# The Stellar Content and Dynamics of Cygnus OB2

*Note*: This proposal is for our continuing long-term MMT/HectoSpec program SAO-9.

**Star Formation in Massive Clusters**

Star formation is one of the fundamental baryonic processes in the Universe, occurring on a wide variety of scales from small star-forming regions such as Ophiuchus to the massive star clusters near the Galactic center and in starburst galaxies. Our current understanding of the star formation process is derived from studies of nearby, low-mass regions, yet massive star clusters are thought to be the birth places of the majority of stars in our Galaxy [1], each containing thousands of OB stars and millions of low-mass stars. These regions are dominated by massive OB stars, whose strong winds and intense UV radiation strongly influence their environment. Understanding these influences and the differences between low-mass and high-mass star forming regions is important for a complete understanding of star formation.

Most star clusters do not survive to maturity, as evidenced by the much lower number of clusters with ages >10 Myrs relative to an extrapolation of the young cluster population [2]. This is usually explained by the process of *infant mortality*, whereby residual gas left over from star formation is forced out of the cluster via massive star feedback, leaving the stars in a super-virial state and prone to dissolution. This long-established theoretical framework assumes the cluster was in virial equilibrium prior to gas expulsion and identifies the star formation efficiency (the fraction of gas turned into stars, ∼5-10%) as the dominant factor in determining cluster stability [3,4,5]. This has recently been called into question: numerous theoretical works have suggested other parameters of equal importance such as the spatial distribution of stars at birth [6], the rate of gas expulsion [7], and the initial virial state of the cluster [8,9].

The disruption of star clusters has implications for the origins of the open cluster and field star populations in our Galaxy. Many different simulations of cluster dynamics have been presented over the last decade, but observational verification is seriously lacking. Existing dynamical surveys are limited by small number statistics or based on integrated light, both biased towards the most massive stars, for which incompletely characterized binarity introduces errors [10].

**Our Nearest Massive Star Cluster, Cygnus OB2**

Studies of massive star clusters are hampered by their rarity and distances, resulting in an inability to study the lowest-mass members and insufficient spatial resolution to diagnose the physical processes at work. Cygnus OB2 is the exception to this at a distance of 1.4 kpc [11] and home to >65 O-type stars [12,13,14] and thousands of OB stars [15]. With a total stellar mass of $\sim 3 \times 10^4$ $M_\odot$ it has drawn comparison with the massive clusters seen near the Galactic center [15,16]. Previous studies of Cyg OB2 have been hindered by its high extinction and the difficulty separating cluster members from the Galactic foreground. The *Chandra* Cyg OB2 Legacy Survey [17] overcomes this by identifying pre-MS stars via their elevated X-ray emission relative to the older field population and its uniform sensitivity gives a completeness of >95% at 1 $M_\odot$. No other massive star cluster can be studied in as much detail as Cyg OB2.

**Spectral Typing and Kinematics with the MMT**

*Chandra* X-ray observations combined with optical and near-IR photometry has unveiled the cluster population down to previously inaccessible depths. However, photometric spectral typing is highly degenerate in regions of high extinction and large age spreads such as Cyg OB2 and therefore optical spectroscopy is necessary to accurately classify members. This will allow more accurate studies of the initial mass function, age spreads, and mass segregation, all of which are

vital for understanding the star formation process in massive star clusters.
The primary use of the spectra is to obtain radial velocities (RVs), offering a number of scientific returns. A key question regarding star clusters is their long term stability against dissolution. The physical processes that determine this are not fully understood and stellar kinematics will allow us to address this question directly. Our first generation HectoSpec observations (2008-9) allowed us to study the dynamics of $\sim$500 members in the center of the cluster. This revealed that the cluster is globally unbound, but the core was found to have a lower velocity dispersion suggesting that it may remain gravitationally bound as the cluster disperses. By extending these observations to a wider area and improving our completeness we can map out the virial ratio across the cluster and identify any bound substructures that may form open clusters.
Since Cyg OB2 has already cleared its natal molecular cloud [18,19], it is an ideal candidate to test theories of cluster dispersal. For infant mortality we should see a radial dispersion of stars, whereas tidal stripping predicts velocities distributed along a specific axis (Fig 1 & [20]). Our existing RV survey showed that the cluster was unbound [21], but did not cover a large enough area to determine the mechanism responsible. We are proposing to extend our existing survey to obtain RVs for the majority of Cyg OB2 members with $i < 20$ using the HectoSpec multi-object spectrograph. To identify unresolved binaries and thereby minimize their influence on the derived velocities, two epochs of observations are required for each source. These observations will be combined to determine spectral types at the highest S/N. This work will produce the first ever 3D dynamical picture of an expanding massive star cluster, an objective never before realized. This will allow us to disentangle our currently static view of star clusters, opening up a new avenue in star cluster research a decade ahead of a likely Gaia-inspired revolution in astrophysics.

**Current status as of February 2012**

This project was started in 2011B and $\sim$1000 sources have been observed so far. These observations confirm our RV accuracy, though a second epoch is necessary to identify and remove close binaries from the sample. A paper presenting the spectral types and RV from our 2008-9 observations is in preparation ([21] & Figs 2-3) and has allowed us to better constrain the age and dynamics of the center of the cluster, though this is only a small fraction of the entire cluster. Extending these observations will allow us to study the propagation of star formation by correlating age and dynamics with position, and will also allow us to test theories of cluster dispersion. So far this project has been allocated 2 nights and we estimate that it will require a further 6–8 nights for completion. We propose to continue our program in 2012B and have identified $\sim$3000 targets that can be arranged in $\sim$15 configs and observed over 3 nights.

**Technical Specification**

We are targeting intermediate-mass stars ($\sim$1-10 $M_\odot$) - bright enough to obtain RVs from spectroscopy and numerous enough to provide a statistically significant sample. We will use the 600 grating (resolution $\sim$2 Å) covering 6500-9000Å (H$\alpha$ to the Ca II triplet), providing sufficient spectral lines for classification and RV measurement to $\pm$3-5 km/s (Fig 3). PMs are calculated from images spanning 7 yrs (Fig 2), providing accuracies of <1 mas/yr (3-5 km/s at 1.4 kpc). This accuracy matches those of RVs obtained so far and are sufficient to resolve internal substructure in a cluster with $\sigma_v \sim 10$ km/s (Fig 2). Targets are divided into narrow magnitude ranges for efficient observing. To reach S/N=10 sources with $i = 16$, 18, and 20 require exposures of 10, 40, and 140 min respectively (split into multiple exposures to remove cosmic rays). Adding overheads of $\sim$20 min / config and a 10 min offset sky exposure for the deepest config, we will be able to obtain spectra for $\sim$3000 sources in $\sim$25 hours, the equivalent of 3 nights May – July.

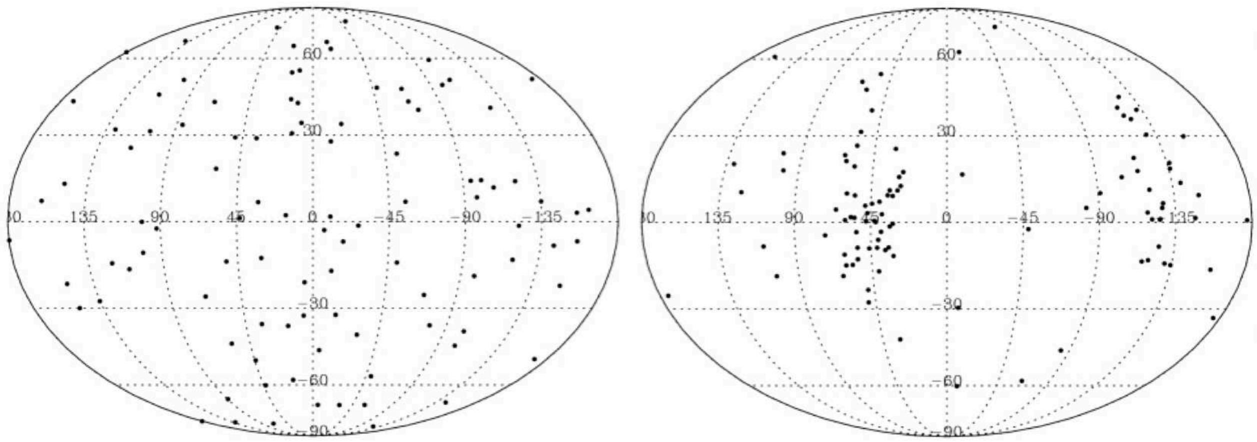

Figure 1: Results of two N-body simulations showing the velocity vectors (projected onto a sphere) resulting from cluster disruption by infant mortality (*left*) and tidal stripping (*right*) [20]. Infant mortality results in a radial dispersion of stars, while tidal stripping induces velocities distributed along a specific axis. Comparison between radial velocity observations and models such as these will allow us to distinguish between these two theories.

## References


[**1**] Portegies Zwart et al. 2010, 48, 431. [**2**] Lada & Lada, 2003, 41, 57. [**3**] Hills 1980, 225, 986. [**4**] Lada et al. 1984, 285, 141. [**5**] Bastian & Goodwin 2006, 369, 9. [**6**] McMillan et al. 2007, 655, L45. [**7**] Baumgardt & Kroupa 2007, 380, 1589. [**8**] Goodwin 2009, 324, 259. [**9**] Offner et al. 2009, 704, L124. [**10**] Gieles et al. 2010, 402, 1750. [**11**] Rygl et al. 2011, arXiv 1111.7023. [**12**] Hanson, 2003, 597, 957. [**13**] Massey & Thompson, 1991, 101, 1408. [**14**] Comeron et al. 2002, 389, 874. [**15**] Knödlseder, 2000, 360, 539. [**16**] Wright et al. 2010, 713, 871. [**17**] Drake et al. 2009, 90D. [**18**] Drew et al. 2008, 386, 1761. [**19**] Schneider et al. 2006, 458, 855. [**20**] Kruijssen 2011, arXiv 1107.2114. [**21**] van der Veen et al. 2012 *in prep.*

**Recent refereed publications based on data from CfA facilities for this project:** Drew, J.E., et al., 2005, MNRAS, 362, 753 (MMT-HectoSpec).

Vink, J.S., et al., 2008, MNRAS, 387, 308 (MMT-HectoSpec).

van der Veen, E., et al., 2012, ApJ, *in prep.* (MMT-HectoSpec).

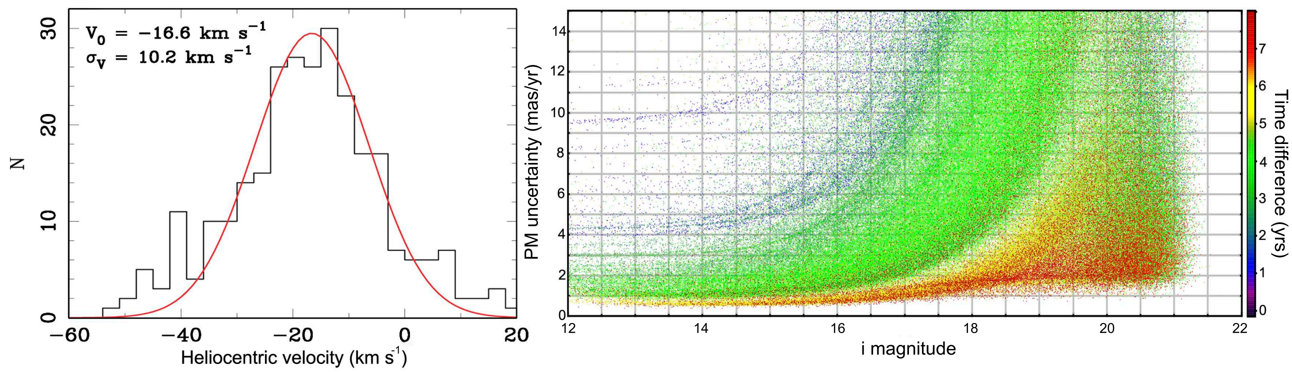


Figure 2: *Left:* Radial velocity distribution of ∼500 stars in Cyg OB2 observed with MMT/HectoSpec in 2008–2009 [21]. *Right:* Proper motion uncertainties as a function of baseline for Cygnus OB2 observations. Combining IPHAS and UKIDSS imaging with new near-IR observations provides a 7 yr baseline.

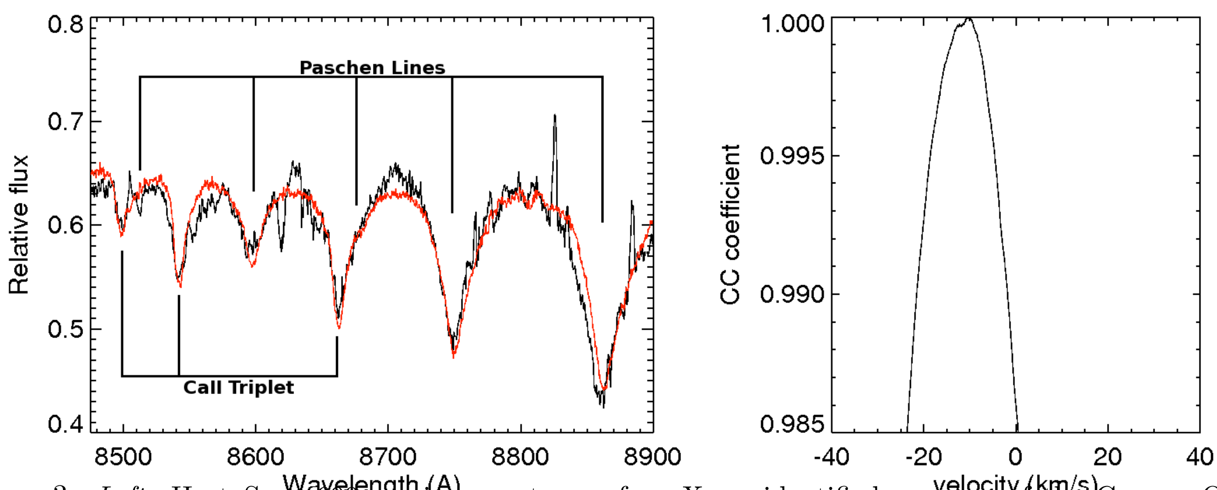


Figure 3: *Left:* HectoSpec 600 grating spectrum of an X-ray-identified member of the Cygnus OB2 association. Overplotted in red is the best fitting A4V standard star spectrum offset with a velocity of -12 $\pm$ 3 km/s. *Right:* Cross-correlation coefficient as a function of radial velocity.