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A Photometric/Spectroscopic Study of Very low-mass objects in R CrA with Subaru/MOIRCS

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IMFs of Very low-mass objects (VLMOs) such as brown dwarfs (BDs; <0.08M$_\odot$) and planetary-mass objects (PMOs; < 0.013M$_\odot$) and their formation processes are still open issues. We have been carrying out deep NIR photometric/spectroscopic surveys (K ~19-21 mag) of VLMOs in low to massive nearby Star Forming Regions (SFRs) to reveal environmental dependance of substellar IMFs and formations of VLMOs. We newly focus on the R CrA region (~150pc). UKIRT/WFCAM photometry identified ~500 VLMO candidates. However, there are uncertainties of background contaminations and age assumptions. Thus, we performed Subaru/MOIRCS multi-object follow-up spectroscopy of ~120 objects including ~30 VLMO candidates. 1 Young BD, 1 PMO and 5 Class I objects have been identified. Here we report their analysis and results.

Introduction

Very Low-mass Objects

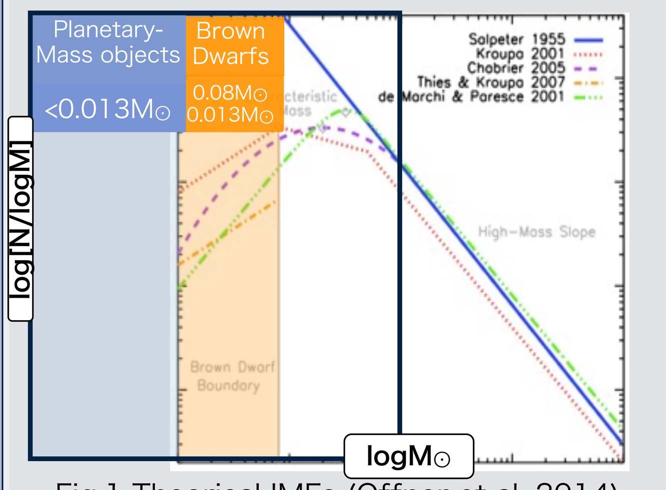


Fig.1 Theorical IMFs (Offner et al. 2014)

Stellar IMFs from 10M$_\odot$to 0.5M$_\odot$ are universal.
Substellar IMFs have large uncertainty.

How abundant are brown dwarfs and planetary-mass objects?
Do their IMFs depend on the local environment or not?

→ Photometric/spectroscopic surveys in the various star forming regions (SFRs) of VLMOs

Survey of Very Low-mass Objects

JHK Photometric Survey
Identify VLMO candidates
- Select YSOs from NIR excess
- Estimate mass with age assumption of 1Myr and evolutionary models

e.g. Lupus I, Ophiuchus (low-mass SFRs)
Serpens, Perseus (intermediate-mass SFRs)
Cygnus, Orion B (massive SFRs)

Follow-up Spectroscopy
Confirm candidates as VLMOs
- Remove background stars from $Br\gamma$ absorption
- Estimate Teff from water absorption band
- Derive mass/age of YSOs comparing with evolutionary tracks in HR diagram

- Derive mass functions
- Compare with cloud properties

e.g. S106, Perseus, Serpens

Lupus I, Ophiuchus (@150pc)
Low-mass SFR

Photometric survey (~3000min^2) with UKIRT/WFCAM identified ~8500 VLMO candidates in total.
Derived IMFs (subtracted reference number) are increasing toward completeness limit.
T Tauri Stars (TTS) and BD ratios differ between the clouds.

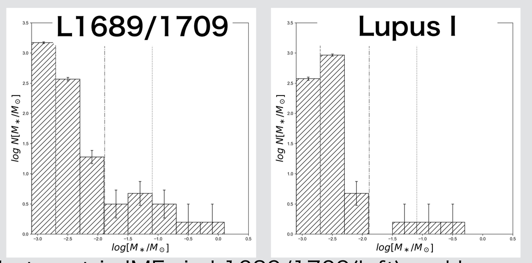
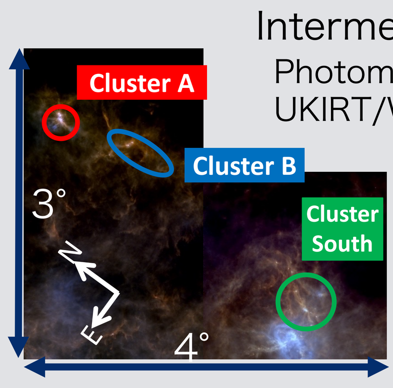


Fig.2 Photometric IMFs in L1689/1709(left) and Lupus I (right)

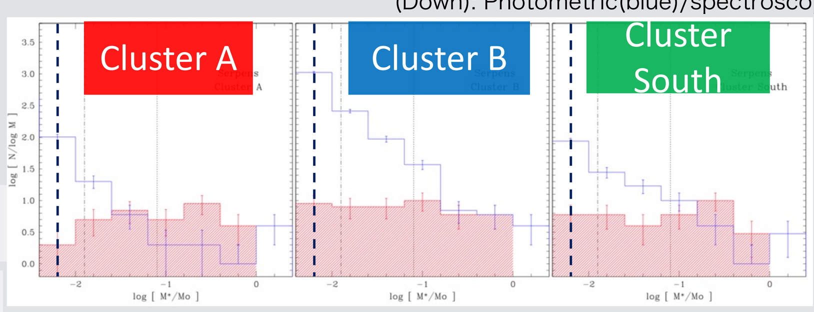
Serpens Cluster (@436pc, Oasa 2021)
Intermediate-mass SFR

Photometric survey with Subaru/MOIRCS and UKIRT/WFCAM identified ~8000 VLMO candidates.



Follow-up Spectroscopy by Subaru/MOIRCS obtained 496 spectra.
→ About 140 YSOs (69 BDs and PMOs) are confirmed, while 2/3 objects were background stars/galaxies.

Fig.3 (Up):Herschel 160/250/500 image.
(Down): Photometric(blue)/spectroscopic(red) MFs in Serpens A/B/South



Photometric MFs (blue; 1Myr assumption) appear to increasing toward PMO regime. Spectroscopic MFs (red) do not show clear increase.

R Corona Australis region

Low to intermediate-mass SFR
Distance: ~150pc (Gali et al. 2020)
Cloud mass: ~820M$_\odot$ (Bresnahan et al. 2018)
R CrA is a Herbig Be star. X-ray to Radio observations were identified dozens of YSOs in this region.
A few BD candidates were detected by photometric surveys with Spitzer (Perterson et al. 2011), but PMO surveys have not been performed.

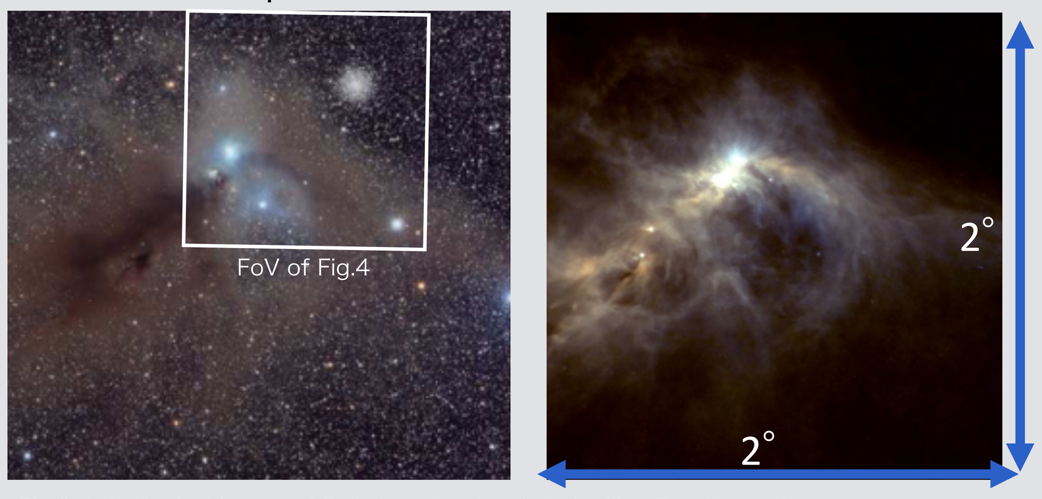


Fig.3 (left):Optical image of R CrA region Credit:Loke Kun Tan.(StarryScapes) (right):Herschel 160/250/500μm composite image

Purpose
・Identify BDs and PMOs in R CrA region.
・Derive their IMFs and spatial distributions to compare cloud properties.

Photometric Survey

For subtracting background contaminations from IMFs

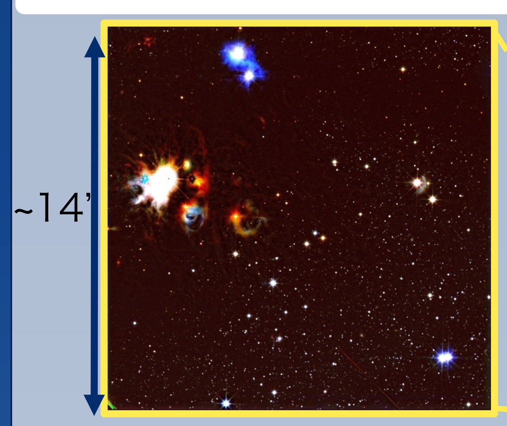


Fig.5 UKIRT/WFCAM JHK 3 color composite image of R CrA region.

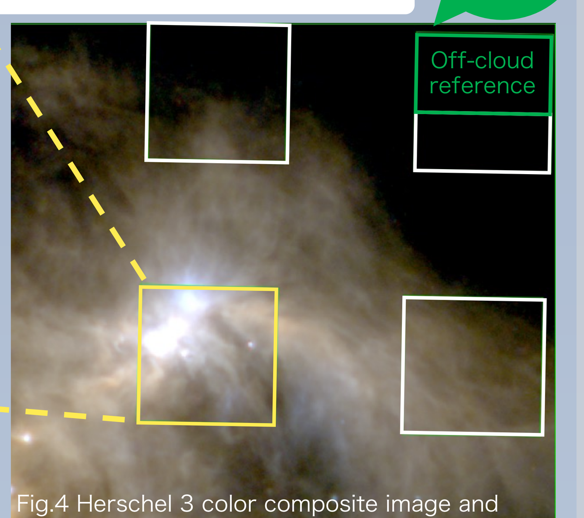


Fig.4 Herschel 3 color composite image and FoV of UKIRT/WFCAM.

Observation

Telescope	UKIRT
Instrument	WFCAM
Observed bands	J, H, K
Date of Observation	2010/08/08
Seeing	~0.8"
Field of View	13.7'×13.7' × 4 fields
Exp. time	800s
Limit mag. (S/N=10)	J ~21, H ~20, K ~19mag

YSO Selection

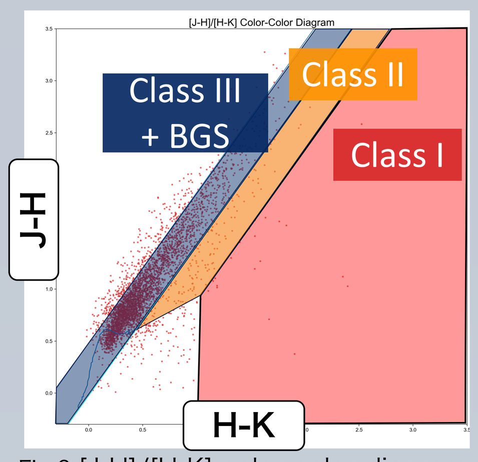


Fig.6 [J-H]/[H-K] color-color diagram

YSO candidates with NIR excess were selected.
Their Av were estimated from JHK colors.

Class III+BGS	Class II	Class I
14492	433	60

Photometric masses of Class II candidates were derived from evolutionaly models (Baraffe et al. 2015) with the **age assumption** of 1 Myr.

PMO Cand.	BD Cand.	TTS Cand.
425	4	4

Comparing VLMO candidates with Cloud

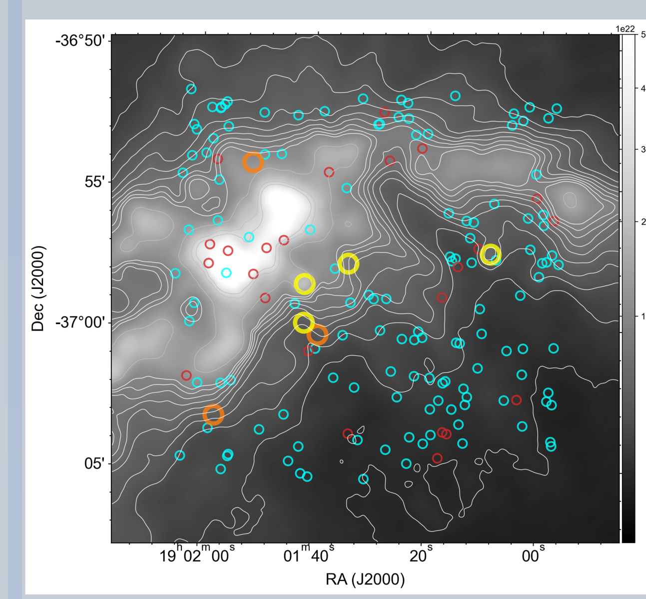


Fig.7 Spatial Distribution of Class II objects with Herschel H_2 column density map.

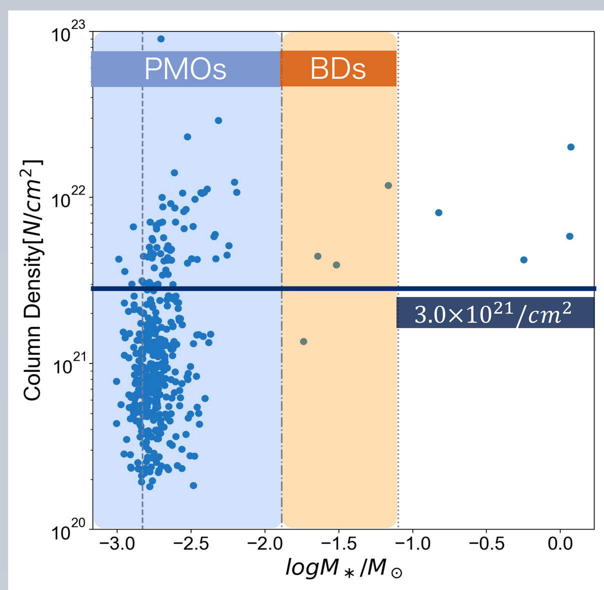


Fig.8 Photometric mass vs Herschel dust column density.

The highest dust density regions are dominated by Class I candidates. Most of BD/TTS candidates are located in southern part of cloud.

Almost all BD/TTS candidates are located in the higher dust density regions ($N_{H_2} \gtrsim 3.0\times10^{21}/cm^2$). PMO candidates are not depending on the local dust densities.

Similar mass-dust relations are also seen in Ophiuchus and Lupus I clouds.
(Follow-up spectroscopy with MOIRCS will be conducted in S23A)

→ Does the local dust density affect the low-mass star formation?

Initial Mass Function

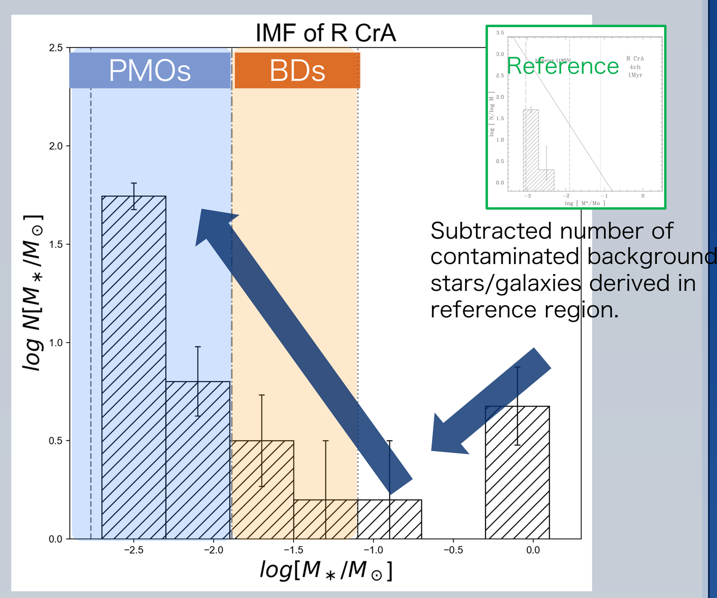


Fig.9 Derived IMF of R CrA region. Numbers of objects estimated in reference regions (up) are subtracted.

Derived IMF shows a local peak in the TTS regime and increases to completeness limit (PMO regime). IMFs in the higher dust density regions shows sallower slopes.

Uncertainties in the photometric survey
・Background contaminations
・Age assumptions
→ Spectroscopy is necessary to derive mass and age of YSOs

Follow-up Spectroscopy

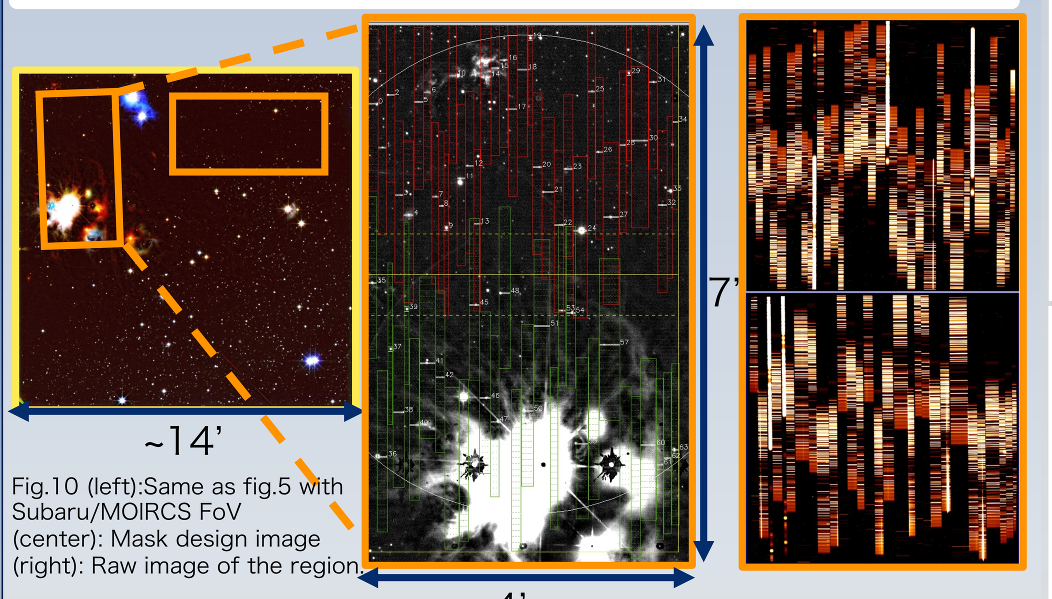


Fig.10 (left):Same as fig.5 with Subaru/MOIRCS FoV (center): Mask design image (right): Raw image of the region

Observation

Telescope	Subaru
Instrument	MOIRCS
Observed bands	HK
Date of observation	2020/09/02
Seeing	~ 0.3"
Field of View	3.9'×6.9' ×2 masks
Number of objects	116
Exp. time	2100s, 2400s
Target mag.	H < 20mag

Derived Spectra

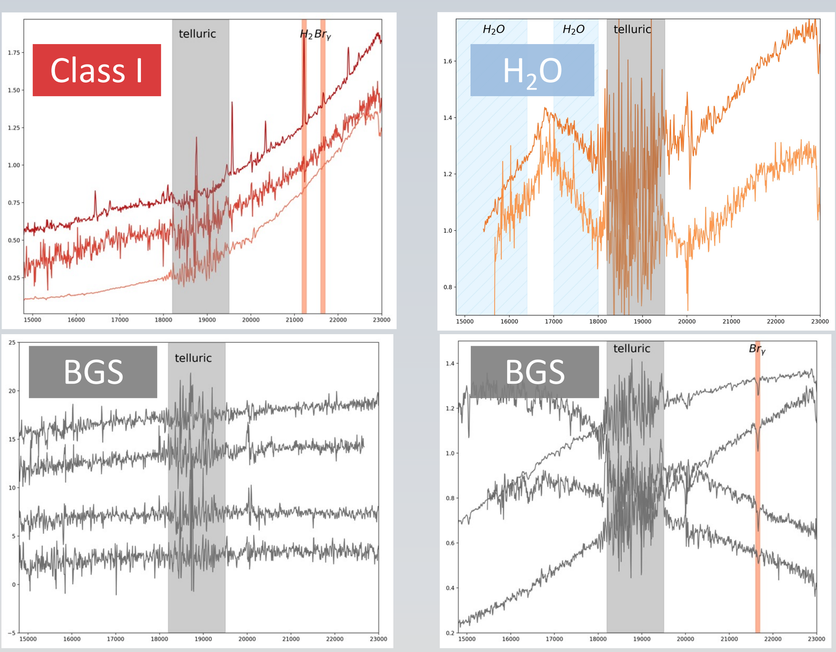


Fig.13 Examples of Derived spectra.

Classified derived spectra with their features.
○YSOs
- Class I : Large IR excess
- H_2O : Water absorption bands in H-band
○Background objects (BGOs; stars/galaxies)
- $Br\gamma$ absorption
- No significant features in HK-band

photometry	PMO Cand.	BD Cand.	Class I	Other
Observed	17	1	10	86
Analysed	14	1	5	65
Poor S/N	12	0	1	37

Poor S/N includes
- Not enough spectral coverage to estimate Q value
- Suffered from bright OH emissions (see "Issues").

T_{eff} Estimate

T_{eff} were derived from the reddening independent water absorption index Q (Oasa 2011)

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

F1=1.56-1.58
F2=1.665-1.685
F3=1.745-1.795(μm)

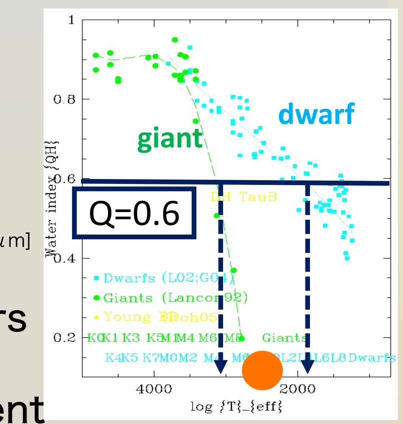


Fig. 14 Q-Teff diagram

Water absorption bands are
・stronger for the cooler stars
・sensitive to **surface gravity**
→ Q-Teff relations are **different** between **dwarfs** and **giants**.
YSOs have intermediate surface gravity of them.
→ T_{eff} of YSOs : Average of $T_{eff\text{-}dwarf}$ and $T_{eff\text{-}giant}$.

Estimating Mass/Age of YSOs

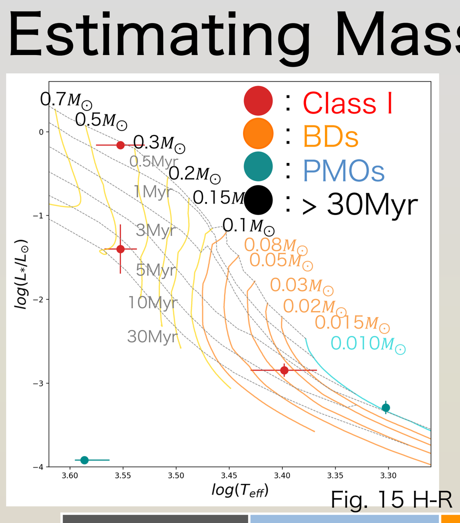


Fig. 15 H-R diagram of objects estimated T_{eff}

Masses and ages of YSOs were estimated from bolometric luminosity and T_{eff} comparing with the evolutionary tracks (e.g. Baraffe et al. 2015).
→ Objects with ages larger than 30Myr are identified as BGOs.

photometry	PMO Cand.	BD Cand.	Class I
Confirmed	1	1	3+2
Other	1	0	1

1 Young BD, 1 PMO and 5 Class I objects have been identified so far.

Issues

Sky OH emissions are too bright, especially for the faint spectra.
Additionally, OH emissions overlap water absorption bands.
→ Derived Q values are unreliable.
1. Subtract sky for A-B pairs.
2. IRAF "background" task to subtract OH emissions.
3. "apall" task to derive spectra
4. Binning 3 or 5 points.

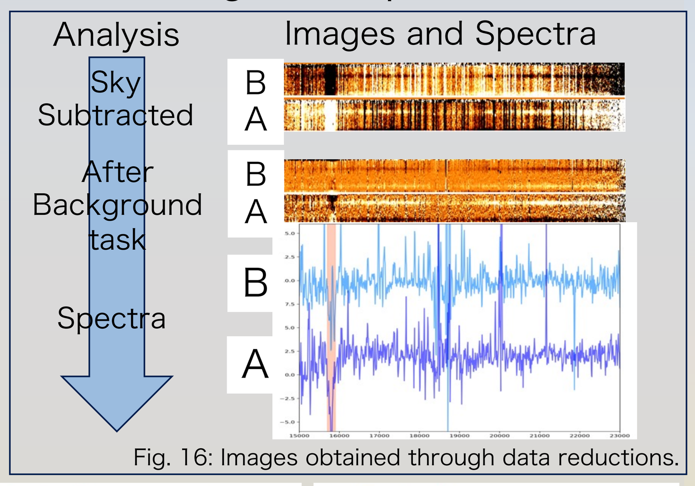


Fig. 16: Images obtained through data reductions.

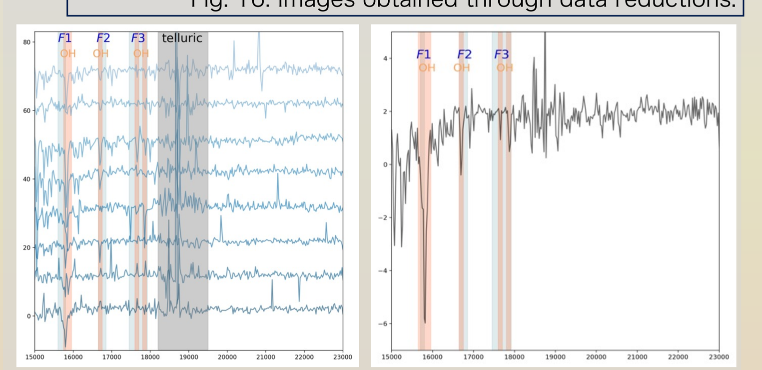


Fig. 17(left):Comparing derived all spectra. (right):Combined spectrum

We plan to interpolate flux suffered from OH emissions. Please comment any other ideas!!

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