Near-Infrared Photometry and Spectroscopy of Young Brown Dwarfs and Planetary-Mass Objects in Serpens

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Abstract

We present the results of deep NIR photometric surveys searching for very low mass young stellar objects (YSOs) such as brown dwarfs (BDs) and planetary-mass objects (PMOs) in Serpens Cluster A/B/South and subsequent NIR spectroscopy with Subaru/MOIRCS. Optical slitless spectroscopy for a part of candidates in Cluster A were carried out with UH88/WFGS2. Spectroscopic observations have demonstrated their youth and low effective temperatures. The spectroscopic temperatures for newly identified objects, together with the bolometric luminosities, indicate that they could be young BDs/PMOs. Some brighter YBDs exhibit Hα/Brγ emissions and/or infrared excesses, ascribed to the presence of accretion and/or circum-substellar disks. All the spectroscopic mass function appear to be flat toward the planetary-mass regime, but their slope slightly change depending on the cloud, while all the photometric mass function appear to be increasing. Comparison the spatial distribution of YSOs with that of CO/H2 column density suggest that more massive YSOs like TTSs are formed in the deep cloud core.

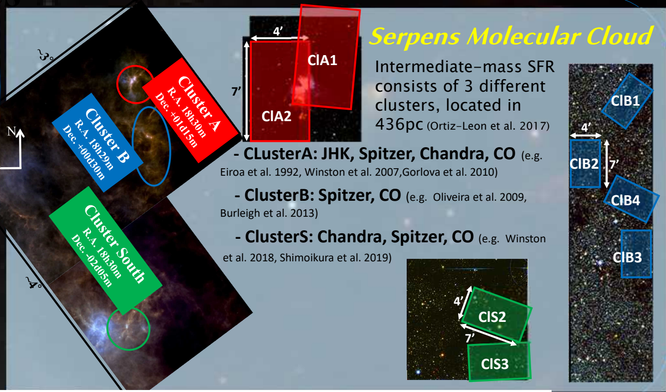
Introduction & Observations

How abundant are brown dwarfs and planetary-mass objects?
How they form?

Is the formation of substellar-mass objects analogous to that of low-mass stars? Or, is it rather similar to that of planets, or..?
Are they ubiquitous?

We have studied properties of very low-mass YSOs and the IMF in Serpens from photometry and spectroscopy.

	Photometry		Spectroscopy			
Telescopes	Subaru	UKIRT	Subaru		Kanata	UH88
Instruments	MOIRCS	WFCAM	MOIRCS	IRCS	HONIR	WFGS2
Date of Obs.	2007/6/8,22	2010/8/9,10,11	2017/8/29,30 2018/9/2,4 2020/9/2,3	2020/9/21	2020/2/18,19	2014/9/23
Cluster	A	B/South	A/B/South	South	A/B	A
seeing	0".4-0".9	0".7-2".1	0".3-0".8	~0".4	1".8-2".5	~2".0
FOV/Number of objects	~8'×8'	~14'×14'×12	479 obj.	2 obj.	15 obj.	~12'×12'(121 obj)
Limit mag./Target mag.	23.2, 22.4, 21.5 (J,H,Ks)	21.5,20.3,19.5(J,H,K)	11-21(H)	16-17(H)	9-12(H)	9-20(r)



Serpens Molecular Cloud

Intermediate-mass SFR consists of 3 different clusters, located in 436pc (Ortiz-Leon et al. 2017)

- ClusterA: JHK, Spitzer, Chandra, CO (e.g. Eiroa et al. 1992, Winston et al. 2007, Gorlova et al. 2010)
- ClusterB: Spitzer, CO (e.g. Oliveira et al. 2009, Burleigh et al. 2013)
- ClusterS: Chandra, Spitzer, CO (e.g. Winston et al. 2018, Shimoikura et al. 2019)

Fig1. Herschel (left) and Subaru/UKIRT 3color composite image (B:160μm/J, G:250μm/H, R: 500μm/K)

Photometry: Identification of YSOs

★ **Classification of sources using Color-Color Diagram** (Fig.2)

Color-color diagram of the all field (top) and cloud field (bottom) in which the H2 column density, N(H2), is greater than 5×10^{21}[cm^{-2}], in Cluster A, B, South (left to right), respectively.

- Background sources are reddened by molecular cloud
- YSOs = Reddened objects with NIR excess (Class I/II color)

★ **Estimate of Luminosity for YSOs**

Dereddened absolute *J*-band luminosity (*Jo*-luminosity)

Extinction= difference between the observed and intrinsic color

Significant fraction of extremely low-luminosity YSOs

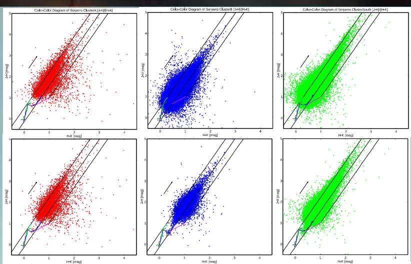


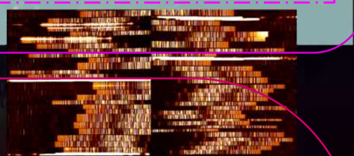
Fig2. Color-Color Diagram of the all (top) and cloud (bottom) in Serpens Cluster A, B, South (left, center, right).

★ **Estimate of Photometric Mass for YSOs**

Jo-luminosity, together with mass-luminosity relation ← mass and *Jo*-luminosity relation is derived from the evolutionary models (Baraffe et al.1998,03;15, Burrows et al. 1997) on the assumption of Class II ages, 1 Myr (typical)

However, it is still uncertain to estimate photometric mass for substellar-mass objects, so spectroscopy is required.

Are they bona fide young BDs and PMOs?



Spectroscopy: Estimate of Mass/Age of YSOs

Spectra and SED

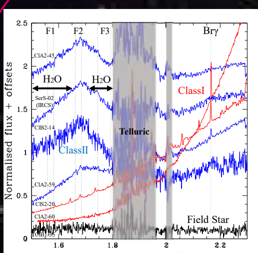


Fig.3. HK band spectra of YSOs such as Class I (red), Class II (blue) and probable field stars (black).

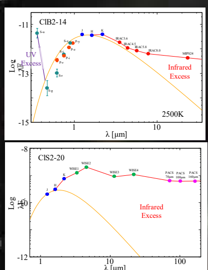


Fig.4. SED of a YBD (top) and a Class I (bottom), whose spectra is shown in Fig.3

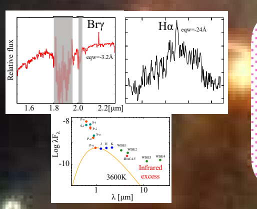


Fig.5. Spectra & SED of ClA1-39 Subaru/MOIRCS NIR spectra (top left), UH88/WFGS2 optical spectra from (top right), and SED (bottom)

★ **Spectra for YSOs** (Fig.3 & 5)

Derived NIR spectra show water absorption feature. From reddening-independent water index, we confirm that very low-luminosity YSOs have low-temperature.

★ **Multi-Photometry: SED fitting of YSOs** (Fig.4)

B.B. fitting for multi-wavelength photometry: Extinction-corrected SED derived from our Subaru/UKIRT *JHK* obs. + SDSS, PS1, Spitzer, WISE, Herschel archival data

← Photosphere (~1μm: *YJH*) + Disk (>2μm)

Very low-luminosity YSOs are indeed cool (<3000K).

Estimate of Temperature of YSOs

$$Q = \left(\frac{F1}{F2}\right)\left(\frac{F3}{F2}\right)^{1.282}$$

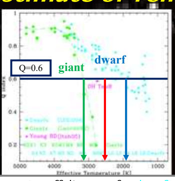


Fig.5: Q-Teff diagram for dwarfs and giants. Bold lines show a part of results in this work. The Q value of YBD (DH TauB) shows between dwarfs and giants.

★ **Temperature of low-mass YSOs** (Fig 5)

Reddening-independent water index:Q

Water absorption feature is shown in the cool stars.

← Cooler stars exhibit stronger water absorption feature.

← BUT, the Q-Teff relation depends on the surface gravity

The Teff derived from Q-T_{dwarf} is ~1000K lower than that derived from Q-T_{giant} relation, at most.

→YSOs have the surface gravity between dwarfs and giants

Teff of YSOs = Average of the Teff derived from Q-T_{dwarf} and Q-T_{giant} relation

Estimate of Mass and Age of YSOs

★ **Estimate Mass/Age on the HR diagram** (Fig. 6)

Together the bolometric luminosity and Teff with the evolutionary tracks (Burrows et al. 1997; Baraffe et al. 2003/15)

⇒ 43 YBDs, 24 PMOs and 58 TTSs are discovered

Some brighter YBDs exhibit Hα/Brγ emissions and/or infrared excesses, ascribed to the presence of accretion and/or circum-substellar disks.

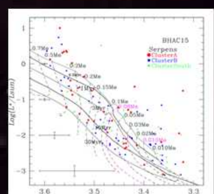


Fig.6. HR-diagram with evolutionary tracks (Baraffe et al. 2015).

Mass Function of YSOs

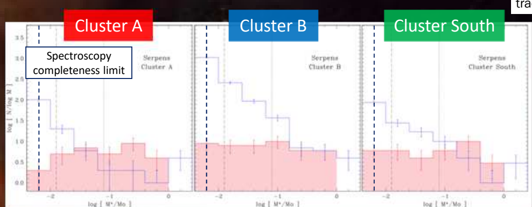


Fig.7: Mass functions in Serpens Cluster A, B, South (left to right). Photometric MF (blue open) and spectroscopic MF (red filled) is shown. The dotted lines, dash-dotted lines, and dash lines represent the star/BD boundary, the BD/PMO boundary, and the completeness limit, respectively.

★ **Mass function for YSOs** (Fig. 7)

Comparison of photometric MFs (open) and spectroscopic MFs (filled) in Cluster A,B, South (left, center, right)

(1) All the photometric MFs appear increasing toward planetary-mass regime.
(2) All the spectroscopic MFs do not show clear increase.
(3) There seems to be a small peak around 0.1 Mo in Cluster A/South.

Spatial Distribution of YSOs in Cluster A

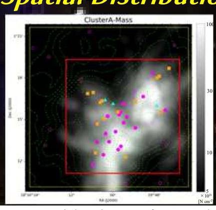


Fig.8:Spatial distribution of YSOs with different mass (filled: NIR, open:Opt) ●:Low-mass YSOs ■:YBDs ▲:PMOs

★ **Spatial Distribution of YSOs and Gas/Dust** (Fig.8&9) Gas(CO:contour) Dust(Herschel:monochromatic image)

(1) More massive YSOs like TTSs are located on the dense gas/dust region.
(2) Younger objects are located on the dense gas/dust region.

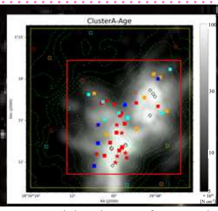


Fig.9:Spatial distribution of YSOs with different mass (filled: NIR, open:Opt) ◇:Class0 (Enoch et al. 2011, Aso et al. 2018) ★:ClassI spectra ■:≦1Myr ■:1-3Myr ■:3-10Myr ■:10-30Myr

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