CO IN PLANETARY NEBULAE AND PROTO-PLANETARY NEBULAE

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The evolution between the asymptotic giant branch (AGB) and the planetary nebula (PN) phases has long been a "missing link" in our understanding of stellar evolution. Through the study of cool IRAS sources, an increasing number of transition objects, or "proto-planetary nebulae", has now been identified. The CO molecule has been found to be a useful tracer of the evolution from the AGB to PN. The detection of CO emission in PNe represents a key piece of evidence that PNe are created from the circumstellar envelopes of AGB stars through the interacting winds process.

1. Introduction

The field of stellar evolution between the asymptotic giant branch (AGB) and planetary nebulae has been very active in the last decade. Since 1986, there have been at least ten conferences devoted to this subject (Kwok & Pottasch 1987; Preite-Martinez 1987; Torres-Peimbert 1989; Mennessier & Omont 1990; Schwarz 1993; Sasselov 1993; Acker & Weinberger 1993; Clegg et al. 1994; Tylenda 1994; Harpaz & Soker 1995). In this talk, I can only give a very brief summary of the recent developments, and the readers are encouraged to get a more comprehensive picture by consulting the above conference proceedings. In line with the theme of this conference, I will emphasize the role that the CO molecule has played in our understanding of the late stages of stellar evolution, in particular in the search for proto-planetary nebulae (PPN).

2. Effects of Mass Loss on the Late Stages of Stellar Evolution

One of the major breakthroughs in the field of stellar evolution in the 1970s was the discovery of large-scale mass loss on the asymptotic giant branch. The evidence for such mass loss first came in infrared photometry, where large infrared excesses were found to be common in late-type stars (Gehrz & Woolf 1971). The detection of thermal emission from CO confirms that gas, in addition to dust, are being lost (Solomon et al. 1971), and CO observations have allowed accurate estimates of the mass loss rates in hundreds of stars (Knapp et al. 1982; Loup et al. 1993).

The rate of mass removal by stellar winds from the surface was found to be much larger than the rate of nuclear burning in the core. The AGB is therefore terminated by the complete depletion of the hydrogen envelope by stellar winds, and carbon may never be detonated under degenerate conditions. The observed mass loss rates of $10^{-6} - 10^{-4} M_\odot$ yr^{-1} will allow stars with initial masses as high as 8 $M_\odot$ to end their lives as white dwarfs, and several $M_\odot$ of neutral material can be ejected over the short ($\sim 10^6$ yr) AGB lifetime of a star.

The detection of CO in the planetary nebula NGC 7027 came as a surprise not only because the molecule has survived in the ionized environment of the PN, but also that the observed mass of the molecular gas ($> 1 M_\odot$) is much higher than the ionized masses ($\sim 0.1 M_\odot$) usually associated with PNe (Mufson et al. 1975). Far infrared observations have also revealed that a large fraction of the total PN energy output is from the neutral component (Zhang & Kwok 1991). If the molecular envelopes observed in PN represent the remnants of the circumstellar envelopes of AGB stars, then stellar winds from AGB stars, not a sudden ejection at the end of the AGB, must be responsible for the formation of PN. This has led to the proposal of the interacting winds model, where a fast wind from the central star compresses and accelerates the remnant AGB wind material, to be the mechanism for the formation of PN (Kwok et al. 1978; Kwok 1982). The interacting winds model predicts the following components in a PN system in addition to the high-density shell: (i) a fast wind, (ii) a halo, and (iii) a hot bubble, all of which have been detected since their prediction (Heap et al. 1978; Chu et al. 1987; Chu & Ho 1995).

3. CO in Planetary Nebulae

The first extensive survey of CO in PN was done by Huggins & Healy (1989) using the NRAO 12 m. Approximately 20% of the 100 PN observed were detected. The amount of molecular mass derived ranges from 10^{-3} to 1 $M_\odot$, and in many cases larger than the amount of ionized mass derived from radio continuum observations. The detection of this previously-unseen mass component conveniently solves the "missing mass" problem in PN (cf. Kwok 1994), where the observed "nebular+stellar" masses of PN are found to be much smaller than the main-sequence masses of their progenitors

(1–8 $M_\odot$). Huggins & Healy (1989) also found that the molecular mass to ionized mass ratio decreases with increasing nebular radius, and suggest that the molecular envelope is gradually depleted by photo dissociation as the nebula evolves.

3.1. MOLECULAR GAS DISTRIBUTION IN PN

With the advent of mm interferometry, a number of PN have been mapped in CO (Bachiller et al. 1989a,b; Bieging et al. 1991). The CO emission regions are generally found to lie outside of the ionized nebula, confirming that the molecular gas represents the remnant of the AGB envelope. The ionized nebula of NGC 7027 ($\sim 10''$) fits neatly into the central minimum of the CO distribution (Bieging et al. 1991). Similar molecular cavities corresponding to the size of the ionized region have also been seen in IRAS 21282+5050 (Likkel et al. 1994; Deguchi 1995). IRAS 21282+5050 is a particularly interesting PN for most of its energy is emitted from the neutral component (Kwok et al. 1993). The CO map of M1-7 (Shibata et al. 1994) shows a double-peaked structure, very similar to the radio continuum structure of most PN. An inner bright ring is seen in the CO map of NGC 7027, suggesting that the molecular gas is compressed by the shock front created by the interacting winds process (Bieging et al. 1991). Comparison of the CO and H_2 maps of NGC 6720 also suggests that a shock is propagating into the molecular envelope (Greenhouse et al. 1988).

3.2. MOLECULAR HYDROGEN EMISSION

The 2.121 μm v=1–0 S(1) electric quadruple vibration-rotation line of H_2 is widely observed in PNe (Latter et al. 1995). It is excited either by shocked gas or fluorescence (Dinerstein et al. 1988). The H_2 line is therefore useful as a probe of the dynamics or the radiation distribution in a PN. It has been suggested that PNe of "butterfly" or "bipolar" morphology have a higher probability of having H_2 emission (Kastner et al. 1994). This correlation could be explained by PNe of these morphological types having higher progenitor masses, which have higher mass loss rates and shorter transition times between the AGB and PN.

4. CO in Proto-Planetary Nebulae

Proto-planetary nebulae, defined as objects in transition between AGB and PN phases, are expected to contain a blueward-evolving central star surrounded by a dust envelope ejected during the AGB phase. Due to the low temperatures of the dust envelopes, PPN should appear as far-infrared sources and can be found among IRAS sources of low color temperatures

(100-200 K). As the central star emerges from the dispersing dust envelope, PPNe will take on a "double-peaked" energy distribution showing both the photospheric and dust components. The central stars of PPNe are found to be mainly of F or G spectral types, and have luminosity classes of I, corresponding to the Class I low surface gravity expected of such objects. Over 30 PPNe have been identified to date (Kwok 1993).

The detection of circumstellar CO emission quickly followed the identification of PPNe (Woodsworth et al. 1990; Likkel et al. 1991; Bujarrabal et al. 1992). The CO observations confirm that these "yellow supergiants" are indeed evolved objects, and their CO envelopes represent the remnant of the AGB mass loss. A summary of the CO observations of PPN is given in Table 1.

Most of the PPN are not resolved in CO, except in the two well-known nearby candidates AFGL 618 and AFGL 2688. In spite of the extremely bipolar morphology of the optical reflection nebulae in these two objects, the CO envelope outside is remarkably symmetric (Deguchi 1995), suggesting that a morphological change occurred during the transition period.

4.1. HIGH VELOCITY GAS IN PPN

One of the major uncertainties in post-AGB evolution is when does the fast wind begin? A significant rate of mass loss during the post-AGB (and pre-PN) evolution will greatly shorten the transition time from AGB to PN. While the PN central-star winds can be detected by P Cygni profiles of the UV-resonance lines, they are difficult to detect before ionization. The only evidence for the existence of a central-star wind during the PPN phase is through the detection of extended wings of the CO line.

The development of SIS receivers has allowed the detection of weak, extended line wings of CO in the PPN AFGL 618 (Gammie et al. 1989; Cernicharo et al. 1989) and AFGL 2688 (Young et al. 1992; Jaminet et al. 1992). Molecular winds of velocities of approximately ten times higher than the AGB wind velocities have been found. Such velocities are in the range of expected escape velocities for the spectral types (B and F) of AFGL 618 and AFGL 2688.

4.2. VIBRATIONAL-ROTATIONAL TRANSITIONS OF CO IN PPN

The vibrational band of CO is one of the strongest absorption features observed in the near infrared spectra of late-type stars. Recent high-resolution infrared spectroscopic observations have detected first overtone ($\Delta v = 2$) vibrational bands of CO in absorption up to $v = 8$ in many PPNe (Hrivnak et al. 1994). Most interestingly, the CO spectrum of IRAS 22272+5435 was found to change from emission to absorption over a 3-month period, sug-

TABLE 1. PPNe detected in CO

IRAS name	Line	$T_{\rm mb}$ [K]	$\int T\,dV$ [K km s^{-1}]	$V_{\rm e}$ [km s^{-1}]	$V_{\rm lsr}$ [km s^{-1}]	Telescope	Ref
04296+3429	2–1	0.4	...	15.6	−62	JCMT	1
	2–1	0.45	8.3	12.0	−66	IRAM	2
07134+1005	1–0	1.3	21	...	72	IRAM	3
	1–0	0.4	6	11.0	75	SEST	4
	2–1	2.2	28	...	73	IRAM	3
	2–1	3.2	44	10.2	73	IRAM	2
17436+5003	1–0	0.8	16	14.9	−35	IRAM	7
	1–0	0.9	19	...	−35	IRAM	3
	2–1	1.8	33	13.2	−35	IRAM	7
	2–1	2.0	36	...	−35	IRAM	3
19114+0002	1–0	1.7	76	...	99	IRAM	3
	1–0	0.3	16	30.4	99	SEST	4
	2–1	3.4	171	...	99	IRAM	3
	2–1	0.5	23	28.1	99	SEST	4
	3–2	2.1	110	37.1	98	JCMT	6
19500−1709	1–0	1.0	21	...	24	IRAM	3
	2–1	0.2	4	13.0	25	SEST	4
	2–1	1.9	48	...	23	IRAM	3
	3–2	0.4	7	13.2	26	SEST	4
22223+4327	1–0	0.25	2	15	−25	IRAM	7
	2–1	0.64	12.3	14.0	−30	IRAM	2
22272+5435	1–0	1.3?	18	10.5	−28	OSO	5
	2–1	3.1	...	9.6	−28	JCMT	1
	2–1	6.27	80	11.8	−28	IRAM	2
	3–2	3.2	38	9.8	−28	JCMT	6
22574+6609	1–0	0.3	10	24	−62	IRAM	7
	2–1	0.5	11	15	−64	IRAM	7
	3–2	0.7	8.3	20	−62	JCMT	6
23304+6147	1–0	0.6	10	8.0	−17	IRAM	7
	2–1	0.7	...	15.5	−16	JCMT	1
	2–1	1.6	25	11.5	−16	IRAM	7
	3–2	0.8	14	17.4	−13	JCMT	6
23321+6545	1–0	0.6	14	15.2	−56	IRAM	7
	2–1	1.2	28	17.0	−55	IRAM	7

1. Woodsworth et al. (1990); 2. Omont et al. (1993); 3. Bujarrabal et al. (1992); 4. van der Veen et al. (1993); 5. Lindqvist et al. (1988); 6. Kwok et al. (1995); 7. Likkel et al. (1991)

gesting recent episodes of mass loss. High-resolution infrared spectroscopic observations have resolved the rotational lines in the first overtone band of CO, and comparison between the observed and the predicted line velocities can be used to study the kinematics of the mass loss process.

4.3. DUST IN PPNE

While most of the dust in AGB stars can be identified as silicates (for oxygen-rich stars) or SiC or graphite for carbon-rich stars, PNe are known to show a family of infrared features attributed to Polycyclic Aromatic Hydrocarbons (PAH). The detection of PAH features in PPNe suggests that these molecules are either synthesized during the evolution to PNe, or produced in the AGB stellar envelopes but excited when the star becomes hotter. Most interestingly, nine carbon-rich PPNe are found to show a strong unidentified emission feature at 21 μm (Kwok et al. 1989; Kwok et al. 1995). This 21 μm feature is often accompanied by unusually strong 3.4–3.5 μm features (Geballe et al. 1994), as well as by an unidentified emission feature at 30 μm (Omont et al. 1995). The strength of the 21 μm feature suggests that it probably originates from a large carbon-based molecule.

5. The Interacting Winds Process as a Cause of "Bipolar" Morphology Observed in PN

It has been long known that most PNe are not spherically symmetric but have a "double-peaked" (sometimes referred to equivocally as "bipolar") morphology. The more extreme cases take on the form of a "butterfly" shape. This is true for the most evolved PNe (Balick 1987) to the youngest PN (Aaquist & Kwok 1990). Balick (1987) suggests that a diversity of PNe morphologies can be explained by the interacting winds process, where small degrees of asymmetries in the AGB envelope are amplified by the fast wind from the central star. Recent 2-D hydrodynamical models based on this idea have been very successful in simulating the observed morphologies of PNe (Mellema et al. 1992, Frank et al. 1993).

6. Planetary Nebula as an Evolving System

Recent multi-wavelength observations have found PNe to be active in almost in all wavebands between the X-ray and radio While the mass of the nebula is provided by the AGB progenitor star, it is constantly being shaped and pushed by a fast wind from the central star. As the star becomes hotter, both the mechanical output (mass loss rate and the wind velocity) and the radiative output (Lyman continuum photons) change, which results in the gradual acceleration and ionization of the nebula. The fact that PN is a

Figure 1. A schematic diagram of planetary nebula evolution.

time-dependent system, consisting of two tightly coupled components (star and nebula) evolving at different time scales, is a new concept with implications we are just beginning to appreciate (cf Kwok 1994). A schematic diagram showing the time-dependent radiative and dynamical interactions between the central star and the AGB wind is shown in Fig. 1.

7. Summary

The CO molecule has been shown to be a very effective tool in tracing stellar evolution from the AGB through the PPN phase to the PN stage. Millimeter-wave spectroscopy of the rotational lines of CO have revealed the presence of massive neutral halos in PNe. The discovery of this previously-undetected component has led to a revolution in our understanding of the origin and evolution of PNe. By interpolating the infrared and CO properties of AGB stars and PNe, we are able to search for and identify objects in transition between these two phases. The discovery of PPNe not only fills a "missing link" in the late stages of stellar evolution, but has also led to new challenges to our understanding of interstellar chemistry.

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