Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution
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^{3}He Abundances in Planetary Nebulae

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Abstract. Determination of the ^{3}He isotope is important to many fields of astrophysics, including stellar evolution, chemical evolution, and cosmology. The isotope is produced in stars which evolve through the planetary nebula phase. Planetary nebulae are the final evolutionary phase of low- and intermediate-mass stars, where the extensive mass lost by the star on the asymptotic giant branch is ionised by the emerging white dwarf. This ejecta quickly disperses and merges with the surrounding ISM.

^{3}He abundances in planetary nebulae have been derived from the hyperfine transition of the ionised ^{3}He, ^{3}He$^+$, at the radio rest frequency 8.665 GHz. ^{3}He abundances in PNe can help test models of the chemical evolution of the Galaxy.

Many hours have been put into trying to detect this line, using telescopes like the Effelsberg 100m dish of the Max Planck Institute for Radio Astronomy, the National Radio Astronomy Observatory (NRAO) 140-foot telescope, the NRAO Very Large Array, the Arecibo antenna, the Green Bank Telescope, and only just recently, the Deep Space Station 63 antenna from the Madrid Deep Space Communications Complex.

Keywords. circumstellar matter – radio: abundances, planetary nebulae.

1. Introduction

Our Universe has been evolving for 13.8 Gyr. Over these years many stars formed and ended their lives enriching the interstellar medium (ISM), and in consequence enriching the Universe (Planck Collaboration *et al.* 2014). Very few elements have been around since the beginning, formed by the Big Bang nucleosynthesis (BBN). BBN is responsible for the formation of most of the helium isotope (^{4}He) in the Universe, along with small amounts of deuterium (D), the helium isotope (^{3}He), and a very small amount of the lithium isotope (^{7}Li) (Alpher *et al.* 1948).

The predicted abundance (by number) of ^{3}He (relative to H) formed by the BBN (just after a few minutes after the Big Bang) is 1.0×10^{-5} (Karakas & Lattanzio 2014). This abundance depends mainly on the parameter of the current density of baryonic matter. The present interstellar ^{3}He abundance, as per all the light elements, comes from a combination of BBN and stellar nucleosynthesis (Wilson & Rood 1994). H II regions are young objects compared with the age of the Universe, and represent zero-age objects. Their ^{3}He abundance is the result of 13.8 Gyr of Galactic chemical evolution. In between is the Solar System, which traces abundances at the time of its formation, 4.6 Gyr ago.

Observed values in pre-solar material (Geiss 1993) and the ISM (Gloeckler & Geiss 1996) imply that ^{3}He/H=$(2.4\pm0.7)\times10^{-5}$. These values from the ISM and pre-solar material are approximately twice that produced by the BBN, implying that the ^{3}He abundance has increased a little in the last 13.8 Gyr. On the other hand any hydrogen-burning zone of a star which is not too hot ($>7\times10^6$ K) will produce ^{3}He via the *p-p* chain, implying that stars of masses $<2.5\,M_\odot$ are net producers of ^{3}He. For those stars,

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p-p burning is rapid enough to produce D *in situ*, and enables the production of ^{3}He (D+ p $\rightarrow$ ^{3}He + γ). Stellar evolution models indeed predict the formation of ^{3}He in significant amounts by stars of 1–2.5 $M_\odot$, yielding an abundance of ^{3}He/H $> 10^{-4}$ (Bania *et al.* 2010), which would have raised the current ^{3}He abundance to ^{3}He/H$\sim 5 \times 10^{-5}$, substantially higher than observed (Karakas & Lattanzio 2014).

Galli *et al.* (1995) presented "The ^{3}He Problem". According to standard models of stellar nucleosynthesis there should be a ^{3}He/H abundance gradient in the Galactic Disk and the pre-solar ^{3}He/H value should be less than what is found in the present ISM. Observations of the ^{3}He abundance in H II regions show almost no enrichment above the BBN value (Rood *et al.* 1979; Bania *et al.* 2007). For the ^{3}He problem to be solved, the vast majority of low-mass stars should fail to enrich the ISM. One suggestion to solve this problem is by adding extra mixing in the red giant branch (RGB) stage. This extra mixing during the standard first dredge-up phase may modify the surface abundances. Eggleton. *et al.* (2006) estimated that while 90% of the ^{3}He is destroyed in 1 $M_\odot$ stars, only 40-60% is destroyed in a 2 $M_\odot$ star model, depending on the speed of mixing.

2. Detecting the ^{3}He$^+$ emission line

The abundance of ^{3}He has been derived from the hyperfine transition at the rest frequency of 8.665 GHz. Detecting ^{3}He$^+$ in PNe challenges the sensitivity limits of all the existing radio telescopes. Composite ^{3}He$^+$ average spectra for six planetary nebulae (NGC 3242, NGC 6543, NGC 6720, NGC 7009, NGC 7662, and IC 289), were collected using the Effelsberg, Arecibo and Green Bank telescopes. They all consistently show possible ^{3}He$^+$ emission at the $\sim$1 mK level. Using the same telescopes later on, a detection was obtained in NGC 3242 and J320. Those detections and the composite spectrum measurements translate into an abundance of ^{3}He/H of a few 10^{-4} (Balser *et al.* 1997, 1999, 2006).

Later on more effort was put into this problem, using the Very Large Array, for several tens of hours 3 planetary nebulae were observed (IC 418, NGC 6572, and NGC 7009). Unfortunately no line was detected and only upper limits in the abundance were obtained (Guzman-Ramirez *et al.* 2013). Recently (beginning of this year) Guzman-Ramirez *et al.* (2016), using the Deep Space Station 63 antenna from the Madrid Deep Space Communications Complex, another ^{3}He$^+$ detection was obtained in the planetary nebula IC 418. With more than 20 years of looking for such detections, so far we have only 3 objects with more than a 3σ detection of ^{3}He: J320, NGC 3242, and IC 418.

Two aspects of these detections needs to be considered. Firstly, the derived ^{3}He$^+$ abundance is well above the model expectations for all the three objects. This tells us that the stars do produce and release ^{3}He into the interstellar medium. Secondly, the ^{3}He$^+$ line profile for all the three objects shows a double peaked shape. Although the full width of the ^{3}He$^+$ line is consistent with the optical expansion velocity, the profile differs from that of the recombination lines, peaking at larger velocities.

Two other planetary nebulae have reported ^{3}He$^+$ detections: J320 (Balser *et al.* 2006) and NGC 3242 (Balser *et al.* 1997, 1999). Both have double peaked profiles, similar to IC 418 (Fig. 1). Both objects have haloes, and in the case of NGC 3242 possibly as large as 18 by 24 arcmin in size. Whether helium in such a halo could be photo-ionized by the star is not clear. A double-peaked profile could arise from an expanding detached shell, which is larger than the beam of the telescope. In this case, the outer components of the profile, which differs that of the recombination lines, come from this large region, whilst the central part of the profile arises from the inner, ionized nebula. Balser *et al.* (1999) also proposed a contribution from a large, low density halo. The emission in the ^{3}He$^+$

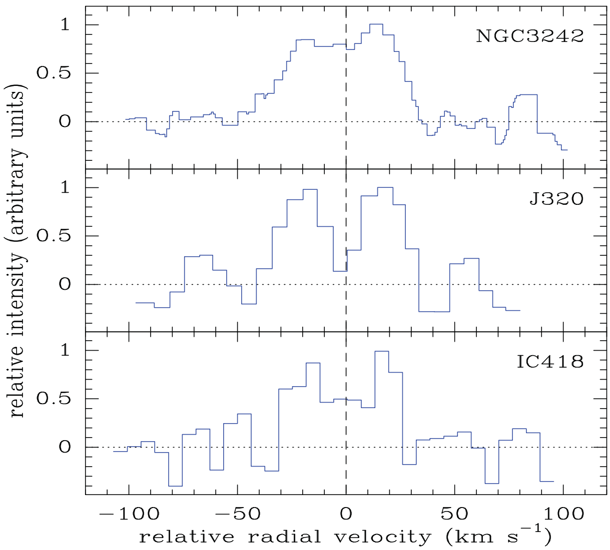

Figure 1. All the ^{3}He$^+$ line detected in planetary nebulae. The sources are NGC 3242 (Balser *et al.* 1999), J320 (Balser *et al.* 2006), and IC 418 (this work). In order to facilitate the comparison, the abscissa is presented as radial velocities relative the LSR systemic velocity of each source (dashed-line), and the intensity scale as fractions of the peak intensity of each source.

hyperfine line scales with $\int n\,dr$ (column density), while that of the recombination lines with $\int n^2\,dr$. Therefore, a low density but high mass halo could explain the difference in profiles.

3. Stellar evolution

The contribution of PNe to the ^{3}He abundance is crucial for understanding the Galactic chemical evolution. The number density of ^{3}He$^+$ atoms, $n(^3\mathrm{He}^+)$, can be obtained by dividing the column density $N(^3\mathrm{He}^+)$ by the averaged optical path, $< \Delta s >$, through the source. Representing a PN as a homogeneous sphere of radius $R = \theta_s D$, where D is the distance, the optical path at an angle θ from the centre is $\Delta s(\theta) = 2\sqrt{R^2 - (\theta D)^2}$, and the optical path averaged over the source becomes $< \Delta s >= \pi R/2 = \pi\theta_s D/2$. To calculate the fractional ^{3}He abundance we divide $n(^3\mathrm{He}^+)$ thus obtained by the H$^+$ density.

Figure 2 shows the ^{3}He abundances of PN IC 418 (the two purple crosses, taken from Guzman-Ramirez *et al.* (2016)). For comparison the upper limits calculated from Guzman-Ramirez *et al.* (2013) observations are presented using the red arrows. Balser *et al.* (1997) observations are shown in green: the cross represents J320 and the arrows are the upper limits, where the mass estimates are from Galli *et al.* (1997). The stellar evolution models are also presented in the same figure.

4. Future

The values observed in these objects proves that ^{3}He is produced at the centre of low-mass stars, and is ejected into the interstellar medium at the end of their lives. However, the large amounts of ^{3}He produced in these models is at odds with the abundance of ^{3}He observed in the interstellar medium and the Solar System. Further research on other planetary nebulae will be needed to solve the ^{3}He problem. As the emission is extremely

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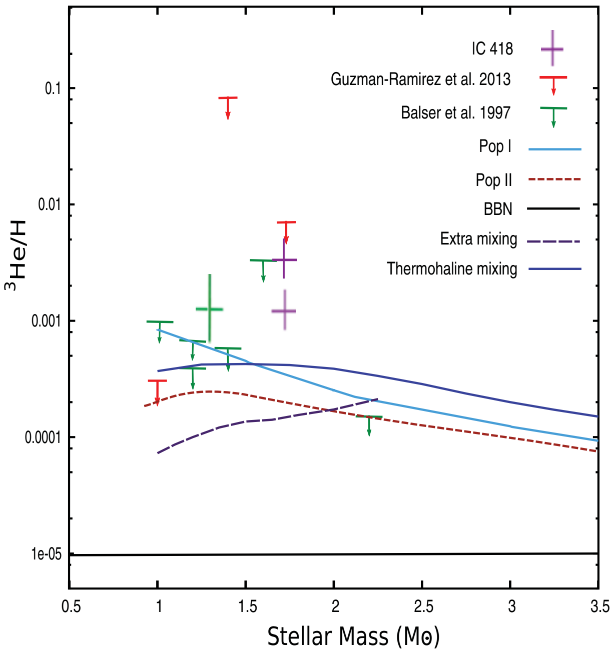

Figure 2. Abundances of ^{3}He (relative to H) for the PN IC 418 (purple crosses, for upper and lower estimates), the size of the bars corresponds to the uncertainty. Red arrows are the upper limits from Guzman-Ramirez *et al.* (2013). The green cross represents J320 and the green arrows represent the sample of 6 PNe from Balser *et al.* (1997). The curves for Pop I (light-blue line) and II (red dashed-line) show the standard abundance of ^{3}He taken from Weiss *et al.* (1996). The purple dashed-line labelled Extra mixing represents the results of models including deep mixing by Boothroyd & Sackmann, (1999), and the blue line shows the stellar models using thermohaline mixing (Charbonnel & Zahn 2007). The black line is the primordial value of ^{3}He/H from the BBN (Karakas & Lattanzio 2014).

weak and hard to detect, many observing hours are needed. Telescopes of high sensitivities like the Square Kilometre Array will be very useful for this research.

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Discussion

MENDEZ: What is the source of your distance to IC418? If the distance is a bit larger, your abundance would go down a little.

GUZMAN-RAMIREZ: The distance was measured using the expansion parallax technique that gives you a very accurate distance. But yes if the distance is higher the abundance goes lower.

GUERRERO: There is not a known halo around IC418. What's the beam size of Robledo antennae? The $^3He^+$ line probably probing a different component than other ionized species do.

GUZMAN-RAMIREZ: The beam size is $115''$ which is very big. So yeah the ^{3}He emission is probably coming from a different component.

Q: Are there destruction mechanisms (e.g. spallation) that could reduce the interstellar ^{3}He abundances from the PN values to what is observed in H IIregions?

GUZMAN-RAMIREZ: Yes, spallation is a possible mechanism. The problem is that it hasn't been tested in the lab yet, so we don't know how much ^{3}He can bed estroyed in the ISM.

Q: 1) Have you considered observing the ^{3}He line at Arecibo? 2) The line widths of the ^{3}He recombination line are > 25 km/s – too large to be associated with a halo. Is there another explanation for the location of ^{3}He emission?

GUZMAN-RAMIREZ: 1) Arecibo is a good option that will be considered; 2) Yes, we are not sure about the halo so we are exploring other possibilities.