DESIGN AND APPLICATION OF HIGH RESOLUTION AND MULTIOBJECT SPECTROGRAPHS: DYNAMICAL STUDIES OF OPEN CLUSTERS

Ph.D. Thesis Statements

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Introduction

Most stars are formed in clusters (Lada & Lada 2003). The processes responsible for cluster formation are important to include in any consideration of the mechanisms of star formation. Understanding how stars like our Sun were born is particularly significant if we are to shed light to our own origins, i.e. the formation of Earth and the Solar System. With more than 200 extrasolar planets known to date it has become obvious that formation of other, extrasolar planetary systems are common. The first step, though, to comprehend the formation of alien worlds, is to develop an understanding of the star formation process itself.

Today, stellar clusters are used as laboratories of stellar evolution research, and with the aid of modern (especially infrared and multiobject) observation facilities our models of cluster and star formation has become very detailed. The increasing sensitivity of infrared studies with both ground-based instruments and the Spitzer Space Telescope has made it more feasible to find and explore very young stellar populations, still embedded in their molecular cloud cradles. Searching for substructure in such cosmic nurseries can provide insight into the earliest phase of stellar evolution and thus help to understand what kind of initial conditions are required to form stars which can host planetary systems.

Building blocks of large scale star forming regions have been identified as spatial structures in the young cluster NGC 2264 (e.g. Lada, Young & Greene 1993, Teixeira 2006). Recent X-ray studies using the Chandra space telescope also found that stars of the well known Orion Nebula Cluster close to its center show a strong spatial asymmetry (Feigelson et al., 2005). It has been also demonstrated in several other cases that the more embedded (youngest) populations exhibit a different, structured spatial distribution, when compared to less obscured sources (e.g the findings of Broos et al. (2007) on the structure of M17).

These studies only provide snapshots at selected epochs of million year long processes. Investigating numerous examples in various evolutionary stages will allow us to see the whole a mosaic at once, but to assemble the overall picture requires to extract and collect all the information available. High resolution optical spectroscopy is a powerful tool of astrophysics, and so its application has been relevant to probe star formation. Most of the known extrasolar planets also had been discovered by echelle spectrographs, through the Doppler effect, i.e. measuring the radial velocity changes of a host star as it orbits around the star–planet barycenter.

Undoubtedly conducting an observation and analyzing the data is the best way to understand the capabilities of a given instrument deliver and what improvements are needed (or can be done) to push the sensitivity limits as new technologies are incorporated into instrumental designs. One of the most recent examples is the HARPS spectrograph (Pepe et al., 2000), routinely delivering $< 1\ ms^{-1}$ accuracy (Rupprecht et al., 2004), measured on stars several hundred light years away. Such amazing precision, however, still limits us to discover planets much more massive than the Earth. But advances in metrology and development of astronomical laser combs (Li et al., 2008) promises $cm\ s^{-1}$ scale measurements, enabling detection of Earth-like planets. In the investigation of star-forming regions the multi-object capabilities are more beneficial than the very high precision. Still, internal consistency of multi-object data sets, proper calibration and removal of any systematic instrumental effects are crucial to derive valuable new information.

Aim of the Thesis

In my MSc thesis I presented the design, construction and application of a moderate resolution, low budget spectrograph, suitable for university practice and teaching. Becoming a predoctoral fellow at the Harvard-Smithsonian Center for Astrophysics (CfA), I had the opportunity to deepen my understanding of instrument design through application and construction of state-of-the-art instruments. The unique and supportive environment offered convenient interaction and collaboration with groups specialized in high precision radial velocity (RV) measurements and spectral analysis (Dave Latham, Guillermo Torres and others) and in star forming regions (Spitzer/IRAC and star formation scientists including Lori Allen, Charles Lada, Tom Megeath and many others).

Therefore the goal of this thesis is twofold:

- provide a detailed overview of spectrograph design through the construction of an echelle spectrograph, with the perspective of the end user and in the light of scientific needs,

- and to study the internal dynamics of star forming regions, through application of high resolution multiobject spectroscopy.

The former is rather a technical aspect of astronomy, and thus might be considered as engineering science than basic astronomical research. The philosophy of my work was that the use of an instrument is the best way to learn its capabilities and thus the best way to provide feedback for development. Therefore instrument building is an essential part of astronomical research.

The second goal is meant to add a so far missing piece to the star formation puzzle. Although several examples of clear *spatial* substructure has been published lately, the *kinematical* structure of young stellar clusters have, to date, remained relatively unexplored. Although high resolution multi object spectrographs have been in service for years, fully exploiting the capabilities of these marvelous instruments has just begun recently on this field. The reason might be partly the unfortunate fact that young systems, which might still show some imprint of the primordial kinematical structure, are highly obscured at optical wavelengths and only a small number of nearby star forming regions can be observed efficiently.

In particular I was aiming to test one of the recent star formation theories, and find observational evidence to the predictions of the model by Burkert & Hartmann (2004). Their work suggests that gravity acting on the edges of simple, isothermal, finite sheets can produce a wide variety of structures that are likely to have some relevance to observed star-forming structures in molecular clouds. In particular, Burkert & Hartmann (2004) have shown that a likely general result of the collapse of a sheet formed by flows in the interstellar medium is a filament with higher mass concentrations at the ends of the filament. The simulated properties suggest that the kinematical structure of the filament develops accordingly: the end clumps contain the largest portion of kinematical energy as well and thus exhibit higher radial velocity dispersion than the rest of the cloud. With access to Hectochelle I had the possibility to first look for then find observational evidence supporting the results of these numerical simulations.

Research Methods

To collect hundreds of spectra suitable for radial velocity measurement and spectral typing, I used the Hectochelle (Szentgyorgyi et al., 1998) high resolution multi object spectrograph at the MMT telescope. The MMT Observatory, a joint venture of the Smithsonian Institution and the University of Arizona. The MMT is an alt-azimuth mounted 6.5m Cassegrain telescope located on the summit of Mt. Hopkins, the second highest peak in the Santa Rita Range of the Coronado National Forest, approximately 55 kilometers (30 miles) south of Tucson, Arizona. The MMT is on the grounds of the Smithsonian Institution's Fred Lawrence Whipple Observatory, also the site of the 1.5m Tillinghast reflector for which I have designed and built in collaboration with the CfA Optical and Infrared Division instrumental group a high resolution, fully cross dispersed echelle spectrograph, the TRES (Tillinghast Reflector Echelle Spectrograph) instrument.

Stellar and calibration data (using the ThAr technique) were collected at the resolution of $R \simeq 34\,000$ in spectral orders including the Hα, Mg (5150–5300 Å) and Li (6708 Å) regions. For the characterization of TRES, spectra were recorded covering the entire visible range (3800–9200 Å) at a resolution of $R \simeq 55\ 000$, using simultaneous ThAr calibration.

For the spectral data reduction and calibration I wrote an automated pipeline, which is in general a Linux shell script calling image reduction and database handling tools. It relies on an instrument specific calibration data base I have built, to enable the entire process being non-interactive. The script runs in Linux/UNIX bash environment and mostly invokes IRAF[1] tasks for the image processing, and STARBASE[2] programs to handle the input and output catalogs/databases. This pipeline was adopted by the CfA Telescope Data Center as the official Hectochelle data reduction procedure.

The radial velocities and stellar parameters were obtained by the cross-correlation technique, using the CfA-developed `rvsao.xcsao` task within the IRAF environment. During this analysis each observed spectrum was compared to a set of synthetic templates in order to find the best matching artificial counterpart for the correlation. This multi-template method was proven to enhance the precision of radial velocity determination. The artificial template libraries used are all based on the atmosphere models of Kurucz (1992), and were calculated by Jon Morse (unpublished), Munari et al. (2005) and Coelho et al. (2005).

For the TRES optical and mechanical design the ZEMAX[3] commercial optical ray tracing code and the I-DEAS[4] CAD software package had been used, along with self-developed scripts to perform system analysis (e.g. tolerancing) and to evaluate optical performance, aid system integration.

[1]IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[2]http://cfa-www.harvard.edu/~john/starbase/starbase.html

[3]www.zemax.com

[4]Integrated Design and Engineering Analysis Software, currently owned by Siemens PLM Software

New Scientific Results

1. I have designed and constructed a high resolution, fully cross dispersed, state of the art echelle spectrograph (TRES – Tillinghast Reflector Echelle Spectrograph), which has been commissioned in 2007 at the 1.5m Tillinghast reflector of the Fred Lawrence Whipple Observatory, AZ, USA. According to initial performance tests the instrument is capable of measuring radial velocities with a ∼5 $m\ s^{-1}$ accuracy using the simultaneous ThAr calibration method. TRES has been gradually taking over the work of the CfA Digital Speedometer (Latham, 1992), and will be serving as the main instrument in the CfA reconnaissance spectroscopic observations of extrasolar planets, and play a key role in the ground follow up work of NASA's Kepler mission[5] [1]

2. I have made significant contribution to the commissioning of the Hectochelle high resolution multi-object spectrograph, by aligning its optical system, developing an optimal calibration system and a data reduction pipeline – essential for productive observations. As a result of application of novel data analysis method I have recognized/determined general rules useful/beneficial in the calibration of these unique instruments, which can improve the internal precision of radial velocity measurements and so far had been missing from the literature. I have demonstrated that sub-optimal wavelength calibration can lead to systematic errors which can be determined and corrected for, significantly improving the self-consistency of large volume radial velocity data sets. [2,3,4]

3. I have demonstrated that young open clusters yielding an age less than a few million years, like NGC 2264, still exhibit substructure not just in their spatial but also in their kinematical structure. I have found significant radial velocity texture in this star forming region previously known to have hierarchical appearance. I have shown that this must be

[5] http://kepler.nasa.gov/

a remaining imprint of the primordial structure of a parental molecular cloud forming the cluster members, as dynamical relaxation processes could have not erased it due to the immature age of the protocluster. My results are in good agreement with distributional analysis of infrared excess sources, also suggesting that younger sources still exhibiting accretions disks are tracing the original stellar birthing sites. The different radial velocity distribution for these and older, diskless sources may indicate distinct, primordial structural elements of the cloud. My results provide evidence that the stellar radial velocities show a high correlation with the velocity of the molecular gas in the cluster, traced by ^{13}CO radio observations. Therefore it can be concluded that any substructure of the parental gas cloud will strongly influence the spatial and kinematical structure of protoclusters. I have interpreted this texture as the result of gravitational collapse of initial clumps of star-forming gas from a more extended structure to a roughly filamentary distribution, according to the prediction of Burkert & Hartmann (2004). [5]

4. I have conducted an extensive radial velocity survey in the Orion Nebula Cluster (ONC) and in the surrounding areas. I have found high degree agreement between the structure of the gaseous and stellar component, suggesting the region is very young, only ~ 1 crossing time old, otherwise gravitational interaction should have been smoothed the fine structure still clearly visible in the data. This is an independent age estimate of this key star cluster, yielding a $\sim$1 Myr value, derived from the physical size and the measured radial velocity dispersion of 3.1 km s^{-1}. Comparing the observational results to the numerical simulations of Hartmann & Burkert (2007) I have found high level of similarity, resulting the following picture of the ONC region:

   on large scales the gas (and stars) exhibit a velocity gradient in the elongated filament, due to rotation or shear running north-south. The curvature seen the position-velocity diagrams suggests gravitational acceleration towards the cluster center. The concentration of gas (and stars) north of the Trapezium region is somewhat in front and is also falling in towards the center, explaining its higher radial velocities. The southern part of the filament may also be falling in, although the motions are much less organized than is apparent in the northern arm.

It might be possible that the process of blowing out the near side of the cloud, in the south, resulted in accelerating and compressing gas which triggered the formation of a small population of stars exhibiting blueshifted velocities. I have also found other signs of triggered star formation in form of a sub-group of stars, which exhibits a strong spatial concentration, yet yields radial velocity values and dispersion notably different from the gaseous component of the same region. This part of the nebula harbors a large number of Herbig-Haro objects shaped like bow-shocks, pointing back toward the Trapezium region. This is consistent with the idea that outflows from the ONC central region (most current star formation) is blowing out material and triggering star formation. [6]

5. I have provided observational evidence, the second known example in our Galaxy, that cluster–cluster interactions take place and can scatter cluster members into unbound, individual stars like our Sun. Most stars are likely to be formed in the high star forming rate protoclusters, but only a few bound associations survive for hundreds of millions of years. This implies that dispersal of members is very efficient, especially in the early evolutionary stages. Nevertheless, aged systems are subject to tidal disruption, but not exclusively by giant molecular clouds or due to passage through the dense galactic disk. As I have shown through the example of NGC 1907 & 1912, cluster–cluster interactions are also responsible for scattering stars into the galactic population. Such tidal disturbance is apparent in the spatial–RV distribution: the observations suggest the presence of a tidal bridge and a hint of a tidal tail. [7,8]

Publications

Papers Regarding the Listed New Scientific Results

[1] "Precision Radial Velocities for the Kepler Era"
Szentgyorgyi, A.H, & **Fűrész, G.**
2007, The 3rd Mexico-Korea Conference on Astrophysics: Telescopes of the Future and San Pedro Mártir (Eds. Stan Kurtz, José Franco, Seungsoo Hong, Guillermo García-Segura, Alfredo Santillán, Jongsoo Kim, & Inwoo Han) Revista Mexicana de Astronomía y Astrofísica (Serie de Conferencias) Vol. 28, pp. 129-133

[2] "Precision of Radial Velocity Surveys using Multiobject Spectrographs – Experiences with Hectochelle"
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[3] "Automating Reduction of Multifiber Spectra from the MMT Hectospec and Hectochelle"
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[4] "The 6.5-m MMT's f/5 wide-field optics and instruments"
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[6] “Kinematic Structure of the Orion Nebula Cluster and its Surroundings”
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[7] “NGC 1907 and NGC 1912: an interacting pair of open clusters?”
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2008, submitted to Astrophysical Journal, positive referee report recieved

[8] “Kinematics and Variable Stars in NGC 1907 and NGC 1912”
Szabó, Gy.M., **Fűrész, G.**, Székely, P.; Szentgyorgyi, A.
2006, Astrophysics of Variable Stars, Pecs, Hungary, 5-10 September 2005, Sterken, C. and Aerts, C. (eds). ASP Conference Series, Vol. 349, p. 339. San Francisco: Astronomical Society of the Pacific

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“High-Resolution Spectroscopy in Tr 37: Gas Accretion Evolution in Evolved Dusty Disks”
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