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The ISO/LWS spectrum of the Egg nebula, AFGL 2688 ⋆

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Abstract. We present an ISO Long Wavelength Spectrometer (LWS) grating spectrum of the carbon-rich proto-planetary nebula AFGL 2688 between 43 and 194 μm. The far-infrared spectrum of AFGL 2688 is dominated by strong rotational transitions of CO which are detected from J=14–13 up to J=23–22. The atomic fine structure lines [O I] and [C II] are not detected. This is consistent with the cool central star of AFGL 2688 not having yet photodissociated the molecular gas ejected during the AGB phase. The far-infrared CO emission in AFGL 2688 appears to originate in shocked dense gas at a temperature of $\sim$ 400 K.

Key words: planetary nebulae: general — planetary nebulae: individual (AFGL 2688) — interstellar medium: molecules

1. Introduction

AFGL 2688 (the "Egg nebula") is one of the rare sources known to be in the rapidly evolving transition from the AGB to the planetary nebula phase. First reported by Ney et al. (1975), AFGL 2688 has been since the subject of numerous observational and theoretical investigations (Latter et al. 1993; Skinner et al. 1996; Cox et al. 1996 and references therein). AFGL 2688 is thought to have evolved from the AGB phase about a hundred years ago (Jura and Kroto 1990). It is a bright infrared source with a bipolar optical and near-infrared nebula scattering the light of the cool central star (F5 supergiant, $T_{\rm eff}$ $\sim$ 6500 K - Crampton et al. 1975). The optical (HST image) and near–infrared (Latter et al. 1993) appearance of AFGL 2688 can be explained by an equatorial torus lying in the east-west direction (Nguyen-Q-Rieu et al. 1986) with the bipolar axis aligned north-south along the reflection nebula. Single-dish measurements in millimeter lines reveal a nearly circular, cold and dense component tracing the slowly expanding AGB envelope, which is shocked by a warm, optically thin, fast wind (Young et al. 1992). The transitory nature of AFGL 2688 is also seen in the

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dust content of this source which displays in the near- and mid-infrared peculiar dust bands attributed to aliphatics and carbon-rich aggregates (Buss et al. 1993; Omont et al. 1995). ¿From KAO observations, the detection of three high rotational lines of CO (13–12, 17–16 and 22–21 transitions) has recently been reported (Justtanont et al. 1996).

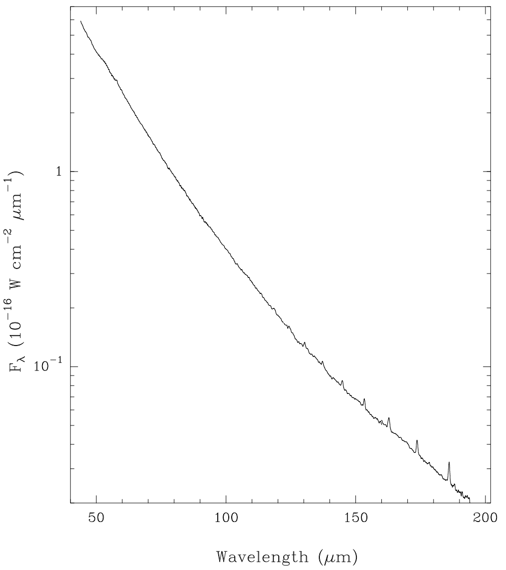

Fig. 1. The ISO LWS spectrum of AFGL 2688 between 43 and 194 μm

This letter presents a grating spectrum of AFGL 2688 between 43 and 194 μm obtained with the LWS on board the Infrared Space Observatory (ISO; Kessler et al. this volume). The LWS instrument and the calibration procedures are described by Clegg et al. and by Swinyard et al. (this volume), respectively.

Table 1 CO and HCN far-IR lines in AFGL 2688

λ_{obs} μm	Flux 10^{-19}W cm^{-2}	Molecule	λ_{vac} μm	Transition
188.16	0.52±0.08	HCN	188.153	J=18-17
185.986	3.84±0.16	CO	185.999	J=14-13
178.27	0.55±0.07	HCN	178.276	J=19-18
173.677	3.57±0.15	CO	173.631	J=15-14
162.816	3.95±0.18	CO	162.812	J=16-15
153.358	3.50±0.16	CO	153.267	J=17-16
144.784	3.65±0.24	CO	144.784	J=18-17
137.134	3.78±0.28	CO	137.196	J=19-18
130.306	3.38±0.44	CO	130.369	J=20-19
124.309	3.64±0.40	CO	124.193	J=21-20
118.576	4.01±0.50	CO	118.581	J=22-21
113.458	3.22±0.35	CO	113.458	J=23-22

2. Observations and results

The LWS grating spectrum of AFGL 2688 was measured during the Performance Verification Phase of ISO in revolution 27 (December 14, 1996), using a non-standard LWS observation mode (COIF). Three observations were made, and during each of them five grating scans were taken with two 0.5 sec integration ramps at each commanded grating position. The spectra were over-sampled, at 1/15 of a resolution element, the latter being 0.3 μm in second order of the grating (detectors SW1–SW5; $\lambda \leq 93\,\mu$m) and 0.6 μm in first order (detectors LW1–LW5; $\lambda \geq 80\,\mu$m). The total on-target time was 15669 sec. The flux calibration of the spectra is relative to Uranus. The overlaps in wavelength between the ten detectors have been used to apply small scaling factors (0.9–1.15) such that the sub-spectra joined smoothly to yield a continuous spectrum from 43 to 194 μm.

The complete LWS grating spectrum after merging the sub-spectra from the ten detectors is displayed in Fig. 1. The smooth and strong continuum is well fitted with dust emission at a temperature of 100 K, adopting an emissivity coefficient $\beta = 1$ (Knapp et al. 1993). The continuum peaks at wavelengths shorter than 50 μm (about 30 μm - see Omont et al. 1995) and decreases at longer wavelengths by more than two orders of magnitude in F_λ within the LWS range. The continuum level around 50 μm is within a few percent of the continuum level measured on the KAO by Omont et al. (1995). On top of the continuum, many lines are clearly seen, particularly at the longer wavelength end where the continuum emission is weakest. To illustrate the line content of AFGL 2688, the continuum subtracted spectrum between 104 and 194 μm is shown in Fig. 2. The strongest lines correspond to the CO rotational lines. Table 1 lists the wavelengths and fluxes of the lines detected, together with their identifications. We note that the 17–16 and 22–21 CO line fluxes are a factor 2 lower than the fluxes given by Justtanont et al. (1996).

The spectrum of AFGL 2688 only contains lines from molecular species. Ten CO pure rotational lines have been detected, from J=14–13 up to J=23–22. The CO lines are strong and do not show a fast drop in the intensity levels over the rotational ladder. Besides the rotational lines of CO, we report marginal detections of two lines of HCN in the $\nu = 0$ vibrational state (J=18–17 and 19–18). These lines are weaker than the CO lines by a factor of 7, a situation which is very different to what is observed in IRC+10°216 where the HCN line strengths are comparable to CO (Cernicharo et al., this volume). The atomic fine-structure lines of [O I] and [C II] which become the dominant emission lines during the PN stage, as in NGC 7027 (Liu et al., this volume), are not detected in AFGL 2688. For example, the [O I] 63 μm fine-structure line is not seen to a level of a few $10^{-19}\,\mathrm{W\,cm^{-2}}$. These findings, which indicate that the entire reservoir of CO molecules is still intact, are consistent with the fact that

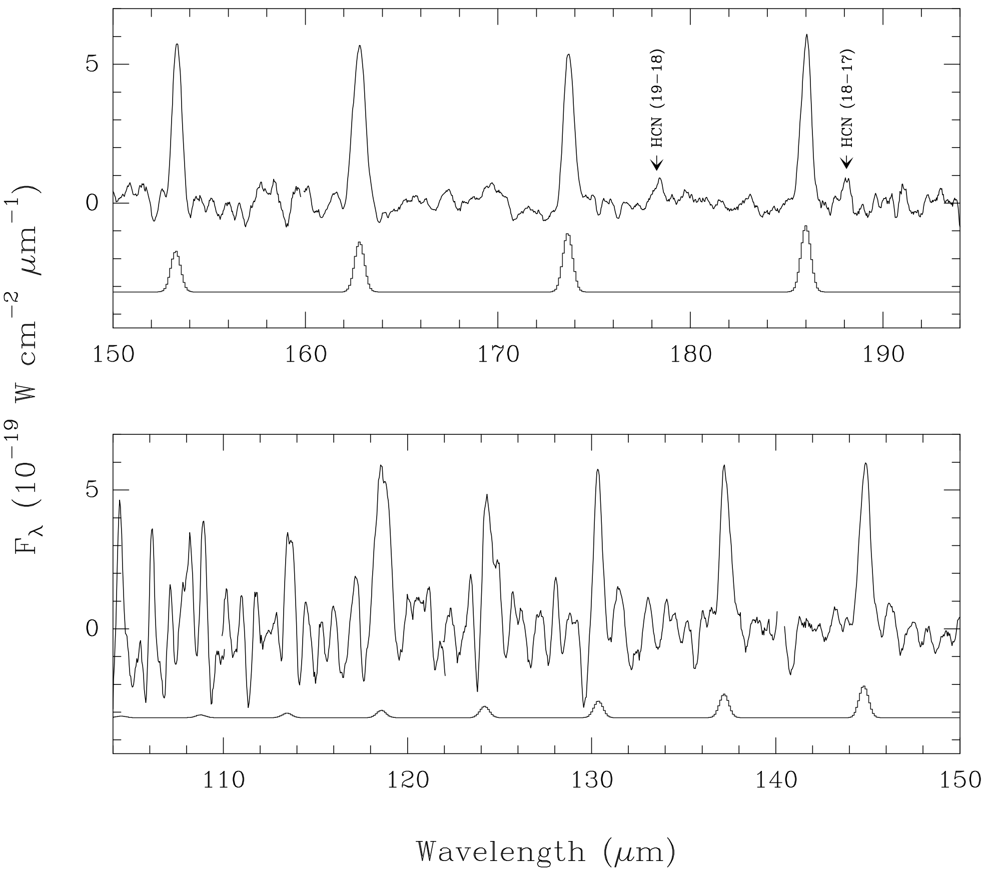

Fig. 2. The continuum subtracted spectrum of AFGL 2688 shown from 96 to 193 μm. The expected CO lines in the case of the AGB-wind model are shown as a histogram. An offset has been introduced to the model for clarity. In this model $R_{int} = 10^{16}$ cm - see text for the other adopted model parameters. Clearly such a model is not able to reproduce the observed spectrum

in AFGL 2688 the central star is still too cool to ionize and/or photodissociate the molecular envelope ejected during the AGB phase.

3. Discussion

We present in the following two models in order to investigate the origin of the far-infrared CO emission from AFGL 2688. The first model assumes a spherical envelope with an r^{-2} density profile, i.e. an AGB-wind model. The second model explores the contribution of the shocked molecular gas which is traced by the H_2 near-infrared lines. It will be shown that the far-infrared CO lines most likely originate in warm and dense shocked gas.

3.1. AGB-wind model

In order to compute the line intensities in CO we have made Large Velocity Gradient (LVG) models which include the 40 lowest rotational levels of CO in the v=0 and v=1 states. The rotational and vibrational radiative excitation of CO is supposed to be due to the radiation field of the cool central star (we also took into account the dust emission). The excitation of CO is by collisions with H_2 and He - with the rate coefficients between the v=0 and v=1 states derived from SiO (Bieniek & Green 1983) after correction for the reduced mass. The model parameters have been adopted from Truong Bach et al. (1990): a mass loss rate of $1.7 \times 10^{-4}\,M_\odot yr^{-1}$, a CO inner abundance relative to H_2 of $X(CO) = 6.0 \times 10^{-4}$, a terminal velocity of $19.5\,kms^{-1}$ and a distance of 1 kpc. These parameters fit very well the J=1–0 and 2–1 millimeter lines in AFGL 2688 (Truong-Bach et al. 1990). No photodissociation by the interstellar radiation field has been considered since the $J \geq 13$ lines detected by the LWS originate deep in the envelope, at radii less than 10^{17}cm, so the CO abundance has been kept constant with radius. Due to the high mass loss rate from the star, rotational levels are close to thermalization across most of the region where the lines are formed. The results are sensitive to the profile of the kinetic temperature (T_{kin}) and to the inner radius of the envelope (R_{int}). For T_{kin}, we have adopted a dependence $T_{kin} = T_{int}\,(R_{int}/r)^{\alpha}$ with $\alpha = 0.65$, normalized so that at $r = 2\,10^{16}$ cm $T_k = 150$ K. In accordance with the inner boundary of the dust distribution derived from

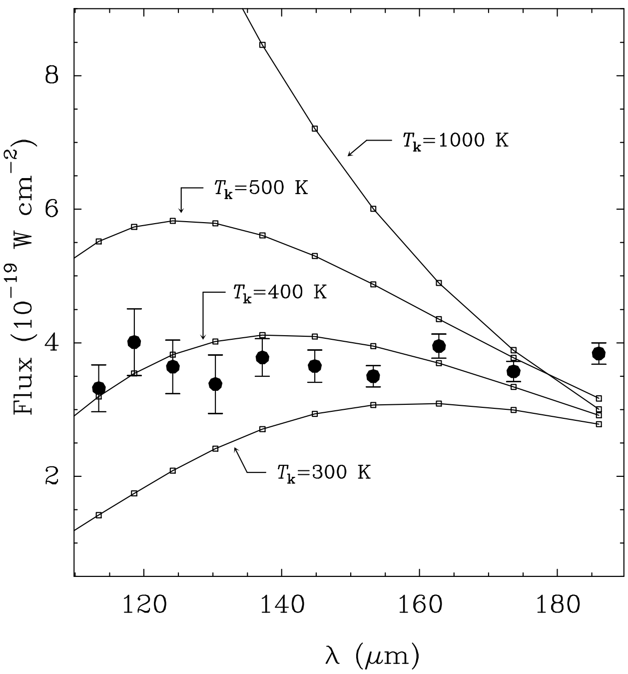

Fig. 3. The expected contribution of shocked gas for various kinetic temperatures (T_K). The curves show the expected CO lines fluxes as a function of the wavelength of the rotational transition. The observed LWS points are shown as filled circles. See text for the adopted model parameters

mid-infrared data (Jura & Kroto 1990), we have adopted $R_{int} = 10^{16}$ cm (see also Jaye et al. 1989).

With the above parameters and a simple spherical geometry, it is not possible to reproduce the far-infrared CO emission from AFGL 2688 (Fig. 2). The temperature of the emitting region is far too low to account for the observed line fluxes. This is a consequence of the adopted value of R_{int}. In order to reproduce the line fluxes of all the far-infrared CO lines in AFGL 2688, the inner radius should have a value of $5\,10^{14}$ cm which is incompatible with the dust temperature of ~ 200 K derived from mid-infrared data (Jaye et al. 1989). Thus we conclude that the above model cannot explain the infrared CO lines observed in AFGL 2688, unless the kinetic temperature is strongly underestimated, which is unlikely.

3.2. Shocked molecular gas

Observations show evidence of high velocity and dense shock-heated molecular gas in AFGL 2688 via the millimeter and submillimeter (mm/submm) CO line wings (Young et al. 1992) and the near-infrared lines of H2 (Cox et al. 1996). The slowly expanding AGB molecular envelope is shocked by the warm, optically thin, fast wind from the central star. The contribution of such a region of dense warm shocked gas could dominate the CO high rotational transitions (e.g., Hollenbach & McKee 1989).

In order to estimate the contribution of shocked gas to the far-infrared CO emission in AFGL 2688, we have considered the following simple model: the size of the shocked region has an angular radius of 3 arcsec, a radial CO column density of $6.9\ 10^{17}\,\mathrm{cm}^{-2}$, a turbulent velocity of 60 km s^{-1} and a pre-shock density of 10^7 cm^{-3}. We kept the kinetic temperature (T_k) as a free parameter. The results are shown in Fig. 3 where we plot the expected CO line fluxes as a function of the wavelength of the rotational transitions for different values of T_k. The data points (shown as filled circles) are well fitted with $T_k \sim 400$ K. This implies a total mass of shocked molecular gas of $5\ 10^{-3}\ M_\odot$ which should be compared with the total mass of $1.6\ 10^{-2}\ M_\odot$ as derived from millimeter studies (Young et al. 1992). The contribution of the shock model predicts line fluxes of 2.2, 11.3 and 36.5 K km s^{-1} in the 2–1, 3–2, and 4–3 CO transitions, respectively, which are lower than the values found for the high-velocity wings observed at mm/submm wavelengths (Young et al. 1992). The results of this simple model are in accordance with the results presented in Justtanont et al. (1996). In their model, however, the gas cools mainly via the [O I] 63 μm line which is not detected in the LWS spectrum. This could be a consequence of the carbon-richness of this proto-planetary nebula.

In conclusion, the molecular gas in AFGL 2688 is heated by shocks and mainly cools via the near-infrared ro-vibrational H_2 and far-infrared CO rotational lines. Further LWS Fabry-Perot measurements will be useful to measure the velocity width of the strong CO far-infrared lines detected in AFGL 2688.

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