ABUNDANCES IN SPIRAL GALAXIES: EVIDENCE FOR PRIMARY NITROGEN PRODUCTION

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ABSTRACT

We present the results of nitrogen and oxygen abundance measurements for 185 H II regions spanning a range of radii in 13 spiral galaxies. As expected, the nitrogen-to-oxygen ratio increases linearly with the oxygen abundance for high-metallicity H II regions, indicating that nitrogen is predominantly a secondary element. However, the nitrogen-to-oxygen ratio plateaus for oxygen abundances less than 12 log (O/H) < 8.45, as is also seen in low-metallicity dwarf galaxies. This result suggests that the observed trend in dwarf galaxies is not due to the outflow of enriched material in a shallow gravitational potential. While the effects of the infall of pristine material and delayed nitrogen delivery are still unconstrained, nitrogen does appear to have both a primary and a secondary component at low metallicities in all types of galaxies.

Subject headings: galaxies: abundances — galaxies: ISM — galaxies: spiral

1. INTRODUCTION

Abundance measurements provide probes of the elemental enrichment process and thus are important tracers of galaxy formation and evolution. Recently, researchers using chemodynamical models have attempted to obtain self-consistent star formation histories for galaxies by combining both chemical and dynamical processes (e.g., Samland, Hensler, & Theis 1997). These models require an understanding of the star formation and enrichment processes, including stellar nucleosynthesis, dust depletion, and gasdynamics. While stellar yields for many elements, such as O, Ne, S, and Ar (e.g., Woosley & Weaver 1995), are in good agreement with their observed enrichment ratios (e.g., Thuan, Izotov, & Lipovetsky 1995), the effective yields and origin of some elements, such as nitrogen, are still a matter of debate. Understanding the origin of nitrogen is particularly important since it is frequently used to derive the primordial helium abundance via regression analysis of the observed enrichment of helium and nitrogen (e.g., Pagel & Kazlaukas 1992). In high-metallicity environments, nitrogen is believed to be synthesized during the CNO cycle in intermediate-mass stars via a secondary process (Renzini & Voli 1981). On the other hand, studies of the N/O ratio in low-metallicity H II regions suggest that there may also be a primary origin for nitrogen (e.g., Edmunds & Pagel 1978; Garnett 1990; Thuan et al. 1995). In this Letter, we examine the relative enrichment of nitrogen and oxygen in spiral galaxy H II regions in order to investigate the origin of nitrogen in a wide range of metallicity environments.

Previous studies of chemically enriched extragalactic H II regions indicate that the effective yield of nitrogen depends on the previous enrichment of C and O, and thus nitrogen is considered a “secondary” element (e.g., Torres-Peimbert, Peimbert, & Fierro 1989; Vila-Costas & Edmunds 1993). The signature for secondary nitrogen production is that the N/O ratio increases linearly with O/H. In contrast, studies of the nitrogen enrichment in low-mass dwarf galaxies indicate that the N/O ratio is constant for oxygen abundances less than 12 log (O/H) < 8.45 (e.g., Garnett 1990; Thuan et al. 1995; van Zee, Haynes, & Salzer 1997b). A constant N/O ratio may be indicative of primary nitrogen production. Primary nitrogen is defined as nitrogen produced only out of the original hydrogen and helium in a star, either directly or through successive stages of burning. Low-metallicity intermediate-mass stars that undergo successive dredge-ups of their enriched core are one source of primary nitrogen (Renzini & Voli 1981). Recent work on the nucleosynthesis of massive stars suggests that primary N may also be produced in low-metallicity massive stars via convective overshoot (Woosley & Weaver 1995). However, the signature of primary nitrogen production, a constant N/O ratio at low metallicities, can also be caused by dynamic processes, such as gas infall or outflow.

Standard “closed box” chemical enrichment models implicitly assume that enriched materials will be retained by the system; this assumption may not be valid in low-mass systems where the gravitational potential well is quite shallow. In such objects, the products of nucleosynthesis may be ejected from the system during supernovae explosions. While Edmunds (1990) states that “simple and pure” outflows will not affect relative enrichment ratios, such as N/O, gas flows are likely to be neither “simple” nor “pure.” For instance, oxygen is predominantly made in high-mass stars that undergo more violent deaths and, thus, is more likely to be removed from the galaxy. This differential outflow results in a decrease in the effective yield for oxygen with a corresponding increase in the N/O ratio. Furthermore, additional complications arise from the possible accretion of pristine gas from external reservoirs. This is par-
The outermost, lowest metallicity spiral galaxy H II regions in spiral galaxies and dwarf galaxies (van Zee et al. 1997a); the solar L2 VAN ZEE, SALZER, & HAYNES Vol. 497

A distinct “knee” is seen at 12 + log (O/H) of 8.45 (~4 of solar). A theoretical curve for primary and secondary nitrogen production (Vila-Costas & Edmunds 1993) is shown.

2. THE DATA

The full details of the observations and data reduction will be presented in van Zee, Salzer, & Haynes (1998, hereafter Paper II). In brief, optical spectroscopy of 185 H II regions in 13 nearby spiral galaxies was undertaken with the Double Spectrograph on the 5 m Palomar6 telescope during 1996–1997. During all observing runs, a 5500 Å dichroic was used to split the light to the two sides (blue and red), providing complete spectral coverage from 3500 to 7600 Å. The spectra were calibrated, and reddening-corrected line intensities relative to Hβ were calculated using the procedures described in van Zee, Haynes, & Salzer (1997a).

The calculation of an elemental abundance from observed emission-line ratios requires an estimate of both the electron temperature and the density of the H II region. Since the observed [S ii] line ratios were all within the low-density limit, we have assumed an $N_e$ of 100 cm$^{-3}$ for all regions. The electron temperature was computed either directly from the observed [O iii] line ratios or, if the [O iii]/λ4363 line was not detected, from a self-consistent temperature estimate based on an estimate of the oxygen abundance. An estimate of the oxygen abundance was obtained from the R23 calibration of McGaugh (1991); the degeneracy between the upper and lower branches of the calibration was resolved based on the observed [N ii]/Hα line ratios. Full details of the oxygen abundance determination and subsequent electron temperature estimate will be presented in Paper II. Finally, the nitrogen-to-oxygen ratio was calculated assuming that N/O = N$^+$/O$^+$ (Peimbert & Costero 1969).

3. N/O ABUNDANCE RATIOS

Figure 1 shows the derived N/O ratio as a function of O/H for the H II regions in the spiral galaxy sample. The solar value is denoted by a gray circle (Anders & Grevesse 1989). Also shown in Figure 1 are the results for dwarf galaxies in the samples of van Zee et al. (1996) and van Zee et al. (1997a). Typical error bars for the O/H and N/O values are illustrated in the lower right-hand corner. As expected, a linear trend is seen for the high-metallicity H II regions, indicating that secondary nitrogen production dominates in high-metallicity environments. At low metallicities, however, there is a strong deviation from the secondary nitrogen line. Also illustrated in Figure 1 is the expected trend for a combination of primary and secondary nitrogen, assuming no time delay between the release of oxygen and nitrogen (Vila-Costas & Edmunds 1993). The area between this line and the secondary nitrogen line can be populated if there is a significant time delay between the delivery or if there are dynamical effects such as outflow or infall. With the exception of one H II region in NGC 1232, the majority of the H II regions fall within these bounds.

It is quite clear in Figure 1 that the spiral galaxy and dwarf galaxy H II regions have similarly high N/O ratios at low metallicities. Thus, in contrast to Roy et al. (1996), it appears that low-mass irregular galaxies do not have systematically lower N/O ratios than massive disk systems. Consequently, it is unlikely that dynamical effects, such as outflow, significantly affect the observed elemental abundances in dwarf galaxy samples. In the absence of other explanations, it seems evident that...
TABLE 1

| OBJECT     | MORPHOLOGICAL TYPE | $R_{25}$ (arcsec) | O/H (dex/$R_{25}$) | N/O (dex/$R_{25}$) | NUMBER OF H II REGIONS |
|------------|--------------------|-------------------|---------------------|--------------------|------------------------|
| NGC 0628   | Sc                 | 314.              | $-0.99 \pm 0.14$    | $-0.57 \pm 0.12$   | 26                     |
| NGC 0925   | Sd                 | 314.              | $-0.45 \pm 0.08$    | $-0.34 \pm 0.04$   | 53                     |
| NGC 1068   | Sb                 | 212.              | $-0.30 \pm 0.07$    | $-0.01 \pm 0.09$   | 13                     |
| NGC 1232   | Sc                 | 222.              | $-1.31 \pm 0.20$    | $-0.32 \pm 0.10$   | 16                     |
| NGC 1637   | Sc                 | 120.              | $-0.37 \pm 0.14$    | $-0.30 \pm 0.17$   | 15                     |
| NGC 2403   | Sd                 | 656.              | $-0.77 \pm 0.14$    | $-0.40 \pm 0.08$   | 40                     |
| NGC 2805   | Sd                 | 189.              | $-1.05 \pm 0.17$    | $-0.29 \pm 0.06$   | 17                     |
| IC 2458    | I0                 | ...               | ...                 | ...                | 3                      |
| NGC 2820   | Sb                 | ...               | ...                 | ...                | 4                      |
| NGC 2903   | Sc                 | 378.              | $-0.56 \pm 0.09$    | $-0.57 \pm 0.17$   | 36                     |
| NGC 3184   | Sc                 | 222.              | $-0.78 \pm 0.07$    | $-0.77 \pm 0.12$   | 32                     |
| NGC 4395   | Sc                 | 395.              | $-0.32 \pm 0.19$    | $-0.04 \pm 0.11$   | 14                     |
| NGC 5457   | Sc                 | 865.              | $-1.52 \pm 0.09$    | $-0.65 \pm 0.09$   | 53                     |

*Morphological type and isophotal radius from the RC3.

Further support for a primary nitrogen component comes from the radial gradient of N/O in the spiral galaxies. If nitrogen is purely a secondary element, the N/O gradient should be identical to that of O/H. The radial gradients for O/H and N/O are tabulated in Table 1 and shown graphically in Figure 2. All radii have been normalized by the isophotal radius ($R_{25}$), as listed in the RC3 (de Vaucouleurs et al. 1991) and tabulated in Table 1. In Figure 2, the filled symbols represent H II regions from the present study. The open circles represent data from the literature: NGC 0628 (McCall et al. 1985), NGC 1068 (Evans & Dopita 1987), NGC 2403 (Garnett et al. 1997), N2903 (McCall et al. 1985), N3184 (McCall et al. 1985), and N5457 (Kennicutt & Garnett 1996). With the exception of the literature data for NGC 1068 and NGC 2403, where the N/O ratios were explicitly calculated, the N/O ratios were calculated using the global relation of Thurston et al. (1996). This relation is valid only for $8.4 < 12 + \log (O/H) < 9.2$. It is quite clear that NGC 5457 deviates from the purely secondary trend at large radii and low metallicity. The solid lines in Figure 2 represent the weighted least-squares fit for the N/O gradient. The dashed lines represent the predicted N/O abundances extrapolated from the O/H gradient. In general, the N/O gradients tend to be shallower than the O/H gradients (Table 1). For instance, the derived slope for N/O in low-abundance H II regions in all types of galaxies do show evidence of primary nitrogen production.
NGC 2805 is significantly shallower than the O/H gradient in this galaxy. On the other hand, galaxies with only high-metallicity H II regions, such as NGC 1637, NGC 2903, and NGC 3184, have very similar O/H and N/O gradients, as expected for regions where secondary nitrogen production dominates.

4. INTERPRETATION

We have presented clear evidence for primary nitrogen production in low-abundance H II regions in both spiral and dwarf galaxies. At metallicities higher than \( \sim \frac{1}{2} \) solar, secondary nitrogen production dominates, and the signature from primary production is less evident. Since the signature for primary nitrogen is seen in the higher mass spiral galaxies, it is unlikely that dynamical processes such as infall or outflow are responsible for the constant N/O ratio in dwarf galaxy samples. While there may still be some concern that even in the spiral galaxy sample the outlying H II regions could be affected by inflow of pristine material, the evidence suggests that there is a substantial contribution of primary nitrogen in both dwarf and spiral galaxy H II regions.

The present H II region data set cannot constrain the source of the primary nitrogen production. However, studies of extremely low metallicity systems can exploit the time delay between the release of oxygen and nitrogen to investigate in which types of stars primary nitrogen is produced. If nitrogen is primarily made in high-mass stars (the mechanism is described in Woosley & Weaver 1995), there will be no time delay between the release of N and O, so the N/O ratio will have a small scatter at low abundances. On the other hand, if nitrogen is predominantly made in intermediate-mass stars (see Renzini & Voli 1981), there will be a significant time delay between the release of N and O. In this case, the N/O ratio will change as a function of time, increasing the observed scatter (e.g., Garnett 1990). Searches for such a signature in H II region abundances have been inconclusive. For instance, while Thuan et al. (1995) find an extremely small scatter in the N/O ratio of blue compact dwarf galaxies, other studies of H II regions in dwarf irregular galaxies result in a statistically significant scatter (e.g., Garnett 1990; Skillman, Bomans, & Kobulnicky 1997; van Zee et al. 1997a). Studies of extremely low metallicity systems are necessary to resolve this issue since the time delay between oxygen and nitrogen enrichment will have the largest effect in such objects.

Low-abundance systems are extremely rare in the local universe; currently, the most extreme objects are I Zw 18 (Skillman & Kennicutt 1993) and SBS 0335-052 (Izotov et al. 1997), at 1/50th and 1/40th of solar, respectively. At high redshift, however, low-abundance systems are quite common. Thus, the investigation of the nitrogen abundance in high-redshift damped Lyα systems can provide additional constraints on the origin of nitrogen. While this is still a relatively new endeavor, preliminary results suggest that the N/O ratio is lower in low-metallicity damped Lyα systems than in comparable low-metallicity H II regions (e.g., Pettini, Lipman, & Hunstead 1995; Lu, Sargent, & Barlow 1998). Furthermore, the scatter increases at low metallicities in these studies. Thus, the high-redshift observations appear to be catching systems during the time delay between the release of oxygen and nitrogen. If this is the case, it is likely that primary nitrogen is predominantly produced in low-metallicity intermediate-mass stars. Further studies of low-metallicity systems at high and low redshift will be needed to confirm these results.

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