Asymmetric Planetary Nebulae III
ASP Conference Series, Vol. XXX, 2004
M. Meixner, J. Kastner, B. Balick and N. Soker eds.

Grain Size Distributions and Photo-Electric Heating in Ionized Regions

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Abstract. In this paper we present results obtained with the new grain code in Cloudy which underline the strong effect of photo-electric heating by grains in photo-ionized regions. We will study the effect that the distribution of grain sizes has on the magnitude of the effect, and show that this effect is nothing short of dramatic. This makes the grain size distribution an important parameter in modeling of photo-ionized regions such as H II regions and planetary nebulae.

1. Introduction

This paper focuses on the grain model in Cloudy, which has undergone a major upgrade in the last couple of years. The first grain model was introduced to Cloudy in 1990 to facilitate more accurate modeling of the Orion nebula (for a detailed description see Baldwin et al. 1991). In subsequent years, this model has undergone some revisions and extensions, but remained largely the same. Recently, our knowledge of grains has been greatly advanced by the results from the *ISO* mission. In view of these rapid developments we have undertaken a major upgrade of the grain model in Cloudy. The two main aims were to make the code more flexible and versatile, and to make the modeling results more realistic. These are the main improvements:

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- We have included a Mie code for spherical particles. The necessary optical constants needed to run the code are read from a separate file.
- A mixing law has been introduced to the code. This allows the user to define grains which are mixtures of different materials.
- The absorption and scattering opacities can be calculated for completely arbitrary grain size distributions (including single-sized grains).
- The size distribution can be resolved in many small bins (the user can choose how many), and all physical quantities are calculated for each bin separately. This allows non-equilibrium heating to be treated correctly for the smallest grains in the size distribution, and more realistic grain emission spectra to be calculated. It will also improve modeling of the photo-electric effect which also depends strongly on grain size.
- The code for non-equilibrium treatment of PAH's has been extensively rewritten for the new grain model. It now works automatically and efficiently with all grain types and sizes, under all conditions.
- We have updated the grain physics following the discussion in Weingartner & Draine (2001). This includes an improved treatment of the photo-electric effect and the electron sticking probability. The code now also uses discrete charge states for the grains, but our treatment deviates somewhat from Weingartner & Draine (2001) in that we use the hybrid grain charge model (van Hoof et al., 2001), instead of a fully resolved non-equilibrium charge distribution. We have shown that the hybrid grain charge model is sufficiently accurate for all realistic astronomical applications.

The new grain model is currently being distributed as part of the beta release of Cloudy 96. Cloudy can be obtained from the Cloudy website[2]. The Cloudy 96 beta release can currently be found under "Other versions".

2. Photo-electric Heating and Grain Size Distributions

It is well known that photo-electric heating by grains in a photo-ionized region has an important effect on the emitted spectrum (e.g., Volk 2001; Dopita & Sutherland 2000). It is however not well known that the size distribution of the grains plays a very important role in determining the magnitude of this effect. In order to test this, we have constructed a set of models with Cloudy 96 beta 5 based on the standard Paris H II region and planetary nebula (PN) models (Péquignot, 1986). The Paris H II region model would be roughly valid for a low-excitation PN as well, while the Paris PN model is valid for a high-excitation PN. The base models contain no dust, and will be used as a point of reference. We constructed 6 models out of each base model by simply adding a dust component. We stress that in all six models the chemical composition and the dust-to-gas mass ratio of the dust is the same, and the only difference is the size distribution. Two models were using single sized grains of 1.0 and 0.1 μm, while the other 4 were using more or less realistic size distributions taken from the literature (as indicated underneath the plots). We also point out that the models are ionization bounded, so the outer radius varies, depending on the total opacity of

[2] http://www.nublado.org/

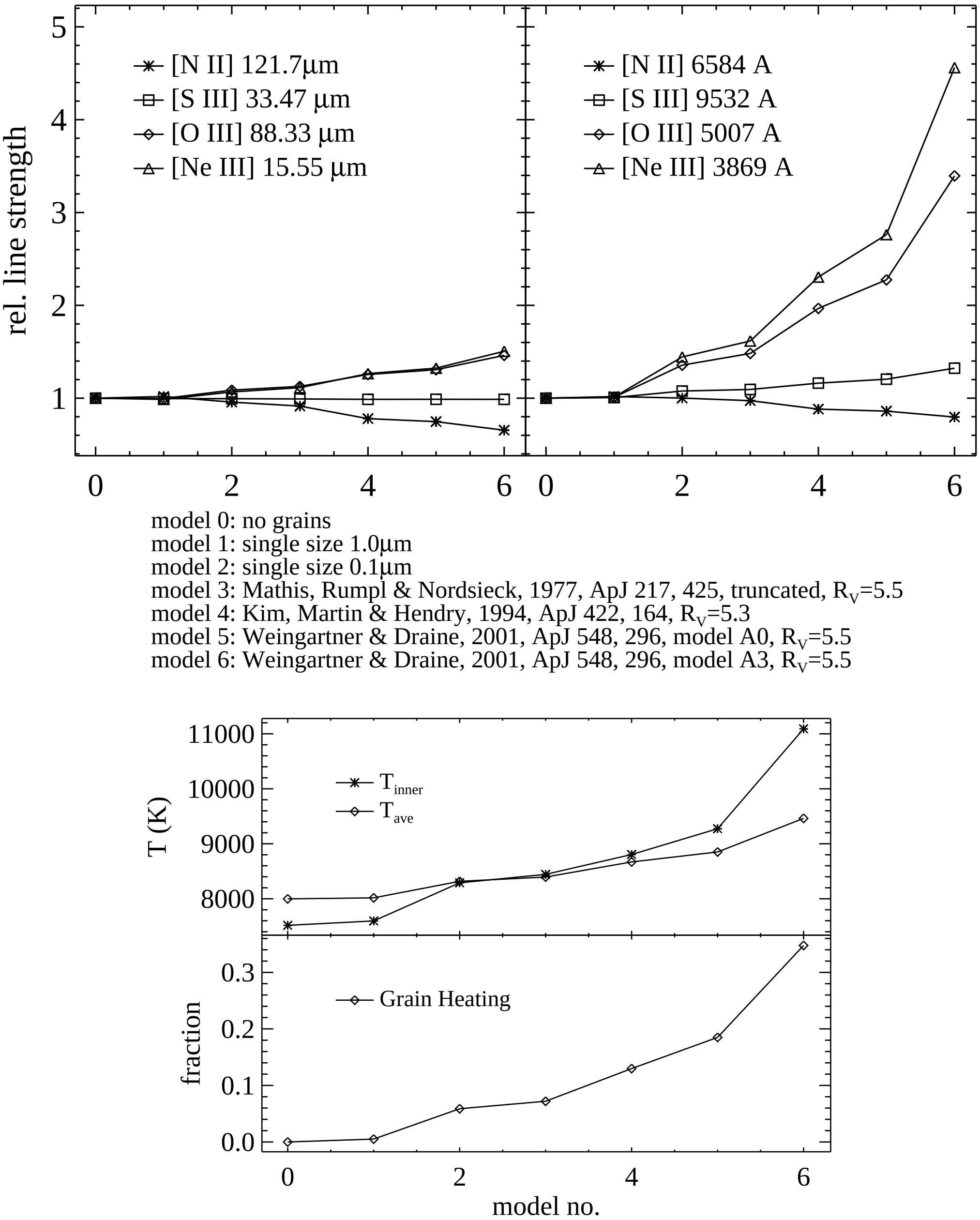

Figure 1. Paris H II region models. In the top left panel we show the relative line strengths for selected infrared fine-structure lines. These are expected to be mostly insensitive to electron temperature and therefore show the difference in the overall ionization structure. The line strengths are normalized to the line strength in the dust-free model. In the top-right panel we show optical/UV forbidden lines of the same species. In the bottom panels we show the electron temperature at the inner edge, as well as averaged over the ionized region, and the fraction of the total gas heating that is due to the photo-electric effect.

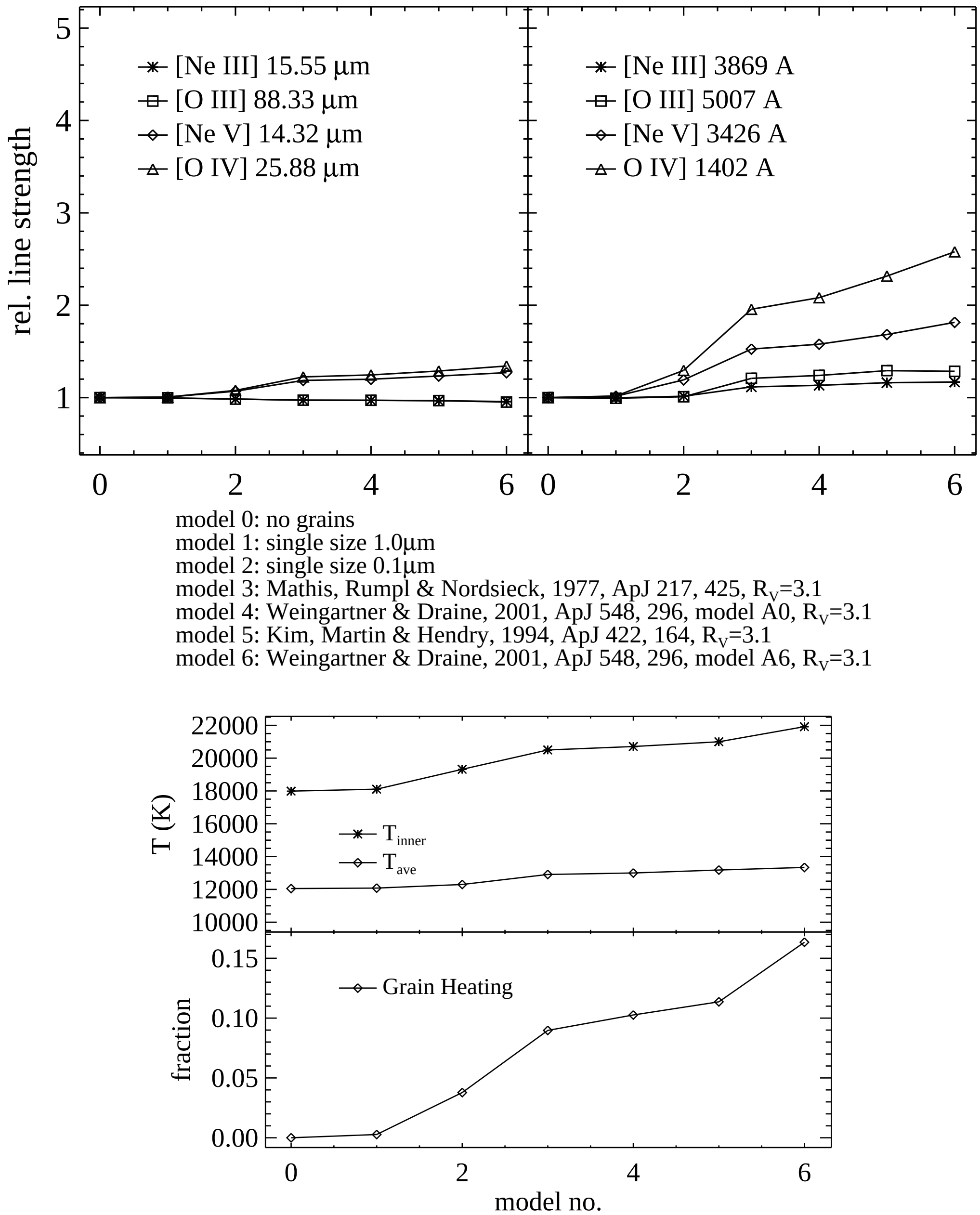

Figure 2. Same as Fig. 1, but for the Paris PN models with graphite only.

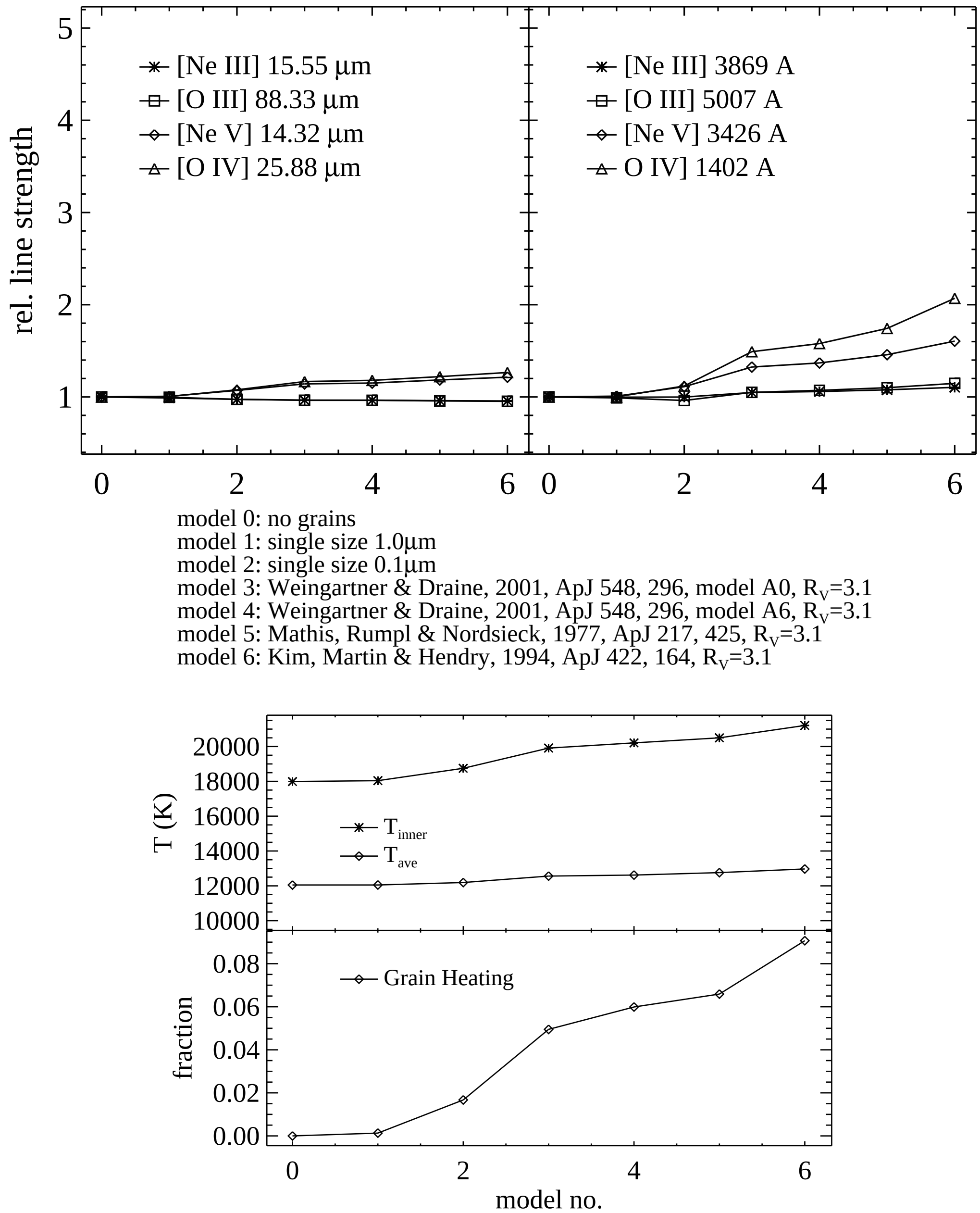

Figure 3. Same as Fig. 1, but for the Paris PN models with silicate only.

the grains (which also depends strongly on the size distribution). For the Paris H II region model we added a mixture of graphite and silicates, while for the Paris PN models we made separate models for graphite and silicates since these grain types are not expected to co-exist. In Figs. 1, 2, and 3 we show the results of these calculation. In the top-left panel we show the strength of selected infrared fine-structure lines. These are expected to be mostly insensitive to electron temperature and therefore show the difference in the overall ionization structure. In the top-right panel we show optical/UV forbidden lines of the same species, clearly showing that the enhancement for these lines is usually much stronger, especially for highly excited lines which are only populated in the inner regions of the nebula. This clearly shows the excess collisional excitation caused by the photo-electric effect. In the bottom panel of each plot this is further illustrated by showing the electron temperature at the inner edge, as well as averaged over the ionized region, and the fraction of the total gas heating that is due to the photo-electric effect.

All these plots clearly illustrate that the size distribution alone has a dramatic effect on the emitted spectrum, and is therefore an important parameter in the modeling of spectra from H II regions and PN.

3. Conclusions

In this paper we studied the effect that the distribution of grain sizes has on the amount of photo-electric heating. We have shown that this effect is nothing short of dramatic, making the grain size distribution an important parameter in modeling of photo-ionized regions such as H II regions and planetary nebulae. Only few studies of grain size distributions exist, and they mainly concentrate on the diffuse interstellar medium (ISM) in order to explain extinction curves. Further study of grain size distributions will be needed in order to enable more accurate modeling of photo-ionized regions. This is especially the case for planetary nebulae since it is not clear whether ISM size distributions are valid for these objects.

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