DEPARTMENT OF OPTICS AND QUANTUM ELECTRONICS
UNIVERSITY OF SZEGED

Early Stages of Stellar Evolution in Young Galactic Open Clusters

PHD THESIS

Zoltán Balog
(assistant research fellow)

Supervisors:
Dr. József Vinkó
(associate professor)
Dept of Optics and Quantum Electronics
Univ. of Szeged

Dr. Scott Kenyon
(Smithsonian Astrophysical Observatory)

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1 Scientific Background and Research Goals

It was recognized long time ago that stellar clusters are perfect laboratories for stellar evolution research. Their study plays a very important role in our current understanding of star formation and stellar evolution. From this point of view the most important property of star clusters is that they contain statistically significant number of stars spanning a wide range of stellar mass within a relatively small volume of space. This provides the ability to obtain information about many stars during a short period of time using relatively simple methods. Because these stars formed more or less simultaneously from the same progenitor molecular cloud, observation of the cluster color-magnitude diagrams can be used to test the stellar evolution theories. Moreover, they provide the smallest physical scale over which the stellar initial mass function can be studied.

Because the cluster is held together by the gravitational attraction of its members, its evolution is governed by Newton's laws. In many body systems these interactions are extremely complicated, so stellar clusters provide important tests for studies of stellar dynamics. Their spatial distribution plays a vital role in mapping the galactic structure. For example, the distribution of the globular clusters helped us to discover the position of the galactic center and the existence of the galactic halo.

Young open clusters provide data on recent star formation in galaxies and in the spiral arms of our Milky Way. These clusters might also be of interest for understanding the origin of our solar system. The presence of short-lived radioactive nuclei in meteoritic samples has suggested that the Sun itself was formed near a massive star and thus likely was a member of a relatively rich cluster.

We know very little about the origin of clusters. Globular clusters of the Galaxy formed billions of years ago, so direct empirical study of their formation is impossible. However, open clusters seem to be formed continuously in the disk of our Galaxy, and, in principle, direct study of the physical processes leading to their formation is possible.

The observations of open clusters is a crucial source of information to the understanding of the physical processes leading from molecular clouds to Main Sequence stars. Stars are formed continuously in our Galaxy so open clusters make it possible to study each step of clustered star formation. The physical properties of Pre-Main Sequence (PMS) stars in open clusters can be determined more reliably than in the case of single stars.

The most important clusters are the young open clusters which preserved their original stellar population. Older ($\tau > 10^7$ yr) open clusters may loose members due to evolution and dynamical effects. However, the study of young open clusters is sometimes complicated, since the stars might still be embedded in dust and gas that reduces the accuracy of the photometric measurements, and may have very non-uniform extinction. 2-3 million year-old clusters are usually undetectable in optical wavelengths, since they are totally embedded in their parental molecular cloud. To study these clusters, we need to use observations in the infrared. This technique, however, started its rapid development only during the last decade.

2 Research methods

During my work I used the equipments of several observatories: Fred Lawrence Whipple Observatory, Tucson, Arizona, USA; German-Spanish Astronomical Center, Calar Alto, Spain; David Dunlap Observatory, Richmond Hill, Canada. I have also analyzed data obtained by my collaborators. I performed the reduction and analysis of the data using self developed computer codes and the IRAF computer program.

I used classical isochrone fitting for the determination of the physical parameters of clusters. I identified PMS stars using their photometric and spectroscopic properties.

I developed a method for spectral classification using spectroscopic indices of different chemical elements. I used similar method for spectroscopically identifying young stars. This method uses the strength of H_α and H_γ to decide, whether a star shows emission or not. Sometimes the H_α emission only fills the core of the absorption line, thus, it is visually undetectable.

In the case of NGC 7538 I used standard IR techniques to study the embedded cluster. I used the cumulative logarithmic K-band luminosity function for determining the slope of the initial mass function.

3 Results

I present the photometric and spectroscopic analysis of two open clusters and an ionized hydrogen cloud (HII region).

1. For the study of NGC 7128 I carried out an extensive photometric campaign in collaboration with researchers of the Instituto de Astrofísica de Andalucia. Using Johnson (UBV) and Strömgren ($uvby$) measurements, I determined the the physical parameters (age, distance, reddening) of the cluster. The result obtained with different methods are consistent. Using Stromgren measurements I calculated the redding laws of the region. The results were consistent with each other but they differed from the standard reddening law for the Galaxy. This confirmed the hypothesis that in the areas of large reddening the reddening slopes differ from the standard values (Balog et al. 2001).

2. I obtained spectra of the brightest stars in the field of NGC 7128 and performed spectral classification for these stars. Using the newly determined spectral types I calculated the average reddening which was in good agreement with the value determined from photometry. I also estimated the reddening from the $\lambda6613$ Å diffuse interstellar band. This reddening also agreed with the previous values within the errors.

During the spectroscopic survey I found H_α emission in the spectra of two stars. I classified these stars as classical Be stars (Balog et al. 2000, Balog et al. 2001).

3. I carried out a spectroscopic survey of NGC 6871. I secured spectra of more than 1500 stars in the field. I detected H_α emission in 44 stars.

For the spectral classification I worked out a method using narrow band spectral indices. With this method I classified the stars in the sample and determined the physical parameters of the cluster using published photometry. Using the individual reddening of the stars I separated the probable cluster members from foreground and background objects (Balog et al. 2002, Balog and Kenyon 2002, Balog, Kenyon and Vinkó 2003).

4. Combining the photometric and spectroscopic information I constructed the reddening-free color-magnitude diagram of NGC 6871. Using this diagram and the emission lines in the spectrum, I separated the PMS stars from other emission-line objects.

I showed that there are 11 PMS stars in NGC 6871. I compared the distribution of their H_α index to the distribution of PMS stars in the Taurus-Auriga molecular cloud. I showed that the peak of the H_α index distribution coincides with the peak observed for WTTS's in the Taurus-Auriga cloud, but in NGC 6871 there are no stars showing strong emission. Since the PMS stars in the Taurus-Auriga cloud are much younger ($\simeq 10^6$ yr) than those in NGC 6871 ($\simeq 10^7$ yr), I concluded that the accretion disk which is the engine of the T Tauri emission, disappears on a timescale of 10^7 yr.

Among the weak line T Tauri stars (WTTS) in the sample, 45% shows [SII], while 36% [NII] emission. These forbidden emission lines have not been detected in such stars so far. This implies that the formation of these lines might not only be associated with accretion phenomena, like jets or disk-wind interaction (Balog et al. 2002, Balog and Kenyon 2002, Balog, Kenyon and Vinkó 2003).

5. I collected near-IR photometry of the NGC 7538 region in K-filter. The measurements were complemented earlier infrared (JHK) data of S. Kenyon, M. Barsony and E. Lada.

I constructed the smoothed stellar density contours of the region from the position of the infrared sources. Using these contours I discovered a young cluster embedded in NGC 7538 and determined the central coordinates. Using infrared color-color and color-magnitude diagrams I showed that the cluster consists of mainly PMS stars and its distance is in good agreement with the earlier estimates of the distance of the associated HII region.

Using luminosity- and color functions I proved the hypothesis that the region can be divided into three parts in which the average reddenings are different.

I constructed the cumulative logarithmic luminosity function of the clusters, and estimated the slope of the IMF of the clusters. The results is in good agreement with the values derived for other star forming regions. Using cumulative logarithmic luminosity functions for the different parts of the region I proved that these regions (defined by McCaughrean) are forming an age sequence (South-Eastern part is the youngest, North-Western part is the oldest).

I calculated the total mass of the cluster by integration of the initial mass function using the slope derived from the cumulative logarithmic luminosity function. The total mass of the cluster is turned out to be similar to the total mass of the Orion Nebula Cluster and the Pleiades, but much lower than the total mass of χ and h Persei (Balog, Kenyon and Vinkó 2003, Balog et al. 2003, Balog et al. 2004).

Refereed publications associated with the dissertation

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