# Modelling the birth of stars

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DiRAC



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#### Importance of stars: Our introduction



#### Importance of stars: The big picture



Stars as light sources: Hubble Ultra Deep Field (nasa.gov)



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#### Importance of stars: Masses

- Main classes of stellar masses
- ✤ Massive stars (M > 8M<sub>sun</sub>)

Low-mass stars

 $(0.08 M_{sun} < M)$ 

 $(M < 0.08 M_{sun})$ 

✤ Brown Dwarfs

 $M < 8M_{sun}$ )





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Evolutionary path is determined by its mass

Image: R.N. Bailey (Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=59672008)

#### Importance of stars: Numbers

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Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 4,696 planet candidates orbiting 3,664 other suns in a search for Earth-size worlds. Launched in 2009, the Kepler space telescope monitored a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses the face of its star. In "Kepler's Planet Candidates," the systems are ordered by star diameter. The star's color represents its temperature as shown in the lower scale, and the letters (A, F, G, K, M) designate star types. The simulated stellar disks and the planet silhouettes are shown at the same scale, with saturated star colors. Look carefully: somesystems have multiple planets. For reference, Jupiter is shown transiting the Sun. Differences can be seen when comparing to the November 2013 "Kepler's Planet Candidates," in particular in the top row. As more data are analyzed and results better understood the Kepler catalog is updated. Many new candidates are added and some are removed in the process. Higher resolutions of this graphic are available at: http://www.nasa.gov/mission\_pages/kepler/multimedia.

www.nasa.gov

#### Low mass stars are much more plentiful than high-mass stars

#### Importance of stars: Numbers

> Number of stars, by mass, for different regions



#### Importance of stars: Numbers



Initial mass function



Drass+(2016) Briceno+(2002) Stolte+(2006

Krumholz & Federrath (2019)



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Evolutionary path is determined by its mass

Image: R.N. Bailey (Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=59672008)





Evolutionary path is determined by its *birth* mass

Image: R.N. Bailey (Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=59672008)

### Star formation: From the beginning



Cannot discuss star formation without discussing disc formation and outflows

Larson (1969); Illustration by Y. Tsukamoto Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

#### Star formation: From the beginning



Relevant processes include
 Gas
 Dust
 Radiation
 Rotation & Turbulence
 Magnetic fields

Larson (1969); Illustration by Y. Tsukamoto Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)







Image: Sky at Night magazine





Magnetic field and column density towards Taurus; Planck Collaboration (2016)



Strong field; large-scale structure



Background represents gas column density



Strong field; large-scale structure



Background represents gas column density



Strong field; small scale structure



Background represents gas column density



Strong field; small scale structure



Background represents magnetic field strength

▶ Both models have similar central gas density, but different magnetic field strengths<sup>32</sup>



- Requirements
  - A problem to solve: How is a star born?





- > Requirements
  - A problem to solve: How is a star born?
  - ★ A description of the physics: radiation non-ideal magnetohydrodynamic  $\frac{d\rho}{dt} = -\rho \nabla \cdot \boldsymbol{v},$

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} &= -\frac{1}{\rho}\nabla\cdot\left[\left(p + \frac{B^2}{2}\right)I - BB\right] - \nabla\Phi + \frac{\kappa F}{c},\\ \rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{B}{\rho}\right) &= (\boldsymbol{B}\cdot\nabla)\boldsymbol{v} + \frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\Big|_{\mathrm{non-ideal}},\\ \rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{E}{\rho}\right) &= -\nabla\cdot\boldsymbol{F} - \nabla\boldsymbol{v}:\boldsymbol{P} + 4\pi\kappa\rho B_{\mathrm{P}} - c\kappa\rho E,\\ \rho\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} &= -p\nabla\cdot\boldsymbol{v} - 4\pi\kappa\rho B_{\mathrm{P}} + c\kappa\rho E + \rho\left.\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t}\right|_{\mathrm{non-ideal}}\end{aligned}$$

 $\nabla^2 \Phi = 4\pi G\rho,$ <sup>34</sup>



- Requirements
  - A problem to solve: How is a star born?
  - A description of the physics: radiation non-ideal magnetohydrodynamic
  - Initial configuration:
     rotating sphere of gas, threaded with a magnetic field





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  - ✤ A numerical method:

smoothed particle magnetohydrodynamic





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✤ A High Performance Computing cluster





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✤ A High Performance Computing cluster

Patience





### Formation of a low-mass star: Expectations

> What we expect to form in addition to a low-mass star:

'Hour-glass' magnetic field morphology



Protoplanetary disc



#### Outflows and/or jets



(Kwon+ 2019)

(ALMA Partnership, 2015)

(Riaz+2017)

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Wurster, Bate & Price (2018c): https://www.youtube.com/watch?v=2SQxgXbdJyg&t=17s

Music: Jo-Anne <sup>40</sup> Wurster

Magnetic fields clearly play an important role in the evolution of the star
 Evolution occurs at a different rate



Magnetic fields clearly play an important role in the evolution of the star

✤ Size & structure of first core outflows

-



Magnetic fields clearly play an important role in the evolution of the star

Size & structure of second core outflows



v, [km/s]

Magnetic fields clearly play an important role in the evolution of the star

Formation of a disc

-

Ideal MHD	Time: 24957 yrs Aligned non-ide	eal MHD Time: 2	25005 yrs Anti-aligned non-ideal MHD	Time: 25380 yrs
Total ion	isation Part	ial ionisation (aligne	ed) Partial ionisation	on (anti-aligned)
50 au Wurster, Bate & Price (2018)	$dt_{sc} = 8.2 \text{ months } i = 0^{\circ}$	50 au dt <sub>sc</sub> =	50 11 years Time since stella	au r core formation: dt <sub>sc</sub> = 9.7 years
-12	-11	-10 -9	-8	-7 -6

Clear ~25au disc

Magnetic fields clearly play an important role in the evolution of the star

✤ Formation of a disc

-

Ideal MHD		Time: 24957 yrs	Aligned non-ideal MHD		Time: 25005 yrs	Anti-aligned non-ideal MHD	Time: 253	380 yrs
Тс	otal ionisatio	on	Partial ion	isation (a	ligned)	Partial ionisa	tion (anti-align	ned)
	<b>R</b>							
Wurster, Bate & Price	50 au (2018)	dt <sub>sc</sub> = 8.2 months	i = 0°	50 au	dt <sub>sc</sub> = 11 years	Time since s	50 au tellar core formation: dt <sub>sc</sub> = 9.	—i .7 years
0	1	2	3	4 ν <sub>φ</sub> [km/s]	5	6	7	8

No disc

~2au disc

Clear ~25au disc

Magnetic fields clearly play an important role in the evolution of the star
The two discs form at different times



#### Star formation: From the beginning

Previous simulations act as controlled 'laboratories' where we can carefully examine and test all various physical processes and characteristics

Stars do not form in isolation

Star forming environments, on the large scale, are turbulent

Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

#### Star formation: Stellar nurseries



Rho Ophiuchi Cloud Complex (image credit: By NASA/JPL-Caltech/WISE Team - WISE)

#### Star formation: Stellar nurseries



30 Doradus (aka Trantula Nebula) (image by HST. credit: NASA, ESA, F. paresce)

#### Star formation: Stellar nurseries



Taurus Molecular Cloud (Credit: ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2. Acknowledgment: Davide De Martin) Taurus Molecular Cloud  $H_2$  column density map with positions of young stars (Goldsmith et. al., 2008)



- Requirements
  - ✤ A problem to solve:

How is a star *cluster* born & *how does it evolve*?

- A description of the physics: radiation non-ideal magnetohydrodynamic
- Initial configuration: sphere of *turbulent* gas, threaded with a magnetic field
- ✤ A numerical method:

smoothed particle magnetohydrodynamic

- ✤ A High Performance Computing cluster
- Patience



- Requirements
  - ✤ A problem to solve:

How is a star *cluster* born & *how does it evolve*?

- > Must make a choice:
  - ✤ A: investigate small scales at high resolution
  - ✤ B: investigate large scales at low resolution



- Resolution example:
- small scales at high resolution (top left)
- large scales at low resolution (bottom right)
- in between (top right)



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#### Low-mass star cluster formation



### **Cluster Formation: Magnetic field lines**

Magnetic fields cross dense filaments approximately perpendicularly
 Magnetic fields are approximately parallel to low-density filaments

log column density [ g/cm<sup>2</sup>]

og column density [ g/cm<sup>2</sup>]





Magnetic field and column density towards Taurus; Planck Collaboration (2016)



#### **Cluster Formation: Stellar Mass**

≻No trend in IMF (although this is low-number statistics)





#### **Cluster Formation: Stellar Mass**

≻No trend in IMF (although this is low-number statistics)





#### **Cluster Formation: Outflows**

≻None (most likely due to low resolution)



#### **Cluster Formation: Protostellar discs**

Large protostellar discs form in *all* nine our models





#### **Cluster Formation: Protostellar discs**

Discs are larger & more varied in these cluster simulations than the isolated simulations



#### **Cluster Formation: Protostellar discs**



Wurster, Bate & Price (2019)

### Cluster Formation: Protostellar discs: Hydro

#### Large protostellar discs frequently form and interact



Bate (2018): https://www.astro.ex.ac.uk/people/mbate/Animations/discdiversity.html

#### Conclusions

>A star's entire life is predetermined by its initial mass

> Understanding star formation is necessary to understand all aspects of astronomy
> Studying star formation necessarily includes studying disc formation and stellar outflows
> High-mass stars live shorter than low-mass stars, but have a greater affect on their environment
> There are more low-mass stars than high-mass stars (initial mass function)
> Star forming regions contain gas & dust and are permeated by strong magnetic fields
> Magnetic fields strongly affect star formation
> Stars seldom form in isolation

Stars can be modelled

>In isolation with high resolution

▶ In cluster environments at lower resolution



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