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TOWARDS AN UNDERSTANDING OF THE FORMATION OF STARS AND PLANETS

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RESUMEN

Los procesos que llevan a la formación estelar son uno de los principales temas de investigación en astronomía. Se han desarrollado rápidamente durante la década pasada, estimulados por la construcción de grandes telescopios y lanzamiento de telescopios espaciales. No obstante, todavía hay muchas preguntas que no han sido respondidas vinculadas a los estados tempranos de la formación estelar así como muchos detalles de los procesos en etapas posteriores. Además, se han encontrado más de 150 exoplanetas que orbitan alrededor de estrellas cercanas, tipo solar, que nos motivan a investigar los procesos involucrados en la formación de sistemas planetarios alrededor de estrellas. En este momento de planeación para la construcción de Grandes Telescopios Coreanos, hemos formado un equipo de investigación para contribuir a la comprensión de estas preguntas fundamentales. También presentamos los temas de investigación que deseamos estudiar con los Grandes Telescopios Coreanos.

ABSTRACT

The processes leading to star formation are one of main topics of research in astronomy. The area has developed rapidly during last decade, stimulated by the construction of large telescopes and the launch of space telescopes. There are still many unanswered questions concerning the early stages of star formation as well as the many detailed processes in the later stages. In addition, more than 150 exoplanets orbiting nearby solar-type stars have been found up to now, and therefore we should also investigate the processes involved in the formation of planetary systems around stars. At this moment of planning to build the Korean Large Telescopes, we have formed a research team to work together and contribute to the understanding of these fundamental questions. The research topics we are planning to study with the future Korean Large Telescopes are presented.

Key Words: **STAR FORMATION — STARS: LUMINOSITY FUNCTION, MASS FUNCTION — STARS: PLANETARY SYSTEMS: PROTOPLANETARY DISKS — PLANETARY SYSTEMS: FORMATION**

1. INTRODUCTION

How did life on earth commence? What made it possible for life on earth to survive and evolve? Has it happened elsewhere in the Universe? The origin and evolutionary history of life on earth is one of the fundamental curiosities of Mankind. This curiosity also extends to the formation of stars and planets. NASA has a flagship project to pursue the origin of life, namely the origins project (`http://origins.jpl.nasa.gov/about/index.html`) under the slogans "**Where did we come from?**" and "**Are we alone?**".

Our research project has similar objectives and similar strategies. We have formed a research team to work together and contribute to an understanding of these fundamental questions. The research topics we are planning to study fall into three categories: (1) the physical properties of giant molecular clouds (GMCs); (2) the formation of star clusters and the early evolution of pre-main sequence (PMS) stars; and (3) the evolution of protoplanetary disks (proplyds) and the formation of planetary systems.

The topic of star and planet formation is related to almost every area of astronomy, from galaxy formation to the origin of the solar system. Our understanding of the early evolution of stars has developed rapidly in the last decade as a result of improved observational techniques, the development of more so-

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phisticated instruments, and the emergence of large ground-based and space telescopes. But there are still many interesting questions that remain unanswered.

Because the field of star and planet formation is a rapidly developing area, it is very difficult to predict with certainty the research topics fit for the future Korea Large Telescopes (KLT) in five to ten years time. We therefore present the research topics conceivable at the present time.

2. RESEARCH TOPICS WITH THE FUTURE KOREAN LARGE TELESCOPES

In most cases, star formation events occur in a clustered manner (Pudritz, 2002). The distribution function of stellar masses resulting from a star formation event in a cloud, the initial mass function (IMF), reflects the star formation processes. Although the case of isolated, single star formation seems to be very rare, it may be the only possible way to make theoretical studies of the processes involved. Moreover, it is the first step toward the understanding of the formation of proplyds and planets.

Star formation and related topics cannot be studied without knowledge of the physical properties of star forming clouds. As this paper focuses on research topics with large optical telescopes, we will mainly describe work at optical and near infrared (NIR) wavelengths. However, we will also briefly outline some research topics at radio and infrared wavelengths at the end of this section. The first proposal is to investigate the universality or variety of the IMF from the deep imaging of many young star forming regions (SFRs). The second topic is to study the formation and evolution of proplyds. To diagnose the three dimensional structure of a protostar, we would like to perform model calculations and compare them with the observed spectral energy distribution (SED) of an individual star.

2.1. *The Stellar Initial Mass Function*

Knowledge of the IMF of a SFR is essential in discussions of star formation and the evolution of stellar systems. The form and mass limits of the IMF and their variation in different star forming environments is critical for studies of star formation, stellar populations, and galaxy evolution. The presence of a flattening or turnover in the IMF and its characteristic mass, the shape of the IMF in the brown dwarf (BD) regime, the minimum mass of freely floating planets, and the variation of these properties with environments can provide discriminating tests of the wide range of theories of how stars with different masses are formed (Luhman 2000, Luhman et al. 2000).

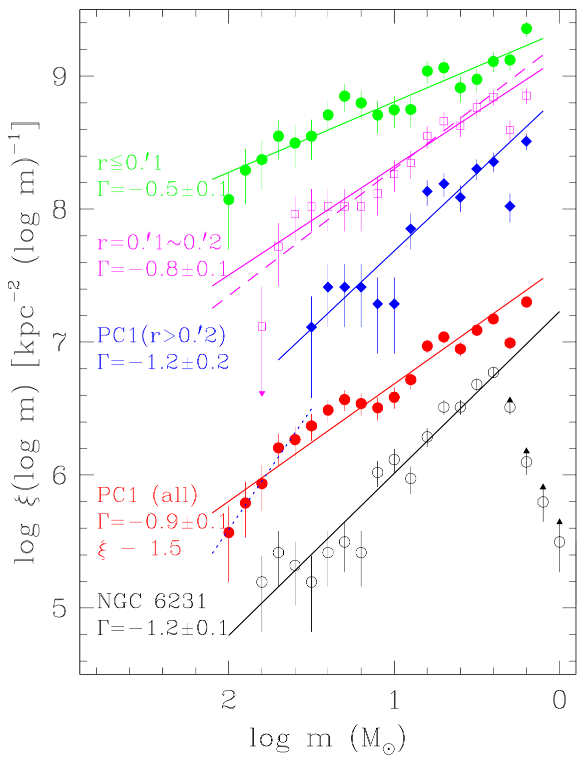

Fig. 1. The IMF of the core of the starburst cluster NGC 3603 derived from HST/WFPC2 images (Sung & Bessell 2004). The slope of the IMF of NGC 3603 is slightly flatter than that of the nearby young open cluster NGC 6231 (Sung, Bessell, & Lee 1998). The surface density of stars in the core of NGC 3603 at a given mass is about 100 times higher than that of NGC 6231 at $m = 10M_{\odot}$.

The IMF is one of the most important tools to understand the underlying stellar populations, the star formation history, the mass-to-light ratios, and the photometric properties of remote galaxies. After the introduction of the concept of the IMF by Salpeter (1955), there have been many discussions concerning the universality of the stellar IMF. From the observations of young open clusters and OB associations in the Galaxy, LMC and SMC, Massey et al. (1995) concluded that the slope of the IMF for $m \geq 7M_{\odot}$ is essentially Salpeter ($\Gamma = -1.1 \pm 0.1$) regardless of large metallicity differences. On the other hand, Hillenbrand (1997) noted the variation of IMFs among SFRs. Later Luhman et al. (2000) found that the stellar IMFs in three nearby SFRs (ρ Oph, IC 348, and the Orion Trapezium) are similar although there are large differences in stellar densities. Recently Sung & Bessell (2004, see Figure 1) derived the IMF of the young starburst cluster NGC 3603 down to $\sim 2M_{\odot}$, and found that the slope of

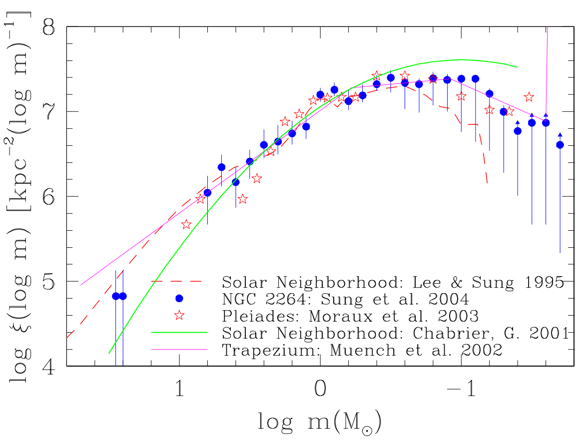

Fig. 2. The IMF of open clusters and the solar neighborhood. The thin line represents the IMF for the solar neighborhood (Lee & Sung 1995). The long-dashed line, dotted line, and star mark represent, respectively, the IMF of the solar neighborhood (Chabrier 2001), of the Orion nebular cluster (Muench et al. 2002) and of the Pleiades (Moraux et al. 2003). The dot denotes the IMF of NGC 2264 around S Monocerotis (Sung, Bessell, & Chun 2004).

the IMF of massive stars is flat at the cluster core ($r \leq 0.'3$). In addition they did not find any signature of a turnover in the IMF down to $\sim 2M_\odot$.

Currently, study of the IMF of low-mass stars is very much an expanding field. For the low-mass field stars in the solar neighborhood, there is no evidence for an increase in the slope of the IMF for stars less massive than 0.1 $M_\odot$ (Bessell & Stringfellow 1993). Moraux et al. (2003) found 29 BD candidates in the Pleiades and constructed the IMF of the cluster down to log $m = -1.4$. The turnover mass of the IMF they derived is slightly higher than that of the solar neighborhood, but this results from incompleteness of faint companions in binary systems. Recently Sung, Bessell, & Chun (2004, see Figure 2) derived the IMF of NGC 2264 around S Mon, the most massive star in the cluster, using deep optical data obtained with the 3.6-m Canada-France-Hawaii telescope, and found that the shape of the IMF is very similar to that of the Pleiades and Trapezium cluster down to the BD transition mass.

Most investigators observe the bright, blue stars in young open clusters to derive the slope of the IMF for massive stars (for example, see Massey, Johnson, & DeGioia-Eastwood 1995). But in most cases there are only a small number of massive stars in an individual cluster, so the derived slope is statistically less meaningful. To address whether the IMF does vary with physical conditions, we need to have large stellar samples for a variety of physical environments. Resolved young rich clusters can provide such samples. We would like to observe many SFRs in the Sgr-Car arm, the local arm, and the Per arm in a homogeneous and systematic manner, and derive the IMF for each SFR down to the BD transition mass.

2.2. *The Evolution of Protoplanetary Disks and the Formation of Planets*

The possibility of disk formation in the protosolar nebula was firstly postulated by Kant in the 18th century and later modified by de Laplace in 1796. Despite good theoretical support for the existence of disks around young stars (Lynden-Bell & Pringle 1974), it was largely ignored for a long time because there was no necessity to introduce it in the interpretation of existing observational data. But after the discovery of a disk around β Pictoris (Smith & Terrile 1984) considerable effort was invested in establishing the frequency with which circumstellar disks surround PMS stars as a function of age (Strom et al. 1989; Beckwith et al. 1990; Sargent & Beckwith 1991). After the emergence of sophisticated space telescopes like the Hubble Space Telescope (HST) with its unprecedented high resolution images and the Spitzer IR space telescope, it is now widely accepted that the formation of disks around young stellar objects is a very natural and ubiquitous process accompanying the formation of low-mass stars.

In the 1990s, many proplyds (proto-planetary-disks) discovered with HST/WFPC2 (O'Dell & Wen 1994) became popular targets of research (O'Dell 1998 and reference therein). O'Dell, Wen, & Hu (1993) found that about 80% of proplyds have infrared counterparts. This result implies that proplyds are a circumstellar disk around protostars. McCaughrean & O'Dell (1996) estimated the mass of proplyds by assuming that the brightness of the silhouette results from the scattered light of the nebula passing through the disk. The mass of proplyd ranges from 0.1 $M_\oplus$ to 1 M_J. If the imperfection of the HST optics is taken into account, the mass they obtained is a lower limit.

As the disk around a protostar is considered to be a potential site of planet formation, the structure and evolution of such disks naturally became a hot research topic also. The structure of the disk is determined by the physical properties of the central protostar. The self-gravity of the disk is negligible because the mass of the disk is much smaller than that of the central protostar. Therefore, the gravity of the central protostar and the centrifugal force determine the dynamical balance in the star-disk system. This is called a passive disk model. The temperature distribution in the passive disk is determined by the irradiation from the central protostar. Current models for the disk structure are the two-layer (Chiang & Goldreich 1997) and flared models (Kenyon & Hartmann 1987). However, for the same size and shape of disk, the SED should differ according to the inclination. That is why we need large samples derived by extensive observations. In addition to the geometry of the disk, another factor that determines the SED of the disk is planet formation, which can create gaps in the disk. The resultant shadow effects from the gaps can alter the SED (e.g. Dullemond 2000).

2.2.1. *Theoretical Approach*

The protostellar disk is difficult to simulate with smooth-particle-hydrodynamics (SPH) because the artificial viscosity is a great obstacle in a differentially rotating system. However, we have a precise particle hydrodynamics code which can be applied to the disk simulation. A Godunov-type particle hydrodynamics code has been developed (Cha & Whitworth 2003a) to overcome the artificial viscosity problem, and it has been applied successfully to a differentially rotating system (Cha & Whitworth 2003b). It is very important to follow the exact thermal evolution of the disk in the late stages of star formation, so radiation hydrodynamical simulations are essential. We have developed a RHD code based on SPH with precise energy treatment (Bastien, Cha & Viau 2004; Viau, Bastien & Cha, 2006). A preliminary simulation for a protostellar disk has been performed, and the resultant SED is presented in Figure 3. The contribution of the disk component is clearly seen in the figure. The SED is a very useful tool to investigate star–disk systems, and the generation of SEDs from the simulations is another huge subject. Various SEDs generated from the simulations will be compared to observations with the KLT (and/or large space IR telescopes) to identify the thermal and dynamical states of star–disk systems. Furthermore, we have plans to simulate cluster formation. Tidal interactions between disks play an important role in the determination of the mass of stars, and eventually have a crucial effect on the IMF. The IMF derived from the open cluster observations should be compared to the simulated IMF.

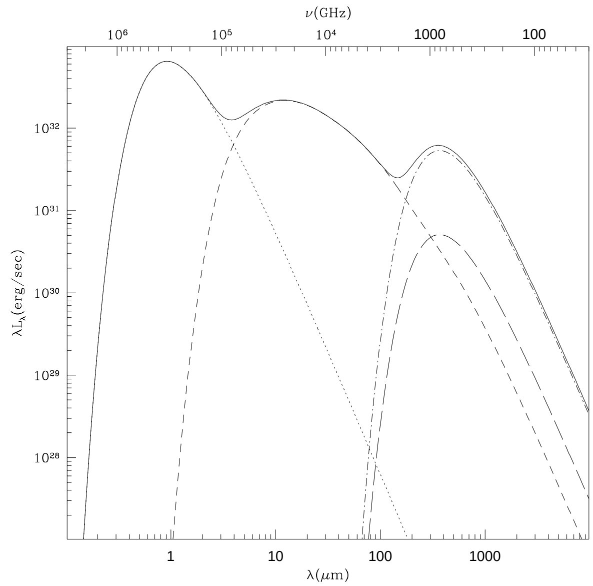

Fig. 3. The resultant SEDs of a young stellar object from Cha (2005). The disk is an inevitable stage due to the initial angular momentum of a collapsing core. The initial core is a Bonnor-Ebert sphere of 1 $M_\odot$, and is at 125 pc approximately. The solid line is the emergent luminosity, and the dotted, short-dashed, dot-dashed, and long-dashed lines are due to the central protostar, disk, infalling and the boundary material, respectively.

2.2.2. *Observational Diagnosis*

Current models of the evolution of proplyds of the central 30 AU (i.e., the radius of the solar system) are completely based on theoretical work, and therefore observations are urgently needed in order to constrain the theoretical models. Current 8-m class telescopes can achieve about 0.06″ resolution at 2 μm (equivalently 9.2 AU at Taurus SFR) and 0.3″ at 10 μm (about 45 AU). Most of light emitted from the disk around PMS stars is in the mid- or far-IR, and therefore it is, for the time being, very difficult to make direct images of a proplyd at about 1 AU or better resolution (that is, enough resolution to diagnose the density fluctuations or structure in the disk) with the sophisticated adaptive optics facility of 8-m or larger telescopes.

Therefore we should try indirect ways to diagnose the structure of proplyds, such as obtaining the SED and polarimetry in conjunction with theoretical models.

2.3. *Other Topics on Young Stars*

2.3.1. *Stellar Masses*

Stellar mass is the most important parameter in determining the evolutionary track of a star. Except for close binaries, it is very difficult to determine the mass of a star from observations. Because the number of such binary systems is very small, in most cases the mass of a star is estimated by employing the stellar and/or PMS evolutionary tracks. The mass of a solar-type star is relatively reliable, but the reliability of the masses estimated from stellar and/or PMS evolution models of young stars, massive stars, and very low-mass stars is poor. For example, the evolution mass of AB Dor c, a massive BD, is estimated to be about 45 M_J, while the dynamical mass is about 90 M_J (Close et al. 2005).

Recently many nearby young stars have been found (Zuckerman & Song 2004). Due to their youth ($\tau_{\rm age} < 50$ Myr), proximity ($d < 70$ pc) and intrinsic low luminosity, they are considered the best targets for direct imaging of hot planets that might orbit them. Currently HST and several 8 – 10 m class telescopes are being used to find young planets (Chauvin et al. 2005a,b). One by-product from the survey is that about 20 – 30 % of them are very close binaries (projected distance of $0.1'' - 0.3''$, equivalent to about 4 – 10 AU). They are best target for adaptive optics observations. We would like to monitor them with adaptive optics for 3 – 10 years and try to determine the dynamical mass of about 100 G – L type stars. This result will greatly improve mankind's knowledge of stellar evolution.

2.3.2. *Stellar Rotation*

Stellar rotation, one of the fundamental properties of a star, is approximately conserved due to the law of angular momentum conservation. Cool stars spin down as they get older through interactions between the stellar magnetic field and the ionized wind (Weber & Davis 1967). In the 1990s, significant progress was made in understanding the decay of rotation and magnetic activity as stars age (Jeffries, James, & Thurson 1998). Most of this work focused on the late-type stars in nearby open clusters such as the Pleiades, Hyades, α Persei, etc. Only a few investigations were devoted to the determination of rotational velocities of early type stars in intermediate-age open clusters. Recently Strom, Wolff, & Dror (2005) studied the rotational velocity of B-type stars in h and χ Persei and found that the distribution of rotational velocity of less-evolved, late-B-type stars in the cluster was far different from that of field counterparts, and the difference was smaller for brighter, more-evolved stars.

Even though Strom et al. (2005) tried to select relatively young field stars (age comparable to that of h and χ Per), it is very difficult to isolate the age effect in the β versus c_0 plane due to binarity, metallicity difference, and other effects on photometric colors. Therefore their results should be checked with more reliable data. To clarify the effect of stellar density on stellar rotation, it is important to gather data for the rotational velocity of early-type stars in

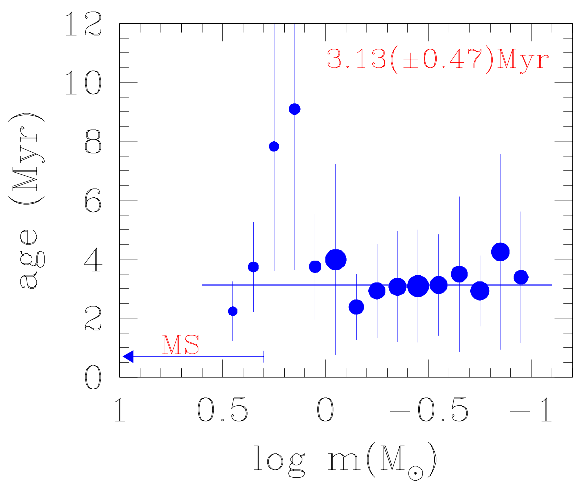

Fig. 4. The age distribution of PMS stars in NGC 2264 (Sung et al. 2004). The PMS stars in the Helmholtz-Kelvin contraction phase are apparently older than the low-mass PMS stars.

young clusters as well as young stars in OB associations in a homogeneous way.

2.3.3. *Age Distribution of PMS Stars*

One important fact about PMS stars in open clusters is that their age can be determined using PMS evolution theory. The age distribution of a cluster represents the star formation history of the cluster. Sung et al. (1997, 2004) showed that the PMS stars in the Helmholtz-Kelvin contraction phase have greater ages than low-mass PMS stars in the contraction phase along Hayashi tracks (see Figure 4). The number of intermediate-mass PMS stars is not small and hence the apparent age spread is not caused by a selection effect. This phenomenon is, as mentioned by Sung et al. (1997), related to the age discrepancy in open clusters and it would be worthwhile for theoreticians to consider whether the Helmholtz-Kelvin contraction time-scale might be overestimated. Such a discrepancy in the age of nearby young stars can also be found in Song, Zuckermann, & Bessell (2003).

2.4. *Physical Properties of Interstellar Medium*

Although this proposal details proposed science with the future KLT, it is nearly impossible to discuss star formation processes without data from radio and IR observations. And therefore we would like to describe research topics with radio telescopes and IR facilities.

2.4.1. *Physical Properties of GMCs*

The origin of the stellar IMF and its relationship with the clump mass function is an important research topic. Also, the physical properties of GMCs, such as temperature, turbulent velocity, mass spectrum of clumps, etc are worth studying. To investigate the range of fluctuation of these properties we would also like to study the physical properties of several GMCs.

In most cases the physical properties of GMCs were determined from the CO $J = 1 \rightarrow 0$ transition. Now it is possible to observe several mid-J transitions of CO molecules with several radio antennae (see, for example, Kim et al. 2005), such as the Nanten II telescope in Chile. A more detailed multi-level analysis is thus possible to determine the physical and chemical properties of GMCs.

2.4.2. *Clump Mass Spectrum*

A good subject for research is the relationship between the radio clump mass function and the origin of the stellar IMF. The mass spectrum of clumps in ρ Oph (Motte et al. 1998, 2001; Testi & Sargent 1998) is very similar to the stellar IMF in a very narrow range of mass. Several large radio telescopes are under construction or are currently being planned. A new result could be obtained on the mass spectrum of clumps in GMCs over a wide mass range.

2.4.3. *Jets and Mass Accretion in Protostars*

The evolution of protostars in a dense molecular core, i.e., the collapsing of the envelope of Class 0 objects, cannot be observed in the optical or near-IR due to strong extinction by the dust in the cloud. And therefore the envelope collapse can be observed only in radio or far-IR observations. An indirect way to study the collapse process is to observe the outflow from the protostar, as it is usually thought that the amount of mass outflow is proportional to the amount of mass accretion. Recently Choi (2005) observed a possibly contradictory result from VLA observations of the proto-binary system IRAS 4A in NGC 1333. The outflow from a protostar may also be observed at optical wavelengths (Hα line) and in the near-IR (2.2 μm H_2 1– 0 S(1)) transition, or the 1.64 μm [Fe II] line (see Pyo et al. 2005).

2.4.4. *Starless Cores*

Starless cores are defined as dense molecular cores ($n_{H_2} \geq 10^4$ cm^{-3}) without IRAS point sources. Several systematic observations of these objects have been performed as ideal laboratories to study very early star formation processes (e.g., Lee, Myers, & Tafalla 1999, 2001). A recent survey of isolated dense cores with the Spitzer Space Telescope finds that several starless cores contain a very low luminosity (< 0.1 solar luminosity) object and hence are not considered to be "starless" (Young et al. 2004). Some of the objects show somewhat different star formation activity. For example, the outflow is detected on a very small scale in both energetics and size, compared with those of typical protostars (Bourke et al. 2005). Either these can be a new type of protostar or proto-brown dwarfs. Near-IR observations of these objects with high angular resolution using the future KLT will give us essential information on the nature of these very low luminosity objects discovered in "starless" cores.

3. REQUIRED SPECIFICATIONS OF THE FUTURE KLT

3.1. *Imaging Capability*

3.1.1. *Adaptive Optics*

For the study of the structure of proplyds, it is very important to get the highest angular resolution. The diffraction-limited image with 8-m class telescopes (angular resolution $\approx 0.''05$ at 2 μm and $\approx 0.''3$ at 10 μm) is far below the required angular resolution to study the density fluctuations in the cluster proplyds, so adaptive optics facilities are the minimum requirement for such a study.

3.1.2. *Wide Field Imaging*

To investigate the shape of the IMF at the bottom of the main sequence band and the BD transition regime, a complete census of members in some young open clusters is very important. To address the variation or universality of the IMF, several young open clusters in the local arm as well as in the Sgr-Car arm and in the Per arm need to be observed. In addition, to check the dependency of the IMF on massive star content, target clusters should be selected evenly according to the OB star content.

To have a complete census of members, wide-field observations should be performed at optical wavelengths as well as in the near-IR to reach the same depth in mass for the clusters in the Sgr-Car arm or in the Per arm and/or for the embedded clusters. The MegaPrime (`http://www.cfht.hawaii.edu/instruments/Imaging/MegaPrime/`) and WIRCAM (`http://www.cfht.hawaii.edu/instruments/Imaging/WIRCam/`) at CFHT are the best instruments available at this moment.

3.2. *Spectroscopic Capability*

3.2.1. *High Resolution Spectroscopic Polarimeter*

As mentioned in §2.2.2, current 8-m class telescopes as well as future extremely large telescopes like OWL (OverWhelmingly Large Telescope) cannot take images that resolve one AU-scale (0.″007 at 145 pc) density fluctuations in the proplyds of young stars in Taurus SFR. The diffraction-limited resolution at 10 μm with a 100-m class telescope is 0.″025. Currently there is no direct way to determine the structure of proplyds, we would like to study the three-dimensional structure of PMS stars indirectly, using the SEDs in conjunction with theoretical models and polarimetry to detect the scattered light from disks and circumstellar material. A high spectral and spatial resolution spectropolarimeter like ESPaDOnS (`http://www.cfht.hawaii.edu/instruments/Spectroscopy/Espardons/`) at CFHT should be developed for this kind of study.

3.2.2. *Near-IR echelle Spectrograph*

Most young open clusters are embedded deeply in interstellar material, and therefore in some clusters, such W51 or M17, even the brightest O-type stars cannot be observed with 8-m class telescopes in the optical regime. A high resolution NIR spectrograph like NIRSPEC at Keck II (McLean et al. 2000) will be very useful therefore for observing young embedded stars to obtain their spectral-types, to place the massive stars in the HR diagram, and to measure their rotational velocities.

3.2.3. *Multi-Object Spectrograph*

To study the rotational velocity of many young stars in open clusters and OB associations, a medium-resolution, multi-object spectrograph also is very useful. As one of the telescopes will be dedicated to wide-field, multi-object spectroscopy, there is no need for detailed discussion of this instrument.

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