Planetary Nebulae and the Chemical Evolution of the Galactic Bulge

R.D.D. Costa, A.V. Escudero, W.J. Maciel

IAG/USP, São Paulo, Brazil

Abstract. Electron temperatures, densities, ionic and elemental abundances of helium, nitrogen, oxygen, argon, sulfur and neon were derived for a sample of bulge planetary nebulae, representative of its intermediate mass population. Using these results as constraints, a model for the chemical evolution of the galactic bulge was developed. The results indicate that the best fit is achieved using a double-infall model, where the first one is a fast collapse of primordial gas and the second is slower and enriched by material ejected by the bulge itself during the first episode.

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INTRODUCTION

Planetary nebulae can constitute important tools to study the chemical evolution of the galactic bulge. As representative objects of its intermediate mass population, they can provide accurate determinations of the abundances of light elements such as helium and nitrogen produced by progenitor stars of different masses. Besides, abundances of heavier elements such as oxygen, sulfur and neon can be also derived. These elements are produced in more massive stars and represent the abundances in the interstellar medium at the progenitor formation epoch.

In this work spectrophotometric results derived for a sample of 57 bulge PNe are reported. Electron temperatures, densities, ionic and elemental abundances of helium, nitrogen, oxygen, argon, sulfur and neon were derived for the sample. Using these observational results as constraints, a model for the chemical evolution of the bulge was developed.

OBSERVATIONS AND DATA REDUCTION

Observations used in this work were carried out in two different telescopes: 1.60 m LNA (Laboratório Nacional de Astrofísica - Brasópolis, Brazil) and 1.52 m ESO (European Southern Observatory - La Silla, Chile). All objects were observed using Cassegrain spectrographs. At LNA a 300 l/mm grid with 4.4 Å/pix dispersion was used and at ESO a 600 l/mm grid, with 2.4 Å/pix dispersion. In both cases long slit of 2" width were adopted. Each night at least three spectrophotometric standard stars were observed in order to secure flux calibration. Observational details can be found in Escudero and Costa (2001) and Escudero et al. (2004).

Data reduction and analysis was performed using IRAF routines for long slit spectra. Interstellar extinction was derived based on the Hα/Hβ ratio, and was corrected using the extinction curve of Fitzpatrick (1999), which proved to produce better results for bulge objects when compared with other curves. Quality of the reddening correction was checked by comparing dereddened and theoretical Hγ/Hβ ratios.

Electron temperatures were derived from the following line ratios: [OIII]$\lambda\lambda$ 4363/5007 and [NII]$\lambda\lambda$ 5754/6584, which define respectively "high" and "low" ionization regions. Electron density was derived from the sulfur ratio [SII]$\lambda\lambda$ 6716/6731, corresponding therefore to an average density of the whole nebula.

Helium abundances were derived taking into account the collisional excitation correction for He I lines. Ionic abundances were derived using the fits by Alexander and Balick (1997), and checked using a three-level atom model, with good agreement between both techniques. Elemental bundances were estimated using ionization correction factors, as described in details in the papers above mentioned. Figure 1 displays the distribution of the derived oxygen abundances, compared to other data from the literature, without objects in common.

CHEMICAL EVOLUTION MODEL

A model was developed in order to describe the formation and chemical evolution of the galactic bulge, using abundances derived from planetary nebulae as representative of its intermediate age population. The results derived in the present work reinforce some evolutive characteristics already derived in previous works, and present improvements such as the inclusion of a second enriched infall to explain peculiarities of the abundance distribu-

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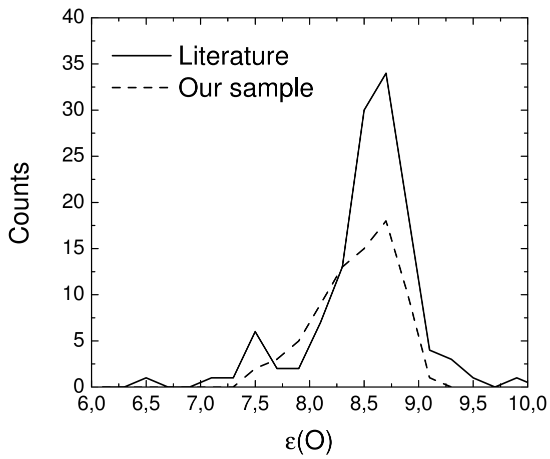

FIGURE 1. Distribution of oxygen abundances for bulge planetary nebulae

tion like the dispersion found in the correlation between nitrogen and oxygen abundances.

Basic ingredients

The model was developed as a C++ code that simulates numerically the chemical evolution of the bulge, using the basic ingredients to describe the evolution, namely stellar formation rate, initial mass function, gas infall rate, stellar yields and mass distribution of SNIa progenitors:

- Star formation rate: To determine the amount of interstellar gas converted to stars at each time interval, the Schmidt law (Kennicutt 1998) was used. The adopted coefficient and exponent of the law were the same as derived by Kennicutt. For some runs, the stellar formation efficiency was varied by two orders of magnitude to test its impact on the derived chemical abundances, without significant differences.
- Initial mass function: basically, the initial mass function adopted was that of Kroupa (2002), which reproduces satisfactorily the observed chemical abundances in planetary nebulae. However, the O/Fe ratio for poor stars obtained from the literature (Pompeia et al. 2003) is higher than the values derived from the model. To solve this problem, the Salpeter law was used for the first 0.3 Gyr of the bulge formation, resulting in chemical abundances closer to those found in stars.
- Gas infall rate: the value of this rate along the Galaxy evolution is probably the least known ingredient of a chemical evolution model. Since the published chemical evolution models adopt a time-exponential infall rate, the same kind of expression was adopted in this model. The only difference is the adopted gas infall scale, as well as its normalization constant, that depends on the total mass of the bulge. This model consists in two gas infall episodes. For the first one, in a time scale of 0.1 Gyr nearly all the bulge population was formed. For the second episode, a time scale of 2.0 Gyr was adopted, close to that derived for the inner disk in chemical evolution models of the galactic disk.
- Stellar yields: the yields were divided in three categories: intermediate mass population, SNII and SNIa. These yields were obtained respectively from van den Hoek & Groenewegen (1997), Woosley & Weaver (1995) and Tsujimoto et al. (1995). To check the results, the data from Tsujimoto et al. (1995) for SNII were also used, resulting in a higher O/Fe ratio, closer to those found in the literature, however the abundance distribution does not change significantly with these new yields. Figure 2 shows the derived distribution of oxygen abundances compared to model results using two different stellar evolution models, and figure 3 shows the evolution of the O/Fe ratio using two yields for SNII.
- Mass distribution of the SNIa progenitors: SNIa have binary systems as progenitors. Their mass distribution is not well known yet. A way to describe this distribution was provided by Chiappini (1997), and assumes that the highest probability for the mass ratio between primary and secondary stars in such a system is one. Since this distribution provides satisfactory results for the disk abundances, it was adopted in the present model.

Main characteristics of this model

The model adopts a mixed scenario to describe the bulge evolution, with two main phases: the first one is a fast collapse of primordial gas and the second consists in a slow collapse of enriched material.

One of the improvements of the model presented here is the small amount of free parameters. Nearly all its ingredients can be checked observationally and are already accepted in the literature. The adopted IMF was that of Kroupa (2002), which is widely adopted in chemical evolution works. The adopted SFR is the Schmidt law, with the constant and density exponent derived observationally by Kennicutt (1998). The amount of binary systems generating SNIa was derived from solar neighbourhood data. Finally, the stellar yields were derived from stellar evolution models (van den Hoek & Groenewegen 1997, Woosley & Weaver 1995 and Tsujimoto et al. 1995). The

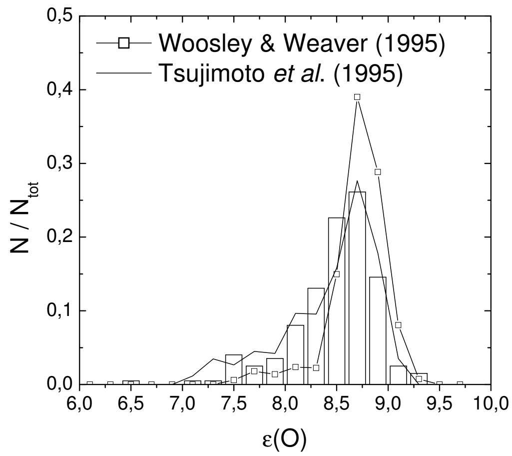

FIGURE 2. Distribution of oxygen abundances compared to model results, using two different stellar evolution models.

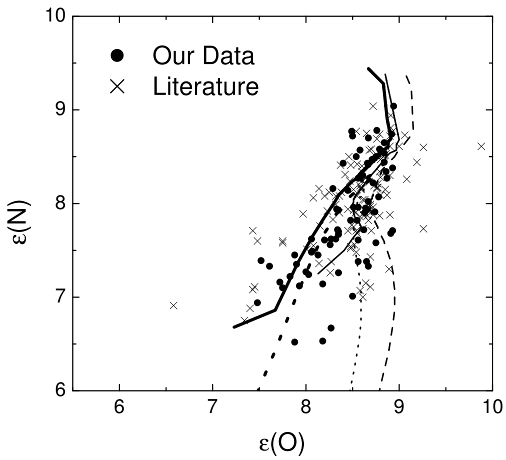

FIGURE 4. ε(N)=12+log(N/H) versus ε(O)=12+log(O/H) ratio for our sample and data from the literature, compared to different model predictions (see text).

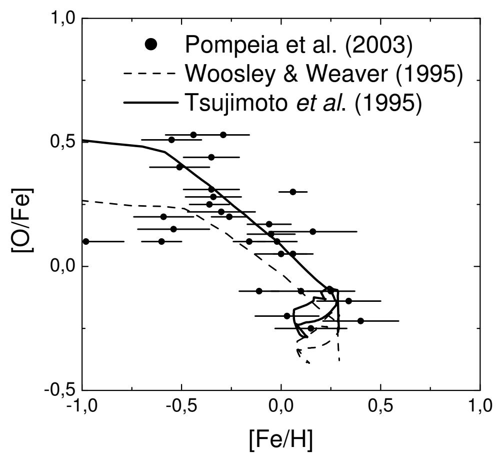

FIGURE 3. Evolution of the O/Fe ratio using two yields for SNII.

only free parameters are infall rate and wind rate. Unfortunately the gas infall and the gas loss/change in the early evolution of the Galaxy are still not clearly described in the literature. These are probably the two main points to be addressed in forthcoming chemical evolution models.

The first phase of the model consists in a fast collapse of primordial gas. To allow a good reproduction of the derived chemical abundances found in low mass objects, the adopted wind rate from supernovae is 50% (40% to the halo and 10% to the inner disk). Based on hydrodynamical simulations (Samland et al. 1997, Mac Low & Ferrara 1998), up to 50% of the elements produced by supernovae can be ejected to the halo or inner disk.

It can be seen from fig. 4 that there is a strong scatter in the derived oxygen abundances for low nitrogen objects. This scatter can be reproduced assuming that the winds produced by supernovae (II and Ia) eject part of the synthesized material. With this process, there is simultaneously a chemical enrichment of the halo and inner disk and a decreasing in the bulge enrichment; as a consequence, in the external regions the abundances of heavier elements such as oxygen and iron are increased with respect to nitrogen and helium, produced in intermediate mass stars. Bulge objects with high oxygen abundances and low nitrogen can also be found. Their presence in the bulge indicates that they were formed from a medium already oxygen-rich. Since oxygen originates from SNII, this population was formed in an epoch when the interstellar medium was already enriched by ejecta from short time-life stars, but still not enriched by elements formed in longer life stars like nitrogen.

To have a low N/O ratio, the oxygen-rich gas would have to fall first in the inner disk, before the beginning of its star-formation history, or in the halo region that later would create the inner disk. If all the gas had fallen directly onto the bulge, its N/O ratio could not explain values smaller than log(N/O)=-1. In a paper on the time variation of the radial metalicity gradient of the Galaxy, Maciel et al. (2003) show that old objects in the inner disk have high oxygen and low nitrogen abundances, indicating the occurrence of a previous chemical enrichment for heavier elements.

Different sets of models are presented in fig. 4. Thick lines represent objects in the central region and thin lines represent those in the external bulge-inner disk region. Therefore, the thin solid line represent objects formed from gas already enriched by supernovae, and the thick solid line represents objects formed by primordial gas, in the central region. In the same figure another model run is shown for both regions, adopting no oxygen and nitrogen yields for stars between 0.8 and 0.9 solar masses (dotted thick and thin lines). It can be seen that there is a considerable difference between the curves for low abundance objects. This is due to the yields for low mass objects, that can vary considerably. The dashed line was produced assuming that 25% of material produced by supernovae was ejected from the bulge to the inner disk. It should be kept in mind that part of the scattering found in this figure can be due to observational uncertainties (Escudero 2001), as well as to the rotation of the progenitor star (Meynet & Maeder 2002).

DISCUSSION

The derived chemical abundance distribution for the observed objects is compatible with other data from the literature. Mean values derived for the chemical species studied are He/H=0.112, ε(N)=7.83, ε(O)=8.43, ε(S)=6.56, ε(Ar)=6.24, ε(Ne)=7.69, adopting ε(X)=log(X/H)+12.

Results indicate that the best fit for the derived distribution of chemical abundances is achieved using a double-infall model, where the first one is a fast collapse of primordial gas and the second is slower and enriched by material ejected by the bulge itself during the first episode.

The galactic bulge had its first stellar formation episode triggered by a large collapse of primordial gas. This episode is a consensus among all galactic formation models, and is required not only by chemical evolution models but also by observational constraints. First, the large quantity of old objects requires an important star formation episode at the beginning of the evolution. Second, the wide distribution of metallicities observed in stars and planetary nebulae can be better explained by a fast gas collapse than by a slow one. Third, the presence of old metal-rich stars can be explained if an abrupt gas collapse enriches rapidly the interstellar medium, generating poor and rich old stars as well.

This first initial collapse has as main characteristic the large mass loss ejected by supernovae for external regions such as halo, disk or event to outside the Galaxy. This mass loss is essential to reproduce the abundance distribution observed in planetary nebulae. This is also a consensus among recent models for the galactic bulge: without this loss the stellar abundances would be higher than those observed. For now, it is not possible to define exactly the amount of gas lost in this episode. In this work, mass losses between 40 % and 60 % are suggested, which are similar to those derived by Ferraras et al. (2003). A better definition of this parameter requires more precise observational data, as well as more realistic hydrodynamical models for the central region of the Galaxy.

The destiny of the ejected material is not clearly understood yet. Samland et al. (1997) propose that this material was ejected to the halo and later fell on the disk. In this work they reproduce many chemical properties of the disk, however one of their conclusions is that the disk abundance gradient begun to form 6 Gyr after the beginning of the disk formation, which is contradictory with the time variation of the abundance gradient derived by Maciel et al. (2003), which indicates an already established gradient at this epoch.

Observational data from stars suggest that the IMF at the beginning of bulge formation is more similar to Salpeter's than to Kroupa's, which means that a large amount of massive objects was formed at the early phases of the formation process, in a time scale of a few million years. In a later phase, between 1 and 3 Gyr after the first collapse, the second gas collapse occurred and formed the inner disk. This material was previously enriched by the gas ejected from the bulge during the first collapse, or even by the chemical evolution of the halo. This previous enrichment of the gas can explain the presence in the inner disk of objects with high oxygen and low nitrogen abundances.

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