The Discovery of Heavy Elements (Z > 30) in NGC 7027

D. Péquignot[1] and J.–P. Baluteau[2]

[1]Observatoire de Meudon; [2]Laboratoire d'Astronomie Spatiale, Marseille

An important aim of nebular spectroscopy is the identification of new elements. Since the pioneering work of Bowen (1928), who identified the "nebulium" lines with forbidden lines of abundant elements, most elements in nebulae have been discovered thanks to forbidden lines. The number of elements known in planetary nebulae and H II regions was 2, 5, 15, 17, and 20 in 1896, 1927, 1938, 1960, and 1975 respectively.

Thus, despite extraordinary improvements of equipment, the identification of new elements in the optical spectrum of classical nebulae did not significantly progress for one third of a century, that is since the end of Bowen's scientific activity. The last new detection goes back two decades. Until very recently the heaviest element known in classical nebulae was Nickel (Z = 28) and no element heavier than Copper (Z = 29) had ever been detected in any nebular object.

Apparently a serious search for "heavy elements", that is elements beyond the Iron peak (Z > 30), has not been undertaken in nebulae. One possible explanation is that solar-system abundances of heavy elements look discouragingly low (no more than $\sim 10^{-9}$ and 10^{-10} by number relative to H on the fourth and fifth rows of the Periodic Table).

However it was suspected for long (Burbidge et al., 1957) and it is now well established on both theoretical (e.g., Iben, 1991) and observational (e.g., Lambert, 1991) grounds, that low- and intermediate-mass stars ($M \leq 8M_{\odot}$) are important sites of heavy-element synthesis by slow neutron captures on ^{56}Fe seeds, during the Asymptotic Giant Branch (AGB) and post-AGB phases. Low-mass stars ascending the AGB eventually evolve into carbon stars which end as carbon-rich planetary nebulae after expelling their envelope. In these stars, freshly synthesized carbon is brought up to the surface by the so-called "third dredge up", which is an accepted consequence of thermal pulses occuring in the helium-burning shell along the AGB (e.g., Iben, 1991). According to present views, these pulses may provide favourable conditions for the operation of the so-called "main s-process" of neutron capture via $^{13}C(\alpha, n)^{16}O$ (Lambert, 1991; Busso et al., 1993), corresponding to the synthesis of s-nuclides with atomic mass $A \geq 85$, that is Krypton and beyond (Käppeler et al., 1989).

The enrichment of typical s-elements observed in AGB stars can reach a factor of 10 or more (Lambert, 1991) and the search for heavy elements in planetary nebulae may not be as hopeless as often believed since even more extreme enrichments may be expected in a more advanced stage of evolution.

In this context, the bright carbon-rich planetary nebula NGC 7027 appears as a good target. Deep optical spectra of NGC 7027 were secured with the CARELEC spectrometer attached to the 193 cm telescope of Observatoire de Haute-Provence. Following an effort toward full identification of permitted lines from common elements, a systematic search for new forbidden and fine-structure lines was undertaken, leading to many new convincing identifications. As a result the number of elements detected in nebulae was increased from ~20 to ~30 (Péquignot & Baluteau, 1994; Baluteau et al., 1995; Péquignot et al., in preparation). In particular, elements with atomic number $Z > 30$ were detected for the first time in a nebula.

Based on a current total of 21 undoubtful emission lines, 15 ions belonging to 8 different elements are considered as certainly or probably detected: [XeVI], [PbII] in p^1, [SeIII], [KrV] (2 lines) in p^2, [BrIII], [KrIV] (3 lines), [SrVI], [XeIV] (2 lines), [BaV] in p^3, [KrIII], [RbIV], [XeIII] (2 lines) in p^4, [SrIV], [BaIV] in p^5, and a permitted multiplet of the 6s ion BaII (2 lines). In this list, the identifications of [BaV] and [PbII] are fragil. A dozen more features quoted by Péquignot & Baluteau (1994) are currently under investigation.

In conclusion, elements Krypton (Z = 36), Xenon (Z = 54), Bromine (Z = 35), Selenium (Z = 34), Rubidium (Z = 37), Strontium (Z = 38) and Barium (Z = 56) are certainly or probably detected in NGC 7027. Lead (Z = 82) and Yttrium (Z = 39) are suspected.

The strength of the newly identified lines almost certainly implies that these elements are at least ten times more abundant in NGC 7027 than in the solar system, confirming that the capture of neutrons onto iron-peak seed nuclei is very effective in progenitor stars of planetary nebulae and showing directly that the by-products of this nucleosynthesis are injected into the interstellar medium.

At first view, the nature of the elements detected is paradoxical in that:
1/ Xenon, predominantly an r–element, was copiously synthesized in a low-mass star,
2/ Krypton and Xenon, predominantly synthesized in very different sites, are enhanced in similar proportions,
3/ Elements typical of the so-called "main s-process component" (Sr, Y, Zr, Ba) are not selectively enhanced in NGC 7027: thus Rubidium shows up as much as Strontium.

However, these results can be reconciled with current ideas about the slow capture of neutrons in stars after noticing that, by some strange coincidence, all of the a priori most enhanced elements are likely to be selectively locked into refractory dust grains. Then the enrichment of NGC 7027 in pure s-nuclides of the main component may approach a factor of a hundred.

It is foreseen that the study of heavy elements in planetary nebulae will provide new important insights into final stages of stellar evolution and chemical evolution of galaxies since several kee elements (particularly Kr and Xe), undetectable in stars, are easily observed in nebulae.

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