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Editors: José Miguel Rodríguez Espinosa, Francisco Garzón López & Verónica Melo Marín

STAR FORMATION RESEARCH AT THE UNIVERSITY OF FLORIDA

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RESUMEN

Las estrellas se forman en los interiores densos de las nubes moleculares, ocultos de visión directa en longitudes de onda ópticas. La Universidad de La Florida tiene un fuerte programa de instrumentación infrarroja que ha sido explotada para observar las fases tempranas de la formación estelar y de la evolución protoestelar. Además, las observaciones radio milimétricas realizadas han permitido estudiar las componentes frias del medio interestelar aportando un complemento esencial a los datos infrarrojos. Lo que sigue resalta al investigación llevada acabo recientemente en la Universidad de La Florida en el campo de la formación estelar así como otros proyectos en marcha, finalizando con una lista de posibles proyectos futuros para el GTC.

ABSTRACT

Stars form in the dense, dusty cores of molecular cloudss shrouded from view at optical wavelengths. The University of Florida (UF) has a strong program in infrared instrumentation that has been exploited to observe the early phases of star formation and protostellar evolution. In addition, millimeter wavelength radio observations allow the cool components of the interstellar medium to be studied and provide an essential complement to the infrared work. This article highlights recent UF star formation research and ongoing projects and concludes with a list of potential future projects for the GTC.

Key Words: **ISM: STAR FORMATION**

1. INTRODUCTION

The origins of our Sun, and all stars in the Galaxy, is one of the most fundamental questions in astronomy and one of the most intensely studied. It is well known that stars form through the collapse of dense cores within molecular clouds, shrouded from view at optical and even near-infrared wavelengths. After a star forms, it gradually disperses its cocoon of dust and gas through outflows and winds with the result that it becomes ever more visible at shorter wavelengths. Thus the combination of radio telescopes operating at millimeter and mid-infrared wavelengths, which can peer through the most compact dusty cores at the earliest stages of star formation, together with near-infrared observations of less embedded, more evolved protostars, is necessary to obtain a comprehensive view of stellar birth and early protostellar evolution.

UF astronomers pursue research in the area of star formation at wavelengths ranging from the near-infrared to millimeter radio observations. Leading through its strong program in infrared instrumentation, UF teams have carried out groundbreaking work in several areas in the field, from the formation of star forming cores to protostellar disks and on to protoplanetary disks. The GTC will allow more detailed and more sensitive observations of star forming regions over a wider range of environments and bridge the traditional galactic/extragalactic divide in the field. In closer systems, it offers the ability to study planet formation processes in greater detail than before. Here, I present some recent results obtained by UF teams, broadly divided by wavelength, and conclude with a brief discussion of potential future research projects in which the GTC can make a significant impact.

2. NEAR-INFRARED STUDIES

The extinction at K is 10 times less than in the visual and thus near-infrared observations can see through most of a molecular cloud and reveal the protostars within. Further, protostellar disks produce infrared excesses above the photospheric emission and their presence can therefore be diagnosed through photometry. Here, I describe three main areas of research being led by Elizabeth Lada.

2.1. *Protostellar disks*

Conservation of angular momentum ensures that a rotating, collapsing cloud will flatten into a disk. Indeed disks are a ubiquitous shape in the Universe from Saturn's rings to spiral galaxies and they are

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observed to surround young protostars (e.g., McCaughrean & O'Dell 1996). The study of protostellar disks is important for understanding the accretion onto a star and the outflows they generate and also for the formation of planetary systems.

Near-infrared imaging of young stellar clusters provides an opportunity to study many objects at the same distance. Infrared excess can be measured through color–color diagrams such as $J-H$ versus $H-K$ and indicate youth (either protostellar envelopes and/or disks). At slightly longer wavelengths, L band data discriminate evolutionary state more precisely, both because there is less scattering and because the stellar photospheric emission is greatly reduced. Compiling $JHKL$ statistics for six clusters, Haisch, Lada, & Lada (2001) studied the fraction of stars with disks as a function of age and environment. They found that the disk fraction is higher in younger clusters than in older clusters and that the overall disk lifetime is 6 Myr.

2.2. *Pre-main sequence binaries*

Most field stars are partners in a binary or multiple system yet the binary fraction is even higher for young stars (Simon et al. 1995). As part of her PhD thesis, Joanna Levine is studying the binary fraction in the NGC 2024 cluster through tip–tilt K band observations that can resolve binaries to within $0.3''$ (Levine, Lada, & Elston 2000). They find a binary fraction higher than that of the field but with a deficiency at wide separations. This finding supports the hypothesis that the binary fraction decreases owing to dynamical interactions (Kroupa 1995).

2.3. *The FLAMINGOS survey of nearby GMCs*

In the past year we have begun a 5 year program at the NOAO 2.1 m and 4 m telescopes on Kitt Peak to carry out the most complete survey of the young stellar content of the five closest northern giant molecular clouds (GMCs). Each cloud will be imaged in its entirety at JHK with follow-up spectroscopy of the brighter objects. The total area of the survey will be a remarkable ~ 100 square degrees and several thousand spectra will be taken. Such a large scale survey was made possible by the new FLAMINGOS near-infrared imager and multiobject spectrometer (Elston 1998). The imaging is well under way[1] and engineering tests are being made of the spectroscopic mode with scientific data expected to be obtained from fall 2002 onwards.

The imaging will be complete to $K \sim 17$; this is two magnitudes fainter than 2MASS and sufficient to detect brown dwarfs at 1 kpc. The spectroscopic follow-up will allow ages and stellar masses to be determined accurately for large numbers of sources over a wide range of environments within and between clouds. The principal goals of this survey are to obtain as complete a census as possible of the young stars in each cloud, to examine their distribution (e.g., how many form in isolation, how many in groups), to measure the age and mass distribution of the stars, and to compare these properties with location in a cloud and from cloud to cloud. Even if just one cloud were studied in this way, the survey would be the most comprehensive of its kind ever performed. With five clouds being studied, it will provide an unparalleled dataset for comparative studies of star formation within and between GMCs.

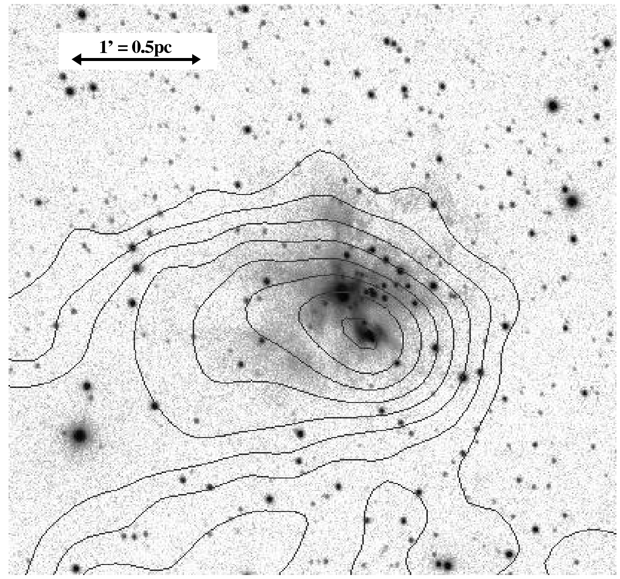

Fig. 1. FLAMINGOS JHK image of a cluster in the Rosette molecular cloud with contours of CS emission overlaid showing the distribution of dense gas.

A natural complement to the these data is a millimeter survey of the dust and gas associated with these young stellar clusters. For his PhD, Carlos Roman is imaging the Rosette molecular cloud with FLAMINGOS and mapping the most prominent clusters at millimeter wavelengths to study the mass, morphology, and dynamics of the associated molecular core (Figure 1). He will compare stellar and gas properties across the cloud from near the H II region (the Rosette nebula) to the far side of the cloud to assess the effect of environment on star formation.

[1]See http://www.astro.ufl.edu/∼lada/sf_survey.html.

3. MID-INFRARED STUDIES

Observations at mid-infrared wavelengths (5–25 μm) are especially challenging because of the high emission from the ambient surroundings but they offer the potential to examine the cooler outer regions of disks and circumstellar envelopes that do not emit significantly at shorter wavelengths. UF is constructing state-of-the-art cameras and spectrometers for observations at these wavelengths (see the article on CanariCam by by Charlie Telesco in this volume, p. 19). Current research with these instruments spans the range from protoplanetary disks to AGN. Here, I discuss recent Galactic star formation research led by Robert Piña and Charlie Telesco.

3.1. *Debris disks*

Since the *IRAS* discovery of excess infrared emission around the main sequence star Vega (Aumann et al. 1984), it has been realized that low mass disks may persist long after the star (and planet) formation process has ended. Because such dust particles would quickly be lost through Poynting–Robertson drag and collisions (see Lagrange, Backman, & Artymowicz 2000) they must be regenerated, most probably through the collisions of larger planetesimals. Since the latter are not readily detectable with technology currently available, their inference through the study of such "debris disks" is of immense importance for understanding the formation of planets.

Mid-infrared observations currently provide the best way to study these objects at sufficiently high resolution to discern their structure. Observations of HR 4796A with OSCIR (Jayawardhana et al. 1998) revealed the presence of a dusty disk of radius 100 AU with a central hole of radius 50 AU. Higher sensitivity and resolution images obtained with Keck II by Telesco et al. (2000) showed a slight brightness asymmetry, which may indicate the presence of planets (Wyatt et al. 1999).

3.2. *Massive star formation*

Only one out of every ~200 new stars is an OB star, but massive stars dominate the energetics of the ISM through their winds, radiation, and demise as supernovae. Their destructive effects can terminate the formation of stars nearby (Hester et al. 1996) but may also propagate star formation in other clouds (Elmegreen & Lada 1977). As with lower mass stars, OB stars form in dense cloud cores obscured from view at optical and near-infrared wavelengths. Three factors make the study of their formation more difficult than for low mass stars, however: their rarity translates to large distances; they form in groups, not in isolation; they form rapidly and reach the main sequence while still deeply embedded. For these reasons, high resolution radio interferometry has been the principal tool for the study of massive star formation but mid-infrared observations also offer high resolution and the ability to penetrate through the dusty cores and these data are now providing insights into the origin of OB stars.

Masers often signpost the hot, dense, early phases of massive star formation. Linear groupings of methanol masers have been proposed to indicate the presence of disks around newly forming stars (Norris et al. 1998) but this identification remained unsure since the stars themselves could not be seen. The recently completed PhD thesis of James De Buizer was a mid-infrared survey of methanol maser groups carried out with OSCIR to locate the stellar sources associated with the maser emission (De Buizer, Piña, & Telesco 2000). He found three cases of elongated mid-infrared emission indicative of a disk and suggested that the methanol masers are pumped by the mid-infrared light. Radio studies also show that high mass stars form in so-called "hot molecular cores" (Walmsley 1995); small, dense, massive structures with kinetic temperatures $\sim$ 50 K. Such cores emit strongly in the mid-infrared and Gemini-North observations by De Buizer et al. (2002) directly detected such a core in G29.96-0.02, thereby constraining the dust properties of the object.

4. MILLIMETER WAVELENGTH STUDIES

Millimeter wavelength (0.3–3 mm) radio observations reveal the cool dust and molecular components of molecular clouds, the birthplaces of stars. Very high velocity resolution, < 0.05 km s^{-1}, can be obtained but the spatial resolution of single-dish telescopes is poor, $> 10''$. Arcsecond imaging can be obtained with interferometers operating at 1.3–3 mm and soon at shorter wavelengths with the Smithsonian sub-millimeter array about to start operation (http://sma-www.harvard.edu). These capabilities allow the structure, dynamics, and chemistry of star forming cores to be explored. UF research into these topics is carried out by the author of this article.

4.1. *Young stellar groups*

Together with UF graduate student, Catherine Garland, I am investigating the formation and evolution of young stellar groups. Sub-millimeter continuum observations reveal the dusty envelopes that surround young clusters and individual protostars. In a recent study of the NGC 2264 star forming region in Monoceros (Williams & Garland 2002), two

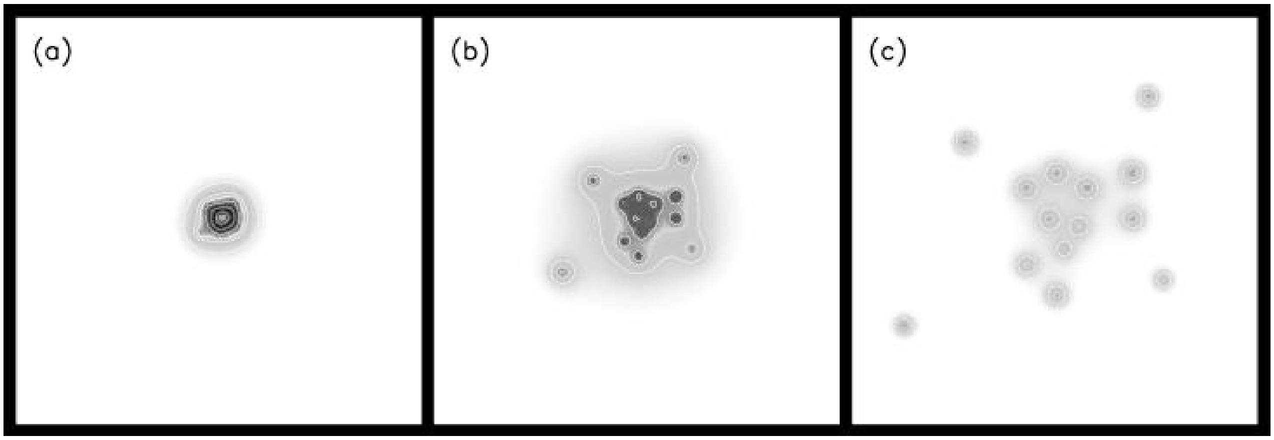

Fig. 2. Schematic model of the formation and evolution of a young stellar cluster. In the first panel, a cluster forms in a dense core and is visible as a bright, compact, sub-millimeter source. As the cluster disperses its surroundings, the sub-millimeter flux decreases and the individual stars begin to migrate away from each other (central panel). As the individual protostellar and collective protocluster envelopes are reduced in mass through accretion and outflows, the cluster becomes faint at sub-millimeter wavelengths but bright in the near-infrared. A combined radio-infrared survey is thus essential to follow these early stages of cluster formation and evolution.

very young groups were compared. We suggested that the kinematic ages of the groups, measured through continuum observations of the spatial dispersion of the cores and line observations of the velocity dispersion, might be used to follow protocluster and protostellar evolution at high time resolution and at far earlier stages (< 1 Myr) than achieved before.

To test this idea, we are carrying out mid-infrared observations of individual protostars in each group to better define their spectral energy distribution and therefore their evolutionary state. Since stars form with a low efficiency, as the cloud core is dispersed through winds and outflows from young stars, their gravitational cohesion is lost and the individual stars migrate away from each other (Lada, Margulis, & Dearborn 1984). Measuring their dispersion in space and velocity provides an estimate of their age. A simple schematic model of how this might proceed is shown in Figure 2. As the stars within a cluster evolve, their spectral energy distribution moves to shorter wavelengths and thus a combination of radio, mid-, and near-infrared observations are essential to follow the complete progression.

4.2. *Molecular clouds and star forming cores*

The structure and dynamics of molecular clouds provide clues to their formation and evolution (Williams, Blitz, & McKee 2000). Observations of molecular lines show the turbulent, rotational, collapse, and outflow motions within them. We have just begun a companion radio survey to the FLAMINGOS near-infrared survey of nearby molecular clouds to learn about the star formation efficiency of cloud cores in different environments and to examine their dynamics and chemistry. Observations are under way with the FCRAO telescope, whose focal plane array and MMIC receivers provide rapid mapping capability in multiple spectral lines. Planned follow-up will include higher resolution observations at IRAM and BIMA and higher transition studies with the CSO and SMT.

5. STAR FORMATION RESEARCH WITH THE GTC

The GTC will have enormous sensitivity and high resolution. It offers the potential to observe brown dwarfs in the Galactic Center and resolve star clusters in other galaxies. It will be, however, a relative latecomer to the 10 m club and will naturally lag behind the Kecks, for example, in such work. There will still be plenty of groundbreaking science to be done, of course, but perhaps mostly through longer term, survey-mode, projects.

A systematic study of the young stellar content of GMCs toward the Galactic Center using EMIR, for instance, will provide insight into how the star formation process and end product (i.e., the IMF) might vary in a high pressure environment. Observations of young stars in other galaxies may show the influence of other environmental factors such as metallicity and allow studies of extreme star forming environments (e.g., Vacca, Johnson, & Conti

2002). Surveys, not just limited single observations, of star formation in other galaxies with 10 m class telescopes will provide unique datasets that can be meaningfully compared with Galactic star formation research. Galactic and extragalactic star formation research are two fields that obviously share a lot in common but which have traditionally been separated because of the differences in sensitivity and resolution of the observations. The GTC can play a major role in bridging these two disciplines, a necessary step toward understanding, for example, the nature of starbursts.

The GTC will operate from the optical to the mid-infrared but its power at these wavelengths may be leveraged to create a bigger impact in the field through coordinated plans to carry out complementary observations at other wavelengths, for example (sub-)millimeter studies with the IRAM 30 m in Granada and eventually the LMT in Puebla. Such multiwavelength work is essential not only for stars formation research but many other areas of astrophysics.

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