Submillimetre Mapping and Photometry of Bipolar Flows - Evidence for Compact Disks

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ABSTRACT: The mm/sub-mm dust emission from bipolar outflow sources is discussed. In nearby outflows the stars driving the flows appear point like and unresolved, i.e. apparent angular sizes $\lesssim$ 7" (i.e. 700AU at 100pc). The spectra are surprisingly flat, suggesting that the dust emission is affected by temperature and density gradients or that the dust surrounding these stars differs from that of the general interstellar medium. If the spectra are characterized with a conventional dust emissivity index, our sample gives an average value of 1.1, rather than the figure of 2, which is usually claimed at these wavelengths for dust in molecular clouds. The total dust and gas masses associated with these stars are a few tenths of a solar mass for nearby low luminosity sources and the gas densities are $>10^7$ cm^{-3}, if the gas is in a shell, and the densities could be much higher if the gas densities fall off as a function of radius, or if the mass is distributed in a disk. These masses correspond to extremely high extinctions, which are not observed, and we therefore argue that the mass distribution must be anisotropic, most likely as an inclined disk surrounding the star. Hence, stars driving outflows are surrounded by a dense disk, possibly an accretion disks and/or collimating disk. If these stars are compared to the more evolved T Tauri stars, we find that the difference in disk mass could account for the mass loss observed in these stars. Because of the high gas densities in the disk, most commonly used molecular lines will be optically thick, and molecular observations should be done in rare isotopes and high density tracers in order to yield reliable results of gas densities and gas dynamics.

The unresolved continuum emission is often found to be surrounded by weaker extended emission, which is typically orthogonal to the outflow direction. There may also be extended emission in the the direction of the outflow, either due to hot dust in the beginning of the flow (jet) or dust compressed by the flow.

INTRODUCTION

During the last two years we have been studying bipolar outflow sources and PMS-stars in the mm/sub-mm continuum using the 15m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The results from these observations are now starting to appear: SSV13/HH7-11: Sandell et al., 1989a; NGC2071IR, LkHα234 and G35.2: Dent et al., 1989; B335: Chandler et al., 1989, although results on the spectacular Rho Oph outflow 16293-2422 and on high luminosity outflows are still in the process of being written up (Sandell et al., 1989b,c). Results on visible PMS stars (T Tauri, FU Ori and Herbig Ae/Be stars) which are more evolved than the deeply embedded bipolar outflow sources, but for which mass loss still occur, are reported on by Weintraub et al. (1989) and Sandell (1989a).

This talk is a first attempt to summarize the general results emerging from these studies and the same time we present some new results from recent observations. The mm/sub-mm emission provides an extremely powerful tool to study the properties of the dust surrounding bipolar outflows. With the current generation of new sub-mm telescopes we can reach much higher spatial resolution than KAO and IRAS, and even though the sub-mm sky at Mauna Kea is at best semitransparent, the large collection area of the JCMT, we can also go fainter and detect sources not seen by IRAS. By mapping we can study the outflow morphology and from multi-wavelength observations we can derive temperatures, densities, masses and the properties of the dust grains in the immediate vicinity of the exciting stars.

RESULTS AND DISCUSSION.

Data obtained from detailed high spatial resolution mm/sub-mm mapping are still rather limited, but one can already see some clear trends. In all nearby low-luminosity sources that have been observed, the star driving the outflow appears point like and unresolved, although there is normally also some extended emission present (Fig. 1). The initial sample was chosen with the aims of searching for disks around the outflows using the following criteria: 1) the bipolar outflow should lie in or close to the plane of the sky, 2) the source should be nearby, 3) there should be some evidence for the presence of a disk, either from molecular line observations or from near-IR imaging and polarization and 4) the star driving the flow should be of low luminosity. The first three criteria were made in order to maximize the detection rate of disks. If the outflow is in the plane of the sky, the disk will be viewed edge on, thus giving the maximum optical depth along the line of sight. It will enhance the likelihood of seeing the disk and perhaps resolving it. Restricting the observations to low luminosity sources makes the heating of the dust from the star much more localized, and the continuum emission will therefore be a more direct measure of the distribution of dust column density.

Although the initial results were quite promising - we found disk like structures in every source we observed (Sandell et al., 1988; Dent et al., 1989), we now believe that these extended orthogonal structures surrounding the outflows have nothing to do with the collimating disks that we were looking for. The fact that these extended structures appear to be perpendicular to the outflow direction suggests that they are remnants from the initial star formation phase, but we cannot see that they would have any influence on the current outflow phase.

What is significant, however, is the unresolved point-like source coinciding with the star driving the flow. Mm/sub-mm photometry of the central sources in the wavelength regime 2mm - 800μm, supplemented with 3mm aperture synthesis continuum data, (when available), suggest that the dust emissivity is close to 1 (Table 1). This is very similar to the results obtained by Weintraub et al. (1989) for T Tauri and FU Orionis stars and to Owens Valley aperture synthesis data on embedded PMS objects (Woody et al., 1989). It should be noted that the dust emissivity (β-index) derived by us is computed using standard assumptions, i.e. assuming single temperature (50 K, except for L723 and B335, for which we adopt T_d = 25K), homogeneous, optically thin dust emission, where the wavelength dependence of the dust emissivity can be approximated as a power law. As pointed out by Weintraub et al. (1989) effects like geometry, temperature or density gradients, can lower the apparent β-index, while if the grains are large compared to the wavelength, the power law assumption is no longer valid, and the spectrum starts to mimick a black body spectrum ($\beta = 0$). Model calculations by Weintraub and Sandell (1989) show that temperature and density gradients alone can explain the hitherto observed mm/sub-mm spectra, although the low apparent β-indexes observed in our sample may also be real (the grain population of dust in the extremely dense surroundings of a young star is expected to differ from dust grains in molecular and dark clouds). However, whatever the cause is, it is rather fortunate, because the less steeply falling spectrum makes the source easier to detect. It should be noted that so far we have a detection rate of a 100%, i.e. stars with outflows are easy to detect in the sub-mm continuum.

Table 1 summarizes the results of our mm/sub-mm obsevations on JCMT. It includes all low luminosity sources that have been observed by us, but gives only a few examples of higher luminosity outflow sources. Some more data can be found in Sandell (1989a). The masses quoted in Table 1 are total masses obtained by assuming a gas to dust mass ratio of 100. The masses are derived using the formula given in Woody et al. (1989) using the assumptions given above and by taking an average of all observed bands. We feel that his is justified, because β cannot be less than 1 (see e.g. Emerson, 1988). We will need to run model calculations in order to obtain more reliable estimates. The densities (n) are calculated by assuming that all the mass is in a spherically homogeneous dust shell, and the visual extinction (A_V) is the extinction that such a dust shell would produce along the line of sight to the star. Both these parameters are lower limits, because the dust will not survive close to the star, and the linear size of the dust shell is in almost all cases an observed upper limit. Even when the star appears resolved, the size may be overestimated due to contamination from fainter extended emission. The star may also appear to be resolved because it is a binary system, which seems to be the case for 16293-2422 (Wootten, 1989). If the mass was distributed in a disk, both the density and the extinction may be severely underestimated. Even a very modest homogenous disk, with an aspect ratio of 3:1, would already increase the density by a factor of two.

The mean value of β from the sample in Table 1 is 1.1, if we exclude the data on HH1/HH2, which may be in error (single observation, only 1.1mm and 800μm). These values are less extreme than those on T Tauri stars (Weintraub et al., 1989), but nevertheless significantly different from 2. In the case of SSV13, the 1.1mm and 800μm mapping by Sandell et al. (1989a) indicates that the β-index of the extended emission surrounding SSV13 is close to 2. This suggest that if the outflow sources are associated with extended emission, we may not be able to derive the true properties of the disk emission using single dish data.

Another striking fact in Table 1 is the high visual extinctions in the line of sight to the stars, which in most cases exceed observed extinctions by more than an order of magnitude, c.f. SSV13: 250^m vs. 15^m; L1551IRS5: 340^m vs. 19^m. If we could put more stringent size constraints on the sub-mm emission, the discrepancies would probably be even higher. We therefore argue that the sub-mm emission cannot originate from a shell, it must be an anistropic distribution, presumably some kind of a disk. This would already be expected from the strong molecular outflows that are seen, because these are driven by the star. At this stage we cannot really predict what the disks look like. We only know their approximate mass and we have a limit to their overall size ($\lesssim$ 2000 AU) for nearby stars. What is crucially needed is to learn about their detailed morphology (thin or thick disk) and dynamics. These are data which must come from mm-aperture synthesis

Table 1: Physical properties of outflow sources observed in continuum on JCMT with the common user bolometer UKT14 (for details about UKT14; see Duncan et al., 1989). Luminosities and distances are taken from Mozurkewich et al. (1986), or occasionally from other sources.

Outflow	Size ["]	d [pc]	L [$L_\odot$]	β-index	M_{tot} [$M_\odot$]	n [cm^{-3}]	A_V [mag]	Wavelength[a]
Low luminosity sources:								
SSV13[b]	$\leq$4x4	350	58	0.7 ± 0.2	0.25 ± 0.05	2×10^{7}	250	3.06/2.73/1.4
HH6VLA	<7	350	18	1.4 ± 0.3	0.28 ± 0.02	5×10^{6}	90	1.1/.79
L1551IRS5	6x8	160	38	1.2 ± 0.3	0.11 ± 0.01	5×10^{7}	340	1.1/.79
16293-2422	11x<5	160	27	1.2 ± 0.1	0.64 ± 0.04	1×10^{8}	910	2/1.3/1.1/.79
L723	<7	300	3	1.0 ± 0.2	0.24 ± 0.02	7×10^{6}	110	1.3/1.1/.79
B335	<6x7	250	1.7	1.1 ± 0.2	0.26 ± 0.05	1×10^{7}	190	1.3/1.1/.79
HH1/HH2VLA	<10[c]	460	50	1.8 ± 0.4	0.47 ± 0.13	2×10^{6}	60	1.1/.79
PVCep	<7	500	80	1.4 ± 0.4	0.32 ± 0.07	2×10^{6}	50	1.1/.79/.45/.35
Intermediate luminosity sources:								
NGC7129FIR	8x10	1000	230	1.2 ± 0.3	4.2 ± 0.1	2×10^{6}	110	1.1/.79
LkHα234	<7x9	1000	10^{3}	1.5 ± 0.5	3.6 ± 0.3	2×10^{6}	120	1.1/.79
High luminosity sources:								
M8E	15x17	1500	2×10^{4}	0.8 ± 0.3	31 ± 6	6×10^{5}	110	2.0/1.1/.79
NGC7538B[e]	19x21	2800	2×10^{5}	1.1 ± 0.2	215 ± 5	3×10^{5}	140	2.0/1.1/.79

[a] This column gives the center wavelength for the filters used to derive β-indexes and masses.

[b] Mass and β-index derived from data in Grossman et al. (1987) and Woody et al. (1989), see Sandell et al. (1989a)

[c] Source size uncertain

[d] β = 1.2 if 450 and 350μm data are omitted.

[e] Fluxes corrected for free-free emission

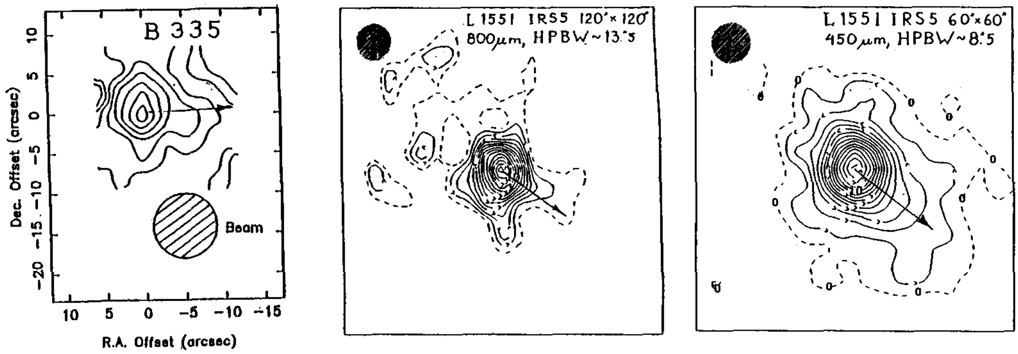

Figure 1. a. 450μm map of B335 (from Chandler et al., 1989). b. 800μm map of L1551IRS5. c. 450μm map of L1551IRS5. The two 450μm maps have a resolution of 8.5", while the resolution of the 800μm map is 13.5". Note that in both cases one can see emission perpendicular to the outflow (marked by arrow), as well as in the flow direction.

telescopes. Sargent (1989) presented data on outflow sources, which suggest that the gas appears to move in Keplerian orbits around the stars, but the data base is very limited. She also noted that one has to observe these disks in ^{13}CO or C^{18}O, because the gas is optically thick. This is very clear from the gas densities derived in Table 1. Since the gas densities could well be in excess of 10^{10} cm^{-3} while the gas is quite cold, the molecules could be frozen onto grains, and the molecular abundances severely depleted. The ideal molecular tracer should have low excitation transitions and very high dipole moment, in order to trace adequately cold, very high density gas.

The deduced masses of the disks in the low luminosity sample are very similar. This may partly be due to the way we have computed the masses, because we chose to neglect differences in the observed β-index, but to a large extent the results are probably real. The sample is quite homogeneous, and most of the outflows are of about the same age. If these masses are compared to the disk masses seen in T Tauri stars (Weintraub et al., 1989), which are presumably much more evolved, but similar objects, one can note that the T Tauri disk are about a few x .01 M$_\odot$, i.e. about 10 times smaller than the embedded stars discussed here. If one crudely assumes that T Tauri stars are ~ 10^6 -10^7 years older, this would correspond to a mass loss rate of 10^{-7} - 10^{-8} M$_\odot$ years^{-1}, if all of the disk mass went into the flow. These mass loss rates appear plausible for T Tauri stars, but are definitely too low for the deeply embedded outflows. However, it is also likely that part of the disk mass will fall onto the star and serve to increase its mass.

As mentioned earlier, bipolar outflow stars are also associated with fainter extended emission. Some of this emission is perpendicular to the flow, but there is also emission in the flow direction. This is illustrated in Figure 1, where we show high resolution 450μm images of B335 and L1551IRS5. In both cases there is evidence for emission perpendicular to the flow, which is more clearly seen in the larger 800μm images (see e.g. Chandler et al., 1989 for an 800μm map of B335). The L1551 800μm map is of poor S/N but appears to confirm the presence of more extended N-S emission. Other outflows that reveal clear extended emission are SSV13, 16293-2422, and LkHα234 (Sandell et al., 1989a,b; Dent et al., 1989). Some of the emission is clearly associated with the large "interstellar disks" seen in ammonia and carbon monosulfide, while for example B335, L1551 and SSV13 also show emission in the outflow direction. This could be due to dust compressed by the outflow along the cavity walls , like in SSV13, or it could be hot dust associated with the beginning of the flow. In order to determine the properties of this relatively faint dust emission one needs deep, well calibrated maps at three wavelengths, which have not yet, as yet, been obtained.

Acknowledgements: The James Clerk Maxwell Telescope is operated on a joint basis between the United Kingdom Science and Engineering Research Council (SERC), the Netherlands Organisation for the Advancement of Pure Research (ZWO), the Canadian National Research Council (NRC), and the University of Hawaii (UH). I want to thank not only all my collaborators in this project: W.D. Duncan, S. Hayashi, C. Aspin, P.A.R. Ade, M.J. Griffin, W.K. Gear, C.J. Chandler, W.R.F. Dent, and E.I. Robson, but also the whole staff at JCMT.

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Discussion:

CAMERON: In your near-IR camera image of the flow from SSV13 there appeared to be emission apparently extending away from HH7. Do you believe that this emission is associated with SSV13 in which case it would imply that the HH7 knot is not the working surface of the optical outflows?

SANDELL: It is not clear whether the faint emission seen in front of HH7 in the IRCAM image by Graden, Burton and Russell relates to SSV13. It may be the case, but there is also another outflow further south.

SOLOMON: Is it possible that the grain emissivity at 350μm, 1mm or $\lambda = 2$mm is simply not known and that the column density (or density) you deduce from these observations is substantially in error? Do we really know the very long wavelengh emissivity of the dust? The grains could be large or elongated.

SANDELL: There are uncertainties, but not large enough to explain these huge discrepancies. The dust emissivity law can be measured, and for young stars associated with outflows or surrounded by dust disks we measure $\beta \sim 1$, regardless of luminosity. Density and temperature gradients may act to lower the measured β-index. If the grains are large (c.f. DG Tau; Weintraub et al, Ap. J. Letters, in press), the definition of the β index breaks down and we essentially just see a black body.

ZINNECKER: Is there a correlation between the derived dust masses and the luminosities of the sources?

SANDELL: Yes, there is, but there is considerable scatter. This is probably due to age effects, i.e., the youngest stars have larger dust masses than more evolved ones, and luminous stars also have more massive disks.