Abundance Patterns in Planetary Nebulae

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Abstract. We previously determined abundances of He, C, N, O, and Ne for a sample of planetary nebulae (PNe) representing a broad range in progenitor mass and metallicity, and we now compare them with theoretical predictions of PNe abundances from a grid of intermediate-mass star models. We find very good agreement between observations and theory, lending strong support to our current understanding of nucleosynthesis in stars below 8M☉ in birth mass. In particular, C and N abundance patterns are consistent with the occurrence of hot-bottom burning in stars above roughly 3.5M☉, a process that converts much of 12C into 14N during the AGB phase. This agreement also supports the validity of published stellar yields of C and N in the study of the abundance evolution of these elements.

1. Introduction

Massive stars (>8M☉) are the principal, and in most cases, the sole, source of elements beyond He. However, for the elements C and N, origins are more ambiguous. Intermediate-mass stars (IMS; 1≤M≤8 M☉) are hot enough in their cores and fusion shells to produce C via He-burning and N via the CNO cycle. Recent theoretical results indicate significant C and N production in IMS (van den Hoek & Groenewegen 1997 (VG); Marigo, Bressan, & Chiosi 1996 (MBC), 1998). Likewise, massive stars, too, synthesize and expel significant C and N (Woosley & Weaver 1995; Nomoto et al. 1997; Maeder 1992). Over the whole stellar mass range, the general conclusion is that N comes predominantly from IMS, while both IMS and massive stars contribute to C.

We compare the set of abundances we determined for a sample of 20 PNe over a broad range in progenitor mass and metallicity with PN abundances predicted from stellar yield calculations of VG and MBC.
2. Abundance Calculations

The heart of our method for determining abundances is the standard one in which abundances of observable ions for an element are first determined using a 5-level atom calculation for each ion. Then these ionic abundances are summed together and multiplied by an ionization correction factor (ICF) which adjusts the sum upward to account for unobservable ions. Finally, this product is in turn multiplied by a model-determined factor $\xi$ which acts as a final correction to our elemental abundance. Our modelling method has been discussed in detail most recently in Henry, Kwitter, & Dufour (1999). Our abundance results along with nebular diagnostics are contained in Henry, Kwitter, & Howard (1996), Kwitter & Henry (1996, 1998) and Henry & Kwitter (1999). Results for the entire sample are reported in full in Table 6 of Henry & Kwitter (1999).

3. IMS Nucleosynthesis: Models Versus Observations

Compilations of observed abundances in PNe, such as those by Henry (1990) and Perinotto (1991) provide strong evidence that IMS synthesize He, C, and N. We can infer that directly by comparing abundance patterns in our PN sample with patterns in the interstellar medium, i.e. H II regions and stars. The two figures show log(C/O) and log(N/O) vs. 12+log(O/H), respectively, for our PN sample (filled diamonds) along with Galactic and extragalactic H II region data (open circles) compiled and described in Henry & Worthey (1999) and F and G star data (open triangles; left-hand figure only) from Gustafsson et al. (1999). Also shown are the positions for the sun (S; Grevesse et al. 1996), Orion (O; Esteban et al. 1998), and M8 (M; Peimbert et al. 1993; left-hand figure only).

Note in the left-hand figure that in contrast to the relatively close correlation between C and O displayed by the H II regions and stars, there is no such relation indicated for PNe. In fact the range in C is over 2.5 orders of magnitude, far greater than for the H II regions and stars and larger than can be explained by uncertainties in the abundance determinations. In addition, C levels in PNe appear on average higher than those typical of H II regions for the same O value, indicating that additional C above the general interstellar level present at the time these stars formed, was produced during their lifetimes. The right-hand figure shows similar behavior for N: H II regions seem to suggest a relation between N/O and O/H in the interstellar medium, yet we see no such pattern for PNe. Also, N/O tends to be systematically higher for PNe than for H II regions, again suggesting that N is produced by PN progenitors.

These figures imply that C and N are synthesized in IMS; evidence from Ne/O strengthens this contention. Limited space prohibits inclusion of a similar figure that shows a constant value for Ne/O over a range in O abundance; the pattern displayed by PNe is indistinguishable from that of the H II regions. For a full discussion see Henry & Worthey (1999).

4. Comparison with Predicted Yields

We used our PN abundance results to test the theoretical predictions of PN abundances; for details see Henry & Kwitter (1999). We tested two published
sets of theoretical calculations. VG calculated a grid of stellar models ranging in mass fraction metallicity between 0.001 and 0.04 and progenitor mass of 0.8 to 8 M_☉. Likewise, MBC calculated models for mass fraction metallicity of 0.008 and 0.02 for stars between 0.7 and 5 M_☉. Both teams employed up-to-date information about opacities and mass loss to calculate yields for several isotopes, including ^4He, ^12C, ^13C, and ^14N.

The progenitor metallicity range consistent with our results is between 1/20 solar and solar. We found that observed abundances of C vs. O are consistent with predictions for both high- and low- mass progenitors. At all metallicities the C abundance is initially predicted to rise with mass but then drop back to low values as mass continues to increase above 2-3 M_☉. This reversal is the result of hot-bottom burning in stars with greater masses than this in which C from the 3rd dredge-up is converted to N at the base of the convective envelope late in the AGB stage.

For N vs. O, the predicted behavior with progenitor mass is positively monotonic and is consistent with our abundances. Apparently the C and N abundances observed in PNe are consistent with progenitor masses in the range of 1-4 M_☉.

Consideration of N vs. He reinforces our conclusions about the PN progenitor mass range. Theoretical abundance predictions for progenitors in the 1-4 M_☉ range are consistent with our observations. The one extreme outlier is PB6, whose unusually high He abundance (He/H=0.20) needs to be confirmed independently.

Our detailed comparison of observed PN abundances with predicted ones has demonstrated good agreement between the two and is indeed encouraging. To the extent to which predicted PN abundances are related in turn to the actual stellar yields, our comparison provides what we believe to be the best empirical support yet for the theoretical calculations. It is imperative, however, that these models continue to be tested with larger samples of PNe whose abundances have been carefully determined. As this is done, we will be better able to ascertain the exact role that intermediate mass stars play in the synthesis of C, N, and He in galaxies.
5. Summary

- Abundances of C and N in PNe, when plotted against O, show a much broader range than H II regions and F and G stars and are generally higher. At the same time, both O and Ne display similar patterns in both PNe and H II regions. Taken together, these results support the idea the PN progenitors synthesize significant amounts of C and N.

- Abundances of C, N and He found in our sample of PNe are consistent with model predictions. We believe that this is the first time that such a detailed comparison of observation and theory has been possible and that the results provide encouragement for the use of published yields of intermediate mass stars in studying galactic chemical evolution, especially in the cases of C and N.

- Our comparisons of observed and predicted PN abundances support the occurrence of hot-bottom burning in stars above about 3.5-4 M_☉.

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