The cosmic saga of $^3$He

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Abstract. We recall the emergence of the “$^3$He problem”, its currently accepted solution, and we summarize the presently available constraints on models of stellar nucleosynthesis and studies of Galactic chemical evolution from measurements of the abundance of $^3$He in the Galaxy.

1 In the beginning was tralphium

The isotope $^3$He probably first entered the astrophysical arena in 1949 with the (unpublished) calculations of Fermi & Turkevich concerning the chemical evolution of the first half-hour of the Universe. The names “tralphium” and “tralphparticles” invented by George Gamow for this isotope and its nuclei, have survived only in his humourous description of nucleogenesis: And God said: “Let there be mass three.” And there was mass three. And God saw tritium and tralphium, and they were good”. And so on to transuranium elements, with Fred Hoyle’s help to bridge the gap at mass five (Kragh 1996). The rough estimate of by Fermi & Turkevich ($^3$He $\sim 10^{-2}$ by mass) was later refined by more detailed calculations, like e.g. those of Wagoner, Fowler, & Hoyle (1967) who showed that $^3$He could be produced at levels comparable to its terrestrial abundance ($\sim 5 \times 10^{-5}$ by mass) during the evolution of a “universal fireball or a supermassive object”, or, as we say today, in the big bang. Thus, at least in principle, the abundance of $^3$He could be used (together with D, $^4$He and Li) to test theoretical predictions, and, in particular, to constrain the baryon density of the Universe. Having gained the special status of “cosmic baryometer” and caught the attention of cosmologists, the interest in $^3$He spread rapidly in the astronomical community.

2 Trouble ahead

At around the same time, Iben (1967) and Truran & Cameron (1971) showed that ordinary stars produce $^3$He in the ashes of hydrogen burning by $p-p$ cycle on the main sequence. They found that the stellar production of $^3$He roughly scales as $M^{-2}$, where $M$ is the mass of the star, indicating that low-mass stars ($M \approx 1-3 M_\odot$) are the dominant site of $^3$He production in the Galaxy. Problems followed soon, when Rood, Steigman, & Tinsley (1976) incorporated the stellar production of $^3$He in simple models of Galactic chemical evolution, and found the predicted present-day abundances to be larger by orders of magnitude than the
value measured in samples of gas-rich meteorites, representative of interstellar medium abundances at the time of formation of the Sun. The paper by Rood, Steigman, & Tinsley (1976) marked the first appearance of the $^3$He problem”. However, additional observations of $^3$He in the Galaxy were needed to confirm the extent of the discrepancy.

### 3 Observing $^3$He

Radioastronomers first learned of $^3$He in 1955 at the fourth I.A.U. Symposium in Jodrell Bank, when the frequency of the hyperfine $^3$He$^+$ line at 8.666 GHz (3.46 cm) was included by Charles Townes in a list of “radio-frequency lines of interest to astronomy” (Townes 1957). The line was (probably) detected for the first time only twenty years later, by Rood, Wilson & Steigman (1979) in W51, opening the way to the determination of the $^3$He abundance in the interstellar gas of our Galaxy via direct (although technically challenging) radioastronomical observations. In the last two decades, a considerable collection of $^3$He$^+$ abundance determinations has been assembled in H$^\text{ii}$ regions and planetary nebulae. The relevance of these results will be discussed in Sect. 4 and 5 respectively.

For many years, meteorites have provided the only means to determine the abundance of $^3$He in protosolar material. The values obtained by mass spectroscopy techniques in the so-called “planetary” component of gas-rich meteorites have been critically examined by Geiss (1993) and Galli et al. (1995). The latter recommend the value $^3$He/$^4$He = $(1.5 \pm 0.1) \times 10^{-4}$. The meteoritic value has been confirmed by in situ measurement of the He isotopic ratio in the atmosphere of Jupiter by the Galileo Probe Mass Spectrometer. The isotopic ratio obtained in this way, $^3$He/$^4$He = $(1.66 \pm 0.04) \times 10^{-4}$ (Mahaffy et al. 1998), is slightly larger than, but consistent with, the ratio measured in meteorites, reflecting possible fractionation in the protosolar gas in favor of the the heavier isotope, or differential depletion in Jupiter’s atmosphere.

The He isotopic ratio in the present day local ISM (inside and beyond the heliosphere at 3–5 AU from the Sun) has been determined by two recent space experiments, and the two results agree within the uncertainties. Helium atoms entering the solar system from the surrounding interstellar cloud and ionized deep inside the heliosphere (the so-called “pick-up” ions), analyzed by the Solar Wind Ion Composition Spectrometer on the Ulysses spacecraft, show an isotopic ratio $^3$He/$^4$He = $(2.5^{+0.7}_{-0.6}) \times 10^{-4}$, with the uncertainty resulting almost entirely from statistical error (Gloecker & Geiss 1998). In the Collisa experiment on the Russian space station Mir, on the other hand, samples of the local neutral ISM were collected on thin metal foils exposed to the flux of interstellar particles, and later analyzed in terrestrial laboratories. The He isotopic ratio measured in this way is $^3$He/$^4$He = $(1.7 \pm 0.8) \times 10^{-4}$ (Salerno et al. 2003).
The age of reason

The old problems have now largely been overcome, and new ones have appeared. As for the cosmological implications, thanks to the continuing effort of Rood and collaborators over more than two decades to determine $^3$He abundances in HII regions (see contribution by Bania et al. in these proceedings), the usefulness of this isotope as a cosmic baryometer has now been fully established. The trend (or better, the absence of a trend) of $^3$He vs. metallicity in a sample of about 40 HII regions reveals the existence of a $^{\text{aHe plateau}}$ at $^3$He/H = $(1.1\pm0.2)\times10^{-5}$, similar in many ways to the celebrated “Li plateau”. The resulting baryon-to-photon ratio $\eta_{10} = 5.4^{+2.2}_{-1.2}$ (Bania, Rood & Balser 2002) is in agreement with other independent determinations of this fundamental cosmological parameter. After fifty years, the program started by Fermi & Turkevich’s theoretical prediction of “tralphium” production in the early universe seems to have reached its fulfillment.

As for the discrepancy between observed abundances of $^3$He and the predictions of models of Galactic chemical evolution, the natural explanation of the problem was found by Charbonnel (1995) and Hogan (1995) in the existence of a non-standard mixing mechanism acting in low-mass stars during the red-giant branch evolution or later, leading to a substantial (or complete) destruction of all their freshly produced $^3$He. In this way, the $^{\text{aHe problem}}$ was reduced to “just another” isotopic anomaly, similar to those commonly observed in the atmospheres of giant stars for elements like carbon and oxygen, as originally suggested by Rood, Bania & Wilson (1984) almost ten years earlier. The characteristics of this mixing mechanism, and the attempts to identify a physical mechanism responsible for its occurrence (rotation?) have been nicely reviewed by Charbonnel (1998), and will not be repeated here. For an impressive demonstration of the effects of extra-mixing on the carbon isotopic ratio in globular cluster stars, the reader should look at Fig. 2 of Shetrone (2003).

Fig. 1 (adapted from Fig. 4 of Romano et al. 2003) shows the evolution of $^3$He/H in the solar neighborhood, computed with the model of Tosi (2000) assuming the standard (without extra-mixing) stellar yields of Dearborn, Steigman, & Tosi (1996) and the extra-mixing yields of Boothroyd & Sackmann (1999) for 90% ans 10% of stars with $M < 2.5 \, M_\odot$ (see Galli et al. 1997 and Romano et al. 2003). Symbols and errorbars show the $^3$He/H value measured in: meteorites (Galli et al. 1995); Jupiter’s atmosphere (Mahaffy et al. 1998); the local ionized ISM (Gloecker & Geiss 1998); the local neutral ISM (Salerno et al. 2003); the sample of “simple” HII regions (Balser et al. 2002). The primordial abundance of $^3$He corresponding to the baryon-to-photon ratio determined by WMAP (Spergel et al. 2003) is indicated by an atow at $t = 0$. Taken together, the observational data support the hypothesis that negligible changes of the abundance of $^3$He have occurred in the Galaxy during the past 4.55 Gyr. The failure of the standard $^3$He yields to account for the measured abundances is not a peculiarity of the particular Galactic model shown in Fig. 1, as the interested reader may see in Fig. 6 of Tosi (1998). It should be noted however that the discrepancy with the observational data is rather model dependent.
Fig. 1. Evolution of $^3\text{He}/\text{H}$ in the solar neighborhood, computed without extra-mixing (upper curve) and with extra-mixing in 90% or 100% of stars $M < 2.5 \, M_\odot$ (lower curves). The two arrows indicate the present epoch (assuming a Galactic age of 13.7 Gyr) and the time of formation of the solar system 4.55 Gyr ago. Symbols and errorbars show the $^3\text{He}/\text{H}$ value measured in: meteorites (empty squares); Jupiter’s atmosphere (errorbar); the local ionized ISM (filled triangle); the local neutral ISM (filled circle); the sample of “simple” H ii regions (empty circles). Data points have been slightly displaced for clarity. The He isotopic ratios has been converted into abundances relative to hydrogen assuming a universal ratio He/H = 0.1. See text for references.

It is evident from Fig. 1 that consistency with the observed abundance of $^3\text{He}$ in the Galaxy is achieved only if the fraction of low-mass stars ($M < 2.5 \, M_\odot$) undergoing extra-mixing is larger than $\sim 90\%$, assuming the $^3\text{He}$ yields of Boothroyd & Sackmann (1999). Thus, to solve the $^3\text{He}$ problem in terms of extra-mixing in low-mass stars, the vast majority of them (90%–100%) must be affected by this phenomenon (Galli et al. 1997). The same conclusion has been reached independently by Charbonnel & do Nascimento (1998) on the basis of the statistics of carbon isotopic ratios in a sample of red-giant stars with accurate Hipparcos parallaxes.

5 A final touch: planetary nebulae

The most direct, model independent, way to test the validity of the mixing solution is to measure the $^3\text{He}$ abundance in the ejecta of low-mass stars, i.e. in planetary nebulae (PNe). The search for $^3\text{He}$ in the ejecta of PNe via the 8.667 GHz spin-flip transition of $^3\text{He}^+$, painstakingly carried out by Rood and
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Fig. 2. Abundance of $^3$He vs. main-sequence masses (determined by Galli et al. 1997) for the six PN of the sample of Balser et al. (1997) and Balser, Rood, & Bania (1999). The curves labeled “Pop I” and “Pop II” show the “standard” abundance of $^3$He computed by Weiss, Wagenhuber, & Denissenkov (1996) for two metallicities. The curves labeled “with extra-mixing” show the results of stellar nucleosynthesis calculations with deep mixing by Boothroyd & Sackmann (1999) (upper curve) and the equilibrium value $^3$He/H = $10^{-5}$ for $M < 2.5 M_\odot$ (lower curve).

coworkers at the Green Bank radiotelescope since 1992 (see summary of results in Balser et al. 1997), has produced so far one solid detection (NGC 3242, see Rood, Bania, & Wilson 1992; confirmed with the Effelsberg radiotelescope by Balser, Rood, & Bania 1999), two tentative detections (IC 289, NGC 6720) and three upper limits (NGC 7662, NGC 6543, NGC 7009). One more detection has been recently obtained with the NRAO VLA in the PN J320 (Balser et al., these proceedings). All these objects can be placed in the progenitor mass–$^3$He diagram (see details of the procedure in Galli et al. 1997), and compared with the predictions of stellar models with and without extra-mixing (Fig. 2). Ironically enough, the position of the six PNe definitely supports the standard $^3$He yields, in particular the (only) solid detection of the sample, NGC 3242. Although the statistical significance of the sample is questionable, and selection biases are certainly present, the only way to reconcile Fig. 1 with Fig. 2 is to conclude that most, if not all, the PNe shown in Fig. 2 belong to the 10% (or less) of low-mass stars which did not experience extra-mixing.
6 Conclusions

We have learned many things about Gamow’s tralphium since 1949. A personal selection includes: (1) the abundance of $^3\text{He}$ has not changed significantly over $\sim 14$ Gyr of Galactic evolution, which is remarkable; (2) it has not changed not because nothing happened, but because two independent processes of opposite sign and equal magnitude were at work, which is truly remarkable; (3) one object does not make a statistically significant sample; (4) many objects do not make it either, if they are selected carefully enough.

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