Disc Formation and Feedback from YSOs

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Star Formation: Early-type discs

Observations of protostellar discs
Magnetic Fields

The ISM is permeated with magnetic fields

galactic B-fields (e.g. R. Beck 2001)
large scale component: \( \sim 4 \mu G \)
total field strength: \( \sim 10 \mu G \)

magnetic polarization measurements in the Pipe nebula
F.O. Alves, Franco, Girart 2008

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Turbulence

Larson relation: Turbulence in Molecular Clouds

⇒ supersonic high mass cores
⇒ sub-sonic low mass cores ($R < 0.1$ pc)

*Larson 1981*
Magnetic Fields

Crutcher 2010

\[ \mu = 2 \ldots 5 \]
Star Formation: Early-type discs

Collapse of magnetised, rotating cloud cores

• **stronger** magnetic fields: $\mu < 5$ in agreement with observations (e.g. Crutcher et al. 2010)

$\mu = 2$

**magnetic braking catastrophe?**

$\Rightarrow$ **too** efficient magnetic braking

$\Rightarrow$ **no** disc formation

Hennebelle & Teyssier 2008, ...
Magnetic Braking Catastrophe

Solutions?

• flux loss by:
  • Ohmic resistivity (*Dapp & Basu 2011*, *Krasnopolsky et al. 2010*)
  • ambipolar Diffusion (*Duffin & Pudritz 2008*, *Li et al. 2011*)
  • turbulent reconnection
    (*Lazarian & Vishniac 1999*, *Santos-Lima et al. 2012*)

• Hall effect (*Krasnopolsky et al. 2011*)
Magnetic Braking Catastrophe

→ Non-ideal MHD and reconnection active only at small scales/high density
→ not effective enough to reduce magnetic braking

→ Li, Krasnopolsky & Shang 2011:
  “The problem of catastrophic magnetic braking that prevents disk formation in dense cores magnetized to realistic levels remains unresolved”
Magnetic Braking Catastrophe

\[ \log \sigma \quad \text{(km/s)} \]
\[ \sigma_s \]
\[ \log L \quad \text{(pc)} \]

\[ \rightarrow \text{what about turbulence?} \]

Larson 1981

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Collapse of Turbulent Cloud Cores

Seifried, et al. 2013

<table>
<thead>
<tr>
<th>Run</th>
<th>$m_{\text{core}}$ (M$_\odot$)</th>
<th>$r_{\text{core}}$ (pc)</th>
<th>$\mu$</th>
<th>Rotation</th>
<th>$\Omega$ ($10^{-13}$ s$^{-1}$)</th>
<th>$\beta_{\text{turb}}$</th>
<th>Turbulence seed</th>
<th>$p$</th>
<th>$M_{\text{rms}}$</th>
<th>$t_{\text{sim}}$ (kyr)</th>
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- low + high mass cores
- strong magnetic field
- with/without global rotation
- sub-/supersonic turbulence
- resolution: 1.2 AU
Collapse of Turbulent Cores

Seifried, RB, Pudritz, Klessen 2012

⇒ discs “reappear”
Collapse of Turbulent Cores
Collapse of Turbulent Cores

- low mass cores
- strong magnetic field: $\mu = 2.6 \mu_{\text{crit}}$
- transonic turbulence $Ma = 0.74$
- no global rotation
- with global rotation

Seifried, et al. 2013
Collapse of Turbulent Cores

velocity structure

2.6-NoRot-M2

2.6-Rot-M2

2.6-NoRot-M100

2.6-Rot-M100
Collapse of Turbulent Cores

due to flux loss?

no turbulence
no disc

$\Rightarrow$ no flux loss
Collapse of Turbulent Cores

accretion flow

low mass core: $M_{\text{core}} = 2.6 \ M_\odot$

high mass core: $M_{\text{core}} = 100 \ M_\odot$

Seifried, et al. 2014
Collapse of Turbulent Cores

Torques

non turbulent case

Robi Banerjee, Stellar Clusters, Copenhagen, Nov 6 2014
Outflows & Jets

- Outflows & Jets are ultimately linked to the formation of stars

⇒ what’s their impact on star formation?
What drives Outflows & Jets?

For 391 outflows: *Wu et al. (2004)*

Outflows launched by magnetic fields
Lorentz force:
(assume axi-symmetry, i.e. $\partial_\phi B = 0$)

$$j \times B = -\frac{1}{2} \nabla B^2 + (B_p \cdot \nabla) (B_p + B_\phi e_\phi) - \frac{B_\phi^2}{R} e_R$$

hoop stress
(jet collimation)

different force types:

- **magnetic pressure**: force along gradient
- **tension**: force along magnetic field lines
- **hoop stress**: force towards axis
Jet Launching

Lorentz force:
(assume axi-symmetry, i.e. $\partial_\phi B = 0$)

$$ j \times B = -\frac{1}{2} \nabla B^2 + (B_p \cdot \nabla) (B_p + B_\phi e_\phi) - \frac{B_\phi^2}{R} e_R $$

hoop stress
(jet collimation)

“beads on a wire”
Blandford-Payne type acceleration

centrifugal acceleration

magnetic pressure acceleration

courtesy Matsumoto & Shibata, 1999
Jet Launching

magneto-centrifugally driven wind
Jet launch if angle of $B_p$ with disk plane $< 60^\circ$
(Blandford & Payne 1982)

$\Rightarrow$ discs are necessary to drive jets & outflows!

Pelletier & Pudritz, 1992
Collapse of Magnetised Cloud Cores

- magnetically driven Jets / Outflow from YSOs
Outflows from Collapse of Magnetised Cores

3D MHD simulation of a massive collapsing cloud core by Daniel Seifried
Feedback: Impact of Jets & Outflows

Jets from Young Stars
PRC95-24a · ST ScI OPO · June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA
Feedback: Impact of Jets & Outflows

• Jets are powerful:

\[
L_{\text{jet}} = \frac{\dot{M}_{\text{jet}} v_{\text{jet}}^2}{2} \approx 2.9 \times 10^{32} \left( \frac{\dot{M}_{\text{jet}}}{10^{-8} M_\odot \text{ yr}^{-1}} \right) \times \left( \frac{v_{\text{jet}}}{300 \text{ km s}^{-1}} \right)^2 \text{ ergs s}^{-1}
\]

\[\sim 8\% L_\odot\]

\[
E_{\text{jet}} = L_{\text{jet}} \tau_{\text{jet}} \approx 10^{44} \text{ ergs}
\]

with \(\tau_{\text{jet}} = 10^4 \text{ yrs}\)

\[\implies \text{cf. } E_{\text{turb}} \sim 10^{46} \text{ ergs}\]

\[\implies \text{Jets from a little stellar cluster } \textbf{could} \text{ maintain the turbulence}\]

\[\implies \text{But how } \textbf{efficient} \text{ do they couple to the ISM?}\]
Feedback: Impact of Jets & Outflows

- numerical experiments with **single**, high Mach number jets (momentum injection)
- detailed analysis with velocity PDFs

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*RB, Klessen & Fendt 2007*
Feedback: Impact of Jets & Outflows

- Turbulent motions are sub-sonic
- Very little supersonic fluctuations
  \[ \Rightarrow \text{“supersonic desert”} \]
Feedback: Impact of Jets & Outflows

- supersonic fluctuations decay quickly: $E \propto t^{-2}$ (Mac Low et al. '98)
- supersonic fluctuations occupy only a small fraction of all fluctuations
Feedback: Impact of Jets & Outflows

Influence of Magnetic Fields

Jets from YSOs cannot maintain the supersonic turbulence observed in MCs. Magnetic fields suppress the amplitude of velocity fluctuations, thereby stabilizing the jet (aligned field) against turbulence. In contrast, an anti-parallel field can enhance turbulent behavior, leading to more chaotic jet dynamics.
Feedback: Impact of Jets & Outflows

Global simulation
Feedback: Impact of Jets & Outflows

- Influence on small scales
- Self-regulated SF?
- Large scale turbulence?
Feedback: Impact of Jets & Outflows

Wang et al. (2010): Collapse of a massive, turbulent cloud core ($M_{\text{core}} = 1600 \, M_{\odot}$) + feedback from jets & outflows

Wang, Li, Abel & Nakamura 2010
Feedback: Impact of Jets & Outflows

Wang, Li, Abel & Nakamura 2010

Outflows & Jets do not stop star formation
Outflows & Jets do not stop star formation

Federrath et al. 2014
Summary

• It is easy to form discs

• Angular momentum is efficiently transported during disc formation by gravitational torques
  $\Rightarrow$ protostellar discs allow efficient accretion

• Magnetic braking catastrophe only for unrealistic ICs

• Influence of Outflow feedback?
  $\Rightarrow$ not conclusive:
  $\Rightarrow$ might not be too important on cloud scales