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Nitrogen synthesis and the 'age' of galaxies

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Summary. We suggest that recent observations of the [N/O] abundance ratio in external galaxies can be understood if nitrogen is a *primary* nucleosynthesis product, manufactured principally in stars of 1–2.5 $M_\odot$. The [N/O] ratio of a galaxy then becomes an indicator of the time that has elapsed since the bulk of star formation occurred, or in other words the nominal 'age' of the galaxy.

The site of nucleosynthesis of nitrogen has remained something of a mystery. Unlike the majority of heavy elements, which are believed to be synthesized in the supernova explosion of massive (10–40 $M_\odot$) stars, the most likely site for nitrogen synthesis has been assumed to be quiescent CNO processing during stellar evolution, where any pre-existing ^{12}C or ^{16}O in the star are converted fairly completely to ^{14}N. The distinction is often made between 'primary' elements (like oxygen), the amount of whose synthesis is fairly independent of the chemical composition of the supernova precursor star at formation, and 'secondary' elements, the amount of whose synthesis depends directly on the initial composition. It has often been suggested that nitrogen is a secondary element (see, e.g. Truran 1977), but it has recently become apparent (Peimbert 1978) – as we shall also argue here – that there is a substantial primary component.

The abundances of primary and secondary elements in the interstellar medium of a galaxy will increase with time (in a closed system) as gas is converted into successive generations of stars. If there remains a fraction μ of the original gas which has formed into a galaxy, then it is easy to show within the 'simple' model for galactic chemical evolution (see, e.g. Lynden-Bell 1975) in the instantaneous recycling approximation, that the expected abundances of a primary element Z_p will follow the relation:

$$Z_p = k_1 \ln (1/\mu) \tag{1}$$

while a secondary element Z_s will follow:

$$Z_s = \frac{k_1 k_2}{2} [\ln (1/\mu)]^2 \tag{2}$$

where k_1, k_2 are constants.

Thus the ratio of abundances Z_N/Z_O of nitrogen to oxygen, on the assumption that nitrogen is a secondary element, is:

$$\frac{Z_N}{Z_O} = \frac{k_2}{2k_1} \cdot Z_O. \tag{3}$$

If nitrogen were a primary product, then an equation analogous to (1) could be written, and the nitrogen to oxygen ratio would be:

$$\frac{Z_N}{Z_O} = \frac{k_3}{k_1} \tag{4}$$

where k_3 is another constant.

As a final refinement we allow the possibility that, although the supernova synthesis of oxygen gives essentially instantaneous recycling, the nitrogen may come from much longer-lived stars and hence its arrival into the interstellar medium may be delayed. Throughout this paper we assume a constant initial mass function for star formation (although more complicated variants could easily be devised), so that if a given amount of gas is formed into stars, the result will be the synthesis of a given amount of oxygen, and a corresponding amount of nitrogen will appear later. We can incorporate this time dependence into equations (3) and (4) by defining functions of time $f_2(t), f_1(t)$ such that their initial values ($t = 0$) will be small (possibly zero) and then tend to unity after some (long) time τ. Our final equations for secondary and primary synthesis respectively are:

$$\frac{Z_N}{Z_O} = \frac{k_2}{2k_1} \, . \, Z_O f_2(t) \tag{5}$$

$$\frac{Z_N}{Z_O} = \frac{k_3}{k_1} f_1(t). \tag{6}$$

The observational results we seek to explain are the following:

(1) The Sc galaxies NGC 300 and M33, and the outer parts of the giant M101, show no radial gradient in N/O, despite significant variation in O/H (Blackwell *et al.*, in preparation). This argues against equation (5).

(2) Fig. 1 is a version of Fig. 3 of Pagel *et al.* (1978), updated with data for NGC 300 and 1365 from Blackwell *et al.* (in preparation). The plot represents observational N/O determinations, plotted against O/H, for H II regions in a variety of galaxies, together with a very old stellar member (Groombridge 1830) of our own Galaxy. The diagonal dotted line represents equation (3), and bears little resemblance to the observational points.

We propose that the easiest way to explain the observations is by equation (6). The lack of N/O gradients is obvious from this equation, provided all parts of a galaxy have roughly the same age, and by 'age' we mean the time since the bulk of star formation occurred. The slight increase in N/O in the centre of M101 could be explained by a rather older population in the central regions compared with the bluer and perhaps younger outer parts.

The ordinate of Fig. 1 would represent an 'age' in the sense that N/O would increase only as the function $f_1(t)$ of time since the bulk of star formation occurred, and not depend on the overall metal abundance. Assuming that our own Galaxy represents a fairly old system, with most of the star formation occurring early in its history, we might imply that $f_1(t_{\rm now})$ is of order one. Systems such as the Magellanic Clouds would then be younger (as judged by the N/O ratio), the 'cartwheel' A 0035 and the Sc spiral NGC 300 even younger. Groombridge (1830) would represent an object formed at time t_1 out of interstellar material when $f_1(t_1)$

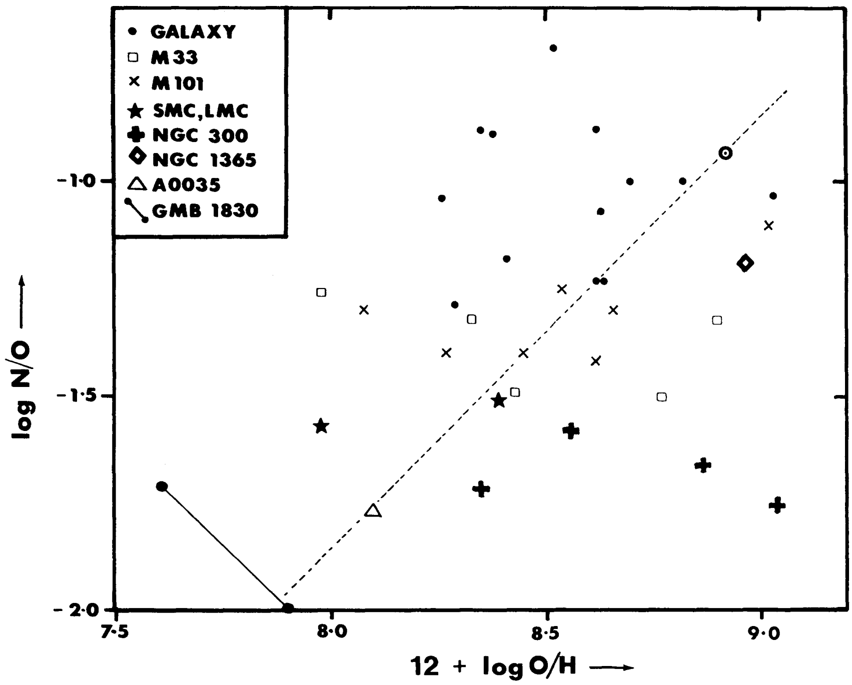

Figure 1. Relative nitrogen abundance N/O as a function of oxygen abundance for galactic and extra-galactic objects. Galactic H II regions from Hawley (1978); for references to the other data points see Pagel *et al.* (1978) and Blackwell *et al.* (in preparation). The diagonal dotted line is the prediction of the simple secondary model, equation (3).

was small. Galaxies would evolve upwards in the diagram with increasing time. It is interesting that the two Magellanic Clouds, which one might reasonably expect to be coeval, do show the same N/O despite different O/H and there are other signs that the LMC may be relatively young (Butcher 1977).

If our suggestion is correct, then it places rather severe constraints on the site of nitrogen nucleosynthesis. Simple primary synthesis of nitrogen in supernovae would follow equation (4) rather than equation (6), and hence not explain (if a constant initial mass critical time τ for the emergence of the synthesized nitrogen after the production of oxygen in short-lived supernovae must be less than about 4×10^9 yr, since the solar N/O ratio is not much different from that observed in the galactic interstellar medium today, and hence $f_1(t)$ must have been close to one when the Sun was formed. This argument again assumes that most star formation occurred very early on in the galaxy. From other evidence (Fosbury & Hawarden 1977) it is possible that A 0035 has an age of only 3×10^8 yr. It would perhaps be unreasonable to ascribe an age of less than 10^9 yr to the Magellanic Clouds, although there are indications of youth such as the blue globular clusters. We therefore require a nitrogen source with τ of order a few 10^8 to a few 10^9 yr. This implies stars of comparable main sequence lifetimes, and hence masses of order 1–$2.5 M_\odot$. Could sufficient nitrogen be produced by such stars? Arnett (1978) concludes that a typical explosive nucleo-synthesis source is a star of mass $30 M_\odot$, which would yield about $4 M_\odot$ of oxygen. For a simple estimate let us assume that oxygen is produced with the same yield by stars in the mass range 25–$40 M_\odot$. Then to give the galactic N/O ratio, with a Salpeter mass function for star formation, requires that stars in the mass range 1–$2.5 M_\odot$ release a fraction of about 3×10^{-3} of their mass in the form of nitrogen. This does not seem an unreasonable amount. Since we require that the nitrogen production must be *primary*, we appeal to Truran & Cameron's (1971) proposal that nitrogen could be produced during advanced asymptotic branch evolution by CNO cycling of material which had previously undergone helium shell flashing. The carbon processed into ^{14}N then comes from the flashed helium, and not from the initial protostellar C or O, and the overall effect is of primary rather than secondary nitrogen production. We do not imply that *all* nitrogen synthesis is primary, since secondary synthesis is bound to occur in some stars, but rather we imply that the *bulk* of nitrogen which finds its way into the interstellar medium is of primary origin.

It is tempting to identify anomalously nitrogen-rich planetary nebulae in the Magellanic Clouds (Dufour & Killen 1977) with our proposed nitrogen source, since these have N/O ratios exceeding even galactic planetaries despite the low oxygen abundance of the clouds. Presumably many more of these will become apparent in the clouds in the future as the $f_1(t)$ for the clouds builds up to one, whereas in the galaxy most of this kind of object dispersed long ago.

In summary, we propose that nitrogen may be mainly a primary nucleosynthesis product if the lack of N/O gradients in some spiral galaxies is to be explained. The N/O ratio of a galaxy is an indidator of its age, in the sense of the time since the bulk of its star formation occurred.

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