Late stages of stellar evolution with the Square Kilometer Array

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Abstract. Stars at the end of their lives return much of their mass back to the ISM. This process is the main source of dust in the ISM, and potentially a source of large molecules. I discuss several areas where SKA will have major impact on our understanding of the mass loss and the circumstellar processes. The resulting requirements for SKA, including frequency coverage and location, are discussed.

1. Introduction

Low and intermediate-mass stars, near the end of their lives, experience a phase of catastrophic mass loss. During this so-called superwind, occurring on the Asymptotic Giant Branch (AGB), between 40% and 80% of the initial mass of the star is ejected at mass-loss rates of typically $10^{-6}$ to $10^{-4}$ M$_\odot$ yr$^{-1}$. The total amount lost determines the ISM recycling rate: the fraction of the gas incorporated in star formation which after a delay of $10^8$ to $10^{10}$ yr is returned to–and rejuvenates–the ISM. In the Galaxy, this rate is of the order of $0.5$ M$_\odot$ yr$^{-1}$. The ejecta are enriched in carbon and nitrogen; at low metallicity, primary oxygen is also produced. The AGB superwind is the site of efficient dust production, and much of this dust survives the later evolution to become part of the ISM. In addition to dust, complex organic molecules can also be formed around AGB stars. If these can survive normal ISM conditions (a topic of current research), AGB stars form a source of pre-biotic molecules into regions of later star formation. Finally, the mass-loss efficiency determines the final stellar mass and is the cause that all stars with $M_{\text{initial}} < 8$ M$_\odot$ form white dwarfs rather than supernovae.

The superwind strongly affects the evolution of galaxies. It determines the lower limit for supernova masses. If, as expected, the superwind is less efficient at low metallicity, this would increase the masses of stellar remnants, and increase the supernova rate in the early Universe. It also predicts two sharp changes in the composition of newly formed dust. The first occurs after $10^8$ yr when the first AGB stars appear. The second follows when the initial main sequence turn-off mass drops below the value (1.5–4 M$_\odot$) where AGB stars no longer become carbon stars, and form silicate rather than carbonaceous dust.

Unsolved issues regarding the AGB superwind include the structure of the wind (morphology, clumps, embedded magnetic fields), and the chemistry and dust formation. The SKA is well suited to studying these: it can resolve the
extended envelopes down to the radio photosphere, and study a wide range of emission processes.

2. Radiation processes

During the superwind, the star is a red giant with a radius of around 1 AU and a temperature of around 3000 K. The extended atmosphere is dominated by radially travelling shock waves, and shows extensive chemistry and dust formation. Optically, the star and its atmosphere tend to be obscured ($A_V \sim 10 - 30$ mag). The radio photosphere is located within the extended atmosphere. After the mass loss ceases, the star heats up very fast and ionizes the ejecta, now visible as a planetary nebula (PN). Depending on the precise evolutionary phase, the SKA will detect radio emission from the following processes:

1. Thermal bremsstrahlung, from the ionized gas of planetary nebulae. This will have a flat $\nu^{-0.1}$ spectrum, except for the youngest objects which are optically thick at low frequencies. For a sensitivity level of 0.1 $\mu$Jy, the bremsstrahlung can be detected to 5 Mpc for the brightest objects. A typical young PN (e.g. NGC 7027) can be resolved to about 1 Mpc, assuming observations at 8 GHz with 10 $\mu$arcsec resolution (1000 km baseline).

2. Thermal dust emission. Within the radio frequencies, this is normally much weaker than the bremsstrahlung. To detect this in PNe, a high dynamic range of 1000:1 will be needed, and frequency coverage should extend to $\nu > 10$ GHz. However, in AGB stars it may contribute significantly.

3. Photospheric continuum emission, from the AGB stars. For a sensitivity of 0.1 $\mu$Jy at 20 GHz, this can be detected to 3–4 kpc, covering around $10^4$ potential targets. At a resolution of 5 $\mu$arcseconds, the radio photospheres (3–5 AU in diameter) can be resolved out to 1–2 kpc. Because of the black-body nature, the preferred frequency range is 10–20 GHz for the optimum combination of resolving power and sensitivity. Nothing is known about radio flares from AGB stars, but these are likely to exist.

4. Molecular transitions, both masing and non-masing. The well-known OH 18-cm lines from AGB stars can be detected throughout the Local Group. Here we assume a typical OH component of 10 Jy over 0.5 km s$^{-1}$, for a source 1 kpc away. At this resolution the line sensitivity is about $10^3$ less than the continuum sensitivity. The OH line is detectable out to 2.5 Mpc and OH/IR AGB stars can be studied throughout the Local Group. SKA will also be able to study all four lines simultaneously. The water masers at 22-GHz are equally important. Other important molecular lines are mainly at frequencies $\nu > 10$ GHz and are detectable for Galactic stars.

5. Radio recombination lines. These are potentially the best lines to get detailed velocity fields, and they also give good abundance determinations as the recombination lines are not affected by extinction, and lack the extreme temperature dependence of (optical) forbidden lines. To observe
a range of lines tracing a range of conditions, the frequency range should go up to $\sim 20$ GHz. Assuming a 5\% line-to-continuum ratio, a bright PN can have a line flux of 0.1 mJy at 200 kpc, measurable at a velocity resolution of 10 km s$^{-1}$. Recombinations lines from heavier elements can also be detected. Faint lines for deuterium and $^3$He may be especially interesting.

6. HI. A young planetary nebula will still be surrounded by a photon-dissociation region, including a larger atomic shell. The young PN NGC 7027 has a circumstellar HI optical depth of around 0.05. The absorption line is detectable to same distance as the recombination lines. They can be used to measure magnetic fields, given the S/N requirements mainly within the Galaxy.

The sensitivity of line emission does not greatly benefit from the new wide-band correlators, such as used for e-VLA (although the continuum will be much better determined, and for weak lines this does increase the S/N). The large collecting area of SKA is a requirement for detecting faint lines.

The above assumes nominal continuum sensitivity. However, the continuum sensitivity within the galactic plane may be limited by confusion. The stellar density for a line of sight through the plane may be of the order of 10 stars per square arcsecond. Radio emission from stars is generally weak but can rise dramatically during strong flares, especially among the numerous M-dwarfs. Thus the background continuum emission is likely to contain a rapid time-variable component.

The numbers given take into account that the sensitivity will depend on frequency and resolution. At high frequencies, the effective collecting area may be reduced. Also, much of the collecting area will be concentrated at shorter baselines. The highest spatial resolution will involve a subset of the array only.

3. Winds, shells and chemistry

3.1. Clumps in planetary nebulae

Planetary nebulae show many varied structures, including rings, jets, cometary structures and clumps. How much of these are directly related to structures in the original AGB wind is not known. Especially the SiO masers show that the AGB wind is intrinsically clumpy. If these clumps survive to become the PNe clumps, they could trace regions with distinct evolution.

Recent analyses of the heavy element, forbidden and recombination line spectra of planetary nebulae (PNe) suggest that there are at least two distinct emission regions in many nebulae, one of ‘normal’ temperature ($T_e \sim 10^4$ K) and ‘normal’ abundances where the strong collisionally excited forbidden lines originate; and another which is inferred to have a very low temperature ($10^3$ K) and very high heavy elemental abundances, which emits most of the observed flux from the heavy element optical recombination lines but emits essentially no forbidden line emission (see the recent review by Liu, 2002). It is tempting, but still unproven, to associate the second component with some of the clumps.
The thermal continuum emission is ideally suited to locate the proposed super-metal-rich gas. The inverse dependence on temperature of free-free continuum emission \(1/\sqrt{T_e}\) in the optically thin case makes these clumps three times brighter than clumps with normal temperature. We assume a size for a clump of \(10^{15}\) cm and density of \(10^4\): the mass of the clump is of the order of \(5 \times 10^{-8}\) M\(_\odot\) and the size 0.1 arcsec at 1 kpc. The radio flux density from the clump is about 1 \(\mu\)Jy (or a little fainter if hydrogen is underabundant.) This is within SKA territory: it will be able to detect individual clumps with such parameters. HST images show that dust in the nebula is causing extinction at very small angular scales. In case of super-metal-rich clumps, an association with dust enhancements is probable. SKA images, not affected by extinction, when compared to AO images, will show the internal dust distribution:

Recombination lines are highly important: they show a stronger dependence of \(1/T_e\) and can obtain the temperature of the gas. Lines from individual clumps will not be detectable, but summed over the clumps, the integrated line profile would be observable. The SKA bandwidth will cover several recombination lines simultaneously. The line strength as function of upper level \(n\) gives an independent measurement of the density of the gas. In addition, velocity fields can be measured. For the first time, a full understanding of the nebulae structure will be obtained. Extreme hydrogen-poor gas (as is observed in a few PNe, e.g. A58) would give strong recombination lines from element such as carbon, giving a new tracer for these unusual environments.

### 3.2. The proto-planetary nebulae

One of the unsolved problems in evolved stars is the origin of the asymmetrical morphologies. Stellar winds are thought to be largely spherical. However, detached circumstellar shells tend to be elliptical or bipolar—e.g. \(\eta\) Car. There are presently about 100 objects known in the phase between the AGB and the PNe, where the shell is already detached but the star not yet hot enough to initiate ionization. These proto-planetary nebulae (PPNe) are almost always highly aspherical, with evidence for dense disks and fast polar outflows. The origin of these structures is not understood, as their immediate progenitors on the AGB show little or no evidence for disks. Suggestions range from infall of planetary companions (with their angular momentum deposited in the wind), to magnetic fields originating in the turbulent convection of the AGB stars.

The youngest outflows can be observed in several maser transitions of OH and H\(_2\)O. (The 43GHz SiO masers will be outside the frequency coverage of SKA.) Zijlstra et al. (2001) have shown that the OH velocity fields of some nearby objects show the characteristic trace of an interaction between winds of different speeds. This results in a swept-up intershell moving at a direction-dependent velocity, which is constant in time. A sharp increase in the wind speed, possibly already on the AGB, may therefore trigger the change in morphology. SKA will be able to resolve the problem in various ways:

- Spatial resolution. The VLA, used to obtain sufficient S/N on long baselines, limits the spatial resolution to about 1 arcsecond. SKA will improve the spatial resolution by a factor of 30 at high S/N. This region, within 10 AU of the star, will show the onset of the acceleration on the AGB.
• Expansion. Brighter maser spots will have their position measured to 1 milli-arcsecond. Assuming an expansion at 30 km s$^{-1}$, the spatial evolution can be detected within 5 years out to 30 kpc. The evolution of the structures can be directly measured. The same method will determine the distance to the Galactic Centre, the Sgr dwarf and the two Magellanic Clouds. However, we expect that this will be measured before SKA by other methods.

• Magnetic fields. Especially OH has a large Zeeman splitting. Identifying Zeeman components gives a measurement for the magnetic field, if one can show that the two components are co-spatial. The 6-cm OH lines are in principle better than the 18-cm ones, giving a larger splitting and better resolution. At present, these have only been detected in a very few objects, but SKA will detect them widely. Provided circular polarisation can be accurately calibrated, SKA will clean up the problem of magnetic field structures in these outflows.

### 3.3. Chemistry

AGB stars become enriched in carbon during the third dredge-up. For intermediate-mass stars, the carbon will eventually outnumber oxygen. In these stars, the photosphere contains C$_2$ and C$_2$H$_2$, which are carried along with the mass loss. Two separate chemical sequences occur: carbon chains build up and eventually become aromatic, while other molecules cluster and form the first condensates. The present evidence is that carbon dust forms from TiC$_2$, which has a high condensation temperature. The aromatic molecules build up to PAHs. Earlier suggestions that the PAHs form dust are not born out by models, however they may become incorporated into dust grains.

The evidence is growing that both the dust and molecules survive the stellar evolution and merge into the ISM. For the dust, direct evidence comes from the inclusions into meteorites. Of the identifiably pre-solar grains found in the solar system, the majority show an AGB origin. This suggests that most of the interstellar dust in the ISM formed in AGB envelopes, and not, as previously believed, in supernovae.

The diffuse ISM also shows a large number of absorption bands (DIBs) which are unidentified but appear to come from large carbon molecules. These must be sufficiently large to be stable against photo-dissociation, and so must be considerably larger than a small PAH. Their origin is unknown. However, given the origin of the dust in the ISM, it is plausible that these molecules also originate from AGB stars. They may either have grown to photo-stable sizes in the gaseous envelopes, or they may have become incorporated in dust and evaporated from dust grains at a later phase.

The first step in forming aromatic molecules is benzene (C$_6$H$_6$). Once this forms, larger rings easily build up. Wood et al. (2002) have shown an efficient chemical route to this molecule, operating in dense, irradiated post-AGB envelopes. This suggests that PAHs do not form during the AGB, but are a later product. The important questions are how (and where) the chemistry is initiated, and where the chemistry ends. Proof of the formation of aziridine (c-CH$_2$CH$_2$N) would be important. Furan (Dickens et al. 2001) is also expected to exist, and is the basis of the simple sugars ribose and deoxyribose, involved in
building RNA and DNA. Glycine, the simplest amino-acid, has been a target for searches (Charnley et al. 2001). If such molecules form and survive into the ISM, they also become part of any subsequent star formation. The pre-solar nebula would in this way have become pre-seeded with organic molecules. Amino acids have been detected in meteorites, suggesting a solar-nebula or pre-solar origin.

SKA can detect and identify such molecules. The lines are faint and the large collecting area of SKA would increase the sensitivity by orders of magnitude. In addition, there are fewer transitions in the SKA frequency range, and these can be measured in the laboratory. This allows an identification of the lines. ALMA, in contrast, observes in a frequency range where there are many overlapping transitions, and identification is problematic. In spectroscopic sub-mm surveys, typically only the brightest lines can be identified and the ‘noise’ consists of many weak unidentified lines. SKA will have a major impact in the rapidly developing field of pre-biotic ISM chemistry.

The best region to get a mix between a sufficient range of molecules detectable without the problems of confusion, is found between 10 and 30 GHz. Furan, as an example, has lines at 23.4 GHz and glycine (e.g. Lovas et al. 1995) at 22.7 GHz.

4. SKA requirements

The sensitivity is taken from the defined SKA parameters. The spatial distribution of the array determines how this changes at the highest spatial resolution. If a trade-off exists between multi-beam and frequency coverage, one can envisage that the highest frequencies will only be offered in a sub-array. For spectral line observations, it is desirable to cover a large number of lines simultaneously, where each part of the spectrum must allow for high resolution, while at the same time the continuum level can also be accurately determined.

Good frequency coverage is crucial. Free–free emission is best studied at higher frequencies, especially for high density, optically thick regions. The OH lines are at 1.6 and 6 GHz. The water masers are at 22 GHz. The large carbon molecules make an upper frequency of order 30 GHz highly desirable. A frequency gap between ALMA and SKA performance should be avoided.

Finally, the majority of the Galactic and near-Galactic environments require observations from the Southern hemisphere. It is also desirable to be able to observe the same targets as ALMA. Accommodating an array of up to 1000 km, able to observe e.g. the Galactic Centre region, suggests a location in Australia or South Africa would maximise the scientific return.

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