Outflows in massive star formation: from the magnetic to the radiative outflow

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Formation of massive stars in magnetised cores

✓ Focus on isolated massive core, threaded by regular magnetic fields
✓ Interplay between magnetic braking and radiative feedback reduces efficiently fragmentation (Commerçon et al. 2011, Myers et al. 2013)
✓ Choice of slowly rotating cores to focus on the star-disk-outflow system formation, without strong fragmentation

Commerçon et al. 2011
✓ Adaptive-mesh-refinement code RAMSES (Teyssier 2002)
✓ Multifrequency Radiation-HD solver using the Flux Limited Diffusion approximation (Commerçon et al. 2011, 2014, González et al. 2015). In this work, just grey
✓ Sink particles using clump finder algorithm (Bleuler & Teyssier 2014)

Gravitational
Radiative
Lorentz force

Ambipolar EMF

\[
E_{AD} = \frac{1}{\gamma_{AD}\rho_i\rho} \left[ (\nabla \times B) \times B \right] \times B
\]
Initial conditions and stellar evolution

✓ 100 M⊙; ρ ∝ R⁻² (ρ_c=2x10⁶ cm⁻³); T = 20 K ; R₀ = 0.2 pc
✓ Solid body rotation Ω=3x10⁻¹⁵ Hz (r_d~650 AU)
✓ Uniform magnetic field (μ_uni=2,5,∞) (B=170, 68, 0 μG), aligned with rotation axis (x-axis)
✓ at least 10 cells/Jeans length

✓ Sink particles : ρ_thre=10¹⁰ cm⁻³ , r_sink=~20 AU (4Δx_min)
✓ Protostellar feedback sources associated to the sink:
  ★ internal luminosity given by Hosokawa et al. tracks (R. Kuiper), L_acc=0
  ★ all the accreted mass goes in stellar content (most favorable case)
  ★ NO sub-grid model for outflow

✓ 4 models: Hydro, IMHD μ=2, ambipolar diffusion μ=2 and μ=5
Hydro collapse

- Formation of a large disk: R~1000 AU
- Binary system: 24 and 13 M⊙
- Radiative outflow/bubble (1500 AU)
iMHD collapse, $\mu = 2$

$M_* = 0.5 \, M_\odot$
Hydro & iMHD: origin of the outflow

- Outflow has a radiative origin
- Magnetic fields disorganised by magnetic flux expulsion (interchange instability, e.g., Masson et al. 2016)
Ambipolar diffusion, $\mu = 2$

$M_* = 0.1 \, M_\odot$
Ambipolar diffusion, $\mu = 5$

$M_* = 0.2 \, M_\odot$
Outflow morphology

AMBI $\mu = 2$

AMBI $\mu = 5$

HYDRO
Outflow collimation

- Outflow collimated by toroidal B-field
- Outflow extends up to 50,000 AU when $M_* = 12M_\odot$, $V_{out,max} = 40$ km/s
- Outflow is strongly magnetized

AMBI $\mu = 2$

AMBI $\mu = 5$

AMBI $\mu = 5$
Is radiative feedback important?

✓ radiative force contributes to the outflow, but does not dominate over the Lorentz force.
Discs properties

**HYDRO**

**IMHD $\mu=2$**

**AMBI $\mu=5$**

**AMBI $\mu=2$**
Discs properties

- Discs are dominated by thermal pressure with AD (i.e. hydro discs)
- Thick and magnetised disk with iMHD
Magnetisation

✓ Bmax reduced by > 1 order of magnitude by AD
✓ plateau @ B<1G
✓ similar to results found in low mass star formation

Masson et al 2016
Conclusion

- Outflow is primarily of magnetic origin
- Magnetic outflow extends up to 50,000 AU
- Radiative force does not overtake with $M_\star < 15 M_\odot$, but contributes to acceleration
- No large disk - $R < 500$ AU
- Observational diagnostics
- Ideal MHD and hydro models have strong limitations wrt
  1. outflow launching
  2. disk properties (as well as for low-mass star formation…)
  3. angular momentum transport

➡️ To do

✓ parameter study, turbulence