Spectral Classification of YSO clusters with FMOS

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1 Introduction

YSO clusters Clusters of Young Stellar Objects (YSOs) are important laboratories for the study of star formation, since most stars are born in such clusters. These YSO clusters are still embedded in molecular clouds from which they formed. Usually, the main part of the cluster, where active star formation is ongoing, is obscured at visible wavelengths. Near-infrared imaging can reveal the whole picture of the YSO clusters.

For example, several NIR images of YSO clusters are shown in Fig. 1. Currently, there are about 100 clusters known within 2 kpc (Lada & Lada 2003). The range of the size, number of stars, total stellar mass, and the age of the clusters are listed in Table 1.

Figure 1: NIR images of YSO clusters

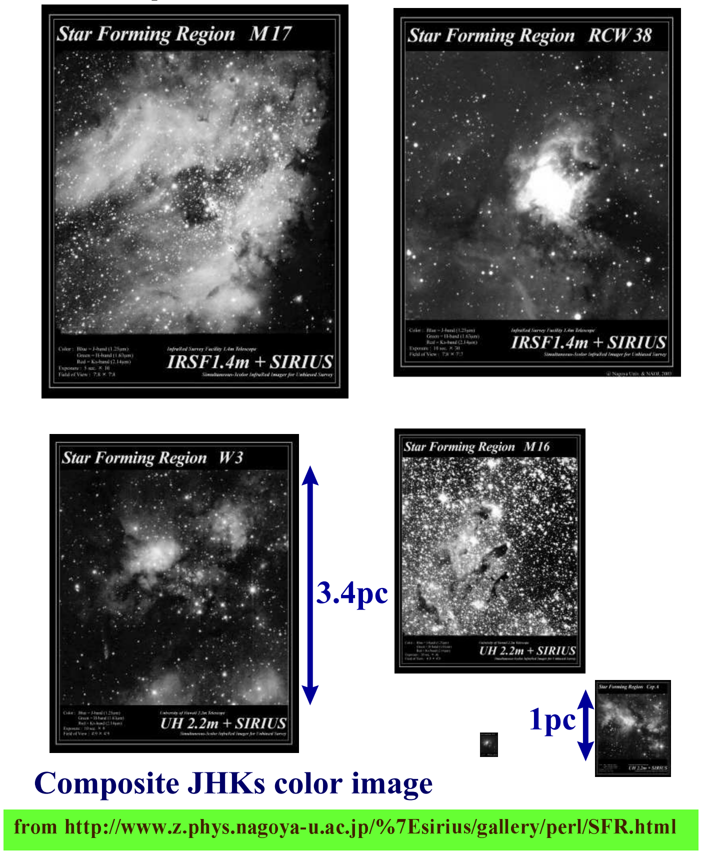


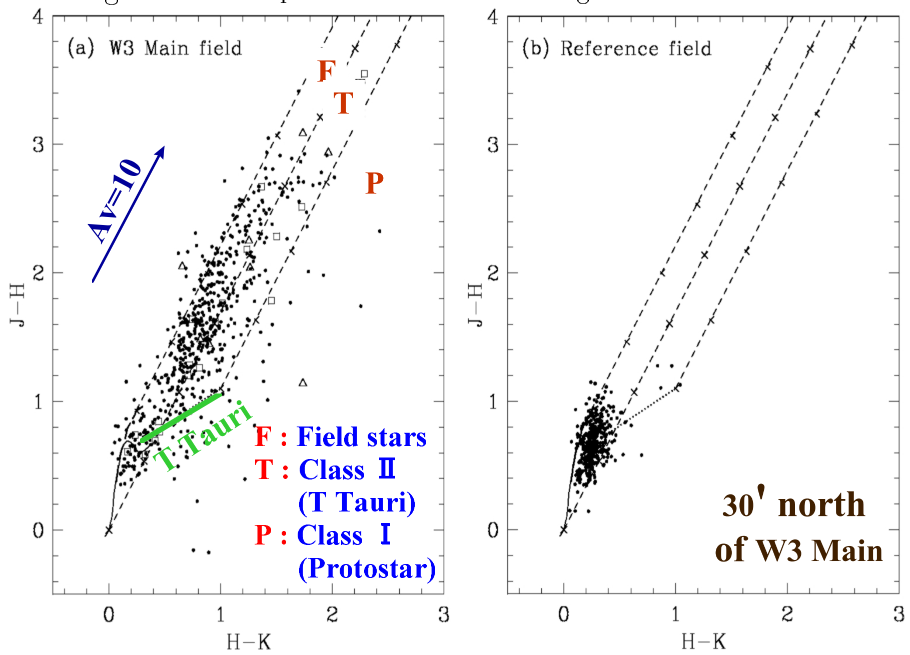
Table 1: Parameters for YSO clusters

Size	0.3–4 [pc]
Number of stars	35–1700
Total stellar mass	20–1000 [$M_\odot$]
Age	0.5–3 [Myr]

Selection of YSO candidates In the near infrared imaging, YSOs are selected based on their colors, because they are associated with the circumstellar material, which radiates at infrared wavelengths. Color-color diagram (generally, J-H vs H-K) is used to select YSO candidates.

Figure 2*a* is the color-color diagram for a YSO cluster, where J-H colors of stars are plotted againt the H-K colors (Ohja et al. 2004). The curve in the lower left represents the main-sequence stars, so out of the cluster region (Fig. 2*b*), stars are concentrated in this part. The arrow in the upper-left of Fig. 2*a* is an extinction vector. Thus stars in the strip of region labeled with “F” are background stars behind the molecular clouds. YSOs can be distinguished from the H-K color excess, which is caused by thermal emission from the circumstellar dust. T Tauri stars (Class II sources) tend to be in the region labeled with “T”. Class I sources, which have larger color excess than T Tauri stars, are distributed in the region labeled with “P”.

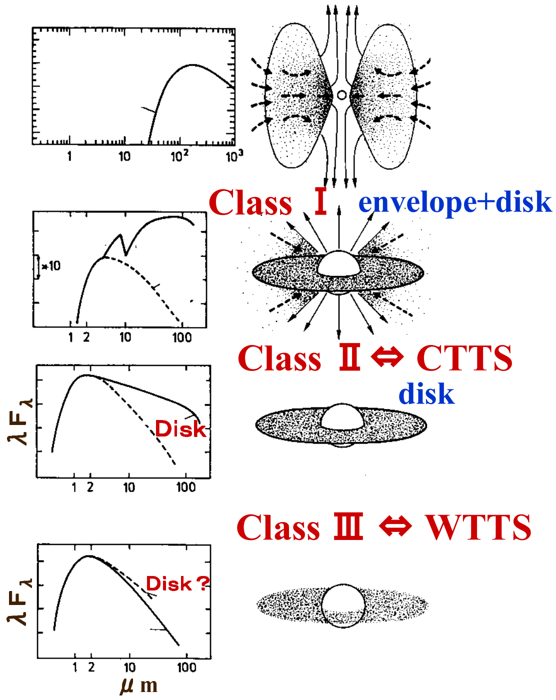
Figure 2: Example of NIR color-color diagram of a YSO cluster



Here we mention the the current picure of the evolutionary sequence of YSOs, which is established for low-mass stars (Fig. 3). In Fig. 3, a star evolves from upper to lower. The evolutionary status is distinguished by the

Spectral Energy Distributions (SEDs), which depend on the circumstellar structure. From the near-infrared two-color diagram (e.g., Fig. 2), we can choose Class I sources, which are surrouded by envelopes and disks, and Class II sources, which are surrounded by disks.

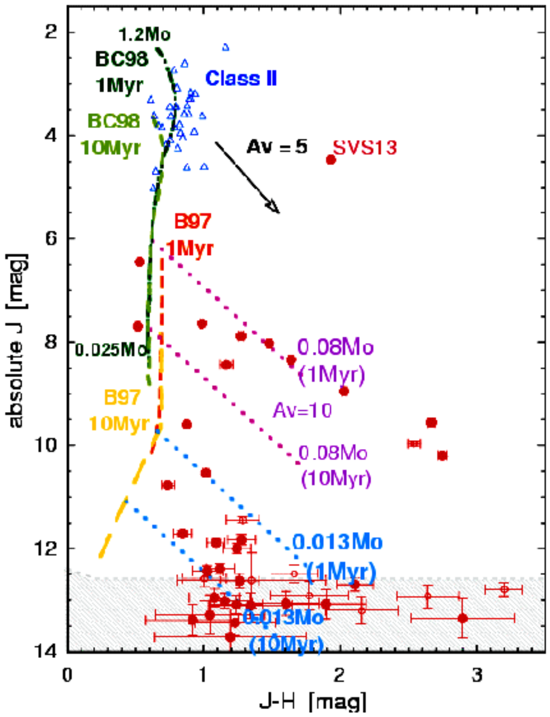
Figure 3: Shematic of the evolution of young stars



There are several problems with the study of NIR imaging. First, identification of the individual members of a cluster is ambiguous, because it only depends on colors. Second, stellar mass and the age cannot be determined independently. To estimate the stellar mass, we often use a color magnitude diagram, for example, J magnitude vs J-H color (Fig. 4). However derived mass depends on the assumption of age. To solve the problems, spectrocopy is neccessary.

NIR spectroscopy of YSOs What's the merits of near-infrared spectroscopy? In infrared, we can observe invisible sources. Moreover, in near-infrared, various lines from both the photoshere and the circumstellar region can be detected. Absorption lines are indicative of stellar parameters, so one could infer the mass and age of a star by placing it on the H-R diagram. Emission lines are thought to arise from the circumstellar region. Therefore, other than SEDs from photometry, near-infrared lines from spectrocopy are potential evolutionary indicators.

Figure 4: Example of NIR color-magnitude diagram of a YSO cluster including very low-mass YSOs.



2 Previous spectroscopic observations

So far, most observations were made with a long slit, so number of observed sources is limited. In addition, most observations were made in the K band, where the extinction is about one tenth of that in the optical.

The small extinction is an advantage of the K band spectroscopy compared to the J/H band spectrocopy (Table 2). However, continuum emission from hot circumstellar dust veils photospheric absorption lines in the K band. The veiling is stronger in younger stars, and it is difficult to detect absorption lines from Class I sources which are surrounded by the dust envelope. Because the dust sublimates at temperatures higher than ~2000 K, the dust emission becomes mitigated in the JH bands.

So, if the high sensitivity is achieved, JH band spectroscopy will be a powerful tool for spectral classification of YSOs including those surrounded by envelopes.

Spectral classification at J/H Then, we will focus on the spectral classification in the J/H bands. For the spectral classification, usually Equivalent Widths (EWs) of the absorption lines are used.[1] To examine the validity of the spectral classification based on the lines, EWs were measured for various

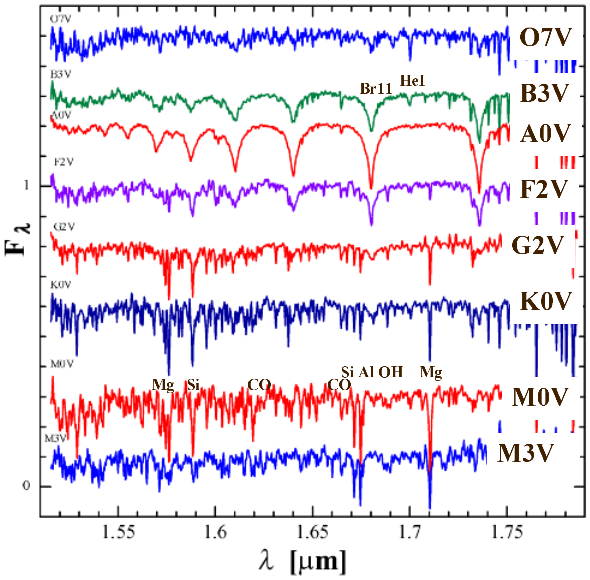
[1]Color induces for molecular bands are also used for late-type stars, which is not discussed further here.

Table 2: Drawback and advantage of the J/H and K band spectroscopy

	J/H	K	Note
Extinction	△	◯	$A_J : A_H : A_K = 1.0 : 0.62 : 0.38$
Veiling	◯	×	Continuum emission from circumstellar dust at $\lambda \gtrsim 2\mu$m

kinds of spectral types. As a result, the classification method is mostly established for MK standard stars (e.g., Wallace et al. 2000; Conti & Howarth 1999; Hanson et al. 1999; Meyer et al. 1998; Hanson & Conti 1996; Ali et al. 1995). In the H band, there are many neutral metal lines, so this band is best to investigate the intermediate spectral types from F0 to K3; On the other hand, J band is rather adequate to investigate the latest spectral types, say, later than M3 (Meyer 2003).

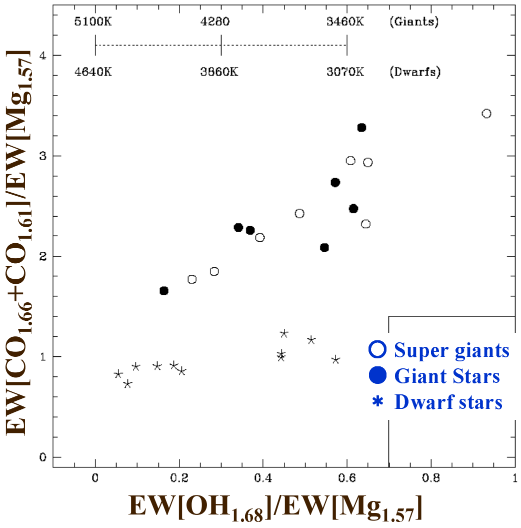
Figure 5: H band spectra of main-sequence stars



For example, H band spectra of main-sequence stars are shown in Figure 5 (Meyer et al. 1998). The spectral resolution is $\lambda/\Delta\lambda \sim 3000$. We can see that O and B stars show He lines, and stars later than F show various metal lines and molecular bands, such as Mg, Al, Si and CO. For YSOs, the photospheric lines are weakened by the circumstellar continuum emission. So EW itself is misleading to determin the spectral types. Instead, ratios of EWs are used.

Figure 6 shows the example of the spectral classification based on EW ratios. Here EW ratio of CO to Mg is plotted against the raio of OH to Mg. Open circles, filled circles and stars represent super giants, giants, and dwarfs, respectively. The figure shows that ratio of CO to Mg can be used as an indicator of the surface gravity, while the raio of OH to Mg is sensitive to

Figure 6: Two dimensional spectral classification at H



the temperature. From such study, Meyer et al. (1998) argued that spectral type can be determined within ± 2 subclass error, from a spectrum with R>1000 and S/N>50.

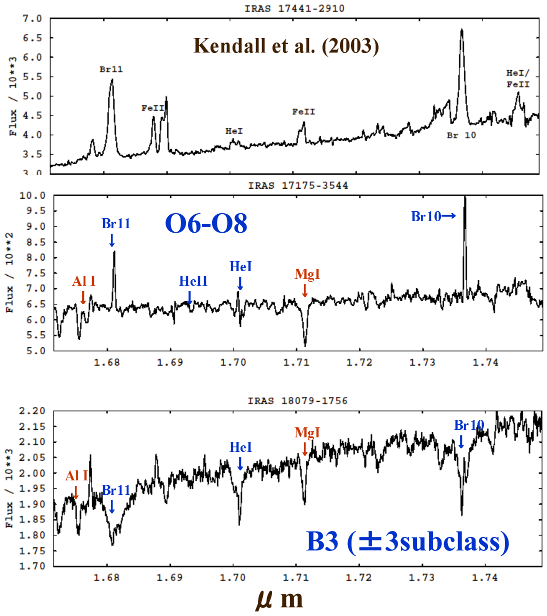
Example : H band spectra of YSOs Currently, there were few studies which applied the classification methods to the H band spectra of young stellar objects. Here, we only introduce one example. Kendall et al. (2003) obtained the spectra of 3 high mass YSOs with resolution R=5000 (Figure 7). For 2 of them, HeI and Br absorption lines were detected and the spectral types were estimated to be O6–O8 and B3. Kendall et al. concluded that spectral type of high-mass YSOs can be determined from a spectrum with R=5000 and S/N>100.

3 Proposed study with FMOS

In summary, JH band spectra should be useful for the spectral classification of YSOs with circumstellar emission. Therefore, we propose to do the spectroscopy of YSO clusters using FMOS to identify the membership of the cluster and to classify them. From this study, morphology of the clusters, age of the members, mass function will be derived. Thus we can understand the entire history of the cluster formation.

Example : W3 To give you a concrete picture of the proposed study, we pick up one star forming region, W3, as an example. Figure 8 is the composit JHK color image of W3. The image was taken with SIRIUS mounted on UH 2.2 m telescope. The FOV is about 5 arcminutes. The limiting magnitude is 19.0 mag at J, 18.1 mag at H and 17.3 mag at K.

Figure 7: H band spectra of high-mass YSOs



This region contains many features of massive star formation in different evolutionary status, from embedded massive YSOs, UCHII regions, CHII regions, and diffuse HII regions. From J-H vs H-K color-color diagram, many YSOs were identified by Ohja et al. (2004)

Figure 9 shows the spatial distribution of the YSO candidates. Circles represent very red source, which have H-K colors more than 2 and which are not detected at J. These stars should be the youngest ones. They tend to be concentrated near the dense part of the molecular clouds. Triangles represent candidate Class I sources, and Stars represent candidate ClassII sources which should be more evolved than the red sources and Class I sources. The Class II sources tend to be more scatterred than the red sources and Class I sources in the region. In total 201 YSO candidates were identified by Ohja et al. (2004)

In our proposal, about 200 YSO candidates are observed in the J and H bands, with spectral resolution of 2000. The J and H magnitudes are brighter than 19 mag and 18 mag, respectively. We need signal to noise ration of more than 35 for the purpose of spectral classification. Then the exposure time will be 5.4 hours for H and 6.5 hours for J. We expect that evolutionary status of YSOs will be classified by their absorption and emission lines.

Figure 8:

W3: Composite JHKs color image

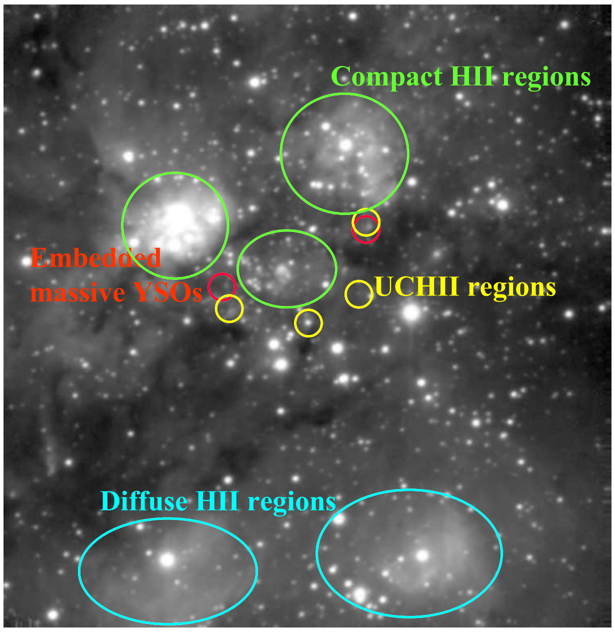
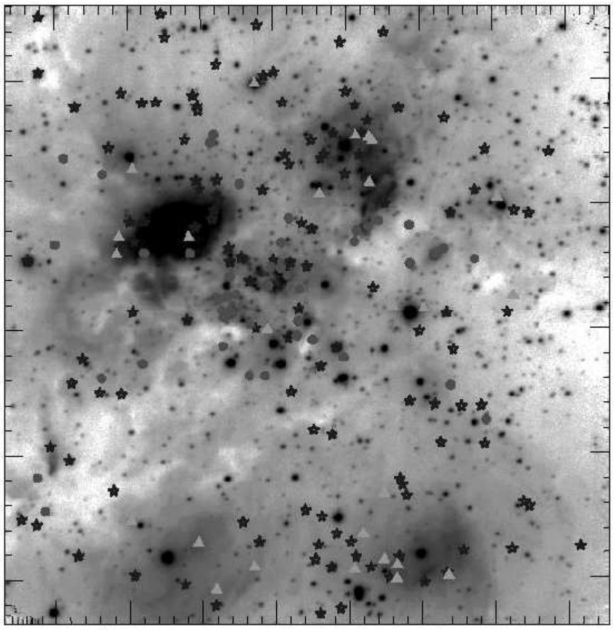


Figure 9: Spatial distribution of YSOs in W3



4 Summary

First we argued that J H band spectroscopy will be useful for spectral classification of YSOs which are obscured and veiled by the circumstellar emission. Then we proposed JH band spectroscopy of YSO clusters with FMOS to constrain the mass and age of the cluster members. We picked up W3 as an example of the proposal. Finally we expect that the JH band spectra of hundreds of YSOs bring us a new aspect for the classification method for YSOs, which is currently base on the SEDs from photometry!

5 References

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