Bipolar Outflows from Massive Protostars

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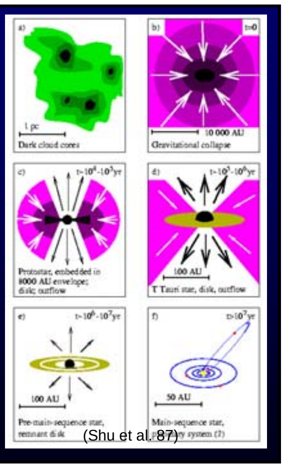
Massive SF

- Massive (>8 $M_{\odot}$) Stars; fundamental in evolution of Gals
  - energize ISM,
  - produce heavy metals,
  - regulate SF
- Massive SF; poorly understood
  - small # -> large distances,
  - fast evolution,
  - large extinction,
  - clustering



(Shu et al. 87)

Two Competing Models

- Traditional accretion model for low-mass SF (Shu 77)

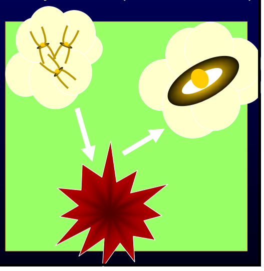
  $dM/dt_{acc} = 0.975c^3/G = 4.4\times10^{-6}\,(T/20K)^{3/2}\;\; M_{\odot}/yr$

  strong radiation pressure (Wolfire & Cassinelli 87)
  long formation time (>10^6 yr)   cf) ~1 M yr for ONC (Palla & Stahler 99)

- Merging model (Bonnell et al. 98; Stahler et al. 00; Bally & Zinnecker 05)

  merging of low-mass (proto)stars

  Orion-KL outflow (Allen & Burton 93)
  mass segregation in young clusters (Hillenbrand & Hartmann 98)
  high stellar density (>10^8 pc^{-3})



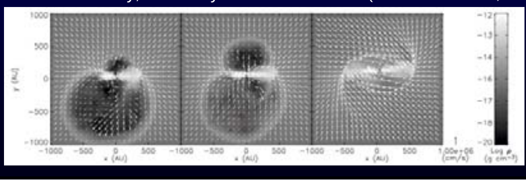
Two Competing Models

- Accretion model (McKee & Tan 02, 03)

  massive star-forming cores: more turbulent (& hotter) (Kurtz 00)
  → denser cores

  high accretion rate (>5×10^{-5} $M_{\odot}$/yr)

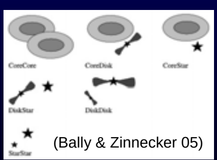
  Disk (Yorke & Sonnhalter 02)
  outflow cavity, instability of radiation bubble (Krumholz et al. 05, 05b)



How to distinguish bet. Two Models

	Accretion	Merging (Cesaroni 05)
disks	well defined	none ?
Inflows	global	local
outflows	common	not common ?
	collimated ?	explosive/impulsive

…



(Bally & Zinnecker 05)

(Kaifu et al. 99)

Outflows from Massive YSOs

- Molecular Outflows; common in massive YSOs?

  high-velocity CO gas in >70%

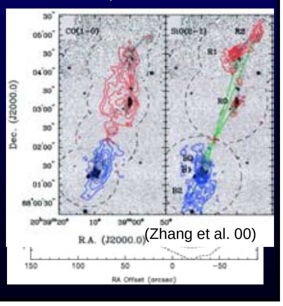
  (e.g., Shepherd & Churchwell 96a; Sridharan et al. 02)

- Characteristics

  (SC 96b; Ridge & Moore 01; Richer et al. 01)

  very massive (> 10 $M_{\odot}$)
  very energetic (> 100 $M_{\odot}$ km s^{-1})
  poorly collimated (fc=1 – 1.8)
  cf) fc=1 – 10

➡ Different driving mechanism ?
(e.g., Churchwell 02)



(Zhang et al. 00)

Occurrence Frequency of Outflows

- Occurrence Rate (CO mapping)

  5/10 of SC96a sample (70%) (35%, Shepherd & Churchwell 96b)
  21/26 of Sridharan sample (84%) (70%, Beuther et al. 02)
  39/69 of Molinari sample (60%, Zhang et al. 01)

  35% - 70%

  Only for sources at l > 50º (Zhang et al. 01) , 90%.

  Only for sources at l < 50º, non-reliable statistics
  because outflow signature is often confused by other velocity components in the same line of sight.

Observations

- Sources: 12 of 48 sources at l>50º

  catalog of 101 massive protostellar candidates (Molinari et al. 96, 98, 00)
  39 of 69 sources observed in CO (2-1) (Zhang et al. 01)
  35 of 39 sources at l>50º (3 sources in common)

  "complete unbiased survey"

SOURCE SUMMARY

Source Number[a]	IRAS Name	Type[a]	α (J2000.0)	δ (J2000.0)	l (deg)	b (deg)	d (kpc)	L_{bol} ($L_\odot$)	Maser H_2O[b]	Maser CH_3OH[c]	CO J = 2−1 Wings	CO J = 2−1 Outflow
2	00117+6412	H	00 14 27.7	+64 28 46	118.961	+1.893	1.8	1.38E3	Y	N	Y	Y
10	05274+3345	H	05 30 45.6	+33 47 52	174.197	−0.078	1.6	4.35E3	Y	Y	Y	Y
14	05553+1631	H	05 58 13.9	+16 32 00	192.161	−3.815	2.0[d]	5.20E3	Y	N	Y	Y
15	06056+2131	H	06 08 41.0	+21 31 01	189.032	+0.784	2.0[d]	1.04E4	Y	Y	Y	Y
16	06061+2151	H	06 09 07.8	+21 50 39	188.796	+1.033	2.0[d]	1.11E4	Y	Y	Y	N
19	06103+1523	H	06 13 15.1	+15 22 36	194.934	−1.227	4.6	1.91E4	N	N	Y	Y
21	06105+1756	H	06 13 28.3	+17 55 30	192.723	+0.040	3.4	1.60E4	N	N	N?	N
27	06382+0939	H	06 41 02.7	+09 36 10	203.205	+2.080	0.8	1.63E2	N	N	Y	Y
124	20227+4154	L	20 24 31.4	+42 04 17	79.885	+2.552	1.7[e]	2.64E3	Y	N	Y	Y
146	22267+6244	H	22 28 29.4	+62 59 44	107.504	+4.488	0.5	1.10E2	N	N	Y	Y
147	22272+6358A	H	22 28 52.3	+64 13 43	108.186	+5.519	1.2	1.97E3	N	Y	Y	Y
163	23545+6508	H	23 57 05.2	+65 25 11	117.315	+3.142	1.3	3.89E3	N	N	Y	Y

- Kitt Peak 12m Observations

  CO (2-1) line (27″) , 2003 Jan & Feb

Results

- Detection of HV gas: 11/12

  not confused by other comps

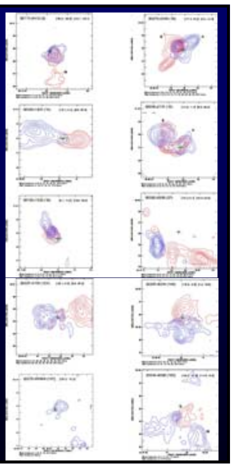
- Detection of Outflow: 10 /12

  1 monopolar outflow
  2 outflows in 2 sources

- Outflow Parameters,

  M > 10 $M_\odot$
  P > 100 $M_\odot$ km/s
  t=(1-10)x10⁴ yr
  dM/dt_{out}=(1-10)x10⁻⁴ $M_\odot$/yr

much more Massive and Energetic
than outflows from low-mass YSOs



Discussion

- Occurrence Frequency: 90%

  42 of all 48 Molinari sources with l > 50º
  outflows at large inclinations, e.g., 10% for i ≥80º
  cf) 40% - 70% (Previous studies)

  Nearly all sources have outflows.

- For low-mass Protostars,

  70% - 90% (Tereby et al. 89; Parker et al. 91; Bontemps et al. 96)
  e.g., 75% of 45 Class 0 & I sources (Bontemps et al. 96)

  Similar occurrence frequency!!

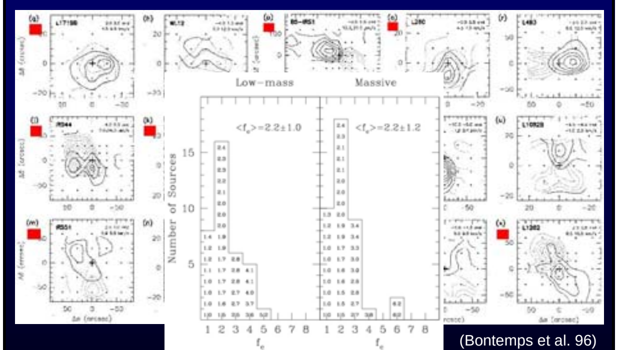
Discussion

- Collimation: fc= 1 – 3.8

  fc > 2.0 for 6 outflows (>3.0 for 3 outflows)
  <fc>=2.3
  ~ 2.1 for 15 massive outflows at 11″ (Beuther et al. 02)
  cf) 1 – 2 for some other massive outflows
  (e.g, Richer et al. 00; Ridge & Moore 01)

  Better collimated than other massive
  outflows observed by previous SD studies.

Discussion



(Bontemps et al. 96)

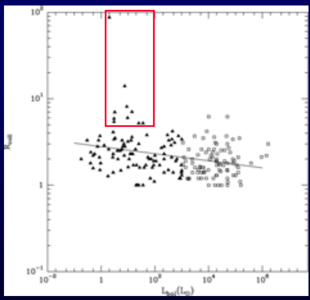
NO significant difference in collimation ?

Discussion

- Wu et al. (05)

$\langle fc \rangle = 2.8 \pm 2.2$
for ~130 low-mass outflows
$\langle fc \rangle = 2.1 \pm 1.0$
for ~100 massive outflows

The differnce is due to
Different Resolutions
$\langle fc \rangle = 2.3$,
if 10 with fc>5 is excluded

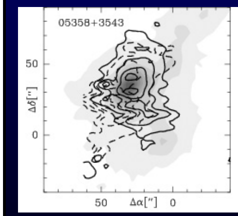


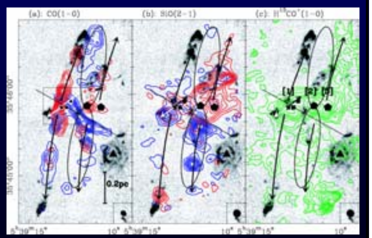
as well collimated as many low-mass outflows!!

Discussion

- No difference in collimation ?

better collimated at higher resolutions (e.g., Beuther et al. 02)
multiple well-collimated outflows (e.g., Beuther et al. 02b)
radio & H_2 jets. (e.g, Garay et al. 2003; Davis et al. 04)





Poor collimation is due to multiple outflows & low resolution ?

Discussion

- Mass Accretion Rate

If massive outflows are momentum-driven by jets and/or wide angle winds as low-mass ones (Konigl & Pudritz 2000; Shu et al. 2000), i.e., (dM/dt)jet/(dM/dt)acc = 0.1 – 0.3,
$(dM/dt)_{out}/(dM/dt)_{acc} = 0.2 – 0.5$ for V_{jet}/V_{out} ~ 20.

$\langle dM/dt \rangle_{out} = 5\times10^{-4}\ M_\odot/yr$
➡ $\langle dM/dt \rangle_{acc} \geq 1\times10^{-4}\ M_\odot/yr$

cf) $10^{-7} – 10^{-5}\ M_\odot/yr$ (e.g., Shu 77; Bontemps et al. 96)

Large accretion rates sufficient to overcome the radiation pressure of the central massive protostars

Conclusions

- Bipolar outflows are as common in massive protostars as in low-mass protostars: 90% occurrence frequency
- Outflows from massive protostars are much more massive and energetic than outflows from low-mass protostars. There seems to be no significant difference bet. the collimations of two groups.
- Outflows observed by this study have mass outflow rates >2x $10^{-4}\ M_\odot/yr$, suggesting large accretion rates of 1x $10^{-4}\ M_\odot/yr$, which are large sufficient to overcome the strong radiation pressure of the central massive protstars.

These can be naturally understood in Accretion Model, but cannot be easily explained by merging model.