The Lambda Orionis Star Forming Region

Spectroscopic Characterization

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M. Morales-Calderón, N. Huélamo,
B. Stelzer, H. Bouy

ESAC–Madrid

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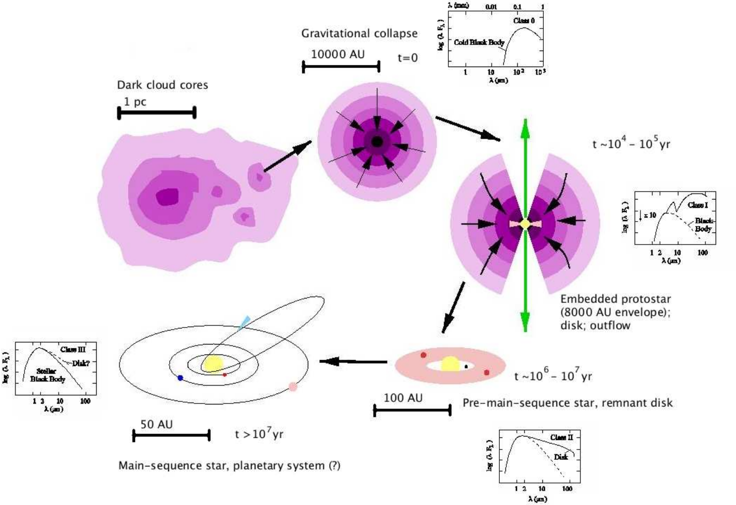
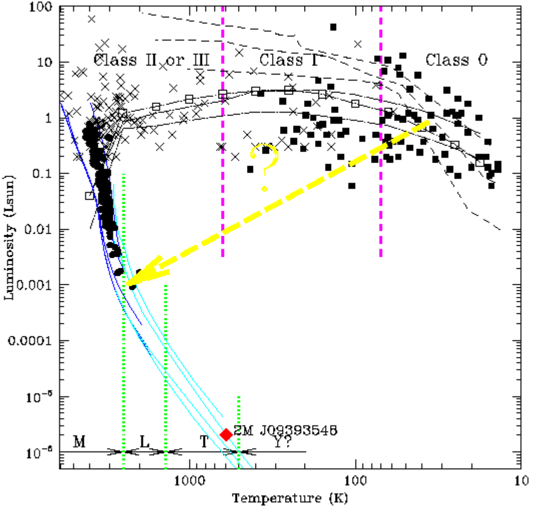
Outline

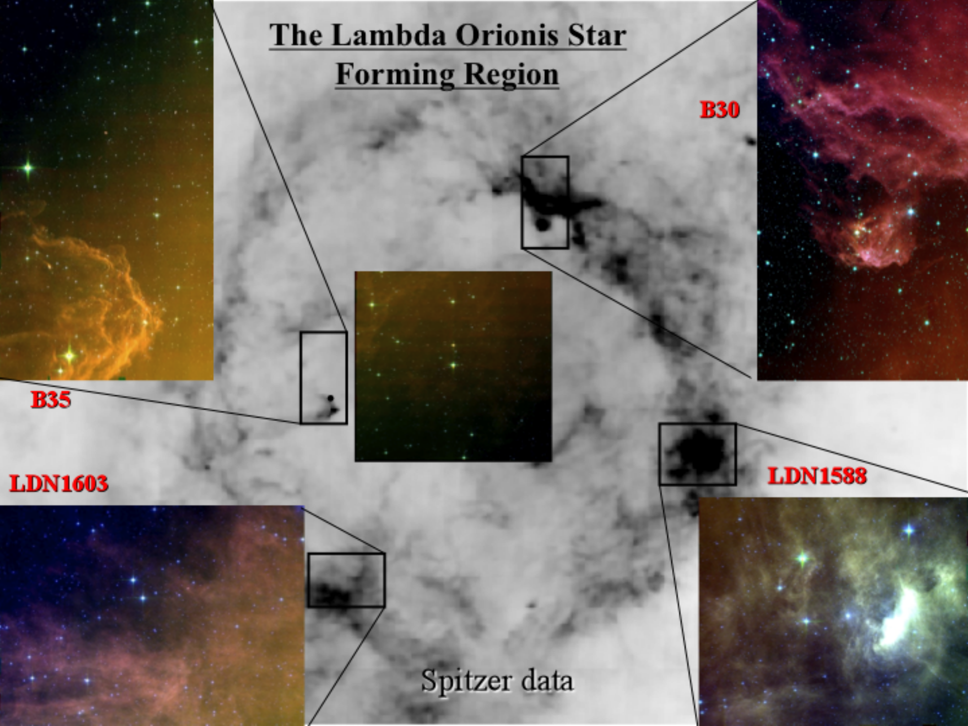
Star Formation Theory

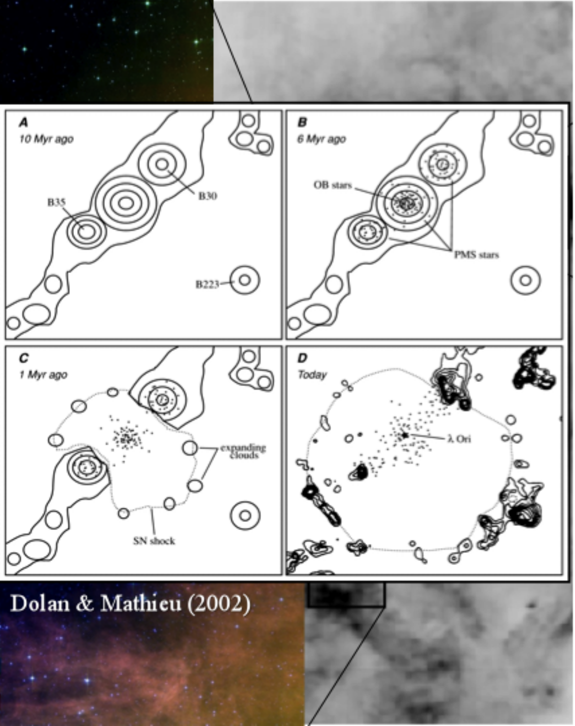


Star Formation Theory



Barrado y Navascués et al. (2009)


The Lambda Orionis Star Forming Region
B30
B35
LDN1603
LDN1588
Spitzer data

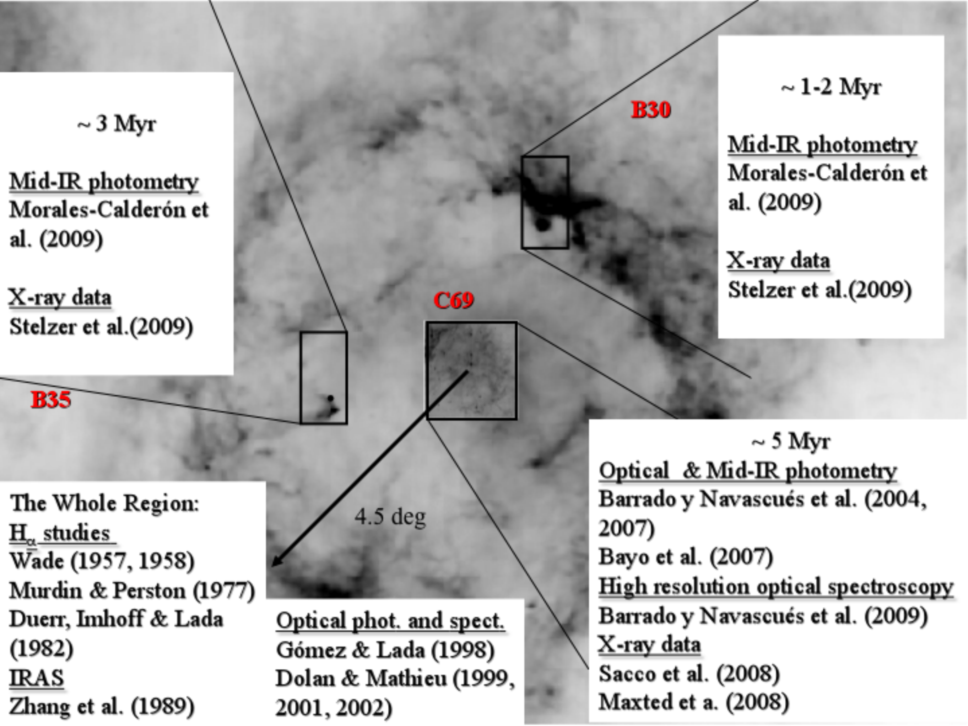


A. ~8–10 Myr ago, the λ Ori region was composed of a starless, roughly linear string of dense molecular clouds.

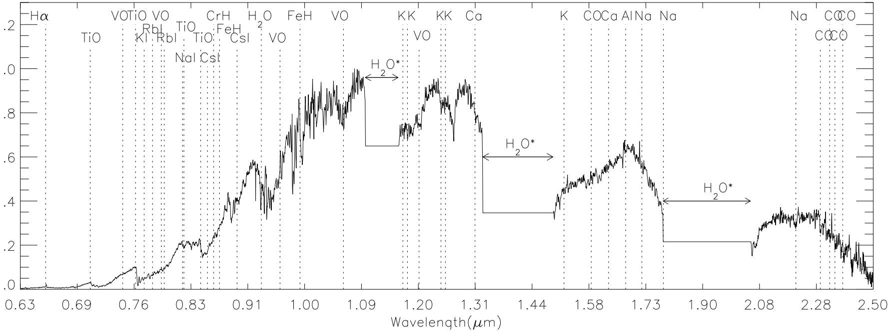
B. Over the next few Myr, stars began to form in the densest portions of this cloud chain. 6 Myr ago, a dozen OB stars formed near λ Ori's present-day position while low-mass stars formed in all productive areas of the star-forming complex.

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.

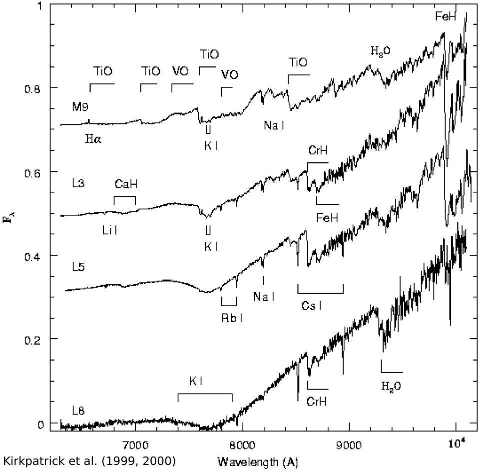

~ 3 Myr
Mid-IR photometry
Morales-Calderón et al. (2009)
X-ray data
Stelzer et al.(2009)
B35
B30
~ 1-2 Myr
Mid-IR photometry
Morales-Calderón et al. (2009)
X-ray data
Stelzer et al.(2009)
C69
4.5 deg
The Whole Region:
Hα studies
Wade (1957, 1958)
Murdin & Perston (1977)
Duerr, Imhoff & Lada (1982)
IRAS
Zhang et al. (1989)
Optical phot. and spect.
Gómez & Lada (1998)
Dolan & Mathieu (1999, 2001, 2002)
~ 5 Myr
Optical & Mid-IR photometry
Barrado y Navascués et al. (2004, 2007)
Bayo et al. (2007)
High resolution optical spectroscopy
Barrado y Navascués et al. (2009)
X-ray data
Sacco et al. (2008)
Maxted et a. (2008)

M dwarfs



- $T_{\rm eff}$ range from ~ 4500 K down to ~ 2000 K
- Molecular bands of TiO (VO for M7 and later); H_2O, CO, FeH
- Atomic lines of Ca II, Na I and K I

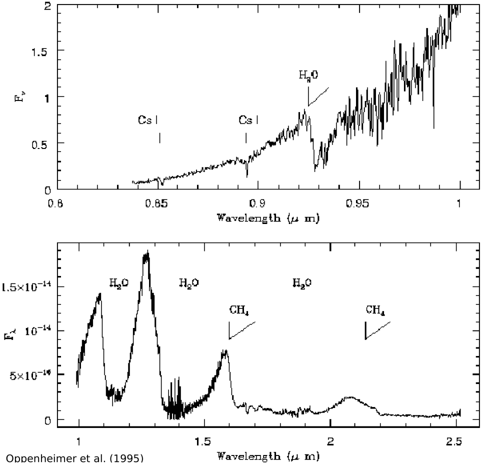
L dwarfs



Kirkpatrick et al. (1999, 2000)

- Mixture of stars and BDs
- $T_{\mathrm{eff}} \sim 2100 - 1500$ K
- Weakened TiO and VO bands (disapp. L5-L6)
- Strengthened FeH, CrH, CaH
- Broadened resonance lines Rb and Cs and K I doublet
- Intense H_2O bands in the IR

T dwarfs



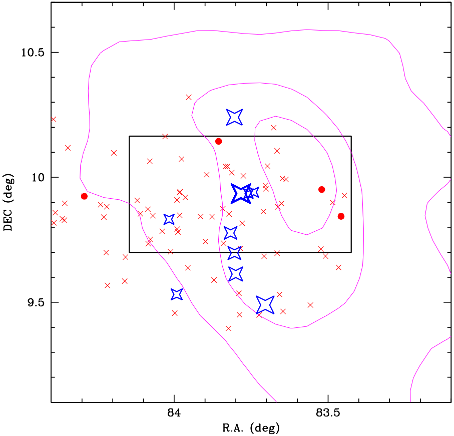
Oppenheimer et al. (1995)

- Brown Dwarfs
- $T_{\mathrm{eff}} \sim 1500 - 1200$ K
- CH_4 absorption bands
- H_2O and H_2 absorptions $\Rightarrow$ Bluer near-IR colours than L dwarfs

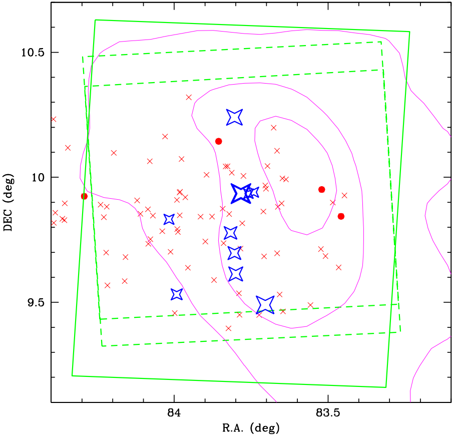
Aims

- 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.

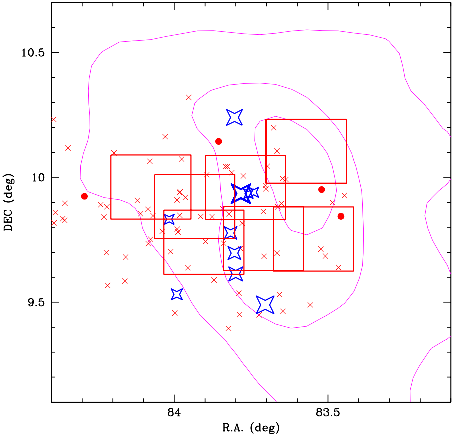
Photometric and X-ray surveys



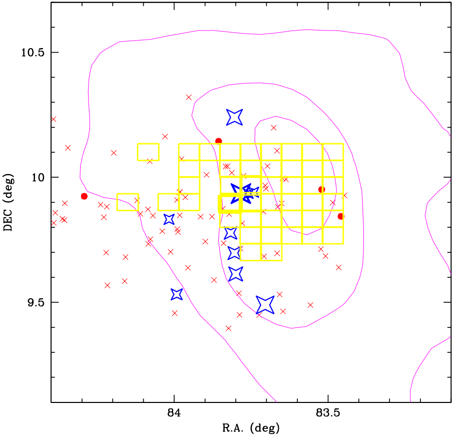
Photometric and X-ray surveys



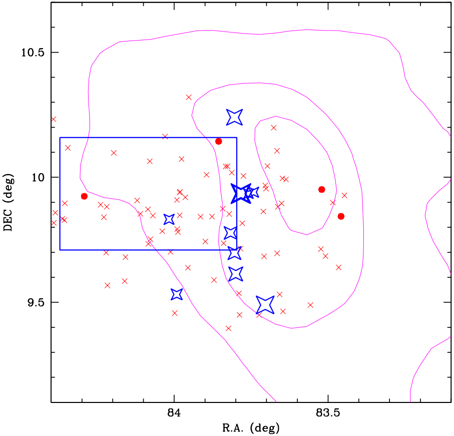
Photometric and X-ray surveys



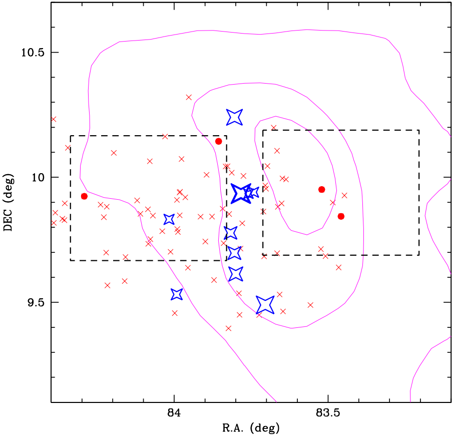
Photometric and X-ray surveys



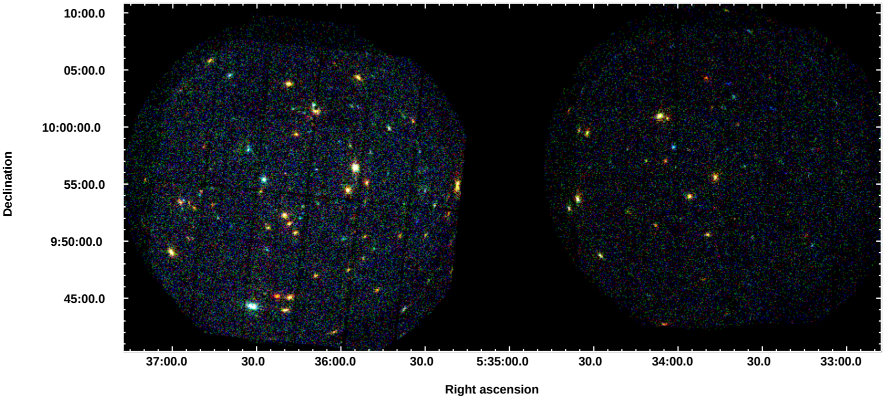
Photometric and X-ray surveys



Photometric and X-ray surveys

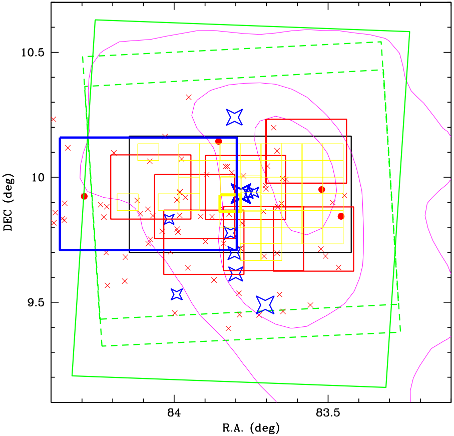


Photometric and X-ray surveys

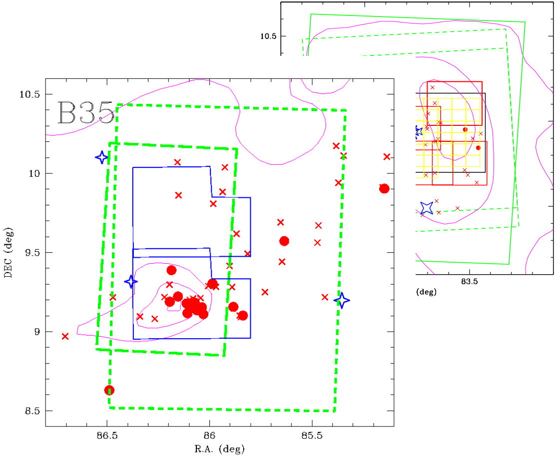


Complete analysis in C69 on-going analysis in B30 and B35

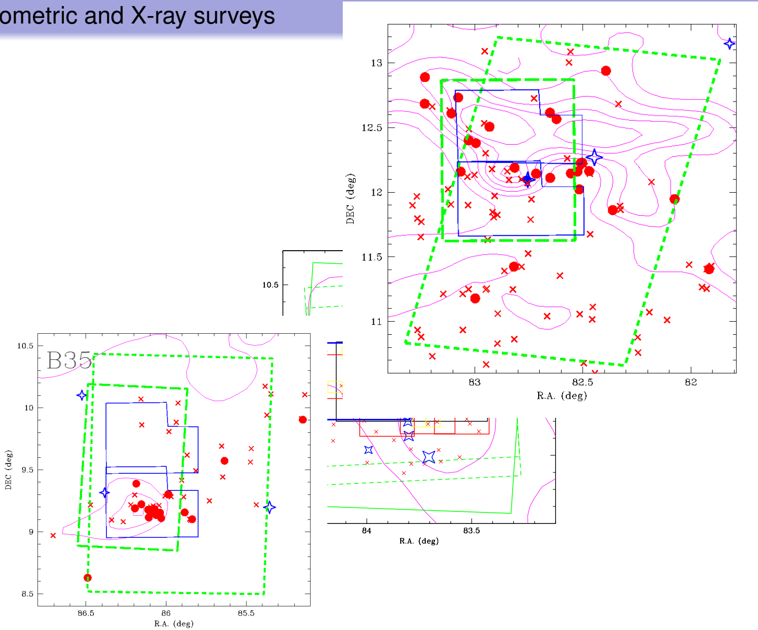
Photometric and X-ray surveys



Photometric and X-ray surveys



Photometric and X-ray surveys

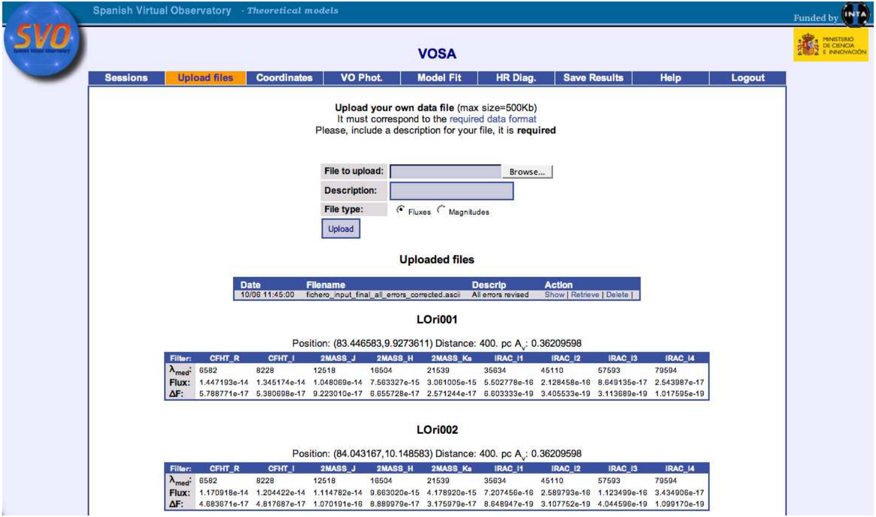


Spectroscopic surveys: C69

Date	Observatory/Telescope/Instrument	Resolution	WL coverage	# Sources observed
November 2-5, 2002	Mauna Kea / Keck I / LRIS	~2650	6425–7692 Å	12
November 2-5, 2002	Mauna Kea / Keck I / LRIS	~ 950	6250–9600 Å	29
December 11-14, 2002	Las Campanas / Magellan Baade / MIKE	~11250	4430–7250 Å	14
March 9-11, 2003	Las Campanas / Magellan II / B&C	~2600	6200–7825 Å	2
March 9-11, 2003	Las Campanas / Magellan II / B&C	~800	5000–10200 Å	3
November 22-25, 2005	CAHA / 3.5m / TWIN	~1100	5600–10425 Å	5
November 20-23, 2006	CAHA / 3.5m / TWIN	~1100	5700–9900 Å	8
Nov. 30 - Dec. 11, 2007	CAHA / 2.5m /CAFOS	~600	6200–10350 Å	37
January 5, 2008	Paranal / UT2/FLAMES	~8600	6438–7184 Å	40

Date	Observatory/Telescope/Instrument	Resolution	WL coverage	# Sources observed
December 22-23, 2004	Mauna Kea / Keck II / NIRSPEC	~2000	1.143–1.375 μm	4
December 9, 2005	Mauna Kea / Keck II / NIRSPEC	~2000	1.143–1.375 μm	9
January 9-11, 2007	La Silla / NTT / SOFI	~950	0.950–2.500 μm	2
November 10, 2008	Mauna Kea / SUBARU /IRCS	~200	1.400–2.500 μm	8

VOSA


Spanish Virtual Observatory - *Theoretical models*

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VOSA

Sessions | Upload files | Coordinates | VO Phot. | Model Fit | HR Diag. | Save Results | Help | Logout

Upload your own data file (max size=500Kb)
It must correspond to the required data format
Please, include a description for your file, it is **required**

File to upload: Browse...
Description:
File type: Fluxes Magnitudes
Upload

Uploaded files

Date	Filename	Descrip	Action
10/06 11:45:00	fichero_input_final_all_errors_corrected.ascii	All errors revised	Show | Retrieve | Delete |

LOri001

Position: (83.446583,9.9273611) Distance: 400. pc A_V: 0.36209598

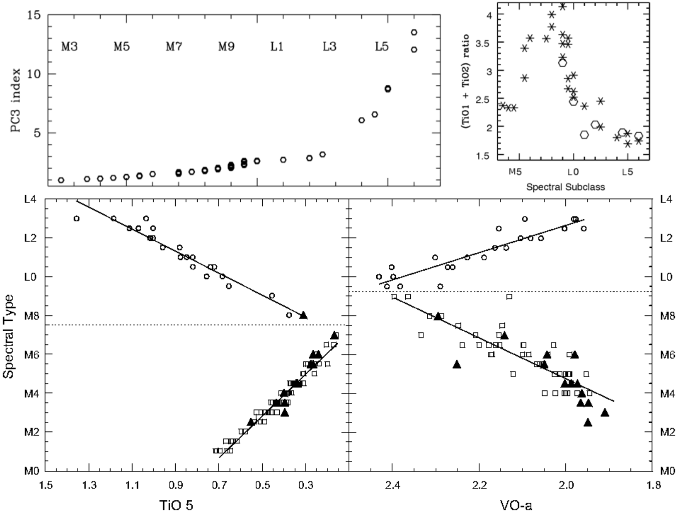
Filter:	CFHT_R	CFHT_I	2MASS_J	2MASS_H	2MASS_Ks	IRAC_I1	IRAC_I2	IRAC_I3	IRAC_I4
λ_{med}:	6582	8228	12518	16504	21539	35634	45110	57593	79594
Flux:	1.447193e-14	1.345174e-14	1.048069e-14	7.563327e-15	3.061005e-15	5.502778e-16	2.128458e-16	8.649135e-17	2.543987e-17
ΔF:	5.788771e-17	5.380698e-17	9.223010e-17	6.655728e-17	2.571244e-17	6.603333e-19	3.405533e-19	3.113689e-19	1.017595e-19

LOri002

Position: (84.043167,10.148583) Distance: 400. pc A_V: 0.36209598

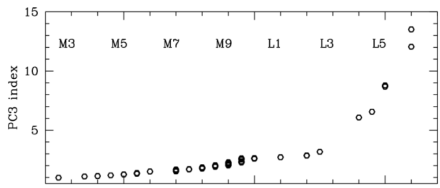
Filter:	CFHT_R	CFHT_I	2MASS_J	2MASS_H	2MASS_Ks	IRAC_I1	IRAC_I2	IRAC_I3	IRAC_I4
λ_{med}:	6582	8228	12518	16504	21539	35634	45110	57593	79594
Flux:	1.170918e-14	1.204422e-14	1.114782e-14	9.663020e-15	4.178920e-15	7.207456e-16	2.589793e-16	1.123499e-16	3.434906e-17
ΔF:	4.683671e-17	4.817687e-17	1.070191e-16	8.889979e-17	3.175979e-17	8.648947e-19	3.107752e-19	4.044596e-19	1.099170e-19

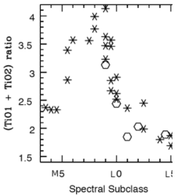
Molecular Bands

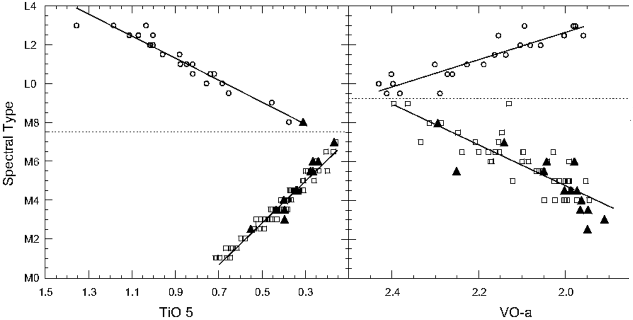


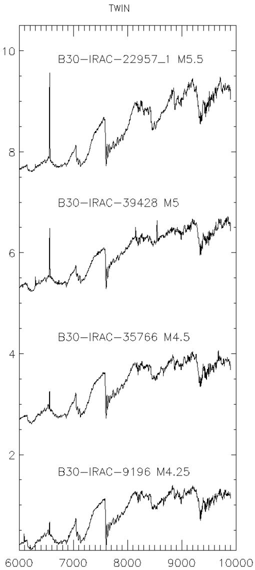
Kirkpatrick et al. (1999), Martin et al. (1999), Reid & Cruz (2002)

Molecular Bands



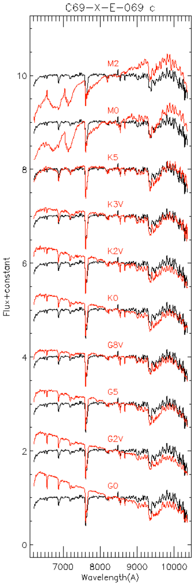


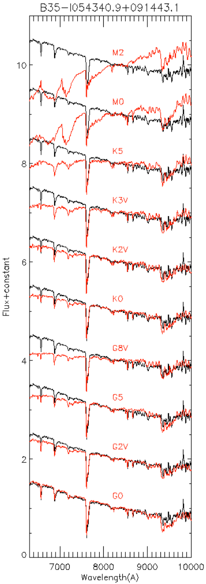




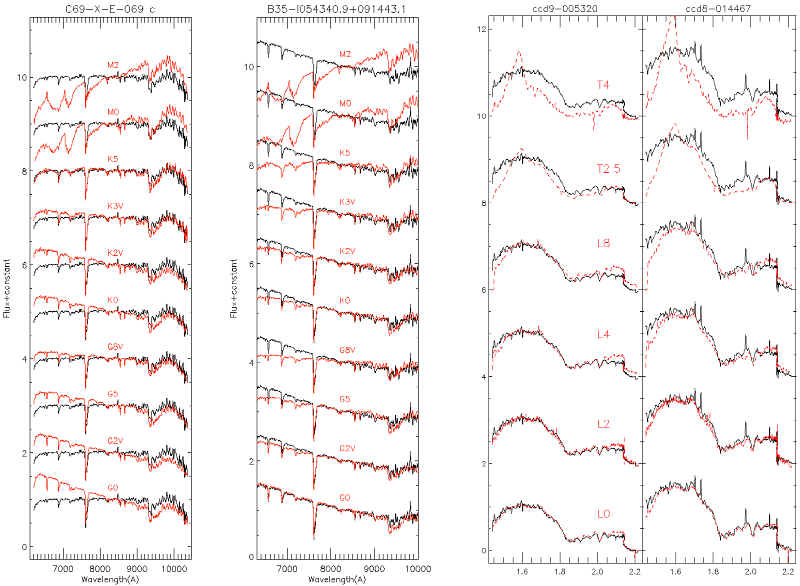
Kirkpatrick et al. (1999), Martin et al. (1999), Reid & Cruz (2002)

Templates

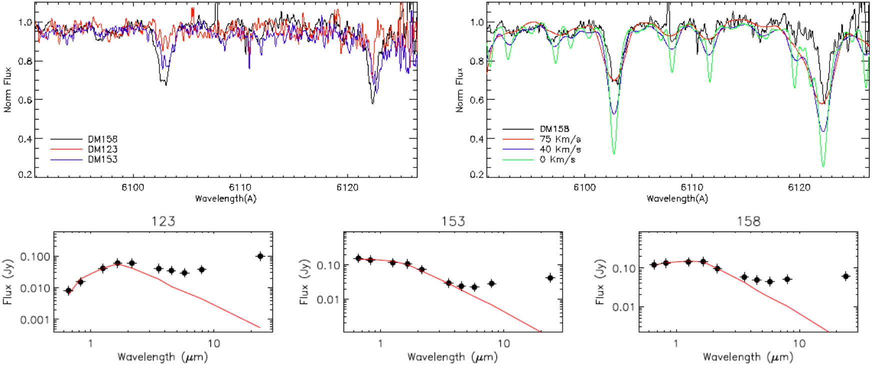

C69–X–E–069 c
M2
M0
K5
K3V
K2V
K0
G8V
G5
G2V
G0
Flux+constant
Wavelength(A)
7000
8000
9000
10000


B35–I054340.9+091443.1
M2
M0
K5
K3V
K2V
K0
G8V
G5
G2V
G0
Flux+constant
Wavelength(A)
7000
8000
9000
10000

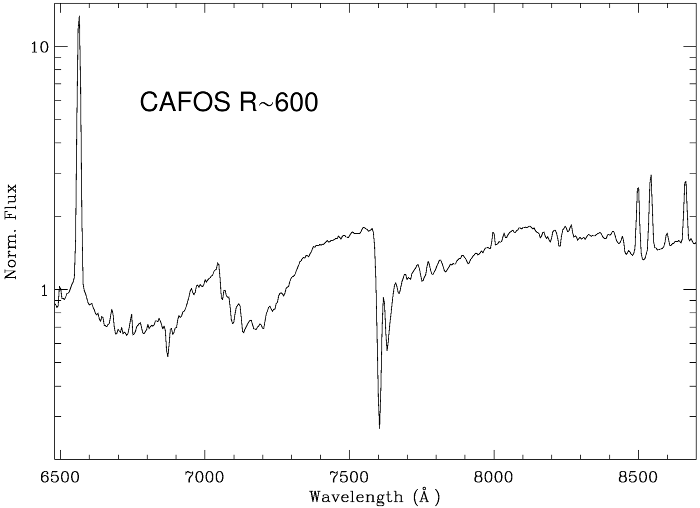
Templates


C69−X−E−069 c
B35−I054340.9+091443.1
ccd9−005320
ccd8−014467
M2
M0
K5
K3V
K2V
K0
G8V
G5
G2V
G0
T4
T2.5
L8
L4
L2
L0
Flux+constant
Wavelength(A)

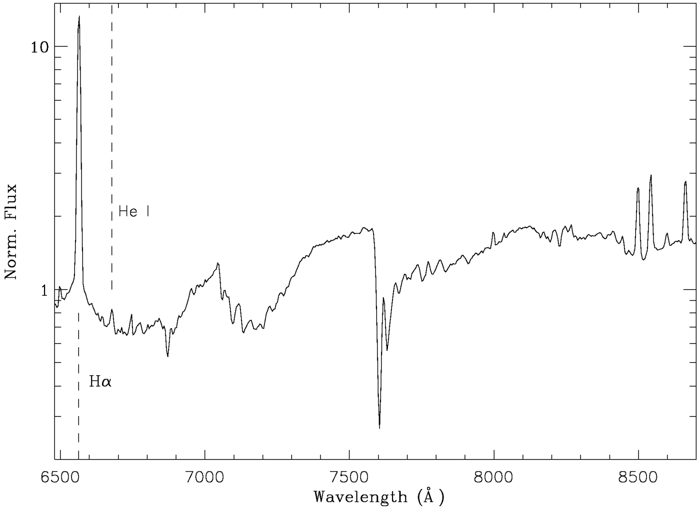
Rotational velocities



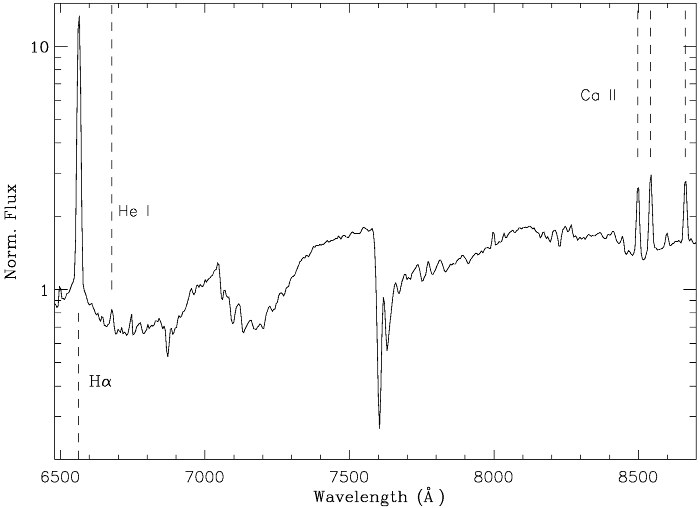
Emission lines



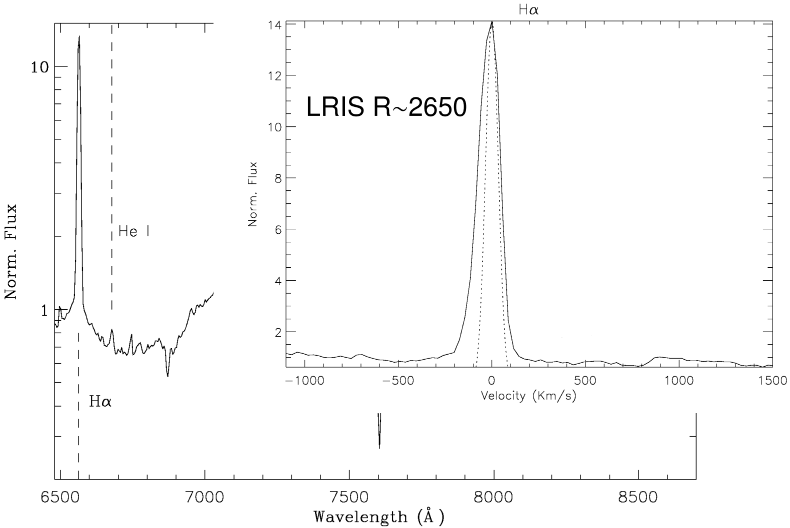
Emission lines



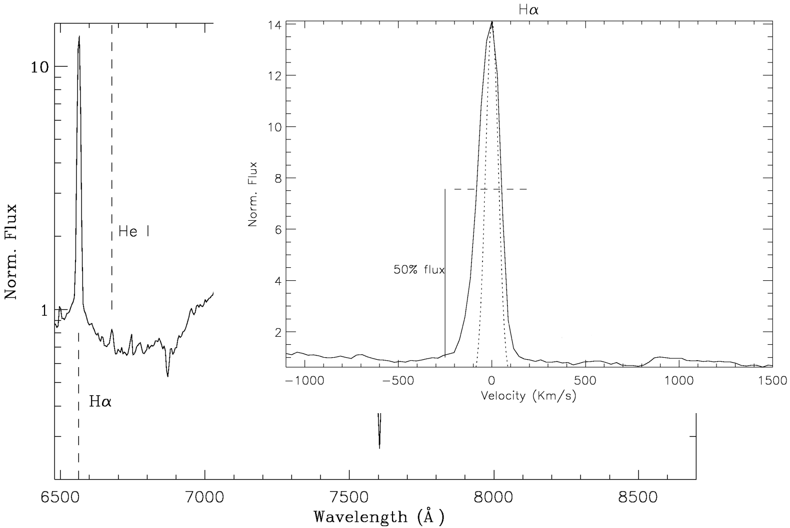
Emission lines



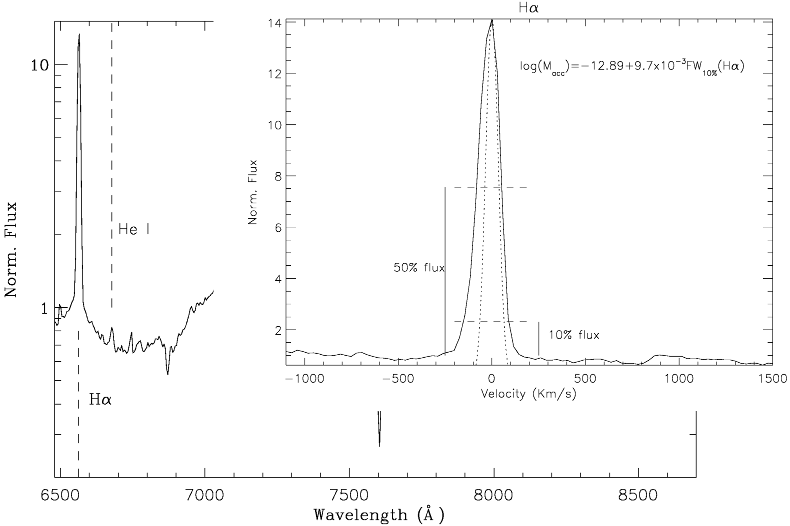
Emission lines



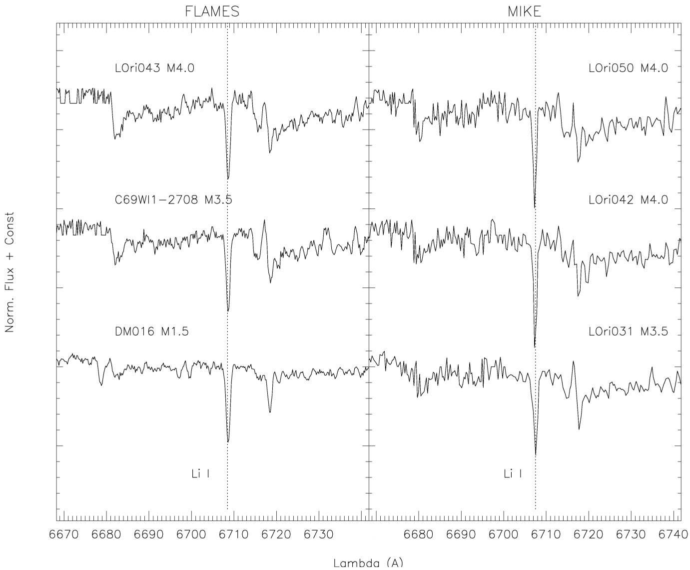
Emission lines



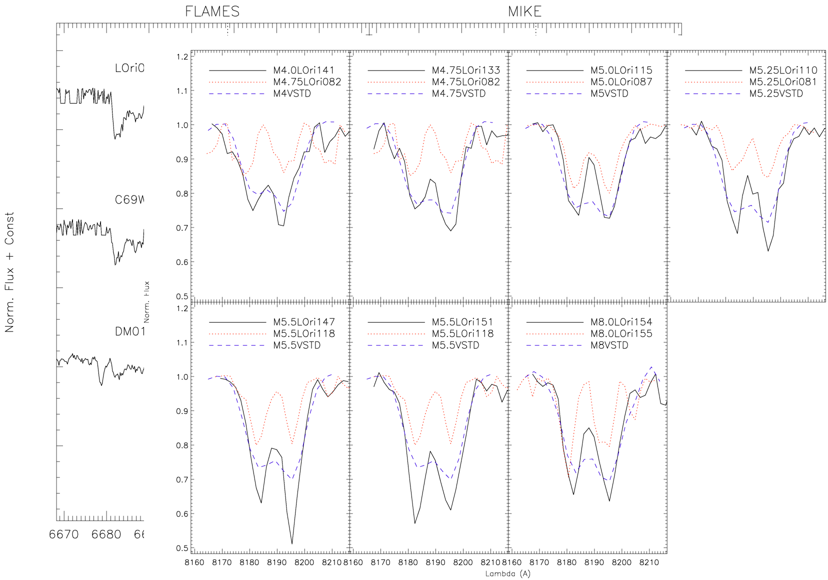
Emission lines



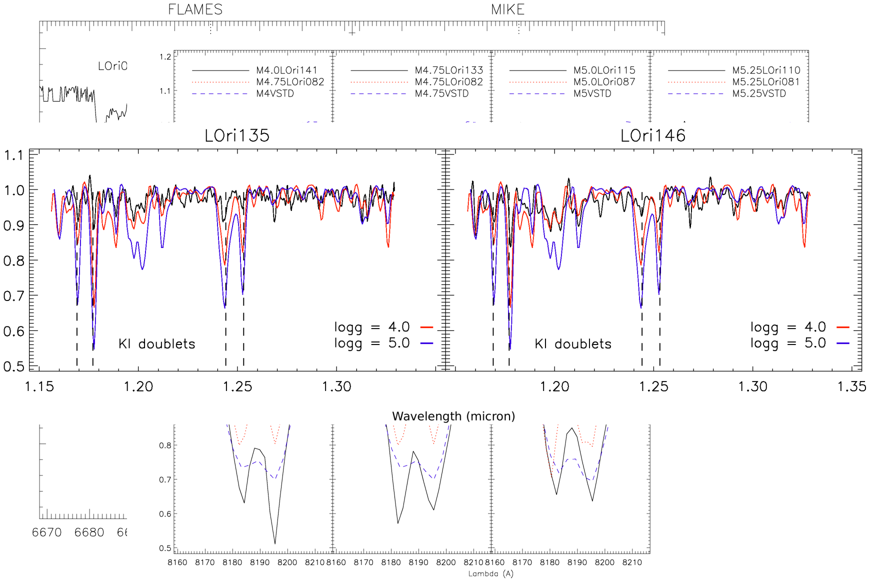
Alkali


FLAMES
MIKE
LOri043 M4.0
C69WI1−2708 M3.5
DM016 M1.5
Li I
LOri050 M4.0
LOri042 M4.0
LOri031 M3.5
Li I
Norm. Flux + Const
6670 6680 6690 6700 6710 6720 6730
6680 6690 6700 6710 6720 6730 6740
Lambda (A)

Alkali

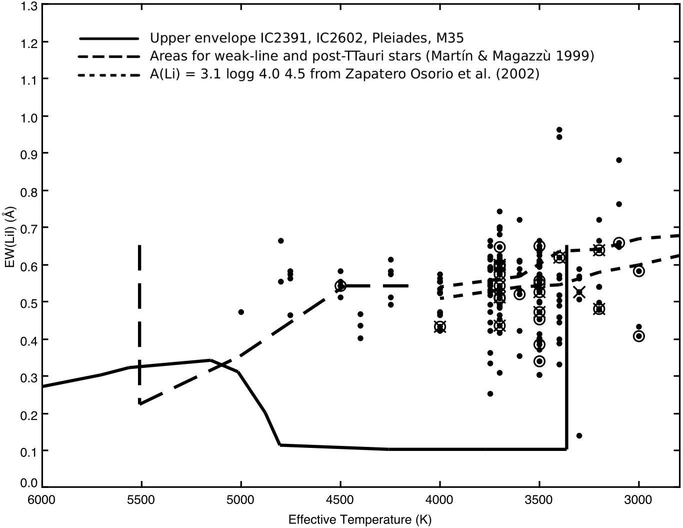

FLAMES
MIKE
LOri0
C69W
DM01
Norm. Flux + Const
Norm. Flux
6670 6680
M4.0LOri141
M4.75LOri082
M4VSTD
M4.75LOri133
M4.75LOri082
M4.75VSTD
M5.0LOri115
M5.0LOri087
M5VSTD
M5.25LOri110
M5.25LOri081
M5.25VSTD
M5.5LOri147
M5.5LOri118
M5.5VSTD
M5.5LOri151
M5.5LOri118
M5.5VSTD
M8.0LOri154
M8.0LOri155
M8VSTD
Lambda (A)

Alkali

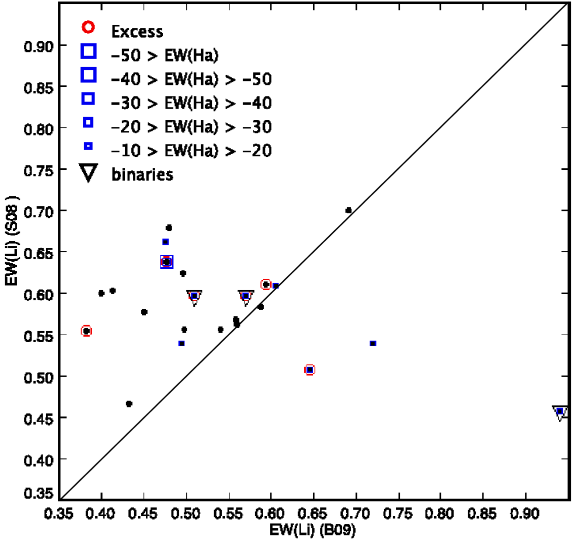

FLAMES
MIKE
M4.0LOri141
M4.75LOri082
M4VSTD
M4.75LOri133
M4.75LOri082
M4.75VSTD
M5.0LOri115
M5.0LOri087
M5VSTD
M5.25LOri110
M5.25LOri081
M5.25VSTD
LOri135
LOri146
KI doublets
KI doublets
logg = 4.0
logg = 5.0
logg = 4.0
logg = 5.0
Wavelength (micron)
Lambda (A)

Lithium vs T_{eff}

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



Alkali variability



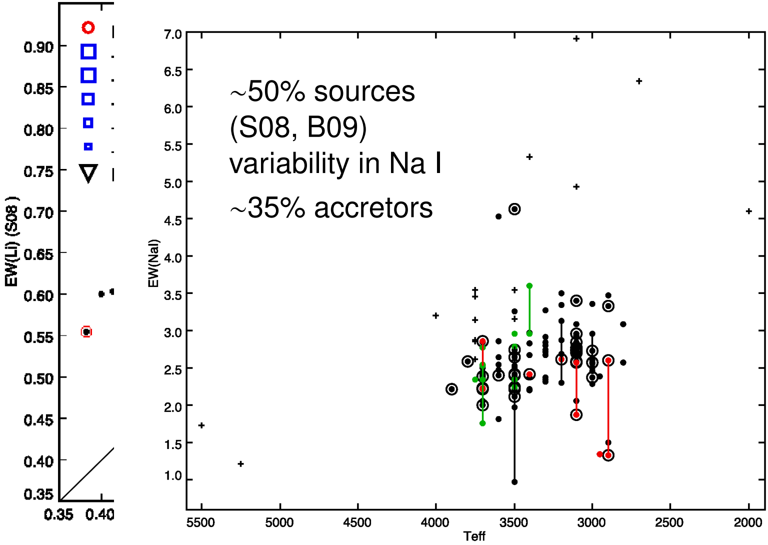
Collinder 69

~47% sources (DM, S08, B09) variability in Li I

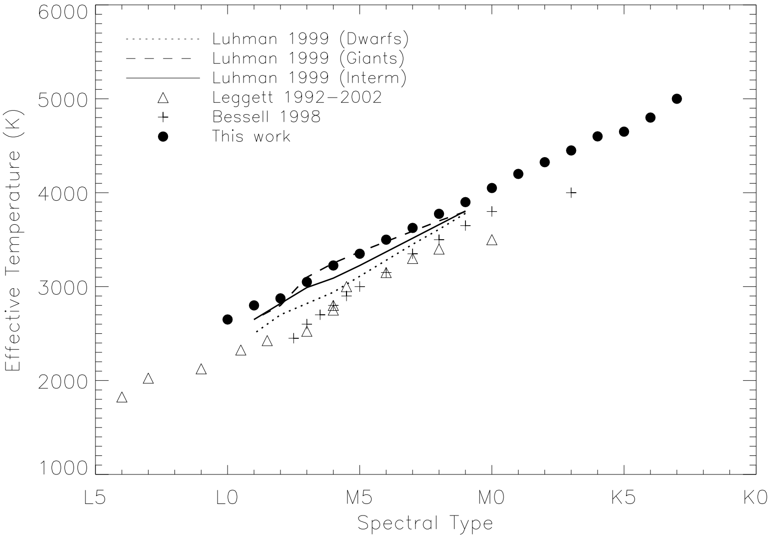
Alkali variability

$\sim$50% sources
(S08, B09)
variability in Na I

$\sim$35% accretors

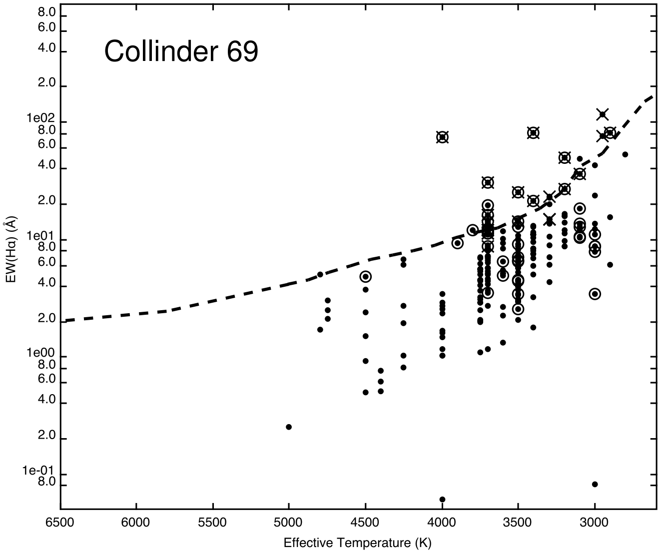


T_{eff} scale

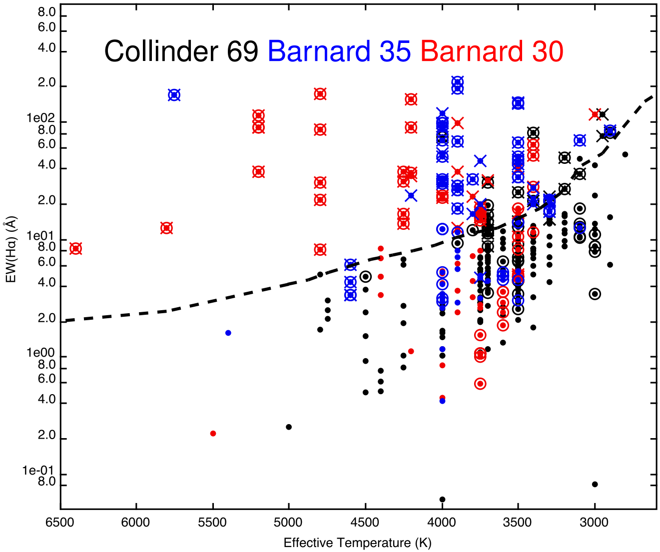


6000
5000
4000
3000
2000
1000
Effective Temperature (K)
Luhman 1999 (Dwarfs)
Luhman 1999 (Giants)
Luhman 1999 (Interm)
Leggett 1992–2002
Bessell 1998
This work
L5
L0
M5
M0
K5
K0
Spectral Type

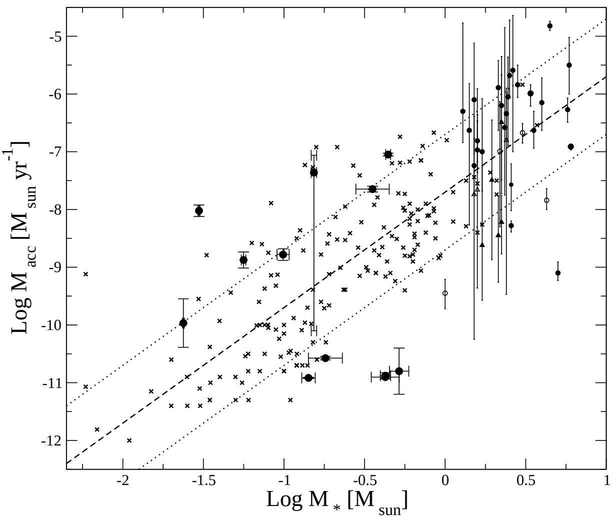
Accretion


Collinder 69
EW(Hα) (Å)
Effective Temperature (K)
8.0
6.0
4.0
2.0
1e02
1e01
1e00
1e-01
6500
6000
5500
5000
4500
4000
3500
3000

Accretion


Collinder 69 Barnard 35 Barnard 30
EW(Hα) (Å)
Effective Temperature (K)
8.0
6.0
4.0
2.0
1e02
1e01
1e00
1e-01
6500
6000
5500
5000
4500
4000
3500
3000

Accretion



Collinder 69

Low mass: Calvet et al. (2004), Muzerolle et al. (2005), Mohany et al. (2005), Natta et al. (2006)

Higher mass: Mendigutia et al. (2010)

Disks Properties

Disk and diskless populations unevenly distributed

Stellar disk fraction 28.5%

Sub-stellar disk fraction

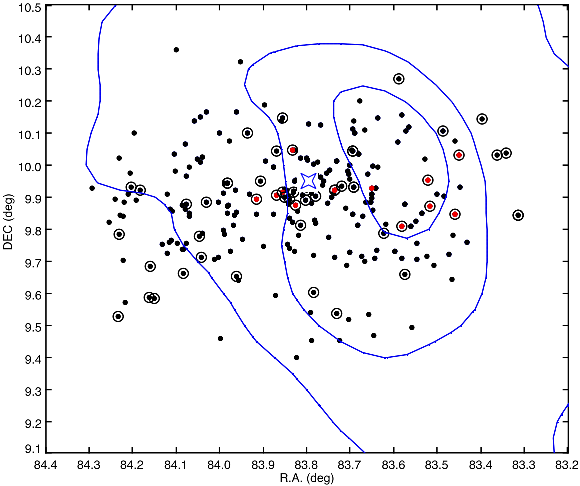
>30%

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

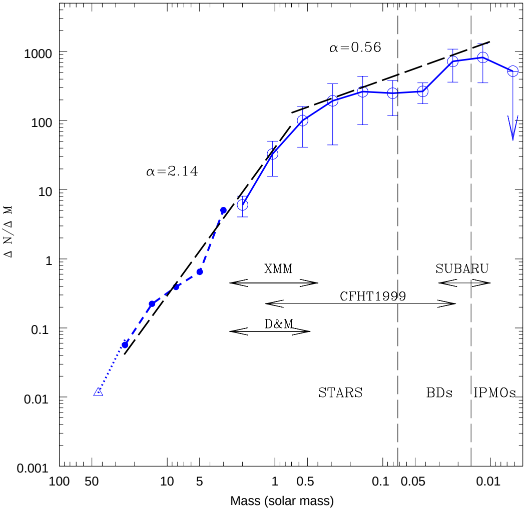
Accretors fraction

sub-stellar 18%

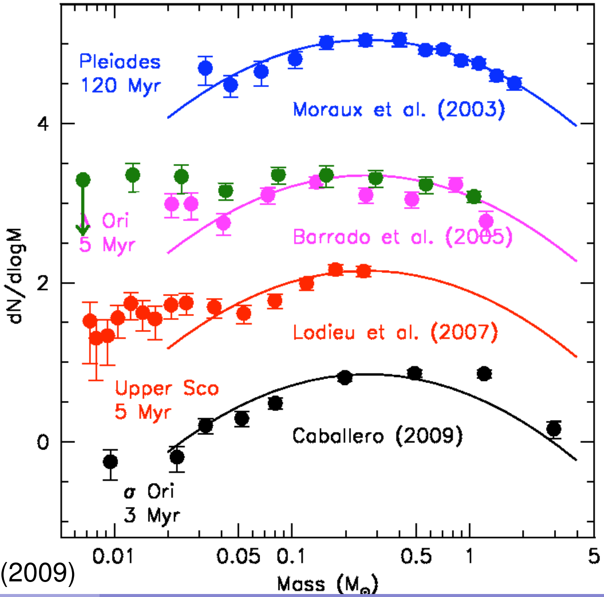
- Scholz et al. (2007) 31% for Upper Sco (low-mass and sub-stellar)



IMF of Collinder 69



IMF of Collinder 69



Bouvier et al. (2009)

Conclusions

- 33 new members spectroscopically confirmed.
- Complete census of ~175 spectroscopicaly confirmed members plus 60 photom. probable members.
- Physical parameters derived for the whole sample: T_{eff}, L_{bol}, Mass.
- Physical parameters derived for the spectroscopic sample: Spectral Type, Hα and Li I equivalent width, accretion rates, etc.
- Temperature scale.
- Age study: upper limit of 20 Myr, optimal 5 Myr.

Conclusions

- Study of the disks properties:
  1. Spatial distribution (inconsistent with SN Hypothesis, D'Orazi et al. 2009 solar metallicity for DM24, posible sub-solar for a member of the OB1b).
  2. Stellar and sub-stellar disk fraction.
  3. Accretors fraction.
  4. Relation Hα mid-IR excess.
- One of the most complete IMF reported so far (from $\sim$20 $M_\odot$ down to 7 $M_{\rm Jup}$)
- No evidence of mass segregation
- Mass fraction limit?

Future Work

- Confirm end IMF Collinder 69
- Complete optical survey analysis for B35 an B30
- Complete X-ray analysis for B35 an B30
- Build final census (no bias) for the two associations (B35, B30)
- Derive disks fractions for B35 and B30 and relate with age and environment (C69)
- Build complete IMF for B35 and B30 and compare with C69 (age/environmental differences?)

THANK YOU!!!