Modeling and distance determination of planetary nebulae

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Abstract. We have developed a self-consistent method to determine the physical parameters of planetary nebulae (PN) and also their distances using the photo-ionization code CLOUDY. To constrain the models, observed emission line ratios, IRAS fluxes, radio fluxes and angular diameters are used. The method has been tested by applying it to artificial data from a planetary nebula model. It can reproduce all distance independent physical parameters with good accuracy. It can also reproduce the distance and all distance dependent physical parameters, but for this an accurate determination of the angular size is crucial.
The method has been further tested by applying it to a sample of five galactic bulge PN. Comparison of the distance independent physical parameters with published data shows that they generally are in fair agreement. The determined distances to these PN have large error margins. However, both the individual distances and the average distance are in agreement with the distance to the galactic bulge.
We conclude that the method that is presented works, provided that good observational data are available, and that sufficient emission lines of various ionization stages are observed in the spectrum to constrain the model.

Key words: planetary nebulae – photo-ionization modeling – distance determination

1. Introduction

The lack of accurate, generally accepted techniques to derive physical parameters and distances is presently the major limitation in the study of the evolution of planetary nebulae (PN) and their distribution in the Galaxy. Our aim is to improve the accuracy of the determination of physical parameters. For this we have developed a method to determine all these parameters simultaneously (van Hoof and Van de Steene, 1995) based on our modified version of the photo-ionization code CLOUDY v84.06 (Ferland, 1993). This method makes a self-consistent best-fit model of the PN using as much observational material as possible. The method is an extension of previous work in that it uses, besides the optical spectrum, the IRAS fluxes, the radio fluxes and the angular diameter. In this paper our aim will be to establish the validity of the method and to assess the reliability of the determined parameters.

To reach this goal we have used a twofold strategy. First we constructed an artificial set of "observations" using our version of CLOUDY. This set is used to prove the validity of the method and to assess the influence of measurement errors.

Second we selected five galactic bulge PN for which other determinations of the physical parameters were published. Hence we could compare our results with the published values and also the distances with the distance to the bulge. These tests will be discussed in full detail in a forthcoming paper.

2. The artificial test model

In order to verify whether the method could correctly reproduce the physical parameters of a PN, we constructed an artificial set of "observables" for which it was known in advance what results our method should yield. We used CLOUDY to calculate this artificial set. The "observations" were more or less typical of a young PN, with a small high density shell of low excitation. The metallicity of the nebula was low: $\log Z \approx -0.65$. We calculated several sequences of models (runs), using different initial estimates. These sequences were stopped when a prescribed accuracy of 0.01 dex ($\approx$ 2.3 %) was reached for all model parameters. By comparing the different runs we could unambiguously assess what the best-fit model was. This way we could reproduce nearly all physical parameters and the distance within the accuracy we had set. The smallest discrepancy was less than 0.01 % for the stellar temperature; the largest discrepancy was less than 3.1 % for the ionized shell mass.

We also wanted to investigate the effect of "measurement" errors in the observables of our artificial test model on the determination of the physical parameters. For this we changed the value of one observable at a time, and calculated for each case the best-fit model. We changed the IRAS and the radio fluxes, the angular diameter and certain line fluxes. We also investigated the influence of changing the filling factor. We defined ζ as the ratio of the relative error in the determined physical parameter and the relative error in the observable. We found that well determined are (i.e. max $|\zeta| \lesssim 1$): the stellar and the electron temperature, the density and the abundances. Reasonably determined are (i.e. max $|\zeta| \approx 1 - 2$): the dust-to-gas ratio and the ionization parameter. Less accurate are (i.e. max $|\zeta| \gtrsim 2$): the distance, the luminosity, the inner and outer radii and the nebular mass. These last parameters critically depend on the angular diameter, which is very difficult to measure accurately.

3. Modeling of the bulge PN

To test our method, including the distance determination, on real data, we selected a sample of five galactic bulge nebulae from Ratag et al. (1990), which is presented in Table I. For all these nebulae alternative determinations of the physical parameters have been published. Many of these studies use the classical line ratio diagnostics to determine the electron temperature and density. It is

TABLE I
The positions of the PN in our sample and the error margins of our distance determinations. The last four columns give the angular diameter, our best-fit distance and the lower and upper 1σ limits resp. for this distance.

PN	PN G	$\alpha(2000)$ h m s	$\delta(2000)$ ° ′ ″	Θ_{d} ″	D kpc	D_{low} kpc	D_{high} kpc
H 1−40	359.7−02.6	17 55 36.1	−30 33 32	1.26 ± 0.27	16.0	5.5	25.7
M 1−20	006.1+08.3	17 28 57.6	−19 15 53	1.98 ± 0.54	6.4	1.3	11.4
M 2−4	349.8+04.4	17 01 06.3	−34 49 39	2.16 ± 0.45	12.0	4.3	19.1
M 2−23	002.2−02.7	18 01 42.7	−28 25 45	0.72 ± 0.14	4.8	1.9	7.5
M 3−15	006.8+04.1	17 45 31.7	−20 58 02	5.40 ± 1.26	27.3	8.0	45.4

not *a priori* clear that these diagnostics give results which are valid for the entire nebula. They also appear to be sensitive to measurement errors, as is reflected by a comparison of the various literature studies. The typical uncertainty for the determination of the electron density using the [S II] line ratio was a factor of two to three, but discrepancies of up to a factor of ten were found. For the determination of the electron temperature the situation was better: the typical uncertainty was 10 to 20 %, although large discrepancies of approximately 50 % were found when comparing the electron temperatures based on the [N II] and the [O III] lines. The problems mentioned above are also reflected in the abundance determination: two studies gave a factor of 20 difference for the nitrogen abundance of M 3−15 although they were based on the same spectrum. The situation for the determination of the stellar temperature was reasonably good. Usually the values agreed within 10 to 20 %.

Our aim is to use as many different observations as possible to constrain our modeling in order to obtain better results. The sometimes large discrepancies between the various literature studies make it hard to assess the accuracy of the physical parameters we determined. In general our results are in fair agreement. When discrepancies occur, reasonable explanations can be found and we still consider our determination to be plausible.

In Table I we present the distances determined with our method and the expected upper and lower 1σ limits. These limits are determined solely from the uncertainties in the angular diameter (Θ_{d}), which are already quite large: 20 to 25 % (Gathier et al., 1983). The measurement errors are amplified in the distance determination, clearly illustrating the need for an accurate determination of the angular diameter. Since all PN in our sample belong to the galactic bulge we assume $D = 7.8 \pm 1.6$ kpc for the distances to the individual PN, based on the distance to the galactic center given by Feast (1987) and an angular radius of 10° for the bulge. Although the error margins on the individual distances are large, they are not in contradiction with the assumption that the PN belong to the galactic bulge.

The logarithmic average of the distances is $R_0 = 11.0 \pm 3.5$ kpc. This result is in agreement with the adopted distance to the galactic center: $R_0 = 7.8 \pm 0.8$ kpc.

We point out that these distances have been determined from first principles, and have in no way been calibrated by any other method. In the modeling we took the filling factor (ϵ) of the gas to be unity. Assuming a lower value will increase the distance as $D \propto \epsilon^{-1}$.

4. Conclusions

A method which enables a fully self-consistent determination of the physical parameters and the distance of a PN is tested on an artificial set of "observations" and it is shown that with this method it is possible to reproduce all parameters. The effect of observational errors is also studied. They have limited effect on most physical parameters. However, the distance and all distance dependent parameters are critically dependent on the angular diameter and thus will be uncertain.

The method has been applied to a sample of galactic bulge PN. The distance independent physical parameters are generally in fair agreement with published data. Although the error margins on the determined distances are large, they are not in contradiction with the assumption that the PN in our sample belong to the galactic bulge.

We conclude that the method works, provided that good observational data are available, and sufficient emission lines of various ionization stages are observed in the spectrum to constrain the model.

Future research will be aimed at reducing the influence of measurement errors, first of all the critical dependence of the distance determination on the angular diameter. We also want to test other model assumptions which may better describe the PN structure and the incident radiation field.

Acknowledgements

For this research the photo-ionization code CLOUDY was used. We wish to thank Gary Ferland for his continuing effort to improve the code and also for his help with the modifications. We thank Alain Smette and the referee for critically reading the manuscript. PvH is supported by NFRA grant 782–372–033.

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