THE CHEMICAL EVOLUTION OF GALAXIES BY SUCCESSIVE STARBURSTS

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Abstract

We propose an evolutionary scenario by successive bursts of star formation to reproduce the chemical properties of massive nearby Starburst Nucleus Galaxies (SBNGs). The N/O abundance ratios in SBNGs are \(\sim 0.2\) dex higher than in normal H II regions observed in the disks of late-type spirals. The variation of the N/O ratio as a function of metallicity follows a primary + secondary relation, but the increase of nitrogen does not appear as a continuous process. Assuming that nitrogen is produced by intermediate-mass stars, we show that our observations are consistent with a model where the bulk of nitrogen in SBNGs was formed during past sequences of bursts of star formation which probably started 2 or 3 Gyrs in the past.

1 Introduction

Recent observations obtained with the Hubble Space Telescope have made clear the urgency of understanding the nature of the starburst phenomenon. Drastic and rapid changes of the population of galaxies have been observed over a short period of time and at a surprisingly recent epoch ([27],[14]). These observations seem to imply that most galaxies formed between redshifts of 1 and 2 ([19]) and support the hierarchical formation of galaxies paradigm. According to this theory, massive galaxies form by successive mergers of smaller mass and gas rich components. If each of these mergers triggers a burst of star formation ([26]), then, consequently, the galaxies form and evolve by a succession of bursts. Is this what we observe in present-day starburst galaxies? The subsequent discovery of forming galaxies at high redshifts with spectral characteristics in the UV similar to those of nearby starbursts ([23],[24]) supports such an interpretation.

That many nearby SBNGs could be the remnants of merging galaxies is already suggested by several observations ([17],[7],[1]). It has also been shown that i) SBNGs are chemically less evolved than normal galaxies with similar morphologies and comparable luminosities ([8]), ii) they are predominantly early-type spirals ([9],[10]) and iii) they follow a luminosity–metallicity relation similar to that of elliptical galaxies ([11]). The SBNGs also have another intriguing property which makes them similar to star-forming galaxies at high redshifts. In their analysis of the properties of the Lyman-break galaxies, [23] concluded that the star formation rate in these galaxies was probably constant
over the last Gyr. In the case of SBNGs, it has been demonstrated that multiple bursts of star formation over a few Gyr period produce nearly constant star formation rates in these galaxies (, [6],[13]). But are these sequences of bursts the consequence of multiple merger events?

In order to gain new insights on the nature and origin of the nearby SBNGs, we have embarked in a new project to establish a more complete picture of their chemical evolution. A new method has recently been devised for estimating nitrogen abundances in metal-rich galaxies ([25]). We have taken advantage of this important advance to determine the abundance of nitrogen in SBNGs and compare it with the values observed in normal spirals.

2 The abundance of nitrogen in SBNGs

Our sample of SBNGs was composed originally of 208 H II regions observed along the bars of 75 Markarian barred galaxies (see [4],[5],[3] for details). From this sample, we rejected 48 H II regions because of their ambiguous classification using three spectroscopic diagnostic diagrams. The same criterion was used by [30] to build their sample of 83 FIR-bright SBNGs. After verifying that they have similar spectroscopic characteristics, we merged the two samples together. The detailed analysis can be found in [12].

In SBNGs, nitrogen appears overabundant as compared to “normal” disk H II regions, with a relative abundance N/O which is ~ 0.2 dex higher ([12]). The range of N/O values found in SBNGs is comparable to that observed in the bulges of normal early-type spiral galaxies ([25],[29]). On this matter, our observations are consistent with the recent discovery made by [25], who showed that H II regions in early-type spirals have slightly higher N/O ratios than H II regions in late-type spirals. In normal galaxies, samples of H II regions are preferentially found in late-type spirals where they are generally more numerous and luminous than in early-type galaxies. The SBNGs, on the other hand, are more numerous among early-type spirals ([11]), explaining the observed higher abundance ratio in this sample.

We conclude that our measurements of the nitrogen abundance in SBNGs are consistent with the chemical evolution of early-type spiral galaxies. This suggests that what we see could be the main production of nitrogen in the bulges of these galaxies.

3 An evolution by successive starbursts

Examining how the abundance of nitrogen varies with the increase of oxygen, we find that, contrary to normal disk H II regions, the SBNGs do not follow the secondary relation (see Fig. 1a). A linear fit yields (with a correlation coefficient of 76%) \( \log(\text{N/O}) = 0.55 \log(\text{O/H}) + 0.8 \), which is consistent with a mixture of primary + secondary mode of production of nitrogen. But the increase of the N/O ratio with metallicity does not seem to follow a continuous process. The N/O ratio rises sharply by about 0.3 dex at an oxygen abundance of ~ −3.4 and stays almost constant in the range \(-3.4 < \log(\text{O/H}) < -2.9\).

In Figure 1a, we show schematically how a sequence of bursts could explain our observations. Our scenario is based on the analytical model presented in [15]. We assume that SBNGs begin their chemical evolution with N/O and O/H ratios typical of H II galaxies. Massive stars are responsible for the increase in oxygen, while nitrogen is only the product of intermediate-mass stars ([28]).

During the first burst, the rapid evolution of massive stars increases O/H and decreases N/O ([15],[22]). Then, after ~ 0.4 Gyr, the evolution of intermediate–mass stars increases only N/O. Models of sequential bursts usually predict that successive bursts will have decreasing intensities ([16],[18]). A second burst, therefore, will produce a slightly lower increase of O/H. The decrease in N/O during oxygen enrichment (the slope of the vector) will also be smaller as it becomes more and more difficult to lower this ratio when the oxygen abundance increases ([15]). Again, 0.4 Gyr after
Figure 1: a) Schematic representation of the process of production of nitrogen in SBNGs by a sequence of bursts. The dispersion is caused by different initial intensities or different ages of the bursts (represented by only three different vector sums in this figure). Deviation of the observed nitrogen abundance from the secondary relation ($\Delta(N/O)$) vs. oxygen abundance: b) in the SBNGS, and c) in normal H II regions. Note how the behavior becomes more starburst-like for normal galaxies with low metallicities.

the beginning of the second burst, N/O will increase, but with an amplitude relatively smaller than in the first burst. If we increase the number of bursts and assume that successive bursts get weaker and weaker, the sum of the vectors should converge towards a line whose slope represents the mean increase of O/H and N/O in time. This slope may resemble the secondary relation. Indeed, it is interesting to note that, according to this scenario, a constant star formation is similar to an infinite sum of very low-intensity bursts of star formation, which is also consistent with the behavior of normal disk H II regions.

The above model predicts that the deviation of the observed N/O ratio from the secondary relation ($\Delta(N/O)$) will decrease with the age of starburst galaxies, or, equivalently, with their increase in metallicity. In Figure 1b, we see that this prediction is satisfied in the SBNGs. The fact that the deviation in Figure 1b is mostly positive could be explained by the different durations of the chemical evolutionary phases. Because massive stars have very short lifetimes, the oxygen enrichment phase is almost instantaneous, and O/H rapidly reaches a maximum (the tip of each horizontal vector in Figure 1a). The lifetime of the stars producing nitrogen, on the other hand, spans a much larger range of values. The nitrogen enrichment probably increases rapidly at the beginning, but extends over a longer period of time, as lower and lower-mass stars evolve. As a result, the top of each vertical vector in Figure 1a is always much more populated, this phase representing a sort of natural stable mode in the starburst’s evolution.

According to the model of [2], the main phase of production of nitrogen in a burst should occur between 0.4 and 1.6 Gyrs after its beginning (this implies the evolution of stars from 8 to 3 M$_\odot$). Considering nearly constant star formation rates over the last 2–3 Gyr ([6]), and assuming a median age of 1 Gyr for one burst, it seems therefore that 2 or 3 bursts (or more if the bursts have shorter durations) are necessary to produce a sufficient number of co-evolved intermediate-mass stars needed to produce in turn the observed abundance of nitrogen. This would then push the origin of the main bursts 2 to 3 Gyrs in the past.
4 Conclusion

The time scales deduced above for the origin of the bursts in SBNGs are much longer than those predicted by interacting-merging galaxy models ([20], [21] for example). It is not clear, therefore, what internal/external phenomenon could allow SBNGs to form stars over such a long period of time. In the literature, we know of only two models which predict sequences of bursts of star formation. The “stochastic self propagation of star formation” theory ([16],[18]) and the “hierarchical formation of galaxies” theory ([26]).

It is generally accepted that the Lyman-break galaxies are the progenitors of present-day normal massive galaxies ([23]). The fact that the SBNGs show similar characteristics to those of these galaxies suggests, therefore, that they may be nearby examples of galaxies still in formation. The SBNGs, consequently, would not be a peculiar phase in the evolution of galaxies, but the result of a process which was much more common in the past of the Universe. This process could be the hierarchical formation of galaxies.

References