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The frontier of ground-based observations

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Abstract. The ESO VLT on Paranal is in transition from first generation instrumentation to second generation, or at least to substantially upgraded instrumentation. The new instrumentation shall establish multipicity gain, high image definition or integral field imaging spectroscopy. Starting from observational highlights, status and trends for groundbased instrumentation will be revisited with emphasis on the field of PNe in all evolutionary phases. This review will concentrate on spectroscopy and scientific cases where groundbased observations offer a particular advantage. To the extent possible, a projection will be given as to the potential of the extremely large telescopes on the horizon, which will work best in the (near-)infrared.

Keywords. line: profiles, instrumentation: adaptive optics, instrumentation: high angular resolution, instrumentation: spectrographs, stars: AGB and post-AGB, stars: evolution, stars: late-type, planetary nebulae: general, galaxies: evolution

1. Introduction

In 1983, surprisingly in the same year, theory (Iben & Renzini 1983) and observations (Weidemann & Koester 1983) concluded, that all stars with a main sequence mass $\leqslant 8M_{\odot}$ will become Planetary Nebulae (PNe) ending as a white dwarf. The progenitor star will eject all mass but the stellar degenerate core into the interstellar medium (ISM). Later these findings have been refined in countless publications. The main sequence upper mass limit for a PN-progenitor is now 9 $M_{\odot}$. Another striking proof of the importance of AGB stars for the enrichment of the ISM stems from the isotopic composition of interplanetary dust particles and meteorites. In many cases the nucleosynthesis must have happened in AGB stars (e.g. Zinner *et al.* 2006). Still the importance of PNe for galactic evolution is not really recognized outside the AGB-PNe coomunity†.

Progress after the pioneering work in the 1980s came from theory - here mostly models for thermonuclear evolution - and observations with new technologies. Especially the Infrared Astronomy Satellite (IRAS), contributed to the understanding of the AGB/PNe stages as an enigmatic and fascinating phase of stellar evolution. As an example e.g. Van der Veen & Habing (1988) have established the AGB-PNe-dust connection based on a large statistical sample which only IRAS could supply.

Due to their aesthetic appearance and their spectral properties PNe are observatory directors' preferred 1st-light objects. Beyond this (ab-)use of PNe observations, however, groundbased studies are crucial to gain an in depth understanding of the processes which lead to mass-loss and which shape the PNe. Hopefully good models of the PNe evolution can settle the question which fraction of the dust, the AGB star has produced, will reach the ISM without being destroyed during the high excitation nebular phase.

† Just a few weeks ago, the author was in a prestigious colloquium where the speaker generously allowed for some contribution to the chemical evolution of the ISM for low-mass stars which have failed to become supernovae of type II: if the low mass star happens to be a binary eventually it can also become at least a supernova of type Ia!

This review is a bit biased toward the infrared. PNe and their progenitors not only are for a major part of their evolution 'infrared objects'. More importantly, looking forward, the next generation of large telescopes will depend on adaptive optics, which for the foreseeable future limits observations to $\lambda \geqslant 1100$ nm. Also, in this review reference is mostly made to instrumentation from the European Southern Observatory (ESO) at its Very Large Telescope (VLT), but the world wide instrumentation efforts are quite similar.

2. Relevant questions and observables for AGB/PNe research

Relevant questions for an optical observer today are:
- nucleosynthesis and chemical evolution on the AGB
- detailed physics of mass loss, PNe formation, dust formation and destruction
- what happens exactly during the AGB → post-AGB → PN transition
- PN evolution and the fate of the dust

With today's 8 m class telescopes one can address:
- AGB and post-AGB photosphere: chemistry, dynamics, imaging
- basic central star parameters: distance, diameter ...
- details of circumstellar environment, morphology and composition
- morphology of post-AGB objects and proto-PNs
- whatever else can constrain mass-loss history
- AGB stars and PNe properties in local group galaxies and beyond
- whatever can be constrained with polarimetry and spectro-polarimetry:
  - ◦ dust properties: shape, amorphous or crystalline
  - ◦ dust alignment mechanisms ..

Large telescopes and well calibrated equipment enable additionally very high resolution spectroscopy, very high definition imaging, and combinations thereof. New large field facilities will also provide for better statistics, complementing galactic catalogues or enable complete surveys in local group galaxies. Representative samples of PNe at the Virgo cluster or beyond are or will be accessible as instrumentation and telescopes progress.

3. New groundbased tools: Promises and pitfalls

3.1. *The Potential and Promise of Groundbased Techniques*

The following observing techniques are either state-of-the art or close to realization:
Crowded Field Imaging to detect AGB stars and PNe in the local group may now be possible with MCAO (multi conjugate adaptive optics) in a way, quite competitive with HST/JWST. Calamida *et al.* (2008) e.g. apply experimental MCAO to study the White Dwarf cooling sequence in globular clusters. For less crowded fields large scale surveys are under way, some of them with time-resolution such as the Large Synoptic Survey Telescope (LSST Science Collaborations, 2009). LSST will provide for many more transitory events such as born-again PNe like Sakurai's Object (V4334 Sgr). LSST will provide for a trigger to document the early evolution of born-again PNe with state-of-the art instrumentation, which has proven quite valuable in the case of V4334 Sgr.
Low Resolution Optical and IR Spectrographs will deliver Spectral Energy Distributions (SEDs) with fibre fed or other multiplexing units for stellar associations.
Echelle Spectroscopy to retrieve chemistry and atmospheric structure of AGB stars and proto-PNe; here groundbased work is the only option.

High Contrast Imaging and IFU or Long Slit Spectroscopy: developement driver for this instruments is the detection of extra-solar planets and to characterize their atmospheres. Still these techniques will allow also for very high dynamic range and contrast imaging including imaging spectroscopy. For observing circumstellar material, 8-10m telescopes beat all competing facilities, also in space. Kervella *et al.* (2011) have recently imaged the circumstellar environment of α-Ori at $\lambda \approx 10\mu m$ using VLT-VISIR. Within few arcsec 4.5 dex of dynamic range have been achieved. Lagadec *et al.* (2011) have established a catalogue of $10\mu m$ images of AGB stars and find only 59 out of the 93 objects observed not resolved (also Lagadec *et al.* this meeting)†. Noteable in this context is, that spectrographs using integral field units (IFU) can compete favourably with coronagraphs (c.f. Thatte *et al.* 2007). Long slit spectroscopy can compete strikingly well with interferometry (Pontoppidan *et al.* 2011, see below).

Interferometry, Especially also LBT-LINC-NIRVANA: NIR to mid-IR model dependent imaging, i.e. plausible models for the source can be constrained by observations (paper by S. Bright, these proceedings).

Lunar Occultations: This nearly forgotten technique gives access to AGB-star imaging and can be quite systematically applied; Richichi *et al.* (2011) lately have published a catalogue of 183 near-IR observations while Käufl *et al.* (2000) describe the method and some results for $\lambda \approx 10\mu m$.

3.2. *Unique Spectral Features for AGB-PNe Studies*

Starting in the near-infrared a cornucopia of spectral features relevant for this symposium exist:

- atomic lines: hydrogen recombination lines: Paβ, Brγ, Brα, Pfβ, Huα ...
- various helium lines
- forbidden lines: e.g.
  - in J-band: [Fe II], in K-band: [Kr III] and in L-band: [Zn IV]
  - in N-band: [Ar III], [S IV] and [Ne II]
- molecular lines:
  - H_2 lines from hot shocked molecular gas (quadrupole transitions)
  - normal dipole rotational-vibrational transitions: e.g. CO, SiO, CxHy
- solid state features:
  - crystaline and amorphous minerals based on SiO, SiC, PAHs, FeO, ices, etc.

A more general overview of astronomy with rotational-vibrational molecular transitions is given in Käufl (2010).

3.3. *Ground versus Space: Pitfalls*

For infrared astronomy, the situation is characterized by the antagonism between sensitivity and resolution both spatial and spectral. Cryogenic space instruments will always be orders of magnitude more sensitive than groundbased instrumentation. Cost and complexity restrict the size of space telescopes, which limits their spatial resolution. Groundbased observations in the past were always a factor of 5–10 ahead, and this will also stay so for the future, e.g. comparing the James-Webb-Space-telescope (JWST) with the various ELT-projects. Similarly spectral resolving powers $\lambda/\Delta\lambda$ exceeding 10^4 in a cryogenic environment are hardly conceivable in space.

A prototypical example of the importance of spatial resolution is given in Waters *et al.* (1998) where an oxygen-rich dust disk surrounding an evolved star was found for the

† These observations have all been done with a rather compromised performance, as VISIR was still equipped with its old detector, plagued by all kind of artifacts and parasitic effects.

central star of the Red Rectangle. The authors had obtained mid-IR spectroscopic data from the Infrared Space Observatory (ISO) satellite which indicated both oxygen and carbon rich dust. The size of the entrance aperture of the spectrograph on ISO was about the same as the field of view of ESO's first 10 μm multimode instrument TIMMI, then at the 3.6m telescope on LaSilla. Complementing the ISO data with diffraction limited narrow-band imaging revealed the disk structure, interpreted by the authors as the first observational proof of a chemistry change in thermally pulsing AGB-stars.

The sensitivity problems on the ground are fundamentally imposed by sky and telescope thermal radiation and thus cannot be mitigated. A rule of thumb, however, is that compact sources from surveys by space cryogenic telescopes can normally be followed up from the ground. This was more or less true when comparing observations from sounding rockets in the early 80s with the first generation of photometers and bolometers and it will hold in future when comparing the latest catalogues from space (AKARI-satellite) to the ELTs.

4. More groundbased observational highlights

The particularly interesting combination of nearly diffraction limited image quality and a spectral resolution of 3 km/s as provided by the adaptive optics assisted infrared spectrograph CRIRES (cf. Käufl *et al.* 2006a) promises unique observational constraints. Figure 1 gives an example from the K-band. More examples and applications of high-resolution long slit Echelle spectroscopy can be found in Käufl *et al.* (2006b).

Long-slit spectroscopy allows for the retrieval of spatial information way beyond the diffraction limit by applying deconvolution techniques. The retrieval of spatial information down to 1 milli-arcsec was reported for young circumstellar disks (e.g. Pontoppidan *et al.* 2011). The general application of this technique to late stages of stellar evolution is still pending.

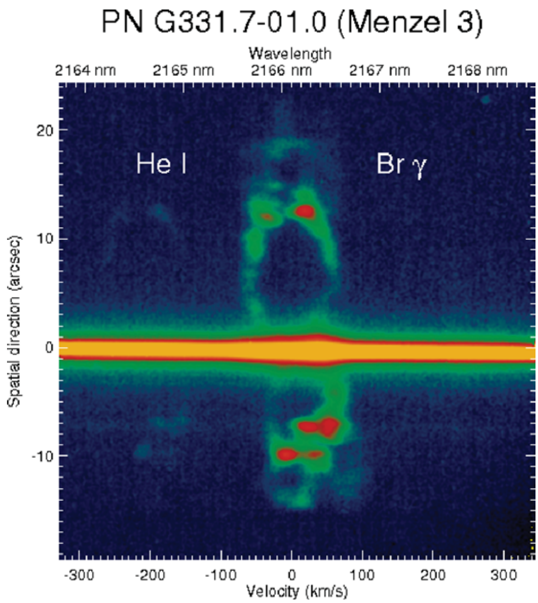

Figure 1. Long slit spectrum taken with CRIRES of the morphologically complex PN Menzel 3. The dispersion axis, horizontal, is calibrated in km/s while in slit direction the scale is in arcseconds. The exposure was centered on the Brα line, while the corresponding helium line is also clerly visible. The object is known for its complex spatial structure, which is 'matched' perfectly by an equally complex velocity distribution.

5. Specific new instrumentation and techniques

5.1. *ESO Adaptive Optics Facility (AOF)*

At ESO a fundamental re-engineering of VLT Unit Telescope #4 has started. It is planned to replace the classical secondary mirror with an adaptive thin-shell mirror, while implementing natural guide star adaptive optics (NGS-AO) and up to 4 laser guide stars. Thus various flavors of AO shall become routine standard observing modes: natural guide star (NGS) single conjugate adaptive optics (SCAO), laser guide star (LGS) SCAO, ground layer AO (GLAO) as a seeing improver and multi-conjugate AO (MCAO). MCAO can allow reproducible photometry over larger fields (see above Calamida *et al.* 2008).

PNe research could profit particularly from MCAO and all LGS-AO flavors, as the AOF would feed the faciliy wide field NIR imager (HAWK-I) and the new MUSE instrument (see below).

To exploit the full potential of the AOF a dedicated Cassegrain instrument, dubbed ERIS, basically a cryogenic focal reducer operating from 1–5 μm is being developed in house at ESO.

5.2. *MUSE, KMOS and SPHERE*

A variety of 2nd generation instruments are being developed and will soon be deployed at the ESO-VLT.

Multi Unit Spectroscopic Explorer - MUSE: Bacon *et al.* (2006) describe this rather complex instrument. It is an adaptive optics assisted optical spectrometer with an fibre based IFU, feeding finally 24 individual spectrographs with nominal spectral resolution $\lambda/\Delta\lambda \approx 4000$. The spaxel size† is $0.2''$. Especially for individual compact or slightly evolved PNe this instrument will deliver what generations of imaging Fabry-Perot-systems have promised: fully calibrated easy to use 3D-data cubes of coordinates vs wavelength.

K-band Multi Object Spectrograph - KMOS: This is a complex multi-IFU low-and medium resolution spectrograph for the J, H and K-band. Sharpless *et al.* (2010) give a recent overview. It will allow to take simultaneously SEDs of up to 24 objects in a patrol field up to 7 arcmin. While the designers most likely had only extragalactic astronomy in mind, KMOS should allow for systematic studies of AGB and PNe populations in local group galaxies as well as the study of intra-cluster PNe up to Virgo, work that so far has been the domain of classic optical instrumentation.

SPHERE, the VLT-Planet-Finder: The system is an extreme adaptive optics bench in connection with three matched instruments: a coronagraphic camera, an imaging polarimeter and an integral field spectrograph. Design wavelength are the J, H and K windows (cf. Wildi *et al.* 2009). Clearly designed for imaging extrasolar planets, a rejection of the light of the central star by 10^{-4}–10^{-5} typically at spatial scales of few $\lambda/D_{\rm tel}$ makes this instrument an interesting facility to study also circumstellar material from the onset of mass-loss at the AGB to more evolved phases.

5.3. *LBT LINC NIRVANA*

This system, once operational, can revolutionize interferometric imaging, and will set the stage for future filled aperture imagers at the various ELTs. By using Fizeau beam combination, the instrument delivers true imaging data equivalent to a 23m telescope, albeit with a 'funny' point spread function. In K-band it can resolve structures down to 20 mas. Herbst *et al.* (2010) give a description of the current status of the project.

† In IFU slang, each image element, for which a spectrum is taken is called a *spaxel*.

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5.4. *GEMINI NICI*

This instrument is a prototype of the next generation high Strehl-ratio and high contrast imaging. Artigau *et al.* (2008) present this advanced adaptive optics coronagraphic imager at the 8m-Gemini-South telescope. NICI is another planet searching facility that can be used for high contrast imaging of AGB/post-AGB stars and compact PNe, ready to use.

5.5. *Upgrades and More New Kids on the Block*

At the various 8m telescopes upgrades of existing facilities are taking place. At the ESO VLT, the VISIR instrument, a complex multimode imager and spectrometer for the thermal infrared (7.7–13.3 μm and 16–24 μm) is being upgraded by Sep. 2012 with a state-of-the-art 1024^2-pixel detector. An overall improvement of the throughput of typically an order of magnitude can be expected, so that VISIR has the potential to become the work-horse instrument for AGB/PNe research in the thermal IR.

In the world of the 4m telescopes new cryogenic cross-dispersed NIR Echelle spectrographs will become availabe, GIANO (Oliva *et al.* 2006) operating in the seeing limit at the 3.5m TNG on LaPalma or the AO-assisted CARMENES project for the Calar Alto 3.5m telescope (Quirrenbach *et al.* 2011) will provide platforms to study chemistry and more generally atmospheres of AGB and proto-PNe. Thus enough observing time may become available to study statistically significant samples of objects e.g. in the galactic bulge. Indeed most galactic AGB-stars are too bright for 8m-class telescopes.

SUBARU will upgrade its wide-field capabilities, again a tool for searches, e.g. intercluster PNe beyond Virgo.

5.6. *Interferometry*

Arguably ESO VLTI is the only facility for interferometry with large telescopes. Especially thermal infrared observations can be applied to the field of PNe. The future second generation instrument, MATISSE (Lopez *et al.* 2008) will enter uncharted territory, by providing 4-telescope beam combination, hence a first step to actual interferometric imaging and imaging-spectroscopy in two wavelength channels: 3–5 μm and 7.7–13.3 μm, thus the perfect complement to the classical ESO-VLT infrared instrumentation (VISIR, CRIRES and ERIS) relevant for PNe research as described above.

6. ESO extemely large telescope instrumentation studies

6.1. *E-ELT Instrumentation Plan and Roadmap*

Starting around 2005, as part of the concept development for ELTs, instrumentation studies began at ESO and elsewhere (for the scope of studies see e.g. IAU Symposium 232, Cape Town, South Africa, November 14-18, 2005). At ESO finally 8 instrument concepts and 2 specialized adaptive optics units have been studied at Phase-A level. For a summary see Ramsay *et al.* (2010)†. Meanwhile three scientific instruments for first light have been singled out. As to the procurement of other instruments a roadmap can be found on the ESO-web site.

Two of the three selected instruments are of particular interest and advantage to the AGB and PNe field and will be discussed in the following. The instrument studies were for proto-typical instruments and observing modes and the final realisation contracts may ask for equipment with modified specifications.

† see also http://www.eso.org/sci/facilities/eelt/instrumentation/phaseA.html

6.2. *HARMONI: E-ELT IFU-Spectroscopy*

The concept is a reflective image slicer in combination with a medium resolution spectrograph for the wavelength range λ: 0.47–2.45 μm. Spectral resolution $\lambda/\Delta\lambda$ will be between 4000 and 20000. The spaxels will be of order of 0.005–0.050 mas. For comparison, the 39m E-ELT will have a diffraction limit of 14 mas at $\lambda \approx 2.2\,\mu$m. This instrument is an extrapolation of the ESO-VLT instrument SINFONI. The HARMONY study is described by Thatte *et al.* (2010).

As most AGB-stars and PNe are 'adaptive optics friendly' this instrument will provide soon after first light high quality data. Especially high contrast imaging during post-AGB and proto-PN phase and mapping in various near-infrared lines in the early PN-phase will provide for completely new observational constraints.

6.3. *METIS: E-ELT Mid Infrared Imaging and Spectroscopy*

The concept here is a multimode instrument, comprising diffraction limited imaging and low- and high-spectral resolution spectroscopy. The diffraction limit of the E-ELT will range from 21 mas at $\lambda \approx 3.3\,\mu$m, the domain of many hydrocarbonate rotational-vibrational lines, to 64 mas at $\lambda \approx 10\,\mu$m, the domain of some interesting solid state features. The highest spectral resolution at $\lambda/\Delta\lambda$ in the centre of the CO fundamental band shall approach 10^5 at $\lambda \approx 4.8\,\mu$m. The wavelength range is for two intervals λ 3–5 μm and λ 7.7–13.3 μm. Operation beyond $\lambda \approx 17\,\mu$m is possible as well, as long as it does not drive cost or complexity. This instrument is an extrapolation of the ESO-VLT instrument VISIR and the long-wavelength arm of CRIRES. The METIS study is described by Brandl *et al.* (2010).

This instrument again will have the advantage of full image quality shortly after first light. Again AGB-stars and PNe are adaptive optics friendly and this instrument will feature an IR-wavefront sensor, so that even obscured objects can conveniently be observed. Extrapolating the impact mid-IR observations have had so far, the METIS observing modes have countless applications in the context of AGB/PN connection.

6.4. *Sensitivity*

As most of the observations of PNe basically depend on surface brightness, any observation that has been done ever with an 8m telescope is possible with the E-ELT, albeit at five times higher spatial resolution. Or teh other way around, PNe in the local group can be observed, as long as they fill at least one pixel or spaxel. This in turn implies, that PNe research with IR-instrumentation at a 40m class telescope will be possible at least up to 1 MPc.

7. Conclusions and outlook

Second and third generation instrumentation is presently being developed or deployed on all major 8m class observing facilities. The next generation of large telescopes is being designed. Some observing cabalities will fundamentally improve, especially w.r.t. spatial resolution and photon collecting power. ESO, for example, has lately released its construction proposal for the *European Extremely Large Telescope* † E-ELT. So the future might be bright and promising. Still Sun Kwok, during this symposion, made a rather strong statement: *Whether PN research has a future depends on whether this community can find new angles to look at the old problems and whether we can create new problems from new observational techniques!* The AGB/PNe galaxy connection hinges

† http://www.eso.org/public/products/books/e-elt_constrproposal/

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mostly around chemical evolution and dust production. Fundamentally new insights in this field in the past came from incorporating new ideas and technologies. High resolution spectrographs may be the most important instruments in groundbased astronomy for AGB research, complementing well ALMA. Even after many decades of Planetary Nebula and AGB research the sequence AGB, post-AGB and PNe are still not really accepted e.g. as a worthwhile science case for the ELTs. The future of groundbased instrumentation and telescopes looks great, now and in the near and far future. The problem for AGB and PNe research might be to connvey this message to the TACs and other committees.

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