OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

A Spectroscopic Study of the Young Open Cluster NGC 2264: A Constraint on the Timescale of Cluster Formation

P.I.: Beomdu Lim (Korea Astronomy and Space Science Institute, Daejeon, Korea; *bdlim1210@kasi.re.kr*; +82-10-5181-3941)

CoI(s): Hwankyung Sung (Dept. of Astronomy & Space Science, Sejong University, Seoul, Korea), Jinyoung Serena Kim (SO)

Abstract of Scientific Justification

Young open clusters are one of the key objects to study star formation processes as about 80 percent of the stars in star forming sites constitute clusters with at least 100 members. In many cases, the ages of pre-main sequence (PMS) stars in young open clusters reveal a somewhat large spread ($\Delta\tau \sim 4 - 10$ Myr). It was believed that the age spread indicated the timescale of cluster formation. However, the debates on the authenticity of the age spread is an ongoing issue. The observed spread depends on adopted evolutionary models for PMS stars as well as the dispersion in the measured luminosity. An independent way to estimate their age is required to infer the timescale of the cluster formation. Most of the lithium (Li) on the surface of PMS stars with subsolar mass is known to be destroyed on timescales of $\sim$ 10 Myr. If old PMS stars ($\sim$ 10 Myr) indeed exist in very young open clusters ($<$ 3 Myr), K–M-type stars are expected to exhibit a spread in the measured equivalent width of Li 6707.8 Å. On the other hand, little Li depletion will support rapid star formation scenario. In order to investigate a general picture of the cluster formation, the nearby young open cluster NGC 2264 ($\sim$ 3 Myr) is selected because a complete membership selection down to 0.25 $M_\odot$ had already been achieved in previous studies. Capabilities of high-resolution multi-object spectroscopy ($R \geq 17,000$) are required to resolve the Li I 6707.8 Å line from the nearby Fe I 6707.4 Å line, and to observe hundreds of PMS stars simultaneously. This scientific goal will be feasible with the Hectochelle attached to the MMT. We propose to measure the Li abundance of PMS stars ($R = 10 - 17$ mag) in NGC 2264.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MMT	f/5	Hectochelle			0.5	grey	Jan	Jan–Feb	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None

no text past this line

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	34803C	06:41:03.19	+09:16:03.0	R=16.76, NGC 2264 member
2	62880S	06:41:03.28	+09:47:55.3	R=15.07, NGC 2264 member
3	62883S	06:41:03.37	+09:30:44.8	R=14.94, NGC 2264 member
4	62890S	06:41:03.49	+09:21:18.6	R=12.31, NGC 2264 member
5	634897C	06:41:03.57	+09:50:35.4	R=15.82, NGC 2264 member
6	62901S	06:41:03.75	+09:17:39.8	R=15.27, NGC 2264 member
7	62911S	06:41:04.04	+09:39:08.6	R=14.39, NGC 2264 member
8	62912S	06:41:04.06	+09:25:21.2	R=15.56, NGC 2264 member
9	62913S	06:41:04.11	+09:23:02.0	R=10.07, NGC 2264 member
10	62917S	06:41:04.18	+09:42:01.9	R=14.47, NGC 2264 member
11	62920S	06:41:04.29	+09:14:52.0	R=15.00, NGC 2264 member
12	62921S	06:41:04.30	+09:38:21.6	R=14.08, NGC 2264 member
13	62924S	06:41:04.41	+09:41:50.0	R=11.94, NGC 2264 member
14	62927S	06:41:04.44	+09:41:26.0	R=14.12, NGC 2264 member
15	62928S	06:41:04.47	+09:43:18.4	R=15.15, NGC 2264 member
16	62933S	06:41:04.57	+09:44:44.0	R=10.13, NGC 2264 member
17	62936S	06:41:04.70	+09:26:26.7	R=10.92, NGC 2264 member
18	635186C	06:41:04.81	+09:34:33.4	R=17.22, NGC 2264 member
19	62943S	06:41:04.97	+09:40:45.9	R=13.78, NGC 2264 member
20	62948S	06:41:05.10	+09:38:47.8	R=15.21, NGC 2264 member
21	62949S	06:41:05.10	+09:41:44.5	R=14.69, NGC 2264 member
22	635263C	06:41:05.14	+09:38:55.6	R=14.67, NGC 2264 member
23	62954S	06:41:05.21	+09:43:15.8	R=14.44, NGC 2264 member
24	62959S	06:41:05.37	+09:23:13.6	R=14.45, NGC 2264 member
25	62967S	06:41:05.69	+09:44:18.8	R=15.12, NGC 2264 member
26	321 objects within 1 square degree			R=10.00–17.30, the members of NGC 2264

Approval for Instrument Use from PI: ______________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Background

Theories on star formation processes have suggested two contrasting paradigms in the star formation timescale, so-called slow star formation and rapid star formation (Burningham et al. 2005). In the slow star formation model (Shu 1977), a molecular cloud is supposed to be in an equilibrium state where pressure by magnetic fields supports gravitational force. Clumps in the molecular cloud can be collapsed through ambipolar diffusion on a timescale of 5 – 10 Myr, if the density becomes higher than a critical value ($n \geq 10^5$ cm^{-3}). The role of the magnetic fields is a crucial factor to regulate star formation in the clumps. On the other hand, the dissipation of supersonic turbulence inside a molecular cloud plays an important role in the onset of rapid star formation (Elmegreen et al. 2000, and references therein). The entire process of the rapid star formation is thought to take place on a timescale of 3 Myr (Burningham et al. 2005, and references therein). As most of the stars (about 80 percent) in star forming regions (SFRs) are formed in clusters with at least 100 members (Lada & Lada 2003), understanding the timescale of star formation is essential for drawing a general picture of star cluster formation.

Extended star formation activity in nearby young open clusters as well as SFRs has been suggested by Palla & Stahler (1999,2000,2002). This is a revised version of sequential star formation speculated by Herbig (1962). According to their argument, star formation gradually took place at an early epoch, and then the star formation rate accelerated in the present epoch. Palla et al. (2005) strengthened their idea invoking a significant Li depletion in 4 pre-main sequence (PMS) members of the Orion Nebula Cluster. On the other hand, Sung et al. (1997) raised a doubt on the sequential star formation scenario from the age distribution of PMS stars in NGC 2264. Hartmann (1999,2001,2003) argued that various factors, such as binarity, variability, extinction, accretion activities, the inclusion of field stars, and the artifact of evolutionary models for intermediate-mass PMS stars, are responsible for the apparent age spread. Although many follow-up studies have examined such factors, the issue of the age spread of PMS stars is still under debate in terms of the cluster formation timescale.

Our recent studies have also focused on interpreting the age spread of PMS stars within several young open clusters in a homogeneous manner (e.g. Sung & Bessell 2010; Lim et al. 2014a,b,c). Figure 1 shows the color-magnitude diagram (CMD) and the age distribution of PMS members in NGC 2264. Sung & Bessell carefully investigated the nature of PMS stars in NGC 2264 using a complete member list obtained from a wide variety of membership selection criteria (e.g. X-ray, UV excess, Hα, and mid-infrared excess emission). Nevertheless, the ages of PMS stars still exhibited a spread of 4 – 5 Myr as shown in the right-hand panel of Figure 1. Few stars even appear to be older than 10 Myr. Thus, the inclusion of field interlopers can be excluded as a major factors affecting the apparent spread. The ages of unresolved binaries are expected to be underestimated because of their higher luminosity compared to a single star, but the influence of binarity cannot explain the apparently old PMS stars. Lim et al. (2014a,c) carried out multiple sets of Monte-Carlo simulations taking into account photometric errors, uncertainties in reddening correction, and variability obtained from observation. As a result, the age spread (1 – 2 Myr) found in the simulations was not as large as that (4 – 5 Myr) estimated from observations. In addition, the reddening vector is almost parallel to the slope of PMS isochrones in the $(V, V - I)$ CMD. Therefore the uncertainty in the reddening correction may not give a significant spread in the age of PMS stars. Lim et al. (2014a,c) also introduced sequential star formation history into interpreting the age spread found in the young open clusters NGC 1893 and NGC 1931. The mean age difference between the youngest and the oldest groups was only about 0.5 Myr. Sung et al. (1997) and Hartmann (1999) pointed out that evolutionary models for intermediate-mass stars ($> 1.5M_{\odot}$) tend to overestimate their age. However, the fraction of intermediate-mass PMS stars is only about few percent out of all the observed stars. Their contribution to the age spread is less significant. The major sources of the apparent age spread have not been clarified so far.

A Proposal for Observation

The assessments described above were based on the Hertzsprung-Russell diagram (HRD). The position of stars in the HRD is very sensitive to the estimated effective temperature. Several uncontrollable factors such as accretion activity and disk inclination prevent one from determining the accurate effective temperature and luminosity of PMS stars. Hence, an independent way to estimate the ages of PMS stars is required to investigate timescale of cluster formation. An alternative way is to measure the Li abundance of PMS stars with subsolar masses. The temperature ($> 2.5 \times 10^6$ K) at the bottom of convective zone inside K–M-type PMS stars is maintained over a few tens of million years. A large fraction of the Li is destroyed inside the stars, and Li-depleted material is transported to their surface. Thus, the amount of remaining Li abundance is a useful age indicator.

We propose to measure the Li abundance in PMS stars to investigate the timescale of cluster formation in NGC 2264 with Hectoechelle attached to the MMT. The equivalent width (EW) of the Li I doublet 6707.8 Å line will be measured from observed spectra, and then the EW will be converted to the Li abundance. We tried to simulate the anticipated result through a Monte-Carlo method by assuming the slow star formation scenario. The initial mass function (IMF) of Salpeter (1955) was assumed to be the underlying IMF in the mass range of 0.4 – 1.2 $M_{\odot}$. The age distribution found in NGC 2264 (Figurer 1) was used as the age distribution of the artificial stars. A total of 100 artificial stars were generated from the evolutionary models of Siess et al. (2000). Figure 2 shows the Li abundance of the artificial stars and isochrones. If star formation indeed persists on a timescale of 5 – 10 Myr, the measured Li abundance will exhibit a large scatter as seen in the figure. On the other hand, little depletion in the Li abundance may support the rapid star formation scenario. According to Soderblom et al. (2013), this method has a few weak points, e.g. the unknown initial Li abundance, intrinsic scatter related to stellar activities (rotation-induced mixing, inhibitory action of convection by magnetic fields, accretion activities), and its dependence on metallicity. Metallicity and the initial Li abundance may not be critical factors in interpreting the measured Li abundance because PMS stars within a SFR can be assumed to have almost the same composition. In addition, the inclusion of other metal lines and Hα 6563 Å in our observation will be helpful to explore the effects of the stellar activities on the strength of the Li line. A description of cluster formation timescale will be feasible with this comprehensive analysis.

References

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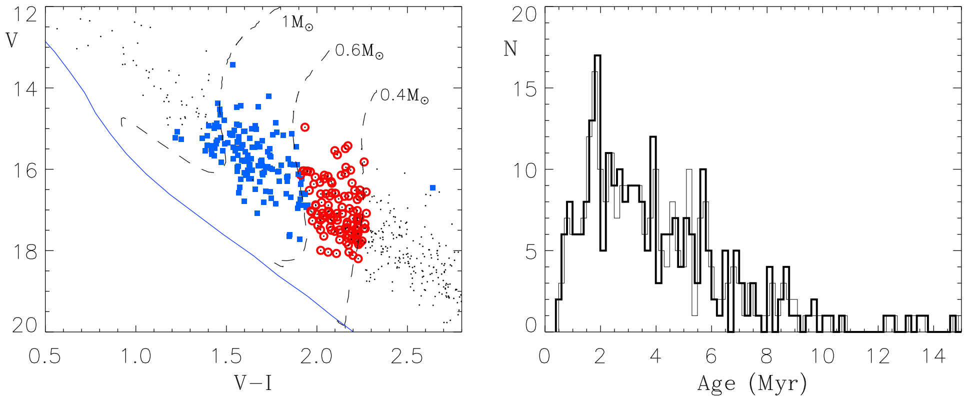

Figure 1: Color-magnitude diagram of pre-main sequence (PMS) members in NGC 2264 (left) and their age distribution (right). The PMS members in mass range of 0.6 – 1.2 $M_\odot$ are shown as blue squares, while the red circles denote the members in mass range of 0.4 – 0.6 $M_\odot$. The solid and dashed lines represent the zero-age main sequence relation and PMS evolutionary tracks for stars of different mass (Siess et al. 2000), respectively. The histograms (thin and thick solid lines) in the right-hand panel were obtained from PMS members with masses of 0.4 – 1.2 $M_\odot$ and based on different binning of the same stars to avoid binning effects.

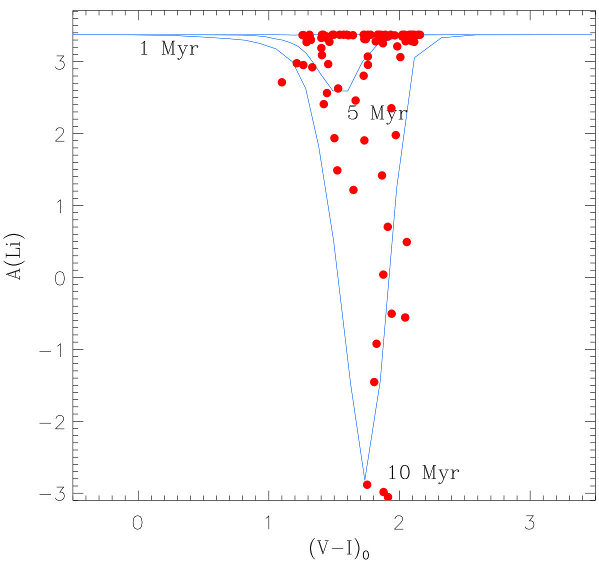

Figure 2: Lithium abundance of artificial PMS stars generated from a Monte-Carlo simulation. The age spread was assumed to have the same distribution as shown in the right-hand panel of Figure 1. The solid lines represent the isochrone obtained from the evolutionary models of Siess et al. (2000).

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Target Selection

A reliable membership selection is the most critical issue in studies of star formation, because most star forming sites are situated in the Galactic plane where a large number of field stars are distributed along the line of sight. We have secured homogeneous sets of CCD photometry with reliable member lists for a few young open clusters. The young open cluster NGC 2264 is the closest cluster to the Sun in our list of the open clusters. The proximity of the cluster allows us to observe PMS stars with subsolar masses, in which Li depletion is measurable. As shown in Figure 1, the PMS members show a wide span of ages ($\geq$ 10 Myr), and therefore the cluster is an ideal site to examine the star/cluster formation timescale problem (issue). The extent of the cluster is about $40' \times 60'$, therefore the field of view of the Hectoechelle (1° diameter) is able to accommodate the whole cluster in one pointing. NGC 2264 will be observable for half the night in January and February (early). Thus, the cluster is accessible by MMT during that period.

Justification of the Requested Instrument/Time

A total of 346 members with masses larger than 0.4 $M_\odot$ were selected as the targets for this observation. In order to efficiently observe all the stars, multi-object spectroscopic observations should be carried out. Since Hectoechelle shares the robot positioner and fiber feed system with Hectospec, a total of 240 fibers are simultaneously available for our observation. The main spectral line is the Li I doublet 6707.8 Å line. The equivalent width (EW) of the line will be used to determine the Li abundance, which is an age indicator of PMS stars. In addition, we will utilize Hα and metal lines within the same order. The Hα emission line will be used to estimate the degree of the accretion and chromospheric activities of PMS stars. The projected rotational velocity can be derived from the metal lines. These spectral lines will be helpful to investigate relations between the stellar activities and the intrinsic scatter in the measured Li abundance. We request to use the OB26 filter which provides an optimal wavelength coverage. Spectral resolution (R) should be higher than 17,000 to minimize blending the Li line and the neighboring Fe I 6707.4 Å line.

The EW of the Li line is expected to be larger than 0.1 Å for stellar ages less than 50 Myr. A total integration time of 90 minutes is required to measure such a small EW in the faintest star ($R = 17.3$) with a reasonable signal-to-noise ratio ($S/N \geq 20$). The targets in crowded regions should be observed by two different configurations to avoid any close encounter between robot positioners. A configuration comprises 3 sets of the same exposure times (30 minutes each) including an operational overhead time of 23 minutes, i.e. a total duration of 113 minutes per field. Another set of observations is required to observe bright targets ($10 < R < 14$). The configuration of this set is almost the same as above, but each exposure time for targets is 10 minutes. We have a plan to take sky spectra for subtracting background emission. The exposure time corresponds to that of a single observation for targets, i.e. 2×30 minutes and 1×10 minutes. Consequently, a total of 6.9 hours are required to observed all the targets we proposed. The capability of Hectoechelle satisfies our observational requirements above.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

We first planned this spectroscopic study of the young open cluster NGC 2264 in August 2014. This is the first proposal to use Hectoechelle attached to the MMT. Almost a half night (6.9 hours) was requested in this proposal. The observation of all the targets (346 stars) can be completed in a night. However, it depends on the weather conditions as well as the stability of the instrument we proposed. If the weather conditions become worse during the observing run, or if the robot positioners malfunction, our observation will not be completed in the given night. That way a few more hours ($\sim$ 3) may be required after this observing run given that typical success rates are betwen 50 and 75 percent.

We have a plan to make observations of 22 bright stars ($R < 10$) in NGC 2264 for 4 nights with BOES/BOAO in October 2014 because the stars are too bright to be observed with the MMT. The fraction of the stars is about 6 percent out of the total targets.

The Korea Astronomy and Space Science Institute has participated in the Giant Magellan Telescope (GMT) project as a consortium partner (K-GMT Project). The K-GMT Science Group (KGSG) is dedicated to improving the scientific capability of Korean astronomers. As a part of their efforts, KGSG could access 4 – 6 m class optical telescopes and invited Korean researchers to make proposals for observations with the telescopes. The MMT is one of the accessible telescopes. Details on the overview of this program as well as policy can be found in the home pages of K-GMT Science Program.[1].

[1]http://kgmtscience.kasi.re.kr/science_program/guideline.html

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

$UBVI$ CCD Survey of Open clusters (PI: J. S. Kim, Co-Is: B. Lim, H. Sung.) We applied to use the Kuiper 61in telescope with the Mont4k CCD for our photometric survey of open clusters in the northern hemisphere. The main purpose of the project is to provide homogeneous photometric data for open clusters. We expect that the data would enable us to tackle issues such as the initial mass function, local spiral arm structure, chemical evolution in the Galactic disk, massive star formation, stellar evolution, etc. A total of 28 nights were awarded during 2011B, 2012B, 2013A, and 2013B. The number of targets observed under photometric conditions is about 80. So far we have carried out PSF photometry for the clusters, and obtained photometric diagrams for 22 clusters. Data reduction and analysis are on-going. Recently, a paper on the young open clusters NGC 1624 and NGC 1931 has been submitted to the Astronomical Journal.