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Cygnus OB2: A Laboratory for Massive Binaries, Runaway Stars, and Triggered Star Formation

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Abstract: The Wyoming Cygnus OB2 Radial Velocity Survey has identified dozens of new OB stars in this region while measuring orbital parameters for 15 binary systems, bringing the known total to 20. From these data we have modeled the distribution of binary parameters. We conclude that the slope of the distribution of periods is approximately flat in log space and that the slope of the distribution of mass ratios is either flat or slightly favoring larger q. However, there appears to be an excess of systems with 3–5 day periods and a deficit of systems with 7–14 day periods. From among $\sim$120 systems surveyed we find only one radial velocity runaway —a binary system! A Search of *Spitzer Space Telescope* images of the Cygnus X region reveals several bowshocks from high-velocity early type stars. We use the principles of bowshock physics to derive a novel technique for estimating the mass loss rates of runaway stars.

1 Introduction to the Cygnus OB2 Radial Velocity Survey

Herein we present results from a 10-year spectroscopic campaign on massive stars in Cygnus OB2. This is primarily the work of PhD student Daniel Kiminki supported by a big team of students at the University of Wyoming using data from the Wyoming Infrared Observatory 2.3 m telescope. The title doubles as my outline. Most of this contribution will focus on the emerging statistics of massive binaries. The remainder will report on searches for runaway stars in this region.

Cyg OB2 is home to one of the largest collections of OB stars in the Milky Way, and it is also one of the nearest. Odenwald & Schwartz (1993) presented a beautiful overview of the busy 5x5 degree region known as Cygnus X toward Galactic longitude l=80°. Their annotated 100 micron map shows the plethora of star forming complexes, molecular clouds, and OB associations as we look several kpc along the local spiral arm. Cyg OB2 sits in the middle of this region and is thought to be located at a distance of 1.4 – 1.7 kpc (Massey & Thompson 1991; Hanson 2003).

Since 1999 we have been conducting a radial velocity survey of $\sim$120 probable Cyg OB2 members using a variety of telescopes and optical spectrographs in order to improve upon the statistics regarding massive binary frequency, period, and mass ratio. Our goal is to improve upon the pioneering work of Garmany, Conti & Massey (1980) who performed a similar survey but over a shorter duration, drawing their sample from bright O stars all over the sky. Our sample is photometrically selected from the survey of Massey & Thompson (1991, MT91), and the sample is supplemented by additional OB stars from the imaging study of Comerón et al. (2002). Our survey was conducted at four major observatories between 1999 and the present, but most of the observations were made at the WIRO 2.3 m telescope with the longslit spectrograph at a resolving power of R$\simeq$ 4000. Details of observations and analysis may be found in Kiminki et al. (2007, 2008, 2009, 2011) and Kiminki & Kobulnicky (2011).

Figure 1 shows the portion of orbital parameter space to which our survey is sensitive. The blue shaded region at upper left indicates sensitivity to primaries with velocity amplitudes greater than about 15 km s^{-1}. As such, our survey will detect binaries with periods of days to perhaps several years, beginning to probe the interesting region of this diagram populated by the progenitors of low-mass X-ray binaries under some standard formation scenarios described by van den Heuvel (1983). Imaging surveys (speckle and interferometric; see e.g. Caballero-Nieves et al. 2011) are complementary in that they probe periods >10 yr.

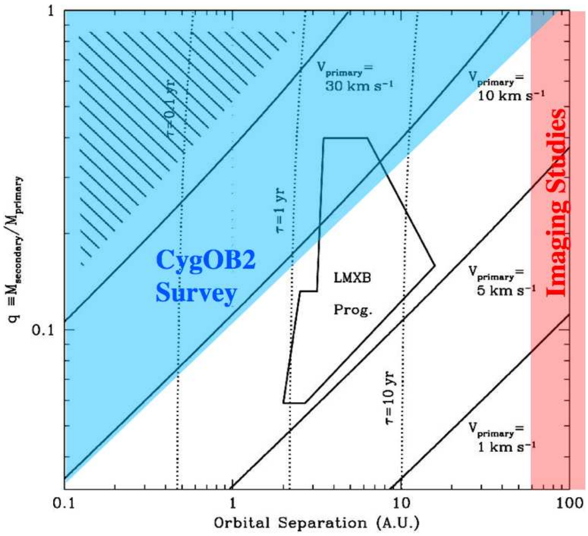

Figure 1: The survey is sensitive to primaries with velocity amplitudes of greater than about 15 km s^{-1}, shown by the shaded region in the upper left. Speckle and interferometric imaging surveys are sensitive to companions with separations greater than ∼100 A.U., shown by the red shaded region. This figure assumes a primary mass of 10 $M_{\odot}$ and circular orbits at inclination 90°.

2 Results on Binary Parameters

The Wyoming Cygnus OB2 Radial Velocity Survey has detected and/or measured orbital parameters for 15 binaries. When added to known systems already in the literature (famous examples such as the non-thermal radio emitters Schulte #5, #8a, #9 (Schulte 1958), see Nazé et al. (2010) for recent results on #9), the number of known massive binaries stands at 20, the largest number in any one cluster or association to-date. Of course, there is no guarantee that they are all members, but they are likely to lie within Cyg OB2 based on their photometric properties (magnitude and reddening) as measured by MT91 and Hanson (2003) and our systemic radial velocity results. We note, furthermore, that information about higher order systems (triples, etc.) is not easily extracted from our data, so we refer to all multiples herein as binaries. A table of the orbital elements for all systems is included in Kiminki et al. (2009) and Kiminki et al. (2011). Finally, there are an additional ∼20 systems for which we detect radial velocity variability, suggesting the presence of additional binaries that will require further observations to refine their orbital elements.

Figure 2 shows the plot of eccentricity versus period and mass ratio, $q \equiv M_2/M_1$, versus period. Filled circles show double-lined spectroscopic binaries (SB2s) and open circles show single-lined spectroscopic binaries (SB1s). As might be expected, the shortest period systems have low eccentricities. At periods longer than a few days, the range of eccentricities increases to cover the range 0 – 0.5. The distribution of Cyg OB2 stars appears similar to the OB stars drawn from the 9th Catalog of Spectroscopic Binary Orbits (Pourbaix et al. 2004). The lower panel shows that the distribution of q spans the full range from 1 to the detection limit of ∼0.1 for all periods between 1.5 and 25 days. The perceptive eye will also notice a dearth of systems with periods between about 7 and 14 days.

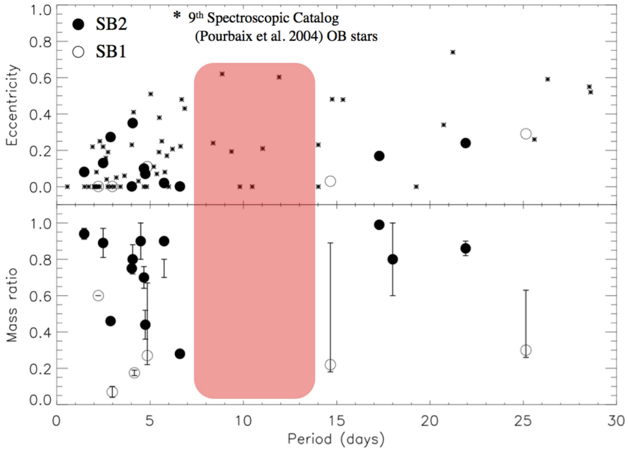

Figure 2: Eccentricity and mass ratio versus period for the massive binaries in Cyg OB2.

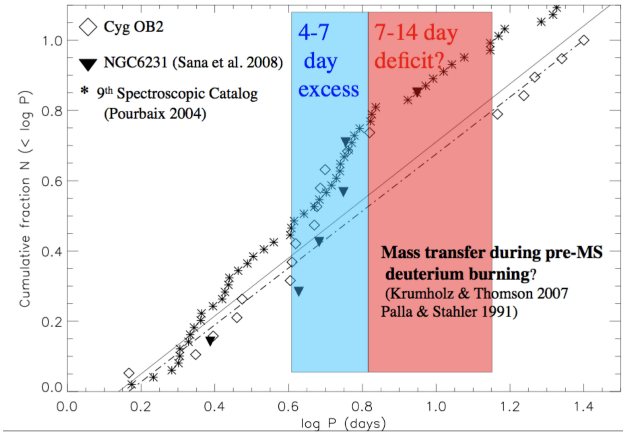

Figure 3: Cumulative distribution of orbital periods in this and other surveys.

The distribution of orbital periods is better seen in Figure 3 where we show the cumulative period distribution (diamonds and left abscissa) versus log(period) in days. Diamonds again show the Cyg OB2 sample. The cumulative distribution rises rapidly over the range 3–5 days, while there are no systems with periods between 7 and 14 days. The solid and dash-dot lines show (with slightly different normalization) a power law given by $f(logP) \propto (logP)^{\beta}$, where $\beta \simeq$0.2. However no power law is consistent with the observed distribution given the large gap in the period distribution.

One possible explanation for the excess of short-period systems and simultaneous lack of systems in the 7–14 day range is Roche-lobe overflow and mass transfer/loss during the pre-main-sequence deuterium burning phase of the primary star. Such a scenario was proposed by Krumholz & Thompson (2007) following Palla & Stahler (1991) in order to produce copious numbers of “twin” systems with mass ratios near unity that binary studies in the SMC seemed to demand (Hilditch, Howarth & Harries 2005; Pinsonneault & Stanek 2006). A mass-losing primary and mass-gaining secondary (possibly coupled with mass lost from the system) would also serve to reduce the orbital period of systems that were (even briefly) close enough to interact. If this is the operative mechanism, then we would expect to see an excess of high q systems having short periods. Such a feature is not obvious, but might be present.

Figure 4 show the distributions, cumulative on the left abscissa and conventional histogram on the right abscissa, for the mass ratios observed in Cyg OB2. Although the bin between q=0.8 and q=0.9 is the most populated, the overall distribution is not far from flat and is roughly characterized by a power law of slope α=0.3 where f(q)$\propto q^{\alpha}$. We find no significant population of “twins” having q>0.9. The survey becomes increasingly incomplete at q<0.3, so it is likely that there are additional systems in this mass range. Full details of the analysis, completeness limits, and results regarding massive binary parameters may be found in Kiminki et al. (2009) and Kiminki et al. (2011).

Velocities of the Cyg OB2 Systems

The mean heliocentric radial velocity for Cyg OB2 stars in our survey is -15.6 km s^{-1} with a dispersion smaller than our typical measurement uncertainty (i.e., <9 km s^{-1}). We find only one system, A36 in the notation of Comerón et al. (2002), that differs by more than 30 km s^{-1} from the mean, the canonical space velocity adopted to designate stars as runaways (Gies & Bolton 1986). A36 has a heliocentric radial velocity of -47 km s^{-1}, making it a probable runaway system—one of only three known runaway binary systems having non-degenerate components (D. Gies, private communi-

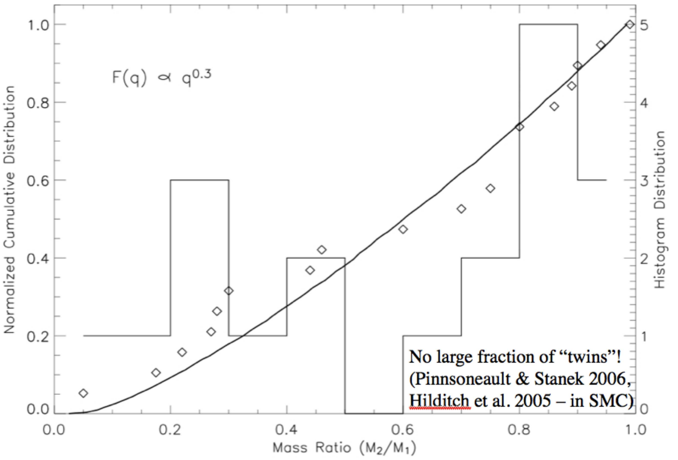

Figure 4: Cumulative (left) and histogram (right) distribution of mass ratios.

cation). Gies & Bolton (1986) find that ∼10% of all O stars are runaways. This would predict ∼12 runaways from Cyg OB2.

We conducted a search for runaways with space motions tangent to the line of sight using data from the *Spitzer Space Telescope* Cygnus X Legacy Survey (Hora et al. 2009) to identify bowshocks, one signpost of a massive star traveling at supersonic speeds. A visual search for arc-like objects within about two degrees of Cyg OB2 revealed 10 candidate bowshocks. Followup spectroscopy from the Wyoming Infrared Observatory confirmed that all 10 contained an object with the spectra and spectral energy distributions of late-O and early-B stars near their centers. However, many other types of astrophysical objects may superficially resemble bowshocks, such as the heads of gaseous pillars illuminated from the outside. We compared the candidate bowshocks to analytical models of Wilkin (1996) and found three of the objects have strong morphological similarity to the theoretical shape of shocks resulting from the supersonic motions of a massive star. We classified the remaining objects as either young stellar objects with surrounding interstellar material (3) or unknown/ambiguous in nature (4). We add BD+43°3654, a known high-velocity runaway and probable escapee from Cyg OB2 (Comerón & Pasquali 2007) to our list, bringing the number of probable runaways to four.

The analytical theory for stellar wind bowshocks has been developed by many authors, including Baranov et al. (1971) and more recently by van Buren et al. (1990) and Wilkin (1996). Working from their derivations and extending the terminology of Povich et al. (2008), we find that the mass loss rate of a star seen as a stellar wind bowshock object can be expressed as

$$\dot{M}_{w,-6} = \frac{0.67[R_0(pc)]^2[V_a(km/s)]^2 n_{a,3}}{V_{w,8}} \, . \tag{1}$$

R_0 is the "standoff" distance between the star and bowshock apsis which can readily be measured from images given the known distance to Cyg OB2. V_a is the velocity of the star, which, while unmeasured, can safely be assumed to be in the vicinity of 30 km s^{-1} based on other observed runaways. $V_{w,8}$ is the velocity of the stellar wind in units of 10^8 cm s^{-1}, which can be adopted from the known spectral type of each star and published wind speeds (e.g., Mokiem et al. 2007). The least certain parameter is $n_{a,3}$, the ambient interstellar density in units of 10^3 cm^{-3}. We estimate this parameter from the measured size and luminosity of each bowshock nebula, in conjunction with dust emissivity models of Draine & Li (2007). The derived mass loss rates are broadly consistent with, but slightly higher than measurements from other methods such as Hα, radio, and UV absorption line studies. Details of this approach, along with images and results may be found in Kobulnicky, Gilbert & Kiminki (2010).

Figure 5 compares the results for bowshock nebula analyzed in this manner (skeletal symbols) to results from other methods (open and filled symbols). There is a clear trend toward higher mass loss rates for the earlier and more evolved stars, and the overall zero point is in reasonable agreement with data from the Mokiem et al. (2007) and Fullerton, Massa & Prinja (2006). While this novel approach is unlikely to supplant more established techniques of mass loss determination, it provides a novel and independent estimate for a select subclass of high-velocity stars evincing bowshocks.

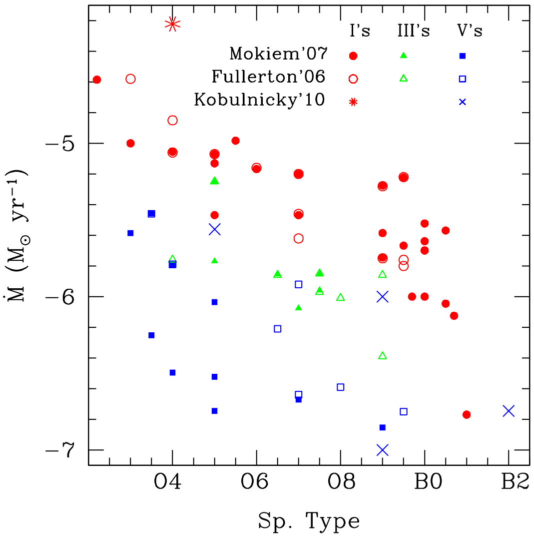

Figure 5: Mass loss rate as a function of stellar type for stars from the literature (open and filled symbols) and the runaway bowshock sample (skeletal symbols).

In conclusion, the Wyoming Cygnus OB2 Radial Velocity Survey is an ongoing observational program that will continue to measure massive binary parameters for additional systems in the coming years. The program also provides science training for many students. A new direct distance measurement to Cyg OB2 using eclipsing systems is now underway. The time-domain nature of the survey leads us to expect additional serendipitous discoveries, and we invite collaborations with astronomers interested in the Cygnus X region.

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Discussion

N. Evans: We are using a photometric technique (X-rays) to look for small q systems. Preliminary results confirm your flat q distribution. As challenge of the well studied 5 $M_\odot$ systems (P $>$ 1 year) we find half of the binaries are triples.

R. Chini: What is the minimum mass ratio that you are able to detect? You cannot detect "face-on" orbits. To what inclinations can you detect binaries?
C. Kobulnicky: We have simulated the completeness levels of the survey as part of our Monte Carlo analysis; I'll include those in future publications.