ISO - SWS OBSERVATIONS OF PLANETARY NEBULAE

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Abstract. First results of the ISO[1] Short-Wavelength Spectrometer on three bright planetary nebulae NGC 6543, NGC 7027 and NGC 6302 provide a wealth of information on solid-state features and spectral lines. Spectra from 2.4 to 45 μm are presented, at a reduced resolution of about 600.

1. Introduction

On 17 November 1995 the Infrared Space Observatory ISO (Kessler et al. 1996) was launched. The Short Wavelength Spectrometer (SWS) onboard this satellite (de Graauw et al. 1996) covers the infrared spectrum from 2.38 to 45.2 μm. In its grating mode, the maximum spectral resolution varies between 1000 and 2000. Planetary nebulae were among the first targets to be observed with the instrument in its performance verification phase. This paper reports results on three nebulae observed early in the mission: NGC 6543, NGC 7027 and NGC 6302.

The SWS has an unprecedented contiguous wavelength coverage in the infrared. Its wavelength range includes the low-order lines of the Brackett and Pfund series, He II lines, many lines of the hydrogen molecule, and many ionic fine-structure lines with powerful diagnostic value for the physical conditions in the nebulae. In addition, the SWS range includes the solid state features attributed to Poly-Aromatic Hydrocarbons (PAHs). The wavelength range between 30 and 45 μm, which is new territory, shows interesting solid-state emissions tentatively attributed to crystalline silicates such as pyroxene and olivine.

[1]Based 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.

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This paper gives an overview of the papers on planetary nebulae prepared by the SWS consortium for the ISO-dedicated volume of *Astronomy and Astrophysics.*

2. The observations

All three nebulae were measured with the low-resolution AOT SWS01 procedure (de Graauw et al, 1996), in its slowest mode. This mode reduces the spectral resolution to values around 1000. NGC 6543 and NGC 7027 were observed on 11 December 1995, in measurements aimed at validating the observing procedures. NGC 6302 was measured in the SWS guaranteed-time programme, on 19 February 1996. The observations were reduced with the SWS Interactive Analysis system. This mostly uses modules that are also part of the routine "pipeline" software, but allows to handle dark-current problems, glitches and detector memory effects more efficiently than the automated "pipeline" can. The data have been smoothed to a final resolution of about 600.

The wavelength calibration is described by Valentijn et al. (1996). The photometric calibration, which is still being improved, is described by Schaeidt et al. (1996). The photometric calibration accuracy of the data presented in this paper is better than 30 %.

The data have some limitations, which should disappear as the calibration of the spectrometer is refined. Some are obvious in the spectra. The wavelength range of the SWS is divided into 12 bands, each of which is observed with a different combination of aperture, spectral order and detector array. At some of the band limits there are obvious discontinuities in the spectra. These can be caused by dark-current variations, by hysteresis in the detectors and by aperture effects (at 13 μm, at 27.5 μm and at 29 μm the effective aperture changes significantly, increasing from 14″ by 20″ to 20″ by 39″). The underlying calibration measurements on celestial targets are sensitive to the same problems. The relative calibration of the range between 27.5 and 29.0 μm is so uncertain that this range is not shown in this paper.

Between 12 μm and 29 μm, the spectra show fringes, arising from resonances in detectors or in filters. In principle the calibration procedure should remove these fringes, but the fringe depth depends on how the source fills the entrance slit and also on dark-current errors. Fringes at shorter wavelengths are not visible at the spectral resolution presented here.

There are still some questions on the reliability of the SWS line fluxes. Some fluxes differ more from earlier results (KAO, IRAS-LRS) than would be expected from the estimated calibration uncertainties. A possible source of error could be unresolved fringes. Such fringes could modulate line inten-

sities and affect the line-to-continuum ratio. The real test for such effects is to re-observe objects at a different radial velocity, making use of the annual variation of the earth's velocity towards the target.

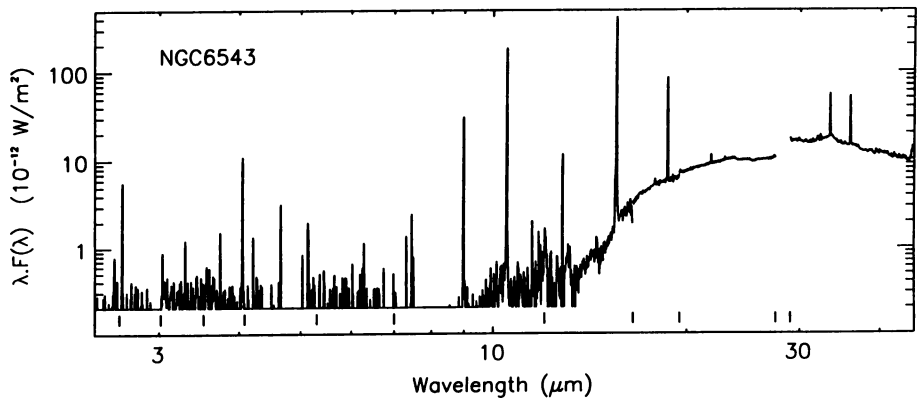

Figure 1. The SWS spectrum of NGC 6543. SWS bands are marked. Below the clipping level no reliable data can be presented

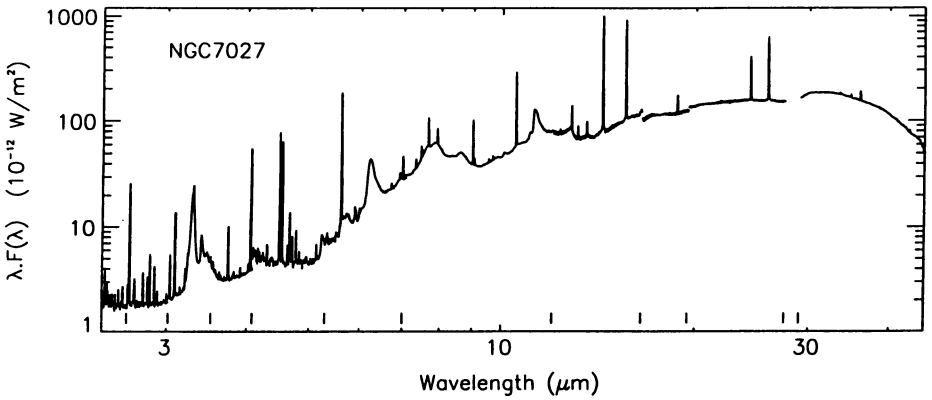

Figure 2. The SWS spectrum of NGC 7027. SWS bands are marked.

3. Solid-state features

NGC 7027 is a C-rich Planetary Nebula, as witnessed by the many PAH features in its spectrum, between 3.3 and 18 μm (see fig 2). Beintema, van den Ancker et al. (1996) present these features in the spectrum of NGC 7027 and in two other C-rich objects, the post-AGB star HR 4049 and the planetary nebula IRAS 21282+50. 24 emission bands are identified

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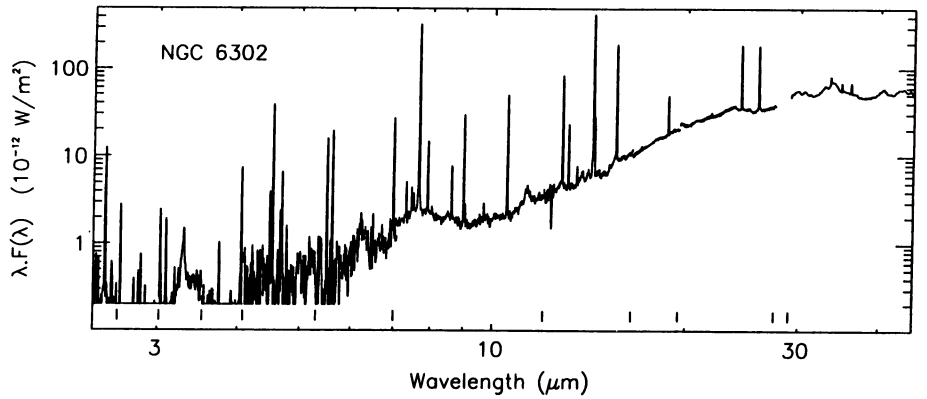

Figure 3. The SWS spectrum of NGC 6302. SWS bands are marked. Below the clipping level no reliable data can be presented

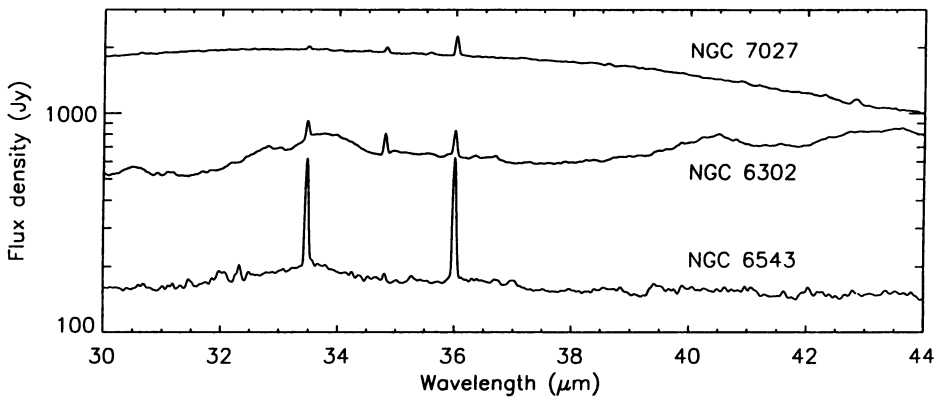

Figure 4. The SWS 30 - 44 μm spectra

in NGC 7027, giving a unique overview at a high signal-to-noise ratio. The differences between the 3 PAH spectra are discussed and interpreted by Molster et al. (1996). In HR 4049, the features around 8 μm dominate the PAH spectrum. In IRAS21282+50 and in particular in NGC 7027, the 11-μm feature and the adjoining plateau out to 13 μm are relatively stronger. The differences are interpreted in terms of excitation (very high in HR 4049) and molecule size (larger for the PN's).

NGC 6302, (fig. 3) is an O-rich planetary nebula, but it shows PAH features, although much weaker than in NGC 7027. The PAH spectrum of this nebula appears to be similar to that of HR 4049. NGC 6543 (fig. 1) shows no sign of PAHs.

Both NGC 6543 and NGC 6302 show spectral structure in the 30-45 μm

range, which is not present in NGC 7027 (fig. 4). Waters et al. (1996) tentatively identify the most prominent emission bumps with crystalline silicates (fosterite at 32.8 μm, olivine near 33.6 μm, pyroxene near 40.4 μm). Similar emission is found from other O-rich dust shells (the AGB W Hya, the RSG NML Cyg, the post-AGBs AFGL 4106 and HD 179821).

The structure seen in NGC 6543 and in NGC 6302 between 22 and 25 μm is remarkably similar. It is absent in NGC 7027 and there is no matching pattern in the SWS spectral responsivity, so these features are probably real. As yet, they are unidentified.

TABLE 1. Fine-structure lines

Ion	Wavelength	Nebulae			Ion	Wavelength	Nebulae		
[Si VII]	2.584			c	[Na IV]	9.041		b	
[Al V]	2.905		b		[Fe VII]	9.527		b	
[Mg VIII]	3.028			c	[S IV]	10.51	a	b	c
[K VII]	3.190		b		[Ca V]	11.48	a		
[Ca IV]	3.207		b		[Co III]	11.89		b	c
[Mg IV]	4.487		b	c	[Ni II]	12.73			c
[Ar VI]	4.530		b	c	[Ne II]	12.81	a	b	
[Na VII]	4.685		b	c	[Ar V]	13.10		b	c
[Mg VII]	5.503			c	[Mg V]	13.52		b	c
[Mg V]	5.610		b	c	[Ne V]	14.32		b	c
[K IV]	5.982	a	b		[Na VI]	14.40			c
[Si VII]	6.493			c	[Ne III]	15.56	a	b	c
[Ar II]	6.985	a	b	c	[S III]	18.71	a	b	c
[Na III]	7.318	a	b	c	[Ar III]	21.83	a		
[Ne VI]	7.652		b	c	[Ne V]	24.32		b	c
[Fe VII]	7.814			c	[O IV]	25.89		b	c
[Ar V]	7.902		b	c	[S III]	33.48	a	b	c
[Na VI]	8.611			c	[Si II]	34.82		b	c
[Ar II]	8.991	a	b	c	[Ne III]	36.01	a	c	c

a = NGC 6543, b = NGC 7027, c = NGC 6302

4. Line spectra

As explained above, the interpretation and publication of the line spectra has been delayed by calibration uncertainties. Although in the mean time many line detections have passed internal consistency checks (comparing fluxes in overlapping bands and in lines observed with the Fabry-Pérot in

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SWS) the quality of the line fluxes needs further confirmation from additional calibration measurements.

A first interpretation of the line spectrum of NGC 7027 by Pottasch et al. (1996) leads to the conclusion that the observed line fluxes indicates that the central star is at a temperature between 350,000 and 400,000 K; the observed fluxes are consistent with a photo-ionization model.

In NGC 7027 (Beintema, van Hoof et al., 1996), the flux in the [Ar VI] line at 4.53 μm was found to be 5 times higher than an upper limit observed with the KAO in 1981 (Beckwith et al, 1984). The increase is hard to explain, but could indicate an increase in the effective temperature of the central star.

In NGC 6543 (Beintema et al., 1996b) the absence of the [O IV] 25.89 μm line is striking. The ionization threshold of 54.9 eV is comparable to the 47.3 eV required to produce the observed [Na III] line. An explanation of the absence of the [O IV] line may be found in a steep drop of the emission of the central star beyond the He II limit.

Table I lists the fine-structure lines observed in the three nebulae. For most of the lines SWS measurements have yielded improved wavelengths (Feuchtgruber et al., 1997).

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