Star Formation & ALMA

Leonardo Testi (ESO/Arcetri)

Thanks: J. Ascenso (ESO), E. Bressert (Exeter/ESO), G. Costigan (ESO/DIAS), G. Fuller (UManchester), C. Goddi (ESO), S. Longmore (ESO), C. Manara (ESO/LMU), N. Peretto (Saclay), L. Ricci (Caltech), J. Tan (UFlorida), ...

- Star Formation as a “local” process
- The extremes of SF as a testbed
- (Setting the stage for Planet Formation)
From Cores to Planetary Systems

- Core
- Disk
- Debris Disk

Leonardo Testi: Star Formation & ALMA, 3 Sep 2012
From Clouds to Cores

- Filaments
  - Turbulence (?)
- Cores
  - Gravity
- Core formation threshold related to filament instability

(Herschel Gould Belt Project: Andre’ Ph. et al.)
From Cores to Stars

- Core Mass Function
  - Matches IMF, with ~30% efficiency
- Spatial distribution of YSOs matches cores distribution
- Output of SF determined by cloud fragmentation
Is Star Formation a Local Process?

- Star Formation is consistent with high efficiency conversion of dense gas into stars
- Clouds -> Filaments -> Cores -> Stars
Check the Extremes

- Formation of Brown Dwarfs and Planetary mass objects
  - Can BDs form as stars from isolated cores?

- Formation of massive stars and groups/clusters
  - Are clusters “needed” to form massive stars?
  - Are filaments and dense cores the right basic recipe?

- Formation of Young Massive Clusters
  - Do the simple laws break down?
  - Do YMCs require “different” conditions to form?
Formation of Brown Dwarfs

- Can Brown Dwarfs fit in the paradigm?
- Formation and Early Evolution of VLMS and BDs

(Dullemond, Natta & Testi 2006)

(Bate 2002; 2012)

(Dominik, Natta & Testi 2006)

Accretion vs mass/age

- NIR hydrogen recombination lines NTT/VLT survey
- ρ-Oph vs σ-Ori
- ~0.5-1Myr vs ~3-5Myr

(Natta et al. 06; Gatti et al. 08)
Accretion vs mass/age

(Natta et al. 06; Gatti et al. 08)

VLT U-Band survey

(Rigliaco et al. II)
Accuracy matters in the BDs domain...

(Manara et al. 2012)

(Natta et al. 2004; Rigliaco et al. 2012)
Accretion vs mass/age

- $\rho$-Oph vs $\sigma$-Ori
- $\sim0.5-1$Myr vs $\sim3-5$Myr

(Rigliaco et al. II)
Accretion vs mass/age

- $\rho$-Oph vs $\sigma$-Ori
- $\sim$0.5-1Myr vs $\sim$3-5Myr

Possible evidence for a change of slope with stellar mass
possible evidence for a faster evolution at the low mass end
Accretion vs mass/age

- $\rho$-Oph vs $\sigma$-Ori
- $\sim 0.5$-$1$ Myr vs $\sim 3$-$5$ Myr

$\rho$-Oph vs $\sigma$-Ori

$\rho$-Oph (Natta et al. 06)
Tr 37 (Sicilia-Aguilar et al. 10)
$\sigma$-Ori

Possible evidence for a change of slope with stellar mass

- Possible evidence for a faster evolution at the low mass end

ONC
Manara et al. 2012
XShooter surveys

- Simultaneous observation of photosphere, accretion and wind indicators across a broad wavelength range

- Surveys:
  - Alcala’ et al. GTO program: TW Hya, Lupus, σ-Ori, +
    - Alcala’ et al. 2011, Rigliaco et al. 2012, Manara et al. 2012b
  - Testi et al.: ρ-Oph
  - Herczeg et al.: Chamaeleon +
  - Several smaller programs
Disk properties in the substellar domain: a major topic for ALMA (sensitivity and angular resolution)
Lessons and questions from BDs

✧ Young BDs can have similar characteristics as low mass stars
  ➢ Consistent with same formation and evolution mechanisms

✧ Ejection/interaction pathways have to become important for the lowest mass objects

✧ Open questions for ALMA
  ➢ Identification of pre-BDs cores?
  ➢ Disk properties around young BDs?
  ➢ Planet formation in the BDs regime?
Memories from a few yrs ago
(The clustered vs dispersed population debate)

• Low-mass stars in nearby associations are found in isolation or loose groups ($\rho_* \sim \text{few } */\text{pc}^3$)

• High-mass stars are found in dense and well populated stellar clusters ($\rho_* \sim 10^4 */\text{pc}^3$)
Clustering properties of HAeBe and O stars

- Possible correlation between clusters and massive stars
- Random sampling not excluded

(Leonardo Testi: Star Formation & ALMA, 3 Sep 2012)
"Isolated" O-stars in 30Dor field

Candidate "isolated" O-stars from the VLT Tarantual Survey

(Bressert et al. 2012)
The birthplaces of O-stars

- ALMA Cycle 0 observations of deuterated species in IRDCs
- Dense massive cores in virial equilibrium
The filamentary structure of IRDCs

(ALMA Cycle 0 observations of $N_2H^+(1-0)$)

-Coherent kinematic structure of filaments

(Peretto et al. 2012)
Disk-outflow systems in high-mass YSO

- Orion: the nearest high-mass YSOs
- Reflected IR VLT spectroscopy and mm/cm data consistent with disk-outflow system
- Scaled-up version of TTauri stars

Table: SiO v=0 J=1-0 (VLA)
SiO v=0 J=2-1 (CARMA)
SiO v=1,2 (VLBA) Radio Cont

Radio Cont (Matthews et al. 2010; Goddi et al. 2011)
(Leonardo Testi et al. 2010)
...not so simple!

- Evidence for interaction with other massive YSOs
- Evidence for interaction with surrounding cloud cores
- Are environment and interactions more important than initial conditions?
- High resolution of ALMA essential to expand sample
Young Massive Clusters precursors

- Td
- Sgr B2
- Sgr A*
- Sgr C
- Quintuplet

Molinari et al. 2011

Ncol

VLT/NACO

Herschel 70um

(Longmore et al. 2012)

(Molinari et al. 2011)
Young Massive Clusters precursors

- Very dense and compact molecular clump
- Widespread SiO, little evidence for ongoing star formation
- Internal structure/filaments?
- Rosetta Stone for origin of Young Massive Clusters
Lessons and questions from HM-YSOs

- Continuum distribution of stellar densities
  - No strong evidence (so far) of causal relationship between clusters and high-mass stars (!highly debated!)
  - HM-stars may form as low mass stars

- Formation of cores from filaments is observed

- Open questions for ALMA
  - Structure of HM cores and relation with filaments?
  - Disk/outflow properties around young HMYSOs?
  - Formation of YMCs and Super Star Clusters?
We think we have a “simple” framework for understanding star formation. The complexity of star formation seems to be captured in the process of converting gas into dense cores. Most of the “extremes” seem to fit in this overall framework:
- The path of more exotic formation mechanisms is open for a small minority of systems.
- These “minority systems” may be dominant SF modes in some peculiar environments.
I have consciously avoided:

- The complex physics of the formation and evolution of a single object and multiple systems (and what this imply for the fate of disks and planetary systems)

- The effects that an object or a population has on other forming stars (and the fate of their disks)

- The processes within disks and of the disk-star interactions that set the stage for the formation of planetary systems

- How the formation of our own Solar System may fit into the overall picture
ALMA SV Science Results

- The multiple protostar IRAS16293
Gas

50 cm

 Disk structures, grain trapping, planet formation

Slowing down radial drift: grain trapping

(Cossins, Lodato, Testi 2010)

ALMA 850 GHz

(Wolf & D’Angelo)
A problem of timescales

- Evolution too fast to reconcile with SS meteoritic evidence
- Need to study the (small) population of long-lived disks

Inner disk clearing: e-folding time $t \sim 2-3$ Myr

(Hernandez et al. 2007)

(Manara et al. 2012)