Recent developments on the formation and evolution of young low-mass stars

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Observations of young clusters that probe:

- The influence of magnetic activity and rotation on early evolution
- The ages of young (low-mass) stars
- Precision dynamics in young clusters
- Early Gaia DR2 results

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Improvements in stellar evolutionary models at young ages
Better match to observed colour-magnitude diagrams
CMD: Still BIG problems for K & M stars at the ZAMS

Gaia DR2 + RV selection – Jeffries et al. in prep
HR diagram: Ages of hotter stars older than those of cooler stars?

Fang, Herczeg & Rizutto 2017, AJ, 842, 123
Problems with stellar evolution models

Radius

Magnetic Inflation?

Mass

Birkby et al. 2012, MN, 426, 1507
More problems: Fundamental Parameters
Low-mass PMS eclipsing binaries appear colder than predicted by the models (i.e. larger at the same mass and luminosity)

Binary in Upper Sco

Binary in Praesepe
More problems: Lithium depletion

A spread of lithium depletion is apparent in young clusters
Fast rotation is correlated with less Li depletion

Confirmed in other clusters (with larger numbers)
K2 rotation periods + WIYN spectroscopy of M35 (age ~ 150 Myr)

Jeffries et al. 2018 in prep.

Delta EW w.r.t median trend
1.7 < (V-K)_0 < 2.5

SLOW rotators deplete more Li
The “spreading” has already begun (with a smaller dispersion) at 5Myr in NGC 2264


EW Li from the Gaia-ESO survey
COROT periods from

Slow rotators

Fast rotators

SLOW rotators deplete more Li
Magnetic fields/starspots can cause “inflation” of an active (young) star.

**Inhibition of convection**

Feiden & Chaboyer 2013, 2014  
Feiden 2016  
Macdonald & Mullan 2014, 2015, 2017

**Starspots**

Somers & Pinsonneault 2014, 2015  
Jackson & Jeffries 2014

**Slows down** PMS evolution.  
Radii are larger, cores are cooler for a given mass/age.
Rotation dependent inflation/spot coverage can explain Li dispersion

Spots block 30% of flux and inflate stars by ~10%

Eclipsing binary in Upper Sco – problem solved?

Surface magnetic flux is clearly correlated with rotation, but saturates at 2-3kG below a Rossby number of 0.1.

Magnetic flux measurements via Zeeman effect:
Saar 1996, 2001;
Reiners & Basri 2007; Reiners+ 2009
Direct evidence for magnetic fields and spots

Spots block **10-40% of flux** from the most active stars. Rough correlation with Rossby Number and poor correlation with modulation amplitude suggests variable spot coverage with high levels of axial symmetry.

Spot coverage from LAMOST
*Fang+ 2016, 2018*

Rotation periods/amplitudes from K2
*Rebull+ 2016; Douglas+ 2016, 2017*
Direct evidence for radius inflation \[ R \sin i = 0.02 \, P \times \nu \sin i \]

Rotation velocities from WIYN/Hydra
Rotation periods from K2;

Models:
Feiden+ 2015 csss...18..171F
Somers+ 2015 ApJ...807..174S

14 ±2 % Inflation

Inhibition of convection
Flux blocking by starspots β=0.16

Jackson+ 2018, MN, 476, 3245
See also Jackson+ 2016; Lanzafame+ 2017; Kesseli+ 2018
SED fitting in young clusters

Radii are ~10% larger than Model predictions


Morrell, Barnes & Naylor in prep – see poster #213
The Gaia-ESO Survey of the Gamma Vel Cluster
Examine the CMD and the Li depletion pattern

A 10% “inflated” isochrone between 18 and 21 Myr matches the data in both diagrams

Similar results for:
Consequences

PMS stars may be:

**OLDER** and **MORE MASSIVE** than you thought.

Cluster formation and disc dispersal lifetimes are proportional to these ages!

Ages and formation of young stellar clusters

HR diagram implies large age spread

- 1. Extinction
- 2. Accretion
- 3. Variability
- 4. Binarity

All contribute to the scatter

Hartmann 2001, AJ, 121, 1030
Resolving Cluster Age Distributions

Multiple sequences in the ONC

Intracluster age gradients $\sim 1$ Myr/pc with SFiNCs/MYSTIX

Getman+ 2018, MN, 476, 1213

Multiple sequences in the ONC
Resolving cluster dynamics

$$\sigma_{1D} \sim 0.7 \left( \frac{M}{10^3 M_\odot} \right)^{\frac{1}{2}} \left( \frac{R}{1 \text{pc}} \right)^{-\frac{1}{2}} \text{km/s}$$

Cha I: 2 Myr cluster - structure/gradient in RV
Core dispersion < stellar dispersion

$\rho$ Ophiuchus: 1 Myr - Partly embedded in parental gas

Stellar dispersion $1.14 \pm 0.35$ km/s

Gas/Core dispersion 0.4 km/s

GES RVs

$^{13}$CO

Gaia DR2

$\Delta V_T = 0.05 \left( \frac{\text{km/s}}{0.1 \text{mas/yr}} \right) \left( \frac{d}{100 \text{pc}} \right) \text{km/s}$

$\Delta d \approx 1 \left( \frac{\Delta \pi}{0.1 \text{mas}} \right) \left( \frac{d}{100 \text{pc}} \right)^2 \text{pc}$

Unprecedented numbers and precision to study

- Cluster distances
- Cluster membership
- Cluster dynamics

$2D > 4D > 5D > 6D > 7D$

Positions + PMs + Parallaxes + RVs + Ages

Adapted from Melis+ 2014, Science, 345, 1029
Gaia DR2 2D Cluster kinematics – pm vector diagrams

Evidence for expansion in some, but not all, young clusters

Some non-expanding clusters may be bound – e.g. the ONC, NGC2362. Rapidly expanding clusters appear unbound – e.g. λ Ori, NGC 6530.
Little evidence that larger clusters form by merger at later times

Kinematic substructure and lack of coherent expansion in OB associations suggest they formed in a highly substructured manner – talks by Wright, Kounkel on Monday
The Gamma Vel Cluster

Gaia-ESO survey – RV precision 0.25 km/s

Single RV component
- poor fit

Two-component fit

$\sigma_A = 0.34 \text{ km/s (virial eqm.)} \quad \text{“Group A”}$

$\sigma_B = 1.60 \text{ km/s (unbound)} \quad \text{“Group B”}$

$\Delta R V = 2 \text{ km/s}$

Gaia DR2 + RVs

Franciosini et al. 2018  arXiv 1807.0362

- Cluster(s) resolved in 7D
- A is closer than B
- B is expanding and moving away from A
- A and B are almost coeval
- A is bound, B is unbound
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**Summary**

- Evidence that low-mass evolutionary models fail for PMS stars
- Magnetic activity/spots may inflate stars leading them to be older and colder than you thought
- Young clusters may have age gradients (multiple populations?), but any merging happens early-on
- Gaia will revolutionise this field – but maximum leverage comes with combined spectroscopy