The population of planetary nebulae near the Galactic centre: chemical abundances * †

O. Cavichia1,2, R. D. D. Costa2, W. J. Maciel2 and M. Mollá3

1 Instituto de Física e Química, Universidade Federal de Itajubá, Av. BPS, 1303, 37500-903, Itajubá-MG, Brazil
2 Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, 05508-900, São Paulo-SP, Brazil
3 Departamento de Investigación Básica, CIEMAT, Avda. Complutense 40, E-28040 Madrid, Spain

Accepted 1988 December 15. Received 1988 December 14; in original form 1988 October 11

ABSTRACT
Planetary nebulae (PNe) constitute an important tool to study the chemical evolution of the Milky Way and other galaxies, probing the nucleosynthesis processes, abundance gradients and the chemical enrichment of the interstellar medium. In particular, Galactic bulge PNe (GBPNe) have been extensively used in the literature to study the chemical properties of this Galactic structure. However, the presently available GBPNe chemical composition studies are strongly biased, since they were focused on brighter objects, predominantly located in Galactic regions of low interstellar reddening. In this work, we report physical parameters and abundances derived for a sample of 17 high extinction PNe located in the inner 2° of the Galactic bulge, based on low dispersion spectroscopy secured at the SOAR telescope using the Goodman spectrograph. The new data allow us to extend our database including faint objects, providing chemical compositions for PNe located in this region of the bulge and an estimation for the masses of their progenitors to explore the chemical enrichment history of the central region of the Galactic bulge. The results show that there is an enhancement in the N/O abundance ratio in the Galactic centre PNe compared with PNe located in the outer regions of the Galactic bulge. This may indicate recent episodes of star formation occurring near the Galactic centre.

Key words: Galaxy: evolution – Galaxy: formation – Galaxy: abundances – Galaxy: disc – Galaxy: bulge.

1 INTRODUCTION
Planetary nebulae (PNe) are the offspring of stars with a large interval of mass (1 − 8 M⊙). Since they are formed from several different stellar evolutionary pathways (Frew & Parker 2010), they have very heterogeneous intrinsic and observed properties. Also, due to their nature, PNe have a very short lifetime dissipating into the interstellar medium (ISM) in a timescale of 3 − 7 × 10⁴ years (Zijlstra & Pottasch 1991). PNe constitute an important tool to study the chemical evolution of the Milky Way and other galaxies, probing the nucleosynthesis processes, abundances gradients and the chemical enrichment of the ISM. They provide accurate abundance determinations of several chemical elements difficult to study in stars, such as He and N, and also others such as O, S, Ar, and Ne. The former have abundances modified by the evolution of the PNe progenitor stars, while the latter reflect the conditions of the ISM at the time the progenitors were formed, although a small depletion of O may be observed due to ON cycling for the more massive progenitors (Clayton 1968), in amounts that depend on metallicity and other properties. Recently, Ne has also been suspected of undergoing self-contamination and its role as a metallicity tracer for the ISM is also uncertain (Milingo et al. 2010).

The currently known number of Galactic bulge planetary nebulae (GBPNe) is ∼ 800 after the publication of the two Macquire/AAO/Strasbourg Hα PNe surveys (MASH Parker et al. 2006; Miszalski et al. 2008). This number is low compared with the estimated numbers of ∼ 2000 GBPNe by Gesicki et al. (2014) and ∼ 3500 GBPNe by Peyaud et al. (2006). The currently number of GBPNe with accurate chemical abundances is ∼ 300, considering the...
works done by Escudero & Costa (2001); Escudero et al. (2004); Cavichia et al. (2010), hereafter IAG-USP sample, and also the works of Górnay et al. (2009), Wang & Liu (2007), Cuisinier et al. (2000), Exter et al. (2004), as compiled by Chiappini et al. (2009). The fact that PNe are originated from stars of different masses and, consequently, evolutionary pathways, hamper the construction of representatives samples for unbiased chemical composition studies.

The presently available chemical composition studies are strongly biased, since they were focused on brighter objects, predominantly located in Galactic regions of low interstellar reddening. The principal obstacle in deriving accurate chemical abundances towards the Galactic centre (GC) is the very high level of extinction close to the Galactic plane, where the interstellar extinction caused by the Galactic disc dust layers can reach $A_V \sim 25$ mag (Gonzalez et al. 2012). However, it is precisely in the region close to the GC, where a large fraction of the PNe population is expected to exist (Jacoby & Van de Steene 2004, hereafter JS04). The chemical abundance distributions of GBPNe in the bulge region within $2^\circ$ of the GC is poorly known, as shown in Fig. 2 of Chiappini et al. (2009). The discovery of 160 GBPNe near the GC by JS04 opens the possibility to overcome this bias in the chemical abundance studies. This sample is relatively large, covering nearly two-thirds of the predicted number of GBPNe expected in the surveyed region of the Galactic bulge. Thanks to the access to larger telescopes, now it is possible to secure chemical abundance analysis of this high-extinction and low-surface brightness GBPNe.

GBPNe near the GC are specially important, since they can shed light on the more general problem of the bulge formation and evolution. For instance, GBPNe can contribute to understand what type of collapse formed the bulge (dissipational or dissipationsless), and the role of the secular evolution within the Galaxy. This latter can be probed by GBPNe near the GC, since the secular evolution causes a significant amount of star formation within the centre of galaxies (Ellison et al. 2011), rejuvenating the stellar populations near the central parsecs of these galaxies (Coelho & Gadotti 2011). If the Galactic bulge is a classical one, then it is formed by gravitational collapse (Eggen et al. 1962) or by hierarchical merging of smaller objects and the corresponding dissipative gas process (Zinn 1985). In this case, the formation process is generally fast and occurs earlier in the Galaxy formation process, before the present disc was formed. On the contrary, if the Galactic bulge is formed by the rearrangement of the disc material, it should be constituted by stellar populations that are similar to those of the inner disc.

A complete survey of the abundances of all known GBPNe is currently beyond our capabilities and we need to observe smaller samples, as in this work, to achieve a more statistically complete coverage of the chemical properties of the intermediate mass population of the bulge. These results would have a significant impact on Galactic evolution theories, providing a much more accurate view of the abundance distribution of GBPNe, especially in the region within $2^\circ$ of the GC and, therefore, producing more reliable constraints for the modelling of intermediate mass stars evolution as well as the chemical evolution of the Galactic disc and bulge. In particular, follow-up spectroscopy of GBPNe can tell us the rate at which the alpha elements were enhanced near the GC. In this paper, for the first time, we report spectroscopic follow-up observations of a sample of GBPNe within a few degrees of the GC. These new data provide chemical composition for PNe located in this region of the bulge and an estimation for the masses of their progenitors to explore the chemical enrichment history of the central region of the Galactic bulge. This paper is organized as follows: Section 2 describes the criteria for sample selection, the observations and the data reduction. Section 3 presents the determination of the physical conditions and the ion and total abundances of our targets. Section 4 is devoted to the data analysis and the comparison of the results obtained in this paper with other results in the literature. Section 5 summarizes the main findings of this work.

2 SAMPLE SELECTION, OBSERVATIONS AND DATA REDUCTION

2.1 Sample selection and bulge membership

The GBPNe population in this work was selected mainly from the catalogue of JS04. In this catalogue, the positions, angular diameters, Hα+ [N ii] fluxes and 5 GHz fluxes are given for a sample of 94 GBPNe. This survey uses a narrow-band imaging in the near-IR [S ii] line at 9532 Å to detect highly extinction GBPNe, since this line is the apparently brightest line in the spectra of typical PNe when the V-band extinction is between 4 and 12 mag. This point will be addressed in more detail in Section 2.2, where the spectra of the GBPNe of our sample will be presented. JS04 estimated that their survey identified nearly two-thirds of the predicted total number of PNe within $2^\circ$ from the GC.

Usually, GBPNe are selected following the standard criteria of Stasińska et al. (1998): they have locations within 10$^\circ$ of the GC, diameters smaller than 12″ and fluxes at 5 GHz lower than 100 mJy. The combination of these criteria leads to the rejection of about 90% of the sources. In this work, we adopt a stricter selection of the GBPNe, since this line is the apparently brightest line in the spectra of typical PNe. We performed spectroscopic follow-up of 33 objects located within $2^\circ$ of the GC, in a region of a very high-level of reddening. From those objects, 17 had spectra with acceptable quality. These new data provide chemical composition for PNe located in this region of the Galactic bulge. This paper is organized as follows: Section 2.2 describes the criteria for sample selection, the observations and the data reduction. Section 3 presents the determination of the physical conditions and the ion and total abundances of our targets. Section 4 is devoted to the data analysis and the comparison of the results obtained in this paper with other results in the literature. Section 5 summarizes the main findings of this work.
Planetary nebulae near the Galactic centre

In order to check the bulge membership of our observed sample, we have calculated individual distances for these objects using the statistical distance scale of Stanghellini et al. (2008) and the data provided by JS04 for the optical angular diameters and fluxes at 5 GHz. Optical diameters were also taken from Parker et al. (2006) for the PPA PNe. The statistical distances may present large errors when used individually and in some cases they are as high as 30% (Stanghellini et al. 2008). However, when applied to a larger number of objects, they can be very useful to probe the chemical evolution of the Galaxy, as can be seen in Maciel et al. (2003); Henry et al. (2010); Cavichia et al. (2011) and references therein. The logarithmic extinctions at Hβ, necessary to derive the distances, were calculated from the fluxes obtained from our own observations. When the fluxes at 5 GHz were not available, equation 6 provided by Cahn et al. (1992) was used to derive equivalent 5 GHz flux from the Hβ flux. In Table 1, column 1 and 2 list the PNG numbers and the PNe names, column 3 the flux in 5 GHz when available or the equivalent flux derived from the Hβ flux. Column 4 of Table 1 shows the optical thickness parameter, as defined by equation 2 of Stanghellini et al. (2008), column 5 the optical radius, in arcsec, from JS04 and from Parker et al. (2006). The Galactocentric distances obtained from this method are presented in column 6. Recent estimates for the Galactocentric distance of the Sun (R0) ranges from 7.5 to 8.5 kpc, and We have adopted the average value R0 of 8.0 kpc, as suggested by Malkin (2013). In Table 1 the minus sign in the distances indicates the cases when the distances are greater than 8.0 kpc from the Sun. Fig. 2 shows the galactocentric distance distribution for our sample. The Gaussian fitted to the distribution has mean and standard deviation of 0.89 and 0.92 kpc, respectively. Considering the distance of R0 adopted, the GBPNe studied in this work are ∼ 0.9 kpc on the average from the GC. Therefore, we are very confident that the present sample is composed by bona fide PNe near the GC. However, for all but one object (JaSt 23) the velocity data are not available in the literature and, since the inner disc can extend into the inner kpc of the Galaxy (see a revision by Bland-Hawthorn & Gerhard 2016), we cannot rule out inner disc PNe contaminants in our sample. In the case of JaSt 23, the OH maser spectrum shows a single peak at VLSR = +115.2 km s−1 (Iscanga et al. 2012), which is compatible with that expected for GBPNe.

Figure 1. The longitude–latitude distribution of the GBPNe from this work (filled red circles) and the data from CCM10 (filled blue squares). The figure also shows the contours of the COBE/DIRBE 2.2μm image from Weiland et al. (1994). Note that only GBPNe from this work with abundances listed in table 9 are included in this figure.

Table 1. Individual Galactocentric distances for GBPNe.

| PNG   | Name     | F (mJy) | τ (arcsec) | θ (kpc) |
|-------|----------|---------|------------|---------|
| 0.344+1.567 | JaSt 23  | 3       | 4.079      | 3.1     | -2.19   |
| 000.2+01.7 | JaSt 19  | 6       | 3.724      | 3.1     | -0.69   |
| 000.2-01.4 | JaSt 79  | 4       | 3.785      | 2.5     | -2.69   |
| 000.4+01.1 | JaSt 36  | 31      | 2.906      | 2.5     | 0.88    |
| 000.5+01.9 | JaSt 17  | 10      | 3.806      | 4.1     | 1.28    |
| 000.6-01.0 | JaSt 77  | 49      | 3.309      | 5.1     | 3.72    |
| 000.9+01.8 | PPAJ1740-2708 | 23   | 3.192      | 3.1     | 1.25    |
| 001.0+01.3 | JaSt 41  | 16      | 3.467      | 3.5     | 1.42    |
| 001.5+01.5 | JaSt 46  | 20      | 3.238      | 3.1     | 1.11    |
| 001.7+01.3 | JaSt 52  | 24      | 3.017      | 2.5     | 0.54    |
| 002.0-01.3 | JaSt 98  | 21      | 3.059      | 2.5     | 0.41    |
| 004.3-01.4 | PPAJ1801-2553 | 3   | 3.955      | 2.7     | -2.48   |
| 357.4+01.4 | PPAJ1734-3004 | 9   | 3.843      | 4.1     | 1.16    |
| 358.5-01.7 | JaSt 64  | 28      | 2.946      | 2.5     | 0.77    |
| 358.9-01.5 | JaSt 65  | 122     | 2.308      | 2.5     | 2.59    |
| 359.5-01.2 | JaSt 66  | 65      | 2.584      | 2.5     | 1.86    |
| 359.9+01.8 | PPAJ1738-2800 | 0   | 4.472      | 2.2     | -9.25   |

1 OH 0.344 +1.567
2.2 Observations and data reduction

2.2.1 Optical data

In 2009 we started an observational program aimed at carrying out a spectroscopic follow-up of GBPNe located within 2° of the GC. The 4.1 m SOAR telescope at Cerro Pachón (Chile) equipped with the Goodman spectrograph was used for this purpose. The long-slit spectra were obtained during the years of 2010, 2011 and 2012 using three different VPH gratings 300, 600 and 400 l/mm, respectively. In table 2 we list the VPH gratings, slits, wavelength coverage and the FWHM resolution achieved for the optical and near infrared (NIR) observations (see section 2.2.2). The log of the observations is provided in table 3 as follows: the PNG number (column 1), the name of the object (column 2), the coordinates RA and DEC (columns 3 and 4, respectively), the Galactic longitude and latitude (columns 5 and 6, respectively), the exposition time in seconds (column 7), and the date of observation (column 8). Column 9 lists the VPH grating used in each observation. Columns 10 and 11 list the log of the near infrared observations (see Section 2.2.2).

The Goodman spectrograph focal plane is imaged onto a Fairchild 4096 × 4096 pixels CCD with a read rate of 100 kHz. The exposition times varied between 1800–2600 s, depending on the faintness of the object. Seeing conditions were in general very good (0.5′′ – 0.9′′). For each night, at least two spectroscopic standard stars were observed, through a 3′′-wide slit, for flux calibration. Frames containing the same spectral data were combined in order to increase the final signal-to-noise ratio (S/N). The data were reduced with standard procedures by using an IRAF package developed by our group, the PNPACK. This package automatically reduces long-slit spectra by doing bias subtraction, flat field correction, extraction of 1-dimensional spectra, wavelength calibration, atmospheric extinction correction and flux calibration. Cosmic rays were removed using the algorithm for cosmic-ray rejection by Laplacian Edge Detection (van Dokkum 2001), implemented in the program L.A.Cosmic. In the case of PN spectra, many lines of the observed spectra are weak and, since the objects are located in crowded Galactic bulge fields near the GC, a multi-step method had to be adopted to perform the 1-dimensional spectra extraction. The best-fitting of the background was achieved after removing sky continuum emissions, telluric and interstellar lines, as well as stellar continuum components. The nebular lines were detected and the line fluxes were calculated following an automatic procedure implemented in the PNPACK code. This procedure uses the IRAF task splot to perform Gaussian fit to emission lines in the spectra and an Gaussian de-blending routine to de-blend lines when necessary. Following this procedure, signal can be attributed to a nebular line only if its value is higher than 2 sigmas of the averaged background noise.

2.2.2 Near infrared data

The optical spectra of the GBPNe near the GC suffer for high-level of extinction caused by the material near the Galactic plane and also in the central regions of the Galaxy. As a result, important diagnostic lines as [OIII] λλ 4363 Å and [NII] λ5755 Å do not have enough S/N ratio to obtain the electron temperature from the temperature diagnostic diagrams. Other important temperature-sensitive lines are those from S[III] and S[II] auroral line at λ6312 Å is presented in most of our optical spectra. However, the other two [SIII] lines necessary to obtain the electron temperature are near infrared (NIR) lines at λλ 9069 and 9532 Å.

In order to observe the NIR [SIII] lines, we started an observational program in 2012 at the Observatório Pico dos Dias (OPD) of National Laboratory for Astrophysics (LNA, Brazil) with the 1.6 m Perkin-Elmer telescope. The spectrophotometry observations were taken according to the log of observations showed in the last two columns of table 2. A Cassegrain Boller & Chivens spectrograph was used with a 300/1/mm grid, which provides a reciprocal dispersion of 0.22 nm/pixel. An Andor Ikon CCD optimized for NIR observations was used with an operating image scale of 0.56′′/pix and a pixel size of 13.5 x 13.5 μm. The science spectra were taken with a long slit of 2.5′′ with a FWHM spectral resolution of ~ 9 Å. In figure 2 we also list the setup for the NIR observations. Each night at least two of the spectrophotometric standard stars CD-32 9927, LTT 7379, LTT 9239, CD-34 241 of Hamuy et al. (1992, 1994) were observed to improve the flux calibration. These stars were observed with a long slit of 7.5′′ width, allowing a more precise flux calibration. Helium-argon arcs were taken immediately after each science spectra in order to perform wavelength calibration. Telluric corrections were not performed since the [SIII] λ9069 and 9532Å are relatively very intense and telluric absorption effects are negligible for these lines.

Table 2. Instrumental setup for optical and NIR observations.

| Grating (l/mm) | Slit width (arcsec) | Coverage (Å) | FWHM (Å) |
|---------------|---------------------|--------------|----------|
| Optical       |                     |              |          |
| 300           | 1.35                | 3600 – 8800  | 11.8     |
| 400           | 1.68                | 4000 – 8050  | 11.2     |
| 600           | 1.68                | 4700 – 7360  | 7.3      |
| NIR           | 300                 | 2.50         | 6010 – 11010 | 9.0 |

Figure 2. Galactocentric distance distribution for the GBPNe from our sample. The continuous line is the result of the histogram data fitted by a Gaussian with mean and standard deviation of 0.89 kpc and 0.92 kpc, respectively.
Planetary nebulae near the Galactic centre

Table 3. Log of the observations.

| PNG Name | RA (J2000) | DEC (J2000) | ℓ (°) | b (°) | Texp (s) | Date | Grating | Texp (s) | Date |
|----------|------------|-------------|-------|------|----------|------|---------|----------|------|
| 0.344+1.567¹ | JaSt 23 | 17 40 23.32 | -27 49 11.7 | 0.35 | 1.57 | 2400 | Jun 28, 11 | 600 | 2400 | Jun 25, 12 |
| 0.002+0.17 | JaSt 19 | 17 39 39.38 | -27 47 22.58 | 0.28 | 1.72 | 2400 | Jun 24, 12 | 300 | 1800 | Jun 26, 14 |
| 0.002-0.14 | JaSt 79 | 17 51 53.63 | -29 30 53.41 | 0.21 | -1.47 | 2400 | Jun 08, 10 | 300 | 2400 | Jun 26, 12 |
| 0.004+0.11 | JaSt 36 | 17 42 25.20 | -27 55 36.36 | 0.49 | 1.13 | 2400 | Jun 12, 24 | 300 | 2400 | Jun 25, 12 |
| 0.005+0.19 | JaSt 17 | 17 39 31.22 | -27 27 46.77 | 0.55 | 1.91 | 2400 | Jun 28, 11 | 600 | 2400 | Jun 27, 12 |
| 0.006-0.10 | JaSt 77 | 17 51 11.65 | -28 56 27.20 | 0.63 | -1.05 | 1200 | Jun 07, 10 | 300 | 600 | Jun 26, 14 |
| 0.009+0.18 | PPAJ1740-2708 | 17 40 50.70 | -27 08 48.00 | 0.97 | 1.84 | 600 | Jun 23, 12 | 400 | – | – |
| 0.010+0.13 | JaSt 41 | 17 42 49.96 | -27 21 19.68 | 1.03 | 1.35 | 2400 | Jun 08, 10 | 300 | 1800 | Jun 25, 12 |
| 0.015+0.13 | JaSt 46 | 17 43 30.43 | -26 47 32.30 | 1.58 | 1.52 | 2400 | Jun 28, 11 | 600 | 900 | Jun 27, 12 |
| 0.017+0.13 | JaSt 52 | 17 44 37.30 | -26 47 25.23 | 1.72 | 1.31 | 2x300 | Jun 08, 10 | 300 | 1200 | Jun 25, 14 |
| 0.020-0.13 | Just 98 | 17 55 46.39 | -27 53 38.90 | 2.04 | -1.38 | 2400 | Jun 08, 12 | 400 | 2400 | Jun 26, 12 |
| 357.7+1.4 | PPAJ1734-3004 | 17 34 46.6 | -30 04 21 | 357.78 | 1.40 | 2600 | Jun 08, 12 | 400 | – | – |
| 358.5-0.17 | JaSt 64 | 17 48 56.04 | -31 06 41.95 | 358.51 | -1.74 | 2x900 | Jun 07, 10 | 300 | 1800 | Jun 25, 14 |
| 358.5-0.15 | JaSt 65 | 17 49 20.02 | -30 36 05.57 | 358.99 | -1.55 | 1800 | Jun 07, 10 | 300 | 2400 | Jun 26, 12 |
| 359.5+0.12 | JaSt 66 | 17 49 22.10 | -29 59 27.00 | 359.52 | -1.24 | 2400 | Jun 27, 11 | 600 | 2400 | Jun 26, 12 |
| 359.5+0.18 | PPAJ1738-2800 | 17 38 11.80 | -28 00 07.00 | 359.93 | 1.88 | 2400 | Jun 24, 12 | 400 | – | – |

¹ OH 0.3447+1.5656
² Near infrared observations.

point will be addressed again in section 2.2.3, were the observed relative fluxes of these lines are confronted with the expected theoretical values. Data reduction was performed using the IRAF package, following the standard procedure for long slit spectra, as in the previous section: correction of bias, flat-field, extraction, wavelength and flux calibration. Atmospheric extinction was corrected through mean coefficients derived for the LNA observatory.

The NIR spectra were normalized to match their optical counterparts using as many as lines as available in the spectra. The normalizing constant for each NIR spectra was obtained by the flux weighted mean of the ratio of the NIR line and the optical counterpart. In general the concordance in flux was good between both spectra (optical and NIR), and the mean ratio of the lines varying between 0.7 and 1.7. The variation of the normalizing constant can be attributed to some causes: atmospheric extinction correction, as we are using the mean extinction absorption coefficients provided by the observatories; the slit widths are different in the optical and NIR observations and this can cause some fluxes loss; cirrus clouds can cause a grey extinction in the spectra and, therefore, change the absolute flux values. In Fig. 3 an example is presented showing the match between the optical and NIR spectra in the region were there are common lines in both observations. It is important to note in this figure that due to the different instrumental setups in both observations, the line profiles are different and the peaks of the lines may not match. The final spectra calibrated in flux and wavelength are shown in Fig. 4. Note that in this figure the spectra were not corrected for interstellar extinction. The reddened fluxes of the GBPNe are listed in Table 4. In this table, the fluxes are presented relative to the one from Hβ line. The errors associated with the fluxes were attributed based on the intensity of the line, as will be explained in Section 3.4.

Figure 3. Calibrated optical (black continuous line) and NIR (dashed red line) spectra for JaSt 98 in the region where the line ratios were used to calculate the normalizing constant. At the top-right panel it is shown a zoom in the faintest lines.

2.2.3 Reddening correction

To perform a good interstellar extinction correction is crucial for high-extinction GBPNe. As pointed out by [Nataf et al. (2013)], for most of the bulge, $A_V \approx 2$ is typical. However, for some regions close to the GC, $A_V \approx 50$. The extinction towards the bulge is not only high but also non-standard. The standard value of $R_V$ (the ratio of the total $A_V$ to selective $E(B-V)$ extinction at $V$) is 3.1 (Fitzpatrick 1999). However, Nataf et al. (2013) find that the optical and NIR reddening law toward the inner Galaxy approximately follows an $R_V \approx 2.5$ extinction curve. On the other hand, [Nataf et al. (2016)] combined four measures of extinction in the bandpasses $VIJK_s$ and observed that there is no compatibility between bulge extinction coefficients and literature extinction coefficients using any extinction parametrization available (eg. Cardelli et al. 1989).
Figure 4. Calibrated optical spectra of low and medium resolution of the GBPNe observed. At the center-top of each optical spectra it is shown the respective NIR spectrum, when available.

Fitzpatrick (1999). Fig. 5 shows a comparison between the extinction curves from Fitzpatrick (1999) in the cases of $R \equiv A(V)/E(B-V) = 3.1$ and 2.5 (black continuous line and red open circles, respectively). The dashed line is the seven degree polynomial fit for $R = 2.5$. The coefficients of the parametrized extinction curve are shown in Table 5. In the same figure, we show for comparison the NIR extinction curve parametrization from Fitzpatrick & Massa (2009) using $R_V = 2.64$ and $\alpha = 2.49$ (see their work for details). Differences between both parametrizations are noted.
for $\lambda > 1\mu m$. Since the most NIR line in our data is the \([S\text{III}]\lambda 9532\) line, we do not expect meaningful variations in the extinction-corrected lines using both parametrizations. In fact, we estimated a difference of $\sim 1$ per cent in our approach compared with the NIR parametrization of Fitzpatrick & Massa (2009) at 9532 Å. Therefore, given the uncertainty in the literature with respect to the NIR ($\lambda > 7500$ Å) extinction, we opted to use the Fitzpatrick (1999) extinction parametrization with $R_V = 2.5$, instead...
of use any of the NIR parametrization provided in the literature.

Our package PNPACK is also able to perform interstellar reddening correction using both extinction curves of Cardelli et al. (1989) and Fitzpatrick (1999). As explained above, in this work we adopted the later extinction curve, since it has been show that it produces better results than the extinction curve of Cardelli et al. (1989) for GBPNe (see e.g. Escudero et al. 2004, for a discussion). The Fitzpatrick (1999) extinction curve is parametrized as a function of $R_V$. 

Figure 4. Continued.
Figure 5. Normalized interstellar extinction curves from NIR through optical. Open circles are the data generated using the Fitzpatrick (1999) extinction parametrization in the case \( R \equiv A(V)/E(B-V) = 2.5 \). The dashed line is the seventh-degree polynomial fit. The black continuous line is the same parametrization in the case \( R_V = 3.1 \). The dotted line corresponds to the NIR extinction parametrization from Fitzpatrick & Massa (2004) in the case of \( R_V = 2.64 \) and \( \alpha = 2.49 \).

Therefore, one can obtain the extinction curve computed for the case \( R_V = 2.5 \) with a seventh-degree polynomial fitting in the form:

\[
\frac{A_\lambda}{E(B-V)} = \sum_{n=0}^{7} a_n x^n,
\]

with \( x = 1/\lambda \) (\( \mu m^{-1} \)). Table 5 shows the coefficients of the polynomial fitting obtained using equation (1).

Table 5. Coefficients of the parameterized extinction curve.

| \( n \) | \( a_n \) |
|-------|--------|
| 0     | 1.29   |
| 1     | -7.80  |
| 2     | 20.60  |
| 3     | -24.84 |
| 4     | 16.77  |
| 5     | -6.21  |
| 6     | 1.17   |
| 7     | -0.09  |

We determined the reddening from the optical spectra, using the H\( \alpha \) and H\( \beta \) Balmer lines and assuming a dereddened H\( \alpha \)/H\( \beta \) flux ratio as given by the recombination theory: \( I(H\alpha)/I(H\beta) \sim 2.86 \). Column three of Table 6 shows the extinction \( E(B-V) \) obtained for each object of our sample. The reddening showed in this table was applied both in the optical and NIR spectra. The remaining columns of Table 6 list the electron densities and temperatures and will be introduced in Section 3.

2.2.4 Line fluxes uncertainties

Sources of errors in the flux measurements can be photon shot and CCD readout noise, bias and sky background induced noise, errors in the standard star calibration and in the interstellar and atmospheric extinction corrections. Bad sky-features subtraction or field stars contamination can also contribute to the uncertainties in the line fluxes. The quality of the data can be evaluated since some line ratios are known from atomic physics. For example, the line ratio \([\text{OIII}]\lambda5007/\lambda4959\) is expected to be 2.98 (Storey & Zeippen 2000). Fig. 6 shows the \([\text{OIII}]\lambda5007/\lambda4959\) ratio as a function of the \([\text{OIII}]\lambda5007\) line flux. The dashed line is the theoretical value of 2.98 and the shaded area corresponds to expected uncertainty of 5 per cent around this value. The dispersion of the observed ratios in this figure is consistent
Table 4. Reddened fluxes relative to Hβ. F(Hβ) is in units of erg cm$^{-2}$ s$^{-1}$.

| $\lambda$ | Ion   | $F(\lambda)/F($H$\beta$) | Error $F(\lambda)/F($H$\beta$) | Error $F(\lambda)/F($H$\beta$) | Error $F(\lambda)/F($H$\beta$) |
|----------|-------|---------------------------|-------------------------------|-------------------------------|-------------------------------|
| 4341.   | H$_2$ | -             | 0.24 | 0.02 | 0.32 | 0.03 | 0.17 | 0.02 |
| 4363.   | OI    | -             | 0.04 | 0.01 | 0.39 | 0.04 | -    | -    |
| 4686.   | HeII  | -             | 0.15 | 0.02 | 0.46 | 0.05 | -    | -    |
| 4861.   | H$_3$+HeII | 1.00 | 0.10 | 1.00 | 0.10 | 1.00 | 0.10 | 1.00 | 0.10 |
| 4959.   | OII   | -             | 3.95 | 0.40 | 3.17 | 0.32 | 5.65 | 0.28 |
| 5007.   | OIII  | 0.22 | 0.02 | 13.29 | 0.66 | 10.82 | 0.54 | 17.70 | 0.89 |
| 5412.   | CIII  | -             | 0.06 | 0.01 | 0.38 | 0.04 | -    | -    |
| 5518.   | CIII  | -             | -    | -    | -    | -    | -    | -    |
| 5558.   | NII   | 1.66 | 0.17 | 0.02 | 0.01 | 0.60 | 0.06 | 0.03 | 0.01 |
| 5576.   | HeI   | 0.85 | 0.09 | 0.52 | 0.05 | 0.51 | 0.05 | 1.76 | 0.18 |
| 6300.   | OI    | 0.79 | 0.08 | 3.06 | 0.66 | 10.82 | 0.54 | 17.70 | 0.89 |
| 6312.   | SIII  | 1.09 | 0.11 | 0.03 | 0.01 | 1.11 | 0.11 | 0.29 | 0.03 |
| 6363.   | OI    | -             | -    | -    | -    | -    | 0.71 | 0.07 | 0.19 | 0.02 |
| 6435.   | ArV   | -             | -    | -    | -    | -    | 0.66 | 0.07 | -    | -    |
| 6548.   | NII   | 19.18 | 0.96 | 0.11 | 0.01 | 2.21 | 0.22 | 1.56 | 0.16 |
| 6563.   | HeI   | 75.86 | 3.69 | 30.06 | 1.50 | 36.68 | 1.83 | 74.44 | 3.72 |
| 6584.   | NII   | 50.23 | 2.81 | 0.35 | 0.03 | 6.64 | 0.33 | 4.91 | 0.49 |
| 6678.   | HeI   | 0.85 | 0.09 | 0.38 | 0.04 | 0.44 | 0.04 | 1.26 | 0.13 |
| 6716.   | SII   | 0.76 | 0.08 | 0.10 | 0.02 | 0.23 | 0.02 | 0.47 | 0.05 |
| 6731.   | SII   | 1.42 | 0.14 | 0.12 | 0.01 | 0.51 | 0.05 | 0.77 | 0.08 |
| 7005.   | ArV   | -             | -    | -    | -    | -    | 2.37 | 0.24 | -    | -    |
| 7065.   | HeI   | 2.19 | 0.22 | 0.30 | 0.03 | 0.89 | 0.09 | 2.91 | 0.29 |
| 7135.   | ArIII | 4.66 | 0.47 | 1.66 | 0.17 | 6.05 | 0.30 | 3.59 | 0.36 |
| 7237.   | ArIV  | -             | -    | 0.07 | 0.01 | 0.44 | 0.04 | -    | -    |
| 7263.   | ArIV  | -             | -    | -    | -    | 0.50 | 0.05 | -    | -    |
| 7281.   | HeI   | -             | -    | -    | -    | -    | 0.41 | 0.04 | -    | -    |
| 7322.   | OII   | 14.79 | 0.74 | 0.37 | 0.04 | 9.76 | 0.49 | 2.28 | 0.23 |
| 7333.   | OII   | 10.26 | 0.51 | -    | -    | -    | -    | 1.98 | 0.20 |
| 7775.   | ArIII | -             | -    | -    | -    | -    | 1.98 | 0.20 | -    | -    |
| 9069.   | SIII  | 115.23 | 5.76 | -    | -    | 21.11 | 1.06 | 49.06 | 2.45 |
| 9532.   | SIII  | 355.35 | 17.77 | -    | -    | 52.47 | 2.62 | 151.65 | 7.58 |

$log(F(\beta))$ -15.602 -14.856 -14.919 -15.079

with an uncertainty of 5 per cent in the flux measures. It is important to note that in cases of lines with a lower S/N or strong blending, the uncertainty is higher and can reach 40 per cent in the worst cases. In cases of strong line blending, as in the 2010 observations due to the low resolution of the 300 l/mm grating, the flux of the line [NII]($\lambda$6548 was calculated from the known ratio [NII]$\lambda6584$/6548 of 3 (Osterbrock & Ferland 2006).

Fig. 4 shows the ratio of [SIII]$\lambda9532$ and [SIII]$\lambda9069$ fluxes as a function of the [SIII]$\lambda9532$ line-flux. The theoretical predicted value by atomic physics of 2.44 is shown in the figure for reference. As can be seen in figures 8 and 4, most of the flux ratios are consistent with a line uncertainty of 5 per cent. In the case of [OIII], all but two objects PPAJ1738-2800 and JaSt 98) have line ratios compatible with flux uncertainties within 10 per cent. In the case of [SIII] objects JaSt 19, JaSt 23, JaSt 46, JaSt 52 and JaSt 77 have line ratios compatible with flux uncertainties of 5 per cent. Objects JaSt 36, JaSt 64 and JaSt 66 have flux uncertainties larger than 15 per cent. Probably a better flux calibration and spectrum extraction and/or correction for telluric lines are needed for these objects. In the case of objects having [SIII] line ratios higher than 2.44, may indicate a telluric absorption in the [SIII]$\lambda9069$. Those having [SIII] line ratios lower than the theoretical value, may indicate an absorption in the [SIII]$\lambda9532$. Therefore, some caution should be devoted in the electronic temperature from [SIII] lines for these objects. The PN JaSt 79 shows a stellar continuum at the NIR in its spectrum that is not observed in the other PNe of our sample. Indeed, this object was classified as a symbiotic star by Miszalski et al. (2006). Also, our spectrum of this object shows high ionization lines as [Fe II] $\lambda$5721, 6087, with reddened fluxes $10^{15}$ and $3.240 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, respectively, confirming its symbiotic nature. Therefore, this object will be excluded from the abundance analysis performed in Section 4.

3 DETERMINATION OF PHYSICAL PARAMETERS, IONIC AND TOTAL ABUNDANCES

3.1 Physical parameters

Table 6 shows the electron densities derived from the abundance analysis performed in Section 4.
Table 4. Continued.

| λ   | Ion | \( F(\lambda)/F(H\beta) \) | Error | \( F(\lambda)/F(H\beta) \) | Error | \( F(\lambda)/F(H\beta) \) | Error | \( F(\lambda)/F(H\beta) \) | Error |
|-----|-----|----------------------------|-------|----------------------------|-------|----------------------------|-------|----------------------------|-------|
| 4341 | H\( \gamma \) | – | – | – | – | 0.27 | 0.03 | – | – |
| 4363 | OIII | – | – | – | – | – | – | – | – |
| 4866 | HeII | – | – | – | – | 0.16 | 0.02 | – | – |
| 4861 | H\( \beta \)+HeII | 1.00 | 0.10 | 1.00 | 0.10 | 1.00 | 0.10 | 1.00 | 0.10 |
| 4959 | OIII | 1.85 | 0.19 | 5.79 | 0.29 | 4.01 | 0.40 | 1.99 | 0.20 |
| 5007 | OIII | 6.30 | 0.32 | 19.85 | 0.99 | 13.46 | 0.67 | 6.62 | 0.33 |
| 5412 | HeII | 0.06 | 0.01 | – | – | 0.05 | 0.01 | – | – |
| 5518 | CIII | – | – | – | – | – | – | – | – |
| 5538 | CIII | – | – | – | – | – | – | – | – |
| 5755 | NII | 0.03 | 0.01 | – | – | 0.51 | 0.05 | – | – |
| 5876 | HeI | 1.01 | 0.10 | 2.44 | 0.24 | 1.72 | 0.17 | 2.01 | 0.20 |
| 6300 | OI | – | – | 1.15 | 0.11 | 2.29 | 0.23 | 0.38 | 0.04 |
| 6312 | SII | 0.04 | 0.01 | 0.63 | 0.06 | 0.39 | 0.04 | 0.28 | 0.03 |
| 6363 | OI | – | – | 0.58 | 0.06 | 0.89 | 0.09 | – | – |
| 6435 | ArV | – | – | – | – | – | – | – | – |
| 6548 | NII | 0.80 | 0.08 | 1.92 | 0.19 | 32.10 | 1.61 | 2.12 | 0.21 |
| 6563 | H\( \alpha \) | 24.91 | 1.25 | 131.13 | 6.56 | 48.23 | 2.41 | 86.62 | 4.33 |
| 6584 | NII | 2.51 | 0.25 | 5.76 | 0.29 | 105.26 | 5.26 | 6.37 | 0.32 |
| 6678 | HeI | 0.52 | 0.05 | 2.82 | 0.28 | 1.36 | 0.14 | 1.66 | 0.17 |
| 6716 | SII | 0.13 | 0.01 | 0.53 | 0.05 | 5.56 | 0.28 | 0.34 | 0.03 |
| 6731 | SII | 0.18 | 0.02 | 1.10 | 0.11 | 9.28 | 0.46 | 0.50 | 0.05 |
| 7005 | ArV | – | – | – | – | 0.25 | 0.02 | – | – |
| 7065 | HeI | 0.42 | 0.04 | 11.67 | 0.58 | 2.25 | 0.23 | 6.53 | 0.33 |
| 7135 | ArIII | 1.81 | 0.18 | 12.30 | 0.62 | 10.98 | 0.55 | 2.35 | 0.23 |
| 7237 | ArIV | 0.55 | 0.06 | – | – | 0.38 | 0.04 | – | – |
| 7263 | ArIV | – | – | – | – | – | – | – | – |
| 7281 | HeI | 0.14 | 0.01 | 1.07 | 0.11 | 0.25 | 0.03 | 0.93 | 0.09 |
| 7322 | OII | 0.41 | 0.04 | 19.55 | 0.98 | 4.43 | 0.44 | 4.51 | 0.45 |
| 7334 | OII | 0.38 | 0.04 | – | – | – | – | – | – |
| 7751 | ArIII | – | – | 5.69 | 0.28 | 4.79 | 0.48 | 1.25 | 0.13 |
| 9069 | SIII | – | – | 97.83 | 4.89 | – | – | 37.53 | 1.88 |
| 9532 | SIII | – | – | 303.73 | 15.19 | – | – | 114.70 | 5.74 |

\( \log(F/H\beta) \) | -14.507 | -14.995 | -14.852 | -15.422 | -14.507 | -14.995 | -14.852 | -15.422 |

Figure 6. Ratio of [O\( 3\)ii]\( \lambda 5007 \) and [O\( 3\)ii]\( \lambda 4959 \) fluxes as a function of the [O\( 3\)ii]\( \lambda 5007 \) line-flux. The horizontal dashed line denotes the theoretical flux ratio [O\( 3\)ii]\( \lambda 5007/4959 \) of 2.98. The shaded area corresponds to the expected uncertainty in the line ratios, considering an error of 5 per cent in the line fluxes. The dashed lines corresponds to the expected uncertainty in the line ratios, considering an error of 10 per cent in the line fluxes.

Figure 7. Ratio of [S\( 3\)ii]\( \lambda 9532 \) and [S\( 3\)ii]\( \lambda 9069 \) fluxes as a function of the [S\( 3\)ii]\( \lambda 9532 \) line-flux. The horizontal dotted line denotes the theoretical flux ratio of 2.44. The shaded area corresponds to the expected uncertainty in the line ratios, considering an error of 5 per cent in the line fluxes. The dashed and solid lines correspond to the expected uncertainty in the line ratios, considering an error of 10 and 15 per cent in the line fluxes, respectively.
Table 4. Continued.

| λ    | Ion     | 001.5+01.5 JaSt 46 | 001.6+01.5 JaSt 42 | 001.7+01.3 JaSt 52 | 002.0-01.3 JaSt 98 |
|------|---------|-------------------|-------------------|-------------------|-------------------|
| 4341 | Hγ      | –                 | –                 | –                 | –                 |
| 4363 | OIII    | –                 | –                 | –                 | –                 |
| 4686 | HeII    | –                 | –                 | –                 | –                 |
| 4861 | Hβ+HeII | 1.00±0.10         | 1.00±0.10         | 1.00±0.10         | 1.00±0.10         |
| 4959 | OIII    | 1.92±0.19         | 2.76±0.28         | 0.40±0.04         | 8.76±0.44         |
| 5007 | OIII    | 6.27±0.31         | 9.32±0.47         | 1.35±0.13         | 27.15±1.36        |
| 5412 | HeII    | –                 | –                 | –                 | –                 |
| 5518 | C3      | 0.03±0.01         | –                 | –                 | –                 |
| 5538 | C3      | 0.03±0.01         | –                 | –                 | –                 |
| 5755 | NI      | 0.10±0.01         | –                 | –                 | –                 |
| 5876 | HeI     | 1.16±0.12         | 0.66±0.07         | 0.57±0.06         | 3.03±0.30         |
| 6300 | OI      | 0.25±0.02         | 0.02±0.00         | 0.34±0.03         | 2.20±0.22         |
| 6312 | SIII    | 0.14±0.01         | 0.02±0.02         | 0.07±0.01         | 0.42±0.04         |
| 6363 | OI      | 0.09±0.02         | –                 | –                 | 0.72±0.07         |
| 6435 | ArV     | –                 | –                 | –                 | 0.30±0.03         |
| 6548 | NI      | 5.46±0.27         | 0.77±0.08         | 4.62±0.46         | 11.94±0.60        |
| 6563 | Hα      | 35.38±1.77        | 42.82±2.14        | 42.84±2.14        | 126.57±6.33       |
| 6584 | NI      | 17.92±0.90        | 2.39±0.24         | 14.78±0.74        | 37.91±1.90        |
| 6678 | HeI     | 0.76±0.08         | 0.81±0.08         | 0.40±0.04         | 2.74±0.27         |
| 6716 | SII     | 0.55±0.05         | 0.23±0.02         | 0.34±0.03         | 0.84±0.08         |
| 6731 | SII     | 1.03±0.10         | 0.34±0.03         | 0.67±0.07         | 1.29±0.13         |
| 7005 | ArV     | –                 | –                 | –                 | 0.14±0.01         |
| 7065 | HeI     | 1.45±0.15         | 1.03±0.10         | 1.27±0.13         | 10.78±0.54        |
| 7135 | ArIII   | 4.53±0.45         | 3.63±0.36         | 1.68±0.17         | 19.65±0.98        |
| 7237 | ArIV    | 0.12±0.01         | 0.50±0.05         | –                 | –                 |
| 7263 | ArIV    | –                 | –                 | –                 | –                 |
| 7261 | HeI     | 0.21±0.02         | –                 | –                 | –                 |
| 7322 | OII     | 1.04±0.10         | 0.86±0.09         | 15.53±0.78        | 18.24±0.91        |
| 7334 | OII     | 0.84±0.08         | –                 | –                 | –                 |
| 7751 | ArIII   | –                 | 2.46±0.25         | 0.28±0.08         | 11.36±0.57        |
| 9069 | SIII    | –                 | 31.80±1.59        | –                 | 79.85±3.99        |
| 9532 | SIII    | –                 | 92.42±4.62        | –                 | 249.31±12.47      |
| log(F(Hβ)/F(HeII)) | –14.048 | –14.864 | –14.745 | –15.572 |

Electron temperatures obtained from [NII]λ5755/(6584+6548) line ratios and [SIII]λ6312/(9532+9069).

The [OIII] temperatures were derived from a linear correlation with [SIII] temperatures obtained by Henry et al. (2004):

\[ T_{\text{e}[\text{SIII}]} = -0.039(\pm 0.11) + 1.20(\pm 0.11) \times T_{\text{e}[\text{OIII}]} \]  

(2)

where temperatures are in units of 10^4 K. Henry et al. (2004) estimated that the [SIII] temperatures can be obtained from this equation with an uncertainty of ~ 1000 K. The \( T_{\text{e}[\text{OIII}]} \) temperatures calculated from this linear correlation included in table 6 also are listed with errors. The errors were calculated from the Monte Carlo procedure explained in Section 3.4 and only include line-flux uncertainties. We prefer to use \( T_{\text{e}[\text{OIII}]} \) calculated from the \( T_{\text{e}[\text{SIII}]} \). However, in some cases \( T_{\text{e}[\text{SIII}]} \) was very low to calculate \( T_{\text{e}[\text{OIII}]} \) from equation 2. In these few cases, we adopted the \( T_{\text{e}[\text{NI}]} \) instead of \( T_{\text{e}[\text{OIII}]} \) and they are listed without errors in table 6. We derived \( T_{\text{e}} \) from [SIII] only in the cases where the line ratio 9532/9069 was within the dashed lines of Fig. 7. By doing this, the individual line fluxes should have errors 10 per cent or lower.

As discussed in Section 2, objects JaSt 36, JaSt 41 and JaSt 64 have uncertainties in the [SIII] 9532 and 9069 Å lines fluxes higher than 15 per cent. This can introduce higher errors in the electron temperatures obtained from [SIII]. In the case of JaSt 64, we opted to use \( T_{\text{e}[\text{OIII}]} \) from \( T_{\text{e}[\text{NI}]} \). In the case of JaSt 41, JaSt 66 where the observed ratio was lower than the theoretical one, indicating a stronger absorption in the 9532 line, the total dereddened [SIII] intensity was taken equal to 2.44 times the 9069 line. In the remaining cases (JaSt 17, JaSt 36 and JaSt 98) where the ratio was larger than the theoretical one, the 9532 line was taken as reference, instead. Examining in detail the spectra of JaSt 41, we noted a contamination by a field star. Therefore some caution should be taken with the results for this object.

In the case of the object JaSt 65, we obtained a non-physical value of 27083 K for the temperature from [SIII] lines. This temperature is not typical for PNe and to calculate the abundances for this object we adopted an upper limit of 2 \times 10^4 K for \( T_{\text{e}[\text{OIII}]} \) and \( T_{\text{e}[\text{NI}]} \). However, since the abundances derived from collisional excitation lines depend strongly on the temperatures, the uncertainties in the abundances for this object are very high. Therefore, this object will not be used in the abundance analysis. JaSt 79 was also excluded from the abundance analysis because of its symbiotic nature.
Table 4. Continued.

| λ      | Ion  | F(\lambda)/F(H\beta) | Error | F(\lambda)/F(H\beta) | Error | F(\lambda)/F(H\beta) | Error | F(\lambda)/F(H\beta) | Error |
|--------|------|------------------------|-------|------------------------|-------|------------------------|-------|------------------------|-------|
| 4341.  | Hγ   | 0.27                   | 0.03  |                        |       |                        |       |                        |       |
| 4363.  | OIII | –                      | –     | –                      | –     | –                      | –     | –                      | –     |
| 4686.  | HeII | –                      | –     | –                      | –     | –                      | –     | –                      | –     |
| 4861.  | Hβ+HeII | 1.00                 | 0.10  | 1.00                   | 0.10  | 1.00                   | 0.10  | 1.00                   | 0.10  |
| 4959.  | OIII | 4.27                   | 0.43  | 3.44                   | 0.34  | 2.04                   | 0.20  | 1.79                   | 0.18  |
| 5007.  | OIII | 14.35                  | 0.72  | 11.34                  | 0.57  | 6.97                   | 0.35  | 6.50                   | 0.33  |
| 5412.  | HeII | –                      | –     | –                      | –     |                        | –     |                        | –     |
| 5518.  | CIII | –                      | –     | –                      | –     |                        | –     | –                      | –     |
| 5538.  | CIII | –                      | –     | –                      | –     |                        | –     | –                      | –     |
| 5755.  | NII  | 0.20                   | 0.02  | 0.14                   | 0.01  | 0.35                   | 0.03  | –                      | –     |
| 5876.  | HeI  | 1.23                   | 0.12  | 1.84                   | 0.18  | 1.83                   | 0.18  | 2.16                   | 0.22  |
| 6300.  | OI   | 1.27                   | 0.13  | 0.85                   | 0.09  | 0.20                   | 0.02  | –                      | –     |
| 6312.  | SIII | 0.63                   | 0.06  | 0.57                   | 0.06  | 0.67                   | 0.07  | 0.26                   | 0.03  |
| 6363.  | OI   | 0.60                   | 0.06  | 0.41                   | 0.04  | –                      | –     | 0.10                   | 0.01  |
| 6435.  | ArV  | –                      | –     | –                      | –     |                        | –     |                        | –     |
| 6548.  | NII  | 9.45                   | 0.47  | 3.71                   | 0.37  | 1.26                   | 0.13  | 2.41                   | 0.24  |
| 6563.  | Hα   | 49.77                  | 2.49  | 84.12                  | 4.21  | 77.70                  | 3.89  | 105.63                 | 5.28  |
| 6584.  | NII  | 29.32                  | 1.47  | 11.63                  | 0.58  | 3.77                   | 0.38  | 7.49                   | 0.37  |
| 6678.  | HeI  | 0.97                   | 0.10  | 1.39                   | 0.14  | 0.98                   | 0.10  | 1.75                   | 0.18  |
| 6716.  | SII  | 2.41                   | 0.24  | 0.47                   | 0.05  | –                      | –     | 0.43                   | 0.04  |
| 6731.  | SII  | 3.88                   | 0.39  | 0.95                   | 0.09  | 0.10                   | 0.02  | 0.64                   | 0.06  |
| 7005.  | ArV  | –                      | –     | –                      | –     | 0.24                   | 0.02  | –                      | –     |
| 7065.  | HeI  | 1.72                   | 0.17  | 5.17                   | 0.26  | 4.72                   | 0.47  | 6.68                   | 0.33  |
| 7135.  | ArIII| 4.71                   | 0.47  | 8.07                   | 0.40  | 4.52                   | 0.45  | 2.37                   | 0.24  |
| 7237.  | ArIV | –                      | –     | 0.20                   | 0.02  | –                      | –     | 0.18                   | 0.02  |
| 7263.  | ArIV | –                      | –     |                        | –     |                        | –     |                        | –     |
| 7281.  | HeI  | 0.33                   | 0.03  | 0.66                   | 0.07  | 0.58                   | 0.06  | 1.00                   | 0.10  |
| 7322.  | OII  | 2.67                   | 0.27  | 8.94                   | 0.45  | 25.68                  | 1.28  | 2.87                   | 0.29  |
| 7334.  | OII  | 2.06                   | 0.21  | –                      | –     | –                      | –     | 2.33                   | 0.23  |
| 7751.  | ArIII| 1.25                   | 0.12  | 3.04                   | 0.30  | 1.83                   | 0.18  | –                      | –     |
| 9069.  | SIII | –                      | –     | 80.96                  | 4.05  | 29.40                  | 1.47  | 36.63                  | 1.83  |
| 9532.  | SIII | –                      | –     | 245.67                 | 12.28 | 88.57                  | 4.43  | 112.91                 | 5.65  |

log(FHβ) | -15.294 | -14.791 | -14.746 | -15.225 |

Planetary nebulae near the Galactic centre

This can be noted in table 5 where the derived [SIII] electron temperature yielded 43105 K, a very high value for a typical PNe. The electron temperature from [NII] for JaSt 23 is also non-typical for PNe. Nonetheless, Te [SII] resulted in a plausible value. In view of the discrepancy between both values, some caution should be taken with the chemical abundances of this object and we prefer not to use its abundances in the abundance analysis.

3.2 Ionic abundances

The abundance for He$^+$ was derived from the average of the recombination lines 4471, 5876 and 6678 Å. The average was weighted by the intensity of each line. New He$^+$ emissivities have recently become available through the work of [2] and recently corrected by [3]. These are the most recent He$^+$ emissivities, and collisional effects are already included in the emissivities calculation. In this work the emissivities of [3] are adopted in order to calculate the He$^+$ abundances. Their emissivities are tabulated for discrete of electron densities and temperatures. Therefore, we fitted the values provided by [3] for $n_e = 10^3$ and $10^4$ cm$^{-3}$ and $T_e$ between $5 \times 10^3$ and $2.5 \times 10^4$ K, using the following parametrization:

$$
\frac{4\pi j_\lambda}{n_e n_{He^+}} = [a + b (\ln T_e)^{d} + c \ln T_e + \frac{d}{\ln T_e}] T_e^{-3},
$$

in units of $10^{-25}$ ergs cm$^{-3}$ s$^{-1}$. The results are shown in Fig. 8 where the He$^+$ emissivities for the lines 4471, 5876 and 6678 Å are displayed as a function of the electron temperature, for two values of electron densities: $10^3$ cm$^{-3}$ (red circles) and $10^4$ cm$^{-3}$ (black squares). Fits using equation 3 are displayed at the same figure as dotted lines ($n_e = 10^3$ cm$^{-3}$) and continuous lines ($n_e = 10^4$ cm$^{-3}$). The coefficients of the fits using equation 3 are shown in Table 7.

Values between the fitted functions displayed in Fig. 8 were interpolated on a logarithmic scale following [4] as:

$$
\log(j_\lambda) = \log(n_{ion}) - \log(n_e^{10^3} n_{He^+}) + \log(n_{ion}) - \log(n_{ion}) = \log(n_{ion}) + \text{in this particular case.}
$$

In our code, the He$^+$ abundance is calculated from the He$^+$ emission line. The recombination coefficients tabulated in [5] were used as well as the Hβ emissivity provided by [6].

continued.
We fitted the ratio $j_{\lambda 4686}^*/j_{\lambda 4861}^*$ with a second-degree polynomial function. For typical densities found in PNe, this ratio do not depend strongly on the density, so that we adopted $n_e = 10^3 \text{ cm}^{-3}$ and the result of the fit is shown in equation (5). Both He$^+$ and He$^{++}$ abundances are calculated using the O$^+$ electron temperature.

For collisionally excited lines, we calculated the ionic abundances using the nebular software [Shaw & Dufour 1995] and the appropriate electron temperature for the corresponding ionization zone.

### 3.3 Elemental abundances

Since the spectral range of the observations is not sufficient to observe all the necessary lines of a given ion, and it is not possible to calculate the total abundance of a particular element by the direct sum of the ionic abundances of all the ions present in a nebula. Instead, it must be calculated by means of the ionization correction factors (ICFs). One of most frequently used ICFs in the literature are those from Kingsburgh & Barlow (1994). However, recently Delgado-Inglada et al. (2014) have published new ICFs formulae based on a grid of photoionization models and they have computed analytical expressions for the ICFs of He, O, N, Ne, S, Ar, Cl and C. According to their work, the oxygen abundances are not expected to be very different from those calculated with the ICFs of Kingsburgh & Barlow (1994). On the other hand, the abundances of N, S, Ar, Ne calculated with the new ICFs show significant differences. A

---

**Table 4.** Continued.

| $\lambda$ | Ion | $F(\lambda)/F(H\beta)$ | Error | $F(\lambda)/F(H\beta)$ | Error |
|-----------|-----|-------------------------|-------|-------------------------|-------|
| 359.5-01.3 | JaSt 68 | 359.9+01.8 | PPAJ1738-2800 |
| 4341. | H$\gamma$ | – | – | – |
| 4363. | OIII | – | – | – |
| 4686. | HeII | – | – | – |
| 4861. | H$\beta$+HeII | 1.00 | 0.10 | 1.00 | 0.10 |
| 4959. | OIII | 3.76 | 0.38 | 2.23 | 0.22 |
| 5007. | OIII | 13.09 | 0.65 | 7.95 | 0.40 |
| 5412. | HeII | – | – | – |
| 5518. | Cl3 | – | – | – |
| 5538. | Cl3 | – | – | – |
| 5755. | NI | – | – | 0.37 | 0.04 |
| 5876. | HeI | 3.77 | 0.38 | 0.70 | 0.07 |
| 6300. | OI | 2.06 | 0.21 | 1.14 | 0.11 |
| 6312. | SIII | 1.40 | 0.14 | 0.17 | 0.02 |
| 6363. | OI | – | – | 0.55 | 0.06 |
| 6435. | ArV | – | – | – |
| 6548. | NI | 2.68 | 0.27 | 10.76 | 0.54 |
| 6563. | H$\alpha$ | 192.20 | 9.61 | 22.49 | 1.12 |
| 6584. | NII | 7.72 | 0.39 | 33.70 | 1.69 |
| 6678. | HeI | 3.29 | 0.33 | 0.61 | 0.06 |
| 6716. | SII | 0.57 | 0.06 | 4.12 | 0.41 |
| 6731. | SII | 1.05 | 0.10 | 5.94 | 0.30 |
| 6905. | ArIII | – | – | – |
| 6965. | HeI | 19.63 | 0.98 | – | – |
| 7135. | ArIII | 14.70 | 0.74 | 3.93 | 0.39 |
| 7237. | ArIV | – | – | – |
| 7263. | ArIV | – | – | – |
| 7281. | HeI | 2.18 | 0.22 | – | – |
| 7322. | OII | 14.60 | 0.73 | 1.70 | 0.17 |
| 7333. | OII | 13.05 | 0.65 | – | – |
| 7751. | ArIII | – | – | – |
| 7909. | SIII | 223.07 | 11.15 | – | – |
| 9069. | SIII | 713.24 | 35.66 | – | – |

We fitted the ratio $j_{\lambda 4686}^*/j_{\lambda 4861}^*$ with a second-degree polynomial function. For typical densities found in PNe, this ratio do not depend strongly on the density, so that we adopted $n_e = 10^3 \text{ cm}^{-3}$ and the result of the fit is shown in equation (5). Both He$^+$ and He$^{++}$ abundances are calculated using the O$^+$ electron temperature.

For collisionally excited lines, we calculated the ionic abundances using the nebular software [Shaw & Dufour 1995] and the appropriate electron temperature for the corresponding ionization zone.

### Table 7. Coefficients for the He$^+$ emissivities.

| $\lambda$ (Å) | $a \times 10^6$ | $b \times 10^3$ | $c \times 10^5$ | $d \times 10^6$ |
|---------------|-----------------|-----------------|-----------------|-----------------|
| $n_e = 10^3 \text{ cm}^{-3}$ | | | | |
| 4471 | 0.52235 | -2.39494 | -0.60726 | -1.47358 |
| 5876 | 7.13671 | 31.32693 | -8.18163 | -20.64105 |
| 6678 | 2.17062 | 9.55600 | -2.49280 | -6.26613 |
| $n_e = 10^4 \text{ cm}^{-3}$ | | | | |
| 4471 | 2.00719 | 9.16167 | -2.34319 | -5.70799 |
| 5876 | 9.73706 | 46.87604 | -11.70238 | -26.85340 |
| 6678 | 3.31042 | 15.59403 | -3.93518 | -9.24089 |

For collisionally excited lines, we calculated the ionic abundances using the nebular software [Shaw & Dufour 1995] and the appropriate electron temperature for the corresponding ionization zone.

### 3.3 Elemental abundances

Since the spectral range of the observations is not sufficient to observe all the necessary lines of a given ion, and it is not possible to calculate the total abundance of a particular element by the direct sum of the ionic abundances of all the ions present in a nebula. Instead, it must be calculated by means of the ionization correction factors (ICFs). One of most frequently used ICFs in the literature are those from Kingsburgh & Barlow (1994). However, recently Delgado-Inglada et al. (2014) have published new ICFs formulae based on a grid of photoionization models and they have computed analytical expressions for the ICFs of He, O, N, Ne, S, Ar, Cl and C. According to their work, the oxygen abundances are not expected to be very different from those calculated with the ICFs of Kingsburgh & Barlow (1994). On the other hand, the abundances of N, S, Ar, Ne calculated with the new ICFs show significant differences. A
direct comparison between the abundances calculated with both ICFs is beyond the scope of this paper and the reader is referred to the original paper of Delgado-Inglada et al. (2014), where some comparisons are done between both ICFs. However, one should mention that a direct comparison between the abundances of N, S, Ar and Ne calculated with both ICFs is missing in that paper.

In our code PNPACK we have implemented the calculation of the elemental abundances by using the ICFs provided by Delgado-Inglada et al. (2014) and also Kingsburgh & Barlow (1994). In this paper, we are adopting the new ICFs proposed by Delgado-Inglada et al. (2014), since they incorporate more recent physics and are derived using a wider range of parameters of photoionization models than the previous ICFs from Kingsburgh & Barlow (1994). One advantage of the new ICFs provided by Delgado-Inglada et al. (2014) is the possibility to compute the errors in the elemental abundances introduced by the adopted ICF approximation. They provide analytical formulae to estimate error bars associated with the ICFs, something not possible until their work. In the case of helium we opted to do not use any ICF, since the relative populations

Table 8. Ionic abundances.

| PNG      | He++ | He++ | O+    | O++   | N+    | S+    | S++   | Ar++  |
|----------|------|------|-------|-------|-------|-------|-------|-------|
|          |      |      | ×10^{-4} | ×10^{-6} | ×10^{-6} | ×10^{-6} | ×10^{-6} | ×10^{-6} |
| 0.344+1.567  |      |      |      |       |       |       |       |       |
|          | 0.058 ± 0.007 |      | 0.66 | 0.06 | 33.57 | 0.27 | 7.30 | 0.66 |
| 0.002+0.1 | 0.075 ± 0.010 | 0.018 ± 0.003 | 0.08 | 2.28 | 0.44 ± 0.15 | 0.04 ± 0.01 | 0.55 | 0.64 |
| 0.002+0.1 | 0.034 ± 0.004 | 0.059 ± 0.011 | 0.08 ± 0.01 | 0.45 ± 0.05 | 2.75 ± 0.30 | 0.13 ± 0.02 | 1.74 | 0.70 ± 0.06 |
| 0.004+0.1 | 0.117 ± 0.016 |      | 0.14 | 3.11 ± 1.39 | 2.90 ± 1.18 | 0.11 ± 0.06 | 2.35 ± 1.50 | 0.57 ± 0.21 |
| 0.005+0.1 | 0.143 ± 0.018 |      | 0.05 | 0.79 ± 0.39 | 3.09 ± 1.23 | 0.06 ± 0.02 | 0.53 | 0.73 ± 0.23 |
| 0.006+0.1 | 0.121 ± 0.013 |      | 0.33 | 2.94 | 2.01 | 0.17 | 2.36 | 0.84 |
| 0.009+0.1 | 0.165 ± 0.017 | 0.019 ± 0.003 | 0.94 ± 0.34 | 3.60 ± 0.78 | 126.05 ± 23.66 | 2.88 ± 0.76 | 7.75 ± 2.39 | 3.56 ± 0.65 |
| 0.010+0.3 | 0.131 ± 0.016 |      | 0.32 | 1.25 | 3.45 | 0.06 | 2.03 | 0.32 |
| 0.015+0.5 | 0.134 ± 0.017 |      | 0.29 ± 0.24 | 1.85 ± 0.89 | 31.55 ± 14.32 | 0.61 | 3.91 | 2.23 ± 0.70 |
| 0.017+0.3 | 0.049 ± 0.006 |      | 0.53 ± 0.37 | 0.14 ± 0.06 | 9.93 ± 5.30 | 0.21 | 0.50 | 0.34 ± 0.11 |
| 0.025+0.3 | 0.130 ± 0.018 |      | 0.17 ± 0.07 | 2.15 ± 0.52 | 7.17 ± 1.77 | 0.06 ± 0.03 | 0.93 | 0.97 ± 0.21 |
| 0.357+0.1 | 0.133 ± 0.015 |      | 0.21 ± 0.09 | 2.19 ± 0.59 | 22.76 ± 5.77 | 0.79 | 6.41 ± 1.95 | 0.96 ± 0.23 |
| 358.5+0.7 | 0.083 |      | 0.06 | 0.76 | 3.16 | 0.12 | 1.31 | 0.51 |
| 358.9+0.5 | 0.076 ± 0.011 |      | 0.10 | 0.26 | 0.67 | 0.01 | 0.71 | 0.22 |
| 359.5+0.2 | 0.120 ± 0.013 |      | 0.11 | 1.03 | 2.97 | 0.06 | 1.32 | 0.22 |
| 359.5+0.3 | 0.115 |      | 0.08 | 1.15 | 1.18 | 0.05 | 2.20 | 0.46 |
| 359.9+0.8 | 0.123 ± 0.013 |      | 0.25 ± 0.09 | 1.04 ± 0.22 | 47.11 ± 10.15 | 2.14 ± 0.49 | 2.52 ± 0.79 | 1.79 ± 0.40 |
of helium ions depend essentially on the effective temperature of the central star. So that, there is no reliable way to correct for neutral helium in our objects.

The reader should to note that in some cases, where the ionic abundance was available, the elemental abundance of the corresponding ion was not possible to calculate, since the ICFs of Delgado-Inglada et al. (2014) are not valid for the specific $v$ and $w$ parameters (see Delgado-Inglada et al. 2014, for more details). In these few cases, in order to obtain the elemental abundances one needs to perform detailed photoionization models of the object. The obtained ionic abundances relative to hydrogen and uncertainties are shown in table 8.

In order to test the ICFs, Fig. 9 shows the values of $(\text{He}^{+} + \text{He}^{++})/\text{H}$, S/O and Ar/O as a function of $\text{O}^{++}/(\text{O}^{+} + \text{O}^{++})$. No significant trend is seen for S/O and Ar/O. For $(\text{He}^{+} + \text{He}^{++})/\text{H}$, since for many PNe we have not detected the presence of $\text{He}^{++}$ lines, the helium abundances are a lower limit for these objects. For low excitation objects the uncertainties in the helium abundances are very high, as showed by the error bars in the figure. This can be attributed to neutral helium, as it is not taken into account by the helium ICF.

The obtained chemical abundances and uncertainties (see next section) of He, O, N, S, and Ar with respect to H are listed in table 9.

3.4 Uncertainties

Uncertainties in the abundances are due to uncertainties in the line fluxes of the abundance diagnostic lines, uncertainties in the diagnostic lines for electron temperature and density, and uncertainties in the ICF that we have assumed for the determination of elemental abundances.

We have computed errors in the abundances and physical parameters, as well as extinction, performing a Monte Carlo procedure. We assumed for each line flux a Gaussian distribution centred at the flux effectively measured and having a dispersion equal to the estimated flux uncertainty. The latter was calculated by comparing the line intensity with that from the $\text{H}\beta$ line. By inspection of our spectra and figures 6 and 7, we have adopted errors of 5 per cent for lines where the relative flux of the line with $\text{H}\beta$ ($F(\lambda)/F(\text{H}\beta)$) was higher than 500. Errors of 10 per cent for those ratios higher than 10 and lower than 500. An uncertainty of 20 per cent was attributed for ratios $F(\lambda)/F(\text{H}\beta)$ higher than 2 and lower than 10. And finally, errors of 40 per cent for lines where $F(\lambda)/F(\text{H}\beta)$ was lower than 2.

For each line, we considered 250 independent realizations and fitted the histogram of the distribution with an Gaussian function. The error bars and the most probable values were estimated from the Gaussian standard error and mean, respectively, obtained from the Gaussian fit. In the cases where the distribution was clearly no Gaussian, as in
most cases of electron densities, we were not able to obtain
dependent realizations from the Monte Carlo simulation for JaSt 36.

Figure 10. Histogram of log(O/H) + 12 values of the 250
independent realizations from the Monte Carlo simulation for JaSt 36.
The continuous curve is the Gaussian fitted to the histogram data.

Table 9. Elemental abundances.

| PNG | Name       | He/H | 12+log O/H | 12+log N/H | 12+log S/H | 12+log Ar/H |
|-----|------------|------|------------|------------|------------|-------------|
| 0.344+1.567^1 | JaSt 23 | 0.058 ±0.036 | 7.85 ±0.16 | 7.61 ±0.17 | 6.87 ±0.18 | 6.11 ±0.26 |
| 0.2+0.17 | JaSt 19 | 0.092 ±0.042 | 8.45 ±0.15 | 7.49 ±0.22 | 6.71 ±0.15 | 6.29 ±0.25 |
| 0.2-0.14 | JaSt 79 | 0.093 ±0.047 | 8.04 ±0.15 | 7.49 ±0.22 | 6.71 ±0.15 | 6.29 ±0.25 |
| 0.4+0.11 | JaSt 36 | 0.119 ±0.043 | 8.52 ±0.20 | 8.44 ±0.31 | 6.69 ±0.29 | 6.29 ±0.25 |
| 0.5+0.19 | JaSt 17 | 0.144 ±0.044 | 7.92 ±0.19 | 8.27 ±0.28 | 6.01 ±0.22 | 6.04 ±0.28 |
| 0.6-0.10 | JaSt 77 | 0.105 ±0.045 | 8.51 ±0.05 | 8.80 ±0.20 | 7.12 ±0.16 | 6.68 ±0.54 |
| 0.9+0.18 | PPAJ1740-2708 | 0.186 ±0.052 | 8.68 ±0.11 | 8.80 ±0.20 | 7.12 ±0.16 | 6.68 ±0.54 |
| 1.0+0.13 | JaSt 41 | 0.128 ±0.051 | 8.20 ±0.06 | 7.47 ±0.19 | 6.39 ±0.09 | 5.61 ±0.22 |
| 1.5+0.15 | JaSt 46 | 0.134 ±0.047 | 8.33 ±0.21 | 8.94 ±0.32 | 6.79 ±0.25 | 6.48 ±0.32 |
| 1.7+0.13 | JaSt 52 | 0.048 ±0.174 | 7.85 ±0.24 | 7.26 ±0.31 | 5.85 ±0.29 | 5.65 ±0.60 |
| 0.0-0.13 | JaSt 98 | 0.131 ±0.044 | 8.38 ±0.12 | 8.59 ±0.26 | 6.22 ±0.15 | 6.17 ±0.54 |
| 7.7+0.14 | PPAJ1734-3004 | 0.111 ±0.046 | 8.38 ±0.12 | 9.02 ±0.25 | 7.05 ±0.21 | 6.15 ±0.55 |
| 8.5-0.17 | JaSt 64 | 0.083 ±0.044 | 7.92 ±0.05 | 8.22 ±0.22 | 6.38 ±0.10 | 5.89 ±0.21 |
| 8.9+0.15 | JaSt 65 | 0.076 ±0.056 | 7.56 ±0.01 | 6.85 ±0.17 | 5.88 ±0.05 | 5.40 ±0.33 |
| 9.5+0.12 | JaSt 66 | 0.117 ±0.005 | 8.06 ±0.05 | 8.05 ±0.22 | 6.32 ±0.12 | 5.50 ±0.53 |
| 9.5-0.13 | JaSt 68 | 0.115 ±0.044 | 8.09 ±0.05 | 7.84 ±0.27 | 6.59 ±0.09 | 5.84 ±0.21 |
| 9.9-0.18 | PPAJ1738-2800 | 0.122 ±0.051 | 8.10 ±0.10 | 8.86 ±0.21 | 6.73 ±0.14 | 6.35 ±0.24 |

Figure 10. Histogram of log(O/H) + 12 values of the 250 independent realizations from the Monte Carlo simulation for JaSt 36. The continuous curve is the Gaussian fitted to the histogram data.

The errors in the ICFs were computed through the recent work from Delgado-Inglada et al. (2014), where the authors have evaluate the uncertainties in the ICFs. Thanks to their work, it is now possible to include these uncertainties in the elemental abundances computed with these ICFs. The final uncertainties on the elemental abundances were calculated by adding in quadrature the uncertainties obtained from the ICFs with the uncertainties obtained from the Monte Carlo simulations. Note that, since the uncertainties in the ICFs are not symmetrical, error bars are also not symmetrical for the final abundances.

4 ABUNDANCE ANALYSIS

In order to seek for differences in the chemical enrichment of GBPNe near the GC and other regions of the Galactic bulge, we compared in this section the abundances obtained in the present work with the GBPNe abundances from our previous work (CCM10), where we performed spectrophotometric observations of GBPNe located in the outer regions of the bulge. Hence, a comparison between both samples can give information about the chemical enrichment of the central parts of the Milky Way galaxy. We should note that the elemental abundances from CCM10 were calculated with the ICFs from Kingsburgh & Barlow (1994) and ours with Delgado-Inglada et al. (2014). To provide a meaningful comparison, we recalculated the abundances from CCM10 with the new ICFs from Delgado-Inglada et al. (2014) and also the He i emissivities from Porter et al. (2013). In this way, we guarantee the same methodology for both samples.

Figure 11 shows the abundances ratios S/O and Ar/O as a function of O/H abundances for our data and our previous work (CCM10). The 1-σ dispersion of the relations from Izotov et al. (2006) for low-metallicity blue compact dwarf galaxies is displayed in the same figure. The GBPNe data seems to follow the Izotov et al. (2006) relations, with most of them inside the 1-σ dispersion. We note that our data for the Ar/O ratio show a higher dispersion than the S/O.
we opted to do not use any ICF, since the relative populations of helium ions depend essentially on the effective temperature of the central star. So that, there is no reliable way to correct for neutral helium for these objects and the uncertainties are incorporated in the error bars for He abundances. As noted by García-Rojas et al. (2010), models by Karakas (2010) cannot predict the low N/O ratio \( \log(N/O) < -1.0 \) shown by some PNe. They pointed out two possible origins for this discrepancy. In the first one, the initial masses of the progenitor stars for these PNe should be lower than 1 \( M_\odot \). However this is unlikely since, using the Padova isochrones as revised by Mollá et al. (2009), the mean lifetime for a star with 0.8 \( M_\odot \) at solar metallicity is 15.8 Gyr, and therefore higher than the expected age of the Universe. The second possibility is that stellar evolution models are predicting too large yields for N.

Since stellar nucleosynthesis models depend on the micro and macrophysics adopted, it is also interesting to compare the data with different models in the literature. The Ventura et al. group provide a new generation of AGB stellar models that include dust formation in the stellar winds. During the core H-burning phase, the assumptions concern the overshoot of the convective core lead to a less efficient dredge-up and to a lower threshold mass for the activation of the HBB then previous models in the literature. A detailed description of these models are given in Ventura et al. (2014a), for \( Z = 0.004 \), in Ventura et al. (2013) for \( Z = 0.001 \) and \( M > 3 \ M_\odot \), and in Ventura et al. (2014b) for \( Z = 0.001 \) and \( M < 3 \ M_\odot \). For \( Z = 0.018 \) and \( Z = 0.04 \) the data were obtained from F. Dell’Agli and J. García-Rojas (private communication). Hereafter we will call all these models as Ventura et al. group, Miller Bertolami (2016) provide AGB nucleosynthesis models including an updated treatment of the microphysics (radiative opacities and nuclear reaction rates) and description of the mixing processes and mass loss rates that play a key role during the thermal pulses on the AGB phase. As a result, the new models lead to the occurrence of third dredge up for lower stellar masses. In Fig. 12, the results are compared with models from Miller Bertolami (2016) (middle panel) and Ventura et al. group (bottom panel). In this figure, we can observe a fair agreement between the data and the models. The different micro and macrophysics adopted by each model change the progenitor masses at higher N/O ratios. The higher N/O ~ 0.6 from our data are compatible with progenitor masses of 3–4 \( M_\odot \) in the case of the models from Miller Bertolami (2016) and of 5–6 \( M_\odot \) in the case of the models from Karakas (2010) and Ventura et al. group. Notice that JaSt 52 has very low abundances of O and a lower N/O ratio compared with the other PNe in our sample. Since neutral helium has an important contribution for this PN, the abundances for this object should be taken with caution.

The N/H abundances as a function of O/H abundances are displayed in Fig. 13. Most of our data is in agreement with the models by Karakas (2010) for higher metallicities. Exceptions are PNe JaSt 17 and JaSt 52 again (see discussion above) with a low O/H not predicted by the models at the given metallicities. In this figure, the predictions of the models are as expected: more massive stars produce larger amounts of N. In the case of the models by Miller Bertolami (2016), there is an offset towards higher O/H abundances compared with the data. The PNe in our sample PPAJ1740-

![Figure 11. Abundances ratios of S/O and Ar/O as a function of O/H abundances. Black filled circles with error bars are GBPNe data from this work. The GBPNe data from CCM10 are represented by blue filled triangles. The light-grey bands for the GBPNe are the 1-σ dispersion of the relations from Izotov et al. (2006) for low-metallicity blue compact dwarf galaxies.](image)
An important difference between our sample and CCM10 is observed in figures 12 and 13: in CCM10 some points are compatible with the lower metallicity model ($Z = 0.004$) by Karakas (2010) and also lower initial masses ($< 4M_\odot$). In our sample a large fraction of PNe have abundances compatible with models at higher metallicities. Also, the superior limit for the initial masses depend on the model adopted. Considering the results from Miller Bertolami (2016), the PNe near the GC are compatible with stellar initial masses $< 3M_\odot$ for $Z = 0.001$. In the case of the models from Ventura et al group for higher metallicities the data are compatible with initial masses $< 6M_\odot$. On the other hand, Gesicki et al (2014) using high resolution imaging and spectroscopic observations of 31 compact PNe derived their central star masses. Post-AGB evolutionary models were used to fit the white dwarf mass distribution and initial-final mass relations were derived using white dwarfs in clusters. They obtained a mass distribution for GBPNe and find a mass limit of 2.5 $M_\odot$, which is lower than the masses obtained from the models in Fig. 12. However, we note that in Gesicki et al (2014) the PNe distribution in their Fig. 9 shows they explored a different region in the bulge since there are no PNe within $2^{\circ}$ from the GC.

The behaviour of Ar/H vs. O/H and S/H vs. O/H are presented Fig. 13. A correlation is found for these elemental abundances for both samples. The linear Pearson correlation coefficients for CCM10 sample are 0.84 and 0.70 for Ar and S, respectively. The slopes of the linear fit are 0.86 and 1.02 for Ar and S, respectively. Considering only the GC sample, the correlation coefficients are 0.65 and 0.63 and the slopes 0.88 and 0.56, respectively. The low number of data points and also the uncertainties in the GC sample may wipe out the expected relations. However, considering all the data (this work + CCM10) the linear correlation coefficients are 0.79 and 0.69 and the slopes 0.89 and 0.99. So that a linear relationship there exist considering both samples. A detailed discussion of the correlations between neon, sulphur, and argon abundances with oxygen in photoionized nebulae of the Local Group is given by Maciel et al. (2017). The predictions of evolution models by Karakas (2010) at $Z = 0.004$, 0.008 and 0.02 are displayed in the graph for S/H vs. O/H. Clearly, models show that S is not modified by stellar nucleosynthesis, independently of the initial stellar mass. On the contrary, O is expected to be modified in progenitor stars heavier than $4 M_\odot$ at low-metallicity environments. In the case of Ar, the models by Karakas (2010) do not give predictions for these elements, so that the abundances could not be compared with theoretical results.

The histograms of the abundances distributions for O/H, S/H, A/Hr and log(N/O) are shown in Fig. 15. We do not find important differences between the distributions of O/H, S/H and Ar/H comparing both samples. The average GC abundances of O/H, S/H, and Ar/H are 0.13, 0.11, and 0.16 dex lower than the average values of the outer bulge sample. However, these differences are within the expected errors in the abundances. On the other hand, despite of the low number of PNe in our sample, some import-

![Figure 12](image-url)
tant differences are evident in the histograms of log(N/O): the distribution for PNe near the GC is shifted for higher values compared with those from CCM10 data. The mean log(N/O) are -0.28 dex and 0.28 dex for CCM10 and GC samples, respectively. So that the difference between both samples in log(N/O) is considerable (~0.56 dex). Only for Ne the comparison cannot be made since, due to the high interstellar extinction in our spectra, we could not observe the [Ne\textsc{iii}] λ3869 Å and [Ne\textsc{iii}] λ3967 Å lines necessary to calculate the Ne elemental abundances. However, as alerted before, this result should be interpreted with some caution, since due to the high interstellar extinction in the direction of the GC it is very difficult to define an metallicity-unbiased sample.

It is important to compare the results obtained in this paper with those from stars located near the GC. Ryde et al. (2016) have measured abundances of Mg, Si, Ca and Fe in 28 M-type giants in the GC region using high-resolution IR spectroscopy. Their data show a trend where the metallicity of the stars increases progressively as closer to the GC the stars are. By means of high-resolution IR spectra, Cunha et al. (2007) observed a sample of cool stars within 30 pc from the GC. They obtained that [O/Fe] and [Ca/Fe] are enhanced by 0.2 and 0.3 dex, respectively, relative the Sun Fe/H abundances. Their results pointed that the width of the [Fe/H] distribution in the GC is narrower than the one obtained for the older bulge population (outer bulge population). We note, however, that the data from Cunha et al. (2007) are located nearer the Galactic centre than the PNe from our sample and the interpretation for the α-enhancement found in their sample might be different. Their interpretation is that the α-enhancement observed in cool stars near the GC might be due to a IMF weighted toward more massive stars or recent local SN II chemical enrichment within the central 50 pc of the Galaxy, or a mixture of bulge red-giant winds feeding the GC ISM. Regarding the results from other spiral galaxies, Florido et al. (2015) used a sample of nearby face-on disc galaxies with available SDSS spectra to derive chemical abundances of the ionized gas. Their results point to an enhancement of N/O in barred galaxies compared with non-barred galaxies. Nonetheless, they do not find any difference regarding O/H. This difference in N/O and not in O/H in the centres of barred galaxies could be due to a different star formation
efficiency in the inner parts of galaxies as a consequence of the influence of gas flows induced by the bars. Indeed, by means of a chemical evolution model, Cavichia et al. (2014) have simulated the gas flows induced by the Galactic bar and the influence on the Galactic bulge abundance distributions, finding no important differences. However, the SFR is enhanced in the bulge when there is a radial gas flow towards the centre of the Galaxy. Nevertheless, the N/O distribution was not investigated in that work. In the present work, we do not find evidence for important differences in the abundances of O/H, S/H and Ar/H in the GC PNe compared with those from the outer regions of the bulge. However, we do find evidence for higher N/O ratios in the GC sample, which is expected for more massive progenitor stars. The results of Fig. 12, 13 and 15 point to recent SFR occurring in the GC, compared with the outer regions of the Galactic bulge. However, this result should be interpreted with some caution, since due to the high interstellar extinction in the direction of the GC it is very difficult to define a metallicity-unbiased sample.

5 CONCLUSIONS

We have performed spectrophotometric observations with the 4.1 m SOAR (Chile) and the 1.6 m OPD/LNA (Brazil) telescopes to obtain physical parameters and chemical abundances for a sample of 17 planetary nebulae located within 2° of the Galactic centre. We derived chemical abundances for He, N, O, S and Ar. The results point to high obscured PNe, with E(B-V) roughly 2.3 on the average. With such high extinction, no lines are seen in the blue part of the spectra, at wavelengths shorter than Hβ. We have implemented the new ICFs from Delgado-Inglada et al. (2014) for the elemental abundances determination and also the new He I emissivities from Porter et al. (2013). S abundances were derived using optical and NIR lines, reducing the uncertainties associated with S ICFs. The abundances predicted by Karakas (2010), Miller Bertolami (2016) and Ventura et al. group for stars of different initial masses and metallicity were used to constraint the masses and initial metallicity of the progenitor stars. An important difference between our sample near the Galactic centre and PNe located in the outer parts of the bulge is observed. In our previous work (Cavichia et al. 2010, outer bulge region) some points are compatible with the lower metallicity model ($Z = 0.004$).
REFERENCES

Aver E., Olive K. A., Skillman E. D., 2010, J. Cosmology Astropart. Phys., 5, 3
Bland-Hawthorn J., Gerhard O., 2016, ARA&A, 54, 529
Cahn J. H., Kaler J. B., Stanghellini L., 1992, A&AS, 94, 399
Cavichia O., Costa R. D. D., Maciel W. J., 2010, RMxAA, 46, 159(CCM10)
Cavichia O., Costa R. D. D., Maciel W. J., 2011, RMxAA, 47, 49
Cavichia O., Mollá M., Costa R. D. D., Maciel W. J., 2014, MNRAS, 437, 3688
Chiappini C., Górnay S. K., Stasińska G., Barbary B., 2009, A&A, 494, 591
Clayton D. D., 1968, Principles of stellar evolution and nucleosynthesis. New York: McGraw-Hill, 1968
Coelho P., Gadotti D. A., 2011, ApJ, 743, L13
Cuisinier F., Maciel W. J., Köppen J., Acker A., Stenholm B., 2000, A&A, 353, 543
Cunha K., Sellgren K., Smith V. V., Ramirez S. V., Blum R. D., Terndrup D. M., 2007, ApJ, 669, 1011
Delgado-Inglada G., Morisset C., Stasińska G., 2014, MNRAS, 440, 536
Eggen O. J., Lynden-Bell D., Sandage A. R., 1962, ApJ, 136, 748
Ellison S. L., Nair P., Patton D. R., Scudder J. M., Mendel J. T., Simard L., 2011, MNRAS, 416, 2182
Escudero A. V., Costa R. D. D., 2001, A&A, 380, 300
Escudero A. V., Costa R. D. D., Maciel W. J., 2004, A&A, 414, 211
Exter K. M., Barlow M. J., Walton N. A., 2004, MNRAS, 349, 1291
Fitzpatrick E. L., 1999, PASP, 111, 63
Fitzpatrick E. L., Massa D., 2009, ApJ, 699, 1209
Florido E., Zurita A., Pérez I., Pérez-Montero E., Coelho P. R. T., Gadotti D. A., 2015, A&A, 584, A88
Frew D. J., Parker Q. A., 2010, PASA, 27, 129
García-Rojas J., Peña M., Flores-Durán S., Hernández-Martínez L., 2016, A&A, 586, A59
Gesicki K., Zijlstra A. A., Hajdułk M., Szyszka C., 2014, A&A, 566, A48
Gonzalez O. A., Rejkuba M., Zoccali M., Valenti E., Minniti D., Schultheis M., Tobari R., Chen B., 2012, A&A, 543, A13
Górnay S. K., Chiappini C., Stasińska G., Cuisinier F., 2009, A&A, 500, 1089
Hamuy M., Suntzeff N. B., Heathcote S. R., Walker A. R., Gigoux P., Phillips M. M., 1994, PASP, 106, 566
Hamuy M., Walker A. R., Suntzeff N. B., Gigoux P., Heathcote S. R., Phillips M. M., 1992, PASP, 104, 533
Henry R. B. C., Kwitter K. B., Balick B., 2004, AJ, 127, 2284
Henry R. B. C., Kwitter K. B., Jaskot A. E., Balick B., Morrison M. A., Milingo J. B., 2010, ApJ, 724, 748
Henry R. B. C., Speck A., Karakas A. I., Ferland G. J., Maguire M., 2012, ApJ, 749, 61
Izotov Y. I., Stasińska G., Meynet G., Guseva N. G., Thuan T. X., 2006, A&A, 448, 955
Jacoby G. H., Van de Steene G., 2004, A&A, 419, 563(JS04)
Karakas A. I., 2010, MNRAS, 403, 1413
Kingsburgh R. L., Barlow M. J., 1994, MNRAS, 271, 257
Maciel W. J., Costa R. D. D., Cavichia O., 2017, RMxAA, submitted
Maciel W. J., Lago L. G., Costa R. D. D., 2006, A&A, 453, 587

ACKNOWLEDGMENTS

This work has been financially supported by the Brazilian agency FAPESP (Proc. 2007/07704-2, 2010/18835-3 and 2012/01017-1). We are grateful to the referee Dr. Zijlstra for his comments and careful reading of the manuscript. O.C. would like to thank J. Garcia-Rojas and F. Dell’Agli for kindly providing the data from AGB nucleosynthesis models.
Planetary nebulae near the Galactic centre

Malkin Z., 2013, in de Grijs R., ed., IAU Symposium Vol. 289 of IAU Symposium, Statistical analysis of the determinations of the Sun’s Galactocentric distance. pp 406–409

Milindo J. B., Kwitter K. B., Henry R. B. C., Souza S. P., 2010, ApJ, 711, 619

Miller Bertolami M. M., 2016, A&A, 588, A25

Miszalski B., Acker A., Moffat A. F. J., Parker Q. A., Udalski A., 2009, A&A, 496, 813

Miszalski B., Parker Q. A., Acker A., Birkby J. L., Frew D. J., Kovacevic A., 2008, MNRAS, 384, 525

Molla M., García-Vargas M. L., Bressan A., 2009, MNRAS, 398, 451

Monreal-Ibero A., Walsh J. R., Westmoquette M. S., Vilchez J. M., 2013, A&A, 553, A57

Nataf D. M., Gonzalez O. A., Casagrande L., et al. 2016, MNRAS, 456, 2692

Nataf D. M., Gould A., Fouqué P., et al. 2013, ApJ, 769, 88

Obreja A., Domínguez-Tenreiro R., Brook C., Martínez-Serrano F. J., Doménech-Moral M., Serna A., Mollá M., Stinson G., 2013, ApJ, 763, 26

Osterbrock D. E., Ferland G. J., 2006, Astrophysics of gaseous nebulae and active galactic nuclei. 2nd ed.; Sausalito, CA: Univ. Science Books

Porter R. L., Ferland G. J., Storey P. J., Detisch M. J., 2012, MNRAS, 425, L28

Porter R. L., Ferland G. J., Storey P. J., Detisch M. J., 2013, MNRAS, 433, L89

Ryde N., Schultheis M., Grieco V., Matteucci F., Rich R. M., Uttenthaler S., 2016, AJ, 151, 1

Samland M., Gerhard O. E., 2003, A&A, 399, 961

Shaw R. A., Dufour R. J., 1995, PASP, 107, 896

Stanghellini L., Shaw R. A., Villaver E., 2008, ApJ, 689, 194

Stasińska G., Richer M. G., McCauley M. L., 1998, A&A, 336, 667

Storey P. J., Zeippen C. J., 2000, MNRAS, 312, 813

Uscanga L., Gómez J. F., Suárez O., Miranda L. F., 2012, A&A, 547, A40

van Dokkum P. G., 2001, PASP, 113, 1420

Ventura P., Criscienzo M. D., D’Antona F., Vesperini E., Tailo M., Dell’Agli F., D’Ercole A., 2014, MNRAS, 437, 3274

Ventura P., Dell’Agli F., Schneider R., Di Criscienzo M., Rossi C., La Franca F., Gallerani S., Valiante R., 2014, MNRAS, 439, 977

Ventura P., Di Criscienzo M., Carini R., D’Antona F., 2013, MNRAS, 431, 3642

Wang W., Liu X.-W., 2007, MNRAS, 381, 669

Weiland J. L., Arendt R. G., Berriman G. B., Dwek E., Freundlich H. T., Hauser M. G., Kelsall T., Lisse C. M.,