RevMexAA (Serie de Conferencias), **1**, 67-76 (1995)

CENTIMETER CONTINUUM EMISSION FROM OUTFLOW SOURCES

Guillem Anglada
Departament d'Astronomia i Meteorologia, Universitat de Barcelona,
Av. Diagonal 647, E-08028 Barcelona, Spain

RESUMEN

Una fracción importante de los objetos estelares más jóvenes presentan emisión en el continuo de radio en longitudes de onda centimétricas. La gran sensibilidad y alta resolución angular de las observaciones realizadas con el VLA en estas longitudes de onda han hecho posible el descubrimiento de objetos profundamente inmersos en núcleos moleculares que permanecían indetectados en otras longitudes de onda, así como identificar cuál es el objeto en donde se origina el flujo expansivo cuando hay varios candidatos muy próximos. En los casos estudiados con mayor detalle, las observaciones en múltiples frecuencias y con resolución angular por debajo del segundo de arco han puesto de manifiesto que estas fuentes de emisión de radio están alargadas en una dirección similar a la del eje de los flujos observados a mayor escala, presentado índices espectrales compatibles con los que predicen los modelos de chorros térmicos. Estos chorros en el radio constituyen, actualmente, la mejor evidencia de la existencia de colimación a muy pequeña escala. Para los objetos de baja luminosidad bolométrica que están asociados con flujos moleculares de alta velocidad, el ritmo de momento del flujo molecular está correlacionado con la luminosidad en el continuo centimétrico. Puesto que para estos objetos la fotoionización esperada es insuficiente para producir la emisión observada, esta correlación apoya el modelo en que la emisión centimétrica es emisión libre-libre, originada en material ionizado por choque, cuando un viento estelar neutro choca con el medio de alta densidad circundante.

ABSTRACT

A significant fraction of the youngest stellar objects are associated with radio continuum emission at centimeter wavelengths. The high sensitivity and high angular resolution of VLA observations carried out at these wavelengths allowed to locate deeply embedded objects, undetected at other wavelengths, and to identify sources of outflow activity in regions where several candidates are found in the same small region. For the best studied sources, multifrequency observations with subarcsec angular resolution reveal that these sources are elongated in a direction close to that of larger scale outflows, with spectral indices consistent with those expected from current models of thermal jets. These radio jets constitute, at present, the best evidence of collimation at a very small scale. For objects of low bolometric luminosity associated with molecular outflows, there appears to be a correlation between the momentum rate in the molecular outflow and the centimeter continuum luminosity. As for these low luminosity objects photoionization is negligible, this correlation provides an explanation of the observed centimeter radio continuum emission in terms of free-free emission originated in shock-ionized gas produced when a stellar wind shocks against the surrounding high density material.

Key words: **ISM: JETS AND OUTFLOWS — STARS: FORMATION — STARS: MASS LOSS — RADIO CONTINUUM: STARS**

1995RMxAC...1...67A

1. INTRODUCTION

The large majority of the youngest stellar objects are associated with detectable continuum emission at centimeter wavelengths (~2/3 of the so-called "Extreme Class I" sources by Lada 1991, or "Class 0" sources by André, Ward-Thompson, & Barsony 1993, have already been detected). Also, a large number of outflow exciting sources (~50) have been detected in the centimeter radio continuum. This number is progressively increasing and observations of this associated emission has revealed as an important tool to study these very young stellar objects, and especially those which are more deeply embedded. In particular, Very Large Array (VLA) observations provide both the very high *sensitivity* and very high *angular resolution* that have allowed a number of advances in the study of the outflow excitation:

1. Since the outflow exciting sources are usually deeply embedded objects, in several cases sensitive centimeter observations have been the first to *discover* the weak outflow sources (e.g., HH1-2: Pravdo et al. 1985; VLA1623: Leous et al. 1990; L1448: Curiel et al. 1990), with subsequent observations at other wavelengths confirming these detections.

2. In many cases, the centimeter observations have provided a significant improvement in the *positional accuracy* (by more than two orders of magnitude in some cases) of the outflow sources. In general, IRAS and other FIR positions have been notably improved (e.g., RNO 43, B 335: Anglada et al. 1992; see Fig. 1). In some cases, the sources have been resolved into several components (e.g., double sources have been found in IRAS 16293−2422: Wootten 1989, Estalella et al. 1991; L723: Anglada et al. 1991; HH1-2 VLA1: Rodríguez 1994).

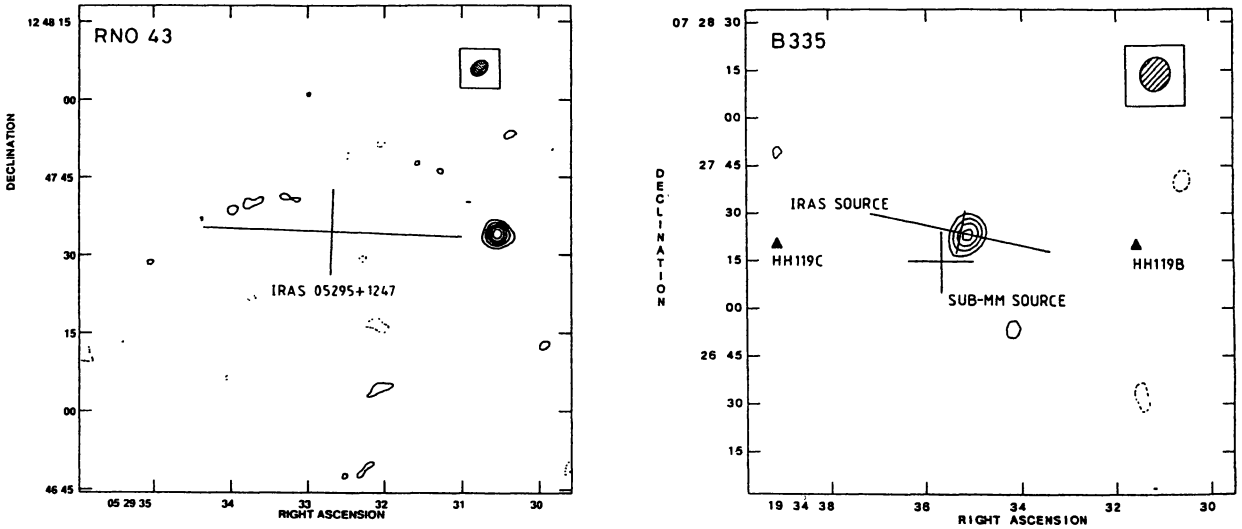

Fig. 1. — Radio continuum sources (λ=3.6 cm) at the center of the molecular outflows in RNO 43 and B 335 (from Anglada et al. 1992).

3. This kind of observations have permitted, in a number of cases, to distinguish and to *discriminate* among several candidates for the outflow excitation. Useful additional criteria used to favor a candidate in front of other candidates are:

(a) Proximity of the source near a high density and/or a temperature peak. Outflow exciting sources are usually deeply embedded objects and are found near an emission maximum of a high density tracer (such association is observed, e.g., in eight of the nine regions mapped in ammonia by Anglada et al. 1989). This association can help in the identification of the outflow sources (e.g., Estalella et al. 1993, Gómez et al. 1994; see §2). In addition, outflow sources interact and perturb their surrounding medium, resulting in measurable local heating and line broadening (e.g., Torrelles et al. 1992).

(b) Jet-like morphology of the radio source. For sources studied with subarcsec angular resolution, these observations have revealed that, in general, the source is elongated approximately in the same direction that the large scale outflow. At present, this elongation has been found in a dozen of sources mapped at subarcsec scale (see Rodríguez 1994, 1995, and references therein), and has been interpreted as evidence of that the collimating processes act at this very small scale. For the best studied cases (e.g., HH1-2: Rodríguez et al. 1990; HH80-81: Martí et al. 1993; Cepheus A HW2: Rodríguez et al. 1994), further (sensitive and very high angular resolution) multifrequency observations have shown that the flux density and angular size dependences with frequency are in agreement with the predictions of the thermal bipolar jet models of Reynolds (1986). These results suggest that all these centimeter continuum sources are tracing thermal radio jets. Unfortunately, these kind of detailed studies have only been carried out for the strongest sources, while most of the sources are weak and the radio jet detailed characteristics (or even the elongation) are difficult to establish.

In the following, I will discuss in some detail a number of cases where recent VLA centimeter continuum observations have been most useful to clarify the outflow excitation (§2). Finally, I will discuss on the nature of the centimeter continuum emission for objects of low bolometric luminosity (§3).

2. RECENT RADIO JET CANDIDATES

2.1. NGC 2264G

NGC 2264G is an interesting example where both the association with an ammonia peak and the jet-like morphology of the radio continuum emission have been used to identify the outflow exciting source. This remarkable molecular outflow (Margulis & Lada 1986; Margulis, Lada & Snell 1988) is centered on IRAS 06384+0958 and extends in an approximately east-west direction, presenting a clear bipolar morphology. Rodríguez & Curiel (1989) discovered with the VLA a centimeter continuum source (VLA 1) inside the IRAS ellipsoid error, and (assuming that both sources were the same object) proposed that the source VLA 1 was tracing the position of the outflow exciting source.

However, recent VLA ammonia observations (Gómez et al. 1994) reveal a compact ammonia condensation near the center of the molecular outflow, with evidence of gas heating near the ammonia peak position. Furthermore, these authors discover a new weak (~0.3 mJy) radio continuum source (VLA 2) at this position. This position is closer to the center of the bipolar outflow and to the nominal IRAS position, while the source VLA 1 and several near-IR sources (Margulis et al. 1990) lie outside the ammonia clump (see Fig. 2).

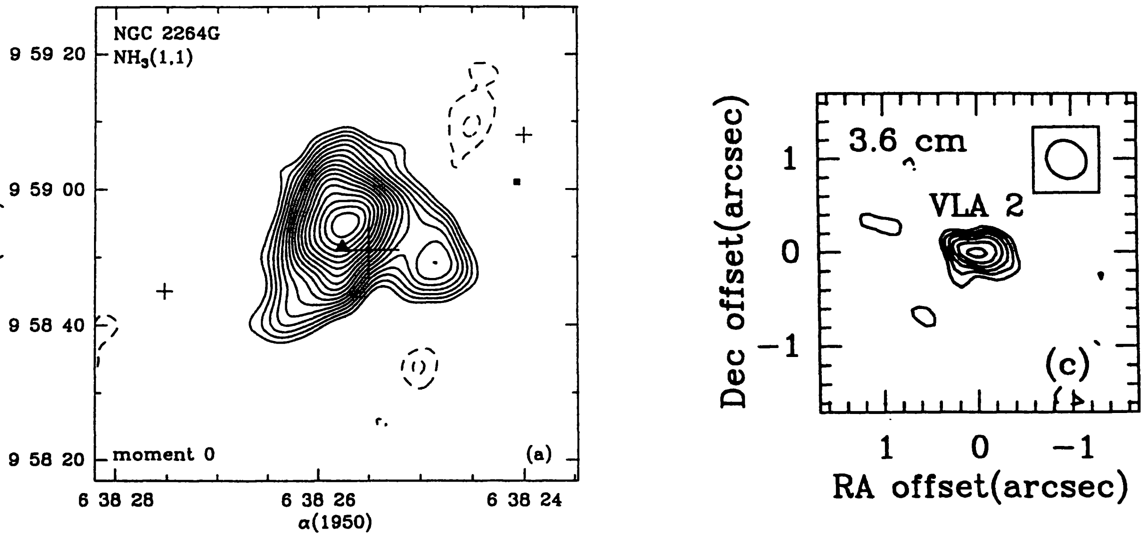

Fig. 2. — (*Left*) VLA contour map of the ammonia clump at the center of the NGC 2264G molecular outflow. The IRAS source, the two 2μm sources (smaller crosses), the VLA 1 (square) and VLA 2 (triangle) radio continuum sources are indicated. (*Right*) VLA contour map (angular resolution $\sim 0''.4$) of the source VLA 2. (from Gómez et al. 1994)

The new radio continuum source VLA 2 is marginally elongated (deconvolved size $0''.8 \times 0''.4$, P.A. = 84°) approximately in the direction of the large scale bipolar outflow, suggesting that this source is a radio jet. Unfortunately its weakness makes difficult a more exhaustive study. Recently, the source has been detected in the submm range (Ward-Thompson, Eiroa, & Casali 1995), and classified as a "Class 0" object. Thus, VLA 2 appears to be an extremely young deeply embedded object, and the most plausible candidate for the outflow excitation.

2.2. L 1287

Snell, Dickman, & Huang (1990) and Yang et al. (1991) mapped in CO a powerful molecular outflow in L 1287. The outflow presents a clear bipolar morphology, with its axis oriented in the northeast-southwest direction, and is thought to be powered by the very cold source IRAS 00338+613, whose position lies near its center of symmetry. A double FU Ori system (RNO 1B/1C) was later found inside the IRAS error ellipsoid (Staude & Neckel 1991; Kenyon et al. 1993), and it was proposed that one or perhaps both of the FU Ori stars is driving the molecular outflow. Kenyon et al. (1993) noted that L 1287 would provide a clear example of association between FU Ori stars and molecular outflows, and suggest that, in a more general context, the periodic outbursts that are believed to characterize the FU Ori phenomenon may explain the molecular outflows commonly observed in star-forming regions.

However, Weintraub & Kastner (1993) noted that molecular outflow exciting sources are usually deeply embedded objects rather than visible stars and, from a detailed polarimetric study of the region, predicted the presence of an (undetected) embedded object located ~ 5″ to the northeast of the star RNO 1C.

High angular resolution (~ 1″) VLA observations in the radio continuum (Anglada et al. 1994) reveal several sources near the center of the molecular outflow (see Fig. 3). The strongest and more interesting source (VLA 3) coincides within ~1″ with the IRAS catalog position and the position of the embedded object predicted by Weintraub & Kastner (1993). The radio continuum source has positive spectral index and presents evidence of elongation approximately along the axis of the molecular bipolar outflow. Preliminary results of higher angular resolution (~ 0.″2) VLA observations (Anglada et al. 1995b) show that the core of the radio source is also elongated approximately in the direction of the axis of the large scale molecular outflow. Thus, this embedded object, predicted from polarimetric studies, detected in the radio continuum, and coinciding with the IRAS source, appears to be the best candidate to drive the L 1287 molecular outflow.

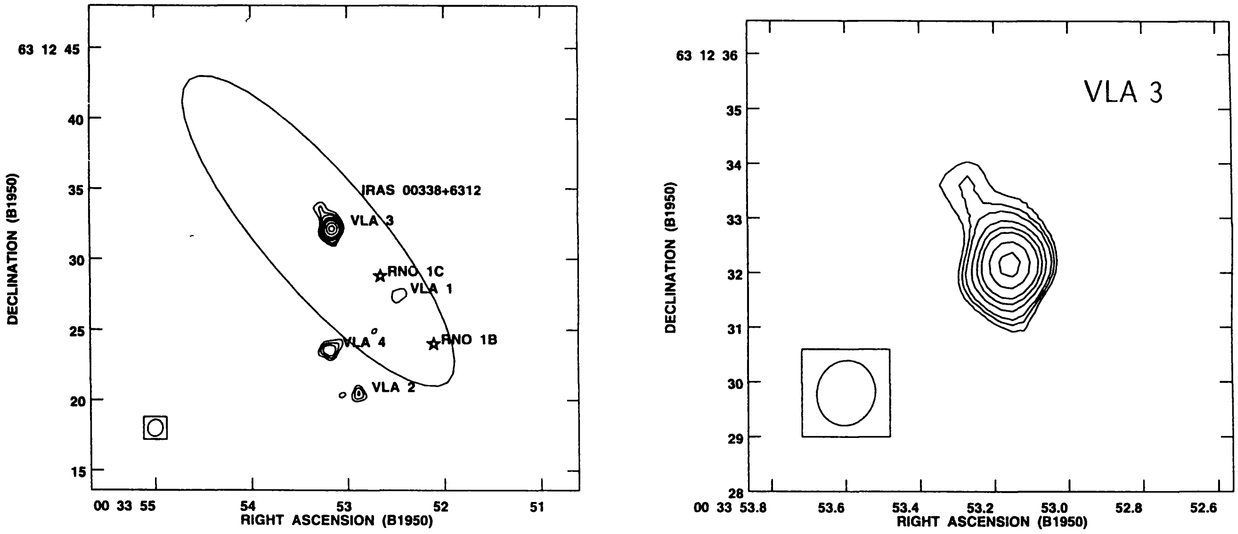

Fig. 3. — (*Left*) VLA map of the 3.6 cm continuum sources at the center of the L 1287 molecular outflow. The error ellipsoid of the IRAS source, the positions of RNO 1B and RNO1 C, and the four sources detected with the VLA are indicated. (*Right*) Close up of the source VLA 3, the proposed exciting source of the molecular outflow. (from Anglada et al. 1994)

2.3. Re 50

Re 50 (Reipurth 1985) is a large optical nebulosity found to be highly variable over a time scale of years (Reipurth & Bally 1986). The illuminating source of this nebula is IRAS 05380−0728 (Scarrott & Wolstencroft

1995RMxAC...1...67A

1988), which is located ~ 1.′5 to the north of Re 50. The IRAS source is surrounded by a small optical nebula whose structure varies on a time scale of a few months, presumably due to very variable excitation and/or illumination. A bipolar molecular outflow, proposed to be excited by the IRAS source, and with its axis parallel to the direction defined by the IRAS source and Re 50 (which is located at the eastern edge of the blueshifted lobe) has been mapped by Reipurth & Bally (1986) and Morgan et al. (1991). However, the position of the IRAS source and its associated nebulosity is not at the center of the outflow, but is displaced to the east of the outflow axis (see Fig. 4).

Morgan, Snell & Strom (1990) observed the region at 6 cm, using the VLA in the C configuration (angular resolution ~ 4″). These authors detected two unresolved radio continuum sources, one of them probably associated with the IRAS source, and the other one displaced ~ 50″ to the west, closer to the axis of symmetry of the molecular outflow (see Fig. 4). Sensitive higher angular resolution observations at 3.6 cm, with the VLA in the A configuration (angular resolution ~ 0.″3), reveal that the eastern source is clearly elongated along a direction with P.A. ≃ −30°, similar to the position angle of the molecular outflow axis (Anglada et al. 1995b; see Fig. 4), while no clear signs of elongation are found in the western source.

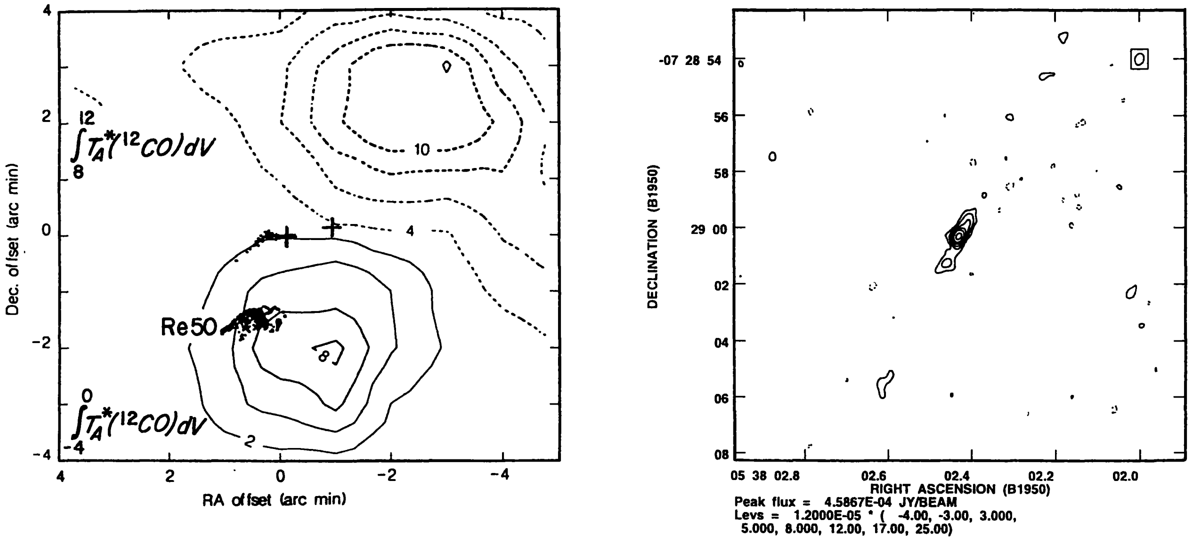

Fig. 4. — (*Left*) CO map of the bipolar outflow in the Re 50 (adapted from Reipurth & Bally 1986). The positions of the optical nebula as well as the positions of the VLA sources (crosses) detected by Morgan, Snell & Strom (1990) are indicated. (*Right*) High angular resolution VLA map of the eastern radio source (from Anglada et al. 1995b).

These results, and the positive spectral index of the eastern source, suggest that it is a thermal radio jet, and favor this object as the outflow exciting source. Assuming a velocity of a few hundred km s^{-1}, the time scale of the observed radio jet is ~ 10 yr, indicating that the ionized gas that we observe is very young, and, also, that proper motions may be detectable in a few years. The radio jet is bipolar, but it appears to be somewhat asymmetric, with the northwest lobe (that would correspond to the red lobe of the molecular outflow) brighter than the southeast lobe. Examples of clearly one-sided radio jets have been found in Serpens (Curiel et al. 1993) and HH 111 (Rodríguez & Reipurth 1994). These asymmetries, that cannot be attributed to obscuration as in the optical jets, might be intrinsic to the source or might be produced by different conditions in the medium in which the jet propagates (for example, an increase in the density of the medium in which the jet propagates would increase the amount of material that can be ionized). It is worth noting that, although optical jets are generally blueshifted, and this result has been attributed to the obscuration of the receding lobe, in some cases the extinction appears to be insufficient to obscure a counterjet of the same intensity, and it has been proposed that the optical jet should be intrinsically asymmetric (e.g., in the HH 34 jet: Stapelfeldt et al. 1991, Anglada et al. 1995a). In addition, other kinds of asymmetries in optical jets, in terms of velocity and excitation, have been recently reported by Hirth et al. (1994). These authors proposed that these asymmetries, that cannot be produced by obscuration, are probably intrinsic to the source itself or its immediate environment, a result that is relevant for the current models of collimated jets.

3. NATURE OF THE CENTIMETER CONTINUUM EMISSION

It is now clear that the centimeter continuum emission observed in association with young stellar objects is dominated by free-free radiation from (partially) ionized material. However, it is still unclear which is the mechanism that produces the required ionization in all these objects. For high luminosity objects photoionization is a viable mechanism; however, there is a number of objects of relatively low bolometric luminosity, for which ionization by stellar photons appears to be insufficient, by a large amount, to account for the observed centimeter continuum emission, in terms of a classical HII region (see Fig. 5). The frequent association of radio continuum emission with the powering sources of molecular outflows suggests a relationship between both phenomena, and it has been proposed (e.g., Torrelles et al. 1985) that the radio continuum emission could arise from shock-ionized gas. In this scenario, the powerful stellar wind that produces the observed molecular outflows could shock with gas in the environment of the star and a modest ionization, similar to that produced by an early B type star, could be created by the shock.

Curiel, Cantó & Rodríguez (1987) and Curiel et al. (1989) modeled this scenario. From their results, and assuming that the stellar wind velocity is 200 km s^{-1} and the electron temperature of the ionized gas is 10^4 K, the momentum rate in the outflow (usually derived from CO observations), $\dot{P}$, and the centimeter luminosity, $S_\nu d^2$, are related by

$$\left(\frac{\dot{P}}{M_\odot\ \mathrm{yr}^{-1}}\right) = \frac{10^{-3.5}}{\eta}\left(\frac{S_\nu d^2}{\mathrm{mJy\ kpc}^2}\right),$$

where $\eta = \Omega/4\pi$ is an efficiency factor that can be taken to equal the fraction of the stellar wind that is shocked, and produces the observed radio continuum.

Rodríguez et al. (1989) studied a sample of 21 low luminosity objects associated with molecular outflows (however, the cm flux density was known for only 7 of these objects, and for the remaining 14 objects an upper limit was adopted), and could not find evidence for a correlation between $\dot{P}$ and $S_\nu d^2$. Anglada et al. (1992) carried out a similar study for 16 low luminosity objects (adding new detections, but not including upper limits), and found evidence for a marginal correlation, $\dot{P} = 10^{-2.6\pm0.5}(S_\nu d^2)^{1.1\pm0.4}$ ($r = 0.6$), consistent with Eq. (1) and an efficiency factor $\eta \simeq 0.1$.

The main source of uncertainty in the data used was the outflow momentum rates (that, in general, are poorly known, mainly because of the lack of knowledge of the outflow geometry, and that present a large scatter in the reported values for the same outflow, because of the different procedures used by different authors to calculate physical parameters). On the other hand, the centimeter luminosity ($S_\nu d^2$) is affected, in some specific cases, by a poor knowledge of the distance to the source, or by confusion in the identification of the outflow exciting source (see §2.1). Thus, it is expected that the correlation could be improved with a better knowledge on these parameters. This appears to be confirmed by the results of Cabrit & Bertout (1992), obtained using only a selected sample of outflows with data of good quality available (containing 8 low luminosity sources detected in the centimeter continuum, 4 high luminosity sources, and 2 upper limits), and correcting the outflow parameters according to their model (Cabrit & Bertout 1986, 1990). These authors found that this, and other correlations between the parameters of the outflows and those of their exciting sources, were greatly improved in this way. The mechanism of shock ionization, for several Herbig Ae/Be stars, has been also considered by Skinner, Brown, & Steward (1993).

Here I present a compilation of 29 objects (Table 1) with detected centimeter continuum emission, but for which the bolometric luminosity is clearly insufficient to account for the observed centimeter continuum luminosity, as can be seen in Fig. 5. In Fig. 5 the solid line gives the expected value of $S_\nu d^2$, assuming optically thin free-free emission from ionized hydrogen with an electron temperature of 10^4 K, and adopting the Lyman-continuum fluxes of a ZAMS of the given luminosity, obtained from Thompson (1984). All the objects listed in Table 1 are believed to be the source of excitation of a molecular outflow, and the inclusion of new detections increases significantly the total number of sources, over previous studies. A plot of the momentum rate in the outflow versus the observed radio continuum luminosity at centimeter wavelengths is shown in Fig. 5. Data are taken from the literature, and the references are given in Table 1. No attempt has been made to correct the outflow parameters, and when these are taken from more than one paper, the geometric mean of the different values has been adopted. The best fit to the data (solid line in Fig. 5) gives

$$\left(\frac{\dot{P}}{M_\odot\ \mathrm{yr}^{-1}}\right) = 10^{-2.5\pm0.3}\left(\frac{S_\nu d^2}{\mathrm{mJy\ kpc}^2}\right)^{1.1\pm0.2} \qquad (r = 0.7),$$

Table 1. Low-Luminosity Molecular Outflow Sources with Detected Centimeter Continuum Emission

Source	$S_\nu d^2$ (mJy kpc^2)	$\dot{P}$ ($M_\odot$ yr^{-1} km s^{-1})	$L_{\rm bol}$ ($L_\odot$)	References
HH 7-11	9.8×10^{-2}	1.1×10^{-3}	80	1, 2, 23
L1489	9.8×10^{-3}	2.0×10^{-7}	4	3, 4, 24
T Tau	1.1×10^{-1}	4.0×10^{-5}	17	5, 6, 25, 26, 19, 1, 27
L1551	9.0×10^{-2}	1.1×10^{-4}	33	1, 6, 28
HL Tau	7.7×10^{-3}	1.4×10^{-6}	9	5, 19, 1, 29, 23, 7
IRAS 16293−2422	7.4×10^{-2}	8.7×10^{-4}	27	8, 9, 30, 31, 32
L723	3.6×10^{-2}	2.6×10^{-4}	2	10, 11, 33, 28
B335	1.3×10^{-2}	7.9×10^{-6}	4	10, 12, 24, 22, 58
PV Cephei	5.0×10^{-2}	1.0×10^{-4}	80	12, 13, 19, 27
L1448 C	9.0×10^{-3}	4.5×10^{-4}	9	14, 15, 34
L1448 N(A)	8.1×10^{-2}	1.2×10^{-4}	10	14, 15, 35
VLA 1623	1.5×10^{-2}	4.5×10^{-4}	1	16, 35
NGC 2264G	2.6×10^{-1}	3.0×10^{-3}	12	17, 18, 36
Haro 4-255 FIR	4.6×10^{-2}	4.4×10^{-4}	26	12, 19, 37, 38
HH 111	1.9×10^{-1}	5.0×10^{-5}	24	20, 21, 23
RNO 43	8.0×10^{-2}	2.1×10^{-4}	12	12, 22, 39
FIRSSE101	2.8×10^{-1}	7.8×10^{-4}	123	37, 40, 41
Re50	1.8×10^{-1}	5.3×10^{-4}	148	42, 37, 40, 23, 41
L1641 N	2.3×10^{-1}	9.4×10^{-4}	120	43, 37, 44
HH 26IR	7.0×10^{-2}	4.3×10^{-4}	40	45, 3, 44, 59
Mon OB1D	1.9×10^{-1}	3.2×10^{-3}	300	17, 44
L483	2.1×10^{-2}	4.0×10^{-5}	14	47, 44, 24
L1251 A	4.2×10^{-2}	8.6×10^{-5}	27	48, 44, 49
L1251 B	4.8×10^{-2}	4.9×10^{-5}	14	48, 44, 49
L1262	1.1×10^{-2}	2.8×10^{-5}	1	47, 50, 51, 44, 46
AS 353A	9.0×10^{-3}	4.5×10^{-5}	3	1, 23, 52, 12
L1228	3.4×10^{-3}	5.4×10^{-6}	1	53, 44
NGC 2071-IRS1	1.2×10^{0}	5.1×10^{-3}	520	54, 55, 2
HH46/47	3.2×10^{-1}	2.3×10^{-5}	19	23, 56, 57

References. — (1) Edwards & Snell 1984; (2) Snell & Bally 1986; (3) Rodríguez et al. 1989; (4) Myers et al. 1988; (5) Calvet, Cantó, & Rodríguez 1983; (6) Cohen, Bieging, & Schwartz 1982; (7) Brown, Mundt, & Drake 1985; (8) Wootten & Loren 1987; (9) Estalella et al. 1991; (10) Goldsmith et al. 1984; (11) Anglada et al. 1991; (12) Anglada et al. 1992 (13) Levreault 1984; (14) Bachiller et al. 1990; (15) Curiel et al. 1990; (16) André et al. 1990; (17) Margulis, Lada, & Snell 1988; (18) Gómez et al. 1994; (19) Levreault 1988; (20) Reipurth & Olberg 1991; (21) Rodríguez & Reipurth 1994; (22) Cabrit, Goldsmith, & Snell 1988; (23) Reipurth et al. 1993; (24) Ladd et al. 1991; (25) Schwartz, Simon, & Campbell 1986; (26) Edwards & Snell 1982; (27) Evans, Levreault, & Harvey 1986; (28) Mozurkewich, Schwartz, & Smith 1986; (29) Torrelles et al. 1987; (30) Mundy, Wilking, & Myers 1986; (31) Mizuno et al. 1990; (32) Walker et al. 1988; (33) Avery, Hayashi, & White 1990; (34) Bachiller, André, & Cabrit 1991; (35) André, Ward-Thompson, & Barsony 1993; (36) Ward-Thompson, Eiroa, & Casali 1995; (37) Morgan et al. 1991; (38) Morgan & Bally 1986; (39) Cohen & Schwartz 1987; (40) Fukui 1989; (41) Morgan et al. 1990; (42) Reipurth & Bally 1986; (43) Fukui et al. 1988; (44) Anglada et al. 1995c; (45) Snell & Edwards 1982; (46) Terebey, Vogel, Myers 1989; (47) Parker et al. 1988; (48) Sato et al. 1994; (49) Kun & Prusti 1993; (50) Yun & Clemens 1994; (51) Parker 1991; (52) Cohen & Bieging 1986; (53) Haikala & Laurenjis 1989; (54) Snell et al. 1984; (55) Butner et al. 1990; (56) Chernin & Masson 1991; (57) Curiel, Wilner, & Rodríguez 1995; (58) Moriarty-Schieven & Snell 1989; (59) Bontemps, André, & Ward-Thompson.

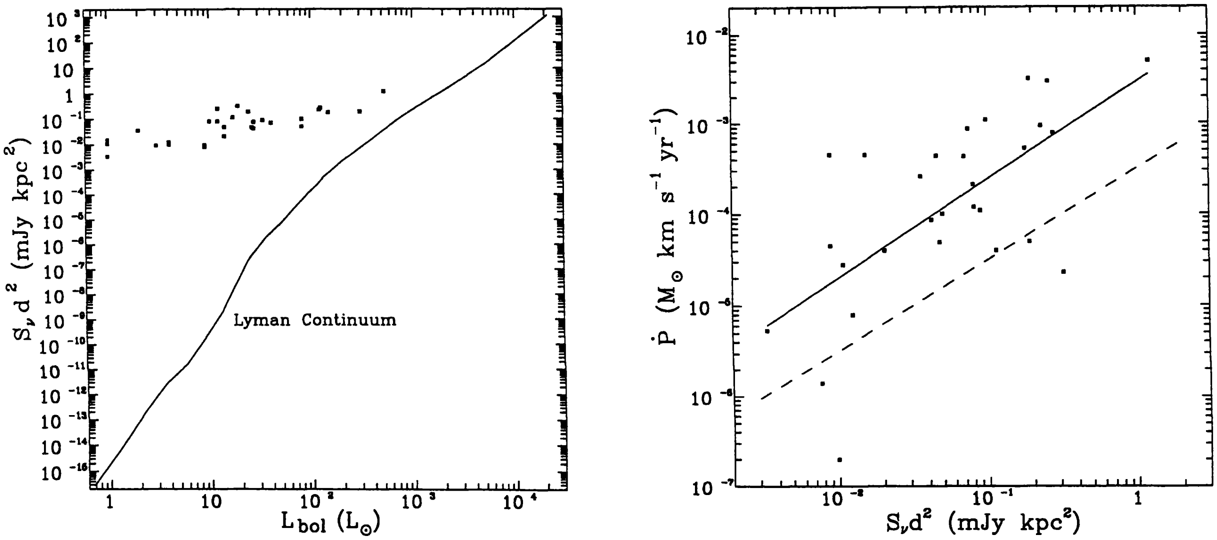

Fig. 5.— (*Left*) Observed radio continuum luminosity, $S_\nu d^2$, vs. the bolometric luminosity, $L_{\rm bol}$, for a sample of 29 objects listed in Table 1. The solid line represents the values expected from Lyman-continuum radiation from a ZAMS star. (*Right*) Momentum rate in the outflow, $\dot{P}$, vs. the centimeter radio continuum luminosity. (data from Anglada et al. 1995c)

a result that is consistent with our previous determinations and with Eq. (1), assuming an average efficiency $\eta = 0.1$.

The dashed line in Fig. 5 indicates the minimum $\dot{P}$ required in the outflow (that is, the $\dot{P}$ required if the efficiency was $\eta = 1$) to explain the radio continuum emission in terms of shock ionization. As can be seen in the figure all the outflows lie above this line (except L1489, and perhaps HH46/47 and HL Tau), indicating that this mechanism, in general, is sufficient to explain the observed emission. A better determination of the outflow parameters, and a confirmation of the association between outflow and radio continuum source will be specially important for these three outflows.

These results, obtained with a significant number of sources, indicate that shock-ionization appears to be a valid mechanism to explain the centimeter continuum emission observed in molecular outflow sources of low bolometric luminosity, providing a causal relationship between the outflow phenomenon and the associated continuum emission.

I am grateful to R. Estalella and L. F. Rodríguez for useful comments and suggestions. I acknowledge financial support from CIRIT de Catalunya and from DGICYT grant PB92-0900 (Spain).

REFERENCES

André, P., Martín-Pintado, J., Despois, D., & Montmerle, T. 1990, A&A, 236, 180
André, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122
Anglada, G., Estalella, R., Rodríguez, L. F., Torrelles, J. M., López, R., & Cantó, J. 1991, ApJ, 376, 615
Anglada, G., Estalella, R., Mauersberger, R., Torrelles, J. M., Rodríguez, L. F., Cantó, J., Ho, P. T. P., & D'Alessio, P. 1995a, ApJ, 443
Anglada, G., Rodríguez, L. F., Torrelles, J. M., Estalella, R., Ho, P. T. P., Cantó, J., López, R., & Verdes-Montenegro, L. 1989, ApJ, 341, 208
Anglada, G., Rodríguez, L. F., Girart, J. M., Estalella, R., & Torrelles, J. M. 1994, ApJ, 420, L91
Anglada, G., Rodríguez, L. F., Cantó, J., Estalella, R., Torrelles, J. M. 1992, ApJ, 395, 494
Anglada, G. et al. 1995b, in preparation

Anglada, G. et al. 1995c, in preparation
Avery, L. W., Hayashi, S. S., & White, G. J. 1990, ApJ, 357, 524
Bachiller, R., André, P., & Cabrit, S. 1991, A&A, 241, L43
Bachiller, R., Cernicharo, J., Martín-Pintado, J., Tafalla, M., & Lazareff, B. 1990, A&A, 231, 174
Bontemps, S., André, P., Ward-Thompson, D. 1995, A&A, in press
Brown, A., Mundt, R., & Drake, S. A. 1985, in Radio Stars, ed. R. M. Hjellming & D. M. Gibson (Dordrecht: Reidel), 105
Butner, H. M., Evans, N. J., Harvey, P. M., Mundy, L. G., Natta, A., & Randich, M. S. 1990, ApJ, 364, 164
Cabrit, S. & Bertout, C. 1986, ApJ, 307, 313
Cabrit, S. & Bertout, C. 1990, ApJ, 348, 530
Cabrit, S. & Bertout, C. 1992, A&A, 261, 274
Cabrit, S., Goldsmith, P. F., & Snell, R. L. 1988, ApJ, 334, 196
Calvet, N., Cantó, J., & Rodríguez, L. F. 1983, ApJ, 268, 739
Chernin, L. M., & Masson, C. R. 1991, ApJ, 382, L93
Cohen, M., & Bieging, J. H. 1986, AJ, 92, 1396
Cohen, M., Bieging, J. H., & Schwartz, P. R. 1982, ApJ, 253, 707
Cohen, M., & Schwartz, R. D. 1987, ApJ, 316, 311
Curiel, S., Cantó, J., & Rodríguez, L. F. 1987, RevMexAA, 14, 595
Curiel, S., Raymond, J. C., Rodríguez, L. F., Cantó, J., & Moran, J. M. 1990, ApJ, 365, L85
Curiel, S., Rodríguez, L. F., Cantó, J., Bohigas, J., Roth, M., & Torrelles, J. M. 1989, Ap. Letters & Comm., 27, 299
Curiel, S., & Rodríguez, L. F., Moran, J. M., & Cantó, J. 1993, ApJ, 415, 191
Curiel, S., Wilner, D., & Rodríguez, L. F. 1995, in preparation
Edwards, S., & Snell, R. L. 1982, ApJ, 261, 151
Edwards, S., & Snell, R. L. 1984, ApJ, 281, 237
Estalella, R., Anglada, G., Rodríguez, L. F., & Garay, G. 1991, ApJ, 371, 626
Estalella, R., Mauersberger, R., Torrelles, J. M., Anglada, G., Gómez, J. F., López, R. 1993, ApJ, 419, 698
Evans, N. J. II, Levreault, R. M., & Harvey, P. M. 1986, ApJ, 301, 894
Fukui, Y. 1989, in Low Mass Star Formation and Pre-Main-Sequence Objects, ed. B. Reipurth (Garching: ESO), 95
Fukui, Y., Takaba, H., Iwata, T., & Mizuno, A. 1988, ApJ, 325, L13
Goldsmith, P. F., Snell, R. L., Hemeon-Heyer, M., & Langer, W. D. 1984, ApJ, 286, 599
Gómez, J. F., Curiel, S., Torrelles, J. M., Rodríguez, L. F., Anglada, G., & Girart, J. M. 1994, ApJ, 436, 749
Haikala, L. K., & Laurenjis, R. J. 1989, A&A, 223, 287
Hirth, G. A., Mundt, R., Solf, J., & Ray T. P. 1994, ApJ, 427, L99
Kenyon, S. J., Hartmann, L., Gómez, M., Carr, J. S., & Tokunaga, A. 1993, AJ, 105, 1505
Kun, M., & Prusti, T. 1993, A&A, 272, 235
Lada, C.J. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 329
Ladd, E. F., Adams, F. C., Casey, S., Davidson, J. A., Fuller, G. A., Harper, D. A., Myers, P. C., & Padman, R. 1991, ApJ, 366, 203
Leous, J. A., Feigelson, E. D., André, P., Montmerle, T. 1990, BAAS, 21, 1086
Levreault, R. M. 1984, ApJ, 277, 634
Levreault, R. M. 1988, ApJS, 67, 283
Margulis, M. & Lada, C. J. 1986, ApJ, 309, L87
Margulis, M., Lada, C. J., & Snell, R. L. 1988, ApJ, 333, 316
Margulis, M. et al. 1990, ApJ, 352, 615
Martí, J., Rodríguez, L. F., & Reipurth, B. 1993, ApJ, 416, 208
Mizuno, A., Fukui, Y., Iwata, T., Nozawa, S., & Takano, T. 1990, ApJ, 356, 184
Morgan, J. A., & Bally, J. 1986, ApJ, 372, 505
Morgan, J. A., Schloerb, F. P., Snell, R. L., & Bally, J. 1991, ApJ, 376, 618
Morgan, J. A., Snell, R. L., & Strom, K. M. 1990, ApJ, 362, 274
Moriarty-Schieven, G. H., & Snell, R. L. 1989, ApJ, 338, 952
Mozurkewich, D., Schwartz, P. R., & Smith, H. A. 1986, ApJ, 311, 371
Mundy, L. G., Wilking, B. A., & Myers, S. T. 1986, ApJ, 311, L75
Myers, P. C., Heyer, M., Snell, R. L., & Goldsmith, P. F. 1988, ApJ, 324, 907
Olberg, M., Reipurth, B., & Booth, R. 1992, A&A, 259, 252
Parker, N. D. 1991, MNRAS, 251, 63

Parker, N. D., Padman, R., Scott, P. F., & Hills, R. E. 1988, MNRAS, 234, 67P

Pravdo, S. H., Rodríguez, L. F., Curiel, S., Cantó, J., Torrelles, J. M., Becker, R. H., & Sellgren, K. 1985, ApJ, 293, L35

Reipurth, B. 1985, A&AS, 61, 319

Reipurth, B., & Bally, J. 1986, Nature, 320, 336

Reipurth, B., Chini, R., Krügel, E., Kreysa, E., & Sievers, A. 1993, A&A, 273, 221

Reipurth, B., & Olberg, M. 1991, A&A, 246, 535

Reynolds, S. P. 1986, ApJ, 304, 713

Rodríguez, L. F. 1994, RevMexAA, 29, 69

Rodríguez, L. F. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 1

Rodríguez, L. F., & Curiel, S. 1989, RevMexAA, 17, 115

Rodríguez, L. F., Garay, G., Curiel, S., Ramírez, S., Torrelles, J. M., Gómez, Y., & Velázquez, A.. 1994, ApJ, 430, L65

Rodríguez, L. F., Ho, P. T. P., Torrelles, J. M., Curiel, S., & Cantó, J. 1990, ApJ, 352, 645

Rodríguez, L. F., Myers, P. C., Cruz-González, I., & Terebey, S. 1989, ApJ, 347, 461

Rodríguez, L. F., & Reipurth, B. 1994, A&A, 281, 882

Sato, F., Mizuno, A., Nagahama, T., Onishi, T., Yonekura, Y., & Fukui, Y. 1994, ApJ, 435, 279

Scarrott, S. M., & Wolstencroft, R. D. 1988, MNRAS, 231, 1019

Schwartz, P. R., Simon, T., & Campbell, R. 1986, ApJ, 303, 233

Skinner, S., Brown, A., Stewart, R. T. 1993, ApJS, 87, 217

Snell, R. L. & Bally, J. 1986, ApJ, 303, 683

Snell, R. L., Dickman, R. L., & Huang, Y. L. 1990, ApJ, 352, 139

Snell, R. L., & Edwards, S. 1982, ApJ, 259, 668

Snell, R. L., Scoville, N. Z., Sanders, D. B., & Erickson, N. R. 1984, ApJ, 284, 176

Stapelfeldt, K. R., Beichman, C. A., Hester, J. J., Scoville, N. Z., & Gautier, T. N. 1991, ApJ, 371, 226

Staude, H. J., & Neckel, T. 1991, A&A, 244, L13

Terebey, S., Vogel, S. N., & Myers, P. C. 1989, ApJ, 340, 472

Thompson, R. I. 1984, ApJ, 283, 165

Torrelles, J. M., Gómez, J. F., Curiel, S., Eiroa, C., Rodríguez, L.F., & Ho, P. T. P. 1992, ApJ, 384, L59

Torrelles, J. M., Ho, P. T. P., Rodríguez, L. F., & Cantó, J. 1985, ApJ, 288, 595

Torrelles, J. M., Anglada, G., Rodríguez, L. F., Cantó, J., Barral, J. F. 1987, A&A, 177, 171

Walker, C. K., Lada, C. J., Young, E. T., & Margulis, M. 1988, ApJ, 332, 335

Ward-Thompson, D., Eiroa, C., Casali, M. 1995, MNRAS, in press

Weintraub, D. A., & Kastner, J. 1993, ApJ, 411, 767

Wootten, A. 1989, ApJ, 337, 858

Wootten, A. & Loren, R. B. 1987, ApJ, 317, 220

Yang, J., Umemoto, T., Iwata, T., & Fukui, Y. 1991, ApJ, 373, 137

Yun, J. L., & Clemens, D. P. 1994, ApJS, 92, 145