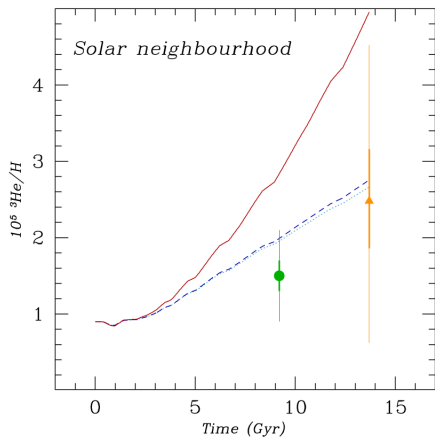
Sweigart & Mengel (1979), Bania et al. (1987), Zahn (1992), Charbonnel (1995)

Stellar Mixing—Thermohaline Instability



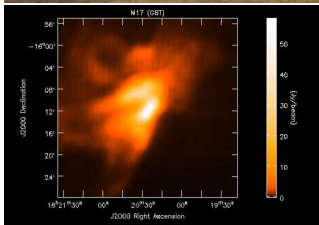
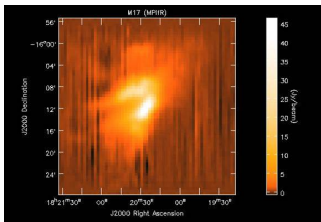
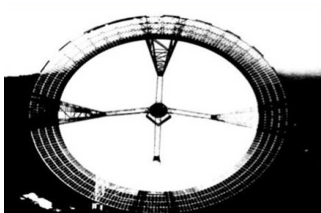
Eggleton et al. (2006), Charbonnel & Zahn (2007), Matteo Cantiello

Stellar Mixing—Galactic Evolution



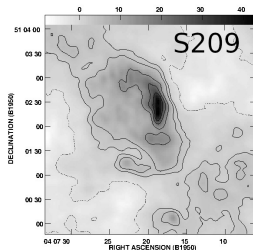
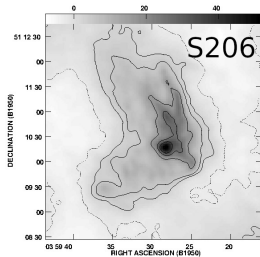
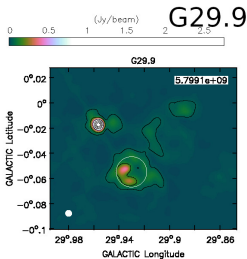
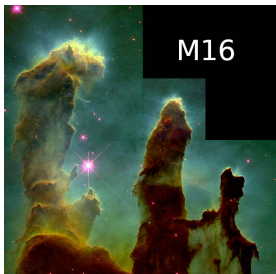
Lagarde et al. (2012); Geiss & Gloeckler (1998); Mahaffy et al. (1998); Gloeckler & Geiss (1996); Bania, Rood, & Balser (2002)

MPIfR 100m vs. Green Bank Telescope (GBT)



Balser et al. (1995), Ghigo et al. (Priv. Comm.)

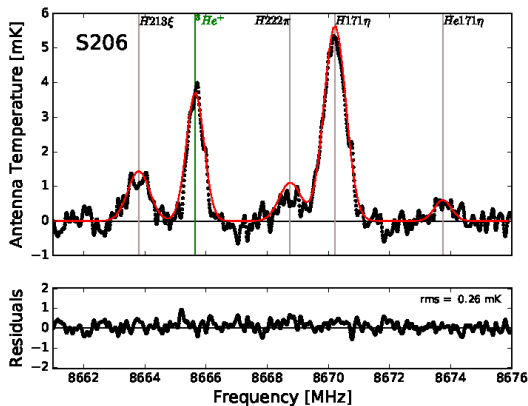
GBT H II Region Observations—Five Simple Sources



Hester & Scowen, ESA/NASA/JPL-Caltech/Whitman College, Balser & Bania (2018), Balser (1995)

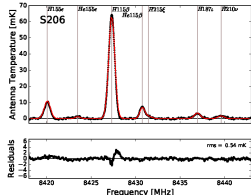
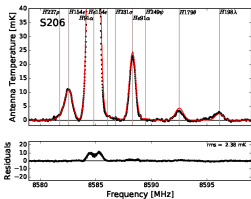
GBT H II Region Observations—Spectra

$^3\text{He}^+$ detections in **all** sources



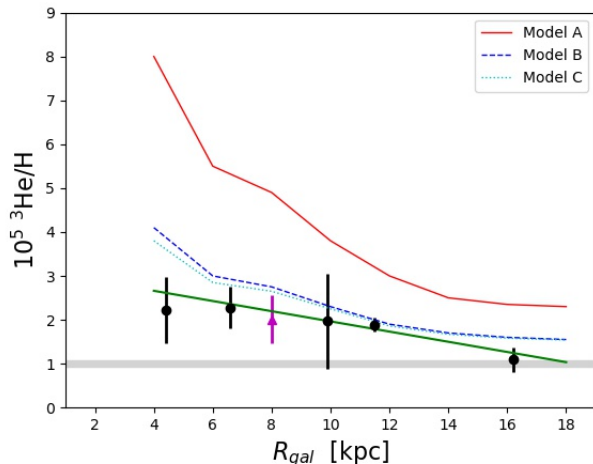
($T_{\text{intg}} = 92 \text{ hr}$)

Over 35 RRLs



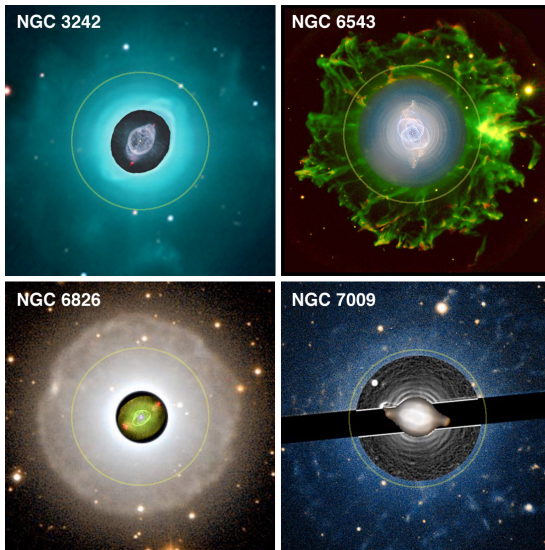
Balser (2006), Balser & Bania (2018)

GBT H II Region Observations—Results



Balser & Bania (2018), Lagarde et al. (2012), Gloeckler & Geiss (1996), Cyburt et al. (2008)

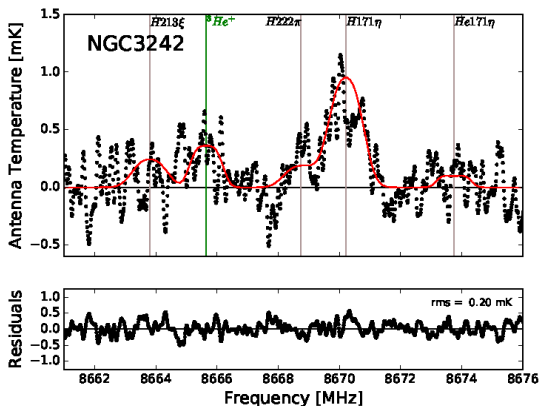
GBT PNe Observations—Four Sources



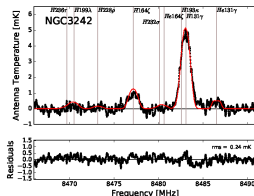
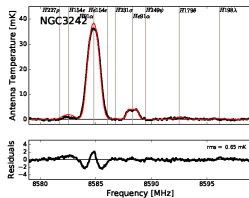
Bania & Balser (2021), Bruce Ballick

GBT PNe Observations—Spectra

No $^3\text{He}^+$ detections

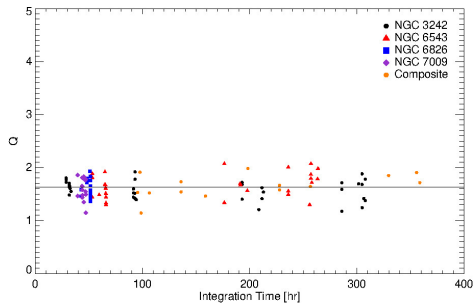


($T_{\text{intg}} = 302 \text{ hr}$)

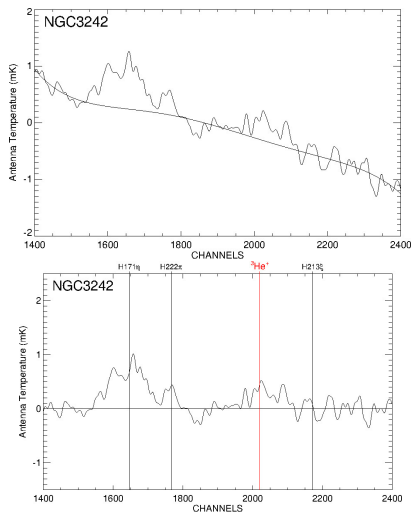


GBT PNe Observations—Spectral Baselines

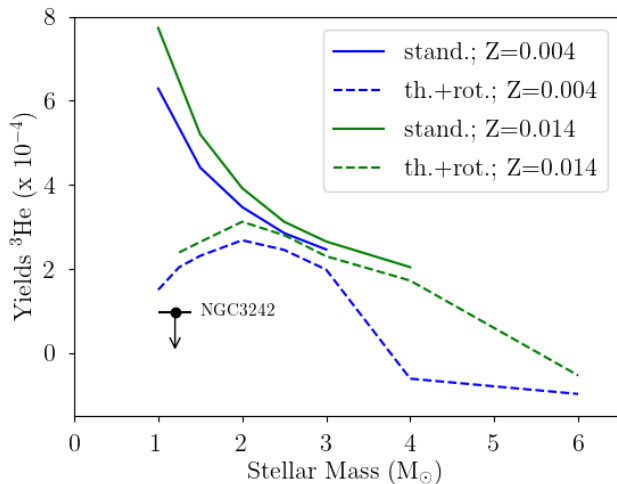
$$Q = (\sqrt{t_{\text{intg}}} \times \text{RMS}) / T_{\text{sys}}$$



Spectra robust for $T_A \gtrsim 1$ mK

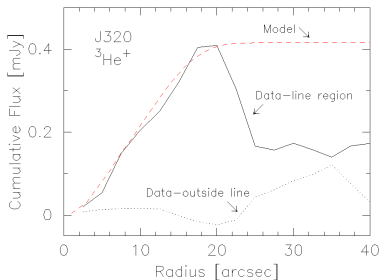
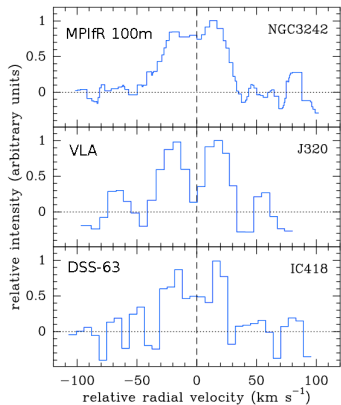


GBT PNe Observations—Results



Bania & Balser (2021), Lagarde et al. (2011)

Previous $^3\text{He}^+$ “Detections” in PNe



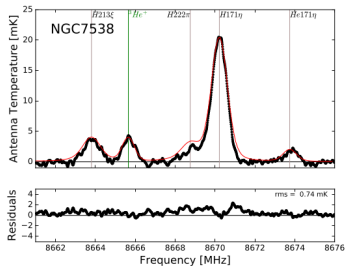
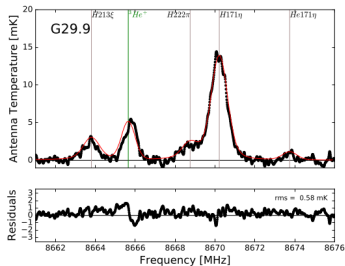
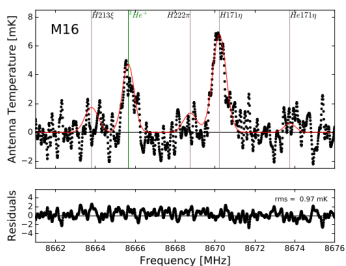
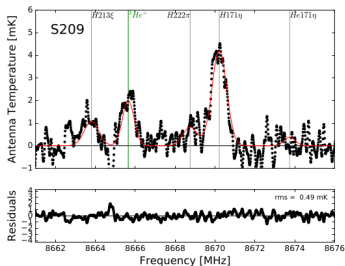
Balser et al. (1997, 2006), Guzman-Ramirez et al. (2016)

Summary and Future Work

- Detect $^3\text{He}^+$ in all five H II regions with the GBT.
- $^3\text{He}/\text{H}$ abundances ratios consistent with thermohaline mixing.
- $^3\text{He}^+$ **not** detected in any PNe with the GBT!
- Evidence of ^3He mixing in NGC 3242.
- $^3\text{He}^+$ PNe observations of J320 with the JVLA (VLA/21A-005).

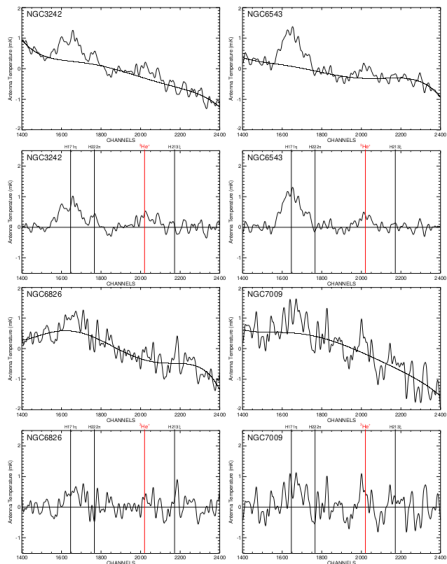
Additional Slides

GBT H II Region $^3\text{He}^+$ Spectra



Balser & Bania (2018)

GBT PNe $^3\text{He}^+$ Spectra



Bania & Balser (2021)