1961-2011:
50(+1) Years of Hayashi Tracks

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Kyoto, May 21, 2012
Pre-MS Evolution: classical theory

Hayashi Phase 1961

PMS contraction
initially fully
convective case: $1 \, M_0$

HHS 1962

lower $T_{\text{eff}}$
for
larger E
Comparison with Observations

STUDIES OF EXTREMELY YOUNG CLUSTERS. I. NGC 2264

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ABSTRACT

Three-color photoelectric and photographic observations of NGC 2264 have been obtained to $V = 17$, in order to investigate the color-magnitude diagram of an extremely young cluster of stars. The diagram indicates that the cluster possesses a normal main sequence extending from O7 to A0, below which the stars fall above the main sequence. The reality of this effect has been confirmed by spectroscopic observations. The shape of the color-magnitude diagram agrees approximately with that predicted theoretically for clusters which are so young that the fainter stars are still in the process of contracting gravitationally from the prestellar medium and have not yet reached the main sequence. The age of the cluster given by the point where the cluster stars depart from the main sequence is about $3 \times 10^4$ years.
Comparison with Observations: NGC 2264

Time Scales: much shorter!

Young Stars!

Fig. 3. Curves for constant ages for stars with different masses as compared with the $H$-$R$ diagram of NGC 2264. Solid curves ($t$ in years) and dotted lines ($t'$ in years) correspond to the present calculation and to the results by Salpeter and Henyey et. al., respectively.
Pre-MS Evolution: classical theory

• A PMS star contracts due to heat loss at a rate

\[ L_{\text{surf}} = 4 \pi R_*^2 \sigma T_{\text{eff}}^4 \]

• The star is fully convective

\[ S_{\text{int}} = \text{constant} \]

• Homologous contraction on a timescale

\[ t_{KH} = \frac{GM_*^2}{R_* L} \gg t_{\text{sound}} \rightarrow \text{hydro equil.} \]

• Star is fully convective due large radius

\[ R_* = 60 \left( \frac{M_*}{M_0} \right) R_0 \rightarrow L_{\text{surf}} (M_* = 1M_0) \sim 600 L_0 \]

\[ L_{\text{surf}} \gg L_{\text{rad}} = L_0 \left( \frac{M_*}{M_0} \right)^{5.5} \left( \frac{M_0}{M_*} \right)^{0.5} \]

• Convection from the surface
Pre-MS Evolution: M-R relation

• A protostar of mass $M$ and radius $R$ forms from a cold, static cloud

\[ E_{\text{int}}(\text{thermal+mechanical}) = 0 \]

• The protostar is gravitationally bound with a negative total energy $\rightarrow$ energy is lost by radiation, dissociation & ionization

\[ \Delta E_{\text{int}} = XM_*/m_H \left[ \Delta E_{\text{diss}}^{H_2}/2 + \Delta E_{\text{ion}} \right] + YM_*/\Delta E_{\text{ion}}^{He}/4 m_H \]

• The thermal energy is $U=-W/2$ and the virial theorem

\[ 0 = -1/2 \left( GM_*^2/R_* + \Delta E_{\text{int}} + L_{\text{rad}}t \right) \]

• If $L_{\text{rad}} = 0$, homologous & adiabatic contraction

\[ R_{\text{max}} = GM_*^2/\Delta E_{\text{int}} \sim 60 R_0 (M_*/M_0) \]
**Pre-MS Evolution: better approach**

• Models of contracting stars: convectively unstable, spatially constant entropy $\rightarrow$ homologous contraction

• Thermal evolution is simple

\[ t_{\text{conv}} \ll t_{\text{contr}} = t_{KH} = \frac{GM_*^2}{R_* L_*} \]

• Over $t_{KH}$: $s_{\text{int}} \downarrow \rightarrow T_c \uparrow (~ R_*^{-1})$

• Since $t_{KH} \gg t_{\text{sound}} \rightarrow$ assume hydrostatic equilibrium despite slow quasi-static contraction

• Stars are not fully convective: contraction in $t_{KH}$, but non-homologous; $s$ varies with $t_{\text{photon diff}} \rightarrow$ variable!
Pre-MS Evolution: standard theory

- *Stars move from the forbidden zone to the border*
- *They descend vertical paths*
- *They join radiative tracks*
- *They reach the Main Sequence*

*The classical HR diagram*
Stellar Evolution:
I. The approach to
The Main Sequence
Recall Hayashi’s assumption

\[ 0 = -\frac{1}{2} \frac{GM_*^2}{R_*} + \Delta E_{int} + L_{\text{rad}} t \]

During collapse, gravitational energy \( \sim \) radiative energy

\[ R_* \ll R_{\text{max}} \]

Set \( M_{\text{acc}} = \frac{M_*}{t} \) and \( L_{\text{rad}} \sim L_{\text{acc}} \)

\[ L_{\text{acc}} = \frac{GM_* M_{\text{acc}}}{R_*} \sim \]

\[ 60 \, L_0 \left( \frac{M_{\text{acc}}}{10^{-5} \, M_0 \, \text{yr}^{-1}} \right) \left( \frac{M_*}{1 \, M_0} \right) \left( \frac{R_*}{5 \, R_0} \right) \]

\( L_{\text{rad}} \sim L_{\text{acc}} \) throughout main accretion phase

\( L_{\text{acc}} \) generated close to the protostar’s surface

\( L_{\text{acc}} > L_{\text{nucl}}, L_{\text{contraction}} \) for low- and intermediate mass stars
Models of protostellar evolution

numerically solve the detailed structure of accreting protostars.

e.g., Palla & Stahler '91, Omukai & Palla '03

Basic eq.: 4 stellar structure eqs.

\[
\begin{align*}
\text{Continuity:} & \quad \frac{\partial r}{\partial m} = \frac{1}{4\pi \rho r^2} \\
\text{Momentum:} & \quad \frac{\partial P}{\partial m} = \frac{-Gm}{4\pi r^4} \\
\text{Energy:} & \quad \frac{\partial \epsilon}{\partial m} = \epsilon_{\text{nuc}} + T \left( \frac{\partial s}{\partial t} \right)_m \\
\text{Heat transport:} & \quad \frac{\partial T}{\partial m} = -\frac{T Gm}{P 4\pi r^4} \nabla
\end{align*}
\]

connected with outer (steady) accretion flow using shock jump condition

- constant acc. rate: \(10^{-6}M_\odot/\text{yr} \leq \dot{M} \leq 10^{-2}M_\odot/\text{yr}\)
Effects of geometry of accretion

Shock boundary condition

Shock

Supersonic flow

Subsonic flow

Radiation

Accretion flow structure is solved, and connected with the protostar by the shock jump condition

High influx of entropy

Photospheric boundary condition

Supersonic flow

photosphere

Accretion disk

Gas softly accretes to the protostar through the disk. Flow structure is not solved, but ordinary photospheric boundary is adopted.

Low influx of entropy
Protostar & Pre-MS Evolution

• **Protostar:** a mass gaining star whose luminosity stems from external accretion

• Assume: - that the relation $M_p$ vs $R_p$ determines the initial conditions for PMS contraction

  - that $t_{\text{PMS}} < t_{\text{acc}}$

• Then, follow standard PMS evolutionary tracks...
Pre-MS Evolution: standard theory

- Stars move from the forbidden zone to the border
  yes, but HRD much more reduced
- They descend vertical paths
  yes & not: not all of them do
- They join radiative tracks
  yes, all of them
- They reach the Main Sequence
  indeed! ... but massive stars are born on the MS

A modern HR diagram
Impact of the $M - R$ Relation on the HR diagram
Impact of the $M - R$ Relation on the HR diagram

$M_\ast$ vs $R_\ast$ Relation

$f(M_{\text{acc}})$
PMS evolution: main features

**low**: $<2 \ M_\odot$
unchanged
no D-MS
tests: Li-depl, binaries

**intermediate**: $\sim2-8 \ M_\odot$
thermal relaxation
no convection
short life time

**high**: $>8 \ M_\odot$
no PMS phase
H-burning
stars on ZAMS

Palla & Stahler 1993, 1999
Protostellar models with different accretion rates & the HRD

Census of Herbig stars in nearby OB assoc’s:

440 Hipparcos stars d<500 pc, age: 3-16 Myr

good match with HRD

inner disk frequency lower by factor of ~10 than in low-mass stars:
rapid disk evolution

Hernandez + 2005
Sample of Herbig Ae/Be stars
(2011, Bagnulo et al. MNRAS)
LETTER TO THE EDITOR

First firm spectral classification of an early-B pre-main-sequence star: B275 in M17


VLT/X-shooter spectrum - SV
V=15.55 mag – K=8.05 mag

Blue spectrum & B-type stars
1st, 2nd overtone CO bands

Emission lines
CaII, OI, Paschen

Log L/L$_{\odot}$ vs. Log T$_{\text{eff}}$
Compact disk around a $\sim 20 \, M_\odot$ YSO (speckle + AMBER/VLTI)

- Disk: low degree of asymmetry...
- Absence of nearby companion (>10 mas)...

problems for self-grav. disks

problems for mergers, comp. accretion
PMS evolutionary models provide two fundamental astrophysical quantities:

- **MASS** $\rightarrow$ **IMF**
- **AGE** $\rightarrow$ **SFH**
Revisiting the Orion Nebula Cluster
2009-2011
In coll’n: N. Da Rio, M. Robberto, L. Hillenbrand, K. Stassun

HST Treasury Program on ONC – PI M. Robberto
→ multicolor visible photometry w/ highest spatial resolution and sensitivity
Ancillary data: CTIO-NIR & WFI/ESO-optical
Most stars formed ~1-2 Myr ago

Notice the large $\Delta L \sim 10$

age spread: real or not?
Revisiting the ONC
HST Treasury Program – PI M. Robberto

blue: from H97, excluding stars with membership P<50%
red: stars with new spectral types
green: M-type with Teff from TiO index

Contamination by fore/background sources with unknown membership: 2-3%
Significant differences for log M<~-0.3, both flatten:
Siess - clear turnover below 0.2 M\(_0\), overabundance @0.2-0.3
PS99 - modest change of slope, agreement with Kroupa IMF
Age distribution

shaded: full sample - blue: completeness corrected

Siess: average ages ~3 Myr
within 1σ: 2.5 – 5 Myr
spread ~0.4 dex

PS99: average ages ~2 Myr
within 1σ: 1.2 – 3.2 Myr
spread ~0.3 dex

Real vs artificial spread
(combined effect…)

Siess (2006)
R_v=3.1

Palla & Stahler (’99)
R_v=3.1

Log(age)
ON THE RELIABILITY OF STELLAR AGES AND AGE SPREADS INFERRED FROM PRE-MAIN-SEQUENCE EVOLUTIONARY MODELS

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Red: constant accretion
Magenta: episodic accretion
Blue: decreasing accretion

★: 0.90 M₀
+ : 0.45 M₀
× : 0.23 M₀
An Evolutionary Model for the Star Formation Efficiency in Gravitationally Collapsing Molecular Clouds.

Manuel Zamora-Aviles & Enrique Vázquez-Semadeni

Evolution of the cloud number density and mass fraction

Stellar age distributions for isolated cloud (left) & GMC (right)
Rapid Star Formation and Global Gravitational Collapse

Lee Hartmann¹, Javier Ballesteros-Paredes², Fabian Heitsch³

local gas densities. We show that two different numerical simulations of dynamic, flow-driven molecular cloud formation and evolution 1) predict age spreads for the main stellar population roughly consistent with observations, and 2) raise the possibility of forming small numbers of stars early in cloud evolution, before global contraction concentrates the gas and the bulk of the stellar population is produced. In general, the existence of a small number of older stars among a generally much-younger population is consistent with the picture of dynamic star formation, and may even provide clues to the time evolution of star-forming clouds.

Results of simulations

Results of observations
Modeling of PMS Evolution

INPUT PARAMETERS
- Initial mass
- Initial chemical composition
- Evolutionary state

NUMERICS
- Stellar model

INITIAL CONDITIONS
- Initial model
- Interaction with surrounding: disk locking

INPUT PHYSICS
- Microscopic:
  - Nuclear reactions
  - Opacities
  - Equation of state
  - Microscopic diffusion
- Macroscopic:
  - Transport and 1D approximation
  - Convection $\alpha$
  - Rotation
  - Internal waves
  - Magnetic field
  - Related transports

BOUNDARIES
- T-Tau law
- Mass loss
- Angular momentum loss

Uncertainties on impact on mass and age accuracies
- Some are under control
- Some require further work
Popular models

Baraffe & Chabrier
1997, 1998…

D’Antona & Mazzitelli

Siess 2000

Palla & Sthaler
1993, 1999

Demarque $Y^2$
Pisa PMS models (2010-12)

M: 0.2 $\rightarrow$ 6 $M_\odot$

large range of $Z$

$Z = 0.01$

0.02 (solar)

Measurements of chemical abundances!
NGC 3603: internal dynamics (1997-2007)

$\sigma_{1D} = 4.5 \pm 0.8$ km/s

Stars with M=1.7-9 Mo have same vel. disp. → cluster not virialized…

$M_{\text{dyn}} = 17600$ Mo vs $M_{\text{cl}} = 10-16000$ Mo

Stars in the r-c gap: 3.5-3.8 Mo

Older 4 Myr stars → previous episode… multiple formation…

Rochau+ 10
Extragalactic PMS evolution: low-mass stars in SFRs

Only HST has the required sensitivity and f.o.v. coverage: impossible to do repeated imaging, spectroscopy of large samples, X-ray monitoring. Advantages:

1. PMS population easily distinguished from field via CMDs
2. Large samples of stars for statistical analyses

Gouliermis 2012
Getting the ~complete IMFs down to sub-solar masses…

knee at ~1 $M_\odot$ and power-laws as in the galactic IMF

NGC602-SMC  
Cignoni et al 2009

LH95-LMC  
Da Rio et al. 2010
Present & Future of PMS Evolution

• Reconstruct Star Formation History of Clusters and Associations & IMF → galactic and extragalactic Local Group and beyond…

• Fundamental quantities: distance, membership, stellar parameters, abundances

• Main issues: coevality vs age spread, IMF, disk evolution, binaries

• Useful diagnostics: Li, surface g, abundances, activity…

• Observations: GAIA-ESO Survey of SFRs/Clusters GAIA…
Looking forward to PMS stars & evolution in Pop III...
DOMO ARIGATO