Mm/radio gas observations of disks

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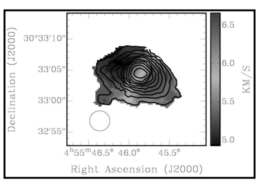
- Overview of submm/radio emission from molecules
- Recent results on disk kinematics and the implications for pre-main sequence star and disk properties
- Separating disks and envelopes in embedded protostars using absorption spectroscopy

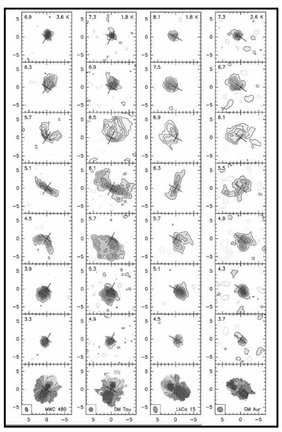
General properties of molecular emission

- At radio through submm wavelengths molecular emission is typically from cool gas, ~20–40K
- Current arrays are able to resolve circumstellar disks both spectrally ($R \geq 10^6$) and spatially (θ_b~1") at radii where most of the disk mass resides ⇒ can use the kinematics to disentangle M_* from inclination, i
- Some problems using molecular emission for studying disks:
  - Radiative transfer is not as simple as for dust because of the molecular partition function
  - Chemical and physical processes (e.g., freeze-out) dramatically affect abundances as a function of T and ρ
  - Some lines of common molecules are optically-thick, and do not trace all the mass

Observations of disks

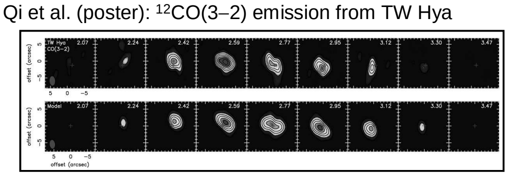
- Simon et al. (2000):
  - ^{12}CO(2–1) emission from 9 T Tauri stars in Taurus-Auriga
- Corder et al. (poster):
  - ^{13}CO(1–0) emission from the Herbig Ae/Be star AB Aur



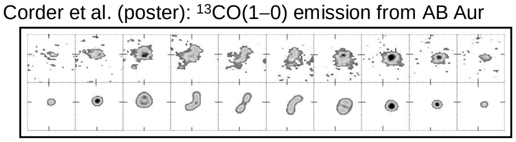


Observations of disks (cont.)

Qi et al. (poster): ^{12}CO(3–2) emission from TW Hya



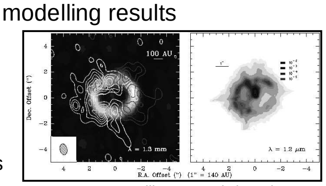
Corder et al. (poster): ^{13}CO(1–0) emission from AB Aur



Classic signature of a rotating disk

Disk modelling results

- Fit for radial dependence of velocity ⇒ $V \propto r^{-v}$
- Results for 9 TTSs from Simon et al.:



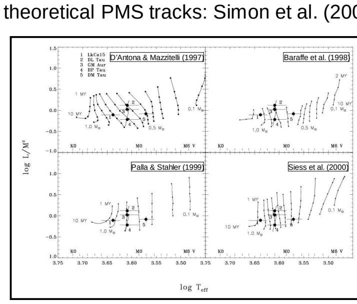
GG Tau: Guilloteau et al. (1999)

TABLE 4
DERIVED PARAMETERS (D = 140 pc)

Star (1)	PA_{cont} (deg) (2)	i_{cont} (deg) (3)	PA_{CO} (deg) (4)	i_{CO} (deg) (5)	R_{out} (AU) (6)	V_{100} sin (i) (km s^{-1}) (7)	$-v$ (8)	M_* ($M_\odot$) (9)
				Singles				
MWC 480	-10 ± 11	26 ± 7	-32 ± 1	$+38 \pm 1$	545 ± 5	-2.38 ± 0.02	0.50 ± 0.02	1.65 ± 0.07
LkCa 15	62 ± 5	42 ± 5	$+61 \pm 1$	$+52 \pm 1$	650 ± 15	-2.30 ± 0.02	0.56 ± 0.03	0.97 ± 0.03
DL Tau	44 ± 3	49 ± 3	$+50 \pm 3$	$+35 \pm 2$	520 ± 50	1.90 ± 0.06	0.55 ± 0.03	0.72 ± 0.11
GM Aur	57 ± 5	54 ± 5	$+51 \pm 2$	$+56 \pm 2$	525 ± 20	2.30 ± 0.08	0.5 ± 0.1	0.84 ± 0.05
DM Tau	-1 ± 5	45 ± 5	-27 ± 1	-32 ± 1	800 ± 5	-1.17 ± 0.02	0.53 ± 0.01	0.55 ± 0.03
CY Tau	-56 ± 7	47 ± 8	-30 ± 7	$+30 \pm 10$	270 ± 10	-1.10 ± 0.10	0.50 ± 0.08	0.55 ± 0.33
BP Tau	...	20 ± 20	-28 ± 3	$+30^{+4}_{-2}$	108 ± 4	1.67 ± 0.06	0.54 ± 0.07	$1.24^{+0.25}_{-0.32}$
				Binaries				
GG Tau A......	7 ± 2	37 ± 1	$+7 \pm 2$	$+37 \pm 1$	~800	2.05 ± 0.06	0.5 ± 0.1	1.28 ± 0.07
UZ Tau E	87 ± 3	54 ± 3	$+86 \pm 2$	-56 ± 2	300 ± 20	-2.83 ± 0.05	0.53 ± 0.03	1.31 ± 0.08

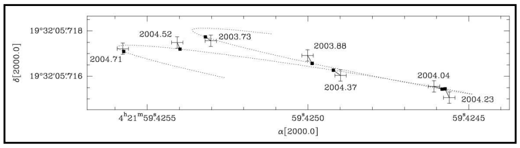
Disk modelling results (cont.)

- Velocities are Keplerian
- Can place strong constraints on M_* and i
- Test theoretical PMS tracks: Simon et al. (2000)



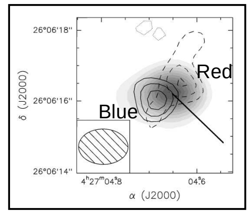
Limitations

- Simon et al. show that constraints on M_* derived from disks now limited by poorly determined distances
- Not really disk-related, but such a beautiful result I have to show it: Loinard et al. (2005) use multi-epoch VLBA observations to measure the non-thermal emission from T Tau S $\Rightarrow$ parallax=7.07 ± 0.14 mas
- D=$141.5\pm^{2.8}_{2.7}$ pc (cf. Hipparcos distance, $177\pm^{70}_{39}$ pc)

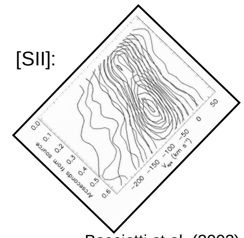


Disks and jets: the case of DG Tau

- Testi et al. (2002): ^{13}CO(2–1) line wings show velocity gradient with rotation in same sense as the [SII]/[OI] jet $\Rightarrow$ first direct evidence of a disk/jet connection and the transport of angular momentum using jets?



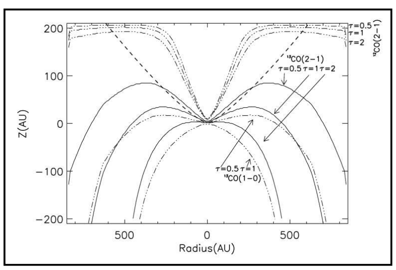
[SII]:



Bacciotti et al. (2002)

Vertical disk structure

- Dartois et al. (2003): ^{12}CO(2–1), ^{13}CO(2–1), and ^{13}CO(1–0) constant τ surfaces vs. radius and height (see also Piétu et al., poster)



Vertical structure: DM Tau

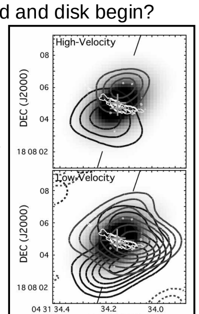
- Dartois et al. observe ^{12}CO(2–1)/(1–0), ^{13}CO(2–1)/(1–0), and C^{18}O(2–1)
- ^{12}CO samples 2–4 scale heights
- ^{13}CO(2–1) samples ~1 scale height
- ^{13}CO(1–0)/C^{18}O(2–1) sample disk midplane
- Evidence that the outer layer is warmer (~30 K) than the midplane (~13–20 K)

Final comment on T Tauri disks

- Only the most massive TT disks can be detected in molecules because of typical depletions ~10–100
- Will have to wait for ALMA to know whether these techniques will work for lower mass disks as well

Protostellar disks

- Made complicated by the presence of a surrounding envelope: where does envelope end and disk begin?
- Extra kinematic components (infall, outflow) complicate matters
- Interpretation becomes more model-dependent: e.g., CS(7–6) emission from L1551 (Takakuwa et al. 2004):
  - High-velocity gas consistent with rotation about central mass 0.15$M_\odot$, but mass from binary motion is 1.2$M_\odot$
  - Low-velocity gas may have contributions from outflow and/or infall + rotation in the envelope



Disentangling disks and envelopes

- Assume "disk" is material centrifugally supported and exhibiting Keplerian rotation
- Need to separate rotation component from outflow and infall
- If there is a *bright, compact* continuum source at the position of the protostar can potentially use absorption spectroscopy to identify the outflow and infall components:
  - outflow will be blueshifted
  - infall will be redshifted
  - rotating gas will absorb at the systemic velocity
- Use the dust emission from the disk itself as the background continuum source

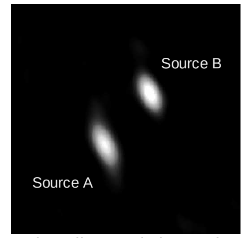
Requirements for absorption spectroscopy

1. Disk must be massive to make the dust emission optically-thick, so that T_B is higher than T_{ex} in foreground cloud
2. Need $\theta_B \sim \theta_{disk} < 1''$
3. $\tau_{dust} \propto \nu^{1-2} \Rightarrow$ need high ν
4. Need a high-dipole moment molecule (high n_{crit}) and a high transition likely to have $T_{ex} < T_{B,dust}$ for absorption (either due to low T_{kin} or sub-thermal excitation)

- SMA gives #2 and #3
- #1 is the hardest requirement to meet! Only possible for a handful of low-mass sources

IRAS 16293–2422

- Class 0 binary protostar in ρ Oph
- Component B has optically-thick dust emission with $T_B=S\lambda^2/2k\Omega=38$ K @ 300 GHz on scales of ~1"
- Good molecules to try: H_2CO, HCN, HCO^+, SO, CS, etc.
- Set out to detect infall using H_2CO (4_{13}–3_{12}) @ 300.8 GHz (E_{upper} = 48 K), but blended with methyl formate emission

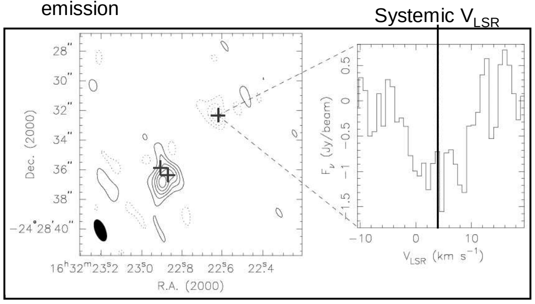


Chandler et al. (poster)

SO(7_7–6_6) absorption against source B

- SO(7_7–6_6) @ 301.3 GHz also detected (E_{upper} = 71 K)
- Cut out short baselines to filter out extended SO emission

Systemic V_{LSR}



Conclusion

- With higher s/n and multiple transitions will be able to invert the absorption to derive contributions from infall and outflow on size scales of the dust emission
- For other results on IRAS 16293–2422 see Chandler et al. (poster)
- Other submm/radio papers at this meeting investigating gas in disks:
  - Lin et al.
  - Andrews & Williams
  - Dent
  - Dominik & Ceccarelli
  - Patience et al.
  - Piétu et al.