Mass loss in AGB Stars - Recent Observational Developments

Raghvendra Sahai[1]

Jet Propulsion Laboratory, California Institute of Technology
MS 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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Address for proofs: Jet Propulsion Lab, MS 169-506
4800 Oak Grow Drive, Pasadena, CA **91109,** USA

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[1] Senior Resident Research Associate, National Research Council, National Academy of Sciences, Washington, DC 20418

Abstract: Extensive mass-loss in red giant (AGB) stars, preceding and leading up to the formation of planetary nebulae, has important consequences for the evolution of the stars as well as the interstellar medium. A brief review, with focus on new studies of mass-loss envelopes involving high-spatial resolution observations made possible by recent technological advances, is presented.

Key words: mass-loss, red giants, planetary nebulae, interferometery, infrared, radio, circumstellar matter

1. Introduction; Extensive mass-loss (with dM/dt upto $\sim 10^{-4} M_{\odot} yr^{-1}$) in intermediate mass (1-8 $M_{\odot}$) stars not only affects their evolution on and beyond the asymptotic giant branch (AGB), preventing stars with masses upto $\approx 8 M_{\odot}$ from becoming supernova, but also enriches the interstellar medium in (i) a variety of nuclides produced by CNO, 3-α and s-process nucleosynthesis, and (ii) dust grains. The circumstellar envelopes (CSEs) resulting from the mass-loss usually have relatively simple and well-defined geometrical (spherical) and kinematical (radially-constant expansion velocity) structures, and thus constitute ideal astrophysical laboratories. Thus, some of the most difficult problems of interstellar cloud chemistry, such as the role played by dust grains, UV radiation, and shocks in the formation and destruction of different molecular species, may ultimately be solved by a study of circumstellar chemistry.

2. **Outstanding Problems:** We lack a theory which can predict the basic mass-loss properties, namely, the rate (dM/dt), expansion velocity (Vexp), and the spatial distribution, from fundamental stellar parameters - luminosity, temperature, and metallicity. A number of hypotheses for mass-loss in cool red giants have been investigated (e.g. Holzer and MacGregor 1985) and a two-step process is currently favoured, whereby stellar matter is first levitated by various processes (e.g. stellar pulsation: Bowen and Willson 1991, sound waves: Pijpers et al. 1990) into an extended atmosphere where grains form. which are then driven outwards (dragging the gas along) under radiation pressure (e.g. Morris 1987). However important questions relating to the history (continuous or episodic) and structure (e.g. smooth or clumped) of the mass-loss, the formation and growth of dust grains, remain unanswered. The origin of equatorially dense structures and fast outflows (50- 100 km s^{-1}) on small angular scales seen in an increasing number of objects with extended spherically symmetric envelopes (e.g. CRL2688: Kawabe et al. 1987) is not clear: models involving binary companions (Morris 1987), planetary systems (Sahai et al. 1991), and magnetic fields (Pascoli et al. 1992.) have been suggested.

3. **Recent Developments:** Until recently, most of our knowledge about CSEs came from observations of millimeter-wave molecular lines using single telescopes. With significant

increase in telescope/receiver sensitivity and the detection of thousands of AGB stars in 12-100 μm emission by IRAS, ~few x 100 CSEs have now been detected through systematic searches (the largest carried out with the IRAM[2] 30-m & the SEST[3] 15-m) in the CO J=1-0 and 2-1 lines (compilation by Loup et al. 1993). Although such studies provide useful information on the envelope-averaged dM/dt and Vexp necessary for studying the statistics of mass-loss, (e.g. Jura & Kleinmann 1989, and references therein) more fundamental questions relating to the nature of the mass-loss can only be addressed with high spatial resolution observations. A new self-consistent model of radiative transfer, molecular excitation, and thermodynamics which simultaneously fits the CO rotational line-emission and the far-infrared (IRAS) emission from CSEs has been developed for reliable estimates of mass-loss rates and circumstellar dust-to-gas ratios (Sahai 1990).

a) Millimeter (& centimeter) wave interferometry. With the advent of millimeter-wave interferometers[4], one can now observe a large number of circumstellar envelopes with adequate spatial resolution. Most studies have focussed on the prominent carbon-rich CSEs. Bieging, Chapman & Welch (1984) reported the first interferometric map of molecular line emission from a CSE: their map of HCN 1-0 in IRC+10216 (well-studied carbon star) suggested a recent decrease in the mass-loss rate (later confirmed by analysis of CO 4.6 μm and mm-wave line emission: Sahai 1987, Sahai & Wannier 1985). Bieging & Nguyen-Q-Rieu (1988a) find evidence for a rotating disk in the protoplanetary object CRL 2688 from HCN 1-0 mapping (BIMA data). VLA[5] mapping of cm-wave line emission of NH_3 & HC7N in CRL 2688 (Nguyen-Q-Rieu et al. 1986) reveal both disk and jet-like structures, as well as departures in the kinematics from pure expansion. Detailed information on the distribution and abundances of various molecules has been obtained for IRC 10216 (VLA maps of NH_3, HC7N and HC_3N by Wootten et al. 1993, BIMA maps of SiS, HC_3N, C_3N, C_2H, HNC by Bieging & Nguyen-Q-Rieu 1988b, Bieging & Tafalla 1993) and CRL 2688 (Nguyen-Q-Rieu & Bieging 1990), providing confirmation of some of our ideas of circumstellar chemistry, as well as raising new problems. Neri et al. (1993) have resolved the HCN 1-0 emission (PdBI data) from the unique high-velocity (200 km/s) outflow in CRL 618 (very young PN), from which they infer that HCN is formed (on a time-scale < 50 yr) in a post-shock region where the high-velocity outflow impacts a more slowly expanding dense envelope. Sahai and Bieging (1993) have used BIMA to map the J=2-1 (v=0) SiO line emission at 86 GHz in oxygen-rich CSEs (see also Lucas et al. 1993), and find that (a) SiO is depleted

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[2] Institut de Radio Astronomie Millimétrique, Grenoble, France

[3] Swedish-ESO-Submillimeter Telescope, La Silla, Chile

[4] these are the Berkeley-Illinois-Maryland Array, Hatcreek (BIMA) and Owens Valley Radio Observatory (OVRO) interferometers in the USA, the Nobeyama Radio Observatory (NRO) interferometer in Japan, & the IRAM interferometer (PdBI) in France

[5] Very Large Array, Socorro, New Mexico

rapidly beyond 0 ^{5}, probably as a result of adhesion onto cold grains (photodissociation due to the interstellar UV becomes important at $>0.5\times10^{16}$ cm) (b) acceleration of the outflows is consistent with radiation pressure on grains condensing within 0-15 stellar radii.

(b) Submillimeter- line observations Observations at submillimeter wavelengths have now become possible with the 15-m JCMT[6] and 0m CSO[7] telescope allowing one to use high-excitation molecular lines as a novel probe of the inner CSEs, one which works equally well for nearby and distant objects. Sahai, Wannier, Andersson (1992) have observed a selected list of CSEs with prominent SiO J=2- (v=0) emission, in the J=5-4, 6-5, 8-7, and 1-10 lines. The high-J SiO line-widths at the base are only 50-75% of the CO line-widths (=2 x terminal envelope expansion velocity) clearly showing that the SiO lines arise in the acceleration region. A map of IRC102 6 (which appears circular on arc-minute scales in CO J=1-0 and 2-1 line emission) in the CO 6-5 line made with the 8" beam of the JCMT, shows that the peak emission occurs about 6" south-west of the stellar position (Sahai, van der Veen, and Stutzki 993).

(c) Molecular Gas in Planetary Nebulae:. AGB mass-loss plays an important role in the formation of planetary nebulae (PNe). The "interacting-stellar-winds" (ISW) model (Kwok 1982) succesfully produces the dense "rims" seen in PNe images, due to the "snowplow" action of a very fast wind (000-2000 km/s) from the central white dwarf, on the AGB envelope. Including an equatorial-to-polar density asymmetry of the AGB envelope in the ISW model (Balick 1987) naturally leads to the bipolar shapes seen in about 50% of all PNe. Until recently, it was difficult to detect the generally weak CO emission from PNe. However, CO emission has now been mapped in a number of PNe, confirming (directly or indirectly) the presence of equatorial density enhancements and/or fast outflows directed along the polar axis (NGC7027: Bieging et al. 1991 & Jaminet et al. 199 , NGC3132: Sahai, et al. 1990, IC4406: Sahai et al. 199 , NGC2346: Bachiller et al. 1989). High-resolution (2'') CO J=2- of PNe (e.g. Bachiller et al. 1993 and references therein) show large-scale (10^{17} cm) fragmentation of their molecular envelopes, and the detection of molecules with large dipole moments (e.g. HCN and HCO^{+}) in PNe (Sahai et al. 1993a) imply the presence of small (10^{15}-10^{16} cm), dense (10^{5} cm^{-3}) clumps (Sahai et al. 1993b).

(d) Near- Infrared Imaging: The interface between the ionised and neutral (molecular) region in PNe is a source of strong emission in the near-IR vibration-rotation lines of molecular hydrogen, which can now be mapped with high spatial and spectral resolution, with the advent of infrared CCD-array cameras and spectrometers. Images of the integrated H_2 S(1) line emission at 2. μm from the compact young PN NGC7027 shows an incomplete elliptical ring of knots bounding the ionised gas, and a thin shell looping around the region with 4-fold symmetry,

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[6] James Clerk-Maxwell Telescope, Mauna Kea, Hawaii

[7] Caltech Submillimeter Observatory, Mauna Kea, Hawaii

coincident with the inner edge of' the CO shell (Graham et al. 1993). Velocity-resolved (long-slit) images of the H_2 S(1) line in another compact young PN, BD+30°3639 (taken with the CSHELL/IRTF[8]) show that the molecular gas is concentrated in a clumpy, tilted toroidal structure (Wannier & Sahai 1992), apparently the result of a collimated high-velocity flow excavating a bipolar cavity in an AGB CSE.

4. **Future Prospects:** A systematic survey undertaken with the upcoming Giant Meter wave Radio Telescope (Punt, India) should produce a substantial increase in the number of AGB stars detected in HI (only 2 detected so far, see Bowers and Knapp 1988), providing the first direct estimates for mass-loss rates, total envelope masses and ages. Increasing use of mm wave (and future submm-wave) interferometers, infrared CCD-array cameras coupled to high-resolution spectrometers, and submillimeter telescopes, in observations of AGB stars and PNe, will lead to a detailed and comprehensive picture of the history and structure of the mass-loss during late stellar evolution.

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[8] Cryogenic Echelle Spectrograph/ Infrared Telescope Facility (NASA), Mauna Kea, Hawaii

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