

The impact of future space observatories on planetary nebula research

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Abstract. A comparison between the past four decades of astrophysical space missions and those expected to be launched over the next decade shows a marked decrease in numbers. However, missions such as *Gaia* and the *JWST* are expected to have a major impact on planetary nebula research. The capabilities of these and other anticipated space missions are discussed.

Keywords. planetary nebulae: general, space observatories

1. Introduction

Like many other astrophysical fields, from the 1970's onwards planetary nebula research has benefited greatly from the availability of powerful space observatories operating at wavelengths from the X-ray to the infrared. Table 1 summarises, decade by decade, the principal past, current and planned general astrophysics space missions.

What are the prospects for the space observatories listed in Table 1 that are currently still fully operational? ESA's *Herschel Space Observatory* was launched in 2009 and current projections point to complete helium boil-off, and therefore the end of the mission, occurring in late-2012 or early-2013. For the *Hubble Space Telescope* the main components at risk are believed to be its complement of detectors, with current estimates suggesting a 50% probability by 2015/6 of catastrophic failure due to cumulative radiation damage.

At X-ray wavelengths, prospects for the current two observatories operating in space are mixed. NASA's *Chandra* observatory, launched in 1999, is expected to be able to stay operational until 2015/6, while the expectations for ESA's *XMM-Newton* observatory, also launched in 1999, are better - a recent review has concluded that it could remain operational till 2025.

While six to nine new observatories have been launched in each of the four decades since 1971, the prospects for the current decade appear bleaker at present, with only four new general astrophysics missions, *GEMS*, *Astrosat*, *Gaia* and the *James Webb Space Telescope (JWST)*, expected to have been launched by 2020.

Currently planned for launch in 2014, *GEMS*, the *Gravity and Extreme Magnetism Small Explorer*, will measure X-ray polarization in order to study spinning black holes and probe magnetic field around neutron stars. The other three missions, *Astrosat*, *Gaia* and the *JWST*, are discussed in more detail below.

2. The *Astrosat* Mission

Astrosat is an Indian Space Research Organisation mission for X-ray and UV/optical astronomy, scheduled for launch in 2012 and expected to have a lifetime in excess of 5 years. In addition to having four different X-ray instruments (see Table 2), it will also be equipped with two 40-cm telescopes for UV and optical imaging, each with an angular resolution of 1.8 arcsec and capable of measuring 20th magnitude objects in 1800s. There

Table 1. Past and Future Space Missions for General Astrophysics¹

Decade	X-ray	UV or Optical	Infrared	TOTAL
1971-1980	4 Ariel-5, SAS-3, HEAO-1, Einstein	4 TD-1, Copernicus, ANS, IUE	1 AFGL	9
1981-1990	3 Exosat, Ginga, ROSAT	2 Astron, HST	1 IRAS	6
1991-2000	4 ASCA, RXTE, Chandra XMM-Newton	3 EUVE, FUSE Hipparcos	2 ISO, MSX	9
2001-2010	1 Suzaku	1 GALEX	4 Spitzer , AKARI, Herschel, WISE	6
2011-2020	2 GEMS, Astrosat ~2014, 2012	2 Astrosat, GAIA 2012, 2013	(1) JWST 2018?	(5)
TOTAL	14	12	(9)	35
Post-2020	ATHENA?	WSO?	SPICA?	

¹ Missions with particular impact on planetary nebula research are boldfaced.

Table 2. *Astrosat* X-ray and UV/Optical Science Instruments

Instrument	Energy Range	Description	Ang. Res.	Sensitivity
SXT	0.3-8 keV	FOV=42'	3-4 arcmin	0.01 mCrab in 10 ⁴ s
LAXPC	2-80 keV	3 Prop. Counters	5 arcmin	0.1 mCrab in 10 ³ s
CZT	10-150 keV	Hard X-ray Imager	8 arcmin	0.5 mCrab in 10 ³ s
SSM	2-10 keV	Scanning Sky Monitor	5-10 arcmin	50 mCrab in 300s
UVIT	1300-5500 Å	Twin 40-cm Telescopes	1.8 arcsec	21st mag in 1800s

will be one broad-band far-UV filter (1300-1500 Å), four broad-band and two narrow-band near-UV filters, plus four broad-band filters in the 3000-5500-Å region. Further details are available at www.iucaa.ernet.in/~astrosat/. Given the very low number of space missions currently planned for the X-ray and UV/optical domains, *Astrosat* is a welcome additional resource, with potential interest for studies of PN central stars.

3. *Gaia*

Gaia is an ambitious ESA mission which aims to measure parallaxes and proper motions for one billion stars out to distances of 50 kpc. During its L2 five-year mission, beginning in 2013, it will survey the whole sky in order to achieve astrometric completeness down to $V=20$. Its gigapixel imaging system consists of 106 CCD sensors each with 1966×4500

pixels. Final positional accuracies will be 7, 20 and 300 μarcsec at $V = 10, 15$ and 20 , respectively. Distances accurate to 1% are expected to be obtained for 10^7 stars out to 2.5 kpc, as well as distances accurate to 10% for 10^8 stars out to 25 kpc. Many PN central stars will therefore have accurate distances available by the end of the *Gaia* mission. The most favourable cases will be for central stars in low surface brightness nebulae, i.e. old PNe, whereas central stars in higher surface brightness PNe will be more problematic (see below).

Gaia has twin telescopes, each with a with rectangular $1.49 \times 0.54\text{m}$ primary, with a fixed wide angle between their lines of sight (LOS). The mirrors in each telescope system are made of sintered silicon carbide, with enhanced silver reflective coatings to optimise their reflectivities in the 3200-10000 \AA region. The spacecraft will rotate around an axis perpendicular to the LOS's of the two telescopes, with a rigid frame of reference being obtained by measuring the relative positions of objects from both observing directions. Each object will be measured about 70 times during the 5-year mission.

Gaia will have three instruments: (1) an astrometric instrument dedicated to measuring the angular positions of stars with V magnitudes in the range 6-20; (2) a photometric instrument covering the same magnitude range, which will acquire spectrophotometry at ultralow spectral resolution and will subsequently convolve the spectra with a range of filter pass-band profiles to generate photometry in 4 broad bands and 11 medium bands, including an $\text{H}\alpha$ band; (c) a high-resolution spectrometer covering the 8470-8740 \AA region at $R=11,500$, which will use the Ca II infrared triplet lines and the H I Paschen-14 line to measure stellar radial velocities to an accuracy of better than 15 km s^{-1} down to $V=17$.

Observations from the photometric instrument should be of particular interest to planetary nebula research. As *Gaia* rotates across the sky, the spectrophotometer splits the incoming light and sends it through prisms to blue- and red-sensitive CCDs, which will respectively cover the 3300-6600 \AA and 6500-10500 \AA wavelength ranges. The resulting spectra will have a dispersion which is a function of wavelength, ranging from 40-320 \AA pixel^{-1} in the blue and 70-150 \AA pixel^{-1} in the red. These spectra have the potential to discover a significant number of young compact PNe and post-AGB objects with emission lines. However, current plans are that data on objects found to have angular diameters larger than 0.7 arcsec will be thrown away, i.e. not transmitted to the ground, which will clearly impact on prospects for measurements of PNe with medium to high nebular surface brightnesses.

4. The *James Webb Space Telescope*

As is well known, the *JWST* is aimed to be NASA's flagship successor to the *Hubble Space Telescope*, with a 15% funding contribution from ESA. It is currently beset by political problems in the US, with a House sub-committee attempting in July 2011 to axe the project, after $\sim \$4\text{bn}$ had already been spent. However, the equivalent Senate sub-committee restored funding for the *JWST* in their version of the spending bill and it appears that it may survive in an eventual reconciled bill. However, budgetary issues had already forced a delay in its expected launch date, from 2014 to 2018.

The *JWST* will have a deployable segmented-mirror primary, equivalent in collecting area to a single mirror with a 6.55m diameter, which will use passive cooling to achieve an operating temperature of $\sim 45 \text{ K}$ at its L2 station, versus $\sim 80 \text{ K}$ for the 3.5-m mirror of the *Herschel Space Observatory*. The *JWST* will have four instruments, a 0.6-5 μm near-IR wide field camera (NIRCam), which will have a coronagraphic mask available; a 1-5 μm near-IR multi-object spectrometer (NIRSpec); a 5-18 μm mid-IR camera and spectrometer (MIRI), also with a coronagraphic mask available; and a Tunable Filter

Table 3. *JWST* Instrument Properties

Instrument	λ -range (μm)	Features	Detectors	Platescale (arcsec)	FoV
NIRCam (SW)	0.6-2.3	R \sim 4, 10, 100 filters +coronagraph	Two 2 \times 2 mosaics of 2048 \times 2048	32	2.2 \times 4.4'
NIRCam (LW)	2.4-5.0	R \sim 4, 10, 100 filters +coronagraph	Two 2 \times 2 mosaics of 2048 \times 2048	65	2.2 \times 4.4'
NIRSpec R=100	0.6-5.0	Slits/microshutters	Two 2048 \times 2048	100	3.4 \times 3.1'
NIRSpec R=1000	1.0-5.0	Slits/microshutters	Two 2048 \times 2048	100	3.4 \times 3.1'
NIRSpec R=3000	1.0-5.0	Integral Field Unit	Two 2048 \times 2048	100	3.0 \times 3.0'
MIRI (Imaging)	5-28	Filters, coronagraph	1024 \times 1024	110	1.4 \times 1.9'
MIRI (Prism)	5-10	R=100	1024 \times 1024	110	1.4 \times 1.9'
MIRI (Echelle)	5-28	IFU R=3000	Two 1024 \times 1024	220-470	3.6-7.5"
FGS-TFI (SW)	1.5-2.5	R \sim 100 etalon	2048 \times 2048	68	2.3 \times 2.3'
FGS-TFI (LW)	3.2-5.0	R \sim 100 etalon	2048 \times 2048	68	2.3 \times 2.3'

Imager (TFI), associated with the optical bench of the Fine Guidance Sensor (FGS) and covering the 1.5-2.5 and 3.2-5.0 μm regions with a resolving power of 75-120. Table 3 summarises the main properties of the four science instruments on the *JWST*, while Fig. 1 compares the expected point source sensitivities of the NIRCam and MIRI imagers with those of several other spaceborne, airborne and ground-based telescopes. At mid-IR wavelengths *Spitzer* went nearly a factor of 100 deeper than ground-based 8-m telescopes, while *JWST* will go a factor of 50 deeper than *Spitzer*. Since young PNe and post-AGB objects usually show strong dust continuum, dust feature and line emission in the 10-20- μm region, they should be easily detectable out to very large distances with the *JWST*.

JWST's huge sensitivity gains have one important consequence, however, namely that its saturation limits will be at unprecedentedly faint levels, preventing observations of many sources in the Milky Way and Magellanic Clouds. For example, even MIRI's R=3000 spectroscopic mode will saturate on sources with 10- μm fluxes of only \sim 0.5 Jy. The LMC post-AGB object SMP 11, which shows a rich mid-IR absorption spectrum from organic molecules such as benzene (Bernard-Salas *et al.* 2006), has a 10- μm flux only just below this level. Photometric studies of AGB stars, post-AGB objects and PNe using NIRCam and MIRI will often only be feasible for targets lying at greater distances than the Magellanic Clouds.

LMC SMP 11 would be detectable at 10σ in 10^4 sec out to a distance of 18 Mpc at 18 μm ; out to a distance of 38 Mpc at 10 μm ; and out to a distance of 47 Mpc at 7.5 μm . Objects discovered via imaging photometry could be followed up from 5-10 μm with MIRI's long-slit R = 100 spectrometer. SMP LMC11 would yield 10σ per spectral resolution element in 10^4 sec at a distance of 14.5 Mpc. These numbers indicate that in the above modes MIRI should be comfortably capable of studying similar objects out to the Virgo Cluster (D \sim 14 Mpc) and beyond.

Planetary nebulae have become important probes of extragalactic stellar systems, using the bright [O III] 5007 \AA line, in which up to 10% of the nebular luminosity can be emitted. Arnaboldi *et al.* (1996) measured velocities for 19 PNe in the outer regions of the giant elliptical galaxy NGC 4406, in the southern Virgo extension region. Although

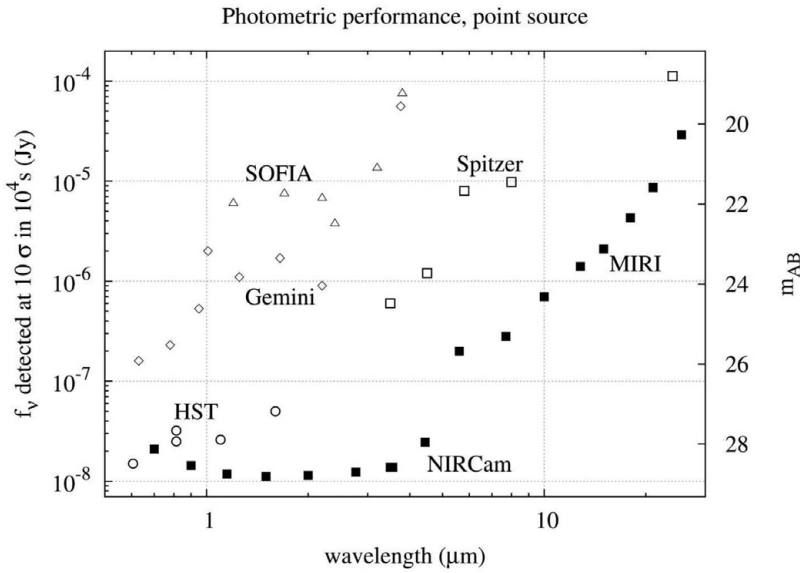


Figure 1. 10^4 s $10\text{-}\sigma$ point source detection limits for *JWST*'s NIRCam and MIRI instruments, compared to those for *HST*, *Spitzer*, *SOFIA* and 8-m Gemini instruments, illustrating the very large sensitivity gains anticipated.

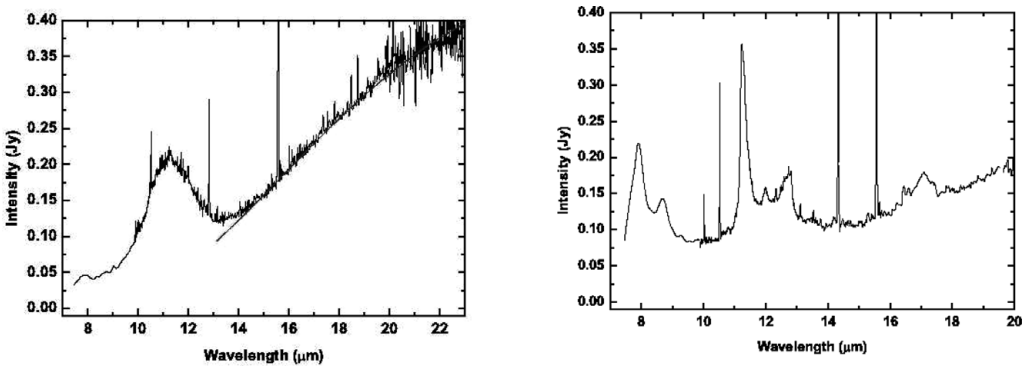


Figure 2. *Spitzer*-IRS hi-res spectra of (left) SMP LMC 8, showing a strong SiC $11.2\text{-}\mu\text{m}$ emission feature and (right) SMP LMC 36, showing very strong PAH emission bands. Both planetary nebulae also exhibit narrow fine structure ionic emission lines in their spectra. The IRS lo-res spectra of these PNe are shown by Bernard-Salas *et al.* (2009)

this galaxy has a peculiar radial velocity of -227 km s^{-1} , three of the PNe had velocities close to 1400 km s^{-1} , the mean radial velocity of the Virgo cluster. It was concluded that they were intracluster PNe. Theuns & Warren (1997) discovered ten PN candidates in the Fornax cluster, in fields well away from any Fornax galaxy - consistent with tidal stripping of cluster galaxies. They estimated that intracluster stars could account for up to 40% of all the stars in the Fornax cluster. Méndez *et al.* (1997) surveyed a 50 arcmin^2 area near the centre of the Virgo cluster, detecting 11 PN candidates. From this, they estimated a total stellar mass of about $4 \times 10^9 M_{\odot}$ in their survey area and that such a population could account for up to 50% of the total stellar mass in the Virgo cluster.

The luminous intergalactic PNe discovered to date at optical wavelengths therefore represent the tip of a very large iceberg. Infrared observations with *JWST* of dust-emitting

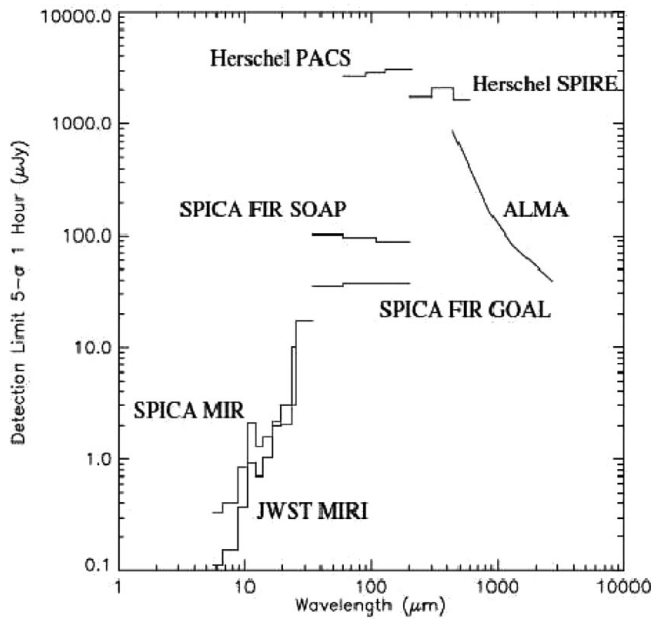


Figure 3. Predicted point source photometric detection sensitivities, in μJy ($5\text{-}\sigma$, 1-hour), for *SPICA*, compared to those for the *JWST*, *Herschel* and *ALMA*. From Swinyard & Nakagawa (2009).

AGB stars and planetary nebulae located in intergalactic regions of the Virgo Cluster appear feasible. Figure 2 shows the *Spitzer* mid-infrared spectra of two LMC planetary nebulae. The fluxes measured for the SiC-emitting nebula SMP LMC 8 indicate that in 10^4 sec MIRI imaging would yield 10σ detections for a distance of $D = 19$ Mpc with the 7.7- and 11.3- μm filters and for a distance of 13 Mpc with the 18- μm filter. For the strongly PAH-emitting PN SMP LMC 36 (Fig. 2), in 10^4 sec MIRI imaging would yield a 10σ detection for a distance of 44 Mpc with the 7.7- μm filter and for a distance of 23 Mpc with the 11.3- μm filter. The carbon star MSX SMC 159 (Sloan *et al.* 2006), would yield 10σ detections in 10^4 sec with MIRI out to a distance of $D = 29$ Mpc with the 5.6- μm filter, to 23 Mpc with the 7.7- μm filter and to 12 Mpc with the 11.3- μm filter. Similar detection limits apply for oxygen-rich AGB stars. As shown by Groenewegen *et al.* (2007), mid-infrared colour indices can be used to estimate mass loss rates and thereby mass inputs from stellar populations hosting AGB stars.

The other *JWST* instruments will also be useful for such studies, e.g. with the Tunable Filter Imager ($R = 100$) a carbon star similar to MSX SMC 159 would give 10σ per resolution element in 10^4 sec for distances out to $D = 24\text{-}29$ Mpc, for wavelengths from 3 μm . There are at least 20-30 AGB stars for every PN, so there should be many detectable AGB stars in Virgo Cluster fields, allowing the total stellar population to be determined, as well as their gas and dust mass inputs into the intracluster medium.

5. Other Future Missions

SPICA is a Japanese-led infrared mission, with ESA participation, which is currently at an advanced design stage, awaiting Phase B approval. It will cover the 5-210- μm wavelength range with a 3.5-m primary cooled to less than 5 K by mechanical cryocoolers, giving it a similar mid-IR sensitivity to that of the *JWST*, despite its smaller primary, and

a far-IR sensitivity a factor of 100 better than *Herschel*'s, see Figure 3. To be launched to an L2 station by the end of the decade, it has a mission lifetime goal of 5 years, potentially extendable to 10 years. It will be equipped with a mid-IR imaging spectrophotometer and coronagraph, a mid-IR medium and high resolution spectrometer and a far-IR imaging spectrometer. As well as supplying the telescope, ESA would provide the far-IR imaging spectrometer, called SAFARI. *SPICA*'s wide-field mid-IR and far-IR cameras and imaging spectrometers will give it a powerful capability to detect IR continuum- and line-emitting objects in blind surveys

The 2.4-m *HST*'s STIS and COS spectrometers currently provide the sole ultraviolet spectroscopic capability to astronomers. However, UV spectroscopic observations receive only a minority of the total time allocated on the the *HST* and beyond 2015/6 *Hubble*'s capabilities may start to fail. There is a clear need for a dedicated UV spectroscopic mission. The 'World Space Observatory' (WSO) is based on a concept that was pioneered and vigorously pursued by the late Willem Wamsteker and is currently a Russian-led international collaboration, see <http://wso.inasan.ru/>. Its 1.7-m telescope would be equipped with R=50,000 spectrometers (Germany) covering the 1020-3100-Å region, a long-slit spectrometer (China) and cameras with a 2.2'-3.4' field of view for 1200-6000-Å UV and optical imaging (Spain). Its UV-optimised mirror coatings would give it an ultraviolet spectroscopic performance as good as or better than that of the *Hubble Space Telescope*. Its operational lifetime in geosynchronous orbit would be 5 years, with a 10-year goal.

6. Some Conclusions

- In common with many other astrophysical research fields, planetary nebula studies need multi-wavelength spectroscopic and imaging coverage from space. Planetary nebula researchers therefore need to make a full contribution to future mission definition studies.

- Cancellation of the *James Webb Space Telescope* could have catastrophic consequences for US space science and technology leadership.

- The decrease in the number of astrophysics space missions per decade, evident from Table 1, needs to be reversed. This may imply proposing somewhat less ambitious and certainly less costly missions in the future.

- New missions should aim for operational lifetimes of 10-15 years.

- Space agencies appear not to like long-term operational commitments. Astronomers should consider pushing for other bodies to take over responsibility for post-launch operations of future missions, e.g. to take effect circa 3-5 years after launch.

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