Silicate Grains in the Disks of Young Free Floating Planetary Mass Objects

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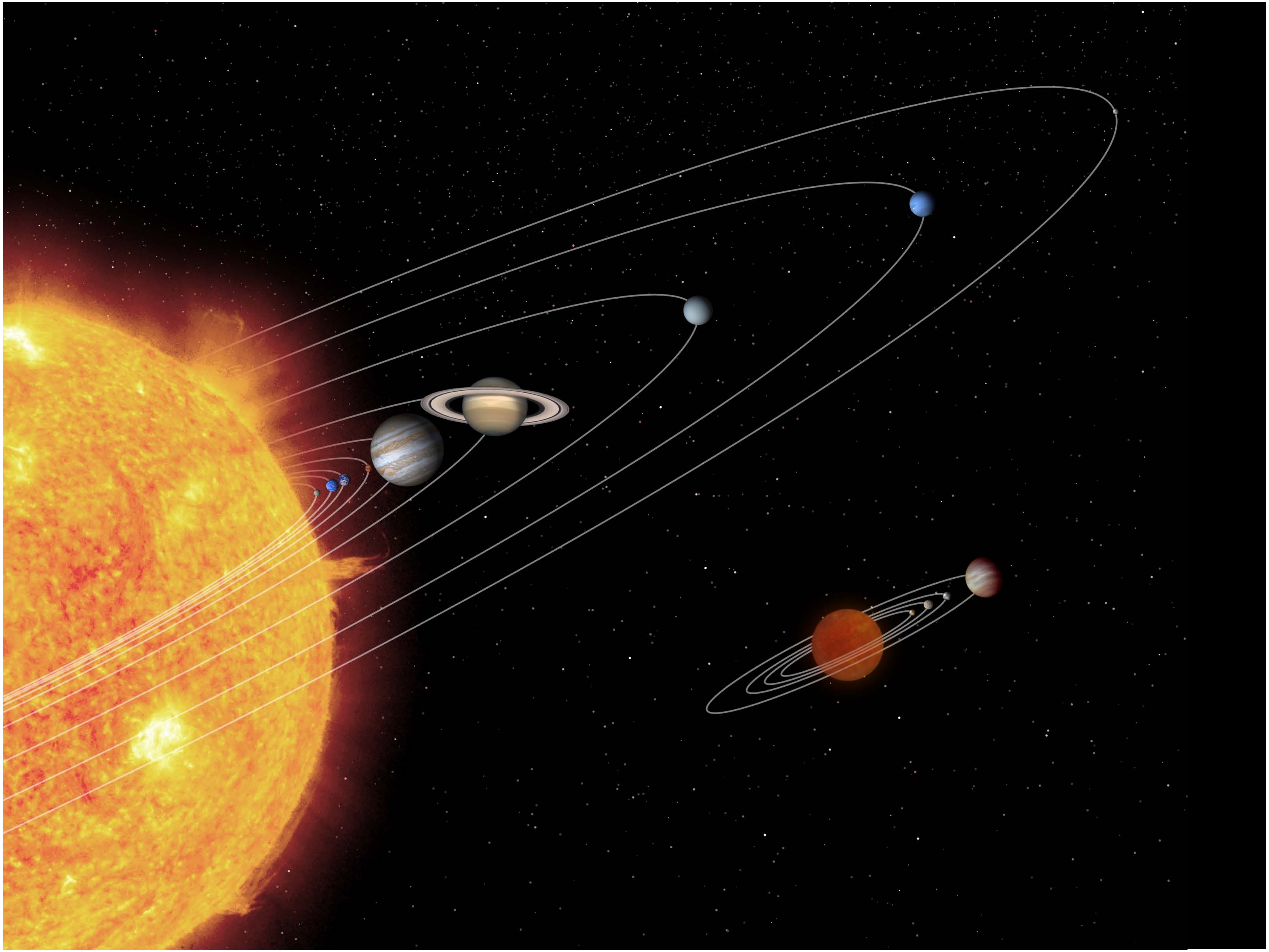
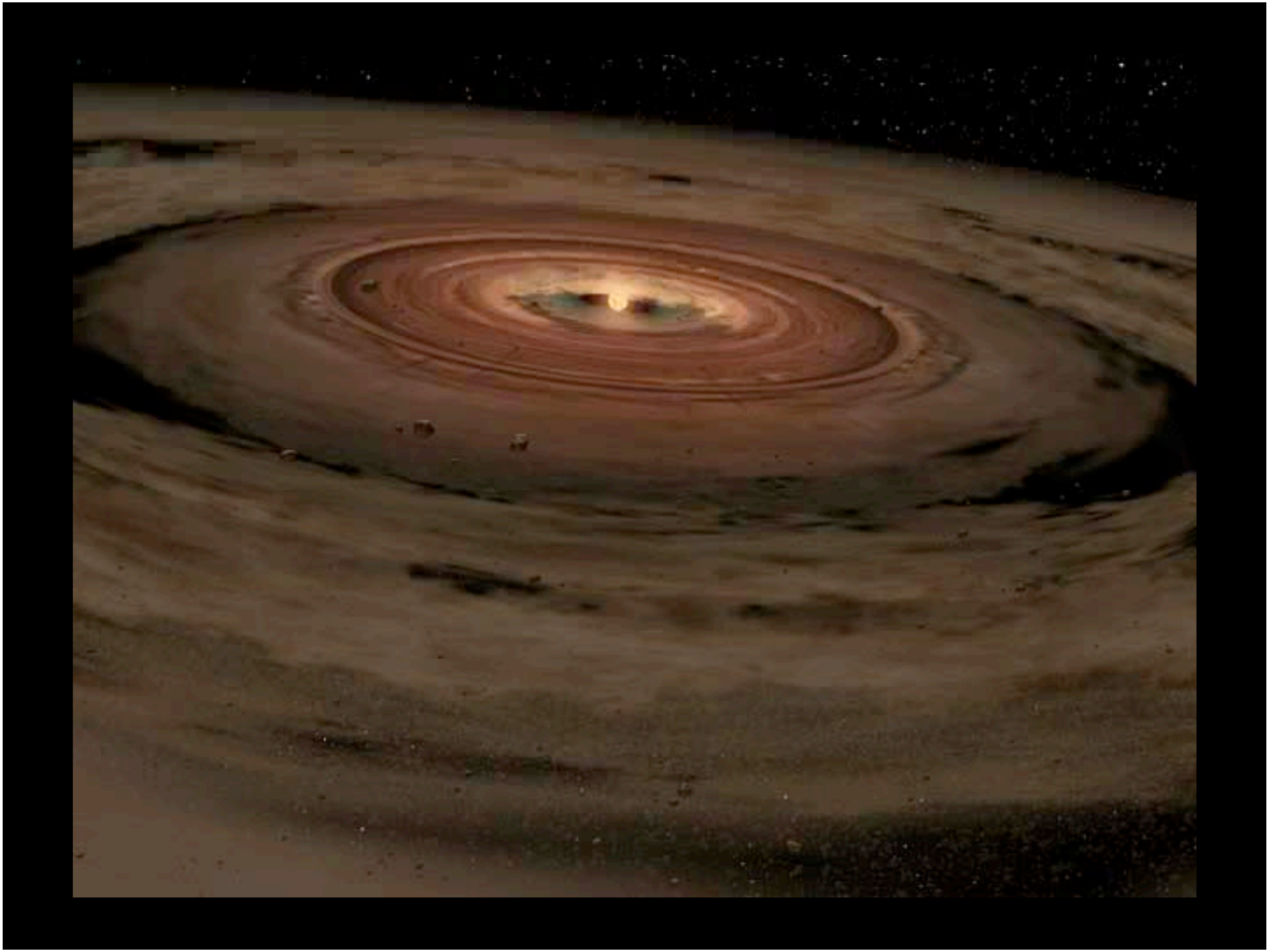
Overview

- Protoplanetary disks exhibit evidence for **grain growth** and **crystallization** of sub–micrometer (μm)-sized dust grains, and **dust settling toward the disk mid-plane**.
- These processes are believed to be linked to planet formation
- Evidence for these processes has been found in the disks of **B**rown **D**warfs (**BD**s), and low- and intermediate-mass stars.
- <u>Planet formation is a robust process occurring in most young circumstellar disks.</u>



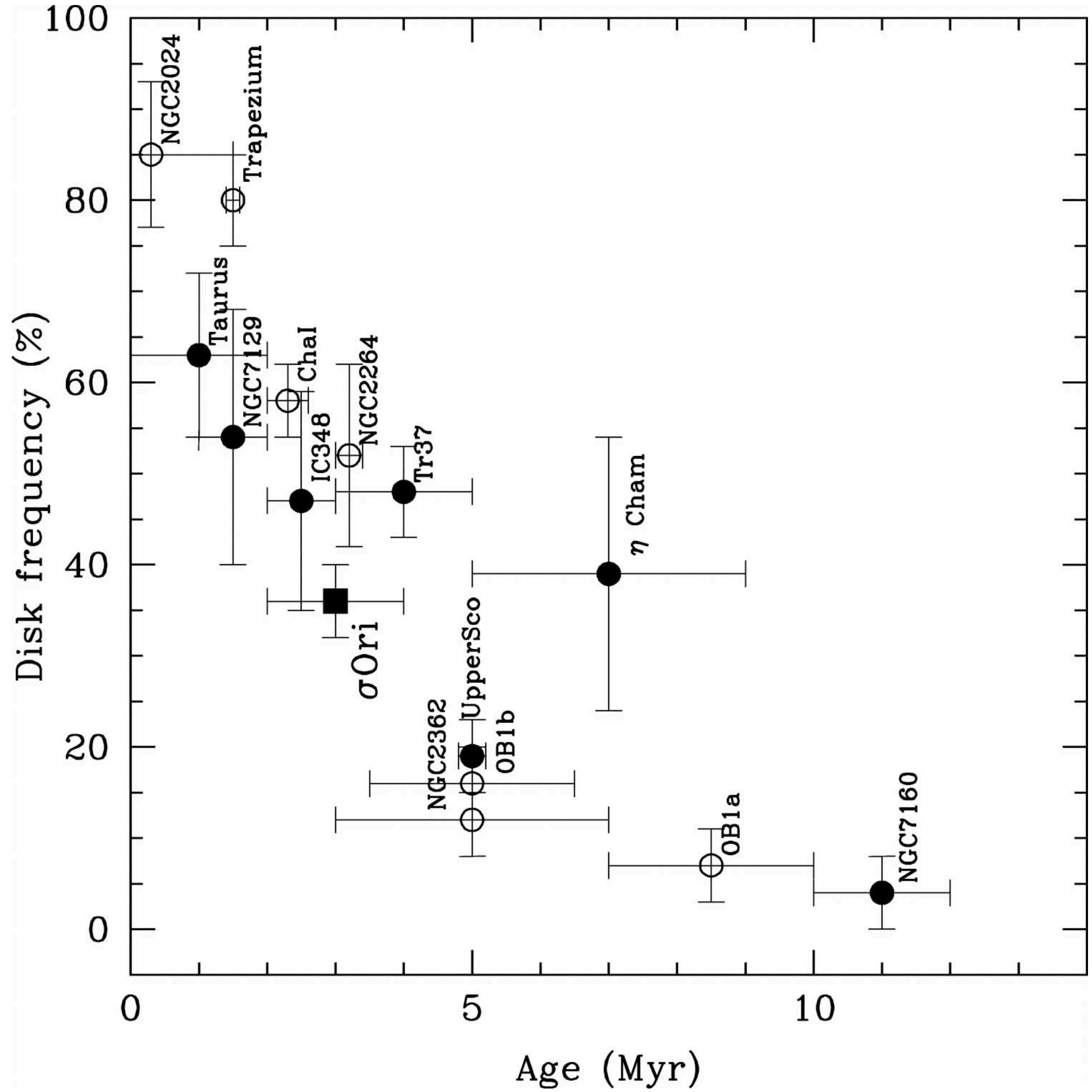


Differences between BDs and their Solar Mass counterparts

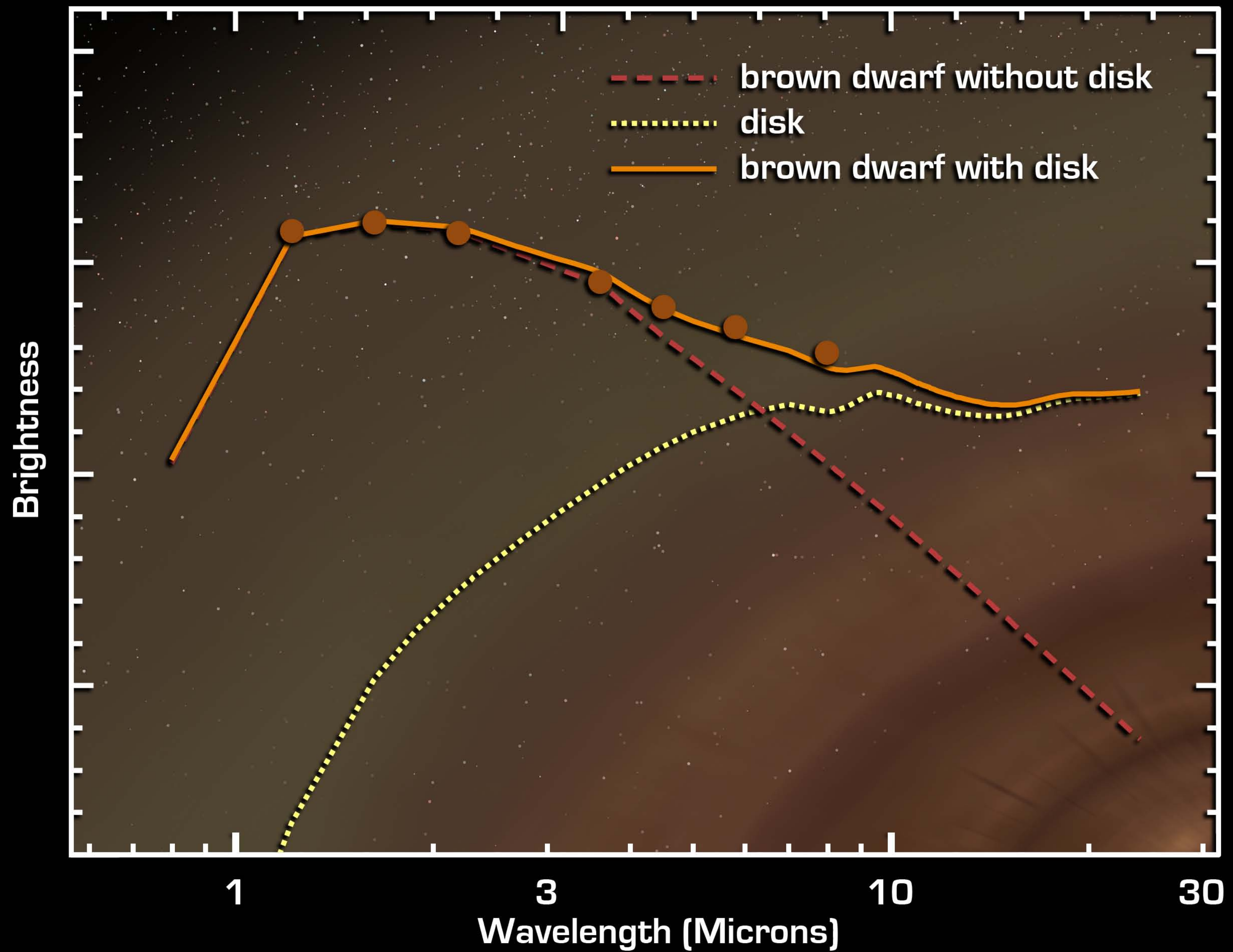
- 1)Disk lifetimes
  - BD disks last longer
- 2) Disk geometry
  - BD disks are flatter (higher mass stars more flared)
- 3) Dust processing in the disk
  - BD disks are more crystalline than solar-like stars
- 4) Strength of 10μm silicate emission feature
  - BDs have weaker 10μm silicate emission
- 5) Disk gas properties
  - Dearth of HCN observed in BD disks

Disk Lifetimes

- The amount of time the available for planet building is set by the disk lifetime.



Hernandez et al. 2007



Brown Dwarf With Protoplanetary Disk

NASA / JPL-Caltech / K. Luhman (Harvard-Smithsonian CfA)

Spitzer Space Telescope • IRAC

ssc2005-06a

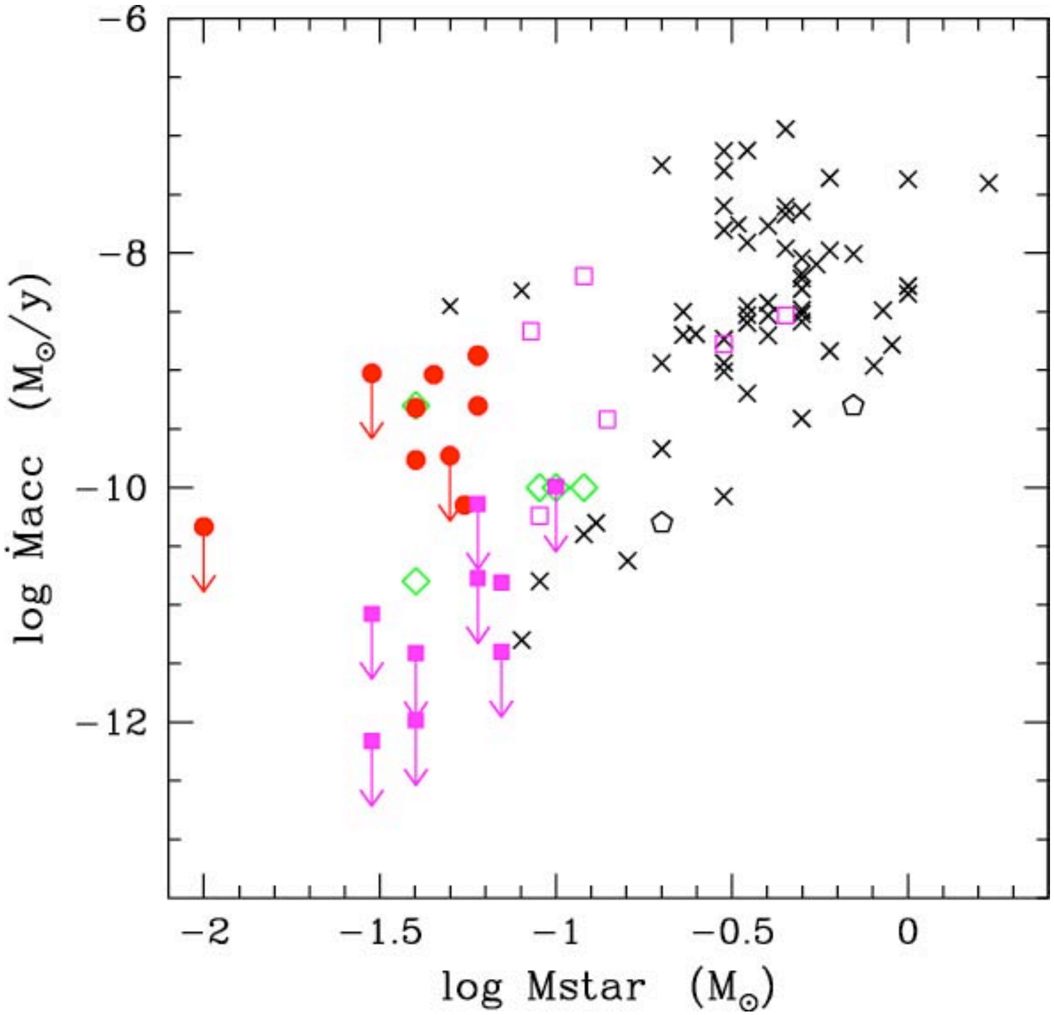
1) Disk Lifetimes are longer for BDs

Star Forming Cloud Age (Myr)	Disk Fraction of Brown Dwarfs (%)	Disk Fraction of Solar-like stars (%)	Cloud name, Ref
10	60	24	TW Hydra, Riaz et al. (2008)
5	37 ± 9	19 ± 4	Up Sco, Scholz et al. (2007)
2-3	42 ± 13	33 ± 4	IC348, Luhman et al. (2005)
~1	50 ± 17	45 ± 7	Cha I, Luhman et al. (2005)

Longer disk lifetimes around Brown Dwarfs means there is more time for planet building.

…but lower mass of Brown Dwarfs yields longer dynamical times for core accretion planet formation.

Accretion Rates: dM/dt ~ M^2

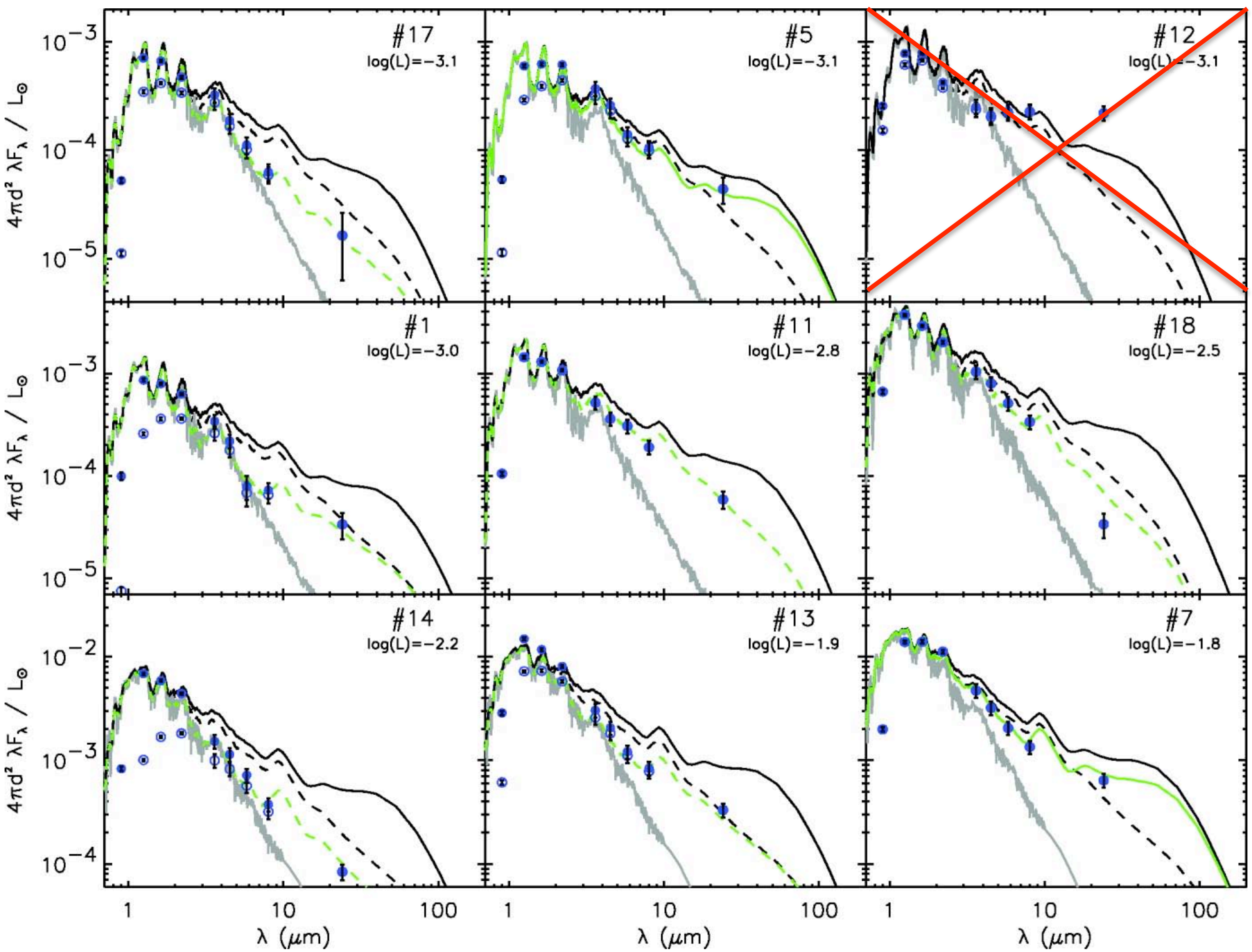


Longer disk lifetimes may make sense since the mass accretion rates scale with mass

Natta et al. 2004

Accretion rate as a function of the mass of the central object. Filled dots and squares are VLMOs in Oph and Cha I, respectively, from this paper; has been determined from

2) Disk Flatness



Allers et al. 2006

High density of flat disks among BDs

TABLE 6
MODEL PARAMETERS

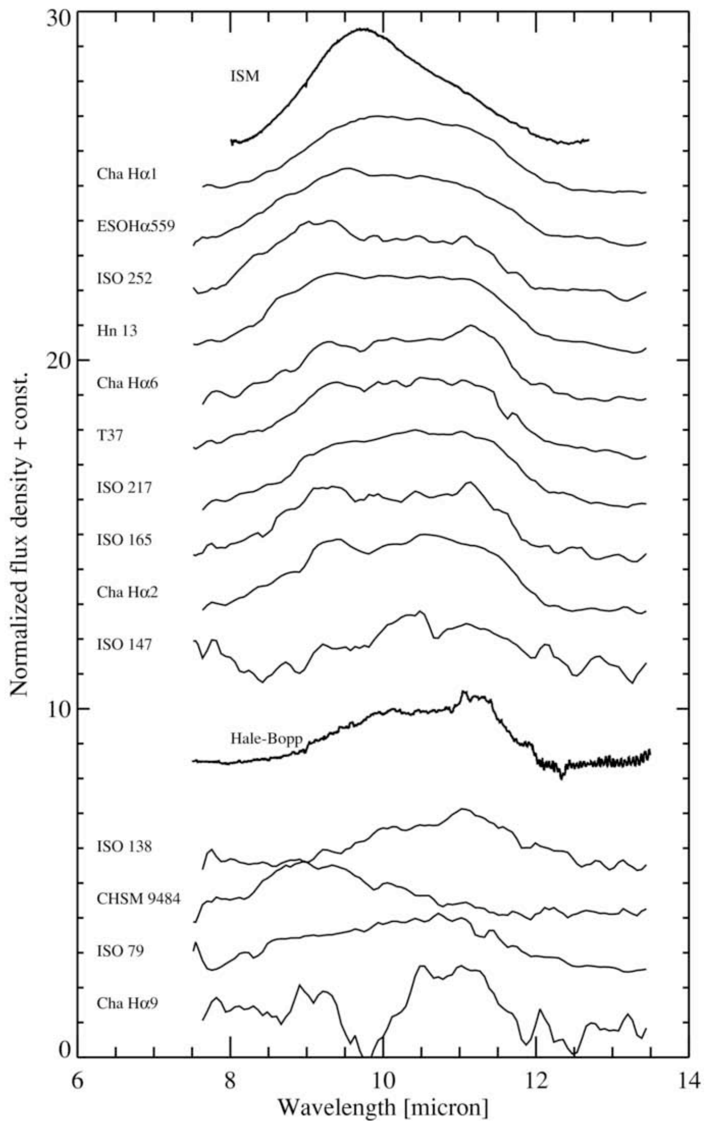
Source Number	L_{model} [$\log(L_*/L_\odot)$]	T_{eff} (K)	M_* ($M_\odot$)	R_* ($R_\odot$)	$\log g$	R_i (R_*)	i (deg)	Geometry
1	−2.99	2207	12	0.22	3.83	4	0	Flat
2	−1.31	2925	100	0.87	3.56	3	0	Flat
4	−0.79	3395	350	1.17	3.84	3	60	Flared
5	−3.14	2100	10	0.20	3.81	1	60	Flared
6	−1.20	3140	175	0.85	3.82	3	0	Flat
7	−1.77	2793	50	0.56	3.63	1	60	Flared
8	−1.48	2853	70	0.75	3.68	1	60	Flat
9	−1.45	2858	72	0.77	3.52	10	60	Flared
10	−0.70	3193	200	1.46	3.40	1	60	Flared
11	−2.81	2207	9	0.27	3.53	1	0	Flat
12[a]	−3.00	2098	7	0.24	3.51	...	...	...
13	−1.94	2746	40	0.48	3.68	3	0	Flat
14	−2.17	2598	30	0.41	3.69	3	60	Flat
15	−1.19	2856	100	1.05	3.39	1	60	Flared
16	−1.08	3023	110	1.05	3.43	1	60	Flared
17	−3.13	2004	6	0.28	3.50	3	60	Flat
18	−2.46	2400	15	0.34	3.54	1	60	Flat
19	−1.64	2768	50	0.66	3.49	5	60	Flat

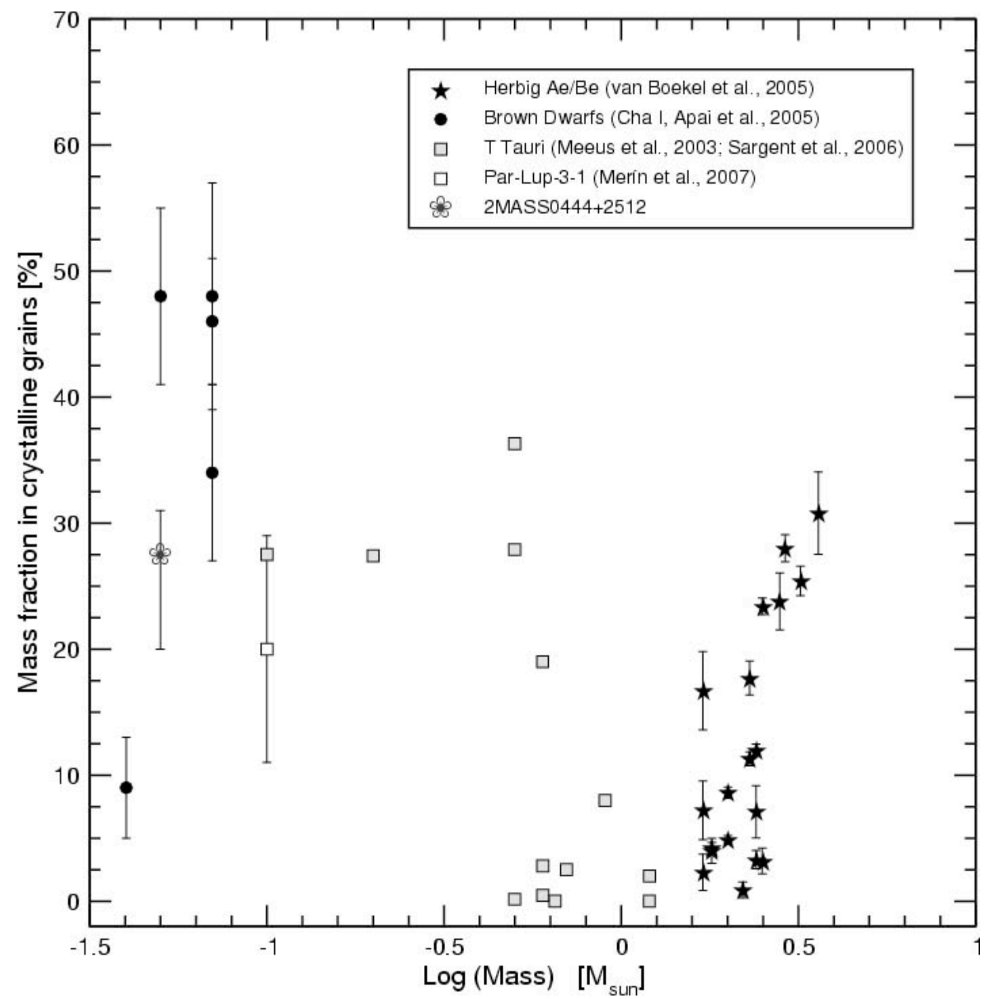
NOTES.—The quantities L_{model}, T_{eff}, M_*, R_*, and $\log g$ are the luminosity, effective temperature, mass, radius, and gravity used in the evolutionary model (Baraffe et al. 1998, 2003), where L_{model} is closest to L_{source} at the age of the cloud (§ 3.3). The last three columns list the disk inner radius (R_i), inclination (i), and geometry for the CGPLUS models that best fit the data (shown as green lines in Figs. 5 and 6).

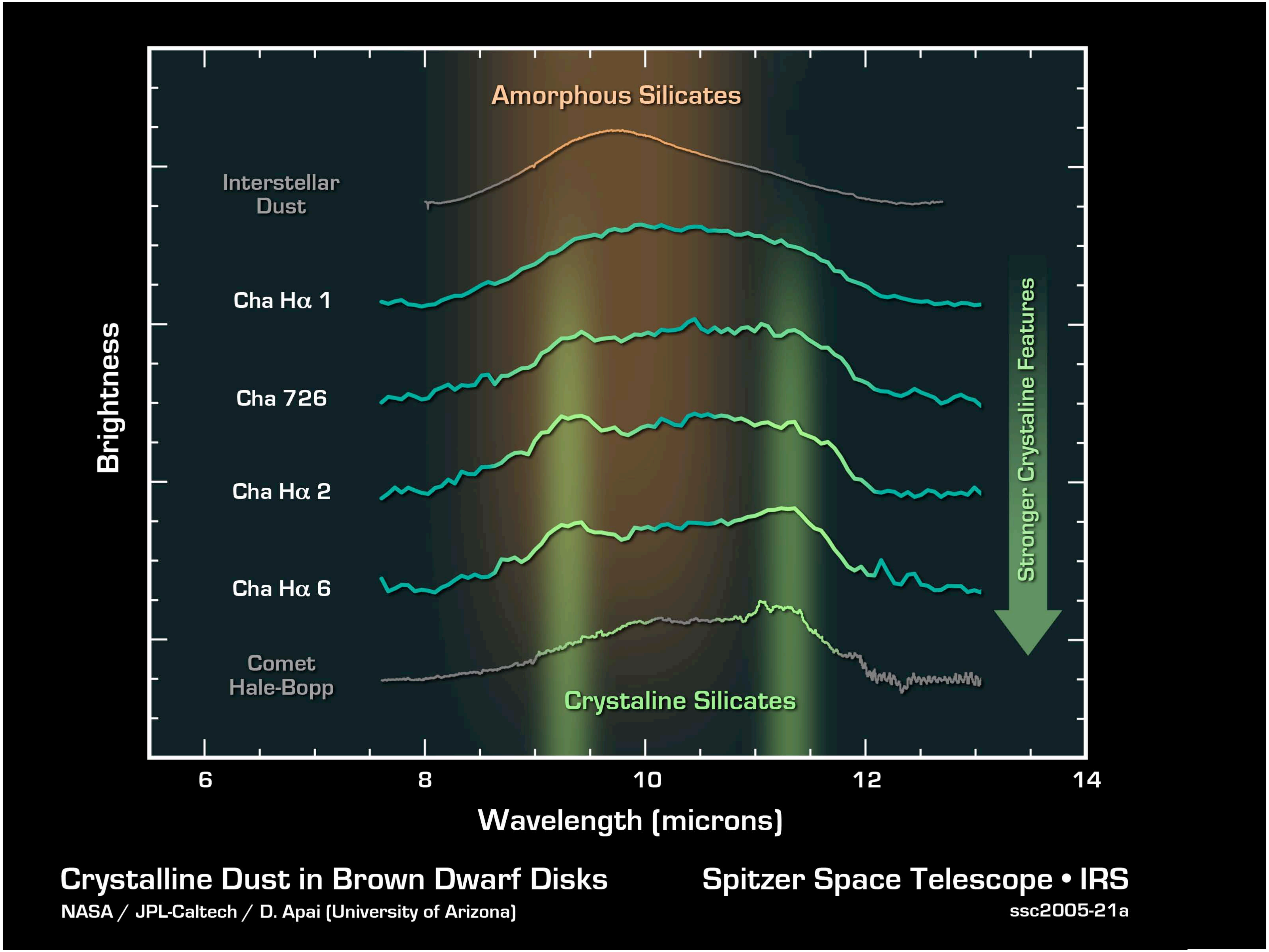
[a] For this source, the flux at $\lambda \geq 5.8$ μm is too large to be fitted by the models presented here.

Allers et al. 2006

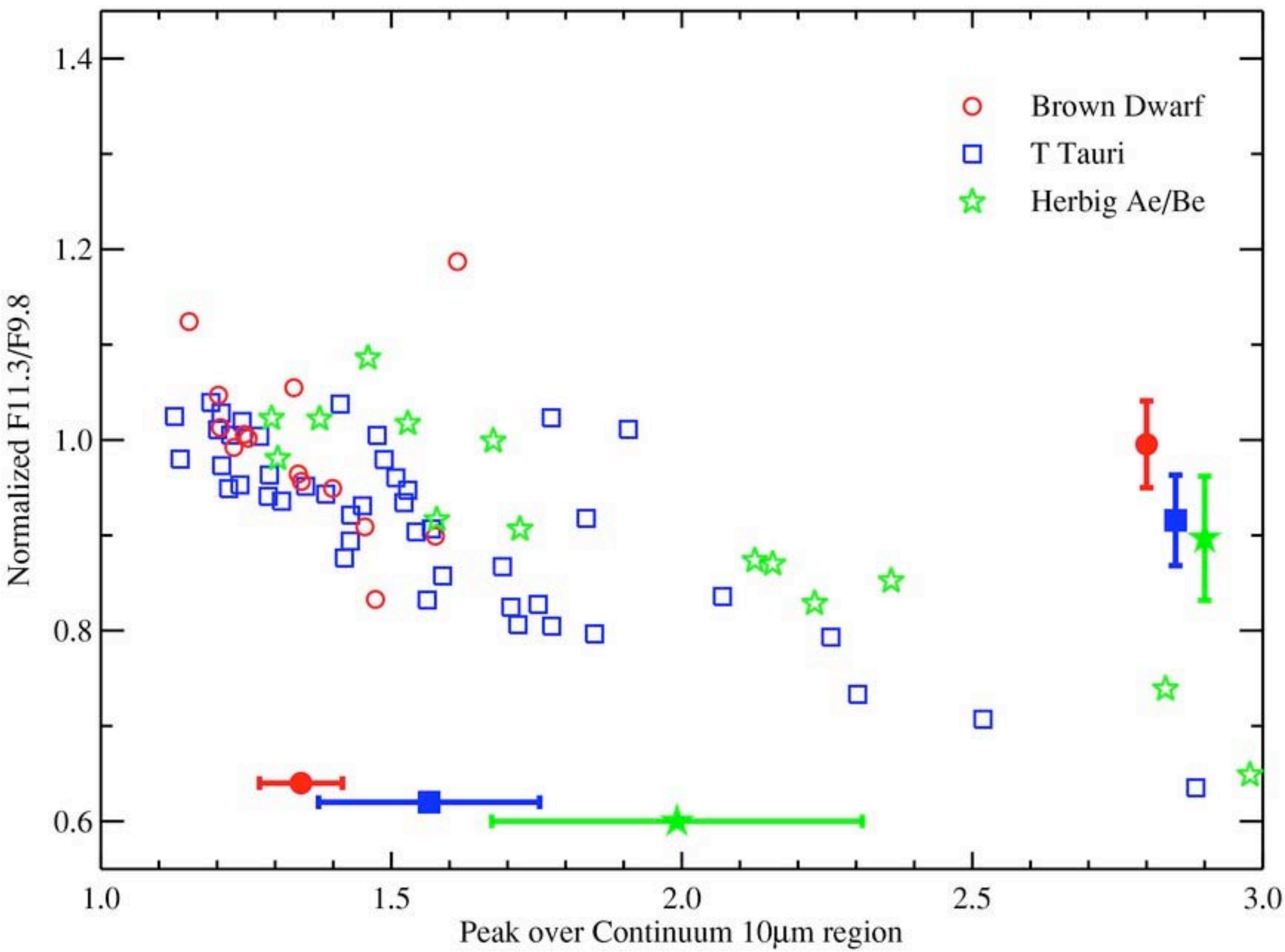
3) Dust Processing and Strength



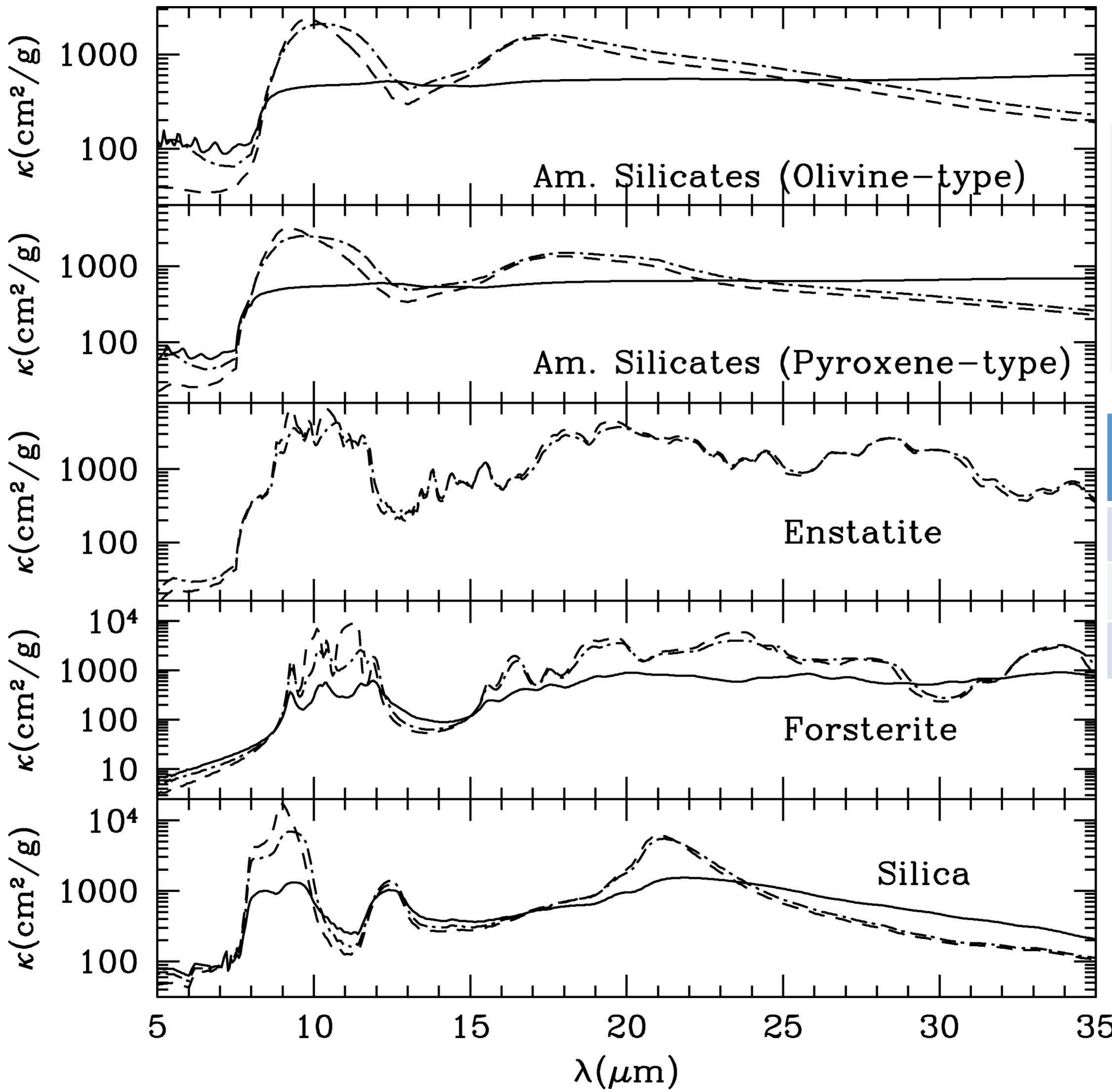




Amorphous Silicates
Interstellar Dust
Cha Hα 1
Cha 726
Cha Hα 2
Cha Hα 6
Comet Hale-Bopp
Crystaline Silicates
Stronger Crystaline Features
Brightness
6
8
10
12
14
Wavelength (microns)
Crystalline Dust in Brown Dwarf Disks
NASA / JPL-Caltech / D. Apai (University of Arizona)
Spitzer Space Telescope • IRS
ssc2005-21a



Brown Dwarf
T Tauri
Herbig Ae/Be
1.4
1.2
1.0
0.8
0.6
Normalized F11.3/F9.8
1.0
1.5
2.0
2.5
3.0
Peak over Continuum 10μm region



<u>Three grain sizes:</u>
- **0.1 μm** dashed
- **1.5 μm** dot-dashed
- **6.0 μm** solid line

Common Name	Molecular Formula
Forsterite	Mg_2SiO_4
Enstatite	$MgSiO_3$
Silica	SiO_2

See refs in Sicilia-Aguilar et al. 2008

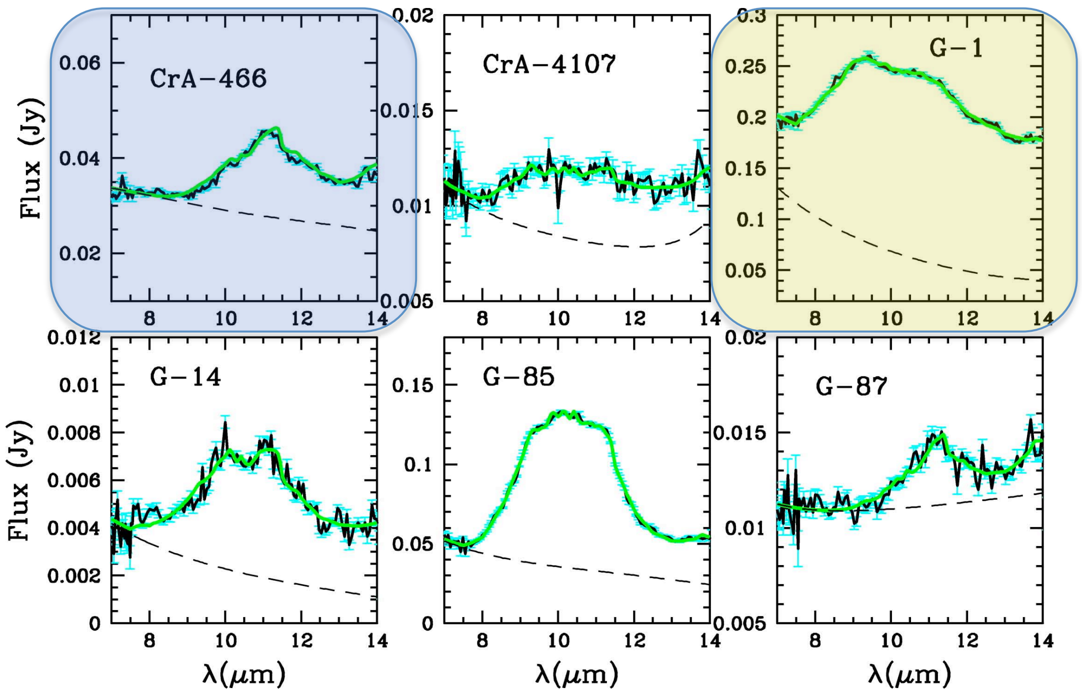


TABLE 8

GRAIN SIZES AND CRYSTALLINITY FRACTION

Name	Size (Am.) (μm)	Size (Cryst.) (μm)	Cryst. (%)
CrA-466	1.5 ± 0.1	4.3 ± 0.5	23 ± 2
CrA-466[a]	4.3 ± 2.9	1.8 ± 2.1	14 ± 7
CrA-4107	5.7 ± 2.6	4.1 ± 3.3	19 ± 11
CrA-4111[a]	...	2.1 ± 1.2	70–100*
G-1	5.2 ± 1.2	2.6 ± 2.1	5 ± 2
G-14	4.5 ± 0.2	0.2 ± 0.4	2.8 ± 0.3
G-85	2.1 ± 0.7	2.4 ± 0.8	14 ± 2
G-85[a]	1.0 ± 0.5	0.7 ± 0.6	16 ± 6
G-87	1.5 ± 0.8	0.7 ± 1.2	26 ± 8

NOTES.—Average grain sizes for amorphous and crystalline silicates and crystallinity fraction (mass fraction of crystalline silicates) from the TLTD fit. An asterisk denotes that for the low-S/N spectrum of CrA-4111, there is only marginal evidence of crystalline silicates, so the crystallinity fraction is constrained taking into account the errors in the marginally detected crystalline silicates. The typical error for this value is ~30%.

[a] Long-wavelength composition (17–25 μm).

TABLE 7

SILICATE COMPOSITION

		AM. (OLIVINE-TYPE)			AM. (PYROXENE-TYPE)			FORSTERITE			ENSTATITE		SILICA		
NAME	χ^2	0.1 μm	1.5 μm	6.0 μm	0.1 μm	1.5 μm	6.0 μm	0.1 μm	1.5 μm	6.0 μm	0.1 μm	1.5 μm	0.1 μm	1.5 μm	6.0 μm
CrA-466	10.2	...	77^{+3}_{-3}	...	...	...	...	$5.2^{+0.3}_{-0.3}$	...	...	$0.01^{+0.24}_{-0.01}$	$1.9^{+1.3}_{-1.1}$	...	...	16^{+2}_{-2}
CrA-466[a]	9.3	1^{+22}_{-1}	28^{+78}_{-26}	...	0^{+10}_{-0}	4^{+12}_{-3}	54^{+38}_{-42}	9^{+10}_{-3}	...	...	...	...	...	$0.4^{+2.4}_{-0.4}$	$3.8^{+8.6}_{-2.4}$
CrA-4107	1.3	$0.2^{+3.1}_{-0.2}$	$2.6^{+7.4}_{-2.5}$	73^{+25}_{-42}	2^{+11}_{-2}	$0.7^{+6.0}_{-0.7}$	3^{+25}_{-3}	$2.0^{+1.1}_{-0.7}$	$0.0^{+2.0}_{-0.0}$	11^{+12}_{-8}	$1.2^{+1.7}_{-0.8}$	$2.2^{+2.6}_{-1.6}$	$0.11^{+0.61}_{-0.11}$	$1.3^{+1.3}_{-0.9}$	$1.3^{+5.0}_{-1.3}$
CrA-4111[a]	1.9	...	...	...	...	...	...	$11^{+5}_{-5.}$	...	...	3^{+47}_{-3}	62^{+13}_{-18}	...	7^{+13}_{-66}	18^{+21}_{-17}
G-1	6.2	2^{+13}_{-2}	...	6^{+17}_{-6}	$0.08^{+0.84}_{-0.08}$	$13.6^{+2.9}_{-9.2}$	73^{+8}_{-26}	$0.48^{+0.23}_{-0.27}$	$0.12^{+0.27}_{-0.12}$	$0.4^{+2.9}_{-0.4}$	$0.02^{+0.14}_{-0.02}$	$2.1^{+0.8}_{-1.2}$	$0.56^{+0.16}_{-0.31}$	$0.4^{+0.3}_{-0.3}$	$1.2^{+1.8}_{-1.1}$
G-14	6.5	$0.7^{+2.7}_{-0.7}$	32^{+2}_{-2}	...	...	...	64^{+2}_{-4}	$2.7^{+0.2}_{-0.2}$	$0.05^{+0.56}_{-0.05}$	$0.02^{+1.67}_{-0.02}$	...	...	...	...	...
G-85	6.1	11^{+2}_{-1}	...	$0.4^{+4.6}_{-0.4}$	...	61^{+5}_{-4}	14^{+10}_{-10}	$3.4^{+0.5}_{-0.3}$	...	...	$2.9^{+0.4}_{-0.3}$	$2.4^{+0.8}_{-0.8}$	...	$0.36^{+0.30}_{-0.29}$	$4.6^{+1.6}_{-1.8}$
G-85[a]	1.1	2^{+19}_{-2}	53^{+19}_{-34}	...	26^{+29}_{-18}	3^{+21}_{-3}	...	$9.5^{+7.1}_{-2.6}$	...	...	$0.8^{+3.8}_{-0.8}$	5^{+3}_{-3}	$0.02^{+0.97}_{-0.02}$	$0.36^{+0.93}_{-0.34}$	$0.3^{+5.1}_{-0.3}$
G-87	3.4	$0.3^{+5.6}_{-0.3}$	55^{+16}_{-35}	...	...	19^{+47}_{-18}	...	12^{+3}_{-2}	$0.3^{+5.0}_{-0.3}$	$0.6^{+11.4}_{-0.6}$	11^{+64}_{-4}	$0.2^{+3.2}_{-0.2}$	...	...	2^{+2}_{-2}

NOTES.—Percentage of the mass fraction of the different materials and reduced χ^2 for each fitted spectrum. The amorphous silicates are classified as having olivine or pyroxene stoichiometry. The crystalline silicates are forsterite, enstatite, and silica. Amorphous carbon grains are included as well. The summary lists the final crystallinity fraction and the mass average grain size (including crystalline and amorphous grains).

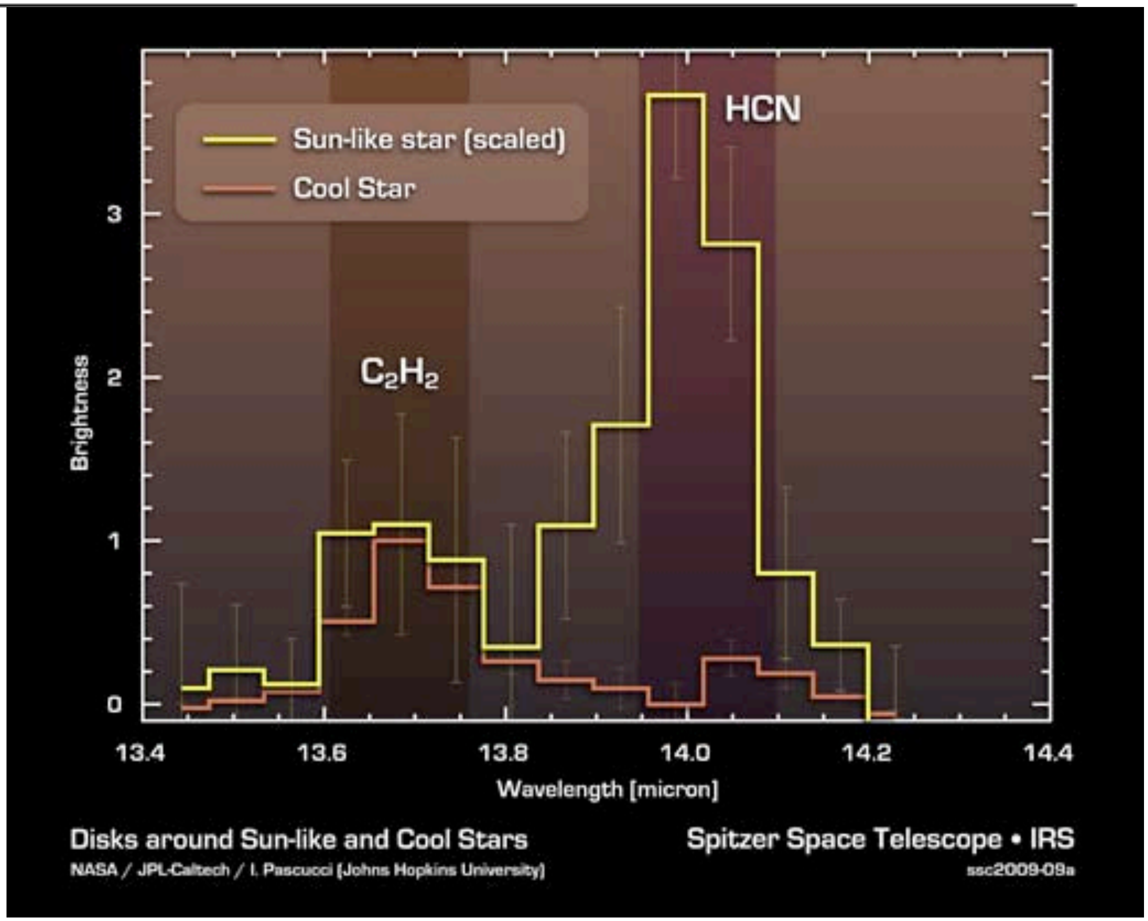
[a] Long-wavelength composition (17–25 μm).

Sicilia-Aguilar et al. 2008

5) Gas content

Statistics on the Firm Detections of HCN and C_2H_2 from the Sun-like and Cool Stars with Disks.

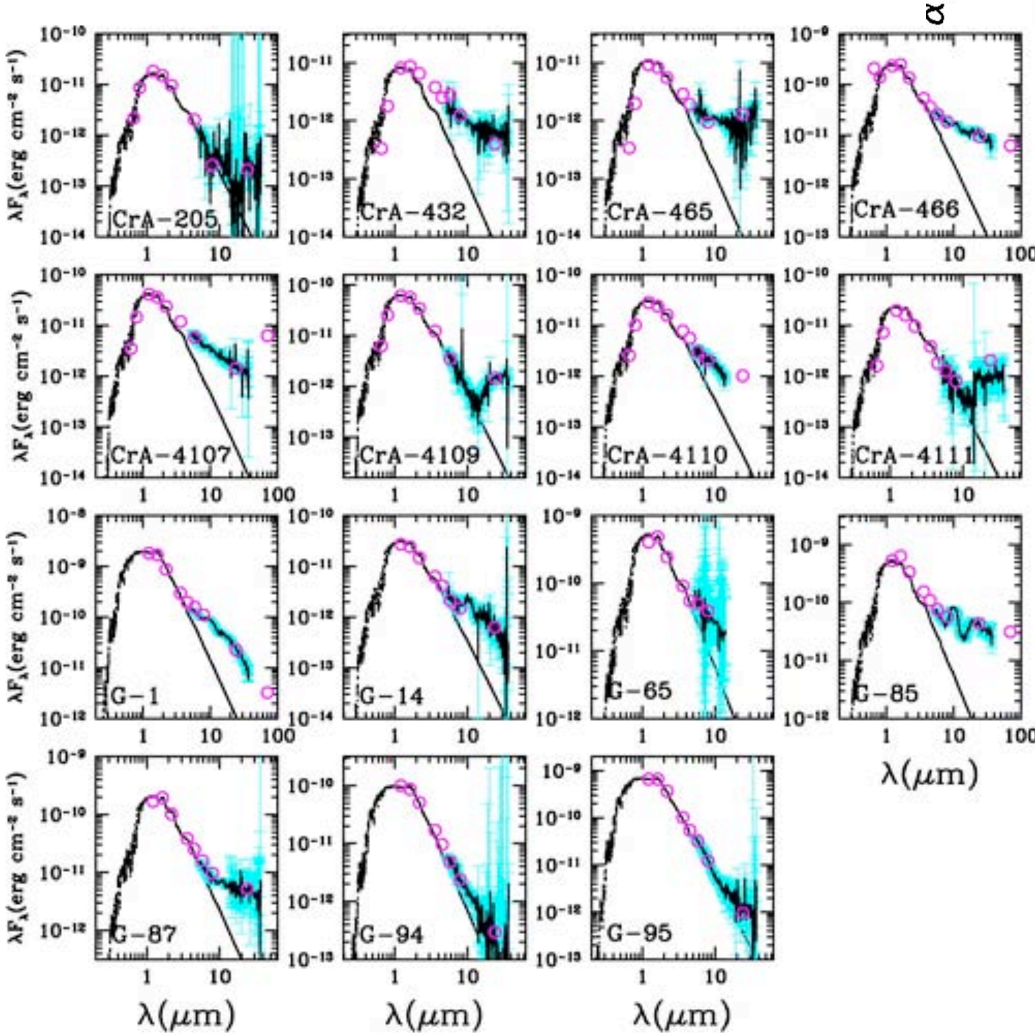
Sample	C_2H_2 Detections	HCN Detections	$\langle T_\star \rangle$ [K]	$\langle M_\star \rangle$ [$M_\odot$]	$\langle R_\star \rangle$ [$R_\odot$]	$\langle \dot{M} \rangle$ $M_\odot$ yr^{-1}
Sun-like Stars	4/44	13/44	3900	0.8	2.1	1.3×10^{-8}
Cool Stars	5/14	0/14	3000	0.1	0.7	$< 3 \times 10^{-11}$



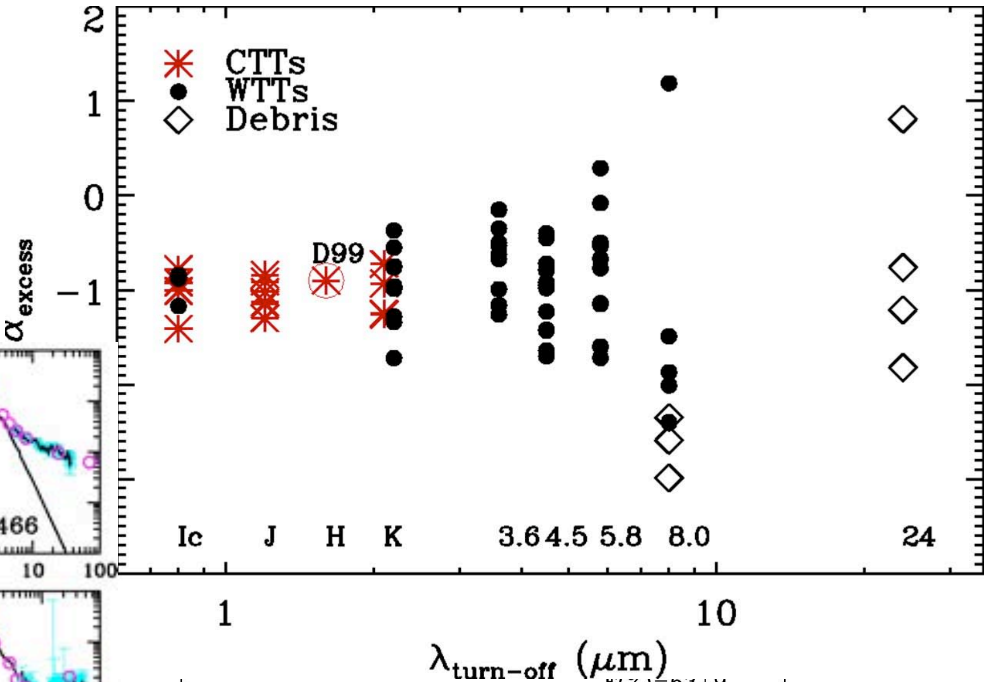
May provide different chemistry for planets around cool stars

[redacted]

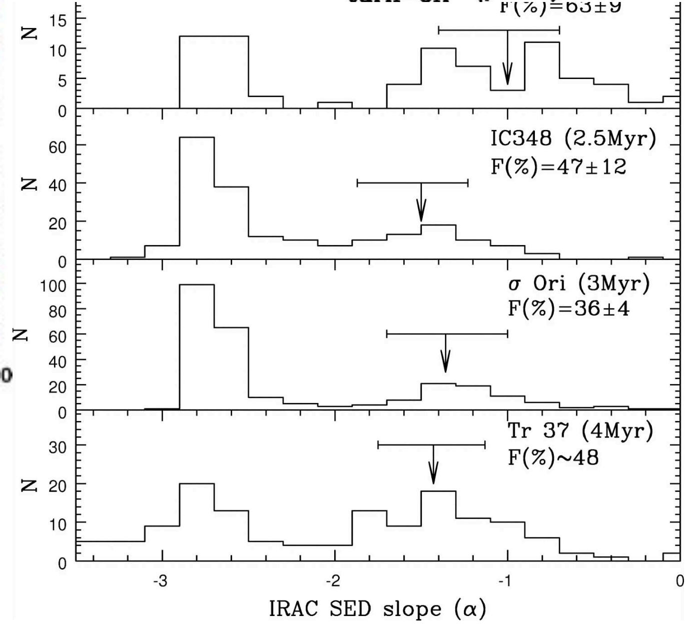
SED Slopes



CrA-205
CrA-432
CrA-465
CrA-466
CrA-4107
CrA-4109
CrA-4110
CrA-4111
G-1
G-14
G-65
G-85
G-87
G-94
G-95
λF_λ(erg cm^-2 s^-1)
λ(μm)



CTTs
WTTs
Debris
D99
Ic
J
H
K
3.6
4.5
5.8
8.0
24
α_excess
λ_turn-off (μm)



IC348 (2.5Myr)
F(%)=47±12
σ Ori (3Myr)
F(%)=36±4
Tr 37 (4Myr)
F(%)~48
N
IRAC SED slope (α)