PROPERTIES OF THE DUST EMISSION OF THE PLANETARY NEBULA NGC 6445

P.A.M. van Hoof[1,4], G.C. Van de Steene[2], D.A. Beintema[3], P.G. Martin[4], S.R. Pottasch[5], G.J. Ferland[1,4]

[1] University of Kentucky, Dept. of Physics and Astronomy, 177 CP Building, Lexington, Kentucky, USA.
[2] Mount Stromlo Observatory, Private Bag, Weston Creek P.O., ACT 2611, Australia.
[3] SRON Laboratory for Space Research, Postbus 800, NL-9700 AV Groningen, The Netherlands.
[4] Canadian Institute for Theoretical Astrophysics, McLennan Labs, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada.
[5] Kapteyn Astronomical Institute, Postbus 800, NL-9700 AV Groningen, The Netherlands.

ABSTRACT

In this paper we present new infrared spectra of the planetary nebula NGC 6445. These data show that the thermal emission from the grains is unusually cool and has a very low flux compared to Hβ. A model of the ionized region is constructed, using the photoionization code Cloudy 90.05. Based on this model we show from depletions in the gas phase elements that little grain destruction can have occurred in the ionized region of NGC 6445. We also find that there is no indication for dust-gas separation in the nebula. The most likely conclusion is that grains are residing inside the ionized region of NGC 6445 and that the low temperature and flux of the grain emission is caused by the low luminosity of the central star and the low optical depth of the grains. This implies that the grains in this nebula could survive exposure to hard UV photons for at least several thousands of years.

1. INTRODUCTION

We have obtained an ISO-SWS spectrum of the planetary nebula (PN) NGC 6445, which is remarkable in the fact that it shows virtually no dust emission (see Figure 2). Since it is commonly accepted that all Asymptotic Giant Branch (AGB) stars form large quantities of dust grains, this spectrum raises interesting questions concerning the fate of these grains.

NGC 6445 is classified as a bipolar type I PN (Corradi & Schwarz 1995; Perinotto 1991), which are thought to originate from massive progenitors. The large size and low density of the nebula indicate it is well evolved. Both the ionized and neutral material (CO) show a high expansion velocity, 38 km s^{-1} (Weinberger 1989) and 33 km s^{-1} (Huggins & Healy 1989) respectively. Such velocities are consistent with a central star which was luminous in the early stages of its post-AGB evolution. Also the high central star temperature we find (Section 4.) is consistent. An image of the nebula is shown in Figure 1.

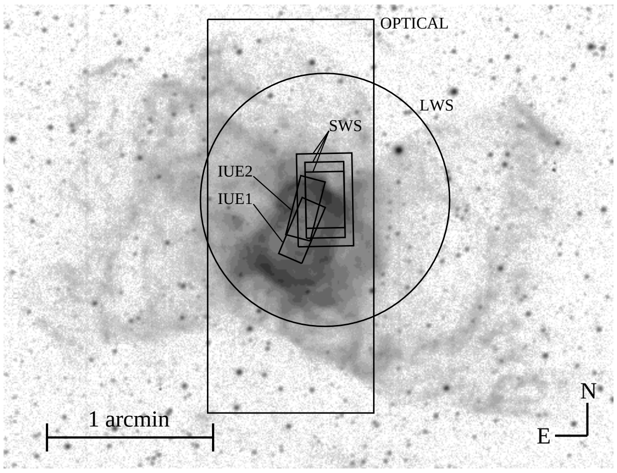

Figure 1. The various apertures plotted over an Hα+[N II] image of NGC 6445 (Schwarz et al. 1992). The image has been scaled logarithmically to emphasize the low surface brightness regions.

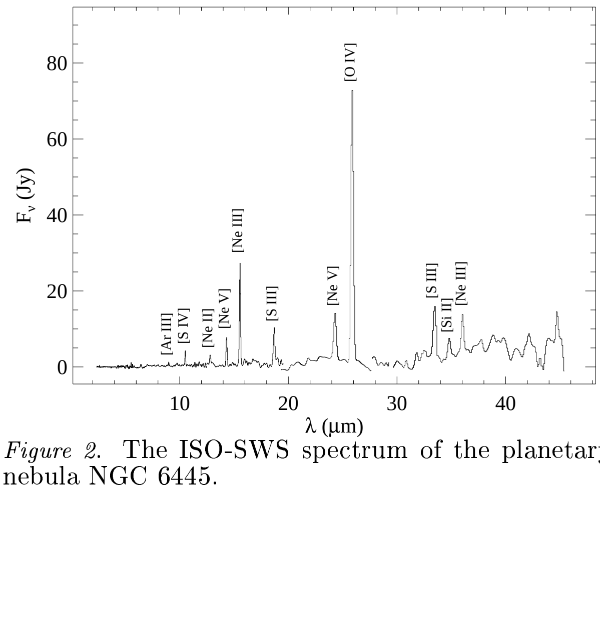

Figure 2. The ISO-SWS spectrum of the planetary nebula NGC 6445.

2. APERTURE CORRECTIONS AND INTERSTELLAR REDDENING

In the analysis of NGC 6445 several spectra were used, covering a wide range of wavelengths. We retrieved International Ultraviolet Explorer (IUE) spectra from the INES catalog in the IUE final archive. We also obtained optical observations with the Boller & Chivens spectrograph at the 1.52-m ESO telescope on La Silla. These spectra were taken using a special technique to obtain large-aperture exposures. The SWS01 spectrum presented in Figure 2 was supplemented with SWS02 data of various emission lines and two LWS01 spectra, one on-source and one off-source.

Multiplication factors have been applied to all IUE and SWS data to correct for the fact that the apertures of these instruments encompass a much smaller part of the nebula than the other apertures. These factors were obtained by integrating the surface brightness distribution shown in Figure 1 over the relevant areas. The correction factors for the IUE data are large since this instrument measured only a small region in the center of the nebula, missing most of the highest surface brightness regions. This correction could have been overestimated due to any of the following three effects. First, errors of a few arcsecond in the satellite pointing could cause more flux to enter the aperture. Second, light from the brightest regions just outside the aperture could have been scattered into the line of sight by the intervening ISM. Third, the lines IUE detected come from highly ionized species which could be more centrally concentrated than the H I+[N II] emission. The IUE fluxes should therefore be considered less accurate than any of the other data.

We also had to correct the data for reddening. Using the 14.7 GHz flux of 322±18 mJy (Milne & Aller 1982) we were able to obtain an estimate for the dereddened Hβ flux using Equation IV-26 given in Pottasch (1984). The resulting value was $\log[F(H\beta)/(\mathrm{W\,m^{-2}})] = -13.06 \pm 0.04$. When we compare this with the observed Hβ flux of $\log[F(H\beta)/(\mathrm{W\,m^{-2}})] = -14.12 \pm 0.04$, we immediately find that $c(\mathrm{H}\beta) = 1.06 \pm 0.06$ dex, or alternatively we find a total extinction of $A(486.1\ \mathrm{nm}) = 2.64$ mag.

We can now determine the shape of the extinction curve for our spectra. The relative line strengths in the recombination spectra of H I and He II depend only little on electron temperature and density and can be predicted using Case B theory (Storey & Hummer 1995). This allows us to determine the total extinction at various other wavelengths using the value of $A(486.1\ \mathrm{nm})$ determined above. The results are shown in Table 1 and plotted in Figure 3.

To obtain an extinction curve, we fitted the law given by Cardelli et al. (1989) to these data, using the ratio of total to selective extinction R_V and the selective extinction $E(B-V)$ as free parameters. The result was $R_V = 3.55$ and $E(B-V) = 0.61$, which is equivalent to $c(\mathrm{H}\beta) = 0.99$ dex. The fit is shown in Figure 3. This extinction law was applied to all observed line fluxes. The resulting intensity $I(\mathrm{H}\alpha) = 363$ is surprisingly large and is not expected by Case B theory.

Table 1. Empirical values for the extinction.

	λ (nm)	Obs. & Pred. Flux (10^{-14} W m^{-2})		$1/\lambda$ (μm^{-1})	$A(\lambda)$ (mag)
H I	954.6	0.146	0.311	1.048	0.82
H I	922.9	0.092	0.216	1.084	0.93
H I	656.3	5.194	24.495	1.524	1.68
He II	541.2	0.051	0.327	1.848	2.02
H I	486.1	0.762	8.699	2.057	2.64
He II	468.6	0.368	4.156	2.134	2.63
H I	434.0	0.334	4.100	2.304	2.72
H I	410.2	0.115	2.272	2.438	3.24
H I	397.0	0.076	1.396	2.519	3.16
He II	164.0	0.399	29.043	6.098	4.65

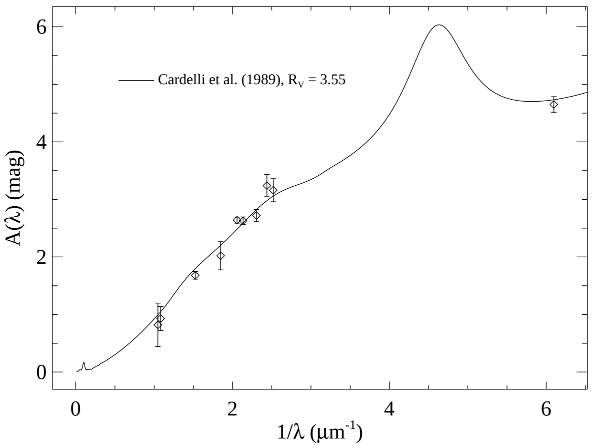

Figure 3. The extinction law for NGC 6445.

A possible explanation could be provided by the fact that the overall shape of the extinction curve can differ from the mean law for different lines of sight (Cardelli et al. 1989). HST observations could be used to investigate the extinction law further.

3. THERMAL GRAIN EMISSION

The fact that hardly any grain emission is detected in the SWS01 spectrum raises the question whether the inner regions of NGC 6445 could be free of grains, either due to grain destruction, or to dust-gas separation. Emission from the grains is detected in the LWS spectrum, which indicates that at least part of the grains survived. This detection is possible because the LWS aperture encompasses a larger part of the nebula. LWS will have detected the emission from the grains closest to the central star, but still may have missed the emission from the cooler grains farther out in the nebula. We also took an off-source LWS spectrum 3′ north of the nebula. This spectrum was intended to measure the background continuum and line emission from the ISM. This spectrum shows two clearly distinct emission components. One very cool component which only becomes detectable at wavelengths longward of 140 μm, and a much warmer component which is visible at shorter wavelengths. The latter is detectable as a smooth background in HIRES images made from IRAS 60 μm and 100 μm

Table 2. Parameters for the fits to the far-infrared continuum.

β	$T_{\rm dust}$ (K)	FIR (10^{-14} W m^{-2})	χ^2/N
0.00	83.0	289	2.16
0.50	65.8	252	1.53
0.86	57.6	235	1.41
1.00	54.9	229	1.42
1.50	47.3	213	1.74
2.00	41.6	200	2.39

data. Using the off-source spectrum we corrected the on-source spectrum for the ISM contribution, which is assumed to be the same in both apertures. The resulting spectrum is shown in Figure 4.

The LWS data for NGC 6445 show evidence for the presence of dust which is unusually cool for a planetary nebula. We will investigate this emission first, before we try to determine where the emitting grains reside. To determine the average grain temperature, we have fitted an emission law of the form $F_\nu = c\,\nu^\beta B_\nu(T_{\rm dust})$ where c, β and $T_{\rm dust}$ are free parameters. The resulting best fit gave $\beta = 0.86$ and is shown in Table 2 and Figure 4. Fits where we kept β fixed to other values are also shown for comparison in Table 2.

The dust temperature of 58 K is considerably lower than what is typically observed in planetary nebulae. Dust grains with such typical temperatures (between roughly 100 K – 150 K) cannot be present in NGC 6445, since they would be readily observable in the SWS spectrum. The ratio of the thermal grain emission to the H β flux of 27.0 is also very low. The presence of strong neutral lines in the spectrum indicates that the nebula is ionization bounded. We therefore assume that no significant fraction of the Lyman continuum or Ly α photons escape the nebula. This implies that all of the grain heating can be accounted for by Ly α photons [$F({\rm Ly}\,\alpha)/F({\rm H}\,\beta)$ = 26.6]. Apparently Lyman continuum photons contribute very little to grain heating and this suggests either that the ionized region is free of grains, or that the ionization parameter is low, resulting in a low optical depth of the grains in the Lyman continuum (Bottorff et al. 1998). To investigate this further we will first construct a photo-ionization model of the ionized region of NGC 6445.

4. PHOTO-IONIZATION MODELING

We constructed a photo-ionization model of the ionized region using a modified version of CLOUDY 90.05 (Ferland et al. 1998) and following the method described in van Hoof & Van de Steene (1998) with the following alterations. Instead of the blackbody assumption we used model atmospheres calculated by Rauch (1997). Furthermore, we used a constant hydrogen density throughout the ionized and neutral regions of the nebula. In view of the complex structure of the nebula we did not constrain the model with an angular diameter, but alternatively fixed the density at the value determined from plasma diagnostics. We also used the electron temperatures determined from various plasma diagnostics as additional constraints on the model. We assumed no dust grains to be present in the ionized region and did not constrain the model with infrared fluxes. The resulting model parameters are listed in Table 3.

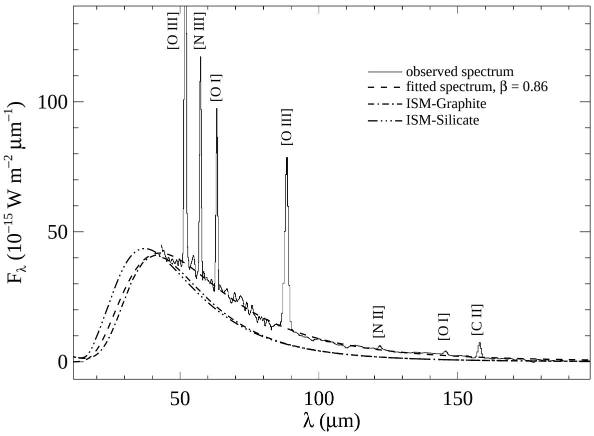

Figure 4. The far-infrared spectrum of NGC 6445.

This model shows the carbon and oxygen abundance to be equal. In view of the fact that the carbon abundance may be overestimated due to the uncertainties in the IUE data, we will assume that the grains in the nebula are silicates. However, the possibility that they are graphite will not be ruled out. First we will investigate whether grain destruction could have taken place in the ionized region of NGC 6445. When dust grains are destroyed, the constituent material is returned to the gas phase, making the composition essentially solar again. This has a profound effect on the spectrum being emitted by the plasma. Many strong lines of elements like magnesium, aluminum, calcium, vanadium, chromium, etc. should be easily detectable in UV or optical spectra (Kingdon et al. 1995; Kingdon & Ferland 1997). The fact that none of these lines are detected in the spectrum of NGC 6445 already indicates that no substantial amount of grain destruction can have taken place in the ionized region. This is confirmed by our photo-ionization model which clearly indicates that elements like magnesium, silicon and calcium are depleted in the ionized region. This proves that the dust grains that contain these elements cannot have been destroyed *in situ*. However, an alternative assumption could be that the ionized region is free of dust grains due to fact that the grains were separated from the gas.

To investigate the hypothesis of dust-gas separation further, we have constructed a photo-ionization model of NGC 6445 that does the opposite: it contains grains at a constant dust-to-gas ratio throughout the nebula. If the grain emission in the model is significantly hotter than the observed spectrum, this would constitute proof that a uniform distribution of the grains is not possible and thus that dust-gas separation must have taken place to some degree in the ionized region of this nebula. We used silicates or graphite with a standard ISM size distribution (Martin & Rouleau 1991). The resulting model spectra are shown in Figure 4. The models include only a small part of the neutral region and are expected to show a flux-deficiency at long wavelengths. The sili-

Table 3. Parameters for the CLOUDY model of NGC 6445. All symbols have their usual meaning, ϵ stands for the logarithmic abundance; $\epsilon(\mathrm{H}) \equiv 12$.

Parameter	Value	rel. to solar[a]
T_{eff} (kK)	184.	
L_* ($\mathrm{L}_\odot$)	1035.	
r_{in} (mpc)	79.	
r_{Str} (mpc)	183.	
n_{H} (cm^{-3})	525[b]	
T_{e} (kK)	11.49[c]	
n_{e} (cm^{-3})	571[c]	
ϵ(He)	11.18	+0.19
ϵ(C)	8.87:	+0.32:
ϵ(N)	8.39	+0.42
ϵ(O)	8.87	+0.00
ϵ(Ne)	8.31	+0.23
ϵ(Mg)	7.23:	−0.35:
ϵ(Si)	6.86:	−0.69:
ϵ(S)	6.90	−0.43
ϵ(Ar)	6.58	+0.06
ϵ(Ca)	< 5.09	< -1.27
D (kpc)	1.5[b,d]	
χ^2	2.9	

[a] Grevesse et al. (1996).
[b] This parameter was not varied.
[c] This is a weighted average over the entire nebula.
[d] Van de Steene & Zijlstra (1995).

cate spectrum shows the presence of grains that are slightly hotter than in the observed spectrum. The discrepancies are small though and the evidence cannot be considered conclusive. In view of the fact that the photo-ionization model has a spherical geometry instead of bipolar, the model may predict too much hot dust. The graphite spectrum is consistent with the observed spectrum. Hence we find there is no need to invoke dust-gas separation in this nebula.

Therefore, the most likely conclusion is that grains are residing inside the ionized region of NGC 6445 and that the low temperature is caused by the low luminosity of the central star combined with the large extent of the nebula. The low flux of the grain emission, when compared to Hβ, is caused by the low optical depth of the grains in the Lyman continuum, which makes Lyα photons essentially the only heating source for the grains. In short, all of these characteristics are a consequence of the fact that the nebula is well evolved. Our conclusion implies that the grains in this nebula could survive exposure to hard UV photons for at least several thousands of years.

5. CONCLUSIONS

1) We presented ISO-SWS and LWS spectra of the planetary nebula NGC 6445 which indicate the presence of unusually cool dust with a very low flux compared to Hβ. The fact that Lyα photons alone could account for all of the grain heating, suggests that either the optical depth of the grains in the Lyman continuum is very low, or that the ionized region is free of grains.
2) A photo-ionization model of the ionized region of NGC 6445 is constructed. Based on this model we show that it is very unlikely that either grain destruction or dust-gas separation has taken place in the ionized region.
3) Hence, the most likely conclusion is that grains reside inside the ionized region of NGC 6445 and that the low temperature and flux of the grain emission is caused by the low luminosity of the central star and the low optical depth of the grains. This would imply that the grains in this nebula could survive exposure to hard UV photons for several thousands of years.

6. ACKNOWLEDGMENTS

This research was partially based on observations obtained at the European Southern Observatory and on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. We thank the NSF and NASA for support through grants AST 96-17083 and GSFC–123. We thank Dr. A. Lazarian for stimulating discussions and C. Kerton for processing the IRAS data. The Canadian Institute for Theoretical Astrophysics is thanked for their hospitality and financial support during our stay in Toronto.

REFERENCES

Bottorff M., LaMothe J., Momjian E., Verner E., Vinković D., Ferland G. 1998, PASP, 110, 1040

Cardelli J.A., Clayton C., Mathis J.S. 1989, ApJ, 345, 245

Corradi R.L.M., Schwarz H.E. 1995, A&A, 293, 871

Ferland G.J., Korista K.T., Verner D.A., Ferguson J.W., Kingdon J.B., Verner E.M. 1998, PASP, 110, 761

Grevesse N., Noels A., Sauval A.J. 1996, in 'Cosmic Abundances', eds. Holt S.S., Sonneborn G., ASP Conference series, Vol. 99, p. 117

Huggins P.J., Healy A.P. 1989, ApJ, 346, 201

Kingdon J.B., Ferland G.J. 1997, ApJ, 477, 732

Kingdon J., Ferland G.J., Feibelman W.A. 1995, ApJ, 439, 793

Martin P.G., Rouleau F. 1991, in 'Extreme Ultraviolet Astronomy', eds. Malina R.F., Bowyer S., Pergamon Press, New York, p. 341

Milne D.K., Aller L.H. 1982, A&AS, 50, 209

Perinotto M. 1991, ApJS, 76, 687

Pottasch S.R. 1984, 'Planetary Nebulae', Reidel, Dordrecht

Rauch T. 1997, A&A, 320, 237

Schwarz H.E., Corradi R.L.M., Melnick J. 1992, A&AS, 96, 23

Storey P.J., Hummer D.G. 1995, MNRAS, 272, 41

Van de Steene G.C., Zijlstra A.A. 1995, A&A, 293, 541

van Hoof P.A.M., Van de Steene G.C. 1998, MNRAS, submitted

Weinberger R. 1989, A&AS, 78, 301