

Review

# Infrared Observations of Planetary Nebulae and Related Objects

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**Abstract:** In this paper, I present how near and mid-infrared observations can be used for the study of planetary nebulae and related objects. I present the main observing techniques, from the ground and space, highlighting main differences and how they can be complementary. I also highlight some new observing facilities and present the infrared observatories of the future to show that the future of infrared observations of planetary nebulae is bright.

**Keywords:** planetary nebulae; infrared observations; observatories

## 1. Introduction

The earth's atmosphere is a great asset for humans, but not necessarily for infrared astronomers. Molecules, mainly water, carbon dioxide and ozone, absorb infrared radiation from space, making ground-based infrared observations difficult. Carbon dioxide and methane are more or less evenly distributed over the planet, which is not the case for water. Water abundances can be lower on some places, that is why many infrared observatory are on the top of dry mountains or onboard planes such as the Kuiper Airborne observatory [1] from the 1970s to the mid 1990s and now SOFIA (Stratospheric Observatory for Infrared Astronomy) [2]. Because these molecules prevent radiation at some infrared wavelengths from reaching us, ground-based infrared astronomy can only be achieved in some atmospheric windows (Table 1). As the science with the James Webb Space Telescope (JWST) and far-infrared space missions is covered in this volume, I will not cover this topic here.

**Table 1.** This table lists the wavelength ranges and names of the different near and mid-infrared observing bands.

Wavelength Range	Band
1.1–1.4 microns	J
1.5–1.8 microns	H
2.0–2.4 microns	K
3.0–4.0 microns	L
4.6–5.0 microns	M
7.5–14.5 microns	N
17–25 microns	Q

## 2. Physical Processes and Observing Techniques

The near and mid-infrared wavelength domains enable the study of a rather large variety of physical processes:

- Dust emission and scattering;
- Gas emission (via lines such as H<sub>2</sub>, CO, Br<sub>γ</sub>, Ne II etc ...);

- Gas absorption (CO, C<sub>3</sub>, C<sub>2</sub>H<sub>2</sub> ...);
- Emission from large molecules/dust (PAHs, fullerenes, 21/30 microns features carriers ...).

Most of the modern telescopes are equipped with IR instruments enabling observations with a large variety of techniques:

- Imaging (with and without adaptive optics);
- Spectroscopy (Long slits, multi-object spectrographs, integral field units ...);
- Polarimetry;
- Interferometry.

In the forthcoming sections, I will describe how these techniques (and combinations of them) can be applied to the study of planetary nebulae (PNe) and related objects.

### 3. Space vs. Ground Based Infrared Astronomy

Space-based IR observations have two obvious advantages with respect to observations from the ground: the sensitivity and the possibility to observe at all IR wavelengths.

Sensitivity from space in the IR is orders of magnitudes better than from the ground, so that there will be some dichotomy between targets observable from the ground and with the future James Webb Space Telescope.

Building infrared observatories on the ground makes it possible to reach larger mirrors diameters (up to 40 m with the forthcoming Extremely Large Telescopes (ELTs)) or interferometers. The main advantage of ground-based observations is thus to reach angular resolutions. The spatial resolution of ground-based interferometers can be more than 10 times sharper than the JWST, the IR space telescope with the largest aperture to date, but it can only observe bright targets.

In the forthcoming sections, I will highlight a few uses of space and ground-based observations of PNe, and also show how these can be combined.

### 4. Space-Based Spectroscopy and Imaging

Spectroscopy has been widely used to study evolved stars with space telescopes such as IRAS, then ISO and Spitzer.

Space missions lead to the first global studies of dust around evolved stars. Some key results include the study of oxygen-rich dust (silicates) [3] and carbon-rich dust (amorphous carbon, SiC [4]) around AGB stars and PNe. Space-based spectroscopy also led to the discovery of dual-dust chemistry objects [5,6]. While there is usually a dichotomy between carbon and oxygen-rich evolved stars, some objects display both carbon and oxygen features. This can be due to the formation of a long-lived circumbinary disc while the star was oxygen-rich, followed by a carbon-rich outflow once carbon has been dredged-up to the surface of the star [5]. A recent dredge-up, not necessarily with the presence of a disc, could also explain some dual dust-chemistry objects [7]. Some PNe in the bulge also appear to be dual-dust chemistry objects, but their central stars are O-rich. The dual-dust chemistry of these objects can be explained by photodissociation of CO in a dense torus, leading to hydrocarbon chains formation [8,9]. A broad feature, centred around 21 micron was also discovered around some carbon-rich post-AGB stars, and its carrier is still unidentified [10]. A 30 micron feature was also discovered around some carbon-rich objects and is often associated to MgS emission [11]. Fullerenes, large C<sub>60</sub> and C<sub>70</sub> molecules, have also been discovered thanks to a PN observations with the Spitzer Space Telescope [12].

The first observations with IRAS enabled to study evolved stars in the Milky Way up to the Magellanic Clouds [13], while Spitzer observations led to the first spectra of evolved stars in the Magellanic Clouds [14–16]. Spitzer also observed evolved stars up to 1.5 Mpc in photometry and 140 kpc [17] in spectroscopy [18]. Studies of evolved stars in other galaxies have two main interests. As the distances of the galaxies are well known, and assuming all stars in the studied galaxies are

at that distance, one can get a better quantitative estimate of their luminosities, mass-loss and dust productions rates. This enabled studies of the global dust production [19,20] in the Magellanic Clouds. The other main interest is that, by studying evolved stars in galaxies with different metallicities, one can study the effect of metallicity on dust formation and mass loss. This was done rather extensively with the Spitzer Space Telescope. It revealed that carbon-rich dust, due to its high opacity, is essential to trigger the superwind at the end of the AGB phase [21]. AGB stars, PNe precursors, do lose mass at metallicities as low as 1/25 of the solar luminosity [22]. Spitzer observations also revealed a very broad variety of dust properties for post-AGB stars in the Magellanic Clouds [23].

Space-based spectroscopy can also be used to study element abundances in PNe. There is less extinction, and many ionic lines of Ar, Ne and S, so no ionization correction factors (ICFs) are needed [24]. Less ionic stages are observed in the optical, so that one needs either these ICFs or multiwavelength observations to determine abundances. Spitzer spectra of planetary nebulae towards the Galactic anti-center (8–21 kpc away) enabled abundances determination using these lines. As these elements are not affected by stellar evolution, their abundances can help us estimate the composition of the gas in which they formed. These observations in the Galactic anti-center show that these elements are less abundant than in the solar neighbourhood, which is consistent with a metallicity gradient between the solar neighbourhood and the Galactic anti-center.

## 5. Ground-Based Infrared Observations

As mentioned before, the main strength of ground-based observations is the angular resolution (down to  $\sim 0.3''$  at 10 microns for a 8 m class telescope, and a few milliarcsecs at the same wavelength for an interferometer like the VLTI). Infrared imaging surveys of such objects have been conducted both in the near [25] and mid-infrared [26]. One has then to keep in mind that the observed morphology may depend on the wavelength, as mid-infrared observations of such objects reveal direct dust emission, while in the near-IR, we are more sensitive to dust scattered light [27], and also reach a better angular resolution.

The shaping mechanism of PNe are not yet fully understood [28]. The angular momentum needed to shape the winds of PNe is certainly provided by a binary companion that can lead to the formation of bipolar outflow after, e.g., common envelope evolution [29]. The angular resolution of ground-based observations, combined with the low optical depth in the IR can enable to study small scale structures in the heart of PNe (such as discs and torii), and to resolve small nebulae, such as young post-AGB stars or pre planetary nebulae (pPNe). Infrared observations of post-AGB objects enable to study the morphology of PNe in the making, showing that no round pre planetary nebula is known [26]. The resolved targets can be divided into nebulae with a dense central core (in the form of a bright central source or a dark lane, resolved or no) that are either bipolar and multipolar and nebulae with no central core, with an elliptical morphology.

To peer into these cores, infrared interferometry is certainly the best tool, as it can study the very inner parts of PNe (down to a few AU), but this is limited to bright targets. Olivier Chesneau's pioneer work with infrared interferometry of PNe enabled the discovery of dusty discs/overdensities in the heart of PNe [30–35]. The discs resolved are relatively flat and have inner radii of about 10 AUs. The dust mass in these discs is of the order of  $10^{-5}M_{\odot}$ , which is small compared to the dust mass in the lobes of the PNe. These discs might be a kind of relic of an essentially polar ejection process [30].

Discs around post-AGB binaries have also been resolved with near and mid-infrared interferometry using the VLTI and instruments such as PIONIER and MIDI. These stars, which in a significant part are RV Tau stars, are binary post-AGB systems hosting a disc and mostly no circumstellar material outside this disc [36]. Infrared interferometry has been a key for the study of these objects, with a first detection of discs via MIR interferometry with MIDI/VLTI [37], confirming their presence suggested by the bimodal spectral energy distribution of these objects. The PIONIER/VLTI milliarcsec resolution image of IRAS 08544–4431 [38] is to date one of the most spectacular ever obtained of the heart of a dusty circumstellar disc, identifying a compact circumpanion

accretion disc, where the outflow very likely originates. Recent studies show that such studies can now be generalised to larger sample, and that imaging via IR interferometry can produce images of the central parts of post-AGB stars down to a few AUs of the central star(s) [39].

Integral field units spectrographs are great tools to map the distribution of molecular gas in PNe or PPNe. A great example is the SINFONI/ESO map (with adaptive optics) of molecular hydrogen around OH 231.8+4.1 [40], with the presence of H<sub>2</sub> around the center of the nebula and in clumps associated with shocks. This near-IR H<sub>2</sub> 1-0 line (at 2.12 μm) is, together with CO, one of the most common tracers of molecular gas in PNe. It can be excited via shocks or UV radiation. It is more common in bipolar PNe [41], where it is observed in dense clumps in equatorial regions. It is also observed to be embedded in ionized regions. High angular resolutions H<sub>2</sub> observations enable to map it precisely. An excellent example of such H<sub>2</sub> observations is the NIRI/GEMINI maps of the PN K 4\_47, where the H<sub>2</sub> emission is seen to come from the walls of a bipolar outflow, and also in a pair of low ionisation knots at the tip of the outflow [42]. This can be explained by the interaction of a bullet-like jet interacting with material ejected during the AGB phase. This confirms that the low ionisation structures observed in PNe are made of a combination of H<sub>2</sub> and ionised material, and are thus mini photodissociation regions. Combining NIR observations with adaptive optics, such as, e.g., GMAOS/Gemini, one can reach resolution down to 60 milliarcsec and exquisite images such as the one of NGC 2346 [43], showing that the molecular hydrogen emission is fragmented into clumps and cometary knots, with sizes of about 100 AU.

## 6. Combining Ground and Space-Based Observations

Space and ground-based observations can be complementary too. Space-based spectroscopy, thanks to its sensitivity and spectral coverage can help to detect features, that can then be spatially resolved from the ground. Since its discovery in laboratory in 1985 [44], fullerene (C<sub>60</sub>) was suspected to be abundant in space. The work of Jan Cami and his team lead to its identification in the PN Tc 1 [12], and we now know that it is present in a large variety of objects [45]. These large carbon-bearing molecules are formed in evolved stars (primarily PNe) and are observed together with strong 6–9 μm and 11–13 μm plateaus and 30 μm features. The central stars of the fullerenes-bearing PNe have fairly low reddening, indicating that not much dust is present in the line of sight. One of the question that arises is how it is formed. To answer this question, ground-based observations are the key.

While space-based observation, combining sensitivity and spectral coverage, were key to discover fullerenes, ground-based observations, with their spatial resolution, can determine the physical conditions and origin of the different components. Ground-based spectroscopy, in the optical and near-IR simultaneously, measured the abundances, density and temperature structure of the nebula [46]. The double peaked lines reveal that Tc 1's expanding shell is an elongated ellipsoid seen nearly pole-on. Ground-based MIR images of the PN Tc 1, using narrow band filters, show that the fullerenes are distributed in a ring of radius ~5 arcsec around the central star. Fullerenes seems to be formed in high temperature, H-poor environments [45].

An alternative exists to achieve high sensitivity, spectral coverage and angular resolution: using telescope mounted on planes, such as SOFIA. A great example of this applied to PNe research is the work by Lizette Guzman-Ramirez and her collaborators [8,9]. During their late stages, dredge-up in low and intermediate mass stars can bring carbon to their surface, and eventually the star can turn from oxygen-rich to carbon-rich. Observations with the FORCAST infrared camera onboard SOFIA, reveal that the inner shell of the PN BD +30°3639 is C-rich, while the outer shell is O-rich [7]. These observations are evidences for a dredge-up event about 100 years ago. They would not have been possible without the spectral coverage achieved with SOFIA, together with its angular resolution.

## 7. The Future

I hope this proceedings convinced the reader that IR astronomy was a great asset to study the physics of PNe and related objects. Much more is to come with forthcoming instruments/telescope.

The most obvious one is the JWST that should be launched in the forthcoming years. Thirty meters class are also coming soon, with the European ELT under construction and that should see its first light in 2025. The three first light instruments will operate in the IR and will be great tools to study PNe. METIS, HARMONI and MICADO will be the three first generation instruments. METIS will be an imager and spectrometer operating between 3 and 20  $\mu\text{m}$ , with an Integral Field Unit (Spectral resolution up to 100,000) with a field of view of about 20 arcsec and a spatial resolution of 23 milliarcsec at 3.5  $\mu\text{m}$ . It will thus be an ideal tool to map dust and molecules around pPNe and PNe and understand dust formation around evolved stars. HARMONI will operate at shorter wavelengths (between 0.5 and 2.4  $\mu\text{m}$ ). It will be an integral field spectrograph with a field of view from 1 to 10 arcsec (resolution up to 20,000) and a spatial resolution of  $\sim 5$  milliarcsec. It will thus be ideal to map velocity fields, molecules spatial distribution and determine abundances for compact PNe. Finally, MICADO (Imaging and spectroscopy between 0.9 and 2.4  $\mu\text{m}$ ), with its field of view of about 1 arcmin, will reach sensitivities similar to the JWST, but with an angular resolution six times better (6–12 mas). It will be a great tool to map PNe's velocity fields, obtain spatially resolved abundances determination, and study PNe in the local group.

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