Prospects for Asymmetric PNe with ALMA

P. J. Huggins

Physics Department, New York University, New York NY 10003, USA

Abstract. Millimeter and sub-millimeter observations have made fundamental contributions to our current understanding of the transition from AGB stars to white dwarfs. The approaching era of ALMA brings significantly enhanced observing capabilities at these wavelengths and promises to push back the frontiers in a number of ways. We examine the scientific prospects of this new era for PNe, with an emphasis on how developments may contribute to the goals of the asymmetric PNe community.

1. Introduction

The Atacama Large Millimeter/sub-millimeter Array (ALMA), is a new, major, international telescope that is currently being built in northern Chile. It will provide significantly enhanced observing capabilities over existing instrumentation in the mm and sub-mm wavebands, and is expected to make important contributions to many areas of astronomy. ALMA’s ability to make high quality, high resolution images in lines and the continuum will provide a new tool to probe the structure and origin of asymmetric planetary nebulae (APNe). This paper outlines prospects for APNe with ALMA. Sect. 2 reviews the contributions of mm and sub-mm observations to our current understanding of the field; Sect. 3 describes ALMA’s main characteristics; and Sect. 4 considers what it might do for APNe.

2. APNe at mm and sub-mm Wavelengths

The most important contributions of the mm and sub-mm wavebands to our current understanding of APNe have been made using molecular line observations. The low lying rotational transitions of CO, $J = 1–0$ at 2.6 mm (115 GHz), $J = 2–1$ at 1.3 mm (230 GHz), and $J = 3–2$ at 0.87 mm (345 GHz), have been especially useful in probing the kinematics, distribution, and mass of the molecular gas. Numerous lines of other molecular species have been detected in spectral scans of some well-studied objects, e.g., AFGL 618 (Pardo et al. 2007) and NGC 7027 (Zhang et al. 2008) and these lines provide valuable diagnostics of physical and chemical conditions. There is an interesting, evolving chemistry in the AGB-PN transition (Bachiller et al. 1997), and the atomic fine structure lines of C I, which are useful probes of photo-dissociation regions, are detectable in the sub-mm (Bachiller et al. 1994; Young et al. 1997).

The history of APNe observations in the mm and sub-mm can be divided into two phases. In the first phase, the observations were made using single-dish telescopes. The angular resolution for single-dish observations is set by the diffraction of the telescope
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($\sim \lambda/D$, where $D$ is the diameter and $\lambda$ the wavelength) typically $\sim 10-60''$; the unit of information is the spectrum; and spatial information is obtained by moving the telescope. One basic contribution of the single-dish work has been in setting the baseline for mass-loss on the AGB. Early detections (e.g., Knapp et al. 1982) spawned numerous surveys, so that we now know the expansion velocity and mass-loss rates of many AGB stars. A second contribution of single-dish observations has helped develop one of the central ideas of PN formation: the ejection of neutral gas in the transition from the AGB. The neutral gas can be traced from the AGB, through pre-PNe, to *bona fide* PNe (e.g., Huggins et al. 1996), and it makes a direct connection to the ionized nebulae and their asymmetric structures. A good example is the CO distribution in the Helix nebula (Young et al. 1999). A further contribution of single dish observations has been the discovery of high velocity wings in the spectra of pre-PNe and young PNe. This has revealed a new ejection mechanism with a momentum excess which we associate with the launching of jets (Bujarrabal et al. 2001) but do not fully understand.

![Figure 1. Examples of CO line interferometry of APNe. Left: Image in CO (1–0) integrated intensity of the disk in KpN 8 (Forveille et al. 1998). Right: CO (2–1) intensity contours of the waist in He 3-1475, superposed on optical HST image (Huggins et al. 2004).](image)

The second phase of mm and sub-mm observations of APNe has involved the use of interferometers (notably BIMA, OVRO, SMA, and the IRAM Plateau de Bure) which provide images/data cubes at higher angular resolution than single-dish telescopes, from $\sim 5''$ to as high as $\sim 0.5''$. CO line interferometry of the circumstellar envelopes of AGB stars (e.g., Fong et al. 2006, Castro-Carrizo et al. 2007, see also Alcolea, this volume) shows that most (though not all) envelopes are roughly spherically symmetric, but exhibit multiple arcs and other asymmetries. This sub-structure in the envelopes is also seen in images of dust-scattered light at optical wavelengths (e.g., Mauron & Huggins 1999, 2006).

CO line interferometry of pre-PNe and young PNe, especially in conjunction with optical HST imaging, has produced striking results. Two examples, observed with the Plateau de Bure interferometer in the CO (1–0) and CO (2–1) lines, are shown in Fig. 1. Recent examples in other CO lines include: $^{13}$CO (2–1) in M1-92 (Alcolea et al. 2007), CO (3–2) in IRAS 22036+5306 (Sahai et al. 2006), and CO (6–5) in CRL 618 (Nakashima et al. 2007). These and similar observations provide a common picture of
early PN formation consisting of enhanced mass-loss in slowly expanding equatorial tori, with molecular gas entrained in jets along bi-polar or multi-polar axes.

The results to date reveal a rich phenomenology on size scales of $10^{16}$–$10^{17}$ cm which is partly explored but not understood. A number of physical processes may be responsible for the outflows that produce the asymmetries. For example, a torus could be produced by rapid rotation, a magnetic explosion, gravitational focusing by a companion, leakage from Roche lobe overflow, or ejection during a common envelope phase. However, there is a lack of quantitative prediction that can clearly discriminate between the various scenarios. The advent of new opportunities to study these phenomena at higher resolution with ALMA offers the possibility of important breakthroughs.

3. ALMA

ALMA is a large, imaging interferometer that will operate in the mm and sub-mm wavebands. It is an international collaboration of North America, Europe, Japan, and Taiwan, in co-operation with Chile. The telescope, which is now being built, will be a significant advance on current mm and sub-mm instrumentation in terms of angular resolution, wavelength coverage, and sensitivity. Part of the array is expected to become available for early science in 2011.

| Table 1. Characteristics of ALMA |
|----------------------------------|
| number of antennas               | 50 (12 m) + ACA |
| frequency range                  | 31–950 GHz |
| maximum baselines                | 0.2–16.3 km $B_{\text{rms}} = 0.079$–6.6 km |
| primary beam ($\theta_p$)        | $21'' \times 300/\nu_{\text{GHz}}$ |
| synthesized beam ($\theta_s$)    | $0.08'' \times 300/\nu_{\text{GHz}} \times 1\ km/B_{\text{rms}}$ |
| continuum sensitivity$^1$        | 0.10 mJ |
| line sensitivity$^2$             | $0.10 \ K (\theta_s = 1.5'') - 709 \ K (\theta_s = 0.018'')$ |

$^1$ Band 6 (211–275 GHz), $t = 60 \ s$  $^2$ Band 6, $t = 60 \ s$, $\Delta V = 1 \ km \ s^{-1}$

For technical information about ALMA, a useful introduction for newcomers is the document: *Observing with ALMA – A Primer*, by Doug Johnstone and colleagues. This and other technical information, including an exposure calculator, can be found at the websites of the ALMA Regional Centers. Additional technical information, and many interesting scientific perspectives can be found in the volume: *Science with the Atacama Millimeter Array: A New Era for Astrophysics* edited by Bachiller & Cernicharo (2008).

Some of the principal characteristics of ALMA that determine how it might be used to observe APNe are listed in Table 1. The main array will consist of at least 50 × 12 m antennas, augmented by an additional small array of 7 m and 12 m antennas – the Atacama Compact Array (ACA) – that can be used for wider field observations, and for total power measurements.

ALMA will be equipped with an extensive complement of receivers that will eventually cover almost the entire mm and sub-mm frequency range from 31 to 950 GHz. The initial receiver development is for wavebands in the range 84 to 720 GHz. The array is located at a high (5,000 m), dry site to minimize atmospheric effects. Even so, the atmospheric transmission at frequencies above about 400 GHz is typically less than 50%, so this needs to be taken into account in planning observations.
The field of view of ALMA (the primary beam, $\theta_p$) is determined by the diffraction of the individual 12 m antennas. $\theta_p = 21''$ at 300 GHz and varies as $\nu^{-1}$. Thus the field of view is very small by the standards of optical imaging. The field can, of course, be extended by making additional, adjacent observations (mosaicing) at the expense of additional observing time.

The angular resolution of ALMA (the synthesized beam, $\theta_s$) is determined by the diffraction of the array (see Table 1). $\theta_s$ varies as $\nu^{-1}$, and at a given frequency can be varied by a factor of $\sim 10$ according to the chosen array configuration, which is characterized by the rms baseline $B_{\text{rms}}$. Common setups are likely to have a synthesized beam of $\sim 0.1''$, so the impact of the instrument in terms of angular resolution will be somewhat similar to the impact of the HST at optical wavelengths. At the highest frequencies and most extended baselines, the resolution is better than 0.01'', although this is likely to be used only for special applications.

The resolution of the array is not an independent quantity, because it is closely linked to the sensitivity of the observations. In measuring the surface brightness of a spectral line, the noise level (in K) varies according to the expression:

$$\Delta T_{\text{rms}} \propto \frac{\eta}{\theta_s^2} \frac{1}{\sqrt{N(N-1)}} \frac{1}{\sqrt{N_p}} \frac{T_s}{\sqrt{\Delta \nu t}}$$

where the first factor on the right hand side is the ratio of the primary beam to the synthesized beam, $\eta$ lumps together various efficiencies, $N$ is the number of antennas, $N_p$ is the number of polarizations, and the last factor is the usual radiometer equation, with $T_s$ the system temperature, $\Delta \nu$ the observing bandwidth, and $t$ the observing time. Thus the noise level is proportional to the inverse square of the synthesized beam. For specificity, some numerical examples for the sensitivity in Band 6 (211–275 GHz) are given in Table 1, for an observing time of 60 s, and (for a spectral line observation) an effective resolution of 1 km s$^{-1}$. The back-end of the ALMA system (the correlator) is extremely flexible and is likely to cover all the spectroscopic requirements of the APN field. The sensitivity in the continuum is particularly high because of the wide (8 GHz) bandwidth available.

From the equation above, it can be seen that the large number of antennas ($N = 50$) plays an important role in the sensitivity of the array. The corresponding number of baselines, given by $N(N - 1)/2$, is even larger (1225). This means that the $u - v$ (Fourier) plane is well sampled, and leads to high quality imaging, even in snapshot (short-exposure) modes. Overall, the gain in sensitivity compared to the state-of-the-art Plateau de Bure interferometer (at $\sim 230$ GHz for the same synthesized beam, etc.) is a factor of $\sim 15$–20. The images shown in Fig. 1 could in principle be obtained in observing times $\sim 1$ min. Thus ALMA is indeed a major development in mm and sub-mm instrumentation.

4. Strategies and Projects

There are many ways in which the capabilities of ALMA can be used to study APNe. Strategies range from using the speed of the instrument to carry out snapshot surveys, to exploiting the highest resolution modes to probe details of objects of special interest. Here we outline some of the possibilities, with an emphasis on the scientific objectives.
Prospects for APNe with ALMA

4.1. AGB Stars

Olofsson (2008) has reviewed the general prospects for AGB stars with ALMA, and the reader is referred to his paper for details. Important developments will be observations of the dust forming regions, and sensitive studies of the chemistry. For APNe, one interesting aspect is that the photospheres and close environs of the nearest AGB stars will be resolved in the continuum with ALMA in the highest resolution configurations. This is a new type of probe at these wavelengths and may have an important bearing on understanding early APN formation. Low luminosity companion stars will not be directly detected in the glare of the AGB star, but they could generate detectable regions of ionized gas under some circumstances, as in the case of Mira at longer wavelengths (Matthews & Karovska 2006).

4.2. AGB Envelopes

As the precursors of APNe, the circumstellar envelopes of AGB stars provide a number of important constraints on the origins of PN asymmetries. First, there is good evidence from optical HST imaging for incipient core activity in some AGB envelopes, as discussed by Sahai (this volume). This activity may be caused by young or weak jets, or some other type of activity which has not yet fully developed. Thus it would be important to determine how widespread this core activity is, and to characterize its structure and kinematics. This could be done using CO line observations of envelope cores at high resolution.

A second perspective on AGB envelopes is directly concerned with probing the presence of a binary companion. If axi-symmetry is induced by interaction with a companion, the secondary star must have been present throughout the entire AGB phase and should leave its imprint on the circumstellar envelope, as emphasized by Huggins et al. (2009).

One way the imprint is effected is that the reflex motion of the AGB star induces a spiral pattern in the circumstellar envelope (e.g., Mastrodemos & Morris 1999; see also Raga, this volume). A clear example of the spiral pattern has been seen in the circumstellar envelope of AFGL 3068 (Mauron & Huggins 2006; Morris et al. 2006) in dust-scattered light observations. This pattern may also be detectable in CO or some other line affected by the weak spiral shock. The radial wavelength of the spiral is \( \lambda \sim \frac{VP}{2\pi} \) where \( V \) is the expansion velocity of the envelope, and \( P \) is the period of the binary. For AFGL 3068 \( P \sim 800 \) yr and \( V \sim 14 \) km s\(^{-1}\). At a distance of \( \sim 1 \) kpc, the angular separation of the arms is \( \sim 2" \). Thus the pattern is in principle relatively easy to resolve at high resolution in other nearby systems with intermediate or long periods.

A related signature of a companion star is the degree to which its gravitational field flattens the AGB envelope. This global shaping of the envelope is the simplest characteristic of a binary companion to observe on a large scale. The magnitude of the effect, which depends on the companion mass and separation and the wind velocity, has been discussed in detail by Huggins et al. (2009). The angular size of an AGB envelope in CO for a mass-loss rate \( \sim 10^{-5} \) M\(_{\odot}\) yr\(^{-1}\) is \( \sim 25"/D_{\text{kpc}} \) where \( D \) is the distance. Thus envelope shapes can be measured for large numbers of AGB stars to probe this effect.

4.3. Magnetic Fields

The role of magnetic fields in AGB stars and PNe has long been a controversial topic. The problem used to be magnetic fields versus binary companions for shaping PNe,
but now that companions seem to be fairly common, and their interactions can generate magnetic fields, the issue has changed focus. There is probably a consensus that MHD is needed to launch and form jets (Frank, this volume). The main issue seems to be: what else do magnetic fields do?

Radio astronomers have long reported the presence of dynamically important magnetic fields in maser spots in AGB envelopes (e.g., Bains, this volume). However, the spots are small, so there is a question whether the strong fields are local or global. Herpin et al. (2009) have recently reported magnetic field measurements using mm CN emission (which is not in spots) at levels equivalent to the fields in the spots. Hence the fields may be globally important. ALMA’s ability to measure polarization and thereby to map the magnetic field strength and geometry is likely to be important in sorting out this issue. See Vlemmings (this volume) for more details.

4.4. Shaping in Pre-PNe

One of the most direct applications of ALMA to the problems of APN formation will be in characterizing the early jet shaping in pre-PNe. As explained in Sect. 2, there is already a generic picture (at least for a subset of PNe), based on current interferometry, as shown in the left hand panel of Fig. 2.

This picture is only partly explored by current observations. The detailed properties accessible to line observations with ALMA include: the geometry and kinematics of the jets and equatorial outflows, the energy and momentum budget, and possible connections with extended circum-binary disks, which are common in other classes of post-AGB stars. A systematic investigation of these and related properties is likely to provide important clues on the physics that controls the outflows. For example, one result based on current mm interferometry is that the kinematic ages of jets and tori are correlated (Fig. 2). They have nearly the same ages, and are therefore ejected nearly simultaneously (Huggins 2007). This points to a fundamental connection between the outflows. It rules out some classes of physical model, and even suggests that slight timing differences between jets and tori can probe the properties of unseen accretion disks.
that are believed by some to be responsible for launching jets. Much more detailed information along these lines is expected to be very productive.

4.5. Globules and Debris Disks

ALMA also has interesting applications in fully developed PNe. One is probing the excess long wavelength continuum emission from debris disks surrounding the central stars of some PNe. The first of these was detected using Spitzer observations of the Helix nebula (Su et al. 2007). The estimated size is ~100 AU. Although the dust continuum is expected to be falling in the sub-mm and mm wavebands, the emission from the nearest examples is detectable with ALMA and the structure should be resolved.

A second application to bona fide PNe is the small scale structure in the neutral gas – the globules, as exemplified by those in the Helix nebula. The Helix globules are about 1′ in diameter with extended tails, and have already been partially resolved using mm interferometry in CO (Huggins et al. 2002). A full characterization of the internal structure and kinematics of the globules and their tails is entirely feasible in the Helix and other nearby PNe, and would be an important step in refining our understanding of their origins.

5. Concluding Remarks

ALMA will be a significant advance on current mm and sub-mm instrumentation, and it will have considerable impact in many areas of astronomy. For APNe, there are major unsolved problems, especially with the physical processes that generate the asymmetries. Several aspects of these are well suited to ALMA’s capabilities. Some approaches are direct extensions of current interferometric observations to higher resolution and sensitivity (e.g., CO imaging), and some are new types of probes (e.g., line polarization). Overall the prospects are excellent for taking the field of APNe forward to the next level.

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