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The central stars of the planetary nebulae NGC 7027 and NGC 6543*

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Abstract. Infrared spectra of NGC 7027 and NGC 6543 ranging from 2.4 to 45 μm were obtained with the Short Wavelength Spectrometer on board the Infrared Space Observatory. A first analysis of these spectra, with the aid of photo-ionization models, is presented.

We report the first detection of the [Ar VI] 4.53 μm and [Ne VI] 7.65 μm lines in the spectrum of NGC 7027. When compared with older observations it is clear that the [Ar VI] line and possibly also other lines have increased in strength since 1981. We argue that a likely explanation for this variability is a change in the spectral energy distribution of the central star, possibly an increase in effective temperature. However, this result needs to be confirmed by further observations.

We also report a non-detection of the [O IV] 25.9 μm line and the first detection of the [Na III] 7.32 μm line in the spectrum of NGC 6543. The non-detection is not expected based on a blackbody approximation for the spectrum of the central star. The ionization threshold for O^{3+} is just beyond the He II limit, and the absence of this line shows that the stellar flux drops at least by a factor 350 at the He II limit. Modeling the [O IV] line may prove to be a valuable test for atmosphere models.

Key words: Stars: evolution – Stars: atmospheres – planetary nebulae: individual – Infrared: ISM: lines and bands

1. Introduction

Both the planetary nebulae NGC 7027 and NGC 6543 are very well studied nebulae. However, a complete study of the infrared spectrum of these sources has not been possible until now. In view of their scientific interest and their brightness they were obvious candidates for early targets to be observed by the Short Wavelength Spectrometer (SWS) on board the Infrared Space Observatory (ISO). In this paper we will present selected ionic emission lines of both SWS spectra. We will also present preliminary photo-ionization models and we will discuss possible interpretations of the reported features.

2. The ISO SWS observations

The SWS spectra of NGC 7027 and NGC 6543 were obtained during the Performance Verification phase, in the 24th revolution of the ISO satellite on 11 December 1995. The ISO satellite is described by Kessler et al. (1996). SWS and its observing templates are described by de Graauw et al. (1996). The observations used the SWS01 template: a spectral scan from 2.4 to 45 μm. The observations were done at the slowest speed, which reduces the spectral resolution to roughly half the nominal resolution of SWS. The spectra were reduced with the SWS Interactive Analysis software (pipeline V4.3) and were subsequently smoothed with a gaussian profile of a half-width corresponding to a resolving power of 800. The wavelength calibration and the flux calibration were done with the set of calibration files adopted as a standard for this issue of A&A letters. The wavelength calibration is discussed by Valentijn et al. (1996); the flux calibration by Schaeidt et al. (1996). The accuracy of the current flux calibration is estimated to be 30 %.

Especially the SWS spectrum of NGC 7027 is extremely rich. More than 100 emission lines were identified, down to a flux of 2×10^{-16} W/m^2. It is impossible to discuss or even present all these features. This will be postponed to a later publication. In this paper we report the first detection of the [Ar VI] 4.53 μm and the [Ne VI] 7.65 μm lines in the spectrum of NGC 7027. This makes Ne^{5+} the ion with the highest ionization potential observed in NGC 7027. In Table 1 the fluxes for these lines are compared with the 3σ upper limits deter-

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Table 1. Comparison of the observed line fluxes in the SWS spectra of NGC 7027 and NGC 6543 with previous observations in the literature. Where appropriate 3σ upper limits are given.

ion	λ	SWS	Lit.	ref
	(μm)	(10^{-14} W/m^2)		
NGC 7027				
Brα	4.05	9.3	16.3	a
[Mg IV]	4.49	13.1	31.0	a
[Ar VI]	4.53	10.6	< 2.0	a
[Mg V]	5.61	34.3	56.0	a
Pfα	7.46	2.4	5.6	a
[Ne VI]	7.65	8.8	< 5.4	a
NGC 6543				
[Na III]	7.32	0.23		
[S IV]	10.51	29.3	43.0	b
[Ne III]	15.55	71.1	53.0	b
[O IV]	25.89	< 0.021	< 6.6	c

a) Beckwith et al. (1984), b) Pottasch et al. (1986), c) Shure et al. (1983).

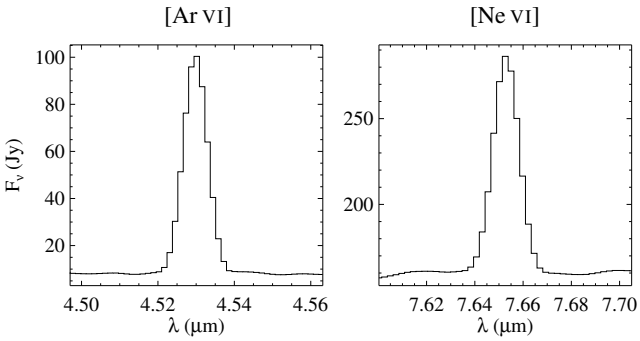

Fig. 1. The observed [Ar VI] and [Ne VI] lines in the spectrum of NGC 7027.

mined by Beckwith et al. (1984; hereafter B84) based on KAO spectra obtained in June 1981. The SWS spectra are shown in Fig. 1. We can see that the SWS detections yield a higher flux than the upper limits given by B84. The first question to ask is whether flux could have been missed outside the aperture or if this discrepancy could be due to problems in the flux calibration in either of the spectra. The ionized part of NGC 7027 measures $9'' \times 13.5''$ based on the VLA 6 cm radio image of Masson (1989). This area fits completely in the aperture used by B84 ($28''$ circular) and the smallest SWS aperture ($14'' \times 20''$). However, in SWS observations pointing errors of up to $4''$ may occur. The absence of wavelength shifts indicates that any errors larger than about $2''$ could only have occurred along the slit ($20''$) and we estimate that signal losses due to mispointing are less than 5 %.

We also compared the fluxes of the four lines that were detected by B84 with the SWS fluxes (Table 1). The average ratio of the B84 fluxes over the SWS fluxes is 2.0 ± 0.3. This might indicate a difference in flux calibration between the spectra. However, if anything, this would only exacerbate the discrepancy between the upper limits derived in 1981 and the detections in 1996. We therefore feel confident that at least the [Ar VI] line and probably also the [Ne VI] line have increased in strength over this period. We will discuss this further in Sect. 4.

We also report the non-detection of the [O IV] 25.9 μm line and the first detection of the [Na III] 7.32 μm line in the spectrum of NGC 6543. The upper limit for the [O IV] line derived from the SWS spectrum is much lower than was previously measured by Shure et al. (1983), as is shown in Table 1. The implications of this non-detection are discussed in Sect. 5.

3. The photo-ionization models

To model the planetary nebulae we used a modified version of the photo-ionization code CLOUDY 84.12a (Ferland, 1993). We assumed that the central star has a blackbody spectrum; that the nebula is spherically symmetric; that the density is constant inside the Strömgren sphere of the nebula, and varies as $1/r^2$ outside; that the dust grains are intermixed with the gas at a constant dust-to-gas ratio and that the filling factor, describing the small scale clumpiness, is unity.

For NGC 7027 the following observations were added to the SWS spectrum to constrain the modeling. The ultraviolet and optical spectrum of NGC 7027 were taken from Middlemass (1990) together with the absolute Hβ flux. The distance to the nebula was taken from Pottasch (1996). The SWS spectrum of NGC 6543 was augmented with the ultraviolet spectrum from Middlemass et al. (1989) and the optical spectrum from Aller & Czyzak (1979). The absolute Hβ flux was taken from Acker et al. (1992) and the distance to the nebula from Van de Steene & Zijlstra (1994). Additionally also infrared continuum fluxes, radio fluxes and an angular diameter were used to constrain the models for both nebulae.

To derive the physical parameters of the planetary nebulae from these observables, we adjust the model parameters until an optimal fit to the observables is found. For this we calculate a goodness-of-fit estimator χ^2, which is minimized. A detailed discussion of the method is given in van Hoof & Van de Steene (1996).

Given the fact that in NGC 7027 the [Ar VI] and likely also the [Ne VI] line have increased in strength since 1981 one might expect that the optical and ultraviolet spectra have changed as well. To minimize the inconsistency we decided to omit the highest ionization levels from the older optical and UV spectra, because these are expected to be influenced most by an increase in stellar temperature.

For NGC 6543 we made two models. The input for both models was identical except that in model 2b a modified blackbody spectrum was used. This is discussed further in Sect. 5. It is well known that NGC 6543 has a very extended halo which contains most of the mass (Middlemass et al., 1989; Manchado & Pottasch, 1989). However, the assumption of constant density inside the Strömgren sphere does not permit us to model this halo. Since the line flux is expected to be completely dominated by the core region, this poses no problem.

The results of the modeling are shown in Table 2. Most symbols have a commonly accepted meaning. Γ denotes the dust-to-gas mass ratio and ϵ the logarithmic abundance of an element (ϵ(H) $\equiv$ 12.00). The quoted number density of hydro-

Table 2. Parameters for the CLOUDY models of NGC 7027 and NGC 6543. Model 1 is for NGC 7027. Models 2a and 2b are for NGC 6543; these are identical except that different central star spectra were assumed. Abundances based on only one line are marked uncertain.

	model 1	model 2a	model 2b
$T_{\rm eff}$ (kK)	161.4	42.3	58.1
L_* ($L_\odot$)	6894.	5023.	3172.
$r_{\rm in}$ (mpc)	2.4	27.	26.
$r_{\rm Str}$ (mpc)	22.	55.	52.
$r_{\rm out}$ (mpc)	345.	55.	52.
$\log(n_{\rm H})$ (cm^{-3})	4.49	3.56	3.60
$T_{\rm e}$ (kK)	16.13	9.36	7.57
$\log(n_{\rm e})$ (cm^{-3})	4.55	3.61	3.64
$\log(\Gamma)$	−2.52	−2.20	−2.06
$M_{\rm ion}$ ($M_\odot$)	0.058	0.085	0.070
$M_{\rm sh}$ ($M_\odot$)	2.10	0.085	0.070
ϵ(He)	10.98	11.11	10.94
ϵ(C)	8.87	8.50	8.96
ϵ(N)	8.12	7.65	8.10
ϵ(O)	8.65	8.44	9.09
ϵ(Ne)	7.79	7.81	8.13
ϵ(Na)	5.94	6.31:	5.82:
ϵ(Mg)	6.82		
ϵ(Al)	4.87:		
ϵ(Si)	6.90:	6.71:	6.39:
ϵ(S)	6.76	6.91	7.04
ϵ(Ar)	6.34	6.41	6.49
ϵ(Ca)	4.64:		
ϵ(Fe)	5.87		
D (pc)	790.	1080.	1080.
χ^2	5.4	29.8	8.6

gen is the value inside the Strömgren sphere. The electron temperature and density are averaged over the nebula.

4. Discussion of the NGC 7027 results

Since infrared fine-structure lines are rather insensitive to electron temperature, the increase in strength of the [Ar VI] line must stem from a change in the ionization structure of the nebula. The ionization structure is the result of photo-ionization by the stellar radiation field and possibly also from shock heating due to the fast wind from the central star. Such a wind has never been observed for NGC 7027, therefore the presence of very strong shocks can be ruled out. Our model predicts that the [Ar VI] line is formed in a region ranging roughly from 6 to 16 mpc from the central star. Based on the [Ar VI] line strength, an Einstein A coefficient of A = 0.0966 cm^{-1} (Mendoza, 1983) and assuming a relative upper level population of 1 % we can derive the minimum width of the line emitting region to be 1.7 mpc. Assuming 20 kK for the average electron temperature, the sonic travel time through the line emitting region would be > 70 yr, considerably longer than the 15 yr over which the spectrum changed. The electron temperature only enters as the square root in the sonic velocity, therefore it would have to be much higher than 20 kK to account for the discrepancy. This can be ruled out based on our models. Adding extra heating to the nebula (due to energy deposition by the stellar wind) equivalent to 10 % of all energy radiated by the central star would only double the electron temperature. Therefore we think that shocks are ruled out as the source of the variability in the spectrum.

By changing the parameters in our photo-ionization model we could assess that changes in the nebular density, inner radius and dust-to-gas ratio have little effect on the line-strength of the [Ar VI] line. An increase in the luminosity of the central star would increase the strength of all lines, which is not observed. Therefore the increased strength of the [Ar VI] line must in all likelihood be attributed to a change in the spectral energy distribution of the central star, possibly an increase in effective temperature. The nebula reacts rapidly to a hardening of the stellar spectrum. We calculated the typical timescale needed to ionize Ar^{4+} to be 0.2 yr.

When we change the stellar temperature in our photo-ionization model, we see that the strength of the [Ar VI] line indeed is sensitive to this parameter. However, in order to account for the large rise in strength of the [Ar VI] line an unrealistic large increase in the stellar temperature of roughly 60 kK to 100 kK is needed. Other lines show an increase in strength which is consistent with a more moderate increase in stellar temperature, or even with a decrease. These mixed results might be caused by calibration problems since the changes for these lines are much more moderate. The evidence gathered so far does favor a change in the spectral energy distribution of the central star, possibly an increase in the stellar temperature. However, more observations are needed to confirm this result.

5. Discussion of the NGC 6543 results

In Table 1 we reported a stringent upper limit for the strength of the [O IV] line in NGC 6543. This is not in contradiction with the detection of O IV 1342 Å P Cygni profile in the IUE spectrum of NGC 6543 since this UV line is formed in the wind coming from the central star, i.e. is formed much closer to the central star (Castor et al., 1981; hereafter CLS). We also report the detection of [S IV], [Ne III] and [Na III] emission. These detections, together with the upper limit, allow us to derive clear constraints on the shape of the central star spectrum. We will discuss this by starting off with a blackbody approximation, an assumption still often made in planetary nebula modeling.

The ionization threshold is 34.8 eV for S^{3+}, 41.0 eV for Ne^{2+}, 47.3 eV for Na^{2+} and 54.9 eV for O^{3+}. The presence of the [Na III] line indicates that sufficient photons with energies above 47.3 eV are present to produce appreciable amounts of Na^{2+}. When using a blackbody spectrum this makes it very likely that there are also enough photons to produce a significant amount of O^{3+}. The [O IV] line is expected to be a more sensitive tracer than the [Na III] line since the oxygen abundance is so much higher that, in all probability, it would more than make up for the lower transition probability of the [O IV] line. Therefore, if significant amounts of O^{3+} were present in the nebula, the [O IV] line should be clearly detectable. From its absence we conclude that the blackbody approximation can not be valid; the stellar flux must make a considerable drop at the He II limit.

Table 3. Comparison of the observed fluxes in NGC 6543 with model predictions.

ion	λ	SWS	model 2a	model 2b
	(μm)	(10^{-14} W/m^2)		
[S IV]	10.51	29.3	5.0	21.0
[Ne III]	15.55	71.1	26.0	71.2
[O IV]	25.89	< 0.021	0.027	0.0040

This is also confirmed by our modeling. When we force the model to obey the upper limit on the [O IV] line when using a blackbody spectrum (model 2a), we see that the excitation of the model spectrum is much lower than what is observed (see Table 3). In general the fit is bad as is expressed by the high χ^2. The effective temperature is in good agreement with the measured H I Zanstra temperature of 47.0 kK (Kaler & Jacoby, 1991). However, the predicted H I Zanstra temperature based on the model spectrum is 31.0 kK, much lower than observed.

We decided to test our hypothesis by modifying the blackbody spectrum such that beyond the H I limit the flux would be multiplied by a constant factor 0.40 and beyond the He II limit by an additional factor 10^{-5}. This resulted in model 2b. We can see that the overall fit of model 2b is much better and also that it has the right degree of excitation. The high oxygen abundance we find does not invalidate our model since the oxygen abundance in NGC 6543 is known to be high (Middlemass et al., 1989; Manchado & Pottasch 1989).

The effective temperature we find is higher than the upper limit for the stellar temperature derived by CLS. However, we argue that this upper limit is not valid. It is based on the He II Zanstra temperature derived from an upper limit for the nebular He II λ 4686 emission. The Zanstra method makes the assumption of a blackbody stellar radiation field, which is clearly not valid. A stellar radiation field of any given effective temperature can satisfy the constraint on the nebular He II emission provided that the flux in the He II Lyman continuum is low enough. This is also confirmed by our model. The predicted nebular He II λ 1640 and λ 4686 emission is 2.25×10^{-16} W/m^2 and 2.46×10^{-17} W/m^2 respectively, well within the restrictions imposed by CLS. The predicted H I Zanstra temperature based on the model spectrum is 41.6 kK, in agreement with the observations. The stellar temperature has also been derived by Lucy & Perinotto (1987). Their preferred value of 51.6 kK is higher than the value adopted by CLS, but still lower than the value we find. Our data point would fall to the left of the curve in their Fig. 2. The effective temperature is sensitive to the adopted multiplication factor at the H I limit. Since the nebular spectrum is not particularly sensitive to this factor, we decided to fix the value such that the predicted stellar V magnitude would coincide with the value from Castor et al. (1981).

Photo-ionization modeling of the [O IV] line can prove to be a valuable test for predictions of stellar atmosphere models, since the results appear to be sensitive rather directly to the magnitude of the drop at the He II limit. This line is more suitable than the He II lines since there can be no ambiguity between stellar and nebular emission.

Using the parameters of model 2b we determined that the stellar flux drops at least by a factor 350 at the He II limit in order to obey the upper limit on the [O IV] line. In a future paper we hope to present a more stringent upper limit.

6. Conclusions

In this letter we reported the first detection of the [Ar VI] 4.53 μm and [Ne VI] 7.65 μm lines in the spectrum of NGC 7027. The strength of the [Ar VI] line and likely 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 an increase in effective temperature. However, further observations are needed to confirm this result.

We also reported a non-detection of the [O IV] 25.9 μm line, and the first detection of the [Na III] 7.32 μm line in the spectrum of NGC 6543. The ionization energy needed to produce O^{3+} is just beyond the He II limit, and the absence of this line shows that the stellar flux drops at least by a factor 350 at the He II limit. Modeling the [O IV] line may prove to be a valuable test for atmosphere models.

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