Do All Low-Mass Stars Undergo Extra Mixing Processes?

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Received 2022 April 27; revised 2022 August 4; accepted 2022 August 5; published 2022 September 12

Abstract

Standard stellar evolution models that only consider convection as a physical process to mix material inside of stars predict the production of significant amounts of $^3$He in low-mass stars ($M < 2 M_\odot$), with peak abundances of $^3$He/H $\sim$ few $\times$ 10$^{-3}$ by number. Over the lifetime of the Galaxy, this ought to produce $^3$He/H abundances that diminish with increasing Galactocentric radius. Observations of $^3$He$^+$ in H II regions throughout the Galactic disk, however, reveal very little variation in the $^3$He abundance with values of $^3$He/H similar to the primordial abundance, ($^3$He/H)$_0 \sim$ 10$^{-5}$. This discrepancy, known as the "$^3$He problem," can be resolved by invoking in stellar evolution models an extra mixing mechanism due to the thermohaline instability. Here we observe $^4$He$^+$ in the planetary nebula (PN) J320 (G190.3–17.7) with the Jansky Very Large Array to confirm a previous $^3$He detection made with the Very Large Array that supports standard stellar yields. This measurement alone indicates that not all stars undergo extra mixing. Our more sensitive observations do not detect $^3$He$^+$ emission from J320 with an rms noise of 58.8 $\mu$Jy beam$^{-1}$ after smoothing the data to a velocity resolution of 11.4 km s$^{-1}$. We estimate an abundance limit of $^3$He/H $\lesssim$ 2.75 $\times$ 10$^{-3}$ by number using the numerical radiative transfer code NEBULA. This result nullifies the last significant detection of $^3$He$^+$ in a PN and allows for the possibility that all stars undergo extra mixing processes.

Unified Astronomy Thesaurus concepts: Stellar evolution (911); Planetary nebulae (1249); Radio spectroscopy (1359)

1. Background

The $^3$He isotope is one of the few elements that not only is produced several minutes after the big bang during the era of primordial nucleosynthesis but also is subsequently made inside stars via stellar nucleosynthesis (e.g., Boesgaard & Steigman 1985). Measurements of $^3$He therefore provide a unique probe of cosmic evolution. Rood et al. (1976) first identified the significance of measuring the $^3$He abundance in the interstellar medium (ISM). They predicted an enrichment of the primordial $^3$He abundance due to stellar nucleosynthesis based on $^3$He yields from low-mass stars ($M < 2 M_\odot$). Rood et al. (1976) argued that (1) the present-day ISM $^3$He/H abundance ratio should be significantly larger than the protosolar value, (2) $^3$He/H should grow with source metallicity, and (3) there should be a radial gradient in $^3$He/H abundance across the Milky Way disk with higher abundances in the more processed central regions.

Detection of $^3$He has proven challenging, however, since there is expected to be about one $^4$He atom for every 10,000 $^3$He atoms. Isotopic shifts for light elements are small compared with typical line widths, so using He recombination lines (e.g., He I 6678) to detect $^3$He is difficult. Nevertheless, anomalously high $^3$He/H abundance ratios have been detected with He recombination lines in some stars (e.g., Sargent & Jugaku 1961). These very high $^3$He abundances are thought to be due to diffusion and are therefore not representative of typical abundances. There have also been anomalously high $^3$He/H abundances detected from in situ measurements of solar energetic particle events (e.g., Wiedenbeck et al. 2020). Potential molecular transitions including $^3$He are rare since helium is inert and seldom found in molecular form. Detection of HeH$^+$ in the planetary nebula (PN) NGC 7027 is a recent exception (Güsten et al. 2019).

Townes (1957) was the first to suggest the $^3$He$^+$ hyperfine transition at 8665.650 MHz (Novick & Cummins 1958) as a possible astrophysical tracer at radio frequencies. Goldwire & Goss (1967) calculated the Einstein coefficient of the $^3$He$^+$ hyperfine transition, corresponding to a relatively short radiative lifetime of 16,000 yr, indicating the plausibility of measuring $^3$He in H II regions (see also Syunyaev 1966). Initial attempts at detecting $^3$He$^+$ in H II regions were unsuccessful and limited by high receiver system temperatures (Seling & Heiles 1969; Predmore et al. 1971).

Rood et al. (1979) made the first detection of $^3$He in the ISM toward the giant H II region W51 with the Max-Planck Institut für Radioastronomie (MPIfR) 100 m telescope. They derived a $^3$He/H abundance ratio similar to the protosolar value and thus found no evidence for the production of $^4$He in low-mass stars. Observations of $^3$He$^+$ in H II regions over the past four decades have yielded similar results—stars are not significant producers of $^3$He (Rood et al. 1984; Bania et al. 1987; Balser et al. 1994; Bania et al. 1997; Balser & Bania 2018).

Accurate determination of the $^3$He/H abundance ratio, the astrophysical quantity of interest, requires models of the density and ionization structure of the H II region. This is because the tracer of $^3$He, the hyperfine transition, is sensitive to $\int n_e \, dl$, whereas the tracer of H, the free–free continuum, is sensitive to $\int n_e^2 \, dl$ (Balser et al. 1999a). Here $n_e$ is the electron density and $dl$ is the path length across the H II region.
Ionization structure is important because H and He have different ionization potentials (Bania et al. 2007). Using this information, Bania et al. (2002) selected sources with simple morphologies that would produce the most accurate \(^3\text{He}/\text{H}\) abundance ratios and found that \(^3\text{He}/\text{H}\) was approximately constant across the Galactic disk—the \(^3\text{He}\) plateau.” They suggested that the \(^3\text{He}\) plateau abundance of \(^3\text{He}/\text{H} = (1.1 \pm 0.2) \times 10^{-5}\) by number is the primordial abundance. This was later confirmed by combining results from the Wilkinson Microwave Anisotropy Probe (WMAP) with big bang nucleosynthesis (BBN) models yielding a primordial abundance of \((^3\text{He}/^4\text{He})_p = (1.00 \pm 0.07) \times 10^{-5}\) (Romano et al. 2003; Cyburt et al. 2008).

Since low-mass stars were expected to be sources of \(^3\text{He}\) enrichment to the ISM via mass loss during the asymptotic giant branch (AGB) phase, similar efforts were made to detect \(^3\text{He}\) in PNe. Rood et al. (1992) made the first detection of \(^3\text{He}\) in the PN NGC 3242 with the MPH IR 100 m (see also Balser et al. 1997, 1999b). They derived an abundance of \(^3\text{He}/^4\text{He} \gtrsim 10^{-3}\), two orders of magnitude larger than abundances found in H II regions, consistent with standard stellar models. Observations of \(^3\text{He}\) were made for a handful of PNe over the next two decades (Balser et al. 1997, 1999b; Guzman-Ramirez et al. 2013, 2016; Bania & Balser 2021). \(^3\text{He}\) detections were also claimed in PN J320 (Balser et al. 2006) and IC 418 (Guzman-Ramirez et al. 2016) with derived abundance ratios of \(^3\text{He}/^4\text{He} \sim \text{few} \times 10^{-3}\). So there seemed to be solid evidence that some low-mass stars were producing copious amounts of \(^3\text{He}\) to be returned to the ISM during the PN phase.

Galactic chemical evolution (GCE) models using \(^3\text{He}\) yields from standard stellar evolution predict significantly larger \(^3\text{He}\) abundances over the lifetime of the Milky Way than are observed in H II regions (Galli et al. 1995; Olive et al. 1995; Galli et al. 1997). Most GCE models also predict negative radial \(^3\text{He}/^4\text{He}\) abundance ratio gradients within the Galactic disk because the central regions have undergone more stellar processing than the outer regions over the lifetime of the Milky Way. This is inconsistent with the \(^3\text{He}\) plateau revealed by observations. Moreover, in situ measurements of helium within the Jovian atmosphere with the Galileo probe yield \(^3\text{He}/^4\text{He} = (1.66 \pm 0.05) \times 10^{-4}\) (Mahaffy et al. 1998). This corresponds to a protosolar abundance of \(^3\text{He}/^4\text{He} = (1.5 \pm 0.2) \times 10^{-5}\), indicating very little production of \(^3\text{He}\) over the past 4.5 Gyr. Galli et al. (1997) called these discrepancies “the \(^3\text{He}\) problem.”

Rood et al. (1984) suggested that some sort of mixing could be taking place in low-mass stars that might explain the lower observed \(^3\text{He}\) abundances than expected in the ISM. They posited that such a mixing mechanism may be related to the destruction of \(^7\text{Li}\) in main-sequence stars and low \(^12\text{C}/^13\text{C}\) abundance ratios observed in low-mass red giant branch (RGB) stars (see also Charbonnel 1995; Hogan 1995; Weiss et al. 1996). Numerous studies indicate that some sort of extra mixing is occurring when low-mass stars reach the luminosity bump on the RGB (e.g., Gilroy 1989; Luck 1994; Charbonnel et al. 1998; Gratton et al. 2000; Pićlowski et al. 2003; Smiljanic et al. 2009). The luminosity bump occurs when the hydrogen-burning shell reaches the chemical discontinuity created by the maximum extent of the convective envelope during the first dredge-up. For many years rotation-induced mixing was thought to be the main mechanism responsible for the abundance anomalies (e.g., Sweigart & Mengel 1979; Charbonnel 1995; Charbonnel et al. 1998; Boothroyd & Sackmann 1999), but more accurate stellar evolution simulations that treat the transport of angular momentum by meridional circulation and shear turbulence self-consistently do not produce enough mixing around the luminosity bump to account for the observed surface abundance variations (Palacios et al. 2006).

A breakthrough occurred when Eggleton et al. (2006) constructed three-dimensional stellar evolution models and discovered the destabilizing role played by the molecular weight inversion that is produced at the external edge of the hydrogen-burning shell by the \(^3\text{He}(^3\text{He}, 2^3\text{He})^4\text{He}\) reaction. Charbonnel & Zahn (2007a) pointed out that the first instability to occur under these conditions is a double-diffusive instability called the thermohaline instability (Stern 1960). As the molecular weight gradient increases, the temperature has a stabilizing effect since the timescale for thermal diffusion is shorter than the time it takes for the material to mix.

Stellar evolution models that incorporate thermohaline mixing are able to account for the anomalous \(^12\text{C}/^13\text{C}\) and \(^7\text{Li}\) abundances that are observed in low-mass stars and predict \(^3\text{He}\) yields that are significantly reduced compared to standard models (Charbonnel & Zahn 2007a; Denissenkov & Pinsonneault 2008; Eggleton et al. 2008; Cantiello & Langer 2010; Charbonnel & Lagarde 2010; Lagarde et al. 2011). Lagarde et al. (2012) used these stellar yields together with GCE models to predict a modest enrichment of \(^3\text{He}\) with time that is consistent with H II region observations in the Milky Way disk (see also Balser & Bania 2018).

There are some outstanding issues that remain concerning the treatment of the thermohaline instability just after the luminosity bump on the RGB (see, e.g., Karakas & Lattanzio 2014). The diffusion coefficient is proportional to \(C\), a dimensionless free parameter that is related to the aspect ratio of the “salt” fingers. Charbonnel & Zahn (2007a) use values of \(C \sim 1000\) because experiments favor thin fingers instead of blobs (Ulrich 1972). Numerical simulations of thermohaline convection, however, predict a lower value for \(C\) than is necessary to solve the \(^3\text{He}\) problem (e.g., Denissenkov & Merryfield 2011). Rotation may also influence the effectiveness of thermohaline mixing (e.g., Maeder et al. 2013; Sengupta & Garaud 2018).

The fact that a few PNe have estimated \(^3\text{He}/^4\text{He}\) abundances consistent with standard \(^3\text{He}\) yields implies that the thermohaline instability is not effective in all low-mass stars. Charbonnel & Do Nascimento (1998) estimate that \(4\%\) of red giant stars have \(^12\text{C}/^13\text{C}\) abundance ratios that are consistent with expectations from standard stellar models. GCE models that allow \(4\%\) of low-mass stars to produce standard \(^3\text{He}\) yields (Lagarde et al. 2012) are still consistent with H II region observations (Baler & Balser 2018). Eggleton et al. (2008) suggested that deep mixing of \(^3\text{He}\) and CNO isotopes is not optional and that this mechanism would destroy most of the \(^3\text{He}\) produced on the main sequence. Charbonnel & Zahn (2007b) proposed that fossil magnetic fields in red giant stars that are descendants of Ap stars could inhibit thermohaline mixing. In sum, stellar modeling has yet to reach a theoretical consensus concerning the fate of \(^3\text{He}\) produced by stellar nucleosynthesis.

There is some question, however, whether \(^3\text{He}\) has been detected in any PNe. Using the Green Bank Telescope (GBT), Bania & Balser (2021) have recently shown that the reported
$^3\text{He}^+$ detection in NGC 3242 with the MPA1R 100 m, and confirmed with independent observations made with the NRAO 140 Foot telescope (Balser et al. 1999b), is not real. This incorrect result probably stems from systematic errors due to standing waves caused by reflections from the telescope superstructure. Observations of $^3\text{He}^+$ from PNe are very challenging since the low ionized mass produces very weak $^3\text{He}^+$ intensities that are at the limits of most radio facilities. The clear aperture of theGBT reduced these systematic errors in the spectral baselines by an order of magnitude. Because of these systematic effects in traditionally designed radio telescopes, Bania & Balser (2021) were skeptical of the claimed detection of $^3\text{He}^+$ in IC 418 with the NASA Deep Space Station 63 (DSS-63) telescope (Guzman-Ramirez et al. 2016). The lack of any serious tests of the spectral baselines, together with discrepancies in the radio recombination line (RRL) parameters, makes this claimed detection dubious. The only remaining detection of $^3\text{He}^+$ in a PN that seems plausible is for J320 observed with the Very Large Array (VLA; Balser et al. 2006). Interferometers have an advantage over single-dish telescopes in that many instrumental spectral baseline effects are removed because the signals between two antennas are correlated. Here we discuss new Jansky Very Large Array (JVLA) observations for the PN J320 made to confirm our previous $^3\text{He}^+$ VLA detection.

2. Observations and Data Reduction

Interferometers typically have stable spectral baselines, but they are not perfect. The Balser et al. (2006) J320 VLA observations suffered from three problems: (1) a 3.3 MHz ripple common to all antennas caused by reflections within the waveguide; (2) a limited number of spectral channels and bandwidth, which together provided very few channels for characterizing the spectral baselines; and (3) only one RRL transition available to assess the accuracy of these measurements. The latter two problems were due to limitations with the VLA correlator. Bania & Balser (2021) have shown that tuning to many RRLs simultaneously can be used to assess the accuracy of the spectral baselines and constrain models of the nebula to derive accurate $^4\text{He}/^3\text{He}$ abundance ratios.

The JVLA overcomes all three of these problems with the VLA observations. Optical fiber has replaced the old waveguides, and the 3.3 MHz ripple is gone. The JVLA Wideband Interferometric Digital ARchitect (WIDAR) correlator provides us with an ample number of channels across a large bandwidth to accurately measure the spectral baseline. The flexibility of WIDAR allows us to tune to many RRLs simultaneously to carefully assess the quality of all the spectral baselines. For example, adjacent RRLs should have similar line profiles, and we know the intensity ratios of various RRLs in local thermodynamic equilibrium (LTE). Moreover, these RRLs, together with the free–free continuum, can be used to constrain the nebular model required to derive accurate $^4\text{He}/^3\text{He}$ abundance ratios.

We therefore used the JVLA at X band (8–10 GHz) in the D configuration to observe $^3\text{He}^+$ in the PN J320 to confirm the VLA $^3\text{He}^+$ detection. Hereafter, we distinguish between the two J320 $^3\text{He}^+$ data sets using the project codes: VLA (AB0794) and JVLA (21A-005). Table 1 summarizes the observations. We observed for a total time of 29 hr to achieve a similar signal-to-noise ratio ($\sigma/N$) to our previous VLA observations. The half-power beamwidth (HPBW) of the primary beam (field of view) is about 5′ at the $^3\text{He}^+$ frequency of 8665.650 MHz, and in the D configuration the synthesized HPBW is about 10′.

We configured the WIDAR correlator so that each of the two 1 GHz basebands was tuned to eight 128 MHz wide spectral windows at full polarization to observe the free–free continuum emission and twelve 16 MHz wide spectral windows at dual polarization to observe various spectral lines. The 128 MHz “continuum” windows each had 64 channels corresponding to a spectral resolution of 2.00 MHz and covering a total of 2 GHz. The 16 MHz “spectral line” windows each had 512 channels corresponding to a spectral resolution of 31.25 kHz (∼1 km s$^{-1}$ at 9 GHz). We sampled the $^3\text{He}^+$ hyperfine transition in two spectral windows for redundancy together with these RRL transitions: seven $^4\text{He}$ transitions: seven $^4\text{He}$, seven $^4\text{He}^+$, and eight $^4\text{He}^+$ (see Table 2 for details). Here $n$ is the principal quantum number and $\alpha$, $\beta$, $\gamma$ correspond to $\Delta n = 1, 2, 3$. The 16 MHz bandwidth provides a velocity span of ∼500 km s$^{-1}$, sufficient to include the corresponding $^4\text{He}^+$, $^4\text{He}^+$, and $^4\text{He}^+$ transitions. The H113/β RRL is blended with the H129/γ RRL, and therefore these transitions were not observed.

We observed J320 between 2021 April 23 and 2021 May 25 during seven distinct epochs, each with a duration of 4–5 hr. We started each epoch by observing the flux density calibrator J0542+4951 (3C 147), which was also used to set the delays and calibrate the bandpass. We then observed our PN J320 interleaved with observations of the gain calibrator J0530+1331 every ∼20 minutes.

We use the Wengen Interferometry Software Package (WISP) to calibrate and image our JVLA data (Wenger 2018). WISP is a Python wrapper for the Common Astronomy Software Package (CASA; McMullin et al. 2007). Here we follow the calibration and imaging procedures discussed in Appendix A of Wenger et al. (2019b). The calibration procedures consist of flagging bad data, calculating the calibration solutions, and applying the calibration solutions. This is an iterative process that includes both automatic and manual flagging.
Table 2

| Spectral Window | Center Freq. \( \text{MHz} \) | Transition | Bandwidth (MHz) | Channels |
|-----------------|----------------------|------------|----------------|----------|
| Continuum       |                      |            |                |          |
| 1               | 8057.50009           | ...        | 128            | 64       |
| 2               | 8185.50009           | ...        | 128            | 64       |
| 3               | 8313.50009           | ...        | 128            | 64       |
| 4               | 8441.50009           | ...        | 128            | 64       |
| 5               | 8569.50009           | ...        | 128            | 64       |
| 6               | 8697.50009           | ...        | 128            | 64       |
| 7               | 8825.50009           | ...        | 128            | 64       |
| 8               | 8953.50009           | ...        | 128            | 64       |
| 9               | 9092.52938           | ...        | 128            | 64       |
| 10              | 9220.52938           | ...        | 128            | 64       |
| 11              | 9348.52938           | ...        | 128            | 64       |
| 12              | 9476.52938           | ...        | 128            | 64       |
| 13              | 9604.52938           | ...        | 128            | 64       |
| 14              | 9732.52938           | ...        | 128            | 64       |
| 15              | 9860.52938           | ...        | 128            | 64       |
| 16              | 9988.52938           | ...        | 128            | 64       |
| Spectral Line   |                      | \(^3\)He\(^+\) | 16             | 512      |
| 17              | 8665.65              | \(^3\)He\(^+\) | 16             | 512      |
| 18              | 8665.65              | \(^3\)He\(^+\) | 16             | 512      |
| 19              | 8045.605             | H\(9\alpha\) | 16             | 512      |
| 20              | 8309.385             | H\(9\alpha\) | 16             | 512      |
| 21              | 8584.823             | H\(9\alpha\) | 16             | 512      |
| 22              | 8872.571             | H\(9\alpha\) | 16             | 512      |
| 23              | 9173.324             | H\(9\alpha\) | 16             | 512      |
| 24              | 9487.827             | H\(8\alpha\) | 16             | 512      |
| 25              | 9816.868             | H\(8\alpha\) | 16             | 512      |
| 26              | 9813.052             | H\(11\beta\) | 16             | 512      |
| 27              | 8427.316             | H\(11\beta\) | 16             | 512      |
| 28              | 8649.099             | H\(11\beta\) | 16             | 512      |
| 29              | 9116.569             | H\(11\beta\) | 16             | 512      |
| 30              | 9362.976             | H\(11\beta\) | 16             | 512      |
| 31              | 9618.343             | H\(11\beta\) | 16             | 512      |
| 32              | 9883.083             | H\(10\beta\) | 16             | 512      |
| 33              | 8283.843             | H\(12\gamma\) | 16           | 512      |
| 34              | 8483.082             | H\(13\gamma\) | 16           | 512      |
| 35              | 8678.122             | H\(13\gamma\) | 16           | 512      |
| 36              | 9086.512             | H\(12\gamma\) | 16           | 512      |
| 37              | 9300.343             | H\(12\gamma\) | 16           | 512      |
| 38              | 9520.936             | H\(12\gamma\) | 16           | 512      |
| 39              | 9748.561             | H\(12\gamma\) | 16           | 512      |
| 40              | 9983.501             | H\(12\gamma\) | 16           | 512      |

Note. The continuum windows span a total of ~2 GHz. The spectral line windows have a velocity span of ~500 km s\(^{-1}\) and a spectral resolution of ~1 km s\(^{-1}\).

We specifically chose a velocity resolution of 11.4 km s\(^{-1}\) to be consistent with the resolution used by Balser et al. (2006) for their reported \(^3\)He\(^+\) detection in J320.

3. Results

The PN J320, discovered by Jonckheere (1916), is both spatially and kinematically complex. The object has two or three bipolar lobes surrounded by high speed knots, together with a surrounding halo (Harman et al. 2004; Rechy-García et al. 2020). The JVLA MS-MFS radio continuum emission of J320, together with its H\(\alpha\) emission image, is shown in Figure 1. J320 is just resolved by the JVLA, consistent with the Hubble Space Telescope (HST) H\(\alpha\) size of about 10\(^{\prime}\) (Harman et al. 2004). The complex nature of this PN is therefore not visible in our radio data. The rms noise in the image is 25 \(\mu\)Jy beam\(^{-1}\), sufficient to detect the free–free continuum emission from J320 with an S/N > 500. The integrated continuum flux density is 23 mJy at the \(^3\)He\(^+\) frequency of 8665.65 MHz, consistent with previous VLA results (see Balser et al. 2006).

Figure 2 shows \(^3\)He\(^+\) and stacked RRL spectra for the spectral pixel (spaxel) in the data cube that corresponds to the brightest region in the continuum image. There is no clear visual evidence of a \(^3\)He\(^+\) line, but we do detect H\(\Pi\) RRL emission in the \(\langle\text{H}\alpha\rangle\), \(\langle\text{H}\beta\rangle\), and \(\langle\text{H}\gamma\rangle\) spectra. We therefore fit Gaussian profiles to the H and He RRLs shown by the red curves in the middle panels of Figure 2. Specifically, we simultaneously fit a first-order polynomial and two Gaussian profiles to the entire spectral window. We fix the location of the He component with respect to the H component by \(-122.47\) km s\(^{-1}\), that is, we do not fit for the center velocity of the He component but rather assume the shift produced by the mass of the heavier He nucleus.

Detecting \(^3\)He\(^+\) emission in PNe is challenging. Instrumental spectral baseline structure can mimic or mask the weak \(^3\)He\(^+\) spectral transition. We therefore need to rigorously assess the quality of the data and, in particular, the robustness of the nondetection of \(^3\)He\(^+\) in J320. We employ several statistical techniques to demonstrate that the \(^3\)He\(^+\) spectrum is consistent with random Gaussian noise.

First, we compare the cumulative distribution functions (CDFs) of the \(^3\)He\(^+\) and RRL spectra with the CDF expected from theoretical Gaussian noise. The results are shown in Figure 3 for the \(\langle\text{H}\alpha\rangle\), \(\langle\text{H}\beta\rangle\), and \(\langle\text{H}\gamma\rangle\) spectra. Here, the spectra have been smoothed to 11.4 km s\(^{-1}\), and the CDF is calculated over the full spectrum. To assess the uncertainty in the CDF distribution, we use bootstrap resampling (Efron 1982). Specifically, we generate 10,000 simulated CDFs, where each distribution consists of \(M\) values, the number of data points, that are randomly drawn from the original data with replacement. That is, we replace the original data with the randomly selected data. So the

\(^{2.5}\) km s\(^{-1}\). Since typical line widths in PNe are \(\gtrsim 30\) km s\(^{-1}\), we also generate data cubes with a coarse velocity resolution of 11.4 km s\(^{-1}\). The CASA task TCLEAN generates the following images and data cubes: (1) a multiscale, multi-frequency synthesis (MS-MFS) continuum image by combining all 16 continuum windows; (2) an MS-MFS image of each continuum and spectral line window; and (3) a multiscale data cube of each spectral line window. Unless noted, the continuum is not subtracted from the spectral line data products.
simulated distributions will miss some CDF values from the original data and have some duplicates, triplicates, etc. The shaded regions in Figure 3 correspond to the 68% confidence interval ($\pm 1\sigma$) determined by bootstrapping. Visual inspection of the CDFs and their uncertainty indicates that the $\text{He}^+$ and $\langle \text{Hn} \rangle$ spectra are consistent with noise.

To estimate the significance of this result, we calculate the $p$-value, the probability of obtaining a result at least as extreme as the value of a test statistic. Here we use the Anderson–Darling (AD) test statistic, which is a weighted sum of the integrated squared difference between the observed CDF and the theoretical Gaussian CDF (see Scholz & Stephens 1987). We use the SciPy implementation of the AD test (see van der Walt et al. 2011). A significance level threshold of 5% is typically used (e.g., Feigelson & Babu 2012), and therefore the spectrum is consistent with random Gaussian noise when the $p$-value is larger than 0.05. To do this, we run 10,000 simulations where in each simulation we perform the following steps:

1. Generate $N$ random observations of a Gaussian distribution, where $N$ is the same length as the data (or residuals).
2. Calculate the “nominal” AD statistic between the data (or residuals) and this Gaussian distribution.
3. Generate two bootstrap samples of length $N$ from the combined data (or residuals) and random Gaussian observations.
4. Calculate the AD statistic for these two samples and compare this to the nominal value in step 2.
5. Calculate the $p$-value: the fraction of the time that the AD statistic for the two bootstrapped samples is greater than the nominal AD statistic.

The results are given in Tables 3 and 4 for the $\text{He}^+$ spectra and stacked RRL spectra, respectively. In Table 3 we list the project, the telescope, the velocity resolution, $\Delta V_{\text{res}}$, the rms noise, and the AD $p$-value. We also summarize the results for the VLA (AB0794) and the combined JVLA (21A-004)/VLA (AB0794) data (see below). The large $p$-values indicate that the $\text{He}^+$ spectrum is consistent with noise. This result implies that we have not detected the $\text{He}^+$ transition and that any instrumental spectral baseline effects are smaller than the expected random Gaussian noise.

In Table 4 we list the RRL order, the velocity resolution, $\Delta V_{\text{res}}$, Gaussian fit parameters and S/N for the H and He RRL components, the rms noise, and the AD $p$-value for the residual and data spectra. The Gaussian fit parameters consist of the peak intensity, $S_p$, the FWHM line width, $\Delta V$, and the LSR velocity of the peak intensity, $V_{\text{LSR}}$. RRLs are only detected with significance in the $\langle \text{Hn} \rangle$ spectra. The residual spectra are consistent with random Gaussian noise, implying that our two-component Gaussian fit is sufficient. The S/Ns of the He RRLs are less than 2, and therefore we cannot estimate reliable $^4\text{He}/\text{H}$ abundance ratios.

The spectral noise in the $\text{He}^+$ spectral window is consistent with random Gaussian noise. Because previous detections of $^3\text{He}^+$ in PNe have been shown to be incorrect (Bania & Balser 2021), we perform several sanity checks on the data.
1. **Does the noise integrate down as expected?** The JVLA exposure calculator tool\(^5\) predicts an rms noise of 51.5 \(\mu\)Jy beam\(^{-1}\), assuming a total time of 29 hr and a velocity resolution of 11.4 km s\(^{-1}\). Based on the number of baselines flagged, we estimate an effective integration time of 18.8 hr, increasing the rms noise to 64.0 \(\mu\)Jy beam\(^{-1}\). This is roughly consistent with our measured value of 58.8 \(\mu\)Jy beam\(^{-1}\).

2. **Do adjacent RRLs behave as expected?** Because RRLs at centimeter wavelengths have large principal quantum numbers, the energy spacing between adjacent RRLs is similar, and therefore these transitions should have similar RRL spectral properties. Moreover, for an optically thin nebula we expect the integrated RRL flux density to increase with frequency: \(\int S_\nu d\nu \propto \nu\) (Wilson et al. 2012). Figure 4 shows that both of these expectations are true for the \(\text{H}\alpha\) RRLs in J320. Individual \(\text{H}\alpha\) RRLs have similar profiles, and the integrated flux density increases linearly with frequency to within the uncertainty. A power-law fit to the data yields an exponent of 1.79 ± 0.84. This is a large deviation from the expected exponent of 1.0 for an optically thin nebula, but consistent to within the uncertainties.

3. **Are the RRLs in LTE?** There have been non-LTE effects detected for RRLs in PNe, but in general we expect centimeter-wavelength RRLs to be close to LTE (see, e.g., Bania & Balser 2021). In LTE we expect the

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\(^5\) See go.nrao.edu/ect.
of Figure 2, the solid black curve is the CDF of the residual spectrum (bottom panel of Figure 2), and the red dotted curve is the CDF of theoretical Gaussian noise with an rms given by the residual spectrum. For the $^3\text{He}^+$ spectrum the residual curve is equivalent to the baseline-subtracted curve and therefore is not shown. The shaded regions correspond to the 68% confidence interval (±1σ) determined by bootstrapping. These figures show significant detections of $\langle \text{H}\alpha \rangle$ and $\langle \text{H} \alpha \beta \rangle$ emission but only upper limits for $\langle \text{H} \gamma \rangle$ and $^3\text{He}^+$ emission.

**Table 3**

| Project | Telescope | $\Delta V$ (km s$^{-1}$) | rms Noise$^\text{a}$ (μJy beam$^{-1}$) | AD | $p$-value |
|---------|-----------|---------------------------|--------------------------------|-----|-----------|
| 21A-005 | JVLA      | 2.5                       | 134.7                           | 0.67 | 0.670    |
| 21A-005 | JVLA      | 11.4                      | 58.8                            | 0.625 | 0.085    |
| AB0794  | VLA       | 8.0                       | 127.0                           | 0.605 | 0.000    |
| AB0794  | VLA       | 11.4                      | 113.3                           | 0.600 | 0.000    |
| Combine | JVLA/VLA  | 8.0                       | 68.2                            | 0.665 | 0.000    |
| Combine | JVLA/VLA  | 11.4                      | 61.1                            | 0.668 | 0.000    |

**Note.**

$^a$ The spectral noise in the data cube.

following integrated intensity ratios: H114$\beta$/H91$\alpha = 0.274$ and H130$\gamma$/H91$\alpha = 0.126$ (Bania & Balser 2021). From Table 4 we measure $\langle \text{H} \alpha \beta \rangle/\langle \text{H} \alpha \rangle = 0.335 ± 0.067$ and $\langle \text{H} \gamma \rangle/\langle \text{H} \alpha \rangle = 0.125 ± 0.071$. So within the uncertainties the RRL emission is consistent with LTE excitation in J320.

Many PNe, including J320, contain diffuse halos that can be detected with deep H$\alpha$ observations. Since the intensity of free–free and RRL emission is proportional to $\int n_e^2 \, dl^2$, these tracers are not a very sensitive probe of the halo. In contrast, the intensity of the $^3\text{He}^+$ transition is proportional to $\int n_e \, dl^2$, and thus the halo could contribute significantly to the $^3\text{He}^+$ emission (see Balser et al. 1997). To increase our sensitivity to $^3\text{He}^+$ emission, we therefore follow Balser et al. (2006) and integrate $^3\text{He}^+$ emission both over the line profile and spatially around J320. Specifically, we first integrate over the expected FWHM line width of the $^3\text{He}^+$ transition, that is, we produce a channel-integrated image from the $^3\text{He}^+$ data cube. Using this image, we then spatially integrate over concentric rings centered on J320.

Figure 5 shows the results of this analysis for the JVLA data. In the left panel we plot the cumulative free–free continuum flux density as a function of radius. The free–free emission levels off beyond about 15″, that is, we do not detect any halo emission with our radio data. This is expected given the low emission measure probed by H$\alpha$ emission in PN halos. In the right panel we plot the cumulative, channel-integrated $^3\text{He}^+$ line flux density as a function of radius. No $^3\text{He}^+$ emission is detected. The noise, shown by the shaded regions for the data and residuals, increases with radius since we are integrating over a noisy signal. The darker shaded region is where the noise envelopes of the data and residual curves overlap.

To compare our results with Balser et al. (2006), we reanalyze their VLA data (project AB0794) using WISP with the same procedures as for our JVLA data for consistency. We also combine the VLA and JVLA data to increase our sensitivity. Since the VLA correlator was limited to spectral windows with 31 channels over a 6.25 MHz bandwidth, we first smooth our JVLA data to the same spectral resolution of 8.0 km s$^{-1}$. Spectra and CDFs are shown in Figure 6. There is a hint of a double-peaked $^3\text{He}^+$ profile in the reprocessed VLA data, which is consistent with the results in Balser et al. (2006, Figure 7). But this feature is
not present in the JVLA data or in the combined data set. Moreover, all spectra are consistent with random Gaussian noise (see the CDFs in Figure 6 and the AD p-values in Table 3).

The spectral line rms noise in the reprocessed VLA data is almost two times higher than the JVLA data using the coarse velocity resolution data cubes with $\Delta V_{\text{res}} = 11.4 \text{ km s}^{-1}$ (see Table 3). There are three factors that account for most of this difference: (1) the lower system noise in the JVLA receivers produces a system equivalent flux density (SEFD) of $\sim 250 \text{ Jy}$ at X band compared to $\sim 310 \text{ Jy}$ for the VLA; (2) the JVLA WIDAR correlator efficiency is 0.93 for the 8-bit samplers, whereas the 3-level VLA correlator had an efficiency of 0.78; and (3) the VLA data require significant flagging due to bad data resulting in an effective integration time of 13.5 hr, whereas the cleaner JVLA data set has an effective integration time of 18.8 hr. In total, these three differences account for a factor of 1.7 in rms sensitivity between the VLA and JVLA data sets. Thus, combining the VLA data with the JVLA data does not significantly change the measured rms noise.

Why did Balser et al. (2006) claim a $^3\text{He}^+$ detection? Their $^3\text{He}^+$ spectrum toward the peak continuum emission is consistent with our results: no significant $^3\text{He}$ detection. The difference arises when generating the cumulative, channel-integrated flux density, where they achieve an S/N of $\sim 9$ (see Figure 8 in Balser et al. 2006). The main reason for the discrepancy stems from performing a continuum subtraction using the few available channels in the VLA correlator to define the line-free regions. This produces a poor spectral baseline fit that artificially amplifies the “noise” bumps visible in the single spectrum centered on J320. The magnitude of the $^3\text{He}^+$ signal increases when calculating the cumulative, channel-integrated flux density. In contrast, the JVLA data have ample channels to define the line-free region; moreover, since the line data are not limited by dynamic range, a continuum subtraction is not necessary. By processing the VLA data in the same way as Balser et al. (2006), we can reproduce their results.

Table 4

| Hydrogen | Helium |
|----------|--------|
| $\Delta n$ | $\Delta V_{\text{res}}$ | $S_L$ | $\Delta V$ | $V_{\text{LSR}}$ | $S/N$ | $S_L$ | $\Delta V$ | rms Noise | AD p-value |
| km s$^{-1}$ | (mJy beam$^{-1}$) | (mJy beam$^{-1}$) | (km s$^{-1}$) | (km s$^{-1}$) | | (mJy beam$^{-1}$) | (km s$^{-1}$) | (mJy beam$^{-1}$) | Residuals | Data |
| 1 | 2.5 | 539.9 ± 19.8 | 47.9 ± 2.1 | −41.6 ± 0.8 | 28.05 | 51.9 ± 22.1 | 38.2 ± 19.4 | 2.41 | 59.0 | 0.665 | 0.000 |
| 11.4 | 540.3 ± 23.7 | 48.0 ± 2.5 | −41.6 ± 1.0 | 24.98 | 52.6 ± 26.4 | 38.5 ± 23.1 | 2.18 | 31.1 | 0.543 | 0.021 |
| 2.5 | 163.7 ± 20.0 | 52.9 ± 7.8 | −40.7 ± 2.8 | 8.45 | 58.7 ± 27.6 | 27.0 ± 15.0 | 2.16 | 62.4 | 0.622 | 0.010 |
| 11.4 | 163.8 ± 19.4 | 53.1 ± 7.6 | −40.7 ± 2.7 | 9.25 | 58.0 ± 26.6 | 27.9 ± 15.1 | 2.37 | 26.8 | 0.688 | 0.024 |
| 2.5 | 48.2 ± 17.2 | 66.8 ± 29.2 | −40.8 ± 11.0 | 2.91 | 7.2 ± 28.3 | 23.7 ± 110.3 | 0.26 | 60.0 | 0.578 | 0.296 |
| 11.4 | 48.6 ± 20.0 | 72.2 ± 36.3 | −35.2 ± 11.1 | 2.70 | 24.6 ± 39.5 | 15.0 ± 28.8 | 0.62 | 31.7 | 0.597 | 0.398 |

Note. We follow Lenz & Ayres (1992) to calculate the S/N.

3.1. J320 NEBULA Model

Deriving a limit for the $^3\text{He}/\text{H}$ abundance ratio in J320 requires a model of the nebular structure for this PN. Balser et al. (2006) modeled J320 as a two-component nebula consisting of a bright shell and a diffuse, extended halo. They

Figure 4. Analysis of individual H$\alpha$ RRL transitions for the JVLA data. Left panel: spectra of seven RRLs (H$\beta$–H$\gamma$) and the stacked (H$\alpha$) RRL spectrum in bold (top), the (H$\alpha$) RRL spectrum after the removal of a spectral baseline (middle), and the residuals (bottom). Right panel: integrated H$\alpha$ brightness as a function of frequency. The solid line is a power-law fit to the points with an exponent of 1.79 ± 0.84.

Table 3

| Hydrogen | Helium |
|----------|--------|
| $\Delta V_{\text{res}}$ | $V_{\text{LSR}}$ | $S/N$ | $V_{\text{LSR}}$ | $S/N$ |
| km s$^{-1}$ | (km s$^{-1}$) | | (km s$^{-1}$) | |
| 1 | 2.5 | 47.9 ± 2.1 | −41.6 ± 0.8 | 28.05 | 539.9 ± 19.8 | 51.9 ± 22.1 |
| 11.4 | 540.3 ± 23.7 | 48.0 ± 2.5 | −41.6 ± 1.0 | 24.98 | 52.6 ± 26.4 |
| 2.5 | 163.7 ± 20.0 | 52.9 ± 7.8 | −40.7 ± 2.8 | 8.45 | 58.7 ± 27.6 |
| 11.4 | 163.8 ± 19.4 | 53.1 ± 7.6 | −40.7 ± 2.7 | 9.25 | 58.0 ± 26.6 |
| 2.5 | 48.2 ± 17.2 | 66.8 ± 29.2 | −40.8 ± 11.0 | 2.91 | 7.2 ± 28.3 |
| 11.4 | 48.6 ± 20.0 | 72.2 ± 36.3 | −35.2 ± 11.1 | 2.70 | 24.6 ± 39.5 | 28.3 ± 10.9 |

$^{+}$This table includes the derived $^3\text{He}/\text{H}$ abundance ratios for each RRL transition.

$^{\dagger}$This table includes the cumulative, channel-integrated AD p-values for the H$\alpha$ RRL transitions.

$^{\ddagger}$This table includes the derived $^3\text{He}/\text{H}$ abundance ratios for each RRL transition.
Figure 5. Spatially integrated free–free continuum (left) and $^3$He$^+$ line (right) flux densities as a function of radius for the JVLA (21A-005) data. For the $^3$He$^+$ line emission we first integrate over spectral channels and then spatially around J320. Data (solid curves): the continuum MS-MFS image of the $^3$He$^+$ spectral line window (left) and the channel-integrated $^3$He$^+$ spectrum (right). Both images were smoothed to 12″ resolution. Residuals (dotted curves): the continuum residual cumulative flux density is measured in the MS-MFS residual image (left), and the $^3$He$^+$ spectral line residual cumulative integrated flux density is measured in the line-free channels (right). The shaded regions represent the 1σ uncertainties determined from the residual (continuum) or line-free channels ($^3$He$^+$ spectral line). Model (dashed curves): results of a similar analysis for the NEBULA model free–free continuum image and $^3$He$^+$ spectral line cube (see Section 3.1).

Figure 6. J320 $^3$He$^+$ spectra (top) and CDFs (bottom) using the VLA (project AB0794; left) and the combined VLA and JVLA data (projects AB0794 and 21A-005; right). Spectra are smoothed and regridded to a velocity resolution of 8.0 km s$^{-1}$. See Figures 2 and 3 for details. Combining the VLA and JVLA J320 data does not lead to a $^3$He$^+$ detection.
used the numerical radiative transfer code NEBULA (Balser et al. 1995; Balser et al. 1999a; Balser & Bania 2018) to calculate synthetic spectra of the free–free continuum, RRL, and 3He emission from this model nebula. Specifically, NEBULA produces a continuum image and spectral line data cubes.

Here, we use more recent optical and infrared data, together with our sensitive JVLA radio data, to constrain the physical properties of J320. We adopt a distance of 3.26 kpc based on Gaia DR2 parallaxes (Chornay & Walton 2020). J320 is morphologically complex, but there exists a brighter shell with an angular diameter of ~7″ embedded within a larger halo of ~25″ (Harman et al. 2004). The angular size of the inner boundary of the shell is difficult to discern from the optical images, so we assume 0″.1. The helium ionization structure is taken from optical recombination lines, where we assume that the doubly ionized helium is negligible (Costa et al. 2004). For an optically thin nebula in LTE the radio recombination line-to-continuum ratio is an accurate measure of the electron temperature that is independent of density (see, e.g., Wenger et al. 2019a). Using the H91α RRL, we derive $T_e = 12,500$ K, consistent with results derived from optical collisionally excited lines (e.g., Milingo et al. 2002; Costa et al. 2004). Using infrared collisionally excited lines of sulfur, Pagomemos et al. (2018) derive an electron density of $n_e = 3350 \pm 600$ cm$^{-3}$. This produces radio continuum emission brighter than observed with the JVLA, so we reduce this value to $n_e = 2100$ cm$^{-3}$ to be consistent with our radio observations. The infrared and radio data are not probing the same volume for this complex nebula; therefore, reducing the density is justified.

The RRL line widths in J320 are broadened by Doppler motions, consisting of both thermal and nonthermal components, together with expansion of the nebula. Harman et al. (2004) measured bipolar lobes expanding with a velocity of $V_{exp} = 46$ km s$^{-1}$, but this value is unlikely to be representative of our RRL emission, which arises from the entire volume of ionized gas. We therefore adopt an expansion velocity of $V_{exp} = 16$ km s$^{-1}$ based on Hα emission of the entire shell (Rechy-García et al. 2020). The thermal motions are determined by the electron temperature, which we derive to be $T_e = 12,500$ K (see above). The nonthermal motions, thought to be caused by turbulence, are constrained by the observed JVLA line widths. That is, we increase the model turbulent velocity until the synthetic RRL line widths are consistent with the observed line widths.

The NEBULA model physical parameters for J320 are summarized in Table 5. Listed are the nebular component, the inner and outer angular sizes, the expansion velocity, the electron temperature, the electron density, and the helium ionic abundances. The physical parameters of the halo are not well determined because the low density produces weak emission lines. We therefore assume that the halo has the same expansion velocity, electron temperature, and helium ionization structure as the shell. Balser et al. (2006) used the $^3$He$^+$ and continuum emission distribution to constrain the halo density and $^3$He/H abundance ratio. Since we do not detect $^3$He with the improved JVLA observations, we arbitrarily set the density to a low value of $n_e = 10$ cm$^{-3}$. A $^3$He/H abundance ratio of $2.75 \times 10^{-3}$ by number produces a limit to our JVLA observations (see below).

We analyze the NEBULA data products of J320 using the same methods as for our JVLA data. The model brightness distribution is convolved with a Gaussian beam with HPBW of 12″. Spectra of the H91α RRL and $^3$He$^+$ transition toward the peak continuum emission in J320 are shown in Figure 7. The synthetic H91α profile is a reasonable fit by eye to the JVLA data. This is expected since the model electron temperature and density were constrained using the JVLA H91α line-to-continuum ratio and the free–free radio continuum emission centered on J320. The NEBULA model produces a $^3$He$^+$ line intensity that is about 2–3 times the rms noise of the JVLA data. We also spatially integrate the synthetic free–free continuum and $^3$He$^+$ line flux densities as a function of radius to increase the sensitivity. The model results are shown as the dashed line in Figure 5. The free–free continuum emission in our model is a good fit to the data, with a cumulative continuum flux density that is slightly less than the value derived from our JVLA continuum observations. The cumulative, channel-integrated modeled $^3$He$^+$ emission is larger than the observational uncertainties at smaller radii. Since the contribution of the $^3$He$^+$ emission arising from the halo may be significant, and we are unable to put stringent constraints on the physical properties of the halo, we cannot derive an accurate $^3$He/H abundance ratio limit for J320. Nevertheless, the synthetic $^3$He$^+$ profile in Figure 7, which is 2–3 times the rms spectral noise, produces a limit of $^3$He/H $\lesssim 2.75 \times 10^{-3}$ by number.

### 4. Discussion

There is ample evidence that stars undergo extra mixing beyond convection as a physical process to stir material in their interiors. There are a variety of tracers, including $^3$He, $^7$Li, $^{12}$C/$^{13}$C, etc., observed in stars and PNe whose abundances are inconsistent with standard stellar evolution models that only include convection. For low-mass stars the best candidates for this extra mixing process are rotation-induced mixing and the thermohaline instability. Rotation alone is not sufficient to explain the abundance anomalies (Palacios et al. 2006), but models that include both of these extra mixing processes predict abundances at different stellar evolutionary states that are broadly consistent with observations (e.g., Charbonnel & Lagarde 2010). Moreover, these extra mixing processes resolve the “$^3$He problem” (e.g., Lagarde et al. 2012; Balser & Bania 2018).

One criticism of thermohaline mixing is that although we might expect all low-mass stars to destroy their $^3$He by processing it into $^4$He, there are several PNe with $^3$He/H abundance ratios consistent with standard stellar yields (e.g., Eggleton et al. 2008). Charbonnel & Zahn (2007b) suggested that strong
magnetic fields could inhibit thermohaline mixing. They posited that Ap-type stars, which have stronger magnetic fields than classical A-type stars, could maintain their magnetic field strength as they evolve into RGB stars, when the thermohaline instability is important. But this may no longer be necessary since the two most significant $^3$He$^+$ detections in PNe, NGC 3242 and J320, have now been shown to be incorrect.

Do all low-mass stars undergo extra mixing? This is still an open question. Charbonnel & Do Nascimento (1998) estimated that 96% of low-mass stars undergo extra mixing on the RGB. Using HIPPARCOS parallaxes, they identified a sample of 191 stars that have passed the luminosity bump in their evolution. It is at this evolutionary stage when these extra mixing mechanisms are expected to be active. Additional processing of material, however, could occur later in the evolution of low-mass stars. To answer this extra-mixing question, we must therefore determine abundances in objects whose material has been fully processed by stellar evolution: PNe.

Here we focus on $^3$He and the carbon isotopic ratio $^{12}$C/$^{13}$C in PNe to explore whether extra mixing occurs in all low-mass stars. One major difficulty with using PN abundances to constrain stellar evolution models is that the progenitor mass, also called the initial mass, $M_\text{f}$, is required. This is because we need to compare abundances derived from observations in PNe with stellar evolution models that depend strongly on the initial stellar mass. Determining the progenitor mass is a two-step process. First, the PN central star mass or final mass, $M_\text{f}$, must be determined. This is typically done by placing the central star on an H-R diagram for comparison with evolutionary tracks from stellar models (e.g., Stanghellini et al. 1993), but there are other methods (see Gorny et al. 1997). Therefore, the PN central star distance is needed to derive the luminosity. Second, a semiempirical initial-to-final mass relation (IFMR) is used to calculate the initial mass given the final mass. The IFMR is calibrated by carefully measuring the properties of white dwarfs in open clusters, where the age and therefore cooling time can be estimated (e.g., Canton 2018). Recently, Marigo et al. (2020) have shown that the IFMR is not monotonic and unfortunately there is a kink in the relationship where low-mass stars reside.

Since we need final masses to determine the initial masses, we therefore search for PNe in the literature with $^3$He/H or $^{12}$C/$^{13}$C abundance ratios that also have an estimate of the central star mass. We then calculate a range in $M_\text{f}$ using the IFMR from three different sources (Canton 2018; Cummings et al. 2018; Marigo et al. 2020). We must first generate a grid of possible initial masses between 0.83 and 7.22 $M_\odot$ with an increment of 0.01 $M_\odot$. We then determine the range of initial masses that are consistent with the PN final mass assuming a 10% error in $M_\text{f}$. The methods used to derive these IFMRs are similar, but the white dwarf samples and detailed analyses are different (for a comparison of these IFMRs see Canton et al. 2021). Our calculated ranges in $M_\text{f}$ therefore provide an estimate of the uncertainty and include the kink in the IFMR discovered by Marigo et al. (2020).

4.1. $^3$He/H Abundance Ratio in Planetary Nebulae

Detecting $^3$He$^+$ in PNe is very challenging since the mass of ionized gas in these nebulae is small, producing very weak emission-line intensities. Typically, a detection of $^3$He$^+$ with current radio facilities translates into an abundance ratio of $^3$He/H $\gtrsim 10^{-3}$. This limit is either consistent with or larger than that predicted by standard stellar models. Therefore, $^3$He/H upper limits are usually not particularly useful, but there are some exceptions (see below). Table 6 summarizes the properties of the three PNe with claimed $^3$He$^+$ detections. Listed are the $^3$He/H abundance ratio and estimates of the final and initial stellar masses. Since IC 418 is a carbon star, the progenitor mass likely has a higher value for the lower limit than the number listed in Table 6, that is, $M_\text{f} \gtrsim 1.5 M_\odot$ (Morisset & Georgiev 2009). Bania & Balser (2021) have clearly demonstrated that the previously claimed detection of $^3$He$^+$ in NGC 3242 is incorrect, and therefore their limits are shown in Table 6. Using the JVLA, we have demonstrated here that the claimed detection of $^3$He$^+$ in J320 is also incorrect, and therefore we include the limits determined in Section 3. Finally, we list the range of $^3$He/H abundance ratios derived by Guzman-Ramirez et al. (2016) for IC 418.

We conclude that there is no longer strong evidence from PN $^3$He$^+$ observations that any low-mass stars fail to undergo extra mixing. Figure 8 plots the $^3$He/H abundance ratio as a function of progenitor mass, where the points correspond to abundances derived from observations and the curves correspond to yields from stellar evolution models. For low-mass stars the expected...
### 4.2. $^{12}$C/$^{13}$C Abundance Ratio in Planetary Nebulae

There are several different tracers used to derive the $^{12}$C/$^{13}$C abundance ratio in PNe. The brightest is the millimeter-wavelength rotational transition of CO (e.g., Palla et al. 2000). There are three problems in deriving accurate $^{12}$C/$^{13}$C ratios using CO: (1) opacity variations, (2) chemical fractionation, and (3) selective dissociation (Stahl et al. 2008). For high densities $^{12}$CO will become optically thick, and therefore the derived $^{12}$C/$^{13}$C ratios will be underestimated. This can be mitigated by observing at least two transitions of CO and using radiative transfer models to determine the opacity (e.g., Balser et al. 2002). Since the molecular gas in PNe is warm (20–50 K), fractionation should be small (Zurays et al. 2020). But Saberi et al. (2020) see variations in $^{12}$C/$^{13}$C from CO due to selective dissociation in the outflows of AGB stars and suggest that HCN is a better tracer. Since $^{12}$CO is more efficiently shielded than $^{13}$CO, the derived $^{12}$C/$^{13}$C ratios can be overestimated when using CO. Nevertheless, observations of multiple molecular tracers (e.g., CO, HCN, CN, HCO$^+$, etc.) to determine $^{12}$C/$^{13}$C abundances produce results that are consistent to within the uncertainties, but there are some exceptions (Zurays et al. 2020).

A less sensitive tracer of $^{12}$C/$^{13}$C abundance is the C III] multiplet near 1908 Å, which has an $F = 1/2–1/2$ transition.

#### Table 6

| PN          | Alias          | $(^{3}$He/He) x $10^{-4}$ by Number | $(^{3}$He/He) x $10^{-4}$ by Mass | Ref. | M$_*$ (M$_\odot$) Value | M$_*$ (M$_\odot$) Error | Ref. |
|-------------|----------------|-----------------------------------|-----------------------------------|------|-------------------------|-------------------------|------|
| IC 418      | J320           | $\leq$27.5                        | $\leq$58                          | This paper | 0.575 | ...                    | G97 | 0.83–2.33 |
| 261.0 + 32.0 | NGC 3242       | $\leq$0.45                        | $\leq$0.96                        | B21  | 0.615 | ...                    | S20 | 0.83–2.57 |
| 215.2–24.2  | IC 418         | 17 – 58                           | 37 – 123                          | G16  | 0.573 | ...                    | G97 | 0.83–2.32 |

Note. Listed are the $^{3}$He/He abundance ratios, the PN central star mass (or final mass M$_*$), and the PN progenitor mass (or initial mass M$_f$). We convert the $^{3}$He/He abundance ratio by number of mass fraction assuming a $^{3}$He/He abundance ratio by number of 0.1 and a metallicity of Z = 0.0061 for NGC 3242 and Z = 0.0122 for J320 and IC 418 (see Bania & Balser 2021).

**References:** B21: Bania & Balser 2021; G16: Guzman-Ramirez et al. 2016; G97: Gorny et al. 1997; S20: Stanghellini et al. 2020.
near 1909.6 Å that is only allowed for $^{13}\text{C}$ (Clegg et al. 1997). Most studies using this ultraviolet transition toward PNe, however, only produce limits to $^{12}\text{C}/^{13}\text{C}$ (see Rubin et al. 2004).

In Table 7, we list PNe with $^{12}\text{C}/^{13}\text{C}$ abundance ratios from the literature that have estimates of the central star mass, $M_\odot$. For PNe with $^{12}\text{C}/^{13}\text{C}$ ratios determined by different tracers we favor those that use CO rather than HCN, CN, or HCO$^+$ instead of CO owing to potential issues with selective dissociation. For PNe with multiple $^{12}\text{C}/^{13}\text{C}$ ratios based only on CO we favor those that use radiative transfer models to derive the $^{12}\text{C}/^{13}\text{C}$ abundance ratios. We only include PNe that have significant limits: $^{12}\text{C}/^{13}\text{C} \lesssim 5$ (see below). There are two independent observations of the C III multiplet transition in the well-known PN NGC 3242 made using HST and the International Ultraviolet Explorer. These data yield abundance ratios of $^{12}\text{C}/^{13}\text{C} \geq 38$ (Palla et al. 2002) and $^{12}\text{C}/^{13}\text{C} \geq 14$ (Rubin et al. 2004), respectively, by number. Inspection of the spectrum from Palla et al. (2002, Figure 1) suggests that the quoted upper limit of $^{12}\text{C}/^{13}\text{C} \geq 38$ is too high. The peak-to-peak fluctuations in the residual spectrum are about 0.2 Å, suggesting a $3\sigma$ limit in the $^{12}\text{C}/^{13}\text{C}$ transition of about 0.2 ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$, a factor of 10 larger than quoted. We therefore list the limit of $^{12}\text{C}/^{13}\text{C} \geq 14$ derived by Rubin et al. (2004) in Table 7.

Figure 9 plots the $^{12}\text{C}/^{13}\text{C}$ abundance ratio by mass as a function progenitor mass. Here we convert the $^{12}\text{C}/^{13}\text{C}$ abundance ratios listed in Table 7 from number density to mass fraction to compare with stellar evolution models. This requires multiplying the $^{12}\text{C}/^{13}\text{C}$ abundance ratios by the small factor of 12/13. The results span a wide range of values but are concentrated at values of $^{12}\text{C}/^{13}\text{C} \leq 20$ and progenitor masses between 1 and 3 $M_\odot$. As expected, the progenitor masses are rather uncertain, with error bars on the order of 1 $M_\odot$. For comparison the predictions of the $^{12}\text{C}/^{13}\text{C}$ ratio from stellar evolution models are shown in the bottom panel. The different curves correspond to yields using standard models and those that include extra mixing from the thermohaline instability and rotation. For low-mass stars there is a significant difference in the expected $^{12}\text{C}/^{13}\text{C}$ ratio between these models, whereas for higher-mass stars the models predict $^{12}\text{C}/^{13}\text{C} \sim 20$, unless there is significant rotation.

In Figure 10, we combine the $^{12}\text{C}/^{13}\text{C}$ results from observations with the predictions from models. Since these stellar evolution models do not include the combined effect of third dredge-up, hot bottom burning, and thermohaline mixing for more massive stars, we only show PNe with progenitor masses less than 2 $M_\odot$. The very low $^{12}\text{C}/^{13}\text{C}$ ratio of 2.2 for M1-16 suggests additional mixing beyond that included in the models. But otherwise interpreting Figure 10 is difficult given the large uncertainty in progenitor masses. For example, a PN with $^{12}\text{C}/^{13}\text{C} \sim 20$ is consistent with the standard model for a progenitor mass of 1 $M_\odot$, but the interpretation is inconclusive if the progenitor mass is 2 $M_\odot$.
the distance. Gaia parallaxes do exist for some PN central stars, but alas not for M1-17. Nevertheless, PN parallaxes from Gaia have been used to calibrate a Galactic PN distance scale based on the correlation between nebular physical radius and Hβ surface brightness (Stanghellini et al. 2020). Applying this new Galactic PN distance scale to M1-17 would yield more accurate estimates for the progenitor mass.

We conclude that, based on the $^{12}$C/$^{13}$C abundance ratios in PNe, there is evidence that some low-mass stars fail to undergo extra mixing. More work is required, however, to confirm this.

In particular, additional observations of HCN or similar tracers toward PNe to derive $^{12}$C/$^{13}$C abundance ratios are needed. In addition, unless parallaxes are available, the new Galactic PN distance scale should be used to derive PN progenitor masses.

5. Conclusions

For many decades there has been evidence that extra mixing beyond convection must occur in low-mass stars. Observations of $^7$Li, $^{12}$C/$^{13}$C, C/O, and other tracers on the RGB isolate this extra mixing to just after the star reaches the luminosity bump, when the

Figure 9. $^{12}$C/$^{13}$C abundance ratios in PNe as a function of progenitor mass. Top: $^{12}$C/$^{13}$C ratios from millimeter molecular transitions (thin diamond: Cox et al. 1992; diamond: Palla et al. 2000; circle: Balser et al. 2002; square: Ziurys et al. 2020) and ultraviolet CIII transitions (triangle; Rubin et al. 2004). Filled symbols have central stellar masses derived with accurate parallax-determined distances (Stanghellini et al. 2020). Bottom: model $^{12}$C/$^{13}$C predictions from Charbonnel & Lagarde (2010) for standard stellar evolution models (dotted) and models that include thermohaline mixing (solid). Also shown are models that include both thermohaline and rotation-induced mixing with various initial stellar rotation velocities (long-dashed line: $v = 110$ km s$^{-1}$; dashed–dotted line: $v = 250$ km s$^{-1}$; dashed line: $v = 300$ km s$^{-1}$). The red curves correspond to $^{12}$C/$^{13}$C ratios at the tip of the RGB, whereas the blue curves are $^{12}$C/$^{13}$C ratios at the end of the second dredge-up.
hydrogen-burning shell reaches the chemical discontinuity created by the maximum extent of the convective envelope during the first dredge-up. The two most likely candidates for this extra mixing are rotational-induced mixing and the thermohaline instability.

Observations of $^3$He in PNe provide an important constraint to mixing mechanisms in stars since they probe abundances in places that have been fully processed by stellar evolution. Standard stellar evolution models that only include convection as a way to mix material inside stars predict the production of significant amounts of $^3$He. But GCE models that use these standard $^3$He yields produce $^4$He/H abundance ratios in the ISM that are much higher than are observed. This "$^3$He problem" can be resolved if most stars undergo extra mixing as predicted by models that include the thermohaline instability. Yet there are a few PNe (NGC 3242, J320, and IC 418) with $^3$He/H abundance ratios consistent with the standard models, indicating that not all low-mass stars undergo extra mixing.

Recent GBT observations of NGC 3242, however, reveal that the detection of $^3$He$^+$ in this PN is not real. A mere detection of $^3$He$^+$ is at the limit of most radio facilities, and therefore each claimed detection must be carefully scrutinized. Moreover, the detection of $^3$He$^+$ in IC 418 is suspect given the lack of any serious tests of the spectral baselines, together with discrepancies in the measured RRL parameters.

Here we observe $^4$He$^+$ at 8665.65 MHz in J320 made with the JVLA in the D configuration to confirm a previous $^3$He$^+$ detection with the older VLA and to produce a definitive result. Our more sensitive observations do not detect the $^3$He$^+$ transition with an rms noise of 58.8 $\mu$Jy beam$^{-1}$. We estimate an abundance ratio limit for J320 of $^3$He/H $\leq 2.75 \times 10^{-3}$ by number using the radiative transfer code NEBULA. Based on $^3$He data, there is no longer strong evidence that some low-mass stars do not undergo extra mixing.

We also explore extra mixing by using the $^{12}$C/$^{13}$C abundance ratio in PNe. Taking $^{12}$C/$^{13}$C data from the literature, we find one PN, M1-17, that is consistent with standard stellar yields, indicating that at least some low-mass stars do not undergo extra mixing. The high $^{12}$C/$^{13}$C ratio of 22 in M1-17 needs to be confirmed, however, by observations of HCN or similar tracers instead of CO, which is susceptible to selective dissociation.

We thank an anonymous referee for valuable comments that improved this paper. We thank Letizia Stanghellini for discussions about planetary nebulae and the initial-to-final mass relation. Emmanuel Momjian provided technical information about the VLA and JVLA. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work is supported by NSF grant AST1714688 to T.M.B. This research has made use of NASA’s Astrophysics Data System Bibliographic Services.

Facilities: VLA.

Software: Astropy (Astropy Collaboration et al. 2013), CASA (McMullin et al. 2007), Matplotlib (Hunter 2007), NumPY & SciPy (van der Walt et al. 2011), WISP (Wenger 2018), NEBULA (Balser & Bania 2018).

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Figure 10. $^{12}$C/$^{13}$C abundance ratios in PNe based on observations (symbols) and models (curves) as a function of progenitor mass. See Figure 9 for details. We only include low-mass progenitor stars ($M_i \leq 2$). All PNe with progenitor masses derived using parallax distances (filled symbols) require extra mixing processes to account for their $^{12}$C/$^{13}$C abundance ratios. The PN M1-17 is labeled in the plot.
