Spectroscopy of Very Low Mass Stars and Brown Dwarfs in the LOSFR.

Enlarging the census down to the planetary mass domain in C69

A. Bayo

collaborating with
D. Barrado, J.R. Stauffer,
M. Morales-Calderón,
N. Huélamo, C. Melo,
H. Bouy, B. Stelzer

ESO, Garching

October 24, 2011
1. Introduction
   - Low mass SF
   - The Lambda Orionis Star Forming Region
   - Goals

2. Our surveys
   - Photometry and X-rays

3. Results
   - SED analysis
   - C69 Age estimation
   - Activity and accretion
   - Disks Properties
   - Spatial distribution
   - The IMF of Collinder 69

4. Conclusions
Low mass SF Theory


- **Ejection scenario** (Reipurth & Clarke 2001): stellar embryos ejected before accreting enough mass for H burning.

- **Photoevaporation** (Whitworth & Zinnecker 2004): winds from massive nearby stars → lost envelopes of protostellar cores.

- **Disk fragmentation** (Goodwin & Whitworth, 2007 and Stamatellos et al 2007): scaled up version of planets.
Spectroscopic Characterization

Photometric studies:
- Duerr 1982
- DM 1999
- ByN et al. 2007

Spectroscopic studies:
- DM 2001, 2002
- Sacco et al. (2008)
- Maxted et al. (2008)

B30 \sim 1-2 \text{ Myr}
B35 \sim 3 \text{ Myr}
LDN1603
C69 \sim 5 \text{ Myr}
LDN1588

4.5 \text{ deg}
A. ~8–10 Myr ago, the λ Ori region was composed of a starless, roughly linear string of dense molecular clouds.

B. Over the next few Myr, stars began to form in the densest portions of this cloud chain. 6 Myr ago, a dozen OB stars formed near λ Ori’s present-day position while low-mass stars formed in all productive areas of the star-forming complex.

C. ~1 Myr ago, one of the O stars became a supernova. The blast quickly dispersed all of the parent core, creating the molecular ring, the large HII region, and the nearby HI structures.

D. Today we see the fossil distribution of young stars within the molecular ring, as well as the remnants of the B30 and B35 clouds within the ionized region.
Aims

- Spectroscopically confirm the lowest mass members of the three associations (including Brown Dwarfs and IPMOS).
- Build complete census for the three regions.
- Relate properties of individual sources (acc. rates, etc.) with three different environments (ages).
- Build a very complete IMF for Collinder 69 from \( \sim 20 \, M_\odot \) down to the planetary mass domain (shared mechanism of formation for low mass domain?).
- “Test" the Supernova hypothesis.
Photometric and X-ray surveys

CFHT (optical)
IRAC & MIPS (MIR)
Omega200 (NIR)
Ingrid (NIR)
Suprime-Cam (optical)
XMM-Newton (X-rays)
Bayo et al. (2008)
### SED analysis

**VOSA: VO Sed Analyzer**

**VO photometry**

This option allows you to increase the wavelength coverage of the SEDs of your objects adding photometry from VO catalogues. Take a look to the corresponding Help Section and Credits Page for more information.

First select the VO services that you want to use

- 2MASS All-Sky Point Source Catalog
  - 2MASS has uniformly scanned the entire sky in three near-infrared bands to detect and characterize point sources brighter than about 1 mJy in each band, with signal-to-noise ratio (SNR) greater than 1. More Info.
  - Filters: [2MASS_J] [2MASS_H] [2MASS_Ks]
  - Search radius: [5] arcsec
  - Show magnitude limits

- Tycho-2 Catalogue
  - The Tycho-2 Catalogue is an astrometric reference catalogue containing positions and proper motions as well as two-colour photometric data for the 2.5 million brightest stars in the sky. More Info.
  - Filters: [TYCHO_B] [TYCHO_V]
  - Search radius: [5] arcsec
  - Show magnitude limits

- CMC-14
  - The full CMC-14 catalog (around 85.85 million source in the region -30° to +50°). More Info.
  - Filters: [SDSS_R]
  - Search radius: [5] arcsec
  - Show magnitude limits

- Stromgren uvby-beta Catalogue (Hauck+ 1997)
  - This catalogue is an updated version of the one published in 1990 (Hauck and Kermillid, 1990) and contains data for more than 63,200 stars in the Galaxy and Magellanic Clouds. More Info.

---

Bayo et al. (2008)

---

C69. Spectroscopic Characterization
### SED analysis

**Object data**

**L0ri029**

Position: (83.855667,10.144083)  Distance: 400. pc  \( A_v = 0.36209598 \)

Data for this object:

<table>
<thead>
<tr>
<th>Filter</th>
<th>Amarr</th>
<th>Flux</th>
<th>( \Delta F )</th>
<th>User Flux</th>
<th>( \Delta F )</th>
<th>VO Flux</th>
<th>( \Delta F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHT R</td>
<td>8582</td>
<td>3.075852e-15</td>
<td>2.835525e-17</td>
<td>3.075852e-15</td>
<td>2.835525e-17</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>CFHT I</td>
<td>8229</td>
<td>4.57908e-15</td>
<td>4.21742e-17</td>
<td>4.57908e-15</td>
<td>4.21742e-17</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2MASS J</td>
<td>12300</td>
<td>4.353110e-15</td>
<td>1.080730e-16</td>
<td>4.353110e-15</td>
<td>1.080730e-16</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2MASS K</td>
<td>21590</td>
<td>2.292320e-16</td>
<td>2.292320e-16</td>
<td>2.292320e-16</td>
<td>2.292320e-16</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>IRAC I1</td>
<td>36634</td>
<td>5.347984e-16</td>
<td>1.47757e-16</td>
<td>5.347984e-16</td>
<td>1.47757e-16</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>IRAC I2</td>
<td>45110</td>
<td>3.143422e-16</td>
<td>8.698593e-19</td>
<td>3.143422e-16</td>
<td>8.698593e-19</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>IRAC I3</td>
<td>57953</td>
<td>1.989886e-16</td>
<td>1.08727e-16</td>
<td>1.989886e-16</td>
<td>1.08727e-16</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>IRAC I4</td>
<td>70594</td>
<td>3.655202e-16</td>
<td>3.655202e-16</td>
<td>3.655202e-16</td>
<td>3.655202e-16</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>MIPS_M1</td>
<td>23844</td>
<td>2.027081e-17</td>
<td>1.308007e-17</td>
<td>2.027081e-17</td>
<td>1.308007e-17</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Excess detected from **IRAC I1**. Points with larger wavelength will not be considered in model fit. You can manually specify where excess starts. Apply excess from **IRAC I1** > **IRAC I2**.

Bayo et al. (2008)
C69. Spectroscopic Characterization
## SED analysis

**Model Bayes analysis**

**LOTr001**

Here you can see, for each model, the relative probability found for each parameter. Only those with a probability higher than 1e-5 are shown.

**The NextGen Model Atmosphere grid.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Probability</th>
<th>logg</th>
<th>Probability</th>
<th>Teff</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0000000</td>
<td>5.0</td>
<td>0.999242</td>
<td>5000</td>
<td>1.000000</td>
</tr>
<tr>
<td>5.5</td>
<td>0.000750</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**The DUSTY00 Model Atmosphere grid.**

<table>
<thead>
<tr>
<th>logg</th>
<th>Probability</th>
<th>Teff</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.905784</td>
<td>9300</td>
<td>1.000000</td>
</tr>
<tr>
<td>5.5</td>
<td>0.034216</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**The COND00 Model Atmosphere grid.**

<table>
<thead>
<tr>
<th>logg</th>
<th>Probability</th>
<th>Teff</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.891237</td>
<td>4000</td>
<td>1.000000</td>
</tr>
<tr>
<td>3.0</td>
<td>0.108763</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Kurucz ATLAS9, ODFNEW /NOVER models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Probability</th>
<th>logg</th>
<th>Probability</th>
<th>Teff</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.50</td>
<td>0.233853</td>
<td>0.50</td>
<td>0.000167</td>
<td>4000</td>
<td>1.000000</td>
</tr>
<tr>
<td>-2.00</td>
<td>0.657809</td>
<td>1.00</td>
<td>0.001607</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.50</td>
<td>0.103944</td>
<td>1.50</td>
<td>0.285539</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.00</td>
<td>0.004745</td>
<td>2.00</td>
<td>0.655479</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.50</td>
<td>0.000958</td>
<td>2.50</td>
<td>0.041791</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>0.000045</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bayo et al. (2008)
Spectroscopic follow-up

Spectroscopic confirmation of candidates

- Alkali lines ⇒ youth indicators
- Emission lines ⇒ activity and accretion
Alkali: signpost of youth
Alkali: signpost of youth

C69. Spectroscopic Characterization

FLAMES

MIKE

Normalized Flux + Const

Lambda (Å)

M4.0L0ri141
M4.75L0ri082
M4.75L0ri133
M5.0L0ri115
M5.0L0ri110
M5.25L0ri110
M5.25L0ri154
M5.5L0ri151
M5.5L0ri118
M5.5L0ri147
M5.5L0ri118
M5.5L0ri147
M5.5VSTD
M5.5VSTD
M5.5VSTD
M5.5VSTD
M5.5VSTD
M5.5VSTD
M5.5VSTD
M5.5VSTD

Alkali: signpost of youth

Spectroscopic Characterization

C69.
The youth of C69

C69: More than 30 new members (~175 spect. confirmed members)

C69 members Paper I
- All
- Accretors (II)
- Disks (Paper II)
- Spec Binaries

C69 new memb
C69 memb from literature

Sigma Ori memb
C69 memb

Spectral Type
The youth of C69

C69: More than 30 new members (~175 spect. confirmed members)
Alkali variability

~30% sources (DM, S08, B11) variability in Li I

All Active stars (Xrays or Hα variability)
Alkali variability

∼30% sources (DM, S08, B11) variability in Li I

All Active stars (X-rays or Hα variability) ∼50% sources (S08, B11) variability in Na I

∼35% accretors

Activity and accretion through emission lines

![Graph showing emission lines and spectral features](image-url)
Distinguishing between accretion and activity

Saturation criteria Barrado y Navascués & Martin (2003)
Distinguishing between accretion and activity

Saturation criteria Barrado y Navascués & Martin (2003)
Disk and diskless populations unevenly distributed ⇒ Not consistent with SN hypothesis.

Stellar disk fraction 28.5%

Sub-stellar disk fraction >30%

- Barrado y Navascúes et al. (2004) 40%
- Scholz et al. (2007) 37.9% for Upper-Sco

Accretors fraction

sub-stellar 18%

- Scholz et al. (2007) 31% for Upper Sco (low-mass and sub-stellar)
Spatial distribution of the members

Homogeneous distribution of both BDs and stars

⇒ Caveats to ejection scenario
$R_{SS} = \frac{N(0.02 \leq M/M_\odot \leq 0.08)}{N(0.08 \leq M/M_\odot \leq 10)}$

Briceño et al. (2002)

Collinder 69 $\Rightarrow$ 0.06

$\sim$ Taurus

Briceño et al. (2002)

< Taurus

revised by Guieu et al (2006)

< ONC

Kroupa et al. (2003)
R_{SS} = N(0.02 \leq M/M_{\odot} \leq 0.08) \\
N(0.08 \leq M/M_{\odot} \leq 10) \\
Briceño et al. (2002) \\
Collinder 69 \Rightarrow 0.06 \sim Taurus \\
Kroupa et al. (2003)
Conclusions

- Complete census of ~175 spectroscopically confirmed members plus 60 photometric probable members.
- Physical parameters derived for the spectroscopic sample: Spectral Type, Hα and Li I equivalent width, accretion rates, etc.
- Age study: upper limit of 20 Myr, optimal 5 Myr.
- One of the most complete spectroscopic IMF reported so far (from ~20 M⊙ down to 20 M_Jup; the photometric reaches 8 M_Jup)
- No evidence of mass segregation (caveats on ejection scenario for BD formation)
- Study of the disks properties: Not consistent with SN scenario

Bayo et al. (2011)
THANK YOU!!!