Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution
Proceedings IAU Symposium No. 323, 2016
X. Liu, L. Stanghellini & A. Karakas, eds.

doi:10.1017/S1743921317000898

Spitzer IRS spectroscopy of planetary nebulae

G. Ramos-Larios[1], M. A. Guerrero[2], H. Mata[1], X. Fang[3], A. Nigoche-Netro[1], J. A. Toalá[4] and G. Rubio[1]

[1]Instituto de Astronomía y Meteorología, CUCEI, Universidad de Guadalajara, Av. Vallarta No. 2602, Guadalajara, Jalisco, Mexico
email: gerardo@astro.iam.udg.mx

[2]Instituto de Astrofísica de Andalucía, IAA-CSIC, C/ Glorieta de la Astronomía s/n, 18008 Granada, Spain

[3]Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong

[4]Institute of Astronomy and Astrophysics, Academia Sinica (ASIAA), Taipei 10617, Taiwan

Abstract. We present *Spitzer Space Telescope* archival mid-infrared (mid-IR) spectroscopy of a sample of eleven planetary nebulae (PNe). The observations, acquired with the *Spitzer* Infrared Spectrograph (IRS), cover the spectral range 5.2-14.5 μm that includes the H_2 0-0 S(2) to S(7) rotational emission lines. This wavelength coverage has allowed us to derive the Boltzmann distribution and calculate the H_2 rotational excitation temperature (T_{ex}). The derived excitation temperatures have consistent values $\simeq$900$\pm$70 K for different sources despite their different structural components. We also report the detection of mid-IR ionic lines of [Ar III], [S IV], and [Ne II] in most objects, and polycyclic aromatic hydrocarbon (PAH) features in a few cases.

Keywords. Planetary nebulae: general — ISM: lines and bands — infrared: general

1. Introduction

Mid-infrared (mid-IR) spectroscopy is a powerful tool for the study of the thermal and molecular emission from PNe, since such observations are much less affected by dust extinction. Mid-IR studies of PNe have focused on imaging surveys, but mid-IR spectroscopy of PNe has only been carried out for individual objects for which chemical abundances and H_2 excitation temperatures were obtained. Currently, mid-IR studies of the excitation temperature of H_2 in PNe are scarce.

2. Results

Our analysis of archival *Spitzer* IRS SL1 and SL2 spectra of a sample of PNe has identified ionic transitions including [Ar III], [Ne II], [Ne V], and [S IV] (see example in Figure 1-left). The detection of emission lines from species of neon and argon imply that the progenitor stars of the PNe were all at least second-generation stars.

The broad PAH feature centred at 11.30 μm is detected in a number of PNe in this sample. The feature is present in the spectra of NGC 2440, NGC 3132, NGC 6445, NGC 6537, NGC 6720 and NGC 6781. There is a possible detection in NGC 2346, but it is absent in M 2-51, NGC 2818, NGC 6072 and NGC 7293.

Using the integrated flux of each H_2 line from the spectrum of each object we calculate the population levels. The population diagram with the upper temperature for

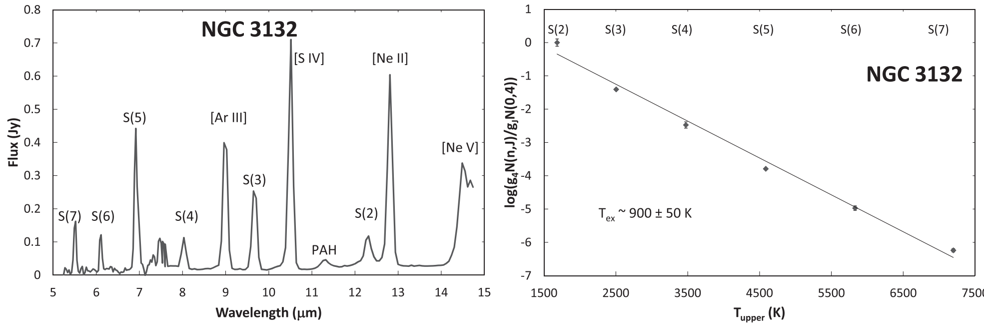

Figure 1. *(left) Spitzer* mid-IR (SL1 + SL2) spectrum of NGC 3132, with H_2 and some ionic lines identified. *(right)* The mean variation in H_2 populations for the $\nu = 0$-0 S(2)-S(7) transitions is represented in the excitation diagram for NGC 3132. The results are based on averages of line strengths for spectral selected positions (error bars are included).

the energy level of each transition is shown in (Figure 1-right). The data points in this figure show a linear trend. Since all the data points correspond to a unique transition ν, this linear trend cannot be directly interpreted as a thermal distribution of the population of the energy levels of the H_2 molecules. At any rate, the negative inverse of the slope of the linear fits can be used to measure the rotational H_2 excitation temperature, T_{ex}(rot). These temperatures shed light on the purely rotational component of the excitation temperatures to complement the rotational-vibrational studies obtained by near-IR observations.

3. Conclusions

We present an investigation of archival *Spitzer* IRS spectra of a sample of PNe to search for mid-IR H_2 lines (see, Mata *et al.* 2016, for complete information). Among the original sample of 14 PNe with useful *Spitzer* IRS SL observations known to exhibit H_2 emission lines in the near-IR, 11 PNe show detectable mid-IR H_2 lines. This result increases the number of known PNe with mid-IR H_2 emission lines from three (NGC 6302, NGC 6781, and NGC 7293) to twelve.

The spectral analysis detects all the H_2 0-0 transitions from the S(2) to the S(7) lines. Among these lines, the H_2 0-0 S(3) λ9.66 μm line is the brightest. The analysis of the population distribution in the H_2 molecules of these PNe reveals a T_{ex}(rot) excitation temperature of $\simeq$900 K for all of them. The conspicuous uniformity of the excitation temperature is intriguing, because the observations trace different morphological features of a non-uniform sample of PNe with different morphologies and evolutionary stages.

Ionic lines of [Ar III], [S IV], [Ne II], and [Ne V] are also detected. Their line intensities show the expected positive correlation of the [Ne V]/[Ne II] line ratio with the CSPN effective temperature. On the other hand, the anti-correlation between the [Ar III]/[Ne II] and CSPN effective temperature is not expected and may imply changes in the elemental ratios that suggest that PNe with hottest CSPNe, probably descending from more massive progenitors, are able to produce neon.

Reference

Mata, H., Ramos-Larios, G., Guerrero, M. A., *et al.* 2016, *MNRAS*, 459, 841