■ Scientific Justification

Stellar clusters provide excellent laboratories for the study of stellar evolution since one of the primary variables – age – is significantly constrained. Recent studies indicate that clusters may account for 70-90% of star formation and that embedded clusters (those still partially or fully enshrouded in their parental molecular cloud) may exceed the number of more traditional open clusters by a factor of ∼20 (Lada & Lada, 2003). Taken together, these two facts mean that most of the stars currently in the galactic disk most likely originated in embedded clusters. Consequently, studies of these clusters can play a critical role in understanding the basic properties of star formation such as the universality of the initial mass function (IMF), the frequency of binaries or multiple stars, and possiblities for planetary companions. Since the lifetimes of the most massive stars are typically less than the evaporation time for embedded clusters, they are also some of the best sites for studying massive stars and protostars.

The origin and evolution of clusters is not well understood, although theoretical work has begun (e.g. Elmegreen et al., 2000). In one possible mechanism, gravitational collapse is precipitated by compression due to shocked gas, although the proposed origin of the shock front varies (refs). The degree of embedding observed young clusters varies widely; some are essentially protoclusters in the process of beginning to emerge from their molecular cloud, while others are nearly free from their nearby cloud. Nearby embedded clusters, such as the ONC/Trapezium, have been the subject of many fruitful investigations (e.g. Luhman et al., 2000); but the best studied clusters do not reach beyond a ∼2 kpc solar circle. Spitzer (1958) first demonstrated that clusters should be disrupted by passing interstellar clouds, such that cluster lifetimes should be a function of galactic radius. Accretion in stellar clusters, which influences the mass ranges, is in part time dependent, but may also depend on metallicities and intercloud interactions (Bonnell et al., 2001). Therefore, to further our understanding of cluster evolution, we must expand our studies beyond those clusters closest to us, to include a variety of embedded clusters which span ages, number of cluster members, and galactic location.

The formation and early evolution of massive stars is one of the least-understood aspects of star formation. Massive stars are believed to form so quickly that they are still be accreting material even as they enter the ZAMS; as a result, the earliest stages are typically still enshrouded in remnants of their natal molecular clouds. Most massive stars are associated with stellar clusters, leading some to suggest that they may form by coalescence of intermediate mass protostars (e.g. Bonnell et al., 1998; Stahler et al., 2000), or by accrection at cluster centers (e.g. Behrend & Maeder, 2001). Observational data, however, is consistent with gravitational collapse according to a standard IMF (Bonnell & Clarke, 1999). The mode of formation of massive stars is still much debated; characterizing the physical conditions of the environments which may contain massive protostars provides crucial information necessary to understanding of their formation and evolution.

How do these forming clusters, and the massive protostars in particular, effect their surrounding regions? Solar mass young stellar objects (YSOs), are well known for producing significant outflows from both stellar winds and jets. Massive stars typically have strong stellar winds, but whether they also have jet outflows is unknown. Evidence of jet outflows is significant to massive star formation theory because jets require the existence of an accretion disk, and whether massive stars have such disks is much debated. Massive stars also produce large amounts of UV radiation, ionizing the nearby gas, and producing photodissociations regions (PDRs) in the boundary layer between the fully ionized gas and the molecular gas. The winds and ionizing radiation produced by the most massive stars in a cluster, are thought to effectively end additional cluster star formation, but the accretion times required of the smaller cluster members makes this questionable.

- **The need for the** *Spitzer Space Telescope:*

Stellar wind and outflows are often highly supersonic, with typical Mach numbers ∼10 (Hollenbach, 1997), therefore they produce shocks both where the wind impacts the natal cloud and within the wind. Evidence of shocks can be found in both in ground-vibrational (v=0-0) modes of H_2 emission (ie. S(5) 6.9 μm and S(3) 19.7 μm) and by studying variations in fine structure lines. Shocks can be dissociative J-shocks, characterized by a jump discontinuity in velocity, density, temperature and high velocities ($\gtrsim$100 km s^{-1}, Hollenbach & McKee 1989), or non-dissociative C-shocks, characterized by a smooth continuous shock front and low velocities. The J and C shocks can be distinquished by the variations in the [Ne II] (12.8 μm) and [Si II] (35 μm) lines since C shocks typically have very low atomic abundances. Other lines characteristic of the slower C-shocks include collisionally-excited lines from neutral atoms such as [S I] 25 μm, and warm H_2. For J shocks, [S I] (25 μm), [C II] (11.4 μm), [Fe I] (24 μm), [Fe II] (26 μm), and [Fe II] (35 μm) are predicted to form in regions of dense gas (Hollenbach & McKee, 1989). The faster J-shocks can also dissociate the molecular gas and sometimes ionize it; in this case we see some warm dust heated by optical forbidden line emission and collisionally-excited lines from singly ionized atomic species which are typically doubly-ionized in H II regions such as [Fe II] 17.0μm and 26.0 μm, and [Si II] 34 μm. Since outflows from winds are typically slower than jet outflows, a difference in the shock intensities provides clues to the velocity of the inducing shock, and therefore the driving mechanism.

A simple velocity dependent differentiation between J-shocks and C-shocks is, of course, not the whole story. There can be radiative precursor region or magnetic precursors (Hartigan et al., 2000), both of which alter the temperature and chemistry of the natal molecular cloud. Collisionally excited H_2 is the dominate species observable in the preshock region, which, because of its short cooling time (Eislöfel, 1997), provides information on where the interaction between the shock and the molecular cloud is currently taking place. In the complicated postshock region, the structure and chemistry varies greatly, as the temperature can drop quickly from $\gtrsim 10^5$ K to $\lesssim$ 100 K (Hollenbach & McKee, 1989). Besides H_2, several atomic species are involved in he cooling processes in this region, among which are [S II] and [Fe II].

The effective temperature of the radiation field from hot stars can be measured from the ratios of [Ne II] 12.8 μm to [Ne III] 15.5 μm line and [S III] 18.7 to [S IV] 10.5 μm lines after correcting for extinction measured from the 10 and 18 μm silicate absorption features (e.g., Simpson et al. 1995; Giveon et al. 2002; Rodríguez-Fernández et al. 2001). The temperature of the ionized gas allows for an estimate of the temperature of the ionizing source and thus provide indirect evidence of the luminosity class of the ionizing source. The ratio of the [Si II] 34 μm line to the neighboring [S III] 33 μm line provides good indicator of the dilution of the photoionizing radiation field (Rubin & Simpson unpublished; Simpson et al. 1987). When observed at several locations, variations in this ratio provide a good indication of the direction and distance of the ionizing source. Differences in warm and hot molecular hydrogen can be measured from spectra in the 10-40 μm ranges, and provide a measure of the dust temperature and column density (e.g., Simpson et al. 1998; Rodríguez-Fernández et al. 2001).

The photodissociated region can be studied using the PAH (formerly UIR) lines, including those at 6.2 μm, 7.7 μm, 8.6 μm, and 11.6 μm. Additional (weaker) PAH emission lines have also been observed at 10.5 μm and 12.5 μm. Variations in the PAH emission line ratios provides information on both the photophysical and chemical processes within the narrow PDR transitional region. Understanding the location and the charater of the typically narrow PDR region, in conjunction with the ionized gas, possible shock emission, and observations of the stellar population (via ground based NIR observations) permits a thorough characterization of embedded clusters, the sight of massive star formation.

- **Proposed Observations:**

We propose to obtain IRAC maps and IRS spectra for four embedded clusters, which we designate G353.41-0.36 (Fig. 1), AFGL 4163 (Fig. 2), IRAS 06058+2138 (Fig. 3) and Sh2-217, which vary in both the degree of remnant dust and gas, and galactic location. The individual objects and the observing stradegy are discussed in more detail in the *Technical Plan*. The requested observations are part of a larger study on variations in the IMF we are conducting using observations of infrared clusters. In the past few years, several groups have utilized the 2MASS survey to search for previously unknown infrared clusters (refs), although follow on NIR observations have shown that many of these are not actual clusters (Dutra et al., 2003; Cotera et al., 2004b). We have obtained higher resolution NIR images of the clusters we propose to observe with *Spitzer* (see Figures 1-3) at the MMT in the northern hemisphere and at the AAT in the southern hemisphere. In addition, we have obtained spectra of 3-5 stars in each cluster for those observed at the AAT, and have been awarded time in March at the KPNO to obtain stellar spectra for the other clusters. We have been able to successfully obtain spectral classifications for many of the stars, which is essential for an accurate determination of the IMF for the clusters (Massey et al., 1995; Leistra et al., 2004). These clusters represent the first of a sample of $\sim$30 clusters, which have been selected for the larger study of the variation of the IMF with Galactic environment.

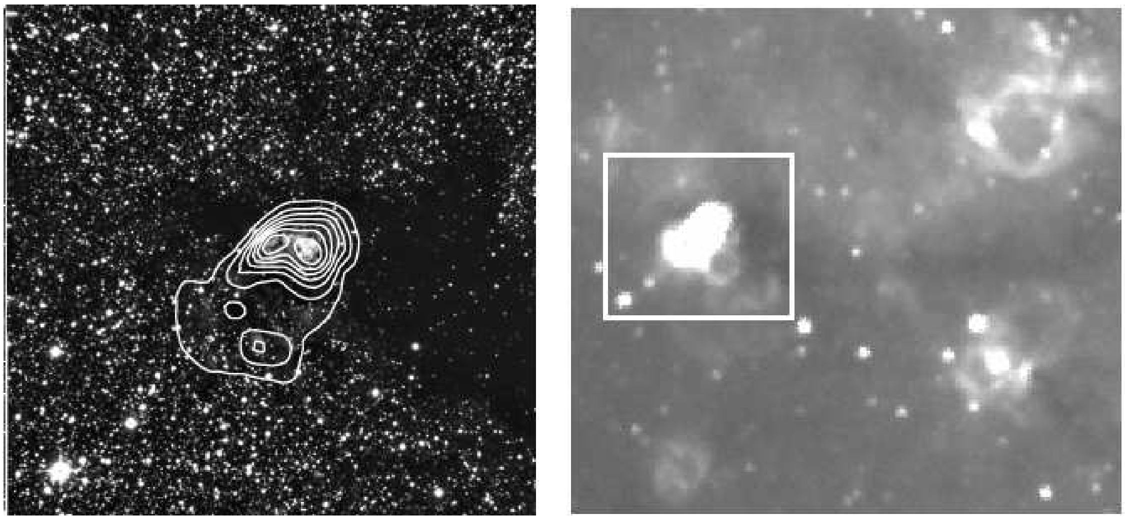

Figure 1: **G353.41-0.36** *Left*: $7' \times 7'$ NIR image obtained at the AAT with the facility instrument IRIS2. The contours are taken from the MSX image of this region. *Right*: $?' \times ?'$ MSX image. As can be seen, there are several apparent wind blown bubbles, possibly associated with massive stars, located adjacent to the cluster location.

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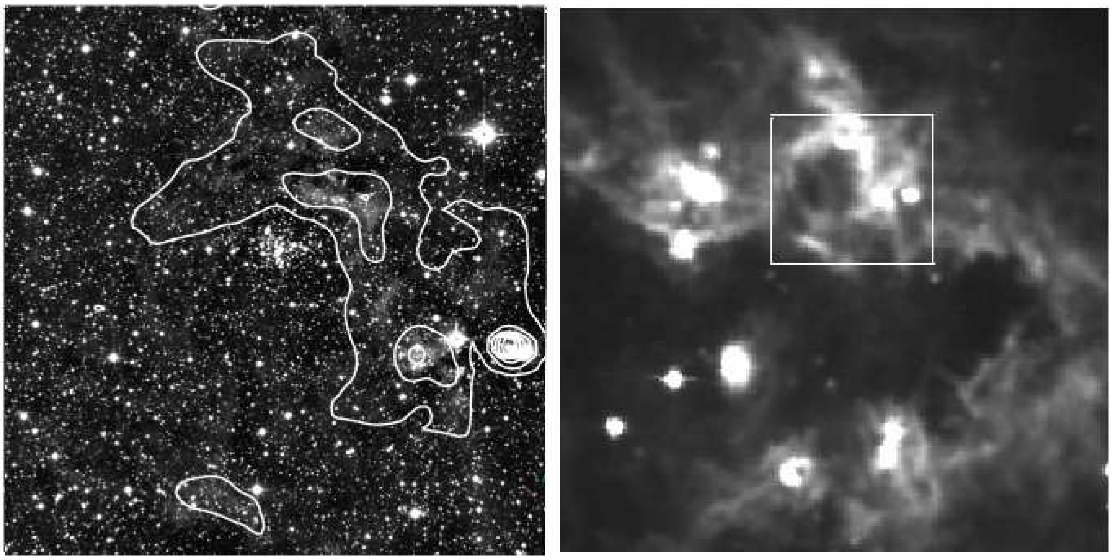

Figure 2: **AFGL 4163** Same as Fig 1. The strong MIR emission seen northwest of the cluster is also at the location of a smaller collection of stars, and may indicate the location of a second round of star formation, induced by the outflows from the observed clusters. NIR spectroscopy of this cluster has identified one Of4 and two B stars.

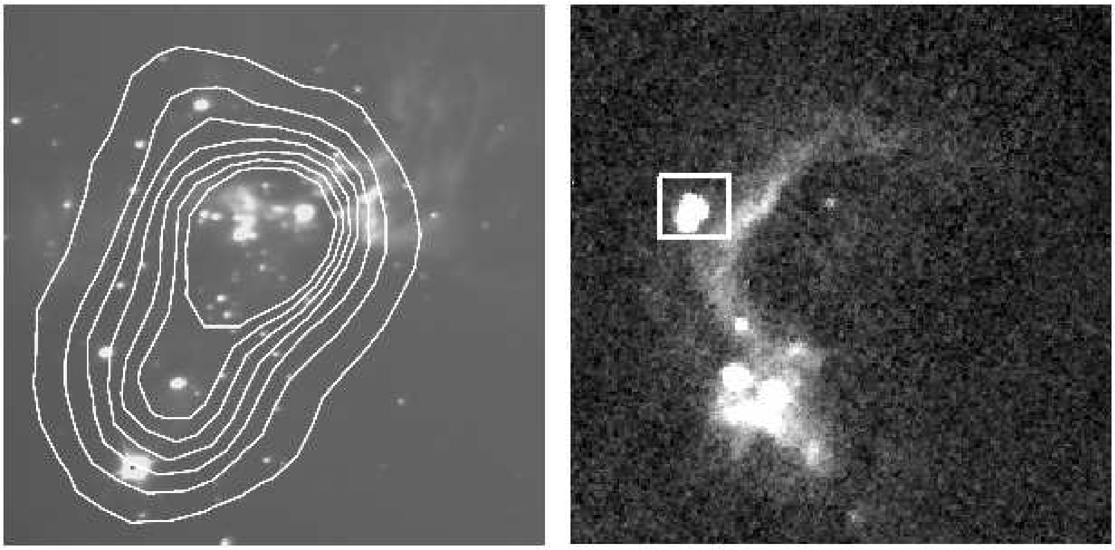

Figure 3: **IRAS 6068+2138** Same as Fig 1. The observed clusters may be the first of several regions of cluster formation, induced by outflow from a source to the northwest. We will be obtaining NIR spectra of the brightest cluster members at the KPNO 4m in March.

Techincal Plan

Individual Targets

- *G353.41-0.36*:
- *SH 217*:
- *AFGL 4163*:
- *IRAS 06058+2138*: