Magnetic Fields of Protostars & Accretion Discs

Origin & Impact on Star / Planet Formation

Credit: Mark Garlick
key role of magnetic fields in star / planet formation
comparable to turbulence next to gravitation
- inhibits fragmentation / hampers formation of a Keplerian disc
- generate jets / outflows / evacuate angular momentum
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collapsing pre-stellar cores
mass to flux ratio close to critical
- confirm key role of magnetic fields

STAR / PLANET FORMATION

Fig. 1.

Fig. 2.

Girart et al. 2006

31 ° 13 ' 30 "
3 ° 29 " 10 ' 8"

α (J2000)

δ (J2000)

0.5
1
1.5

0

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STAR / PLANET FORMATION

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class I-III PMS stars
central engine of star / planet formation
class-I protostars < 0.5 Myr
cTTSs : classical / accreting T Tauri stars
wTTSs : weak-line / non-accreting T Tauri stars
FU Ori : accretion discs in outbursts
Main Questions

Magnetic topologies of protostars & accretion discs?
- Fields detected for a few tens of TTSs and a few accretion discs
- Origin on these fields, fossil vs dynamo
- Evolution of fields as stars contract to the MS
**Main Questions**

- Magnetic topologies of protostars & accretion discs?
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**Impact on Star / Planet Formation?**

- Alter disc dynamics, accretion & outflows
  - Carve magnetospheric gap in inner disc
  - Evacuate angular momentum through magnetic winds / jets / ejections
  - Modify stellar structure, planet formation / migration / survival?
- When is the field dissipated?
direct: polarized Zeeman signatures from cores & protostars
at cm wavelengths (H, OH, CN) for cold diffuse pre-stellar cores (10-100 µG)
shock-induced masers (H2O, OH) for denser high-mass protostars (10-100 mG)
at optical wavelengths for the warm dense PMS disc FU Ori, kG

- field ~10 µG for n < 300 cm⁻³ then B ∝ n¹.⁶₅±⁰.⁰₅ (Crutcher 2012)
- pre-stellar cores slightly supercritical (relative M/Φ > 1)
**MAGNETIC FIELDS OF ACCRETION DISCS**

Direct: polarized Zeeman signatures from cores & protostars at cm wavelengths (H, OH, CN) for cold diffuse pre-stellar cores (10-100 µG) shock-induced masers (H$_2$O, OH) for denser high-mass protostars (10-100 mG) at optical wavelengths for the warm dense PMS disc FU Ori, kG
- field ~ 10 µG for n < 300 cm$^{-3}$ then B $\propto$ n$^{0.65\pm0.05}$ (Crutcher 2012)
- pre-stellar cores slightly supercritical (relative M/Φ > 1)

Indirect: polarisation of dust emission at mm & sub-mm wavelength for class-0 & class-I protostars
- field strength from dispersion of orientation (Chandrasekhar Fermi)
- hourglass shape of field lines confirming key role of fields
- fields ~mG & clouds slightly supercritical
- contamination from scattering by dust grains (Kataoka et al 2015, Yang et al 2016)
magnetic field of pre-stellar core NGC 1333 - IRAS 4A

- 1.2 M\(_\odot\) class-0 core viewed edge-on
- field ~5 mG (n ~4 \(10^7\) cm\(^{-3}\)) slightly super critical (relative M/\(\Phi\) ~1.7)
- field stronger than turbulence (\(\beta\) ~0.02)
- magnetic tension / gravity ~0.2
- but scattering likely playing a role (Yang et al 2016)
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~1.2 $M_\odot$ class-0 core viewed edge-on
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magnetic field of protostar IRAS 16293−2422 B

~0.3 $M_\odot$ class-0-I young protostar viewed face-on
- field ~5 mG ($n \sim 8 \times 10^7$ cm$^{-3}$) slightly super critical (maser 110 mG nearby)
- turbulent to magnetic energy ratio $\beta \sim 0.32$
- radial field twisted by Keplerian disc?
- impact of scattering unclear (Yang et al 2016)
MAGNETIC FIELDS OF ACCRETION DISCS

Magnetic fields in outer disc of HL Tau?

0.55 M\(_\odot\) star, 0.14 M\(_\odot\) disc, <1 Myr, viewed at i=45°

- poor fit assuming magnetic field aligning grains (Stephens et al 2014)?
- in fact Rayleigh scattering by grains <150\(\mu\)m (Yang et al 2016, Karaoke et al 2016)
MAGNETIC FIELDS OF ACCRETION DISCS

magnetic fields in inner disc of FU Ori
0.3 $M_\odot$ star, 0.02 $M_\odot$ disc, 1-2 Myr, viewed at $i=60^\circ$

- clear Zeeman detection indicating the presence of a field
- $\sim 1$ kG vertical field plus weaker azimuthal field @ 0.05 AU from central star
- field concentrating in material rotating at sub-Keplerian velocities
- not compatible with predictions of disc dynamos

Donati et al. (2005)
MAGNETIC FIELDS OF ACCRETION DISCS

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Tomography through long-term monitoring?
- First attempt in 2008 - not published yet :(  
  - Variability in Stokes I profiles
  - Axisymmetric field confirmed
MAGNETIC FIELDS OF ACCRETION DISCS

magnetic fields of protostars & accretion discs

strong fossil fields in the collapse phase, hampering disc formation

- fossil field likely dissipated by turbulence in dense cores (n~10^{15} cm^{-3}) ?
- formation of a Keplerian disc ? sustain dynamo fields ?
- magnetic instabilities driving accretion ? jet launching ?
- impact on planet formation / migration ?
MAGNETIC FIELDS OF ACCRETION DISCS

- magnetic fields of protostars & accretion discs
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  - fossil field likely dissipated by turbulence in dense cores ($n \sim 10^{15} \text{ cm}^{-3}$)?
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- map magnetic fields of accretion discs
  - using niR spectropolarimetry w/ SPIRou for the inner regions ($<0.5$ AU)
  - using ALMA / NOEMA for the outer regions ($>1$ AU)
    - measure $B$ vs radius in accretion discs of class-I & -II PMS stars
    - poloidal vs toroidal topology - fossil vs dynamo fields
    - link with planet formation
  - magnetic probes from the early Solar System?
detecting magnetic fields

Zeeman effect on spectral lines
- broadening / intensification yields magnetic flux
- polarisation yields large-scale topology
**MAGNETIC FIELDS** of TTSs

Detecting magnetic fields
- Zeeman effect on spectral lines
  - Broadening / intensification yields magnetic flux
  - Polarisation yields large-scale topology
- Infrared measurements (stronger Zeeman effect)
  - kG surface fields / often stronger than thermal equipartition
  - Little to no information on field topology

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Johns-Krull et al. 1999
MAGNETIC FIELDS OF TTSS

Detecting magnetic fields:
- Zeeman effect on spectral lines
  - Broadening/intensification yields magnetic flux
  - Polarisation yields large-scale topology

Broadening/intensification of spectral lines:
- Infrared measurements (stronger Zeeman effect)
  - kG surface fields / often stronger
  - Little to no information on field topology

Polarisation of spectral lines:
- Optical measurements, often through many spectral lines
  - Strong/complex fields in the photosphere (0.1 kG)
  - Stronger simple fields in accreting regions (kG)
  - Reconstruct large-scale through tomographic techniques
the wTTS LkCa 4

~0.9 M\(_{\odot}\), ~2 Myr old observed @ CFHT in 2014 Jan

- reconstructing surface brightness (spots & plages) & magnetic topology

**MAGNETIC IMAGING OF TTSS**

The main parameters of this local profile are similar to those of TTS ends up being more efficient when applied to data.

$$I, Q, V$$ equivalents; more-so, they depend in a much stronger way on the actual magnetic topologies to be imaged (described as a low-resolution, axisymmetric and rather complex in shape, with as much as 60% above that of the mean value of over 50 (for a null magnetic field and an unspotted photosphere).

No similar fit to the data can be achieved if we force the code to modeling the observed modulation of LSD profiles (also contrasted here and published in Casagrande et al. 2015) but also bright plages as well - known to be participating to the activity of very active stars, especially those featuring extreme levels of photometric variability in the unpolarized LSD profiles. The second most important feature is that the reconstructed maps.

[$Image$]
the wTTS LkCa 4  
~0.9 M_☉, ~2 Myr old observed @ CFHT in 2014 Jan  
- reconstructing surface brightness (spots & plages) & magnetic topology

Stokes I LSD

Stokes V LSD

surface spots

Log surface brightness

Radial magnetic field

Azimuthal magnetic field

Meridional magnetic field

large-scale B field
the cTTS V2129 Oph
~1.3 $M_\odot$, ~2 Myr old, observed @ CFHT at several epochs
- reconstructing surface brightness, magnetic topology & accretion spots

- Magnetic imaging of TTSs
- large-scale B field
- surface brightness
- accretion hot spot
MAGNETIC IMAGING OF TTSS

the cTTS V2129 Oph

~1.3 $M_{\odot}$, ~2 Myr old, observed @ CFHT at several epochs

- extrapolating large-scale field (assumed potential) & modeling magnetosphere
the cTTSs TW Hya
~0.8 M\(_\odot\), ~8 Myr, observed @ CFHT at several epochs
- large changes detected already
- little impact on magnetospheric cavity & close-in exoplanets?

**MAGNETIC IMAGING OF TTSS**

2012 February, LSD profiles
2012 February, Ca II IRT
2012 February, He I D\(_3\)

**TW Hya 2012**

LSD profiles  Ca II IRT  He I D\(_3\)**

stronger

stronger

stronger
Magnetic Imaging of TTSs

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2014 February, LSD profiles
2014 February, Ca II IRT
2014 February, He I D₃

TW Hya 2014

Low veiling
Weak field
Stronger
Weaker field

LSD profiles
Ca II IRT
He I D₃
**MAGNETIC FIELDS OF TTSS**

Properties of the large-scale field:
Fields detected for a few tens of TTSs.
Topology relates to stellar structure:
- Strong & simple for largely convective stars
- Weaker & more complex for largely radiative stars
- Large-scale field impacts stellar structure
**MAGNETIC FIELDS OF TTSS**

**properties of the large-scale field**

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Graph showing comparison of theoretical Hertzsprung-Russell (HR) diagrams with observed data for stars in Upper Sco. The magnetic isochrone for stars with a 10 Myr age is plotted as a solid yellow line. Values inferred from standard model HR diagrams are compared to the observational locus of Upper Sco. The magnetic stellar model isochrone lies on to matches predictions from a 5 Myr standard model isochrone. Although the model predicted radii are not exactly the same as observed, the inferred transition region in Fig. (b) agrees with the observed transition in the empirical HR diagram.

- Better fit to HR diagram of upper Sco when compared to non-magnetic isochrone at 10 Myr.
- Core mass fractions are consistent with observed data.
- Magnetic isochrone look nearly identical to a 5 Myr non-magnetic isochrone.
MAGNETIC FIELDS OF TTSS

properties of the large-scale field
- weaker & more complex for largely radiative stars
- new evidence for star / disc magnetic coupling

Figure 7. The Astrophysical Journal

origin, evolution & impact of the field
- topology + variability = clear evidence for dynamo fields
- fields get more complex as stars age & become largely radiative
- slow evolution of magnetospheric gap?
- rotation rate increases as fields get weaker & more complex
- new evidence for star / disc magnetic coupling
Magnetospheric accretion

Star / disc magnetospheric interaction

2D & 3D simulations of accretion along magnetic funnels
- Simulations for realistic large-scale fields
- Estimate angular momentum loss

Romanova et al. 2003+
**Magnetospheric Accretion**

Control angular momentum evolution
- Magnetosphere extending beyond co-rotation, i.e. $\Omega_*/\Omega_K > 1$
  - CME-like ejections in propeller regime
  - Angular momentum loss > angular momentum gain + contraction
  - Good agreement with existing observations

Observed vs predicted accretion modes
- Stable accretion when $\Omega_*/\Omega_K > 0.6$
- Unstable chaotic accretion otherwise
**Magnetospheric Accretion**

- **Control angular momentum evolution**
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- **Observed vs predicted accretion modes**
  - Stable accretion when $\Omega_* / \Omega_K > 0.6$
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**IMPACT ON CLOSE-IN PLANETS**

- **close-in planets**
  - stellar-mass dependent drop in occurrence rates of inner planets
  - corotation radius better than planet / stellar tides & dust / viscous sublimation
  - planet formation / migration stopped at magnetospheric boundary?

![Graph showing the location of a cutoff in planet occurrence rate for different mechanisms in different spectral type bins.](image)
close-in planets
stellar-mass dependent drop in occurrence rates of inner planets
• corotation radius better than planet/stellar tides & dust/viscous sublimation
• planet formation/migration stopped at magnetospheric boundary?

newborn close-in giant planets recently detected
hot Jupiter orbiting in 4.93 d (0.057 AU) around the 2 Myr-old wTTS V830 Tau
eclipsing hot Neptune around the 5-10 Myr wTTS K2-33
candidate hot Jupiter around 2-Myr cTTS CI Tau?
• close-in giant planet likely generated through migration
• avoided falling into the host star thanks to the large-scale field
• viable for all magnetospheric configurations?
• detect planet magnetic field with LOFAR?
growing body of magnetic field observations
for dense cores and class-0 protostars / discs
- field slightly super critical, playing a key role in collapse
- first exploration of large-scale magnetic fields of TTS
- field relates to internal structure
- impacts angular momentum evolution, affects convection zone

*CONCLUSIONS & PERSPECTIVES*
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for dense cores and class-0 protostars / discs.
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multiple detections of newborn planets
including close-in giants that survived migration
- role of large-scale stellar fields?
- estimate fields of close-in giants?
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lots of progress expected soon on disc magnetic fields thanks to SPIRou & ALMA
more spectropolarimetry :)

CONCLUSIONS & PERSPECTIVES