The Discovery of Brown Dwarfs

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and

Consejo Superior de Investigaciones Científicas

BD30, La Gomera September 1st, 2025

Outline

- First searches
- The discovery of the first Brown dwarfs (chronology, images, spectra, publications)
- Subsequent early findings
- Conclusions

First theoretical developments

- *In the early 1960s, Kumar and Hayashi independently postulated the existence of brown dwarfs: objects unable to sustain stable hydrogen fusion, with degenerate matter in their interiors, these objects should be similar in size to Jupiter but up to 75 times more massive.*

My interest in brown dwarfs started in 1990, when we observed a very low-mass star, UX Tau C (in Taurus), using the Isaac Newton Telescope on the island of La Palma.

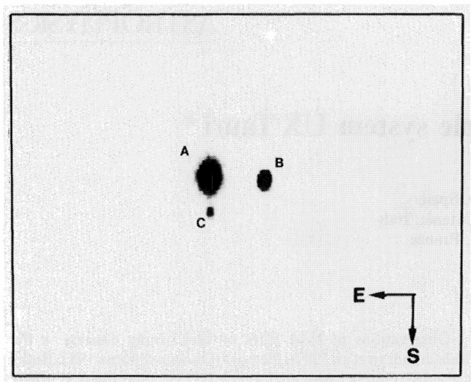


Fig. 1. An image of the UX Tau triple system taken with the guiding TV camera of the Isaac Newton Telescope

by an image of the guiding TV camera (Fig. 1), and to take spectra of this faint component.

On the first night, we observed the UX Tau system using a grating with a reciprocal dispersion of 36 pm pixel^{-1}, which allowed us to have both the Li I λ670.7 nm line and Hα in the same range. On the night of March 10 the three stars of the system were observed only in the lithium region, with a higher resolution grating (reciprocal dispersion 22 pm pixel^{-1}). These latter observations were repeated, as a test, on the 12. No appreciable difference was found between these two sets of spectra. Exposure times ranged from 500 to 1500 s. All the observations were performed with a slit width of 150μm (0″.8 on the sky), giving an effective spectral resolution of about 2 pixels, in either configu-

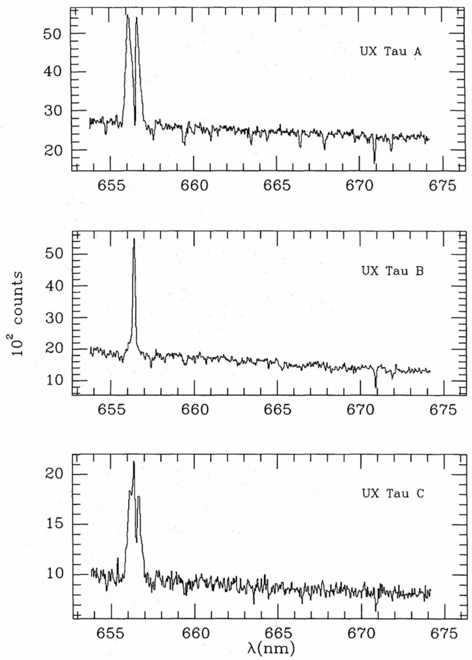


Fig. 2. Our 36 pm pixel^{-1} spectra of the UX Tau system. Note the correspondence between the side peaks of Hα in the UX Tau C spectrum and the double-peaked Hα in UX Tau A

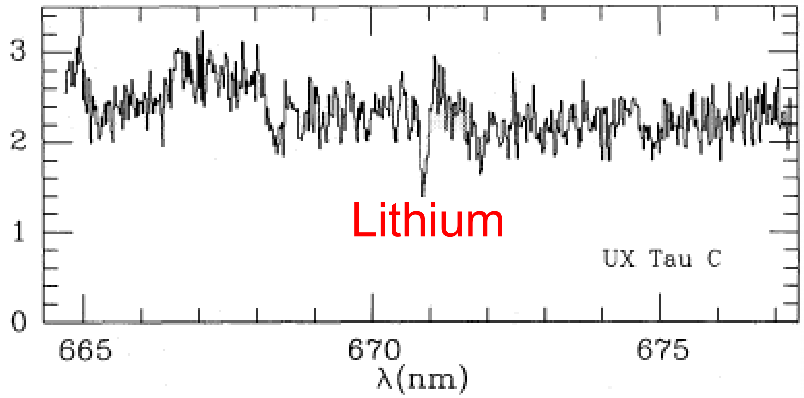
Astron. Astrophys. 249, 149–155 (1991)

ASTRONOMY AND ASTROPHYSICS

Lithium in the pre-main sequence triple system UX Tauri *

A. Magazzù [1,2], E. L. Martín [1,3], and R. Rebolo [1]

[1] Instituto de Astrofisica de Canarias, E-38200 La Laguna, Tenerife, Spain
[2] Osservatorio Astrofisico di Catania, Città Universitaria, I-95125 Catania, Italy
[3] Institut d'Astrophysique de Paris, 98bis Bd. Arago, F-75014 Paris, France



LITHIUM AND BERYLLIUM IN MAIN SEQUENCE STARS

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38200 La Laguna, Tenerife
Spain

3.3. M STARS

Li measurements of such cool stars in the MS are scarce. In stars of the age of the Hyades, the extrapolation of the Li-T_{eff} curve suggests abundances far below log N(Li)=-2. In the Pleiades, however, detection is possible (see García López et al., 1990b). In these objects, destruction of Li during the PMS is very efficient, as discussed in Section 2. Measurements of Li in post T-Tauri M stars would be a crucial test to distinguish the quantity of Li destroyed by these stars during the PMS.

This situation of increasing destruction of Li as we move to less massive stars should change radically at the mass at which the object cannot reach the Li burning temperature (2.5 10^6 K) in its interior. It is interesting to note that stellar structure calculations on very low mass stars, conducted by different authors (D'Antona and Mazzitelli, 1984; Burrows et al., 1989), predict that this temperature cannot be attained in objects with masses lower than 0.06 $M_\odot$, which corresponds to the domain of sub-stellar systems, i.e. objects that fail to reach stable hydrogen ignition (brown dwarfs). So it is possible to use Li detection in those brown dwarf candidates as a criterion to establish their nature. The observations of UX Tau a, Magazzù, Martin and Rebolo (1990) have shown that this type of work is feasible.

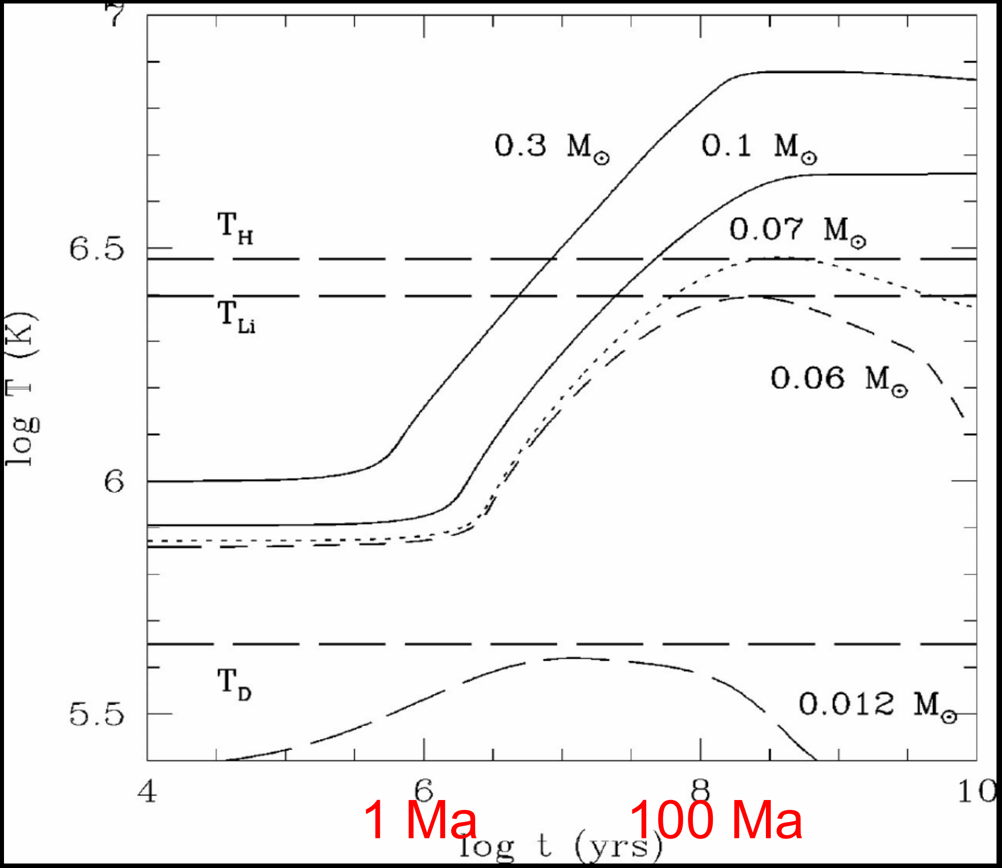
G. Michaud and A. Tutukov (eds.), Evolution of Stars: The Photospheric Abundance Connection, 85–97.

Exploring substellar interiors
The lithium test

Rebolo, Martín and Magazzú 1992 ApJ Lett.
Magazzú, Martín and Rebolo 1993 ApJ Lett.

- ^{7}Li+p → alfa + alfa

- Lithium-7 nuclei are destroyed in the interiors of low-mass stars, BUT they would be completely preserved in brown dwarfs with less than 6% of the Sun's mass (0.06 M☉).



(Chabrier & Baraffe 2000)

Status of brown dwarf searches before 1995

- Field objects and companions
  - Gl 473 (uncertain dynamics), GJ 569 B (not known to be a binary at that time).
  - The coolest known field objects were M9 dwarfs (six reported but age and mass unknown).

  Hawkins and Bessell 1988, Tinney 1993, Kirkpatrick et al. 1994

Star cluster searches before 1995

Star cluster and star-forming regions

- Pleiades:
  - Jameson and Skillen 1989
  - Stauffer et al. 1989
  - Hambly et al. 1991, 1993
  - Stauffer et al.1994

- alpha Persei: Rebolo et al. 1992
- Hyades: Legget and Hawkins 1989
- rho Ophiuchi: Rieke and Rieke 1990,
  - Comerón et al. 1993
- Taurus:
  - Stauffer et al. 1991
  - Magazzú et al. 1991
- No brown dwarf identified at the Workshop

"The bottom of the Main Sequence and Beyond", ESO Garching, ed. C. Tinney, August 1994

In 1993, The IAC80 telescope started science operations and we had the plan to perform a large survey of the Pleiades in the R and I band (limiting magnitudes of 21.5 and 19, respectively).
Follow-up observations would be in the IR with 1.5 m TCS and 2.5 m NOT, for spectroscopy we would use the 4.2 m WHT

Who?

Eduardo Martín and Rafael Rebolo at Museo de la Ciencia y el Cosmos (next IAC headquarters, La Laguna)

Maria Rosa Zapatero Osorio at her IAC office en su oficina del IAC   at La Laguna (1995)

“Discovery of a brown dwarf in the Pleiades star cluster”

Rebolo, Zapatero Osorio, Martín. 1995 (Nature 377, 129)

Teide 1: A member of the Pleiades star cluster based on its photometric, spectroscopic, and motion properties, with a mass < 70 Mjup

submitted on May 22, 1995
published on September 14

LETTERS TO NATURE

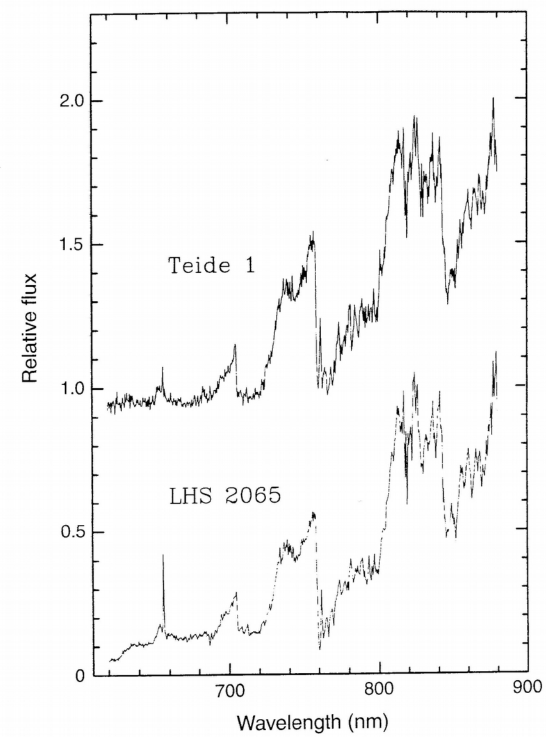


FIG. 1 The optical spectrum of Teide 1 (upper trace) and of the M9 dwarf LHS 2065 (lower trace). The flux scale of both spectra is normalized to unity at 825 nm. An offset has been added to the spectrum of Teide 1 for clarity.

Discovery publication:
brown dwarfs exist
September 14, 1995

Discovery of a brown dwarf in the Pleiades star cluster

R. Rebolo, M. R. Zapatero Osorio & E. L. Martín

Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

BROWN dwarfs are cool star-like objects that have insufficient mass to maintain stable nuclear fusion in their interiors. Although brown dwarfs are not stars, they are expected to form in the same way, and their frequency of occurrence should reflect the trends seen in the birthrates of low-mass stars. But finding brown dwarfs has proved to be difficult, because of their low intrinsic luminosity. The nearby Pleiades star cluster is widely recognized as a likely host for detectable brown dwarfs because of its young age—the still-contracting brown dwarfs should radiate a large fraction of their gravitational energy at near-infrared wavelengths. Here we report the discovery of a brown dwarf near the centre of the Pleiades. The luminosity and temperature of this object are so low that its mass must be less than 0.08 solar masses, the accepted lower limit on the mass of a true star[1–3]. The detection of only one brown dwarf within our survey area is consistent with a smooth extrapolation of the stellar mass function of the Pleiades[4], suggesting that brown dwarfs, although probably quite numerous in the Galactic disk, are unlikely to comprise more than ~1% of its mass.

Only about half a dozen extremely cool dwarfs with spectral types M9 or later have been identified[5]. At present they are the best candidates for brown dwarfs. Their mass–luminosity and

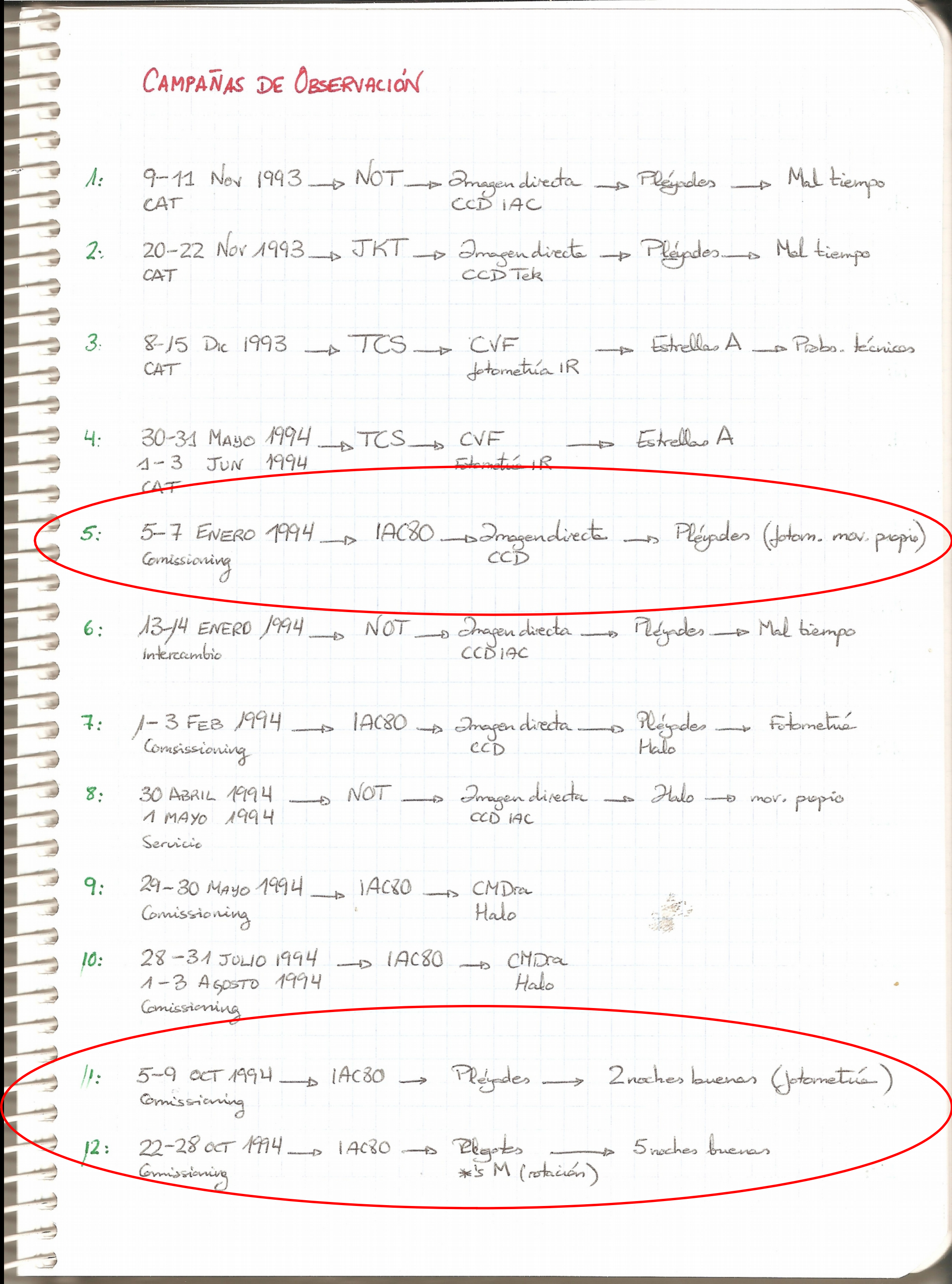
Chronology of the Discovery of Teide 1

- *January 5–7, 1994: Imaging campaign with the IAC 80 cm telescope (Teide Observatory)*
- *October 14, 1994: Spectroscopy with the 2.5 m Isaac Newton Telescope (La Palma)*
- *December 29, 1994: Spectroscopy with the 4.2 m WHT (spectrum published in Nature).*
- *Teide 1 is an M8–M9 dwarf with velocity and proper motion consistent with the Pleiades cluster*
- *May 20, 1995: Manuscript submitted to Nature*
- *August 14, 1995: Publication accepted*
- *September 14, 1995: Published*

List of observing campaigns

(manuscritpt notes by Maria Rosa Zapatero Osorio)

First Photometric measurements
And Proper motion determined
using new IAC80 observations
and 2.5m INT archive images



CAMPAÑAS DE OBSERVACIÓN

1: 9-11 Nov 1993 → NOT → Imagen directa → Pléyades → Mal tiempo
CAT — CCD IAC

2: 20-22 Nov 1993 → JKT → Imagen directa → Pléyades → Mal tiempo
CAT — CCD Tek

3: 8-15 Dic 1993 → TCS → CVF → Estrellas A → Probs. técnicos
CAT — fotometría IR

4: 30-31 Mayo 1994 / 1-3 Jun 1994 → TCS → CVF → Estrellas A
CAT — Fotometría IR

5: 5-7 Enero 1994 → IAC80 → Imagen directa → Pléyades (fotom. mov. propio)
Comissioning — CCD

6: 13-14 Enero 1994 → NOT → Imagen directa → Pléyades → Mal tiempo
Intercambio — CCD IAC

7: 1-3 Feb 1994 → IAC80 → Imagen directa → Pléyades → Fotometría
Comsissioning — CCD — Halo

8: 30 Abril 1994 / 1 Mayo 1994 → NOT → Imagen directa → Halo → mov. propio
Servicio — CCD IAC

9: 29-30 Mayo 1994 → IAC80 → CMDra
Comissioning — Halo

10: 28-31 Julio 1994 / 1-3 Agosto 1994 → IAC80 → CMDra
Comissioning — Halo

11: 5-9 Oct 1994 → IAC80 → Pléyades → 2 noches buenas (fotometría)
Comissioning

12: 22-28 Oct 1994 → IAC80 → Pleyades → 5 noches buenas
Comissioning — *'s M (rotación)

October 14, 1994

First spectroscopy of Teide 1 (unpublished)

Telescope Isaac Newton 2.5m

INT observing log for night: Fri 14 Oct 1994

Observers: Eduardo Martin, Rafael Rebolo, Emilio Harlaftis
Telescope operator: Jose Norberto Glez
Support astronomer: Emilio Harlaftis

Tape: INTD

Focus: CASS Instrument: IDS Detector: C.C.D Chip: TEK3
Camera: 500 Collimator: AgRed Grating: R150V
Pixels: 1124x1124 Pixel size (microns): 24.0 Window: X1= -49, Xs=1124, Y1= 1, Ys=1123; Binning: in X=1, in Y=1

Run No.	Object name	RA	DEC	Eqnx	UT start	ZD start	HA start	Time sec	Air mass	GDX	GDY	Slit ″	PA °	Parl °	Grat °	Cenw Å	ND	CF	AF	BF	Seeing	Comments
65	PLEIAD BD	03:47:16.8	24:22:08		05:34	29.4	02:10	1800.0	1.148	503815	584029	2.16	270.0	74	105.81	7669	0	0	0	0	0.0	
66	CU NE	03:47:17.7	24:22:06		06:08	36.9	02:44	0.0	1.249	503273	584029	2.16	270.0	74	105.81	7669	0	0	0	0	0.0	
67	JET	05:36:06.2	34:06:29		06:13	14.0	01:00	300.0	1.030	503273	584029	2.16	270.0	108	105.81	7669	0	0	0	0	0.0	
68	CUNE	05:36:06.1	34:06:29		06:21	15.6	01:08	1.0	1.038	503273	584029	2.16	270.0	105	105.81	7669	0	0	0	0	0.0	
69	HD 19445 FLUX	03:05:28.6	26:09:04		06:29	49.3	03:44	30.0	1.530	503273	584029	2.16	270.0	73	105.81	7669	0	0	0	0	0.0	
70	JET	05:36:05.5	34:06:15		06:32	17.8	01:19	400.0	1.050	503273	584029	2.16	270.0	102	105.81	7669	0	0	0	0	0.0	
71	CUNE	05:36:05.6	34:06:14		06:41	19.7	01:28	1.0	1.062	503273	584029	1.73	270.0	99	105.81	7669	0	0	0	0	0.0	
72	HR1864 FAST ROT	05:33:54.7	14:18:25		06:56	28.4	01:45	10.0	1.137	503273	584029	2.16	270.0	55	105.81	7669	0	0	0	0	0.0	
73	CUNE	05:33:54.7	14:18:25		06:59	29.1	01:48	1.0	1.144	503273	584029	2.16	270.0	55	105.81	7669	0	0	0	0	0.0	
74	HR1864	05:33:54.8	14:18:26		07:02	29.6	01:51	5.0	1.149	503273	584029	2.16	270.0	56	105.81	7669	0	0	0	0	0.0	
75	FLAT LAMP + ND	07:32:40.3	97:51:53		07:09	68.7	-00:00	5.0	2.735	503273	584029	2.16	269.9	180	105.82	7692	0	0	3	4	0.0	
76	FLAT LAMP + ND	07:34:25.3	28:34:10		07:10	0.2	-00:00	5.0	1.000	503273	584029	2.16	270.0	335	105.82	7692	0	0	3	4	0.0	
77	FLAT LAMP + ND	07:36:10.0	28:34:10		07:12	0.2	-00:00	5.0	1.000	503273	584029	2.16	270.0	335	105.81	7669	0	0	3	4	0.0	
78	FLAT LAMP + ND	07:37:54.6	28:34:09		07:14	0.2	-00:00	5.0	1.000	503273	584029	2.16	270.0	335	105.81	7669	0	0	3	4	0.0	
79	FLAT LAMP + ND	07:39:39.1	28:34:09		07:16	0.2	-00:00	5.0	1.000	503273	584029	2.16	270.0	335	105.81	7669	0	0	3	4	0.0	
80	Bias frame	07:43:25.9	28:34:10		07:19	0.2	-00:00	0.0	1.000	503273	584029	2.16	270.0	335	105.81	7669	0	0	3	4	0.0	

31 OCT 1994 → IAC80 → Pléyades → 1 noche buena
1-2 NOV 1994
Comissioning

6-7 NOV 1994 → NOT → CCD IAC → Pléyades → Fotometría Mar propia
CAT

26-27 NOV 1994 → Calar Alto 2.2m → CCD Tek → Pléyades

29 DIC 1994 → WHT → ISIS → Teide 1
Servicio

23 ENERO 1995 → WHT → ISIS → Teide 1
Servicio

21 MARZO 1995 → INT → IDS → Halo (binarias) Seeing ≃ 4"
CAT

4-6 ABRIL 1995 → JKT → CCD → *'s M (periodos de rotación)
CAT

1: 10 ABRIL 1995 → IAC80
Comissioning

1: 6-7 JUNIO 1995 → IAC80 → Halo (binarias)
Comissioning

2: 27-29 OCT 1995 → Calar Alto 3.5m → TWIN → Pléyades (EMs)

3: 27-28 OCT 1995 → WHT → ISIS → Pléyades (EMs)
CAT

4: 20-21 NOV 1995 → Keck → → Teide 1

5: 13-14 SEPT 1995 → Calar Alto 2.2m → Echelle → Halo

6: 14-17 DIC 1995 → Calar Alto 1.23m → Imagen directa → Pléyades Periodos rotación

7: 8-15 NOV 1995 → JKT → Grupos y periodos rotación
CAT

28: 22-28 NOV 1995 → JKT → Periodos rot. *'s M y Pléyades
CAT

29: 19-21 DIC 1995 → INT → Foco primario : Pléyades
CAT

30: 9-14 FEB 1996 → INT → Foco primario : Pléyades & Praesepe
ITP

31: 9-10 FEB 1996 → WHT → Whircam (Pléyades)
ITP

32: 18 FEB 1996 → Keck → Calar 3

33: 16-19 FEB 1996 → WHT → ISIS Roque 1 y Calar 1
CAT

34: 16-19 MAR 1996 → IAC80 → Pléyades y Praesepe.
Comissioning

35: 19-22 AGO 1996 → IAC80 → *'s deficientes en metales y periodos rot. *'s M
Comissioning

36: 3-11 SEP 1996 → IAC80 → *'s deficientes en metales y periodos rot. *'s M
Comissioning

37: 19-20 SEP 1996 → INT → Foco primario : Pléyades
ITP

38: 10-28 SEP 1996 → NOT → Arnica : Pléyades.
ITP

39: 10-11 OCT 1996 → NOT → Brocam : Pléyades
ITP

40: 12-13 OCT 1996 → JKT → Pléyades
ITP

41: 25-26 OCT 1996 → JKT → Pléyades
ITP

42: 29 OCT 1996 → WHT → Whircam : Pléyades.
ITP

43: 31 OCT - 1 NOV 1996 → 2.2m Calar Alto → Magic : PPl 15, B9-10

44: 11-13 NOV 1996 → UKIRT → Teide 1, Calar 3, BR 10021, vB10

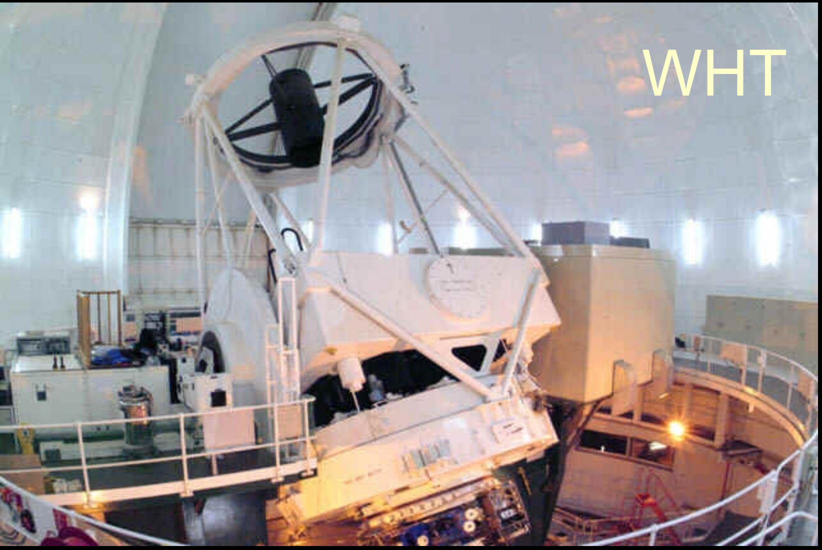
45: 7-8 DIC 1996 → WHT → ISIS
ITP

December 29, 1994

WHT 4.2m

"Observing notes"

R. Rebolo



Dia 29 de Diciembre de 1994. WHT. (Eduardo y yo)

Set up. R 158 R sin dicroico (2.98 Å/pixel)

0.9" proyecta en 1.8 pixels (sobre el TEK)

observer

wht_observer

altair ! /scratch /lpss3 / nombre ~~fichero~~ directorio / nombre fichero

(ejemplo 940701

94 29 12

DEKKER 6.

SETUP ISIS

SETUP RED

ACQCOMP

CENWAVE RED

WINDOW RED

1

xsize 1123

Y 200

Xorigin 1

Yorigin 401

Standard de velocidad radial tipo M7.

Flux standard.

T Tauri con litio tipo M6 o más tardío.

R = 21.4

Gl 406 (Wolf 359) M6 V (obs. Jan)

Gl 752B (VB10) M8 V (obs. Jul.)

Gl 65 A y B M6 V (obs. Oct-Dic.)

¡ UX Tau C !

Kirkpatrick et al. Ap. J. 402, 643 presenta espectros de ✱s M2 - M9 entre 0.6 - 1.4 μ. con resolución de ~18 Å en el azul.

SETUP SLIT 0.92" ⇒ FWHM (arc) = 1.8 pixel.

run

13255 arc CuNe 7200 Å

256 FLAT W

257 "

258 "

259 "

260

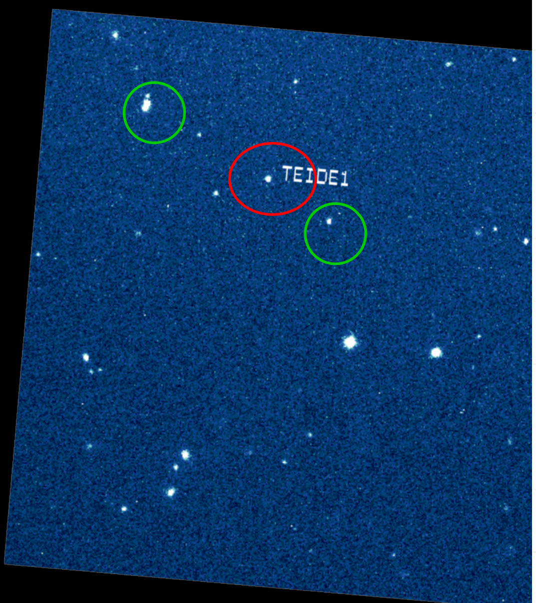
261

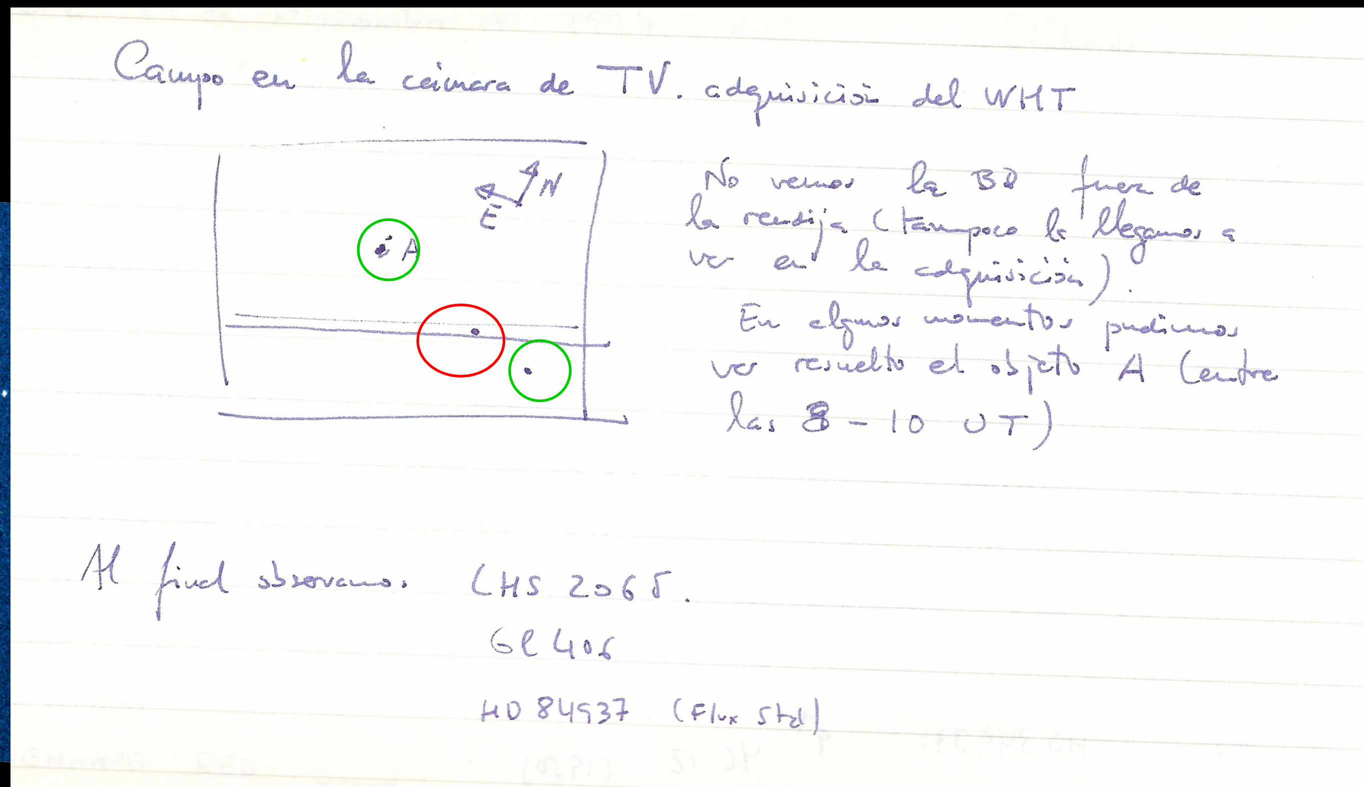
62 BIAS

63

December 29,1994

William Herschel Telescope, Teide 1 spectroscopy





" Manuscript Notes taken during the Observing Campaign " R. Rebolo

WHT observing log for night: 1994 Dec 29/30

Observers: R. Rebolo, E. Martinez; M. Breare, N. Walton
Support astronomer: M. Breare
Telescope operator: J. Rey
PATT/CAT ref.: C14; W39

Weather: GOOD, few high clouds
Seeing (first half, arcsec): 1.0
Temp. (first half, °C): 4.4
Humidity (first half, %): 76

Telescope focus: 97.10

Phase of moon: D

Focal station: CASS
Instrument: ISIS
Dichroic: 6100
Programme: El objeto menos luminoso de las Pleyades: enana marron?; SN's for

Arm:	RED	BLUE	FOS	AUX	UES
Detector:	TEK2	TEK1	FOS	TEK5	-
Pixels:	1124X1124	1124X1124	400X590	1124X1124	-
Pixel-size(microns):	24	24	-	24	-
Collimator focus:	10403	6001			

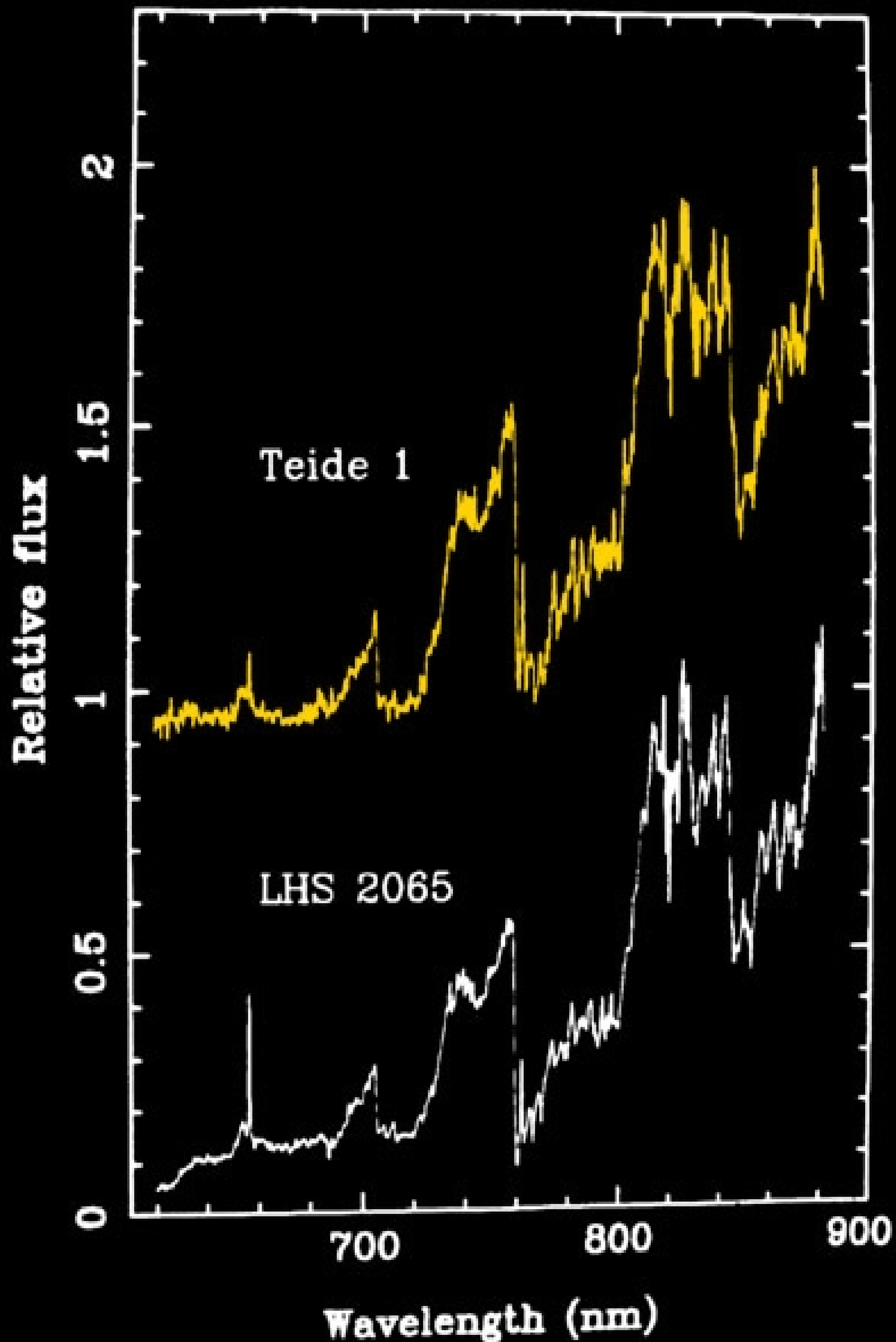
window red changed from run 132286 onwards: start 0,295 size 1124,400

Windows (bottom-corner, size): 1,250 1123,500 (R) 1,285 1123,400 (B) 0,0 0,0 (F) 0,0 0,0 (A) 0,0 0,0 (U) 0,0 0,0 ( )

Tape: WHTD127

Number	Object name	RA hh:mm:ss.ss	Dec. sdd:mm:ss.s	Eqnx. cyyyy	UT hh:mm	Airm.	I	Exp. sec	Sky PA	Sli PA	Slit wid"	Slit len"	Grat.	Cenw A	AutogX /r	AutogY /theta	Aux filt	PF filt	
132280	PLBD	03:44:18.45	24:13:15.9	B1950	23:28	1.033	R	3600	285.0		0.925		R158R	7492	25002	169998	B		
132281	PLBD	03:44:18.45	24:13:15.8	B1950	00:29	1.131	R	2200	285.0		0.925		R158R	7492	25002	169998	B		
132282	CUNE	03:44:18.44	24:13:15.8	B1950	01:08	1.242	R	4	285.0		0.925		R158R	7492	25002	169998	R		
132283	LHS2065	08:51:05.61	-03:18:07.1	B1950	01:13	1.445	R	600	317.0		0.925		R158R	7492	25002	169998	R		
132284	FLUXST	09:46:12.56	13:58:41.6	B1950	01:25	1.401	R	30	300.0		0.925		R158R	7492	20975	160000	R		HD 84937 (oke y Gunn)
132285	CUNE	09:46:12.59	13:58:42.1	B1950	01:28	1.389	R	4	300.0		0.925		R158R	7492	20975	160000	R		
132286	CUAR 30 SEC	10:47:01.40	17:16:30.6	J2000	01:37	1.662	B	30	293.0		1.097		R158B	4896	20975	160000	R		
132287	CUAR 2 SEC	10:47:01.39	17:16:30.6	J2000	01:38	1.659	R	2	293.0		1.097		R158R	7541	20975	160000	R		
132288	CUNE 2 SEC	10:47:01.39	17:16:30.6	J2000	01:41	1.631	R	2	293.0		1.097		R158R	7541	16988	109002	R		
132289	CUNE 7 SEC	10:47:01.39	17:16:30.6	J2000	01:41	1.628	B	7	293.0		1.097		R158B	4896	16988	109002	R		
132290	SN1994AE R FIL	10:47:01.39	17:16:30.6	J2000	01:46	1.592	A	10	293.0						16988	109002	R		
132291	SN1994AE VFILT 1	10:47:01.39	17:16:40.6	J2000	01:50	1.561	A	10	293.0						16988	109002	V		
132292	SN1994AE BFILT 3	10:47:02.09	17:16:40.6	J2000	01:55	1.529	A	30	293.0						16988	109002	B		
132293	SN1994AE IFILT 3	10:47:02.79	17:16:40.6	J2000	01:57	1.512	A	30	293.0						16988	109002	I		
132294	SN1994AE UFILT 1	10:47:02.79	17:16:40.6	J2000	02:00	1.496	A	120	293.0						16988	109002	U		
132295	SN1994AE UFILT 3	10:47:02.79	17:16:40.6	J2000	02:03	1.477	A	300	293.0						16988	109002	U		
132296	SN1994AE 200S	10:47:01.39	17:16:30.3	J2000	02:14	1.412	R	200	293.0		1.097		R158R	7450	16988	109002	U		
132297	SN1994AE 200S	10:47:01.39	17:16:30.4	J2000	02:14	1.410	B	200	293.0		1.097		R158B	4927	16988	109002	U		
132298	SN1994AE 300S	10:47:01.38	17:16:30.4	J2000	02:19	1.385	B	300	293.0		1.097		R158B	4927	16988	109002	U		
132299	SN1994AE 300S	10:47:01.39	17:16:30.3	J2000	02:20	1.383	R	300	293.0		1.097		R158R	7450	16988	109002	U		
132300	SN1994AE 300S	10:47:01.38	17:16:30.3	J2000	02:26	1.352	B	300	293.0		1.097		R158B	4927	16988	109002	U		
132301	SN1994AE 300S	10:47:01.38	17:16:30.3	J2000	02:26	1.352	R	300	293.0		1.097		R158R	7450	16988	109002	U		
132302	CUAR 30S B	10:47:01.39	17:16:30.3	J2000	02:32	1.324	B	30	293.0		1.097		R158B	4927	16988	109002	U		
132303	CUAR 2S R	10:47:01.38	17:16:30.4	J2000	02:32	1.323	R	2	293.0		1.097		R158R	7450	16988	109002	U		
132304	CUNE 2S R	10:47:01.39	17:16:30.3	J2000	02:33	1.319	R	2	293.0		1.097		R158R	7450	16988	109002	U		

Total exposure time in hours (for each arm) for 25 observations recorded on this page = 2.01 (R) 0.24 (B) 0.00 (F) 0.14 (A) 0.00 (U) 0.00 (unlabelled)



Teide 1
LHS 2065
Relative flux
Wavelength (nm)
0
0.5
1
1.5
2
700
800
900

sistent with Teide 1's being a member of the Pleiades cluster. But the proper motions and radial velocities of Pleiades stars are similar to those of general field M dwarfs, as stated in ref. 18, so we considered the probability that Teide 1 might simply be a field M9 dwarf superimposed on the Pleiades (that is, lying at a distance of 60–100 pc, closer than the widely accepted cluster distance of 125 pc). The luminosity function at the end of the Main Sequence has been addressed recently as a result of a deep (completeness limit $R=19$), large-area (27.3 deg^2), CCD survey

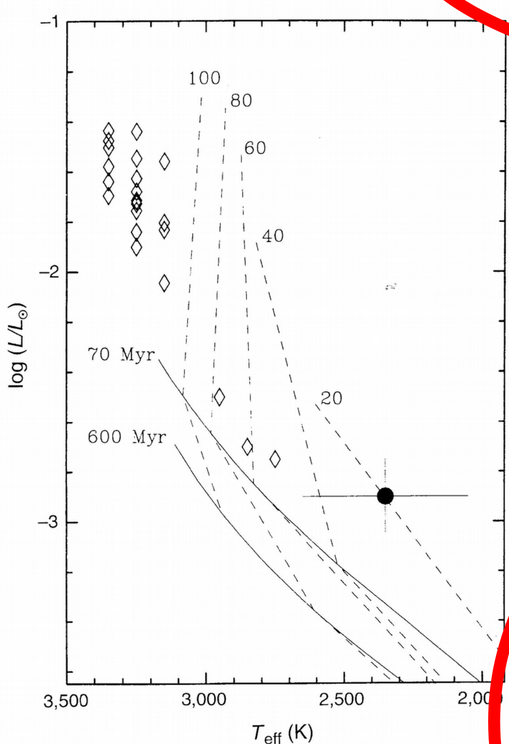


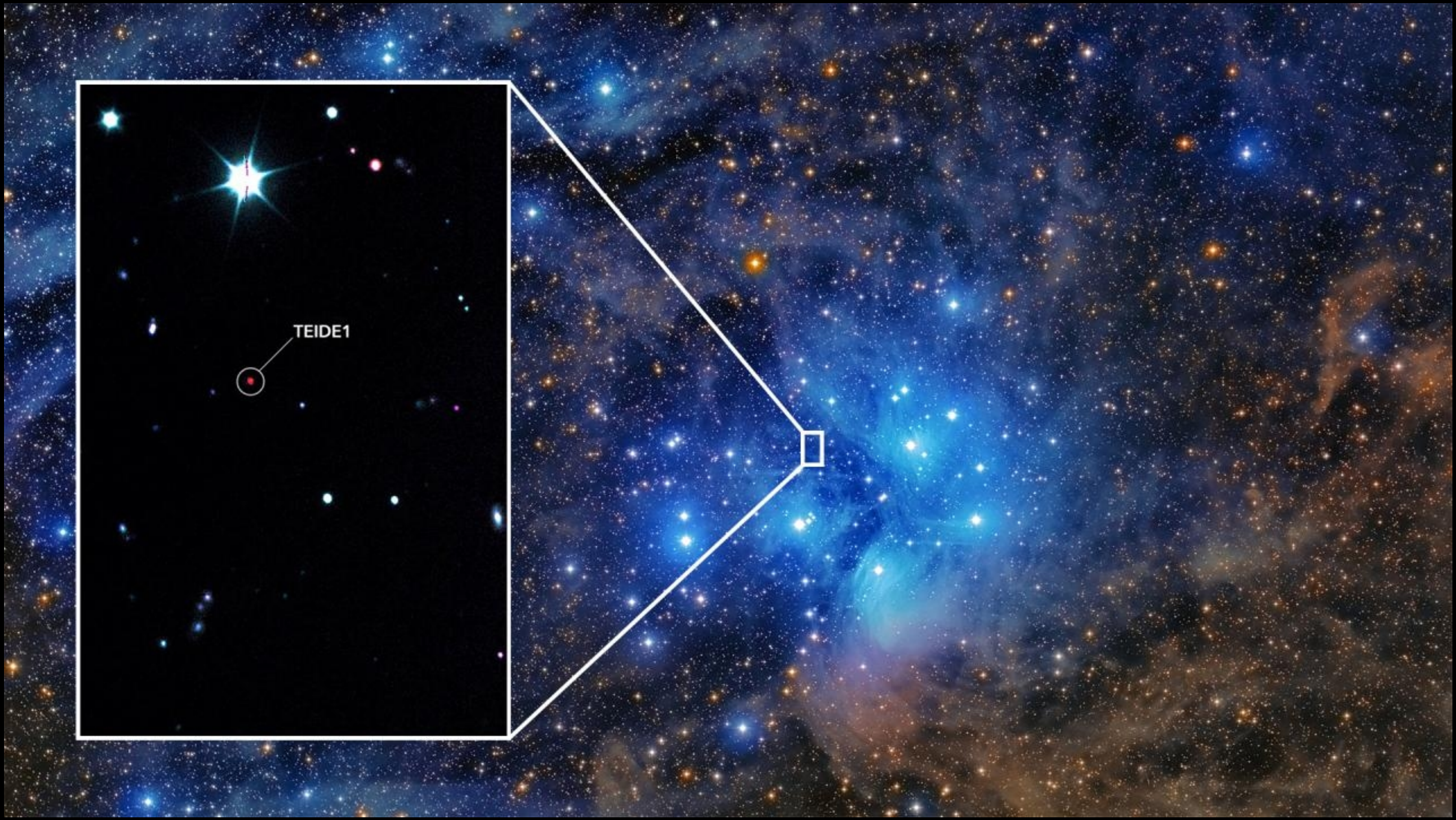
FIG. 2 The position of Teide 1 (filled circle) on the H–R diagram, with error bars corresponding to uncertainties in luminosity and temperature (see text). Other Pleiades proper-motion members with known spectral types are also located for comparison (open diamonds). Theoretical tracks[1] are plotted with broken lines and are labelled with approximate jovian masses. Two isochrones are plotted with solid lines.

the dimmest Pleiades brown-dwarf candidates with measured proper motions and published spectral types[12,13,29,30]. We have derived their luminosities and temperatures in the same way as for Teide 1. Our object is the coolest and faintest brown-dwarf candidate discovered so far in the Pleiades. From its location on the H–R diagram and after comparison with the set of theoretical tracks shown in Fig. 2 we obtain an upper limit to the mass of Teide 1 of 50 jovian masses (M_{Jup}) and a most likely mass in the range 20–30 M_{Jup}. If we use other sets of theoretical tracks[2,3,31], we always obtain masses <70 M_{Jup}. We conclude that Teide 1 must be a brown dwarf, or else the theory is seriously wrong.

Observational tests of the substellar nature of Teide 1 are valuable. Definitive proof would be the detection of lithium in the atmosphere. If its mass is indeed lower than 50 M_{Jup} as inferred from the theoretical H–R diagram, this object should not have destroyed lithium at all, in marked contrast with stars above the substellar mass limit, which have destroyed most of this element at the age of the Pleiades[12,13]. Calculations of the formation of Li I lines in the atmospheres of very cool dwarfs[10,11,32] indicate that fairly strong absorption features should be present at optical wavelengths. In particular, we predict on the basis of our estimated temperature for Teide 1, an equivalent width of ~5 Å for the Li I 670.8-nm resonance doublet. The upper limit to the equivalent width inferred from our spectrum in Fig. 1 is too poor to constrain its lithium content. Detection of this line should be pursued with mid-resolution spectroscopy employing the new class of very-large-diameter telescopes.

We have presented compelling evidence for membership of an M9 dwarf in a young open cluster of known age. This allowed us to estimate an upper limit for the mass that is below the substellar borderline, and conclude that the body is a brown dwarf. It is encouraging that our survey to limiting magnitude $I=19$ ($R=21.5$), so far covering only ~0.3% of the total Pleiades cluster area, has provided one object of this nature. This was, in fact, what we had expected from a smooth extrapolation of the available mass function of the cluster[4]. This extrapolation predicts that 175 brown dwarfs in the mass range 80–40 M_{Jup} may be present in the cluster, forming one of the most populated mass intervals, even comparable to that of M-type dwarfs ($M \sim 0.5$–$0.08\ M_\odot$) where 500 objects are expected. Although massive brown dwarfs could be quite numerous, their contribution to the total mass of the cluster is expected to be $\lesssim 10\ M_\odot$, that is, <1%. If the formation of stars and brown dwarfs in the

Pleiades star cluster



Prediction in our Nature paper that the Pleiades contain 175 brown dwarfs (with masses greater than 40 Mjup)

W26

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PETICIÓN DE TIEMPO DE OBSERVACIÓN (CAT NOCTURNO)
Observatorios del Roque de Los Muchachos y del Teide

1. Título (Máx. 10 palabras): Palabras clave: 1 [X] 2 [ ] 3 [ ] 4 [ ] 5 [ ] 6 [ ]

Espectroscopía de candidatos a enana marrón en los cúmulos de las Pléyades y Praesepe.

2. Investigador Principal — **Centro**

María Rosa ZAPATERO OSORIO — Instituto de Astrofísica de Canarias, IAC

Coinvestigadores

Rafael REBOLO — IAC
Eduardo L. MARTÍN — IAC

Contacto Principal
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Dirección: Instituto de Astrofísica de Canarias
Vía Láctea S/N
38200 La Laguna, Tenerife
Teléfono: (922) 605369
FAX: (922) 605210
E-MAIL: mosorio@iac.es (Internet)

3. Resumen del Programa:

Como resultado de la búsqueda fotométrica que nuestro grupo está realizando en las Pléyades, hemos encontrado 9 nuevos candidatos a enana marrón con fotometría similar a Teide 1 y, por tanto, dentro del dominio subestelar admitido para el cúmulo, sugiriéndose un aparente incremento en la función de luminosidad, hasta hoy día desconocido, para las magnitudes más débiles y los colores más rojos [I>18, ($R-I$)>2.3]. Con esta propuesta pretendemos obtener la espectroscopía de baja resolución que nos permita confirmar la pertenencia de estos nuevos objetos a las Pléyades. Un resultado afirmativo implicaría que el número de enanas marrones con 18<I<19 presentes el cúmulo sería ~30 veces mayor que el número estimado a partir las funciones de luminosidad más recientes que hay para las Pléyades y, por tanto, la contribución de estos objetos a la masa total del cúmulo sería mucho mayor que la esperada. Para la segunda parte de la noche, proponemos la espectroscopía de los objetos menos luminosos y más fríos en Praesepe con el fin de seguir caracterizando la baja secuencia principal muy próxima al límite subestelar de los cúmulos abiertos en la Galaxia.

4. ¿Es parte de una Tesis? [X] **Nombre del doctorando:** María Rosa ZAPATERO OSORIO

5. Tiempo de observación solicitado:

Telescopio	Instrumento y detector	Noches	Luna	Fechas óptimas	Fechas imposibles
WHT	FOS-II	2(1)	0	Febrero	Las restantes

Justificar las fechas imposibles: Por la posición de los objetos.

Comentarios: Es importante que el cúmulo de las Pléyades esté visible el mayor tiempo posible, y en el semestre 96A ocurre para el mes de febrero.

6. Fecha/Firma Investigador Principal — **Fecha/Firma Director Centro**

30/09/1995 — P.A.

September 30, 1995

"…we have found 9 new Brown dwarf candidates with photometry Similar to Teide 1"

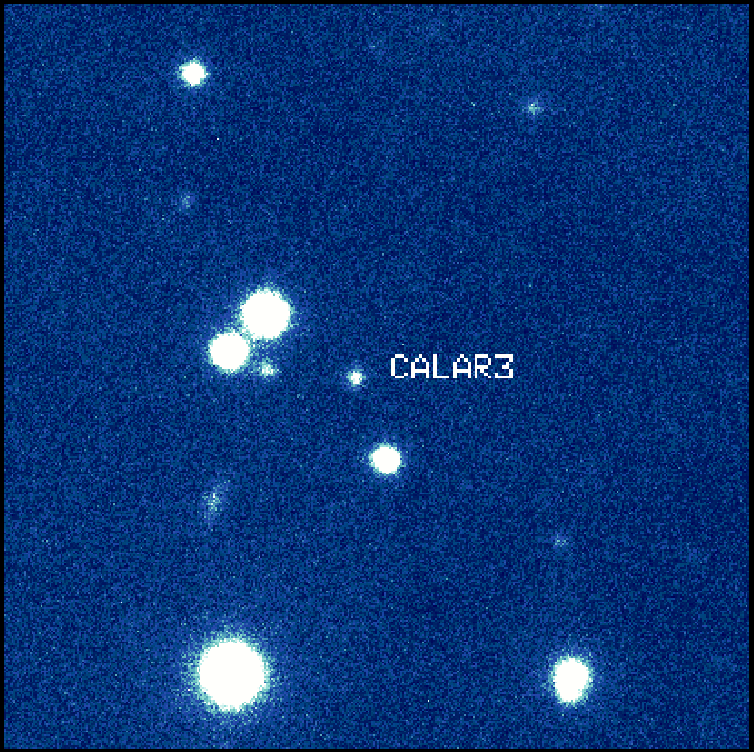
More results after the publication of Teide 1

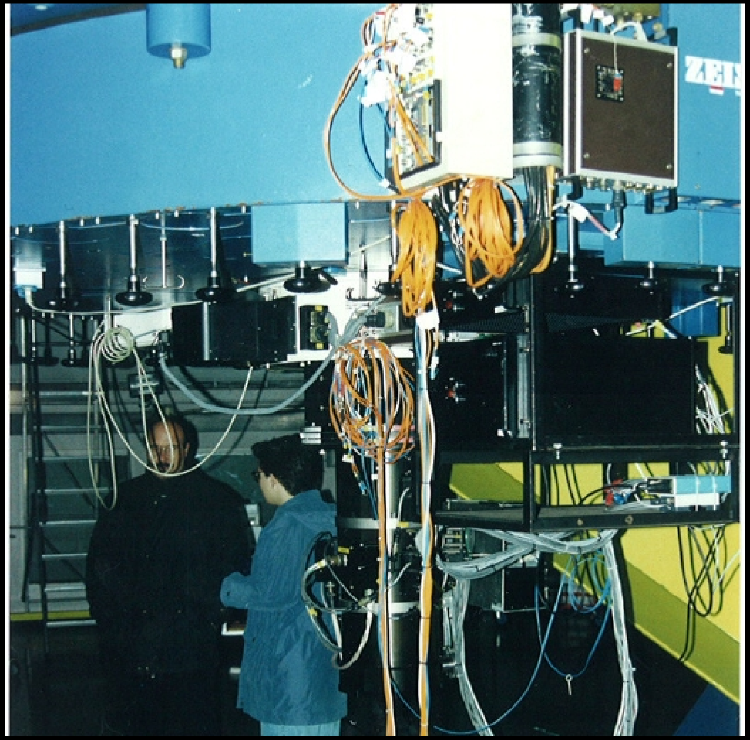
- October 27-29 1995 First Spectroscopy of Calar 3 a phtometry twin Brown dwarf we discovered in the Pleiades

- Mid November 1995: We discovered lithium in Teide 1 and in Calar 3 using the Keck I, the largest telescope in the world. The preservation of lithium provided compelling evidence that both objects are brown dwarfs.

October 27-29, 1995

Observing campaign at Calar Alto 3.5m Telescope





M.R. Zapatero Osorio and R. Rebolo at 3.5m Calar Alto

We performed spectroscopic observations with the TWIN Spectrograph of several photometric analogues to Teide 1 : among them Calar 3

November 20, 1995

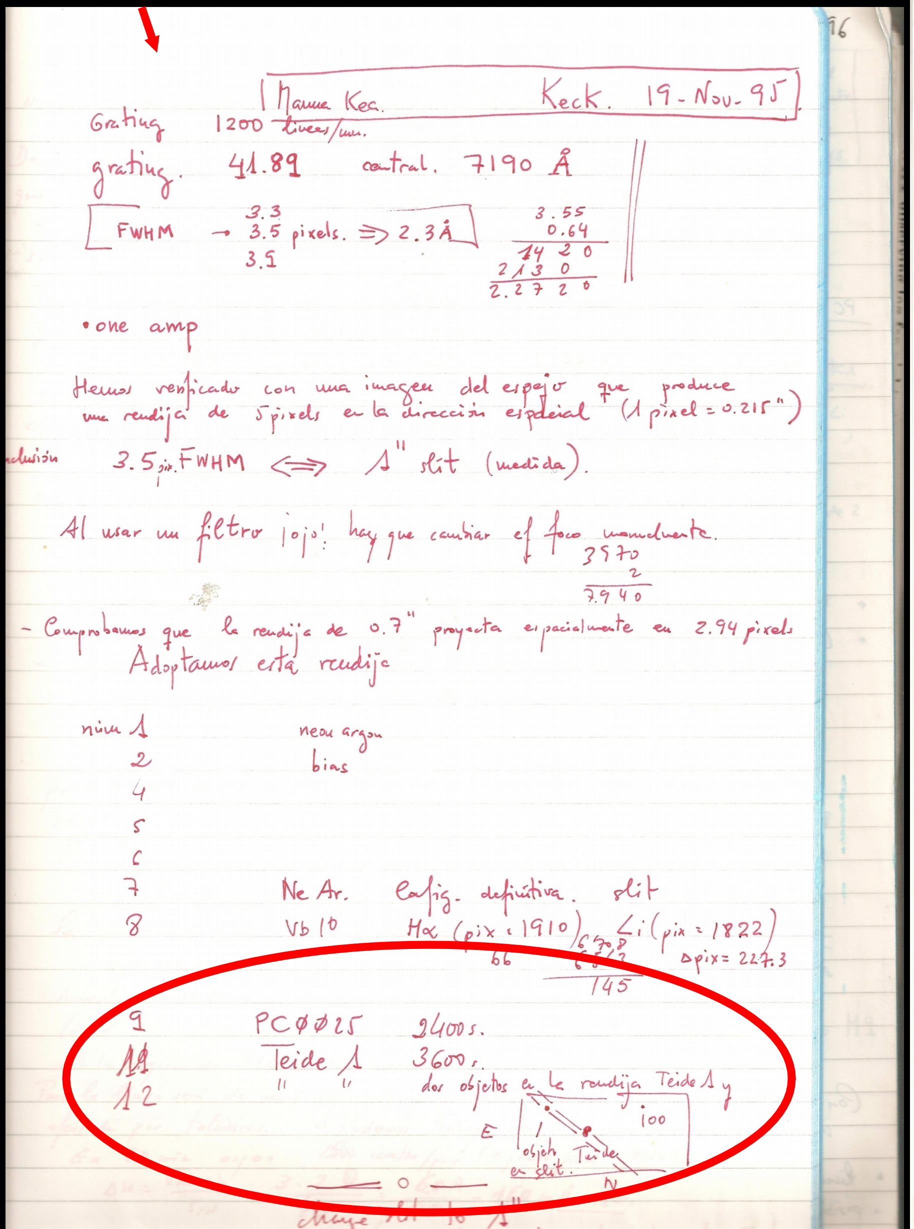
- Observing Campagin at the Keck telescope (at that time the largest in the world)

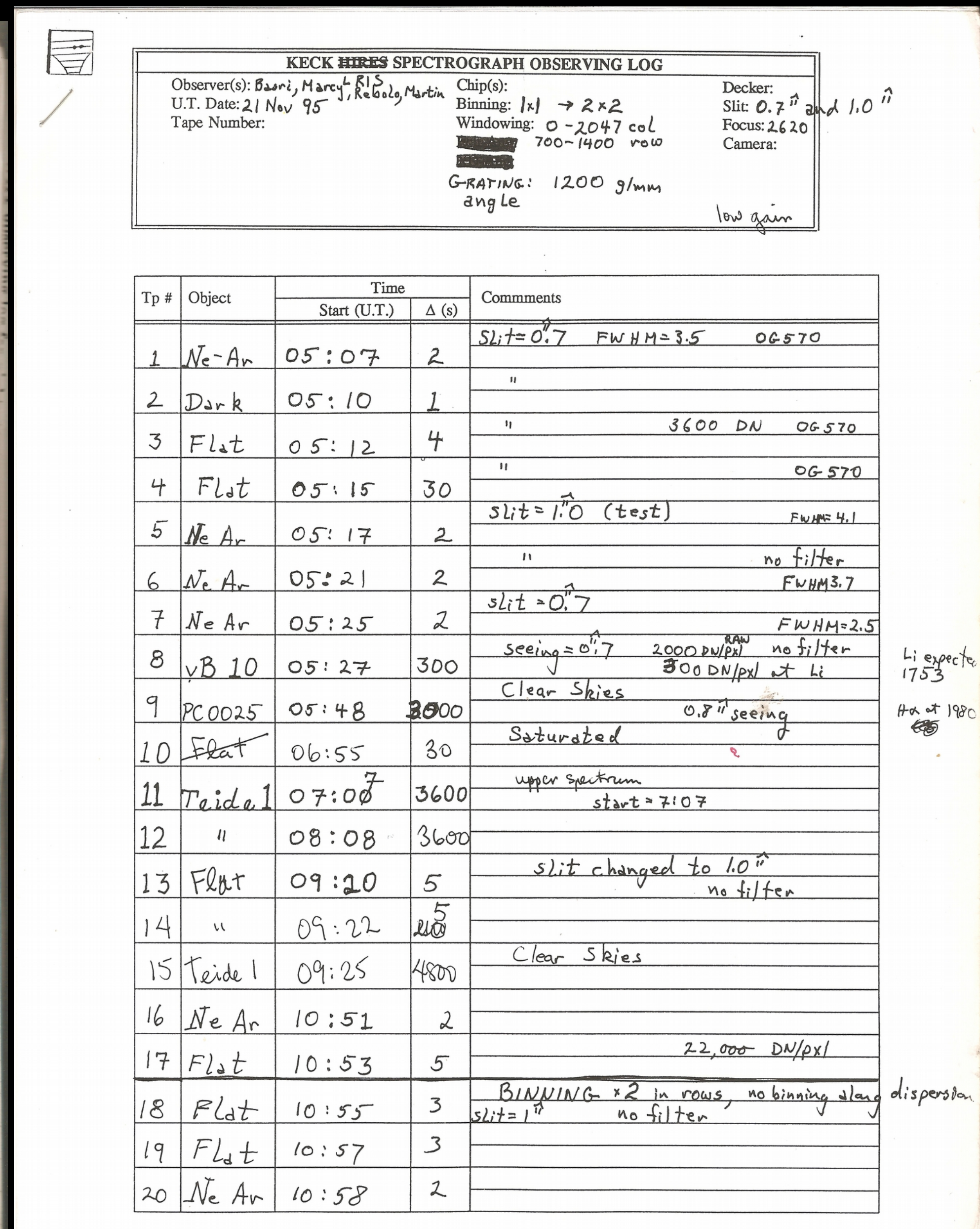
We discovered lithium in Teide 1 and Calar 3 using the Keck I. Compelling confirmation of their substellar nature

November 19-21 1995; the Keck campaign,

G. Basri, G. Marcy, E. Martín, R. Rebolo

Manuscript notes. R.Rebolo





KECK ~~HIRES~~ LRIS SPECTROGRAPH OBSERVING LOG

Observer(s): Basri, Marcy, Rebolo, Martin
U.T. Date: 21 Nov 95
Tape Number:
Chip(s):
Binning: 1x1 → 2x2
Windowing: 0 - 2047 col; 700 - 1400 row
[redacted]
GRATING: 1200 g/mm angle
Decker:
Slit: 0.7" and 1.0"
Focus: 2620
Camera:
low gain

Tp #	Object	Time Start (U.T.)	Δ (s)	Comments
1	Ne-Ar	05:07	2	Slit = 0."7 FWHM = 3.5 OG570
2	Dark	05:10	1	"
3	Flat	05:12	4	" 3600 DN OG570
4	Flat	05:15	30	" OG570
5	Ne Ar	05:17	2	slit = 1."0 (test) FWHM = 4.1
6	Ne Ar	05:21	2	" no filter FWHM 3.7
7	Ne Ar	05:25	2	slit = 0."7 FWHM = 2.5
8	vB 10	05:27	300	seeing = 0."7 2000 DN/pxl RAW no filter; 300 DN/pxl at Li
9	PC0025	05:48	~~3600~~ 2400	Clear Skies 0.8" seeing
10	~~Flat~~	06:55	30	Saturated
11	Teide 1	07:07	3600	upper spectrum start = 7:07
12	"	08:08	3600	
13	Flat	09:20	5	slit changed to 1.0" no filter
14	"	09:22	5	
15	Teide 1	09:25	4800	Clear Skies
16	Ne Ar	10:51	2	
17	Flat	10:53	5	22,000 DN/pxl
18	Flat	10:55	3	BINNING ×2 in rows, no binning along dispersion; slit = 1" no filter
19	Flat	10:57	3	
20	Ne Ar	10:58	2	

Li expected 1753
Hα at 1980

Noche 19-20 Nov. 1995. Resumen

Despues de comenzar con una rendija de 0.7" y sin binning especial, comprobé que obteníamos muy poca S/N. aprox 40 cuentas por pixel en 1 h. de observación de Teide 1. Primero abrimos la rendija a 1", mejorando sólo ligeramente la situación, posiblemente las primeras dos observaciones de Teide 1 perdieron un 20% de fotones por problemas de seeing o guiado. Conseguí convencer a Gibor y Geoff de realizar binning aun a costa de tener que invertir tiempo en nuevos flats. Con el binning en la dirección espacial mejoramos bastante, en 80 min. obtenemos 100 cuentas por pixel en el espectro final pero con una calidad muy superior. Las 3 últimas exposiciones confirmaron la presencia de Li 6708 en Teide 1 con una intensidad notablemente superior a la publicada en PPl 15.

R.R.
28.11.95.

La detección implica reconsiderar el programa de la 2ª noche.

Dado que Teide 1 puede (parece) haber destruido buena parte de su Li inicial podemos pretender una precisa medida de su masa a partir de las curvas de destrucción.

Mi impresión es que va a resultar alrededor de 0.07 M☉ pero podría estar entre 0.075 y 0.065 dependiendo de la edad de Teide 1 (No estoy seguro de que podamos hablar de una edad para las Pléyades).

Es fundamental estar seguros de que interpretamos correctamente la abundancia de Litio porque así acotaremos la masa.

Debemos detectar la 8126 Å y así lo propuse en el telescopio inmediatamente después de concluir la positiva detección de litio.

En la región de 8126 Å esperamos 10 veces más cuentas que en 6708 Å. Pero la línea será de unos 100 mÅ y probablemente esté terriblemente afectada por telúricas. ¿Podemos trabajar con LRIS + 1200 ℓ/mm?)

En 80 min espero 1500 cuentas/pix (espectro final a 8126 Å) resol.

$$\Delta W = \frac{\sqrt{2n}\,\Delta\lambda}{S/N} = \frac{3 \cdot 2.0}{40} = \frac{6.0\ \text{Å}}{40} = 150\ \text{mÅ}.\ 1\sigma.$$

4 espectros serían suficiente t = 5 horas

KECK HIRES SPECTROGRAPH OBSERVING LOG

Observer(s): Basri, Marcy, Rebolo, Martin
U.T. Date: 21 Nov 95
Tape Number:

Chip(s):
Binning: 2x2
Windowing: col 0-2047, row 350 to 700
~~Ech-Ang:~~
~~XD-Ang:~~
Grating

Decker:
Slit: 1.0"
Focus: 2620
Camera:

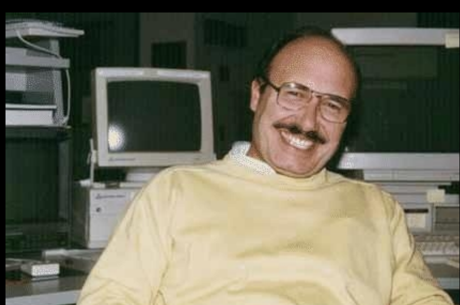
Tp #	Object	Time Start (U.T.)	Time Δ (s)	Comments
21	Teide 1	11:04	4800	Binning 1x2, slit=1" no filters; seeing ~0.8"
22	Teide 1	12:35	4800	Clear Sky
23	UX Tau C	13:58	200	guided carefully on C; excluded A
24	HHJ339	14:04	600	
25	G191B2B	14:19	20	
26	G191B2B	14:20	90	
27	V410 X3	14:26	300	strom² paper
28	V410 X6	14:36	300	
29	LHS 2065	14:53	120	
30	"	14:57	300	
31	NeAr	15:04	2	
32	Flat	15:06	3	no filters
33	Flat	15:07	3	
34	Praesepe	15:27	300	2048x2048 IMAGING MODE; R filter
35	"	15:28	300	moved the field a bit; I filter; ← 36 Praesepe I field
37	LHS 2065 field	15:44	3	I filter
38	"	15:47	3	R filter
38	Dome flat		3	R filter
40	Dome flat	16:12	6	R filter.
41	Dome I flat	16:14	6	I filter
42	"	16:17	6	I filter

Noche 19-20 Nov. 1995. Resumen

Después de comenzar con una rendija de 0.7" y sin binning especial, comprobé que obteníamos muy poca S/N. aprox 40 cuentas por pixel en 1 h. de observación de Teide 1. Primero abrimos la rendija a 1", mejorando sólo ligeramente la situación, posiblemente las primeras dos observaciones de Teide 1 perdieron un 20% de fotones por problemas de seeing o guiado. Conseguí convencer a Gibor y Geoff de realizar binning aun a costa de tener que invertir tiempo en nuevos flats. Con el binning en la dirección espacial mejoramos bastante, en 80 min. obtenemos 100 cuentas por pixel en el espectro final pero con una calidad muy superior. Las 3 últimas exposiciones confirmaron la presencia de Li 6708 en Teide 1 con una intensidad notablemente superior a la publicada en PPl 15.

R.R.
20.11.95

Conclusion of the Keck telescope campaign: Teide 1 has not destroyed lithium and therefore cannot fuse hydrogen.



RR at Keck Nov. 1995

THE ASTROPHYSICAL JOURNAL, 469:L53–L56, 1996 September 20

BROWN DWARFS IN THE PLEIADES CLUSTER CONFIRMED BY THE LITHIUM TEST[1]

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AND
M. R. ZAPATERO-OSORIO
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Received 1996 June 14; accepted 1996 July 11

ABSTRACT

We present Keck Observatory 10 m telescope spectra of the two Pleiades brown dwarfs, Teide 1 and Calar 3, showing a clear detection of the Li 670.8 nm resonance line. In Teide 1, we have also obtained evidence for the presence of the subordinate line at 812.6 nm. A high Li abundance [log N(Li) $\geq$ 2.5], consistent with little if any depletion, is inferred from the observed lines. Since Pleiades brown dwarfs are unable to burn Li, the significant preservation of this fragile element confirms the substellar nature of our two objects. Regardless of their age, their low luminosities and Li content place Teide 1 and Calar 3 comfortably in the genuine brown dwarf realm. Given the probable age of the Pleiades cluster, their masses are estimated at 55 $\pm$ 15 M_J.

Subject headings: open clusters and associations: individual (Pleiades) — stars: abundances — stars: low-mass, brown dwarfs — stars: evolution — Stars: fundamental parameters

1. INTRODUCTION

In stellar interiors, ^{7}Li nuclei are destroyed via proton collisions at relatively low temperatures ($\sim 2 \times 10^6$ K). This element has long been used as a tracer (see, e.g., Rebolo 1991; Michaud & Charbonneau 1991) of internal structure in stars of different types. The strong convection of very low mass stars ($M \leq 0.3\ M_\odot$) causes an extremely efficient mixing of Li, and, indeed, significant depletion has been observed in these stars, even in the very young ones (Zapatero-Osorio et al. 1996c; García López, Rebolo, & Martín 1994; Martín, Rebolo, & Magazzù 1994). Objects with masses $M \leq 0.065\ M_\odot$ ($\sim 65\ M_J$) are well below the minimum mass for hydrogen burning and cannot reach the Li burning temperature; thus, unlike very low mass stars, they must preserve a significant amount of their initial Li content during their lifetime. This can be detected spectroscopically and therefore can provide a diagnostic of substellar nature for brown dwarf candidates (Rebolo, Martín, & Magazzù 1992; Magazzù, Martín, & Rebolo 1993).

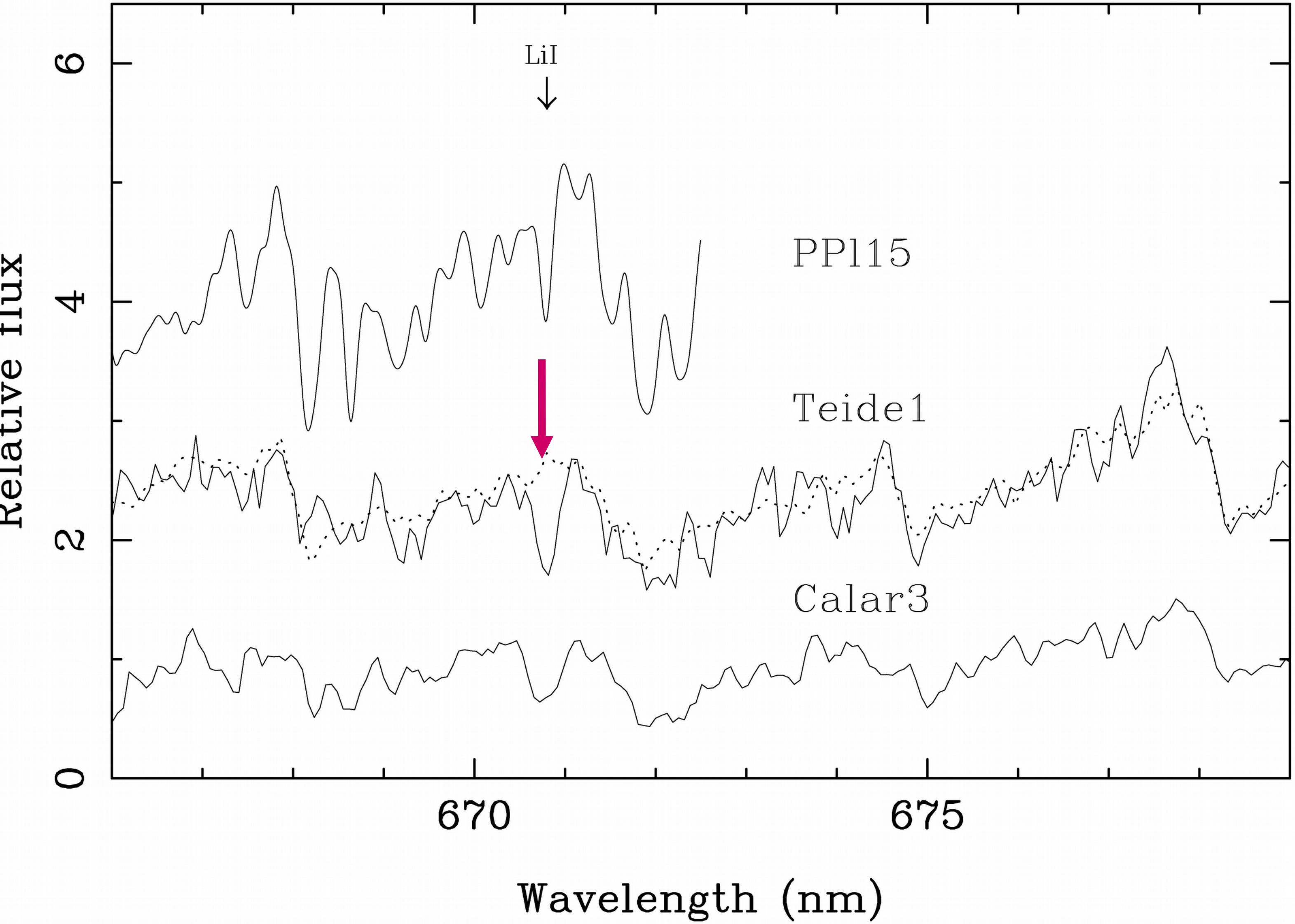
At the age of the Pleiades cluster even the most massive brown dwarfs (80–60 M_J) should have preserved a large amount of their initial Li, but searches (Martín et al. 1994; Marcy, Basri, & Graham 1994) of the faintest proper motion members failed to detect it. An obvious conclusion was that brown dwarfs had not yet been discovered in the cluster. This prompted the search for new fainter and cooler candidates that led to the discovery of Teide 1 and Calar 3 (Rebolo, Zapatero-Osorio, & Martín 1995; Zapatero-Osorio, Rebolo, & Martín 1996b). These are two very late-type dwarfs near the center of the cluster with radial velocities, photometric and spectroscopic properties, and a proper motion measurement (in the case of Teide 1) consistent with Pleiades membership (Rebolo et al. 1995; Zapatero-Osorio et al. 1996b; Martín, Rebolo, & Zapatero-Osorio 1996). Their luminosities and effective temperatures qualify them, according to all the available evolutionary models, as brown dwarfs. However, a definitive confirmation of their substellar nature can only be obtained via the Li test. Such confirmation is a key step to consolidate our understanding of brown dwarf interiors. Very recently, Li has been discovered (Basri, Marcy, & Graham 1996) in PPl 15, a photometric member (Stauffer, Hamilton, & Probst 1994) of the Pleiades ~1 mag brighter than Teide 1 and Calar 3, which strongly encouraged us to extend the search for Li in these new objects. PPl 15 appears to define the Li reappearance boundary in the Pleiades, and it sits on the frontier between stars and brown dwarfs.

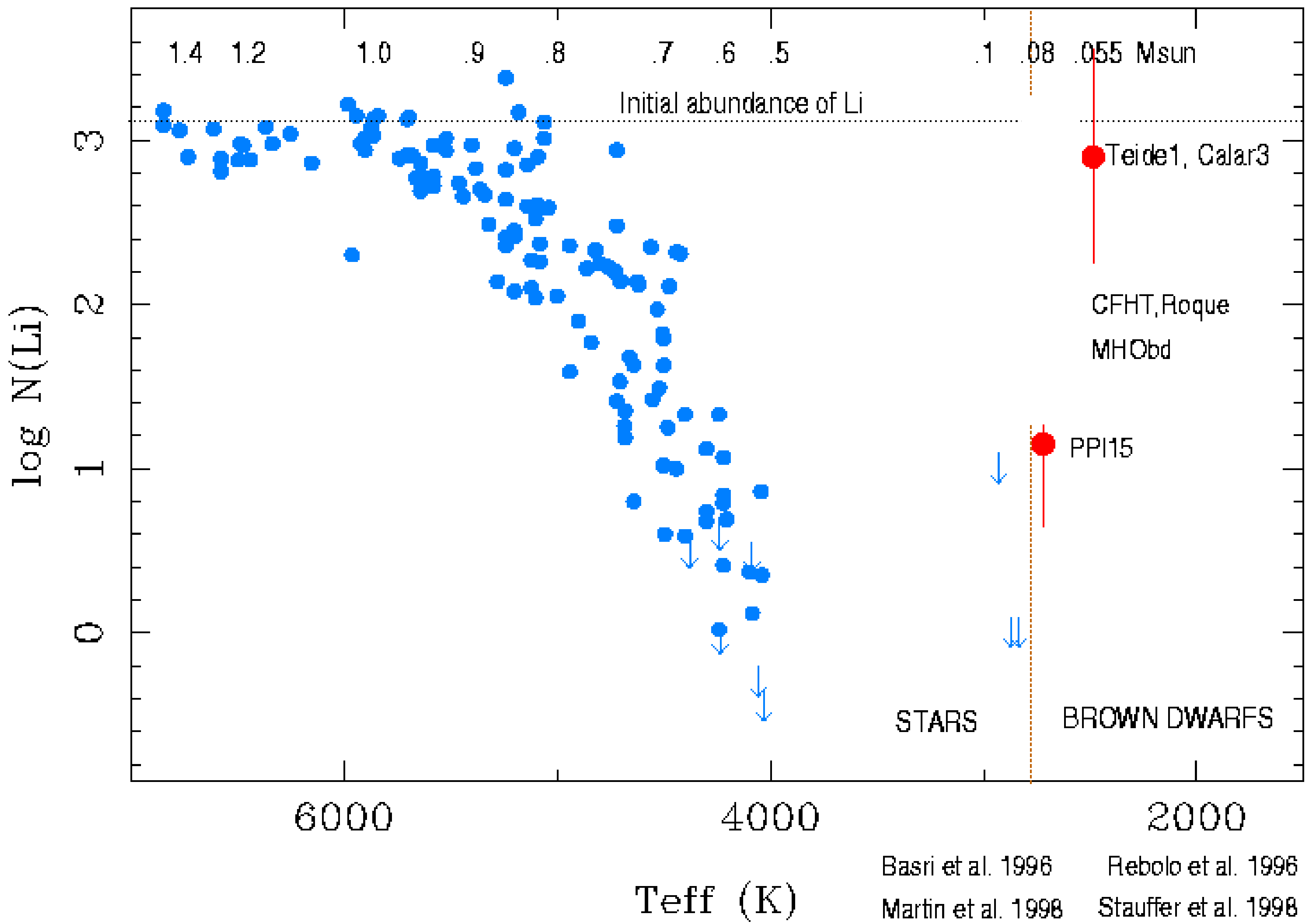
2. OBSERVATIONS AND RESULTS

We report spectroscopic observations of Teide 1 and Calar 3 that provide clear evidence for the presence of Li in both. The observations were carried out at the Keck Observatory 10 m telescope (Mauna Kea, Hawaii) on 1995 November 19 and 20 and 1996 February 16 using the low-resolution imaging spectrograph (LRIS). The 1200 g mm^{-1} grating provided a dispersion of 0.64 Å pixel^{-1} on the TEK (2048 × 2048 pixels) detector in the region of the λ670.8 nm Li I resonance doublet and 0.6 Å pixel^{-1} in the region of the subordinate Li I 812.6 nm line. The 1″ slit width finally gave an effective resolution of ~2 Å. The total integration time for Teide 1 in the spectral regions of the Li I lines 670.8 and 812.6 nm was 8.2 and 4 hr, respectively (individual exposures ranged

Lithium detection in Teide 1 and Calar 3

Teide 1 and Cala3: Rebolo et al. 1996 ApJ Lett. 469, L53
PPl15: Basri, Marcy and Graham 1996 ApJ Lett 458, L87

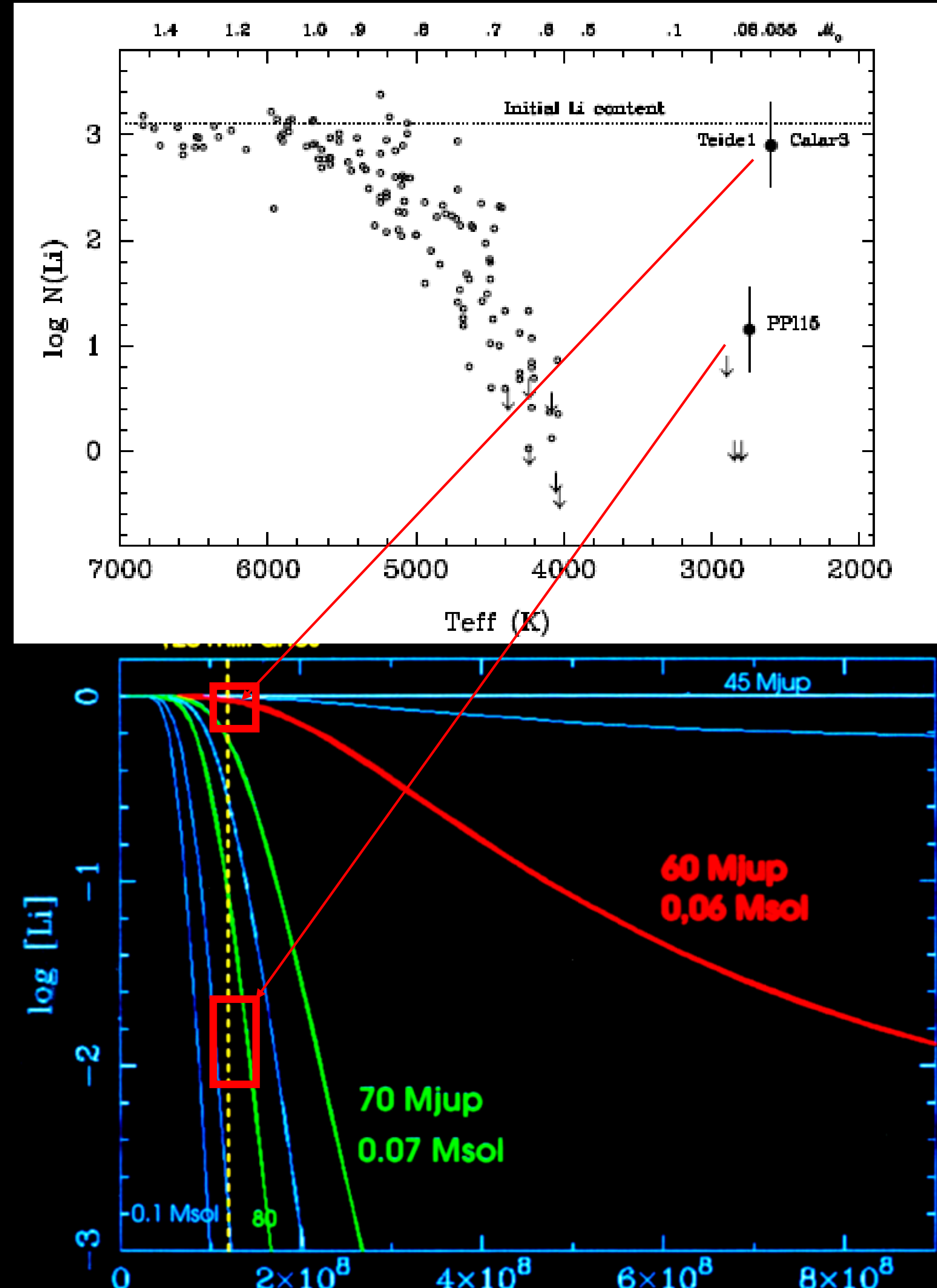




1.4
1.2
1.0
.9
.8
.7
.6
.5
.1
.08
.055 Msun
Initial abundance of Li
Teide1, Calar3
CFHT,Roque
MHObd
PPl15
STARS
BROWN DWARFS
log N(Li)
0
1
2
3
6000
4000
2000
Teff (K)
Basri et al. 1996
Martin et al. 1998
Rebolo et al. 1996
Stauffer et al. 1998

PPl 15 lies at the boundary between stars and brown dwarfs.

Teide 1 and Calar 3 are brown dwarfs.



Basri and Martin (1999) will show later that PPl15 is a binary (total mass 125-145 M_Jup)

November 30 and December 1, 1995:

The direct detection of a cool brown dwarf companion to the M-dwarf star Gl 229 is published

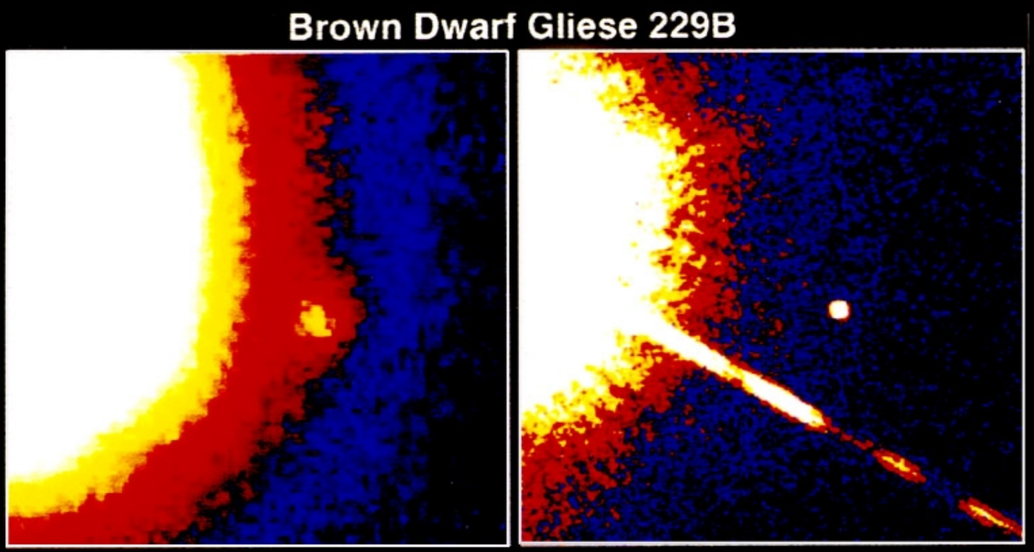
"Discovery of a cool brown dwarf"
Nakajima, Oppenheimer Kulkarni et al. 1995
(Nature 378, 463)

Gl 229B is a very faint companion of a very nearby star to the Sun,
Reference for a new spectral type T

Mass 30–50 Mjup

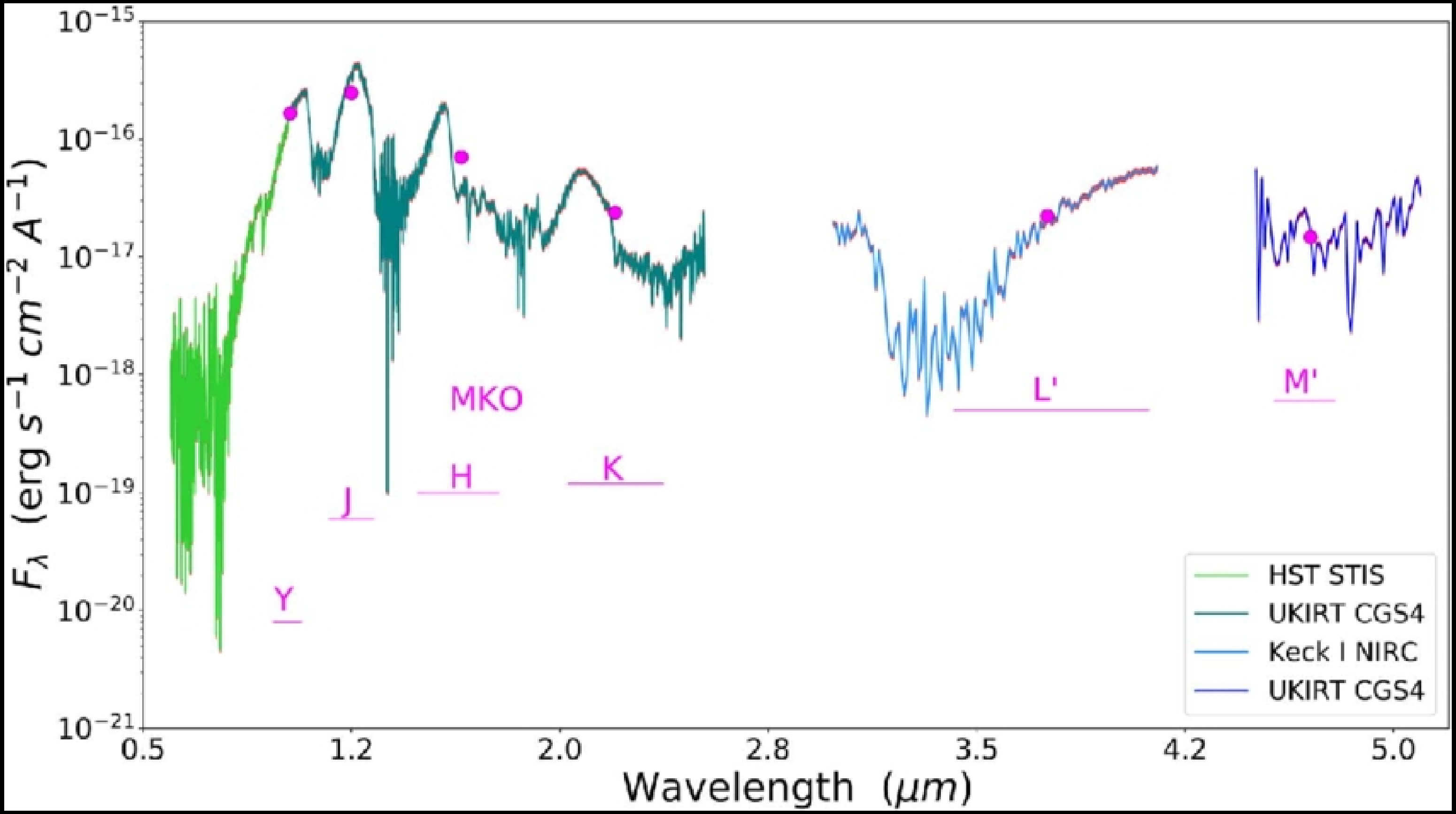
Submitted on September 25, 1995
Published on November 30, 1995

See also Oppenheimer et al. Science, December 1, 1995*
(spectroscopy paper)



SED of Gl 229 B, distance calibrated

Calamari et al. 2022, ApJ

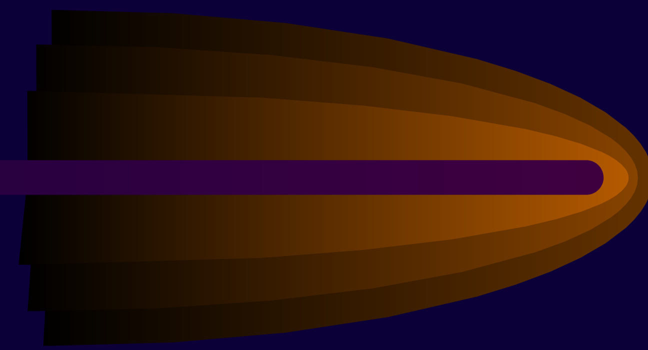


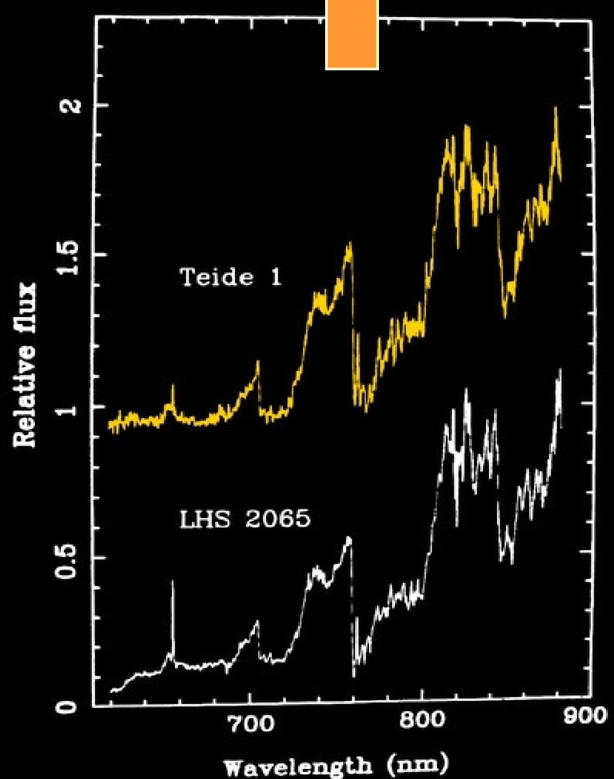
Note that recently it was shown with Gravity VLT that Gl 229B is a close binary Brown dwarf.

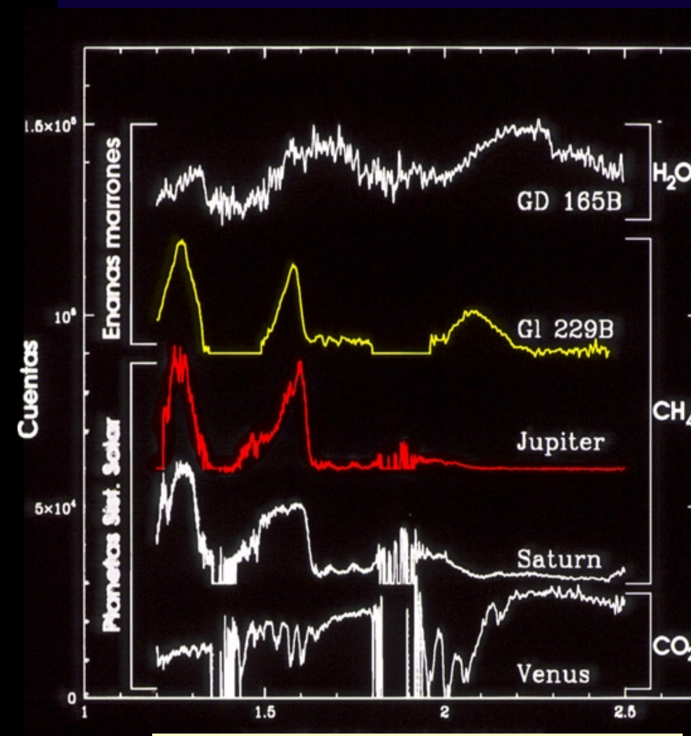
Xuan et al (2024, Nature)

Old Brown dwarf

Young Brown dwarf



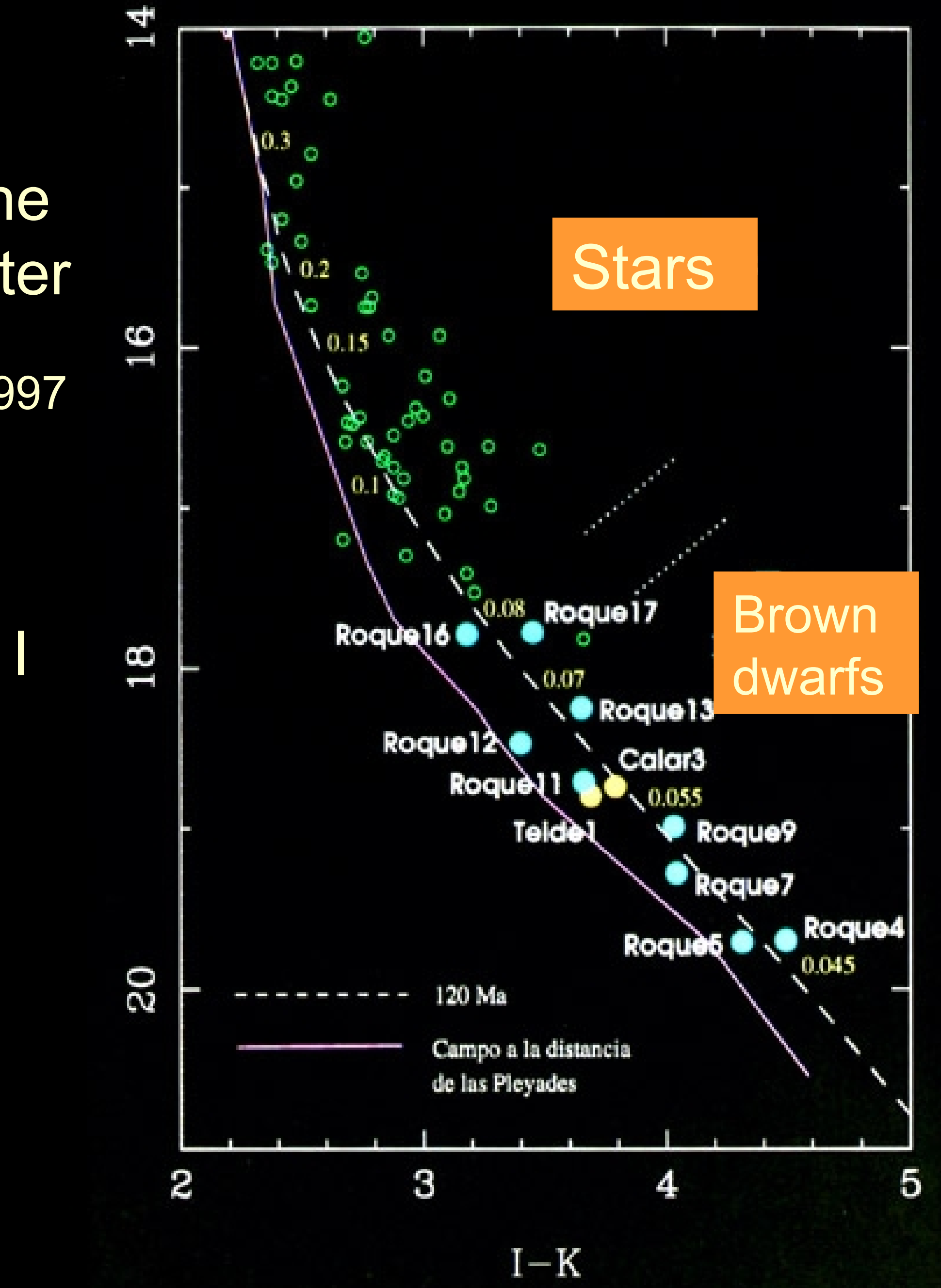




Year 1997

Colour-magnitude diagram for the Pleiades cluster

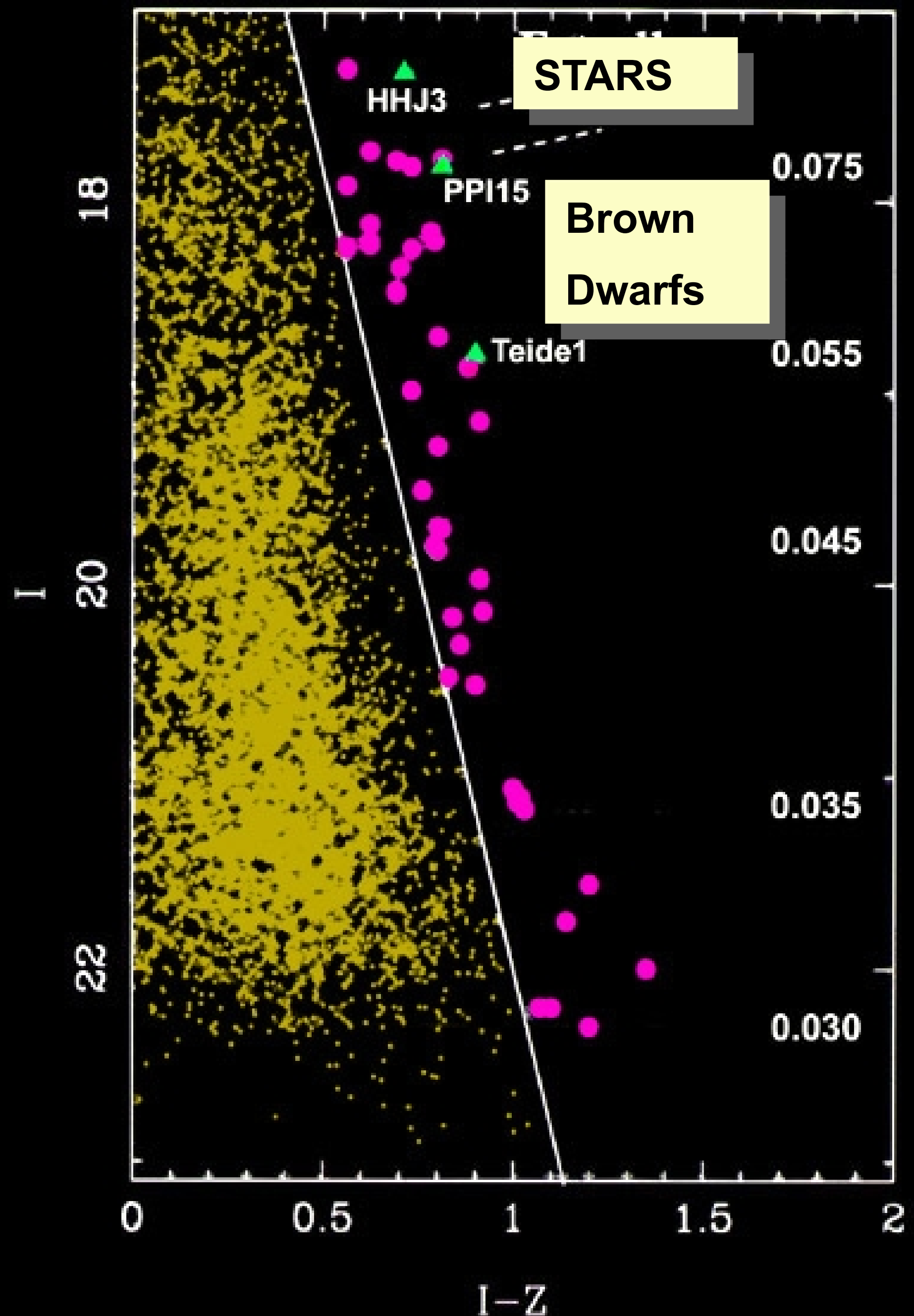
Zapatero-Osorio, Martín, Rebolo 1997 (A&A)



Pleiades

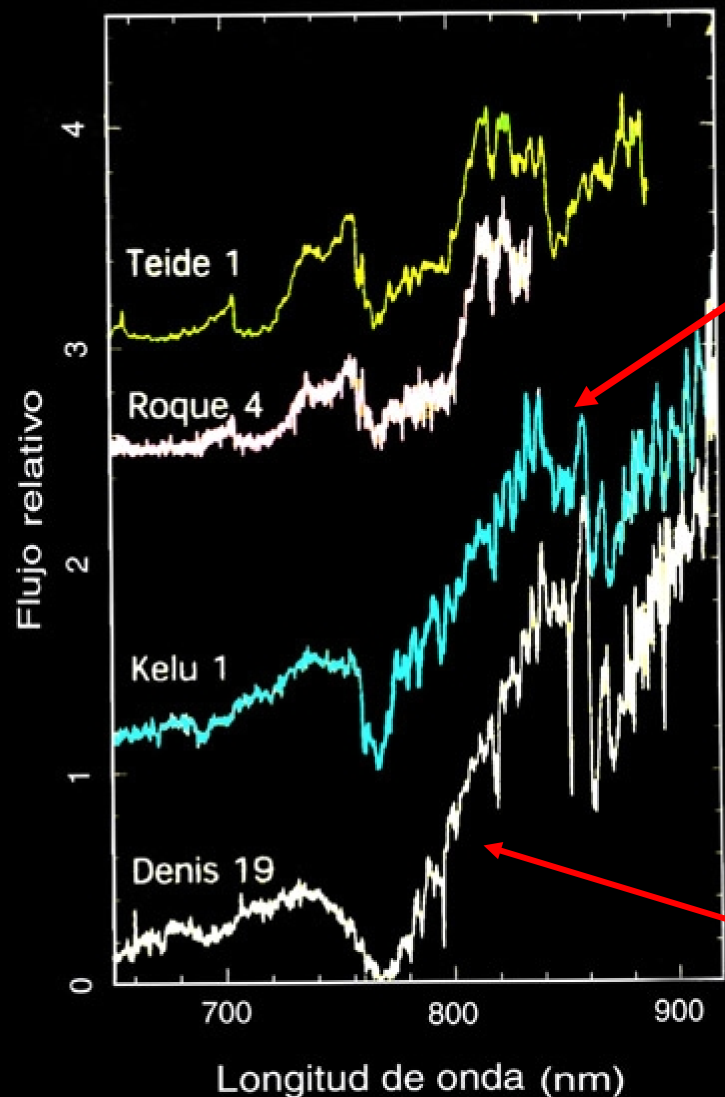
1 square degree IZ Survey

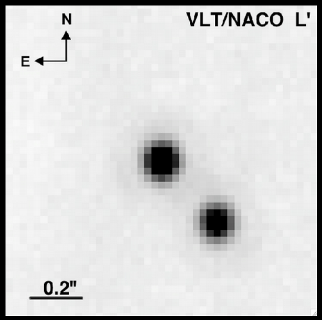
Zapatero-Osorio et al. 1997 ApJ



1997:
First free-floating Brown dwarfs detected in the solar neighbourhood

New spectral type "L"
Martín et al. 1997





Ruiz et al. 1997 ApJ Lett

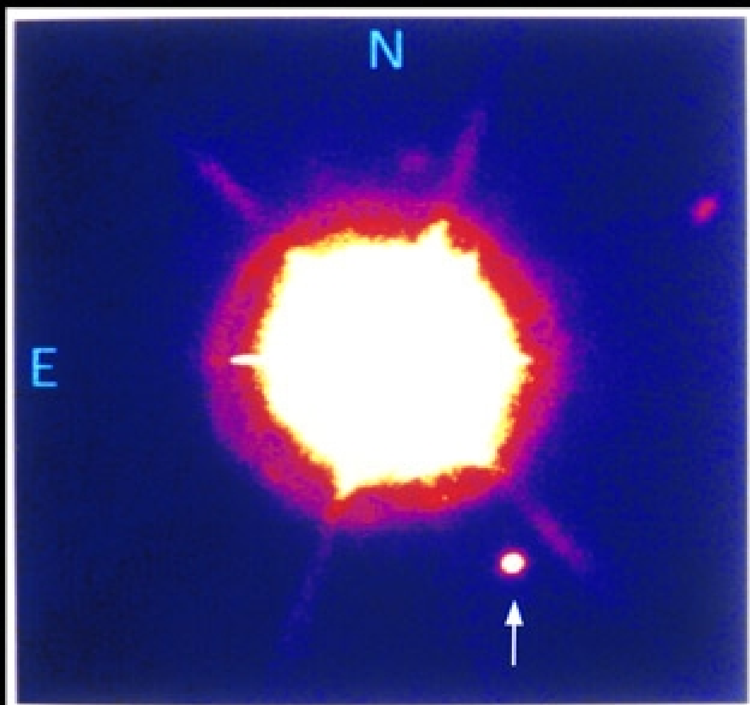
Delfosse et al 1997 A&A

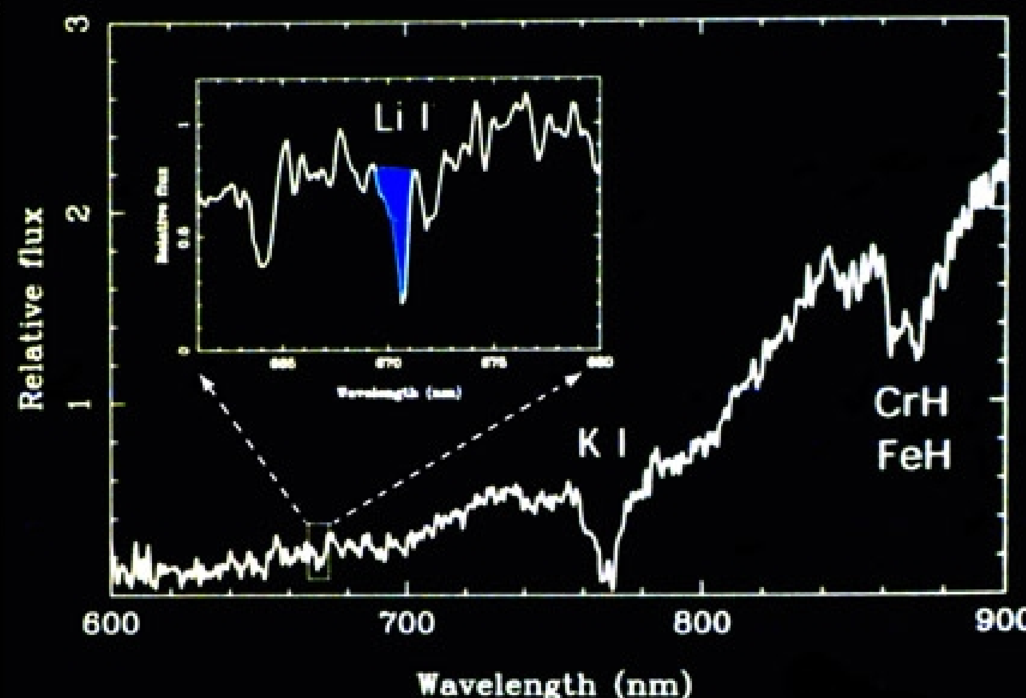
2MASS J0345+25 (>M10)
Kirkpatrick et al. 1997 ApJ

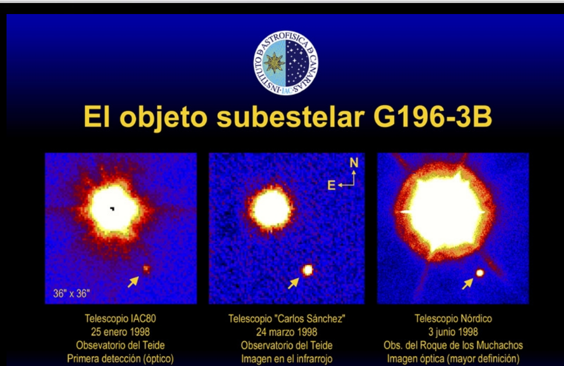
Year 1998

Imaging substellar objects around stars

- G 196-3B: ~ 20 M_{jup} companion to a nearby M-dwarf orbiting at a projected separation of ~350 AU



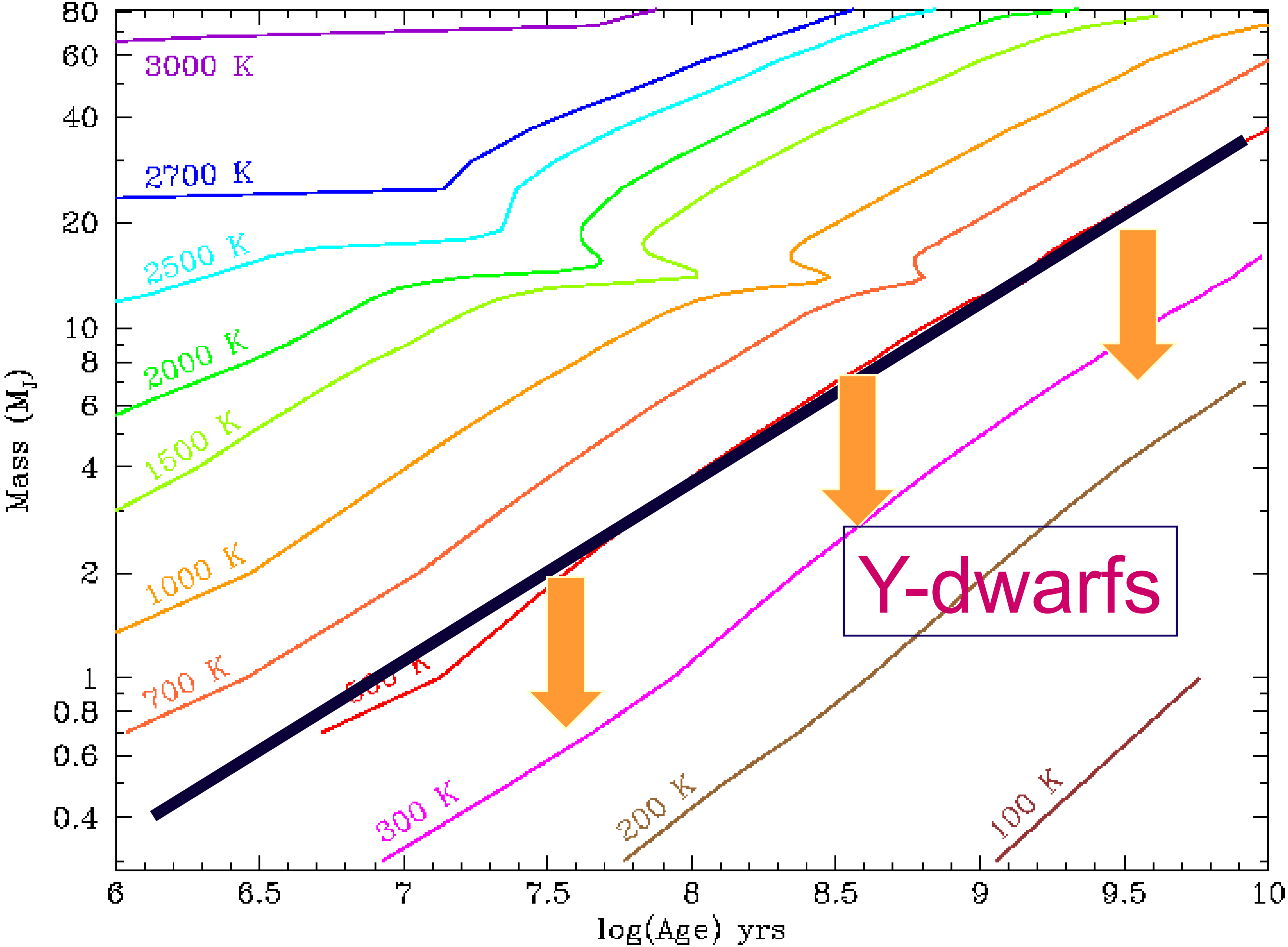




Rebolo et al. 1998 (Science 282, 1309)

30 years of Brown dwarf surveys at Large Scales, in Star clusters/star-forming regions and searches for Close and Wide companions of stars

Discovery of thousands of Brown dwarfs of L, T and Y spectral type.



Y-dwarfs
3000 K
2700 K
2500 K
2000 K
1500 K
1000 K
700 K
300 K
200 K
100 K
Mass (M$_J$)
log(Age) yrs
80
60
40
20
10
8
6
4
2
1
0.8
0.6
0.4
6
6.5
7
7.5
8
8.5
9
9.5
10

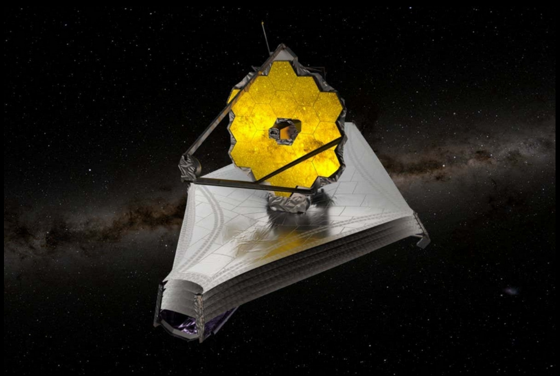
Conclusions

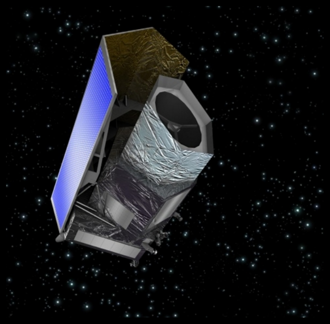
*In the 1990s, major advances were made in our understanding of substellar objects:

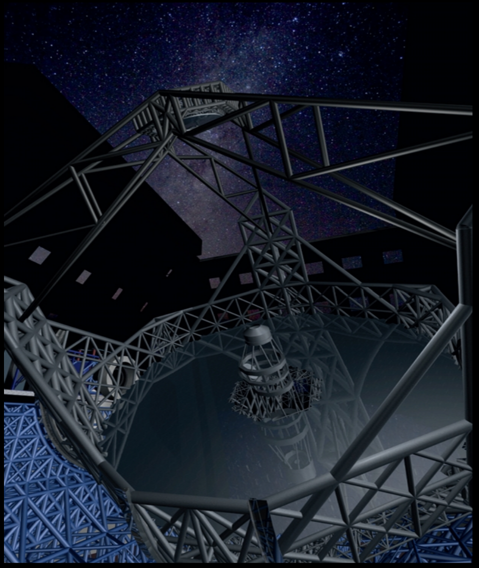
the discovery of brown dwarfs in 1995
the identification of objects of new spectral types (L and T)
the first measurement of the substellar mass function
the discovery of young free-floating super-Jupiters

More recently, the exploration of new frontiers led to the discovery of ultracool Y-type brown dwarfs, halo brown dwarfs and super-Jupiters populating the solar neighborhood.

With very low luminosities and temperatures below 300 K, characterizing the atmospheres of the less luminous Brown dwarfs poses a major challenge even for JWST and the future giant ground-based telescopes, but also offers the opportunity for new and extraordinary discoveries, some of them will surely be addressed in this workshop*



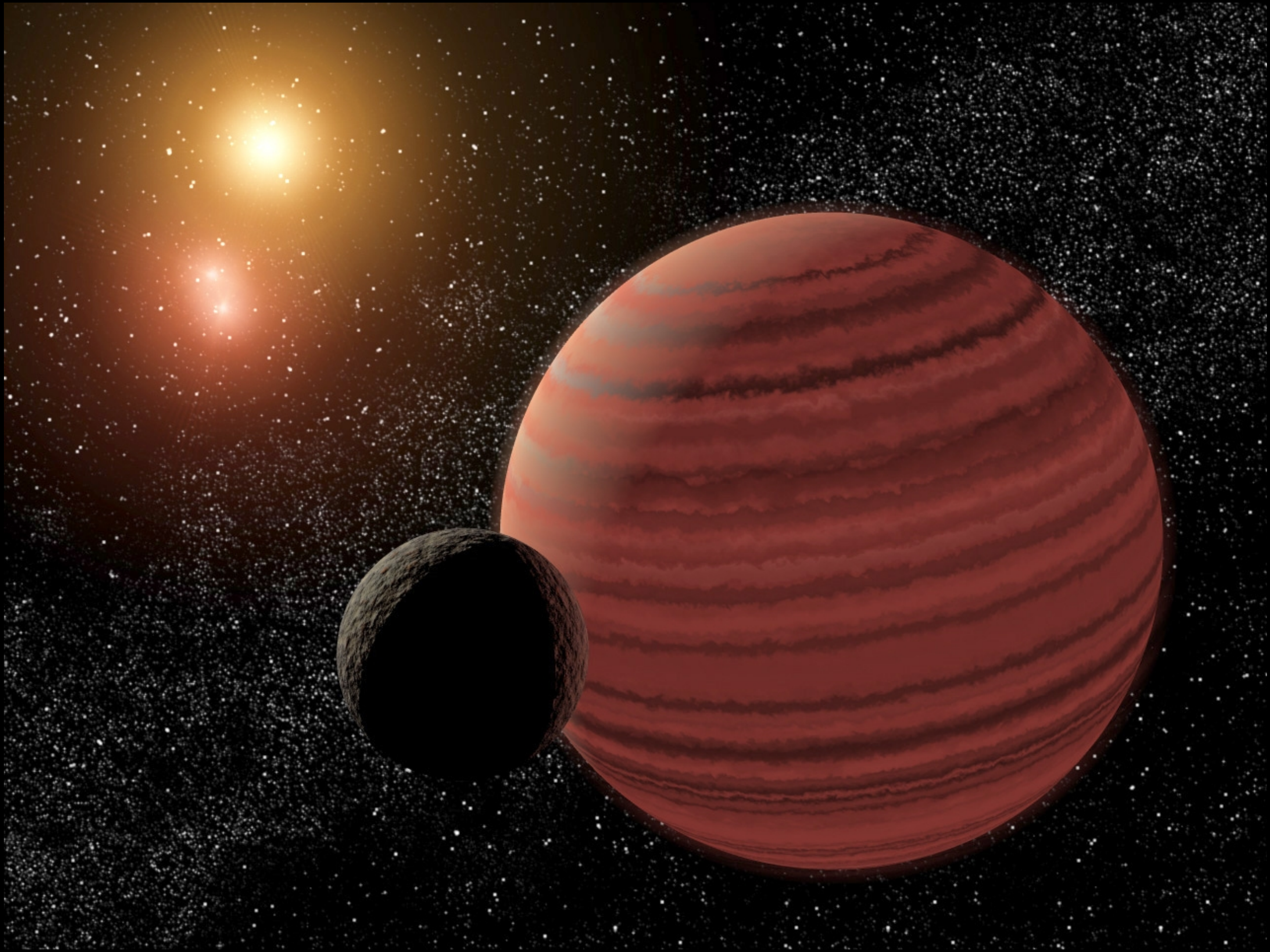




The determination of the IMF indicates tens of billions of Brown dwarfs and free-floating planets exist in our Galaxy ...

so, a lot of interesting research is granted for at least another 30 years !

Thanks for your attention



Additional slides

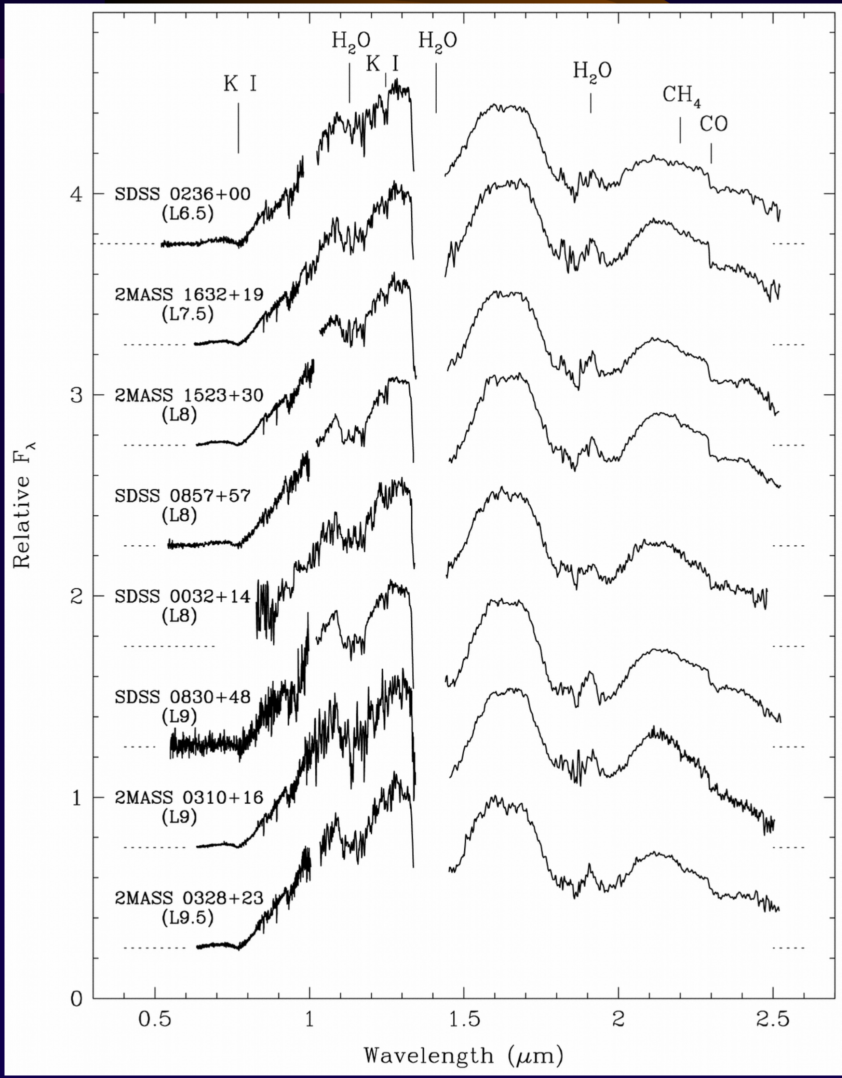
Enanas de tipo L

The L dwarf sequence is characterized by:

- the disappearance of the red TiO and VO bands from the optical spectrum
- The increasing dominance of broad absorption resonance lines of Na I and K I, and strong H_2O absorption bands and persistent CO overtone bands at 1-2.5 μm
- J-K>1.3
  Martín et al. 1999, Kirkpatrick et al. 1999, 2000
  Legget et al. 2000, Nakajima et al. 2004
- Effective temperatures:

Teff =(2380 ± 40) – (138 ± 8) SpT

where SpT is L0-L8 Burgasser 2001

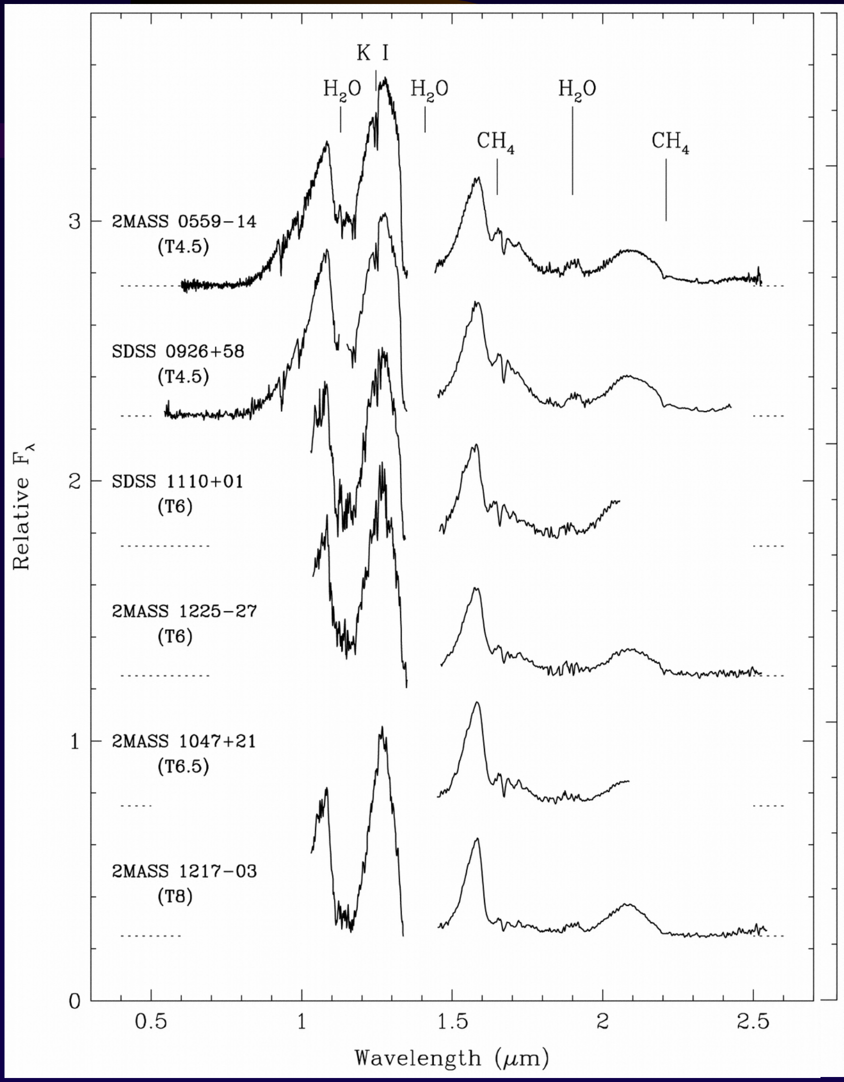


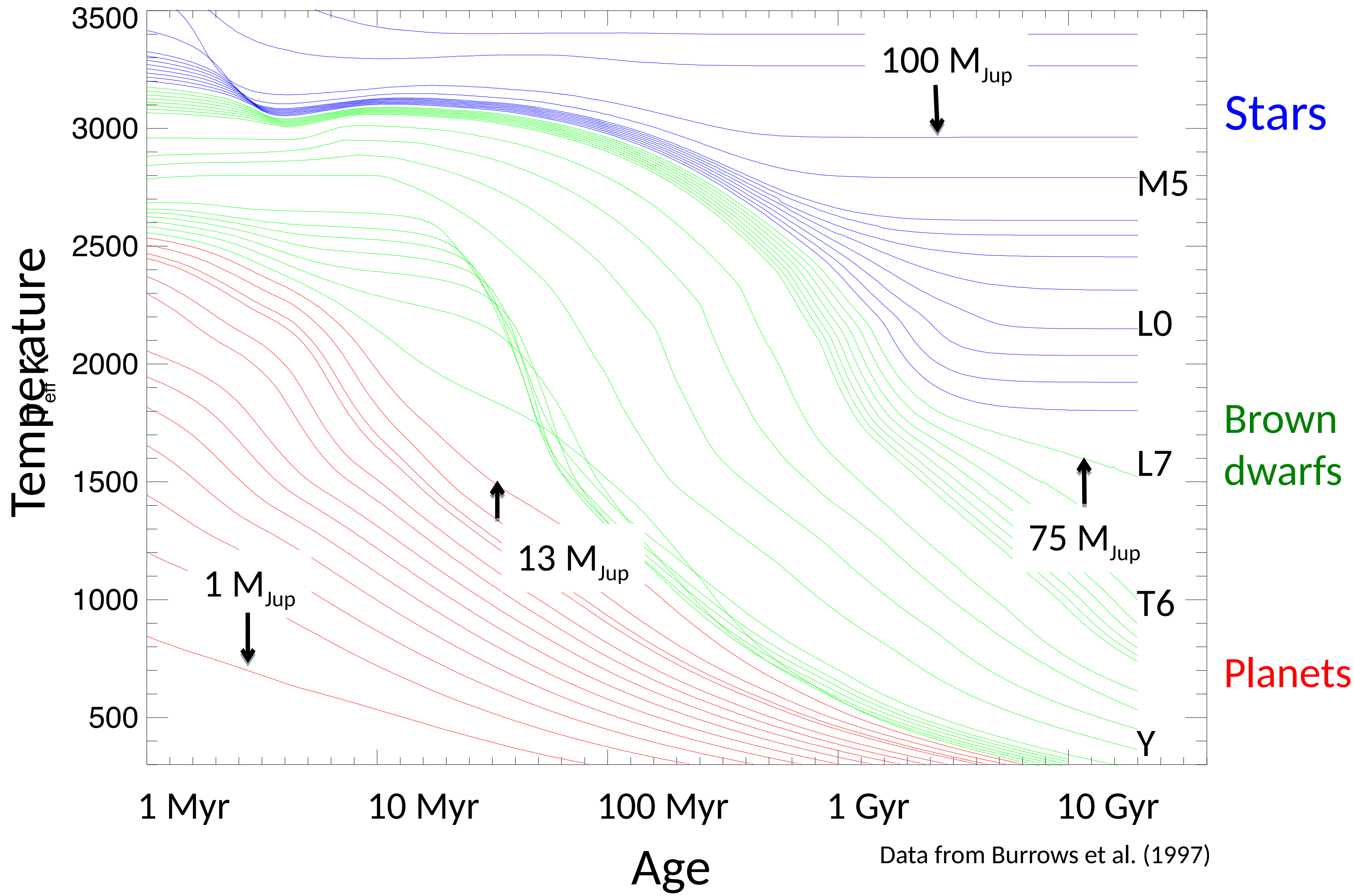
Enanas de tipo T

- The T dwarf sequence is characterized by:
  - the CO bands are replaced by stronger and more extensive absorptions of CH_4 in the H and K bands.
  - Further strengthening of water bands.
  - Blue infrared colours J-K~0

Kirkpatrick et al. 1999, Oppenheimer et al. 1995, Nakajima et al. 2004

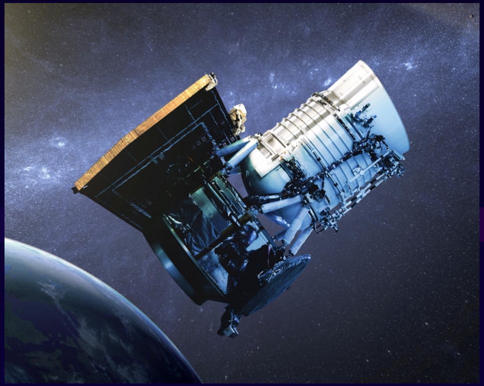
- Spectral classification of T dwarfs
  Geballe et al. 2002, Burgasser et al. 2002
- A relation between effective temperature and Sp Type derived from the K-band bolometric correction shows monotonic behavior throughout the L-T sequence (Nakajima et al. 2004).





Data from Burrows et al. (1997)

¿Qué sabemos de las enanas marrones de tipo Y ?



- El satélite WISE encontró varias en todo el cielo W2=14-14.5, W3 ~ 12

  (Cushing et al. 2011, Kirkpatrick et al. 2012)

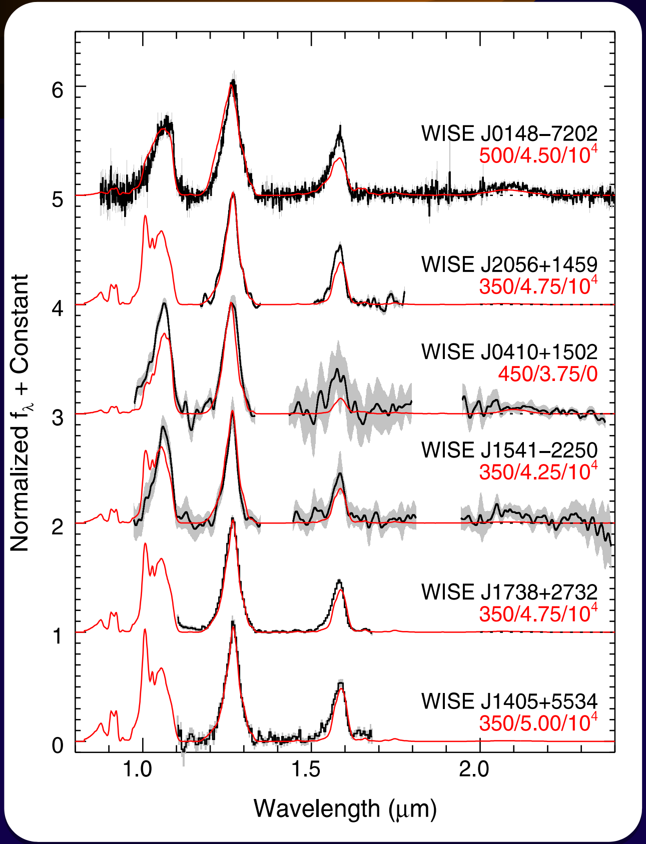
- Generalmente tienen J-W2 >5,
  - una de las más extremas (WISE 1828+2650) J-W2>9

- WISE mide colores para las Y:
  - W1-W2 >3.9
  - W2-W3=1.7-2.6

El color más extremo : J-W3 >11 M_J>20

WISE tiene como límite de detección W3=11.2-11.9

W2=15.0-15.7



Leggett+ 2017 arXiv:1704.03573v

The Astrophysical Journal Letters, 786:L18 (6pp), 2014 May 10 doi:10.1088/2041-8205/786/

DISCOVERY OF A ~250 K BROWN DWARF AT 2 pc FROM THE SUN*

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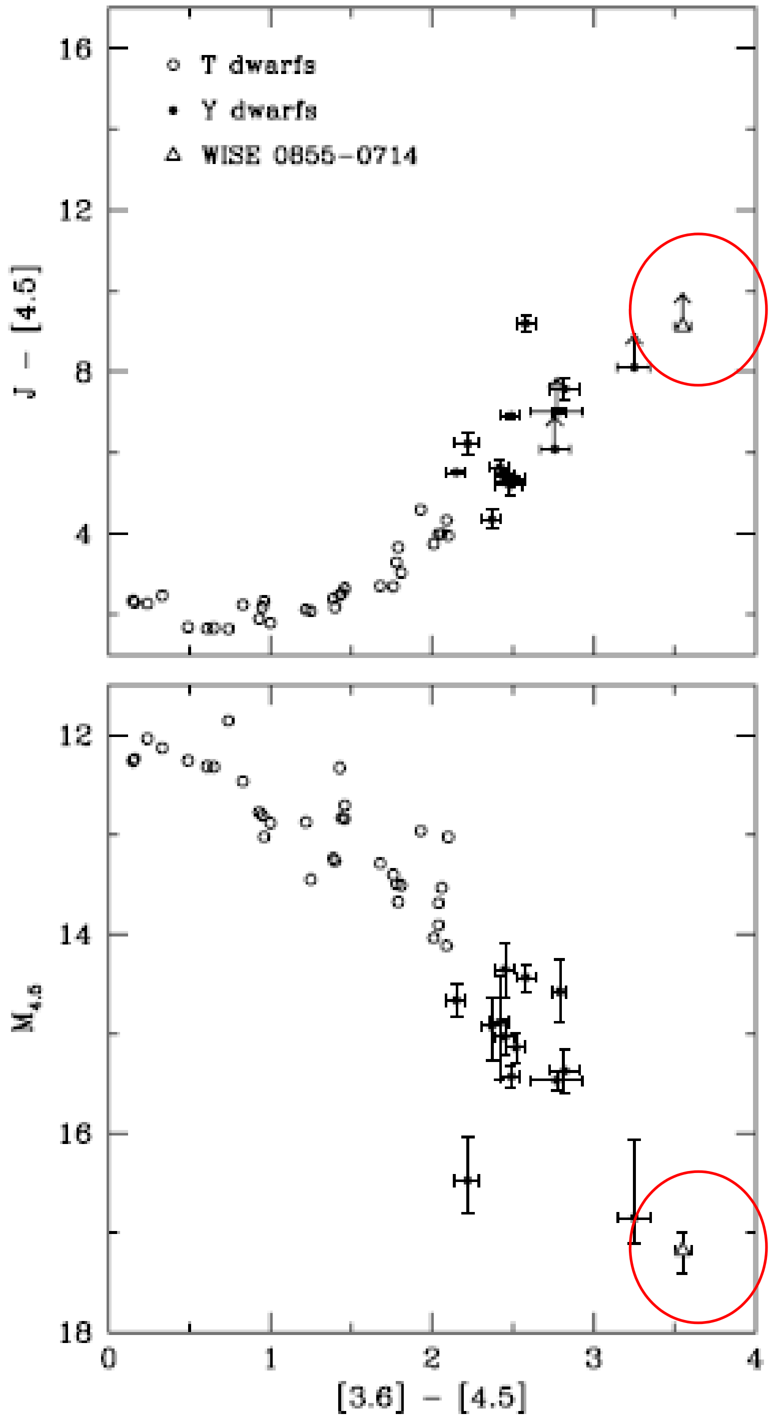
ABSTRACT

Through a previous analysis of multi-epoch astrometry from the *Wide-field Infrared Survey Explorer (WISE)*, I identified WISE J085510.83−071442.5 as a new high proper motion object. By combining astrometry from *WISE* and the *Spitzer Space Telescope*, I have measured a proper motion of $8.1\pm0.1''$ yr^{-1} and a parallax of $0.454\pm0.045''$ ($2.20^{+0.24}_{-0.20}$ pc) for WISE J085510.83−071442.5, giving it the third highest proper motion and the fourth largest parallax of any known star or brown dwarf. It is also the coldest known brown dwarf based on its absolute magnitude at 4.5 μm and its color in [3.6]–[4.5]. By comparing $M_{4.5}$ with the values predicted by theoretical evolutionary models, I estimate an effective temperature of 225–260 K and a mass of 3–10 M_{Jup} for the age range of 1–10 Gyr that encompasses most nearby stars.

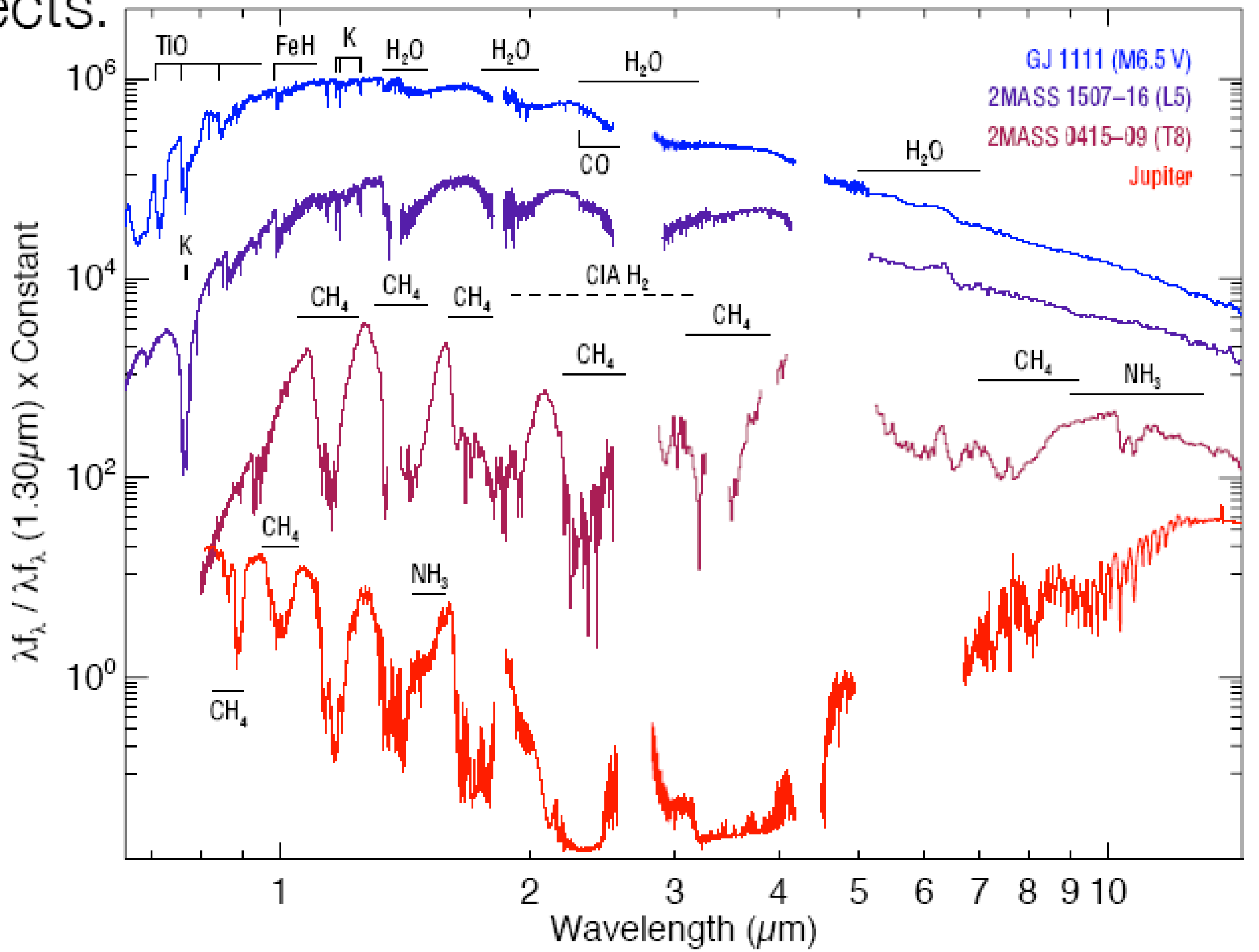
Key words: brown dwarfs – infrared: stars – proper motions – solar neighborhood – stars: low-mass

- super-Jupiter de temperatura atmósferica 250 K
- W2=13.89 (Spitzer and WISE)
- W1=17.44 (only Spitzer)
- J>23

Luhman 2014



objects.



¿Es Jupiter una enana Y?

¿Cómo se forman las enanas marrones?

- ¿Son embriones eyectados?

  Reipurth and Clarke 2001, Bate et al. 2002, Delgado-Donate et al. 2003

- ¿Se forman como las estrellas ordinarias, a partir de la fragmentación de partes de una nube molecular que colapsa ?

  Bodenheimer 1999, Shu et al. 1987

¿ Se forman como los planetas, por ejemplo mediante inestabilidades gravitatorias en los discos circumestelares?

Papaloizou and Terquem 2001

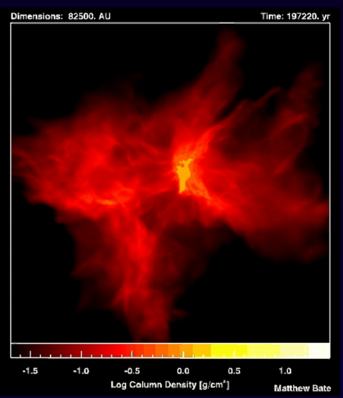
?

¿Tienen las enanas marrones discos protoplanetarios?
¿Pueden las estrellas de cualquier masa tener compañeros subestelares?

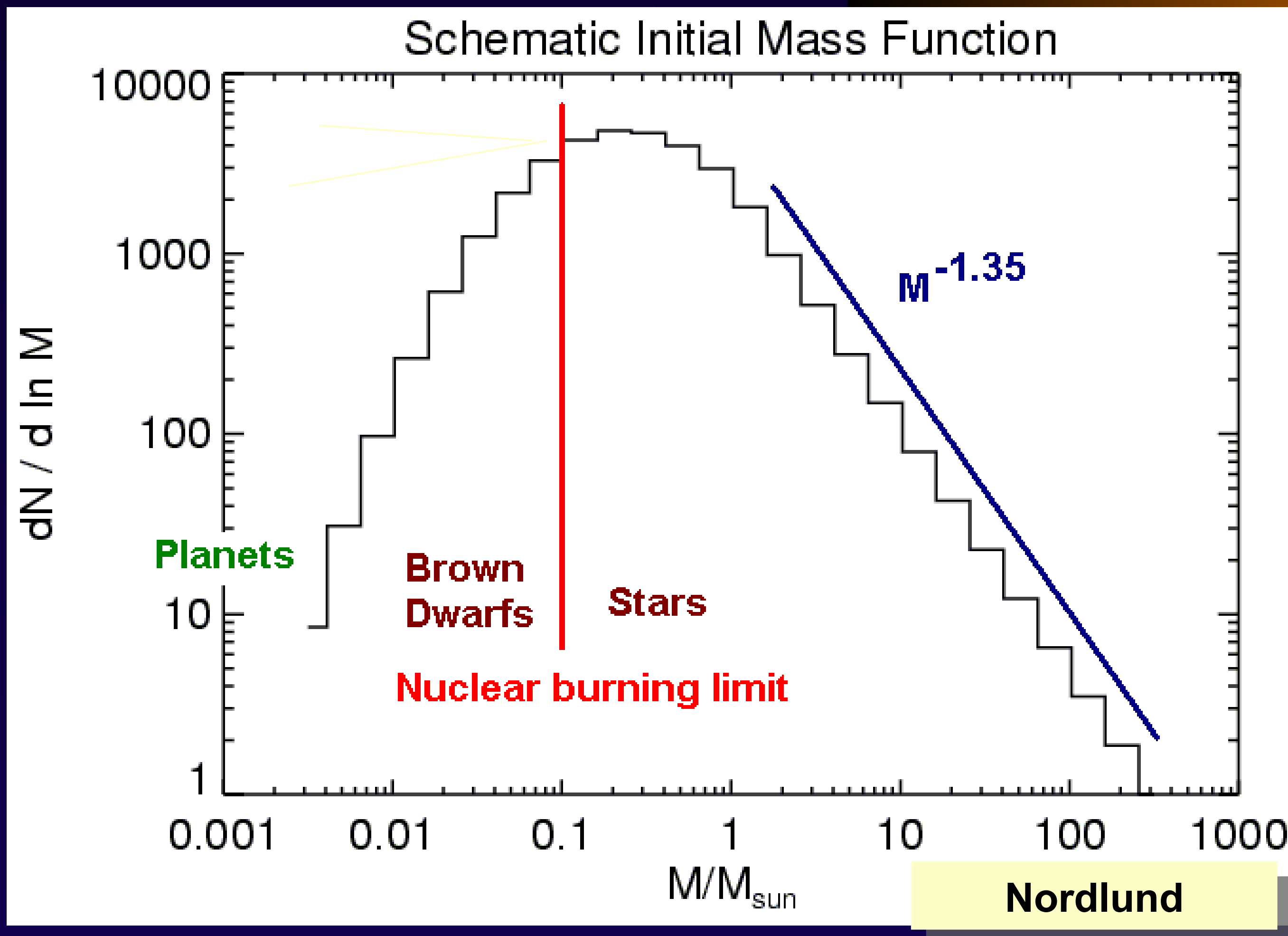
Observables:

Función Inicial de Masas
Distribución espacial
Binariedad/Multiplicidad? Discos?

¿Cuántas enanas marrones hay en la Galaxia?



- Los modelos de fragmentación de nubes moleculares predicen funciones iniciales de masa como las de la figura



Supersonic turbulence

Exploremos las regiones de formación estelar y comparemos el número de estrellas y enanas marrones

- R I Z J (K): 850 $arcmin^2$ (línea blanca)
- Completitud: I=21.5 J=19.5
  - Béjar, Zapatero-Osorio, Rebolo 1999 ApJ
- I Z (J K): 1.12 deg^2 (línea amarilla)
- Completitud I=23 J=21
- Zapatero-Osorio et al. 2000 Science

Sigma Orionis

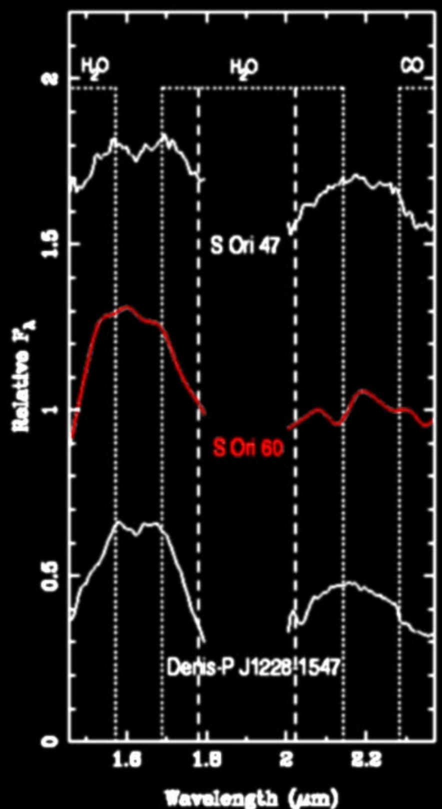
Edad 3-5 Ma

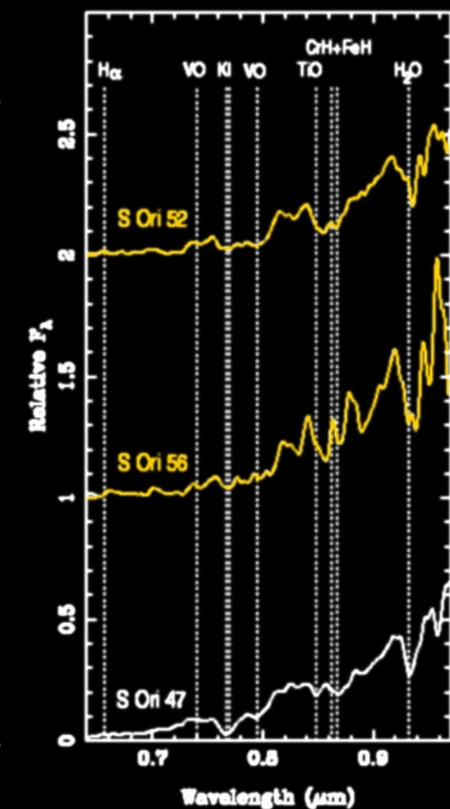
E(B-V)=0.05

Diagrama color-magnitud

- Símbolos rojos: candidatos a miembros del cúmulo. Más de 120 objetos siguen la secuencia fotométrica esperable para las enanas marrones.
- Masas estimadas a partir de modelos 5 Ma.
- Tipos espectrales:
  - M6 ~ 75 Mjup
  - M8 ~ 25 Mjup
  - L1 ~ 15 Mjup
  - L5 ~10 Mjup

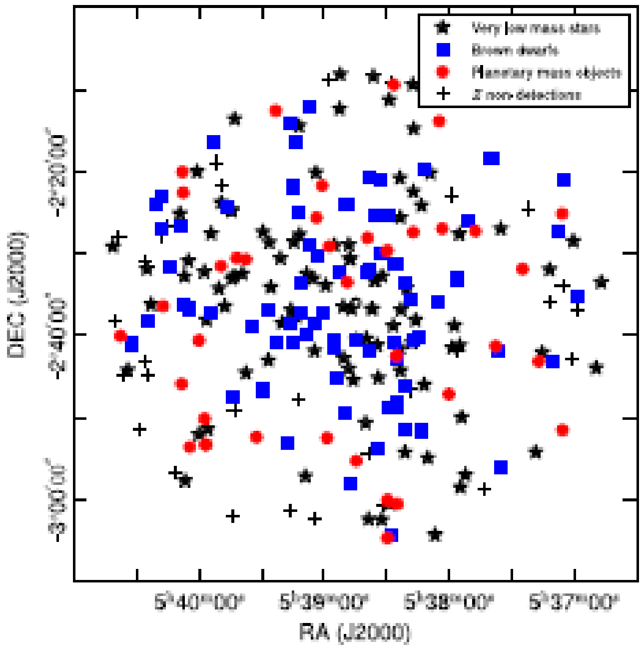
Búsquedas profundas detectan jóvenes super-Jupiters

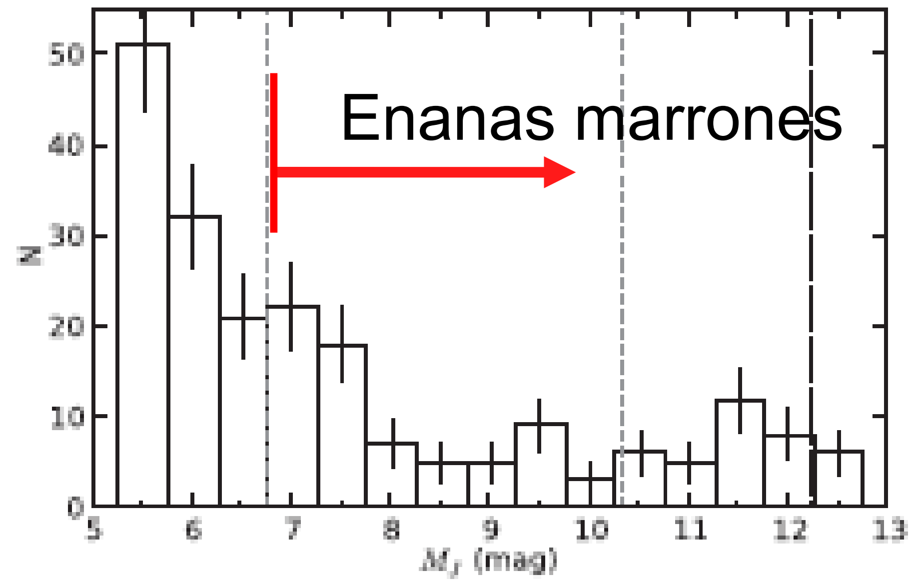


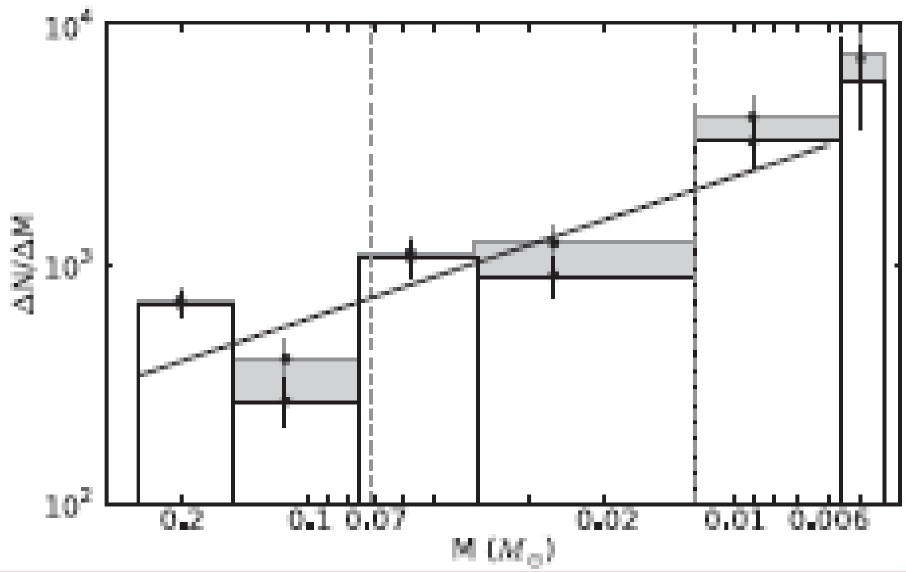


sigma Orionis
(edad~3 Ma)

Zapatero-Osorio et al. 2000, Science

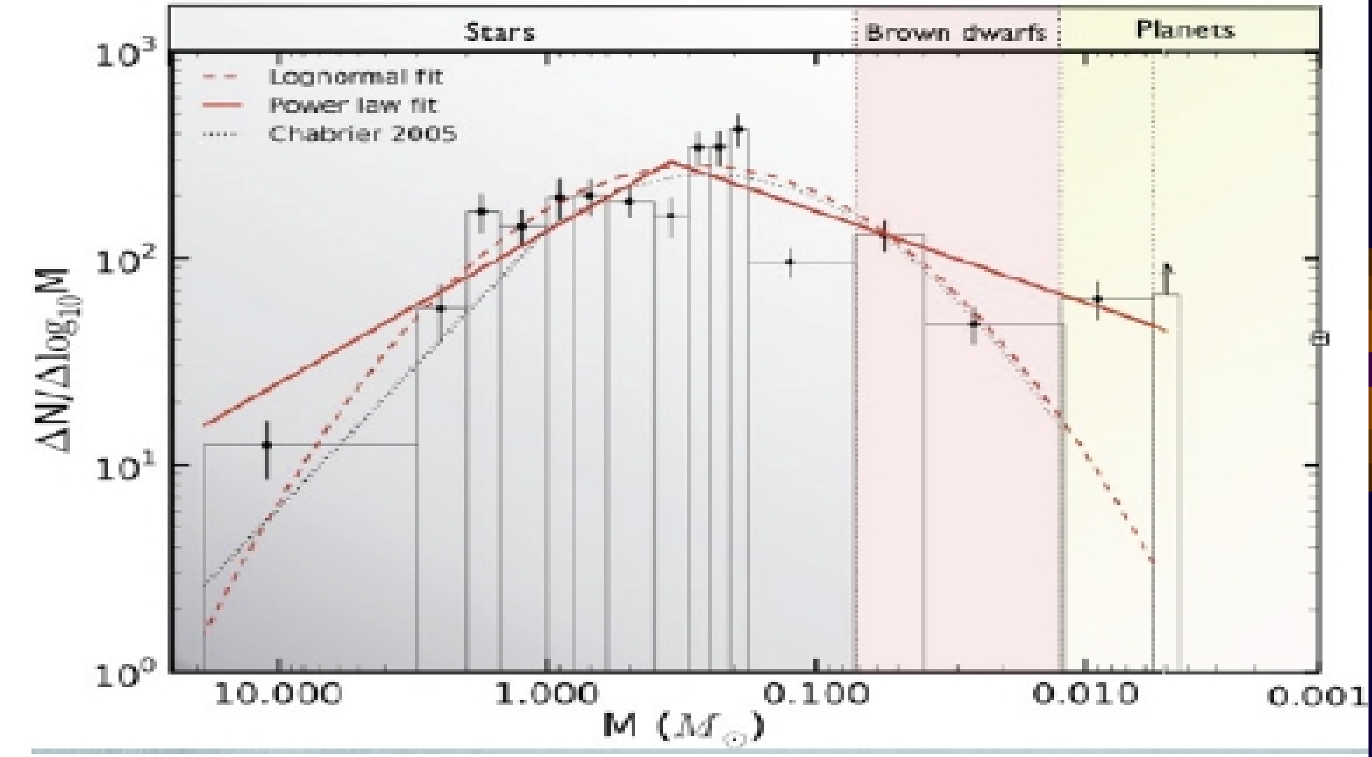






El espectro de masas de sigma Orionis se ha podido obtener hasta ~5 M_{Jup}

Ley de potencias para el espectro de masas con índice 0.6 ±0.2 , que es típico de las regions de formación y cúmulos estelares



Peña Ramírez et al. 2012

Peña-Ramírez et al. 2012

El modelo de fragmentación turbulenta de nubes moleculares puede explicar la función de masas entre 10 M_solar y 10 M_Jup, pero no el exceso de objetos con unas pocas veces la masa de Júpiter

Exploraciones realizadas en los últimos 20 años en numerosos cúmulos estelares y en la vecindad solar proporcionan resultados similares

Las enanas marrones se comparan en número con las estrellas.

Estimamos que en nuestra Galaxia debe haber unos 100 mil millones de enanas marrones

Conclusions (I)

- Free-floating super-Jupiters, exist in young clusters and in the solar neighbourhood

- In the sigma Orionis cluster the number ratio of free-floating super-Jupiters (mass 10-5 Mjup) to solar-type stars (1-0.5 solar masses) is 1:1. Brown dwarfs and super-Jupiters also compare in number. Similarly in the Pleiades cluster, but deeper searches are needed.

- Brown dwarfs and super-Jupiters form in clusters but then evaporate. It is very likely that they populate the solar neighbourhood (remember that the second nearest system to the Sun is a brown dwarf binary),

- Microlensing events (Suni et al. 2011) suggest that the number of free-floating Jupiter-like objects is even higher than we infer from direct imaging surveys in clusters.

Conclusions(II)

The nearest free-floating superJupiter could be located at a distance less than 3 pc of the Sun.

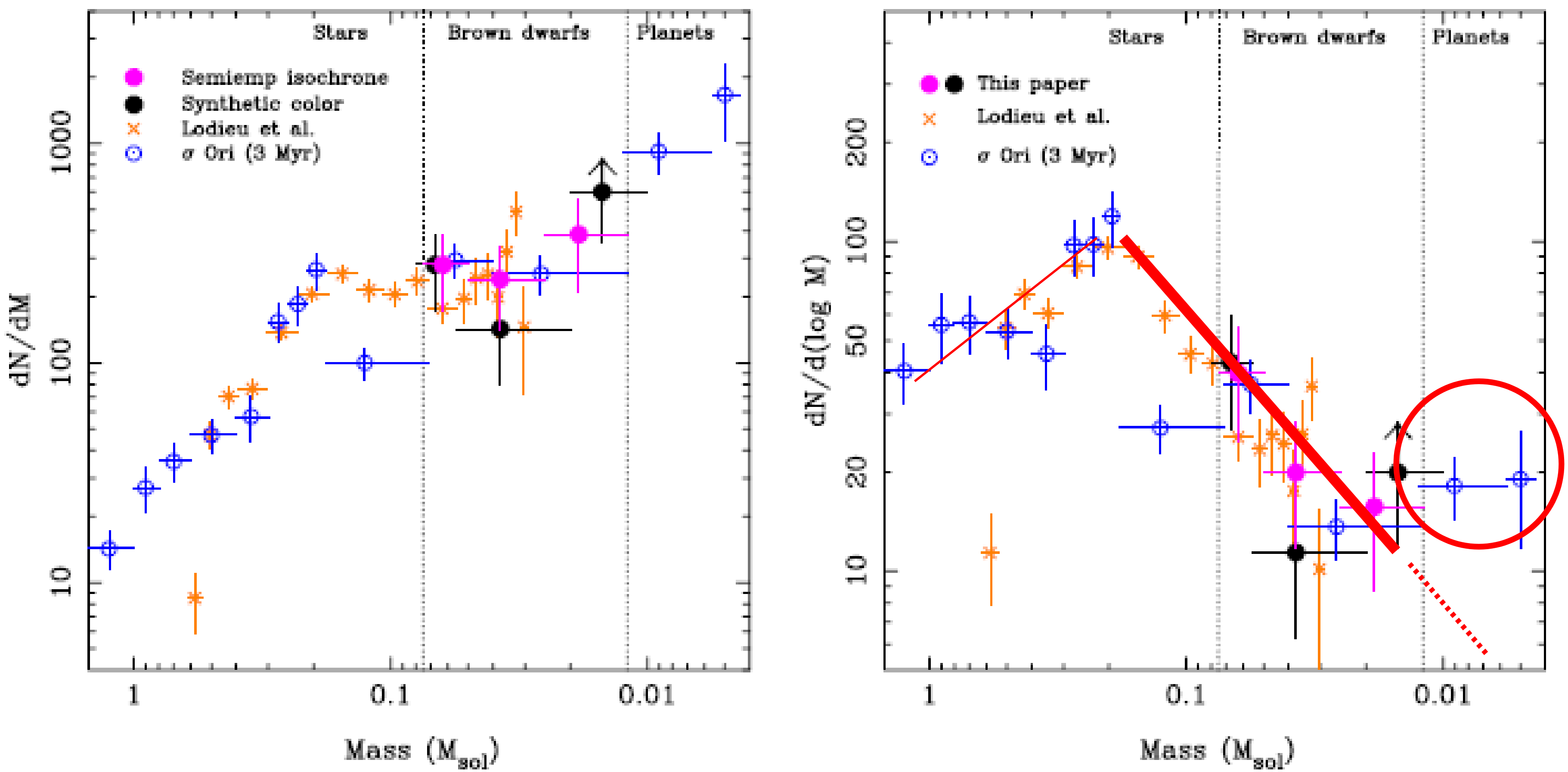
Old free-floating super-Jupiters will look like the coldest Y-dwarfs. Several are known within 6 pc but current age uncertainties translate into large mass uncertainties questioning the nature of the candidates.

- RV surveys of field stars show the scarcity of orbiting super-Jupiters. They appear to be 100 times less abundant than free-floating . Why? How super-Jupiters form? Are there two different mechanisms?
- Understanding the mechanism of formation of super-Jupiters remains as a major theoretical and observational challenge

Mass spectrum for sigma Orionis and the Pleiades clusters

Evidence for an excess in the sigma Orionis mass function at super-Jupiter masses.

A&A 568, A77 (2014)



Discovery of a brown dwarf in the Pleiades star cluster

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Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

BROWN dwarfs are cool star-like objects that have insufficient mass to maintain stable nuclear fusion in their interiors. Although brown dwarfs are not stars, they are expected to form in the same way, and their frequency of occurrence should reflect the trends seen in the birthrates of low-mass stars. But finding brown dwarfs has proved to be difficult, because of their low intrinsic luminosity. The nearby Pleiades star cluster is widely recognized as a likely host for detectable brown dwarfs because of its young age—the still-contracting brown dwarfs should radiate a large fraction of their gravitational energy at near-infrared wavelengths. Here we report the discovery of a brown dwarf near the centre of the Pleiades. The luminosity and temperature of this object are so low that its mass must be less than 0.08 solar masses, the accepted lower limit on the mass of a true star[1–3]. The detection of only one brown dwarf within our survey area is consistent with a smooth extrapolation of the stellar mass function of the Pleiades[4], suggesting that brown dwarfs, although probably quite numerous in the Galactic disk, are unlikely to comprise more than ~1% of its mass.

Only about half a dozen extremely cool dwarfs with spectral types M9 or later have been identified[5]. At present they are the best candidates for brown dwarfs. Their mass–luminosity and mass–spectral-type relationships[6,7] show that these objects are indeed very close to the substellar limit, but uncertainties in

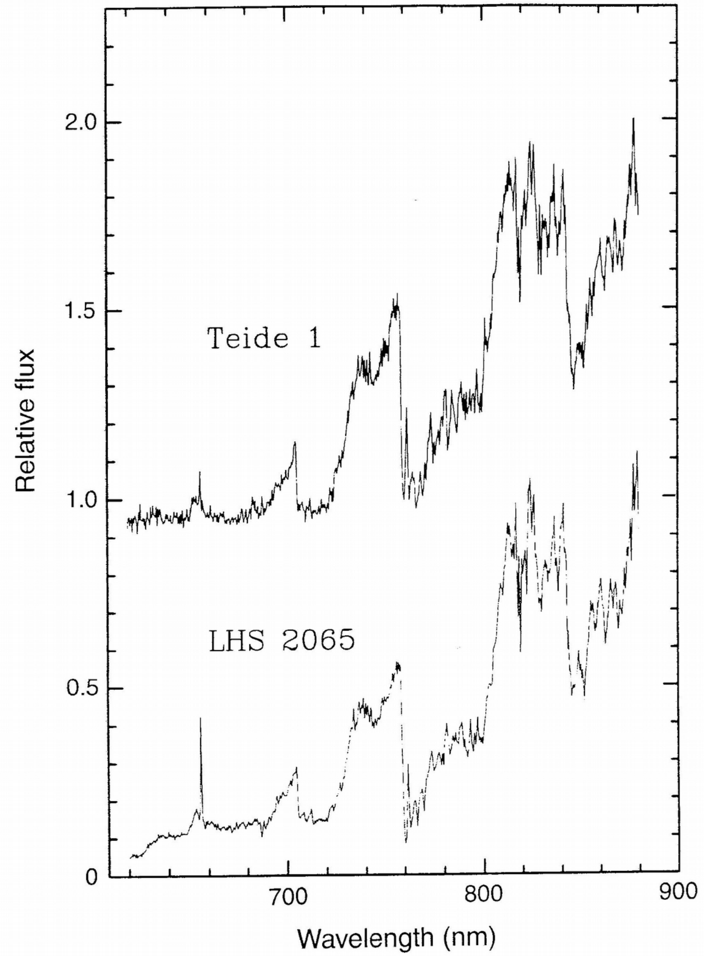


FIG. 1 The optical spectrum of Teide 1 (upper trace) and of the M9 dwarf LHS 2065 (lower trace). The flux scale of both spectra is normalized to unity at 825 nm. An offset has been added to the spectrum of Teide 1 for clarity.

09/09/2025

Status of brown dwarf searches before 1995

- Field objects and companions
  - Gl 473 (uncertain dynamics), GJ 569 B (not known to be a binary at that time).
  - The coolest known field objects were M9 dwarfs (six reported but age and mass unknown).

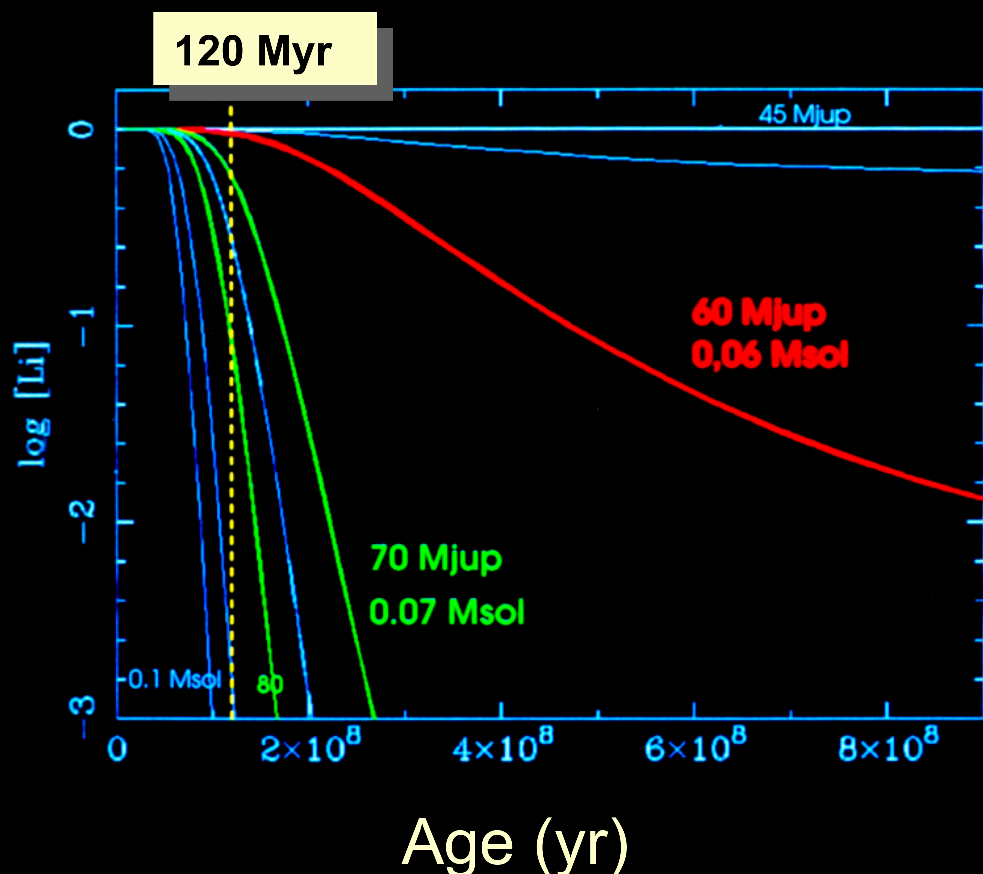
  Hawkins and Bessell 1988, Tinney 1993, Kirkpatrick et al. 1994

- No BD candidate displayed lithium in the spectrum (Magazzú et al. 1993 ApJ, Martín et al. 1994 ApJ, Marcy et al. 1994 ApJ)

- No brown dwarf identified at the Workshop

"The bottom of the Main Sequence and Beyond", ESO Garching, ed. C. Tinney, August 1994

- A la edad del cúmulo Pléyades (~120 Ma) las enanas marrones con m < 0.07 Msun preservarían su contenido inicial de litio
- test: Li I doblete de resonancia a 6708 Å



Mass spectra in young clusters and star-forming regions: $dN/dM \sim M^{-\alpha}$

Rho Ophiuchi: $\alpha \sim 1.1$ Williams et al. 1995
(mass range 1-0.03 M_{sun})

NGC 2024: $\alpha \sim 1.2$ Comerón et al. 1996
(mass range 0.5-0.04 M_{sun})

Chamaleon I: $\alpha \sim 1.2$ Comerón et al. 2000
(mass range 1-0.03 M_{sun})

(linear mass units)

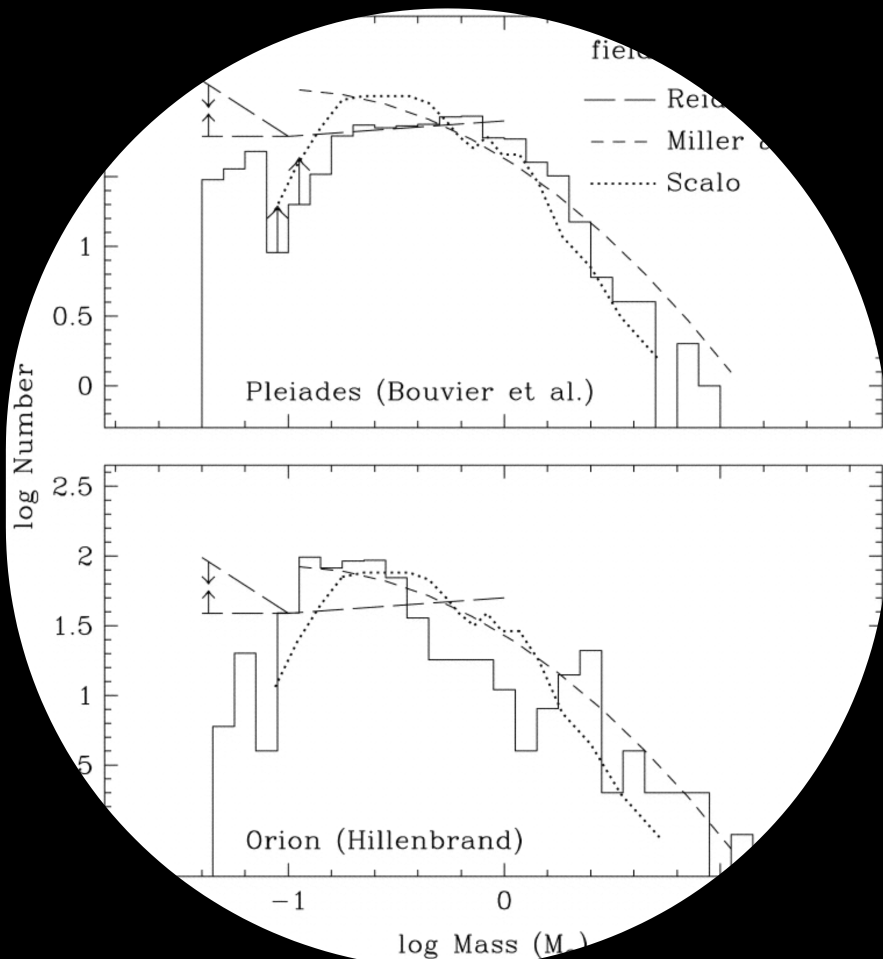
the 600R grating (nominal dispersion 0.79 Å per pixel, effective resolution 1.6 Å). Teide 1 was cross-correlated with the template[21] GL 873, a dM4.5e star with $v_r = 0.47 \pm 0.24$ km s^{-1}, yielding $v_r = 0.3 \pm 5.5$ km s^{-1} for our object. These two independent determinations are consistent with the mean radial velocity[22] of 5.9 km s^{-1} for the Pleiades.

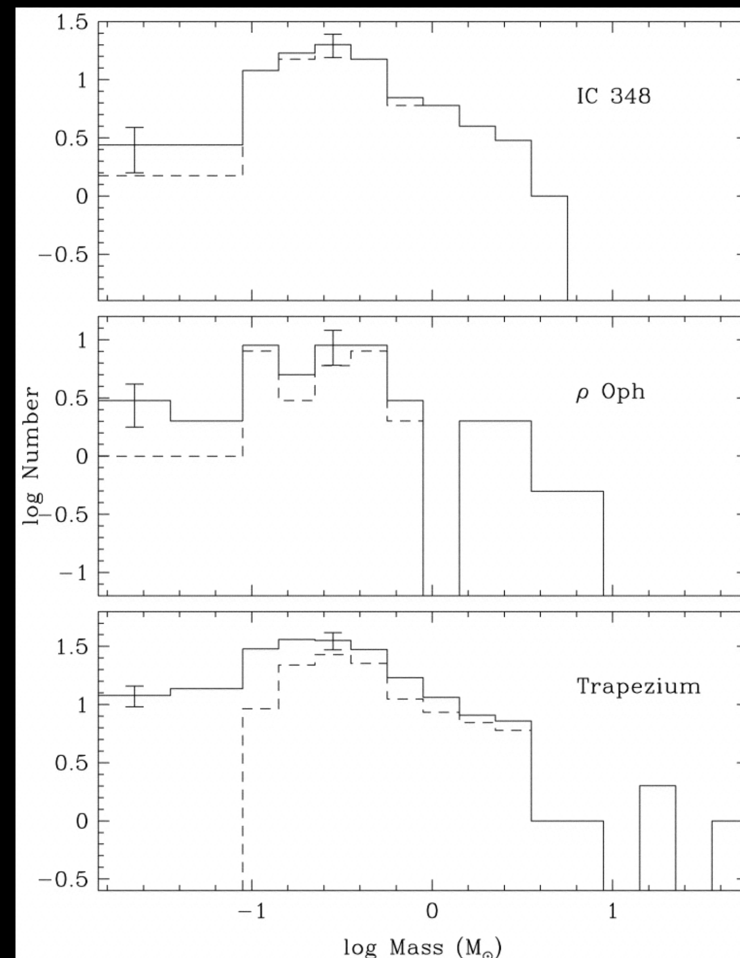
The strength of the VO band centred at 750 nm depends strongly on the effective temperature[5] in stars with spectral types later than M7. We used the VO spectral index defined in ref. 5 (the ratio of the flux in the near pseudocontinuum at both sides of the VO feature to the actual flux observed in the minimum of the band) to derive the spectral type of Teide 1. We measured a value of 1.145, which corresponds to M9 (the range given in ref. 5 for this spectral type is 1.120–1.170). For LHS 2065 the same index gave 1.137, confirming its classification as M9. Using a spectroscopic database for very cool dwarfs kindly provided by J. D. Kirkpatrick, and a cross-correlation peak-technique, we determined a spectral type of M8.5±0.5 for Teide 1. This shows that both methods yield consistent classifications within the error bars. In addition, we found that the Na I doublet (very sensitive to spectral type in late M dwarfs) has an equivalent width of 6±1 Å in Teide 1, a value similar to those of field M9 dwarfs.

The measured proper motion and radial velocity, the Hα emission, the dM9 spectral type and the RI photometry are all consistent with Teide 1's being a member of the Pleiades cluster. But the proper motions and radial velocities of Pleiades stars are similar to those of general field M dwarfs, as stated in ref. 18, so we considered the probability that Teide 1 might simply be a field M9 dwarf superimposed on the Pleiades (that is, lying at a distance of 60–100 pc, closer than the widely accepted cluster distance of 125 pc). The luminosity function at the end of the Main Sequence has been addressed recently as a result of a deep (completeness limit $R = 19$), large-area (27.3 deg^2), CCD survey for cool dwarfs[23]. In this survey, only one extremely cool dwarf (spectral type M8.5) was found in a space volume of 412 pc^3, suggesting that the local density of M8.5–M9 objects is ~0.0024 pc^{-3}. Because our survey covered a volume about 80 times smaller, the probability of finding such late-spectral-type objects along the line of sight towards the cluster is <1.5%. The discovery of our object can, however, be understood in terms of the much higher stellar density in the Pleiades cluster than in the field.

To estimate the mass of Teide 1 we had to determine its location on the Hertzsprung–Russell (H–R) diagram. The luminosity and effective temperature were derived from the I magnitude and the dM9 spectral type. Using the parameters of the Pleiades cluster (distance modulus of 5.53, extinction $A_I = 0.07$ mag), and the I bolometric correction[24] suitable for LHS 2065, we obtained $\log L/L_\odot = -2.9 \pm 0.1$, where $L_\odot$ is the luminosity of the Sun, and the error comes from uncertainties in I magnitude, extinction, and distance. At present, there is no agreed temperature scale to place very-low-mass stars and brown-dwarf candidates in the H–R diagram. Therefore we adopted a mean temperature from several recent calibrations[25–28] of 2,350±300 K. The error bar covers the total temperature range obtained with the different calibrations. In Fig. 2 we show the H–R diagram with a set of theoretical evolutionary tracks and isochrones[1] for stars close to the substellar limit, and for brown dwarfs. Superimposed are the dimmest Pleiades brown-dwarf candidates with measured proper motions and published spectral types[12,13,29,30]. We have derived their luminosities and temperatures in the same way as for Teide 1. Our object is the coolest and faintest brown-dwarf candidate discovered so far in the Pleiades. From its location on the H–R diagram and after comparison with the set of theoretical tracks shown in Fig. 2 we obtain an upper limit to the mass of Teide 1 of 50 jovian masses (M_{Jup}) and a most likely mass in the range 20–30 M_{Jup}. If we use other sets of theoretical tracks[2,3,31], we always obtain masses <70 M_{Jup}. We conclude that Teide 1 must be a brown dwarf, or else the theory is seri-

The initial mass function in the Trapezium Cluster





Luhman et al. 2000, ApJ

Pleiades mass function

E. Moraux et al.: Brown dwarfs in the Pleiades cluster

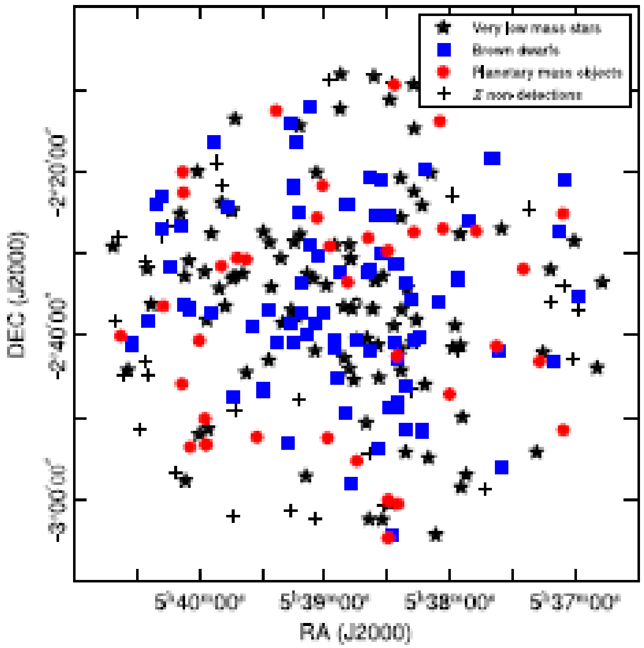
Survey	Area sq. degree	Completeness limit	Nb of new BD candidates	IMF index	Mass range ($M_\odot$)
Stauffer et al. (1989)	0.25	$I \sim 17.5$	4		0.2-0.08
Simons & Becklin (1992)	0.06	$I \sim 19.5$	22		0.15-0.045
Stauffer et al. (1994)	0.4	$I \sim 17.5$	2		0.3-0.075
Williams et al. (1996)	0.11	$I \sim 19$	1		0.25-0.045
Festin (1997)	0.05	$I \sim 21.6$	0	≤ 1	0.15-0.035
Cossburn et al. (1997)	0.03	$I \sim 20$	1		0.15-0.04
Zapatero et al. (1997)	0.16	$I \sim 19.5$	9	1 ± 0.5	0.4-0.045
Festin (1998)	0.24	$I \sim 21.4$	4	≤ 1	0.25-0.035
Stauffer et al. (1998)	1.	$I \sim 18.5$	3		0.15-0.035
Bouvier et al. (1998)[a,b]	2.5	$I \sim 22$	13	0.6 ± 0.15	0.4-0.04
Zapatero-Osorio et al. (1999)[b]	1.	$I \sim 21$	41		0.08-0.035
Hambly et al. (1999)	36.	$I \sim 18.3$	6	≤ 0.7	0.6-0.06
Pinfield et al. (2000)[b]	6	$I \sim 19.6$	13		0.45-0.045
Tej et al. (2002)	7	$K \sim 15$		0.5 ± 0.2	0.5-0.055
Dobbie et al. (2002)[b,c]	1.1	$I \sim 22$	10	0.8	0.6-0.030

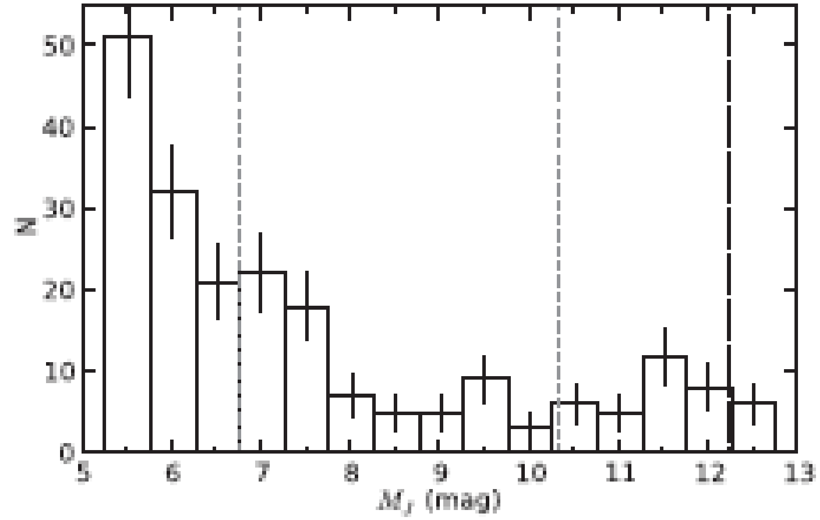
[a] BD candidates have been confirmed by Martín et al. (2000) and Moraux et al. (2001) and the IMF index has been revised to 0.51 ± 0.15.
[b] Jameson et al. (2002) have compiled these surveys and using new infrared data they find that the Pleiades mass function is well represented by a power law with index $\alpha = 0.41 \pm 0.08$ for $0.3M_\odot \geq M \geq 0.035M_\odot$.
[c] These authors used the results from Hodgkin & Jameson (2000) and Hambly et al. (1999) to conclude that the $\alpha = 0.8$ power law is appropriate from $0.6M_\odot$ down to $0.03M_\odot$.

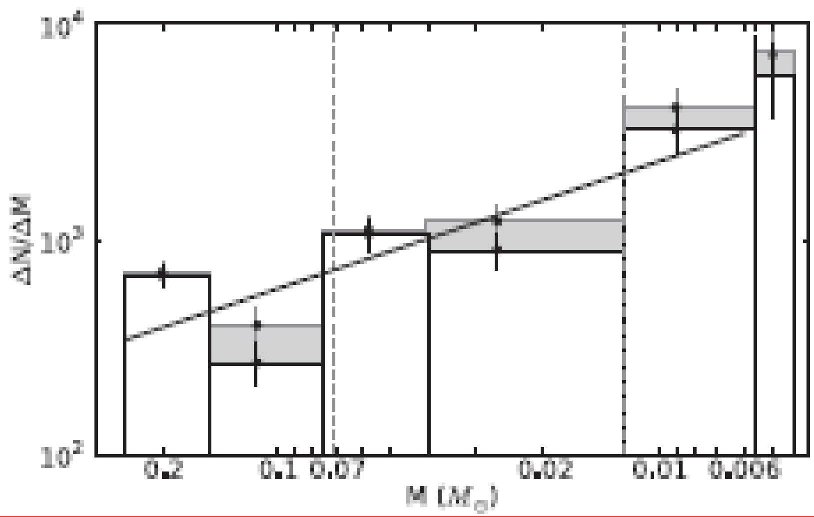
Moraux et al. 2003 6.4 I~ 22 29 0.6 0.45-0.03

Mass function in young clusters

PEÑA RAMÍREZ ET AL.



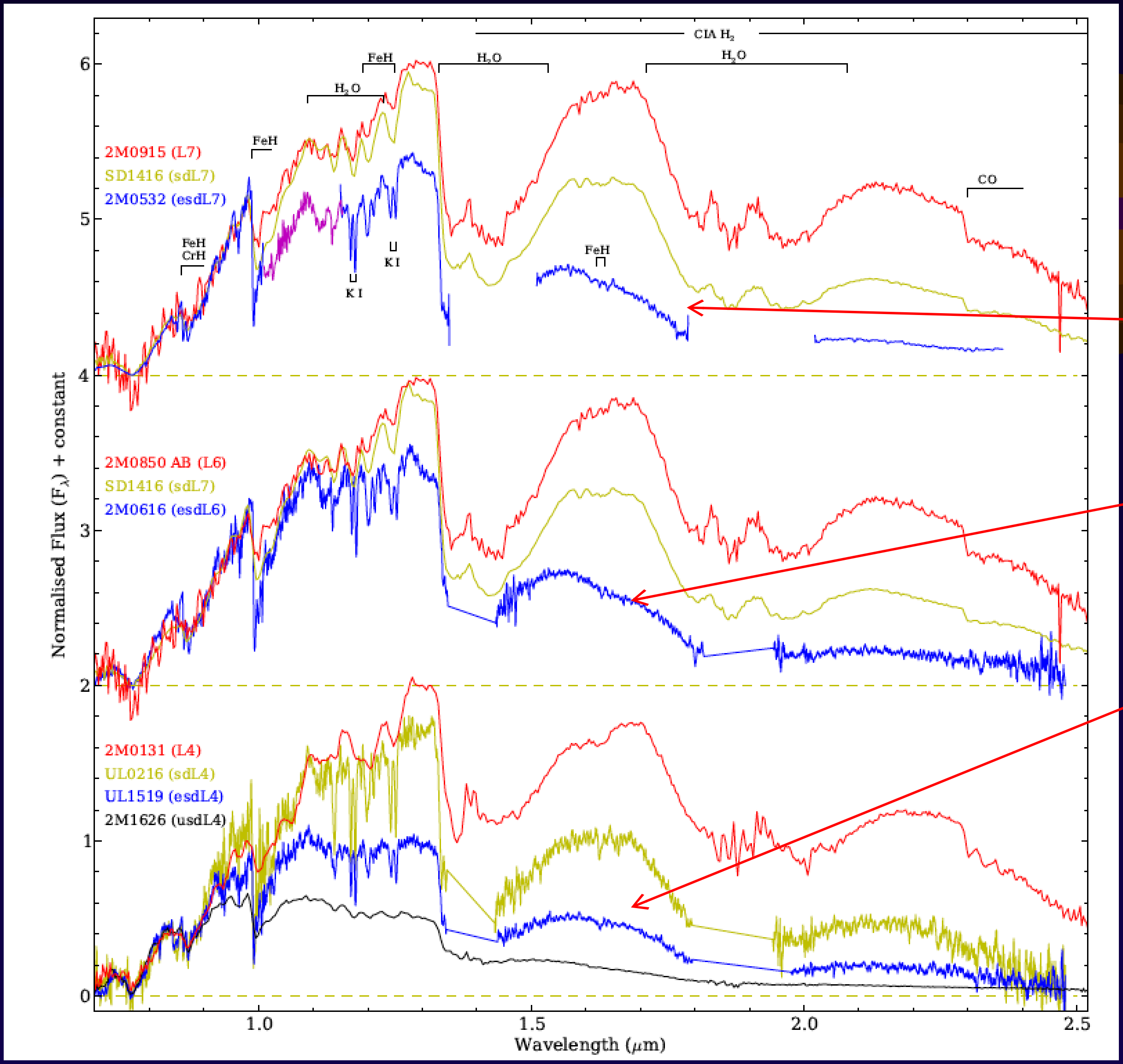




The mass spectrum of sigma Orionis smoothly extends down to ~4 M_{Jup}

Mass spectrum power-law index 0.6 ± 0.2

Very low mass halo stars are known: Ultracool subdwarfs



Zhang et al. 2017 and reference therein

Metal poor L7

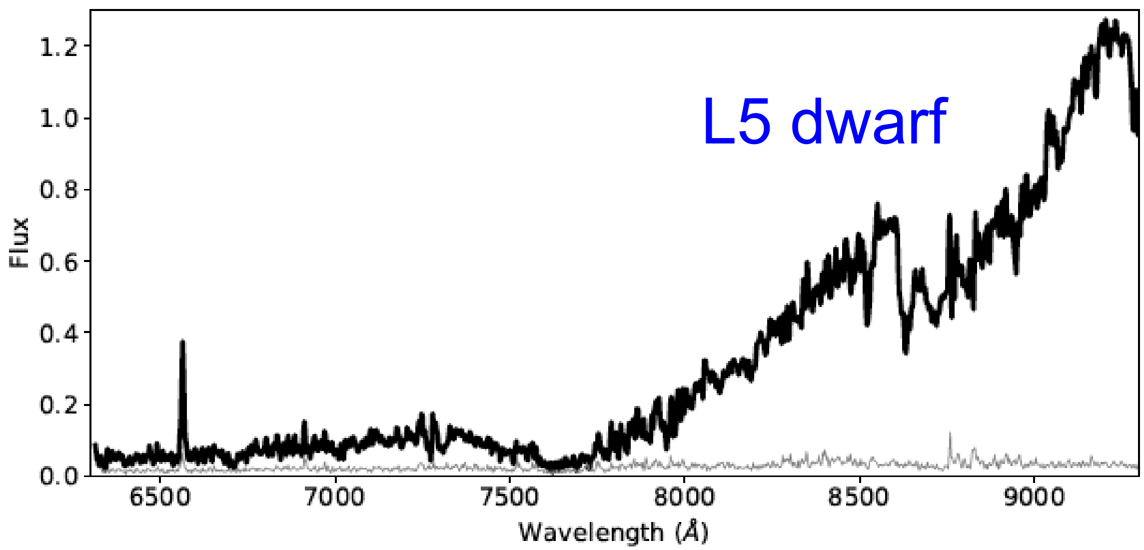
L6

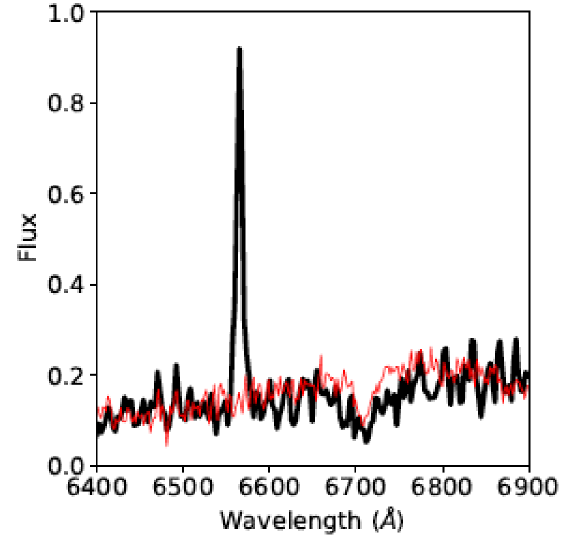
L4

[Fe/H] -1→-2

Mass estimates at 0.09 $M_{\odot}$

Lithium in Hyades Brown dwarfs





Observations with GTC 10.4m
La Palma, Canarias Observatories

Lodieu, RR, Perez-Garrido, 2018

SpT	L5.0±0.5
$\log(L_{bol}/L_\odot)$	−4.30±0.07 dex
T_{eff}	1581±113K
pEW (Li)	18±4 Å
pEW (Hα)	−150 to −45 Å
Li abundance	−3.0±0.4 dex

Can we find lithium in the T dwarfs?

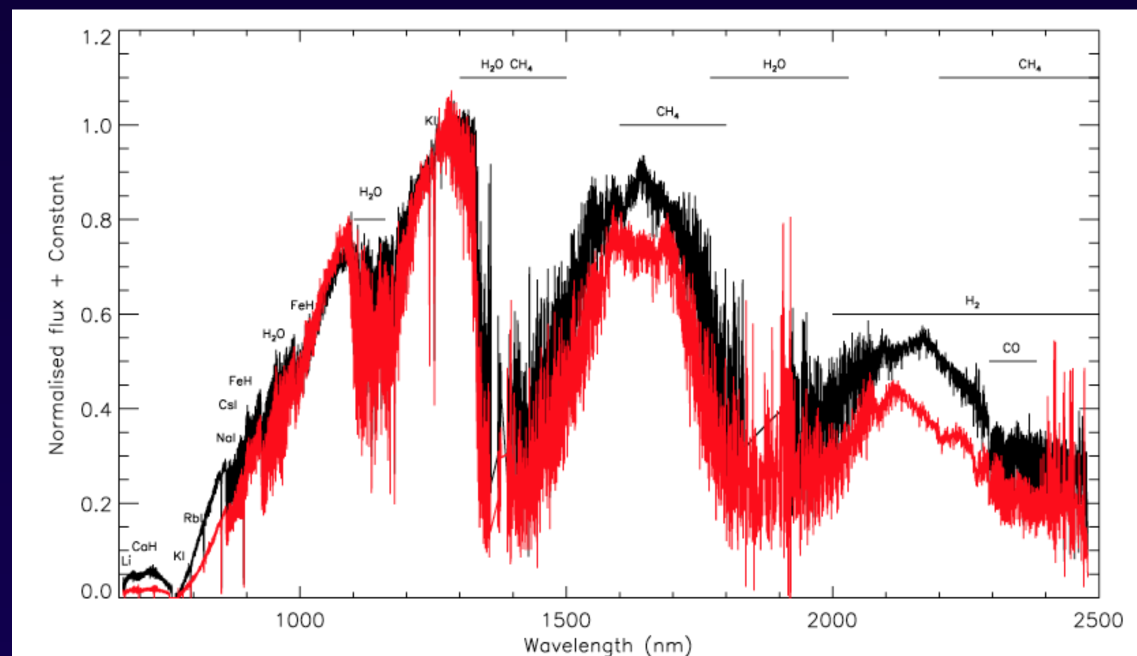
A&A 581, A73 (2015)
DOI: 10.1051/0004-6361/201424933

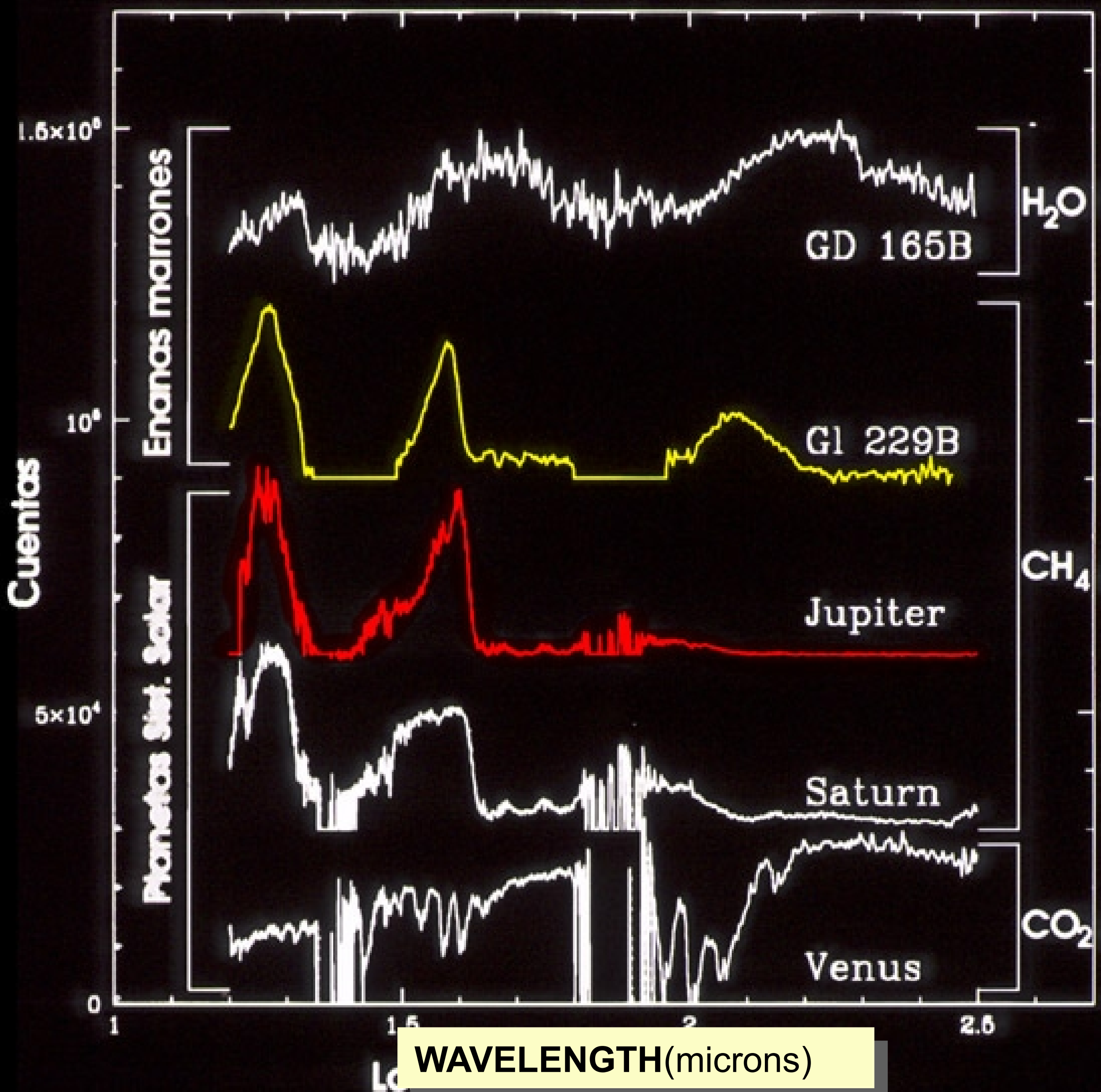
Astronomy & Astrophysics

VLT X-Shooter spectroscopy of the nearest brown dwarf binary★,★★

N. Lodieu[1,2], M. R. Zapatero Osorio[3], R. Rebolo[1,2,4], V. J. S. Béjar[1,2], Y. Pavlenko[5,6], and A. Pérez-Garrido[7]

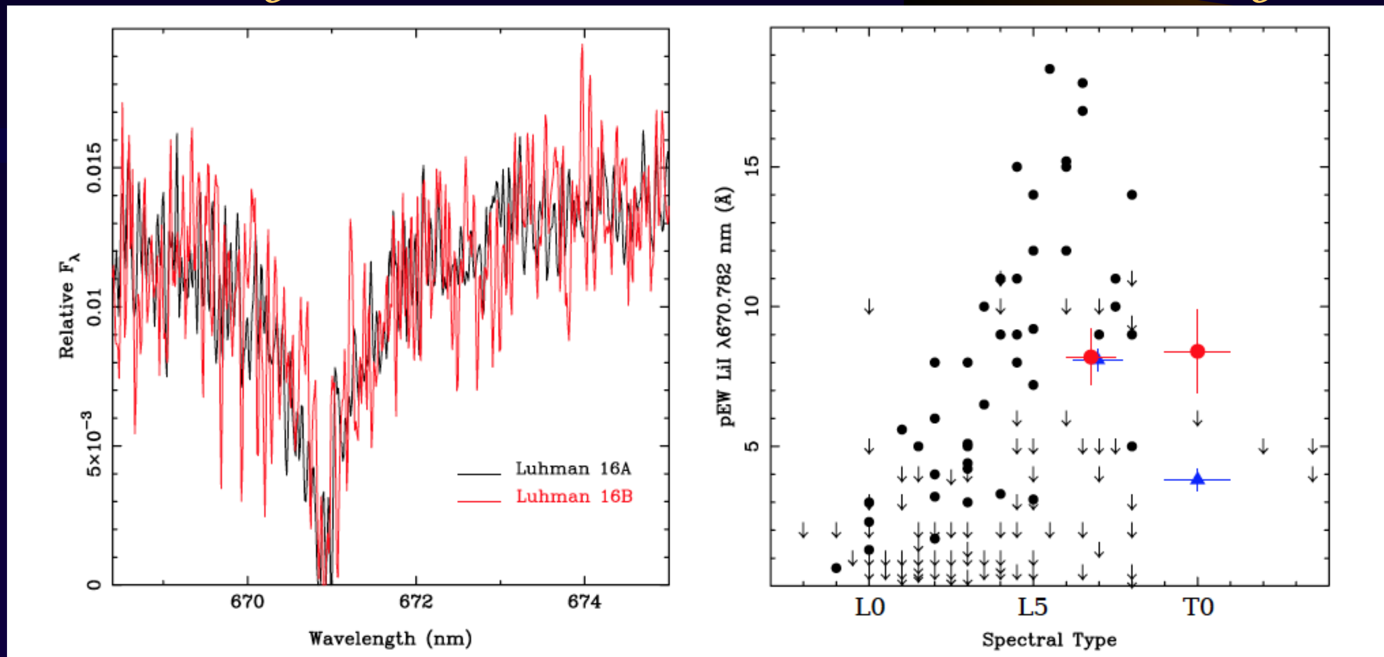
Luhman 16AB (Luhman 2013)





1.5×10^5
10^5
5×10^4
0
1
1.5
2
2.5
Cuentas
Enanas marrones
Planetas Sist. Solar
GD 165B
Gl 229B
Jupiter
Saturn
Venus
H2O
CH4
CO2
WAVELENGTH(microns)

Can we find lithium in T dwarfs?



Age	Luhman 16A			Luhman 16B		
	Mass	Radius	$T_{\rm eff}$	Mass	Radius	$T_{\rm eff}$
Gyr	$M_\odot$	$R_\odot$	K	$M_\odot$	$R_\odot$	K
0.5	0.028 ± 0.003	0.102 ± 0.005	1223 ± 60	0.029 ± 0.003	0.102 ± 0.005	1238 ± 60
1	0.041 ± 0.003	0.093 ± 0.005	1280 ± 60	0.041 ± 0.003	0.093 ± 0.005	1296 ± 60
2	0.055 ± 0.003	0.086 ± 0.005	1328 ± 60	0.055 ± 0.003	0.086 ± 0.005	1344 ± 60
5[a]	0.067 ± 0.003	0.082 ± 0.005	1368 ± 60	0.067 ± 0.003	0.082 ± 0.005	1383 ± 60

Lithium spectral synthesis consistent with full preservation