7 Conclusions and outlook

7.1 Conclusions

In this thesis a new method is presented to determine the physical parameters of an emission line nebula in a fully self-consistent way. This method is based on the photo-ionization code CLOUDY, which was altered for this purpose. Part of these alterations were aimed at making the code more suitable for infrared predictions. This was done so that the method could be used for analyzing infrared spectra taken with ISO, although use of the method is not limited to analyzing only these spectra. In Chapter 2 the details of the method are presented, while the alterations to the code are described in Chapter 8.

Before the method could be applied to any real data, several tests had to be performed to assess the correctness of the method and the accuracy of its results. First, a formal convergence test was performed on an artificial set of ‘observations’ and it is shown that it is possible to reproduce all physical parameters with this method. Next, the effect of observational uncertainties on the derived physical parameters was studied. This way it could be shown that all the important physical parameters could be reproduced with good accuracy, i.e. their determination was stable against observational error. It could also be shown that photo-ionization models are less sensitive to noise in the optical spectrum than classical line diagnostics when determining the electron temperature, electron density and the abundances.

The biggest disadvantage of photo-ionization modeling is that various assumptions have to be made for the physical model of the nebula. These assumptions, by necessity, are sometimes very simplistic and involve parameters which are difficult or even impossible to measure. Inevitably, the model assumptions will have an effect on the derived physical parameters, and an attempt was made to investigate these effects. They were found to be different from what is commonly expected. The most critical are the assumed stellar spectrum and the assumption that the inner radius of the dust is the same as the inner radius of the gas. Modeling bipolar nebulae can also lead to less accurate results, especially if the polar regions are optically thin in the Lyman continuum. Also important, but only for the distance dependent parameters, is the assumed distance itself. Deviations from the density structure used in the modeling were not found to be very influential, provided that the real density structure is spherically symmetric. The determination of the stellar and electron temperature by our method was found to be very robust in all circumstances. Line diagnostics assume only constant electron temperature and density. The dependency on the electron density of these methods is usually quite weak and hence they suffer much less from the effects described above. The major uncertainties in determining abundances with line diagnostics are the lesser accuracy of the electron temperature derived from line diagnostics and the uncertainty in correcting ionic abundances for unobserved ionization stages. In favorable circumstances, the correction factors can be very small and it is thus not a priori clear that photo-ionization modeling yields more accurate abundances than line diagnostics. This can only be the case when care is taken that the model assumptions are appropriate for the nebula being modeled.

In an early phase of this work an experiment was conducted where the distance was kept as a free parameter. This resulted in models where the accuracy depended very critically on the angular diameter. This dependence was considered unacceptable and this way of modeling data was later abandoned. From this we can learn that the modeling assumptions, the number of free parameters and the set of observables have to be carefully tuned to get the most stable method. More investigation into this is certainly needed. Minimization algorithms which yield a covariance matrix might prove very helpful in this respect.

The method has been applied to a sample of five galactic bulge planetary nebulae (PNe). Comparison of these and other, published, results shows that the stellar temperatures are generally in fair agreement but that there is a large
spread in the electron temperatures, electron densities and the nebular abundances, even when the same method was applied. This clearly shows the need for more accurate methods.

Our conclusion is that our method for making photo-ionization models works, provided that ample observational data of good quality are available and that sufficient emission lines of various ionization stages are observed in the spectrum. Where possible, particular care should be taken to make the model assumptions as realistic as possible.

In view of the importance of an accurate determination of the angular diameter, an investigation has been conducted into one of the methods used for this purpose. When the observed nebula is only partly resolved, often a technique called 'gaussian deconvolution' is used. It was found that this technique was only weakly founded in theory. The technique uses a conversion factor to convert the deconvolved FWHM of the nebula into the true diameter. In Chapter 3 a complete description is given of the necessary theory to calculate conversion factors for the case where both the nebula and the beam are circularly symmetric. It was already known that this conversion factor depends on the (assumed) intrinsic surface brightness profile and on the beam size of the observation when gaussian fits are used. In this thesis the following additional conclusions were reached. First, in the case when second moments are used, the conversion factor is different from the conversion factor when gaussian fits are used. When second moments are used, the conversion factor is independent of beam size, but does depend on the assumed surface brightness profile. Second, the conversion factor is very sensitive to optical depth effects, so care should be taken when comparing angular diameters determined at different wavelengths. Also, for optical observations the conversion factor depends on the chosen emission line. In all cases differences of several tens of percent are possible. Third, nebulae which have a power law drop-off in their density distribution usually have a 'fuzzy' edge and the Strömgren radius will be situated in the faint surface brightness regions of the nebula. For such nebulae the conversion factor can become very large and is a very sensitive function of the assumed geometry of the nebula. Since this geometry cannot be assessed accurately in general, it is not meaningful to apply a conversion factor in such cases.

The method to analyze nebular spectra presented in Chapter 2 has been applied several times. Three of these applications are described in this thesis. First, in Chapter 5 the first radio continuum detection of a planetary nebula in the LMC is presented. The object, which contains a [WC] star, was also detected by IRAS. It is shown that all IRAS-detected PNe in the LMC are likely to be young objects. The PN was also compared to [WC]-type objects in the galaxy, and it is found that the LMC object has much bluer IRAS colors than its galactic counterparts. The preferred explanation is that its circumstellar envelope is more compact due to a lower expansion velocity, caused by a lower metallicity. This is supported by photo-ionization model-

ing of the spectrum of SMP 58. Other possible explanations however cannot be ruled out completely.

In Chapter 6 we report the first detection of the [Ar VI] 4.53 μm and [Ne VI] 7.65 μm lines in the SWS spectrum of NGC 7027. The strengths of the [Ar VI] line and probably also the [Ne VI] line have increased since 1981. The most likely explanation for this variability is a change in the spectral energy distribution of the central star, possibly due to an increase in effective temperature. However, further observations are needed to confirm this result.

In Chapter 6 the non-detection of the [O IV] 25.9 μm line is reported in the SWS spectrum of NGC 6543. The ionization energy needed to produce $O^{1+}$ is just beyond the He II Lyman limit, and the absence of this line shows that the stellar flux drops at least by a factor 350 at the He II limit. Hence modeling the [O IV] line may prove to be a valuable test for atmosphere models.

These three examples show how photo-ionization models can be useful for individual studies of nebulae. They allow new insights into the various physical processes that operate in the nebulae. Hence photo-ionization modeling can be instrumental in deepening our knowledge of post-AGB evolution. CLOUDY can also be used for a different approach of the same problem, where theoretical predictions for post-AGB evolution are used as the starting point, instead of observations. In Chapter 4 such an approach is taken and new calculations of the spectral evolution of a hydrogen burning post-AGB star are presented. The intention of these calculations is to deepen our understanding of the implications that the assumptions in the theoretical predictions have on the observed infrared spectra of the nebulae. Hopefully this will lead to a better understanding of the observations, which in turn can lead to more realistic assumptions for the theoretical predictions. The main new ingredient of the calculations in Chapter 4 was the possibility of extracting timescales for the post-AGB central star evolution from the most recent evolutionary calculations. Contrary to previous studies, this allowed the investigation of other AGB and/or post-AGB mass loss rates and different prescriptions for the start of the post-AGB phase. The fact that a dust code is built into CLOUDY, gave the opportunity to study the evolution of the infrared emission of the circumstellar material.

The evolutionary calculations for hydrogen burning post-AGB stars show that the evolutionary rate is very dependent on the assumed mass loss rate as a function of time. This effect was investigated by modifying the mass loss prescription. The newly calculated evolutionary rates and density distributions were used to model the spectral evolution of a post-AGB star, where dust absorption and emission were included in the radiative transfer. Different assumptions for the dust properties and dust formation were considered. It was shown that by varying these parameters in a reasonable way, entirely different paths were followed in the IRAS color-color diagram. First of all, the effects of the evolution of the central star on the expanding dust shell could not be neglected. Also the dust properties and
the definition of the end of the AGB phase had an important effect. The possible presence of hot dust due to dust formation in the post-AGB wind could have considerable influence on the IRAS colors as well. The model tracks showed that objects occupying the same location in the IRAS color-color diagram can have a different evolutionary past, and therefore the position in the IRAS color-color diagram alone can not a priori give a unique determination of the evolutionary status of an object. This is certainly part of the explanation why planetary nebulae do not occupy a well-structured region in the IRAS color-color diagram. An alternative color-color diagram, the K-[12] vs. [12]-[25] diagram, was introduced. The tracks in this diagram appear to be less affected by the particulars of the grain emission. This diagram may be a valuable additional tool for studying post-AGB evolution, e.g. it may provide additional selection criteria which would make the search for new post-AGB stars more efficient.

7.2 Outlook

In this thesis several studies have been presented which are aimed at giving a more solid foundation to certain aspects of the analysis and interpretation of observations of emission line nebulae. Ultimately, all studies presented here, either directly or indirectly, intend to increase our knowledge of post-AGB evolution. This is a vast field of study and this thesis can only be viewed as a small step towards achieving the goal of understanding this evolution. Many groups around the world are currently working on this problem and it would be simply too much to try and describe all the work they are currently undertaking. So in this outlook I will limit myself to the work in which I am involved, be it in the center or in the periphery.

In Chapter 2 a new method has been presented to analyze spectra of emission line nebulae. This method was subsequently used to study the propagation of errors from the observations to the model parameters. In principle this study is only valid for the particular set of artificial ‘observations’ that was used. Although it can be expected that these results are valid in a more general context, it is also clear that there must be certain limits to that validity. This needs to be studied further. However, an analysis of the type presented in Chapter 2 is very cumbersome and certainly not suitable for routine application. Hence new ways of studying the error propagation are needed. In Chapter 8, the new optimization algorithm PHYMIR was briefly mentioned, which was primarily developed for making optimum use of the computing power on parallel computers. This algorithm might also be extended in order to yield the Hessian matrix and ultimately the covariance matrix of the $\chi^2$ function. These matrices can be used to speed up the convergence and, more importantly, to study the error propagation. Currently no optimizing algorithm is available which is able to yield a covariance matrix when the derivatives of the fitting function are not available, as is the case when fitting a numerical model to observed data. Hence, developing such an algorithm would have an impact far beyond the scope described here.

Another fundamental problem hampering the interpretation of observations is the alleged presence of electron temperature fluctuations in the ionized regions of both PN and H II regions. In PN research this problem is commonly known as the $\chi^2$-problem and it can severely affect e.g. abundance determinations. Theory does not predict the presence of such fluctuations, but certain observations indicate the possibility that they exist. An observational programme has been started to search for the possible presence of these fluctuations. Where possible, this programme should be combined with a search for the explanation of the discrepancy between abundances derived from recombination lines and collisionally excited lines. Most planetary nebulae are point sources for ISO, hence also an H II region was chosen to be studied. This nebula has an extent which is large enough that even with ISO spatially resolved spectroscopy can be obtained.

In a research proposed by Dr. S.R. Pottasch an investigation has been started to study the central star temperatures of high excitation PN by observing specific lines, belonging to high ionization stages, with SWS. These data will hopefully yield more accurate stellar temperatures for the hottest, and therefore probably also the most massive central stars.

A line of research which is very much related has been proposed by Dr. G.J. Ferland. In certain nebulae, especially bipolar type I nebulae, high velocity outflows are observed. These outflows produce shocks and heat certain parts of the nebula to X-ray temperatures. Interaction of this X-ray emitting gas with cooler parts of the nebula could raise the level of excitation beyond what would be expected based on the stellar spectrum alone. Identification of this mechanism would be important to study the $\chi^2$-problem mentioned above, but would also be important to obtain more accurate central star temperatures for these objects and to find their true place in the HR diagram.

In Chapter 1 it has already been argued that the AGB mass loss history can best be traced in very young post-AGB stars, before the fast post-AGB wind alters the structure of the nebula. Only few genuine post-AGB stars and very young PN are known to date and more need to be identified to get a better sample to study these processes. In a collaboration with Dr. G.C. Van de Steene we think that we have identified such a sample. We are currently observing this sample to establish the exact evolutionary status of the objects. In the future we want to give high priority to further study of this very interesting sample. Our first priority will be to establish the stellar temperature and luminosity class of all objects. After their post-AGB nature has been established, we wish to start studying the AGB ejecta, first of all the dust characteristics and the morphology. Also we would like to reconstruct the evolutionary past of the objects and establish whether there is an evolutionary connection between the various types of objects in our sample.
Additionally, we want to monitor our sample for possible evolutionary changes.

In Chapter 4 we proposed a new near-infrared color-color diagram to study post-AGB stars: the $K$-[12] vs. [12]--[25] diagram. We would like to investigate this diagram further and see how the post-AGB sample described above fits into this diagram.

In the phase prior to the launch of ISO, a comprehensive list of infrared allowed and forbidden atomic transitions has been compiled. Hopefully, in the near future this list will be updated, enlarged and combined with transition probabilities to make it even more versatile.

Hopefully these projects will lead to more accurate determinations of basic stellar and nebular parameters, a better understanding of their accuracy and ultimately to a better understanding of post-AGB evolution, post-AGB mass loss and the formation and shaping of planetary nebulae. These new insights will be needed for studies of galaxies and galaxy evolution. Post-AGB objects are important for understanding the chemical evolution of galaxies, especially of the lighter elements like carbon, nitrogen and oxygen.

Furthermore, the luminosity function of planetary nebulae is used as a distance indicator for galaxies. Planetary nebulae are also important for understanding the ultraviolet spectrum of galaxies. They might even be useful in constraining the initial mass function at earlier epochs of the evolution of a galaxy, although this possibility seems very remote at the moment.