THE ORIGIN OF THE HIGH-VELOCITY BIPOLAR OUTFLOWS IN PROTOPLANETARY NEBULAE

V. Bujarrabal[1], A. Castro-Carrizo[1], J. Alcolea[1], and C. Sánchez Contreras[1,2]

[1]Observatorio Astronómico Nacional, Apartado 1143, E-28800 Alcalá de Henares, Spain
[2]Jet Propulsion Laboratory, MS 183-900, 4800 Oak Grove Drive, Pasadena CA 91109, USA

Abstract

Protoplanetary nebulae show fast bipolar flows that are known to carry high amounts of mass (a fraction of a solar mass), linear momentum and kinetic energy. In some nebulae, this momentum is so high that it cannot be provided by the stellar radiation pressure, given the expected short acceleration times and general conditions for the transfer of momentum to the gas. It is known that this component is, because of its low temperature, well probed by observations of mm-wave CO lines. We have studied all the protoplanetary nebulae that have been detected in CO up to date, a sample containing 37 objects. New accurate CO observations were performed for 16 of these objects. About 80% of the 27 objects for which the CO data allow a reasonable interpretation show these energetic flows. Radiation pressure could explain the whole dynamics of the nebulae in only 6 objects. Remarkably, 4 of these 6 objects are known to have low initial mass; excluding them, we find that less than 10% of the (well studied) protoplanetary nebulae do not show such very energetic bipolar flows.

It is thought that these bipolar flows are accelerated by shock interaction between the old AGB wind (dense and slow) and post-AGB bipolar ejections (fast but relatively diffuse). Such an interaction would be the main dynamical phenomenon in the protoplanetary evolution, i.e. in the planetary nebula shaping. However, the shock fronts themselves have not been studied yet. CO probes the already cooled material, and the shocked regions observed in the optical and NIR contain very small amounts of mass and kinetic energy; moreover, because of their spatial distribution, they often seem to correspond to inner shocks and not to the relevant forward shock. A very fast cooling or a very high obscuration may avoid its detection at these wavelengths. ISO observations of molecular and atomic lines could have detected this component, but the lack of velocity information avoids any clear identification and reliable study. The observation with high spectral resolution of intermediate-excitation lines at intermediate wavelengths (FIR) is necessary for such a task.

Key words: stars: AGB and post-AGB - stars: circumstellar matter – radio-lines:stars – planetary nebulae

1. Introduction

Recent detailed observations of molecular lines in the protoplanetary nebulae (PPNe) OH 231.8+4.2 (Sánchez Contreras et al. 1997), M 1–92 (Bujarrabal et al. 1998), HD 101584 (Olofsson & Nyman 1999), and M 2–56 (unpublished observations) have pointed out the presence of very massive bipolar outflows, carrying very high linear momenta and kinetic energy. Values of the nebular mass close to 1 $M_\odot$ are found, the kinetic momentum and energy being as high as $\sim 3\ 10^{39}$ g cm s^{-1} and $\sim 10^{46}$ erg, respectively. The gas in these outflows shows a very low excitation, with typical temperatures $\sim$ 10–20 K. The kinematics of these well studied objects is dominated by a bipolar fast expansion in the direction of the symmetry axis of the nebula, in which most of the momentum and energy flows. Outflow velocities ~ 100 km s^{-1} are found. It has been argued that this axial flows are the result of the acceleration of previous AGB wind, that is massive and slow, by shock interaction with the post-AGB ejections, that are fast and take mainly place in the axial direction.

Such a high linear momentum cannot apparently be supplied (by orders of magnitude) by radiation pressure, in the relatively short times during which we think that the wind interaction phenomenon took place, 100 – 200 yr. For example, in M 1–92, the momentum carried by the molecular outflow is $\sim 3\ 10^{39}$ g cm s^{-1}; the star emits about 4 10^{37} erg s^{-1}, equivalent in momentum to 4 10^{34} g cm s^{-1} per year. So the star would need about 10^5 yr to release such a high linear momentum, but the wind interaction probably lasted just ~ 100 yr. So, the radiation pressure does not have enough momentum by 2-3 orders of magnitude.

However, the question on whether these flows appear in very peculiar objects, not representative of post-AGB evolution and observed due to some strong selection bias, or are a systematic phenomenon in this evolutionary phase, is still not clear. In order to address this problem, we have cataloged all well identified PPNe showing CO emission; we have performed accurate new observations in some of these nebulae and have systematically calculated the nebular mass and the linear momentum and kinetic energy of the flows. Our work will be published in two papers. In Bujarrabal et al. (2001a), Paper I, we present the observational CO data and calculate these parameters. In Paper II (Bujarrabal et al. 2001b), we discuss the comparison of

Table 1. General properties of the PPNe that have been observed in CO: coordinates, systemic velocities, inclination of the nebula axis with respect to the plane of the sky (i), distance, and luminosity. Accurate new CO observations for the first 16 sources are presented in Paper I. See other names, references, and further comments in Paper I.

name	coordinates α (2000)	δ (2000)	$V_{sys}LSR$ (km s^{-1})	spectral type	i (°)	D (kpc)	L ($10^3 L_\odot$)	comments
IRAS 04296+3429	04 32 57.0	34 36 13	-65	6500(F5)	25	5?	7	
CRL 618	04 42 53.4	36 06 54	-21	B0	45	1.7	30	
Frosty Leo	09 39 54.0	11 58 54	-12	K7III	15	3	2.7	
IRAS 17436+5003	17 44 55.5	50 02 40	-35	F2-5Ib	?	4	60	
He 3–1475	17 45 14.1	-17 56 47	48	Be	60	5	9	
89 Her	17 55 25.1	26 02 59	-8	F2Ibe	ISOT.	0.6	3.3	low-mass PPN
AFGL 2343	19 13 58.6	00 07 32	98	G5Ia	ISOT.	5.6	580	yellow hypergiant
IRC +10420	19 26 48.0	11 21 17	76	F8Ia	ISOT.	5	700	yellow hypergiant
IRAS 19500-1709	19 52 52.6	-17 01 50	25	F2-6	?	1	1.5	
CRL 2477	19 56 48.4	30 44 00	5	?	?	1.3	4	PPN?
CRL 2688	21 02 18.8	36 41 38	-35	F5 Iae	15	1.2	25	
NGC 7027	21 07 01.6	42 14 10	26	pec.	30	1	10	young PN
IRAS 22272+5435	22 29 10.4	54 51 07	-28	G5Ia	30	1.7	8.3	
IRAS 23304+6147	23 32 45.0	62 03 49	-16	G2Ia	90?	1.3	1	
IRAS 23321+6545	23 34 22.7	66 01 51	-55	?	?	?	0.6	
M 2–56	23 56 36.1	70 48 17	-27	Be	15	3	10	
Red Rectangle	06 19 58.2	-10 38 15	0	A1	15	0.38	1	low-mass PPN
IRAS 07134+1005	07 16 10.3	09 59 48	72	F5	50	3	13.5	
OH 231.8+4.2	07 42 16.9	-14 42 50	33	M9III	40	1.5	10	well studied
Hen 3–401	10 19 32.5	-60 13 29	-30	B1	15?	3	3.6	
Roberts 22	10 21 33.8	-58 05 48	0	A2Iab	15	2	30	
HD 101584	11 40 58.8	-55 34 26	41	F0Iape	?	1	3	well studied
Boomerang Nebula	12 44 45.5	-54 31 12	-4	G0III	?	1.5	0.3	well studied
He 2–113	14 59 53.5	-54 18 08	-56	WC10	?	1.2	5	
Mz–3	16 17 13.6	-51 59 06	-17	B0	20	1.8	5.7	
M 2–9	17 05 37.9	10 08 32	80	Be	17	0.64	0.55	low-mass PPN
CPD –568032	17 09 00.9	-56 54 48	-60	WC10	?	1.5	5.2	
IRAS 17150–3224	17 18 19.7	-32 27 21	14	G2	?	2.42	11	
OH 17.7–2.0	18 30 30.7	-14 28 57	61	F0	?	2	2.9	
R Sct	18 47 29.0	-05 42 19	56	G0–K2	?	0.4	4	low-mass PPN
M 1–92	19 36 18.9	29 32 50	-1	B0.5IV	35	2.5	10	well studied
IRAS 19475+3119	19 49 29.6	31 27 16	18	F3Ia	?	6	12.6	
IRAS 20000+3239	20 01 59.4	32 47 32	14	G8Ia	?	?	0.55	
IRAS 20028+3910	20 04 35.9	39 18 45	6	?	?	2.5	6.6	
IRAS 21282+5050	21 29 58.5	51 04 01	18	O9.5,WC11	90	3	5.3	
IRAS 22223+4327	22 24 31.0	43 43 09	-30	G0Ia	?	?	0.36	
IRAS 22574+6609	22 59 18.3	66 25 47	-64	?	?	?	0.15	

our results with the momentum and kinetic energy that can be supplied by the stellar radiation pressure (including any possible increase of its efficiency) and by other possible mechanisms.

2. CO data and their interpretation

As we discuss in detail in Paper I, we have compiled the existing published data on CO emission from all nebulae that have been properly identified as protoplanetary. Our sample of PPNe is given in Table 1, including a summary of the nebular properties. The first 16 objects in this table have been accurately observed by us in the ^{12}CO and ^{13}CO J=1–0 and J=2–1 transitions, using the IRAM 30m telescope at Pico Veleta (Spain). For the others we took observations from the bibliography. Note the presence of 3 objects that show properties similar to those of PPNe: two hypergiants and one young planetary nebula. Also note that for 4 objects we have good reasons to think that they have initial masses lower than 1 $M_\odot$.

From these CO data it is possible to estimate the mass of the emitting gas, see methods in Paper I. The mass is calculated for the two components often found in CO profiles: the line core, that corresponds to the part of the AGB envelope that has not been (yet?) affected by the wind interaction and subsequent axial acceleration, and the high-velocity wings, that come from the fast bipolar flows. Since the CO observations accurately give the radial velocity of the emitting gas (and assuming a geometry similar to that found in well studied objects), it is also possible to measure the linear momentum and kinetic energy of these components.

It can be shown that the possible errors of the method are not important. In particular, no significant overestimation of the mass, momentum, and energy is expected. Major errors can appear if CO is not abundant in an object (as often happens in planetary nebulae) or if the inclination of the nebular axis with respect to the plane of the sky is much closer to zero than expected. In both cases, underestimations of the values estimated for the mass, momentum and energy may appear. Other errors due to unexpected geometries are found to be moderate (see below). If our assumptions on the CO rotational temperature (about 15 K) or on the low optical depth of the ^{13}CO J=1–0 line (that is used as far as possible) are not satisfied, we also expect underestimations, not overestimations, of these parameters. Therefore, our conclusions on the very high mass, momentum and energy of the CO nebula would not be invalidated by these possible error sources.

In Table 2 we show the results obtained for the sources accurately observed by us, see details in Paper I. For a few of the the others the data are poor and no reliable results can be obtained. We calculate values for both the slow and the fast (probably bipolar) components. Note that, in some cases, we used different source models (with different excitation, geometry and/or kinematics), but that our results are quite independent of these assumptions (provided that extreme cases are not present).

The high values found are remarkable. Masses as high as 1 $M_\odot$ are found in many nebulae. In order to give an idea of how high the momentum is, we have shown in Table 2, fifth column, the (distance-independent) ratio between the gas momentum and that carried per year by the stellar radiation. We argue in Paper II that, because of the short acceleration times expected (and the general properties of the momentum transfer in our case), radiation pressure cannot explain the acceleration of the bipolar flows when this ratio is larger than about 2000 yr. This is the case for most objects; an exception is for instance IRAS 22272+5435, the only PPN for which no trace of line wings were found after a deep search.

3. Statistics

Our sample includes 34 PPNe, two hypergiant stars showing dense envelopes and one young planetary nebula. Results are obtained from our CO observations (Table 2) and from data by other authors (see Paper I). In 5 objects, the poor observations do not allow a sensible study of the line wings. We have already mentioned the high nebular masses ($\sim 1\ M_\odot$), a good fraction of which is in the fast flows. Only 4 of the studied objects show no line wings, down to a level $\sim 1/10$ of the line peak (IRAS 22272+5435, IRAS 07134+1005, M 2–9, and R Sct).

Momenta in the fast outflows are studied for a subsample of 30 objects, discarding hypergiants and sources with poor CO data (in three other objects the comparison with the stellar momentum was not conclusive). High momenta are found, with values often ranging between 10^{39} and 10^{39} g cm s^{-1}. The comparison with the stellar radiation momentum reveals that such values are very high (i.e. $\frac{P}{L/c} \gtrsim 2000$ yr, see Paper II) in 21 objects (78%). Only in 6 PPNe, out of 27 well studied nebulae, the whole dynamics could be explained by radiation pressure. So, we conclude that the presence of fast bipolar flows carrying large amounts of momentum is systematic in PPNe.

Remarkably, 4 of the 6 PPNe showing relatively low linear momenta in fast flows are the 4 objects for which the initial mass is known to be low. (Note that perhaps some of the other nebulae in our sample are also low-mass objects, since in some cases our knowledge on the general properties of the sources, in particular of its distance, is poor.) In M 2–9, the amount of mass in CO is just a small fraction of the total nebular mass and extends to a small region (but this is not clear for other low-mass PPNe; see Zweigle et al. 1997 and Paper I). In the case of M 2–9, at least, the analysis of the CO data underestimates the total mass and momentum of the nebula, probably due to a strong photodissociation of molecules.

Finally we note that, if we do not take into account the case of the low-mass PPNe, only 2 out of 23 PPNe do not show high-momentum bipolar flows. This means that for more than 90% of the studied PPNe the momentum of the fast bipolar flows is so high ($\frac{P}{L/c} \gtrsim 2000$ yr) that their acceleration can in principle not be explained by radiation pressure.

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Table 2. Calculations of the mass, momentum, and kinetic energy for the sources observed in CO by us. Both slow (probably spherical) and fast (probably bipolar) components are considered. See details on the calculation method and the different source models used in Paper I.

source	mass $M(M_\odot)$	momentum $P(\mathrm{g\,cm\,s^{-1}})$	kinetic energy E(erg)	$\frac{P}{L/c}$ (yr)	comments
IRAS 04296+3429					$L/c = 2.8\ 10^{34}$ g cm s^{-1} yr^{-1}
slow component	0.13	2.5 10^{38}	1.3 10^{44}	9 10^{3}	
fast outflow	3.7 10^{-3}?	3.3 10^{37}?	7.7 10^{43}?	1.2 10^{3}?	from ^{12}CO J=1–0
CRL 618					$L/c = 1.2\ 10^{35}$ g cm s^{-1} yr^{-1}
slow component	0.65	2.1 10^{39}	1.8 10^{45}	1.8 10^{4}	assuming T_{rot} = 25 K
fast outflow	0.045	8.4 10^{38}	5.2 10^{45}	7 10^{3}	from ^{12}CO J=1–0
Frosty Leo					$L/c = 1.1\ 10^{34}$ g cm s^{-1} yr^{-1}
slow component	0.36	8.0 10^{38}	4.5 10^{44}	7 10^{4}	
fast outflow	0.56	9.0 10^{39}	4.0 10^{46}	8 10^{5}	bipolar model
fast outflow	0.60	4.6 10^{39}	8.1 10^{45}	4.2 10^{5}	spherical-isotropic model
fast outflow	0.56	6.5 10^{39}	1.1 10^{46}	6 10^{5}	disk, constant radial velocity
IRAS 17436+5003					$L/c = 2.4\ 10^{35}$ g cm s^{-1} yr^{-1}
slow component	0.57	1.2 10^{39}	6.2 10^{44}	5 10^{3}	
fast outflow	0.11	6.1 10^{38}	8.6 10^{44}	2.5 10^{3}	weak wings
He 3–1475					$L/c = 3.6\ 10^{34}$ g cm s^{-1} yr^{-1}
slow component	0.16	2.5 10^{38}	1.1 10^{44}	7 10^{3}	
fast outflow	0.47	1.8 10^{39}	3.1 10^{45}	5 10^{4}	
89 Her					$L/c = 1.3\ 10^{34}$ g cm s^{-1} yr^{-1}
slow component	3.3 10^{-3}	2.2 10^{36}	3.8 10^{41}	1.7 10^{2}	
fast outflow	1.0 10^{-3}	2.9 10^{36}	1.7 10^{42}	2.2 10^{2}	
AFGL 2343					$L/c = 2.3\ 10^{36}$ g cm s^{-1} yr^{-1}
unique, fast component	4.8	2.8 10^{40}	4.4 10^{46}	1.2 10^{4}	spherical envelope
IRC +10420					$L/c = 2.8\ 10^{36}$ g cm s^{-1} yr^{-1}
unique,fast component	2.1	1.5 10^{40}	2.6 10^{46}	5 10^{3}	spherical envelope; extended
IRAS 19500-1709					$L/c = 6.1\ 10^{33}$ g cm s^{-1} yr^{-1}
slow component	0.026	5.0 10^{37}	2.5 10^{43}	8 10^{3}	
fast outflow	6.7 10^{-3}	5.3 10^{37}	1.4 10^{44}	9 10^{3}	
CRL 2477					$L/c = 1.6\ 10^{34}$ g cm s^{-1} yr^{-1}
unique, fast component	0.11	4.4 10^{38}	6.1 10^{44}	2.8 10^{4}	bipolar outflow (?)
CRL 2688					$L/c = 1.0\ 10^{35}$ g cm s^{-1} yr^{-1}
slow component	0.69	2.2 10^{39}	1.7 10^{45}	2.2 10^{4}	
fast outflow	0.062	9.6 10^{38}	3.9 10^{45}	1.0 10^{4}	bipolar model; i=15°
fast outflow	0.062	5.0 10^{38}	7.8 10^{44}	5 10^{3}	spherical model
NGC 7027					$L/c = 4.0\ 10^{34}$ g cm s^{-1} yr^{-1}
main component	0.60	1.8 10^{39}	1.3 10^{45}	4.5 10^{4}	from ^{12}CO J=1–0; extended
main component	0.17	5.2 10^{38}	4.0 10^{44}	1.3 10^{4}	from ^{13}CO J=1–0
very fast outflow	0.033	3.7 10^{38}	8.5 10^{44}	9 10^{3}	from ^{12}CO J=1–0; spherical model
IRAS 22272+5435					$L/c = 3.3\ 10^{34}$ g cm s^{-1} yr^{-1}
unique, slow component	0.14	2.6 10^{38}	1.2 10^{44}	8 10^{3}	spherical envelope; extended
unique, slow component	0.20	3.6 10^{38}	1.7 10^{44}	1.1 10^{4}	spherical envelope; T_{rot} = 25 K
unique, slow component	0.18	2.9 10^{38}	1.2 10^{44}	9 10^{3}	AGB envelope model
no fast outflow detected		$<$ 6.1 10^{37}		$<$ 1.8 10^{3}	
IRAS 23304+6147					$L/c = 4.0\ 10^{33}$ g cm s^{-1} yr^{-1}
slow component	5.9 10^{-3}	9.5 10^{36}	1.3 10^{42}	2.4 10^{3}	from ^{12}CO J=2–1, underestimation ?
fast component	8.0 10^{-4}	2.1 10^{36}	1.4 10^{42}	5.3 10^{2}	from ^{12}CO J=2–1, underestimation ?
IRAS 23321+6545					$L/c = 2.3\ 10^{33}$ g cm s^{-1} yr^{-1}
unique, fast component	0.014	6.0 10^{37}	5.9 10^{43}	2.6 10^{4}	bipolar (?); i=30°, D = 1 kpc (?)
M 2–56					$L/c = 4.0\ 10^{34}$ g cm s^{-1} yr^{-1}
slow component	0.046	1.3 10^{38}	9.5 10^{43}	3.3 10^{3}	from ^{12}CO J=1–0
fast component	0.059	1.3 10^{39}	8.7 10^{45}	3.3 10^{4}	from ^{12}CO J=1–0