OB STARS AND STELLAR BOW SHOCKS IN CYGNUS-X: A NOVEL LABORATORY ESTIMATING STELLAR MASS LOSS RATES

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Received 2009 January 7; accepted 2009 December 10; published 2010 January 20

ABSTRACT

We use mid-infrared images from the Spitzer Space Telescope Cygnus X Legacy Survey to search for stellar bow shocks (BSs), a signature of early-type “runaway” stars with high space velocities. We identify ten arc-shaped nebulae containing centrally located stars as candidate BSs. New spectroscopic observations of five stars show that all are late-O to early-B dwarfs, while one is a previously classified B0.2 giant. These stars have moderate radial velocities, differing by \( \Delta V < 10 \text{ km s}^{-1} \) from members of the Cygnus OB2 Association. The spectral energy distributions (SEDs) of the other four stars are consistent with late-O to early-B dwarfs at the nominal \( \sim 1.6 \) kpc distance of Cyg OB2. Our morphologically selected sample of BS candidates encompasses diverse physical phenomena. Three of the stars appear to be pre-main-sequence objects on the basis of rising SEDs in the mid-IR, and their nebulae may be photon-dominated regions illuminated by the central star but shaped by external sources such as winds from Cyg OB2. Four objects have ambiguous classifications. These may be partial dust shells or bubbles. We conclude that three of the objects are probable BSs, based on their morphological similarity to analytic prescriptions. Their nebular morphologies reveal no systematic pattern of orientations that might indicate either a population of stars ejected from or large-scale hydrodynamic outflows from Cyg OB2. The fraction of runaways among OB stars near Cyg OB2 identified either by radial velocity or BS techniques is \( \sim 0.5\% \), much smaller than the \( \sim 8\% \) estimated among field OB stars. We discuss possible reasons for this difference. We also obtained a heliocentric radial velocity for the previously known BS star, BD+43\(^{3}\) 3654, of \( -66.2 \pm 9.4 \) km s\(^{-1}\), solidifying its runaway status and implying a space velocity of \( 77 \pm 10 \) km s\(^{-1}\). We use the principles of momentum-driven BSs in conjunction with the observed sizes, BS luminosities and SEDs, and dust/polycyclic aromatic hydrocarbon emission models to arrive at a novel method for estimating stellar mass loss rates. Derived mass loss rates range between \( 10^{-7} \) and \( 5 \times 10^{-6} M_\odot \text{ yr}^{-1} \) for the three O5V–B2V stars identified as generating BSs. These values are at the upper range of, but broadly consistent with, estimates from other methods. We calculate a relatively large mass loss rate of \( 160 \times 10^{-6} M_\odot \text{ yr}^{-1} \) for O4If star BD+43\(^{3}\) 3654 using the same method.

Key words: open clusters and associations: individual (Cygnus OB2) – stars: early-type – stars: individual (BD+43\(^{3}\)3654, HD 195229, GSC 03161–01188)

1. INTRODUCTION

Most OB stars lie within the associations in which they were born. However, a significant fraction (17%–50%) having high (30–200 km s\(^{-1}\)) space velocities wander far from such associations and are known as “runaways” (Blaauw 1961; Stone 1982; Conti et al. 1977; Gies & Bolton 1986). Often, these associations and are known as “runaways” (Blaauw 1961; Stone 1982; Conti et al. 1977; Gies & Bolton 1986). These stars’ proper motions allow them to be traced back to a known OB association in which they presumably formed. The speed necessary for a star to be classified as a runaway varies from \( \sim 30 \) to \( 40 \) km s\(^{-1}\), depending on the stellar mass. We adopt the 30 km s\(^{-1}\) criterion used by Gies & Bolton (1986).

Blaauw (1961) suggested that runaway stars are ejected from OB associations when one member of a binary system sheds a large fraction of its mass, as in a type II supernova. In this case (known as the binary-supernova scenario), the surviving companion is released with a velocity comparable to its previous orbital velocity. Blaauw (1961) cited the low binary frequency of runaway stars as evidence for this model, though Gies & Bolton (1986) found a few runaway binaries in their survey. Whether and how frequently supernovae in binary systems produce an unbound, high-velocity O star is an active line of investigation.

Gies & Bolton (1986) proposed that runaway stars are ejected during close encounters between binary systems in OB associations. This model, known as the dynamical-ejection scenario, explains the existence of binary runaway systems, since hard encounters among three or more stars can produce both single runaway stars and binary runaway systems. Leonard & Duncan (1988, 1990) performed numerical simulations of young star clusters, showing that dynamical encounters can readily account for the number of observed runaways and that runaway binary systems are possible.

Hoogerwerf et al. (2000) used precision proper-motion measurements of nearby runaways to find evidence for both binary-supernova and dynamical ejection mechanisms. They concluded that the runaway \( \zeta \) Oph likely resulted from the dissociation of a binary system wherein the other member became the pulsar PSR J1932+1059. They also concluded that the runaways AE Aurigae and \( \mu \) Columbae and the binary system \( \iota \) Orionis were produced in a binary—binary encounter.

Traditionally, runaway stars reveal themselves through their high proper motions or unusually large radial velocities (Gies & Bolton 1986; Mdzinarishvili & Chargeishvili 2005). Identification using radial velocities requires high-precision spectra, and this technique is sensitive only to runaways with large projected radial velocity components. Identification on the basis of high proper motions requires precise astrometric data, such as those made by the Hipparcos (Perryman et al. 1997) mission, along with secure distance measurements. This technique is only sensitive to runaways with large tangential motions.
Runaway O stars have also been identified by detecting the tell-tale “bow shocks” produced when the stellar winds of stars traveling supersonically impinge upon the surrounding interstellar medium (ISM). Bow shocks (BSs) appear as symmetric arc-shaped features with apsidal orientations in the direction of the stars’ motions and at distances from the star determined by momentum balance between the wind and the ambient medium. van Buren & McCray (1988), van Buren et al. (1995), and Noriega-Crespo et al. (1997) used Infrared Astronomical Satellite (IRAS) images to locate arc-shaped features associated with high-velocity O stars. These studies noted that a variety of phenomena can produce BS-like morphologies, including partial stellar wind bubbles and dust shells, HII regions with density gradients, and genuine high-velocity stars. Indeed, we conclude that our sample is comprised of a mixture of such objects. Several more recent studies have used Hα surveys, Midcourse Space Experiment (MSX) and Spitzer Space Telescope infrared (IR) images to detect BSs and associate them with high-velocity O stars (Brown & Bomans 2005; Comerón & Pasquali 2007; Gvaramadze & Bomans 2008; Povich et al. 2008). BSs are also seen in environments such as the Orion Nebula where winds and jets from young encounter the O-star winds that power the nebula (e.g., the Hubble Space Telescope images of Bally et al. 2000).

In this paper, we use IR images from the Spitzer Cygnus-X Legacy Survey (Hora et al. 2008) to identify BS candidates in the vicinity of one of the Galaxy’s richest OB associations. The association Cygnus OB2, at the heart of the Cygnus X region, contains over 100 OB stars, including an O3If and O4If (Massey & Thompson 1991; Hanson 2003; Comerón et al. 2002; Comerón & Pasquali 2007). The spectroscopic OB survey of 142 stars in Cygnus OB2 by Kiminki et al. (2007) did not detect any runaway stars on the basis of radial velocities. However, in a region as rich in young massive stars as Cygnus OB2, one would also expect to find stars ejected with large motions in the plane of the sky. Comerón & Pasquali (2007) implicate Cygnus OB2 as the origin of one such star, the O4If runaway BD+43°3654, using the morphology of the BS seen in MSX images. Given the superior sensitivity and angular resolution of Spitzer, a more complete search may now be conducted for runaway stars hosting BSs in this region. Herein, we describe the discovery of ten candidate BSs near Cygnus OB2, and we report followup optical spectroscopy that allows us to determine the spectral types and radial velocities for a subset of the central stars that power each candidate. We refer to the BS candidates and their central stars separately as BS 1–10 and Stars 1–10. We also investigate a novel method of determining the mass loss rates of these stars using the principles of momentum-driven BSs.

Modern distance estimates to Cyg OB2 range from 1.7 kpc (Massey & Thompson 1991; Torres-Dodgen et al. 1991) to 1.4 kpc (Hanson 2003). We adopt \( d = 1.6 \) kpc, at which distance 1 pc corresponds to 130″ on the sky.

2. DATA

2.1. Spitzer Space Telescope

We retrieved data from the Spitzer archive obtained as part of the Spitzer Legacy Survey of the Cygnus-X Complex (Hora et al. 2008) using data from the Infrared Array Camera (IRAC) at 3.6, 4.5, 5.8, and 8.0 \( \mu m \) (Fazio et al. 2004) and the Multiband Infrared Photometer for Spitzer (MIPS) bandpasses at 24 & 70 \( \mu m \) (Rieke et al. 2004). One of us (H.A.K.) visually examined mosaiced single-band and multi-color images of the \( \sim 24 \) deg\(^2\) survey area to identify BS candidates on the basis of symmetric arc-shaped structures less than a few arcminutes in size enclosing a symmetrically placed stellar source. The complex ISM structure in this region, coupled with the large dynamic range of features, renders BS identification a subjective and imprecise task. In practice, the 8 \( \mu m \) band (sensitive to emission from polycyclic aromatic hydrocarbon (PAH) features excited by non-ionizing photons) and the 24 \( \mu m \) band (sensitive to emission from warm dust) were the principal images used to locate candidate BSs. While a plethora of arc-like structures appear in both bands, very few exhibited a high degree of symmetry and included a point source near the apsis. In total, ten objects were deemed to be BS candidates and were retained for further investigation. Table 1 lists the equatorial and Galactic coordinates and Two Micron All Sky Survey (2MASS) JHK, and Spitzer IRAC photometry of the central stars for each object. The final column provides common stellar cross-identifications from other works, where applicable.

Figure 1 is a three-color image \( \sim 2^\circ \) square centered on Cygnus OB2 (\( \ell = 80.3^\circ, b = +1.0^\circ \)) showing the location of the first seven candidate BSs. Blue, green, and red represent the 4.5, 8.0, and 24 \( \mu m \) images, respectively. Objects 8–10 have Galactic latitudes \( b < 0.15^\circ \) and lie off the lower edge of Figure 1. Figures 2–11 show enlarged views of each BS candidate using the same color scheme as Figure 1. We discuss each object in detail in Section 3.

2.2. WIRO

We obtained optical spectra for several of the stellar sources located near the apsides of candidate BSs. We observed five of the stars (Stars 1, 2, 3, 5, and 8) at the Wyoming Infrared Observatory’s (WIRO) 2.3 m telescope equipped with the Longslit spectrograph on 2008 June 23–30, 2009 May 20, and 2009 September 16. The 1800 l mm\(^{-1}\) grating was used in first order. The spectral coverage was 5210–6680 Å. Exposure time varied from 360 s for Star 3 (HD 195229) to 3600 s for Stars 2 and 5, yielding signal-to-noise ratios ranging from 50:1 for Star 5 to 450:1 for Star 2. Copper–argon lamp exposures were taken after each stellar spectrum for wavelength calibration.

The spectra were reduced, extracted, wavelength calibrated, and Doppler corrected to the heliocentric frame using standard IRAF\(^4\) tasks in the KPNO SLIT package. The absolute radial velocities were checked against the standards HD161096, HD 161797, HD131156, HD171391, and HD188512. Table 1 lists the heliocentric radial velocities, which are typically accurate to 6 km s\(^{-1}\) rms.

2.3. WIYN

We also obtained spectra of BD+43°3654 and HD195229 during an observing run at the WIYN\(^5\) 3.5 m telescope on 2008 June 11–16 using the Hydra multispectrograph. We used the Red camera and 3″ blue fiber cables with the 1200 l mm\(^{-1}\) grating in second order. Exposure times were 600 s and the spectral coverage was 3820–4500 Å. Copper–argon lamp exposures were taken to wavelength calibrate the spectra. The spectra

\(^4\) IRAF is distributed by NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^5\) The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and NOAO.
Table 1
Stellar Sources Associated with BS Candidates

| No. | R.A. (J2000) | Decl. (J2000) | ℓ | b | J (mag) | H (mag) | K (mag) | [3.6] (mJy) | [4.5] (mJy) | [5.8] (mJy) | [8.0] (mJy) | [24] (mJy) | S.T. | \(V_{\text{helio}}\) (km s\(^{-1}\)) | Name |
|-----|--------------|--------------|---|---|--------|--------|--------|-------------|-------------|-------------|-------------|------------|------|-------------------|------|
| 1   | 20:34:28.9   | +41:56:17.0  | 80.8621 | 0.9749 | 9.02(0.02) | 8.45(0.01) | 8.21(0.01) | 138(2)     | 91(2)       | 79(4)       | 47(4)       | ...        | O9Va  | 90.920 +0.9828     | GSC03161−01188 |
| 2   | 20:34:34.5   | +41:58:29.3  | 80.9020 | 0.9828 | 11.35(0.02) | 10.78(0.02) | 10.51(0.02) | 32(2)      | 35(3)       | 74(6)       | 161(8)      | ...        | B1V−B3V   | −17 ± 6   | G80.920+0.9828 |
| 3   | 20:28:30.2   | +42:00:35.2  | 80.2632 | 1.9137 | 7.34(0.02) | 7.36(0.01) | 7.32(0.02) | 287(8)     | 204(7)      | 126(6)      | 64(4)       | ...        | B0.2III   | −3 ± 2    | HD195299    |
| 4   | 20:28:39.4   | +40:56:51.0  | 79.4172 | 1.2703 | 14.25(0.03) | 12.31(0.02) | 11.32(0.01) | 19(2)      | 14(2)       | 10(3)       | 17(2)       | ...        | B2V−B3V   | ...       | G79.4172+1.2703 |
| 5   | 20:34:55.1   | +40:34:44.0  | 79.8224 | 0.0959 | 9.54(0.02) | 8.70(0.02) | 8.25(0.02) | 185(2)     | 127(3)      | 96(4)       | 131(6)      | ...        | O9Va  | ...    | −10 ± 10   | A10c         |
| 6   | 20:36:13.3   | +41:34:26.1  | 80.7657 | 0.4966 | 16.04(0.08) | 13.90(0.06) | 12.76(0.03) | 23(2)      | 35(4)       | 68(4)       | 133(6)      | 1245(24)   | B4V−B6V   | ...       | G80.7657+0.4966 (YSO?) |
| 7   | 20:36:04.4   | +40:56:13.0  | 80.2400 | 0.1354 | 8.56(0.03) | 7.97(0.01) | 7.68(0.02) | 376(3)     | 141(2)      | 135(7)      | 54(3)       | ...        | O5V     | ...       | A37c        |
| 8   | 20:20:11.6   | +39:45:30.1  | 77.5168 | 1.9047 | 10.5(0.02) | 10.00(0.02) | 9.71(0.01) | 34(2)      | 26(2)       | 59(4)       | 157(8)      | 4600(80)   | B1V−B3V   | 2 ± 4     | G77.5168+1.9047 (YSO?) |
| 9   | 20:25:43.9   | +38:11:32.2  | 76.8437 | 0.1231 | ...       | ...       | ...       | 8(2)       | 20(3)       | 41(2)       | 63(3)       | 677(12)    | B7(2)     | ...       | G76.8437−0.1231 (YSO?) |
| 10  | 20:29:22.1   | +37:55:44.3  | 77.0511 | −0.6092 | 10.33(0.02) | 9.63(0.02) | 9.27(0.01) | 74(7)      | 49(9)       | 50(3)       | 81(5)       | ...        | B1V−B2V   | ...       | G77.0511−0.6092 |
| 11  | 20:33:36.1   | +43:59:07.4  | 82.4100 | 2.3254 | 6.64(0.02) | 6.19(0.02) | 5.97(0.02) | ...        | ...         | ...         | ...         | ...        | O4Ifa | −66 ± 4   | BD+43° 3654 |

Notes.
\(^a\) Spectral type based on spectroscopic identification.
\(^b\) Spectral type adopted by assuming a main-sequence star consistent with the near-IR SED if at the nominal 1.6 kpc distance of Cygnus X.
\(^c\) Comerón et al. (2002).
3. ANALYSIS

3.1. BS Identification and Images

Figure 1. *Spitzer* three-color image in Galactic coordinates of the Cygnus-X region centered on Cygnus OB2 with [4.5] in blue, [8.0] in green, and [24] in red. Seven of the ten BS candidates are labeled with their BS number and identifications for the central stars from Table 1. Several other prominent *IRAS* IR sources are labeled, some of which are the heads of gaseous pillars pointing toward Cyg OB2, such as IRAS 20343+4129.

Figure 2. *Spitzer* three-color image of BS Candidates 1 (GSC03161–01188) and 2 (G80.9020+0.9828) with the same color scheme as Figure 1. These two objects present a striking contrast as BS 1 is seen only at 24 μm and longer wavelengths, while BS 2 has strong PAH emission in the IRAC bands and is weaker at longer wavelengths. The arrow shows the direction toward the core of Cyg OB2.

were reduced, extracted, wavelength calibrated, and Doppler corrected to the heliocentric frame using standard IRAF tasks in the TWODSPEC and RVCOR packages. Radial velocities of standards HD 131156, HD146233, HD161096, HD161797, and HD171391 from this run agreed with published values to ±2 km s⁻¹.

Figure 1 shows a portion of the Cygnus-X region surrounding its most massive and energetic constituent, Cygnus OB2. This region encompasses a complex array of nebulae and
star-forming regions located at various distances along the line of sight, with most of the activity located in the local or “Orion” spiral arm at a distance of 1–2 kpc. Odenwald & Schwartz (1993) present a schematic three-dimensional representation of the Cygnus-X region, while Schneider et al. (2006) provide velocity-resolved molecular maps of Cygnus-X and individual star-forming objects nearby. One apparent feature of this region is the relative absence of dust (red) and PAH emission (green) at the location of Cyg OB2 itself, except at the southern edge. This apparent “hole” is consistent with a cavity cleared by the winds of >100 evolving massive stars. Some of the prominent star-forming regions labeled in Figure 1 clearly constitute the heads of gaseous pillars, most of which point toward Cyg OB2, the dominant source of luminous and mechanical energy in this vicinity. These pillars are reminiscent of those in M 16 (Indebetouw et al. 2007; Hester et al. 1996),
RCS 49 (Whitney et al. 2004), and other massive star-forming regions.

The seven BS candidates labeled in Figure 1 lie around the periphery of Cyg OB2, none falling within the main concentration of Cyg OB2 stars but all within ~5–8 pc of the canonical Cyg OB2 center. The orientations of the features, seen more clearly in Figures 2–11, appear random, having no preferential alignment with respect to Cyg OB2. Generically, BS orientation reveals the relative motion between the star and surrounding matter. We might have expected, if the stars were all runaways from Cyg OB2, that the BSs would point away from the Association in the direction of the stars’ motions. On the other hand, if the hydrodynamics of material surrounding Cyg OB2 were dominated by a hot outflow from an over-pressured region, we might have expected many of the BSs to point back toward the source of mechanical energy, as do three BSs near M 17 and at least one near RCW 49 (Povich et al. 2008). The absence of either signature suggests that (1) the central stars...
Figure 7. Three-color image of BS Candidate 6, with [8.0] in green, [24] in red, and the $^{12}$CO (1−0) map between LSR velocities −7 to −4 and 9−14 km s$^{-1}$ in blue and contours. Star 6 and BS Candidate 6 lie adjacent to a gaseous pillar containing several massive young protostellar objects at its head (IRAS 20343+4129).

Figure 8. Three-color image of BS Candidate 7, as in Figure 1.
driving the BSs, if they are runaways, have different origins, and (2) there is no large-scale supersonic wind emanating from Cyg OB2. Only candidates 2 and 4 have orientations consistent with their stars being runaways having an origin within Cyg OB2.

3.2. Nebular and Stellar SEDs

The colors of the candidate BS nebulae, best seen in the individual zoomed images in Figures 2–11, at first glance reveal two classes of objects. Candidates 1, 3, 4, 7 are seen exclusively at 24 μm and longer wavelengths while the rest exhibit strong emission in the IRAC bandpasses with some additional contribution at longer wavelengths.

We performed aperture photometry of each BS candidate in each of the six bandpasses using the Spitzer Science Center (SSC) post-basic calibrated data mosaic images by assigning irregular crescent-shaped polygonal apertures defined visually on the [8.0] and/or [24] images. We also manually defined
background regions surrounding each BS. Because these objects lie in complex regions of diffuse emission, care was taken to select multiple background regions judged to be representative of the local background away from the nebula but within several arcminutes. We applied aperture corrections, as recommended in the IRAC and MIPS calibration Web sites, using values appropriate to a circular aperture of equivalent area to the polygonal apertures. These corrections are less than 1.3 in all cases and are sometimes less than unity for the IRAC bands. Given the imprecision of the aperture corrections and the high and variable background levels, we adopt a minimum uncertainty of 20% in all bands. Table 2 gives background-subtracted aperture fluxes in mJy for all of the nebulae. In some cases, only 1σ upper limits are given, mostly in the IRAC bands where some objects are not detected.

For each BS candidate we were able to identify a symmetrically placed point source, presumed to be the energizing star, behind the apsis. Figure 12 is a 2MASS $JHK$ color–color diagram showing each of the ten stars (diamonds) associated with the BSs. The solid and dashed curves (asterisks and crosses, respectively) show a fiducial main sequence and supergiant sequence. A solid line illustrates the reddening vector for $A_V = 5$ mag. The majority of stars lie in a close group near $H - K = 0.3$, $J - H = 0.6$, consistent with early-type stars seen behind 4–7 mag of visual extinction. This range is similar to other OB stars in Cyg OB2 (Massey & Thompson 1991), suggesting that they lie at a similar distance. Stars 4 and 6 are much redder, suggesting 12–15 mag of visual extinction, under the assumption that these are also early-type stars. The $K$-band magnitudes for these two stars are 2–3 mag fainter than the other targets, indicating either a larger distance or the effect of localized regions of high extinction. Star 6, in particular, is surrounded by a more substantial region of warm dust and photo-excited material, consistent with localized extinction. Star 3 (HD195229), a known B0.2III, is much less red, consistent with $\sim 1$ mag of visual extinction, and consistent with the known variability of extinction across Cyg OB2 (Massey & Thompson 1991).

We performed aperture photometry on the central star of each BS at the mid-IR IRAC bandpasses using the SSC basic calibrated data frames, a 10 pixel circular aperture for which the aperture correction is minimal, and a much larger annulus to measure the diffuse background levels. Most of the stars were saturated at IRAC $[3.6]$ and $[4.5]$ bands in the 10.4 s exposures, so the high-dynamic-range (HDR) 0.4 s exposures were used. Table 1 lists these fluxes and their uncertainties.

Figure 13 shows the spectral energy distributions (SEDs) of the BS candidates and central stars at the 2MASS, IRAC, and two MIPS bandpasses. Asterisks denote photometry of the BS
alone, while diamonds denote the star plus BS. The BSs are not detected at 2MASS JHK bands and are sometimes undetected in the IRAC bandpasses. In only three cases (stars 6, 8, and 9) are pointlike sources detected at [24], indicative of dust in the immediate vicinity of the stars. Uncertainties are always smaller than the plotted points. The solid black bodies fit to the JHK photometry, while the dotted curves are fits to the IRAC and MIPS data using scaled (Draine & Li 2007) dust emission models. In Sections 3.4 and 4, we discuss the details of the fitting, the models, and model results for each object individually.

3.3. BS Candidate Morphologies

The shape of a momentum-driven BS is a universal function that scales as the “standoff distance,” $R_0$, between the star and the BS apsis, as shown analytically by Baranov et al. (1971), Dyson (1975), van Buren et al. (1990), and Wilkin (1996). Using the formulation of Wilkin (1996, Equation (9)), we generated synthetic BS “images,” applying arbitrary size, rotation, and intensity scale factors to facilitate comparison with the data. Figure 14 shows a selected subset of BS candidates (1, 2, 3, 5, 6, and 7) at [8.0] (green), [24] (red) and the scaled synthetic BS (blue). The simulated BSs are all shown at zero degree inclination, while the inclinations of the BS candidates are unknown.

The morphologies of candidates 5 and 7 (central stars O9V and O5V) show striking similarity to the theoretical shape. The agreement is best at [24] where the BS can be traced to larger radial distances than at [8.0] where the BS is less extended and exhibits a more irregular morphology. For object 2, there is also good agreement, although the BS itself is faint and difficult to see because of the large dynamic range in the images. For objects 1, 3, and 6 the morphological agreement is considerably less good. We take this as evidence for a physical origin other than a BS. The morphologies of the other objects 4, 8, 9, and 10 (not pictured) also differ from the canonical BS shape, appearing more irregular and clumpy. We interpret the good agreement between the model shape and objects 2, 5, and 7 as support for the momentum-driven BS nature of these objects.

3.4. Individual Objects

3.4.1. BS Candidate 1 and Star 1 (GSC03161−01188)

BS candidate 1, pictured in Figure 2, is associated with the $V = 13.3$ star GSC03161−01188 from the Guide Star Catalog, also known as 1288 from the work of Reddish et al. (1966). Figure 15 (bottom) shows the WIRO spectrum of GSC03161−01188. We classify GSC03161−01188 as O9V on the basis of the HeI/HeII line ratios and by comparison to a Jacoby et al. (1984) spectral library O9V star (top). We compute a spectrophotometric distance for the K = 8.21 star GSC03161−01188 by adopting a visual extinction of 4.5 mag from Figure 12 ($A_K = 0.51$ mag), an intrinsic color $V - K = -0.85$, and assuming an absolute magnitude for an O9V star of $M_V = 4.05 \pm 0.2$ (Martins et al. 2005).
Given the lack of similarity to the theoretical shape and the modest radial velocity of the central star, this nebula is unlikely to be a BS. We assign this object an ambiguous classification. Possibilities include a dusty asymmetric bubble or a partial shell.

3.4.2. BS Candidate 2 and Star 2 (G80.9020+0.9828)

Figure 2 shows BS candidate 2 and Star 2 (G80.9020+0.9828). Figure 16 (bottom) shows the WIRO spectrum of this star and a comparison B2 dwarf equivalent from the model atmospheres of Lanz & Hubeny (2003, top). The relative strengths of the H\textsc{i} 6563 Å and the He\textsc{i} 6678 Å and He\textsc{ii} 5876 Å lines lead us to classify this star as B2V, plus or minus several spectral subtypes, owing to the low signal-to-noise spectrum. Its heliocentric radial velocity is $-12 \pm 15$ km s$^{-1}$, consistent with the range of radial velocities observed for Cyg OB2 members (Kiminki et al. 2007). We compute a spectrophotometric distance from the 2MASS photometry ($K = 10.5$) by adopting a visual extinction ($A_K = 0.51$), an absolute magnitude for a B2V star of $MV = -2.4 \pm 0.4$, an intrinsic $V-K$ color of $-0.4$. This yields a spectrophotometric distance of 2500 $\pm$ 500 pc, where the error is driven primarily by the uncertainty on the spectral-type/absolute magnitude. A high-surface-brightness apsis lies $9''$ (0.07 pc projected separation) from the star toward the upper left in Figure 2, and there is also a more extended region of 8 $\mu$m emission preceding the apsis to the upper left. The [24] lima-bean shaped nebulosity and the arc-like structure seen at [8.0] do not share a common symmetry axis, so it is difficult to ascertain which wavelength best traces the putative BS.

Figure 13 shows that BS 2 is a strong detection at the IRAC and MIPS bandpasses. The relative faintness of the BS in [4.5] relative to the other three IRAC bandpasses is consistent with strong PAH emission in the shock. The central star dominates the 2MASS bandpasses. Star 2 is fainter than Star 1 and is well fit by a B2V–B3V star ($T_{\text{eff}} = 20,000$ K, $R = 4 R_\odot$) at a distance of 1.6 kpc with an extinction of $A_V = 4.5$ mag (solid line).

Although this candidate BS nebula is faint and difficult to represent owing to a large dynamic range in the images, the morphological agreement with the theoretical shape is reasonably good. The apsis of this nebula is bright at [8.0] and...
Figure 16. Model atmosphere B2V equivalent spectrum from Lanz & Hubeny (2003) (top) smoothed to the resolution of the data and WIRO spectrum of Star 2 (bottom). The relative strengths of the H\textsc{i} 6563 Å and the He\textsc{i} 6678 Å and He\textsc{i} 5876 Å lines lead us to classify this star as B2V, plus or minus two spectral subclasses. IS denotes interstellar bands.

Figure 17. Standard B0.2III spectrum from Jacoby et al. (1984, top) and WIRO spectrum of Star 3 (HD195229, bottom). The WIYN spectrum of Star 3 in Figure 18 was used to determine this star’s spectral type.

Figure 18. Standard B0.2III spectrum of HD108639 (Walborn & Fitzpatrick 1990) and WIYN spectrum of Star 3 (HD195229, bottom). The strengths of the Si\textsc{iv} 4089, Si\textsc{iv} 4116 Å, and C\textsc{iii} 4069 Å lines identify the star as B0.2III.

3.4.3. BS Candidate 3 and Star 3 (HD195229)

BS candidate 3 appears to be generated by its attendant star, HD195229, listed as B0.2III in SIMBAD. Figures 17 and 18 show our WIRO and WIYN spectra of this star, from which we confirm a B0.2III spectral type. From these spectra we find a heliocentric radial velocity of \(-3 \pm 2\) km s\(^{-1}\), slightly less negative than other massive stars near Cyg OB2. The luminosity for a B0 giant is somewhat uncertain because the evolutionary tracks for massive giant and supergiant stars are nearly vertical in an H–R diagram (Marigo et al. 2008). Assuming \(M_V = -5 \pm 0.5\), \(V - K = -0.8\) and \(A_V = 1.0\) from Figure 12 for this \(K = 7.3\) star lead to a spectrophotometric distance of 1800 \(\pm 500\) pc, consistent with the distances of massive stars in Cyg OB2.

HD195229 is also known as a high-proper-motion star with \(\mu_R,\alpha = 0.14 \pm 0.55\) mas yr\(^{-1}\), and \(\mu_{\text{decl.}} = -2.89 \pm 0.47\) mas yr\(^{-1}\) (Perryman et al. 1997). Its \textit{Hipparchos} proper motion corresponds to a velocity of \(28 \pm 8\) km s\(^{-1}\) in the plane of the sky at 2000 pc. Combining this with the star’s radial velocity gives a space velocity of \(32 \pm 8\) km s\(^{-1}\), placing it above the nominal 30 km s\(^{-1}\) threshold for runaway status. The yellow bar in Figure 3 shows the implied sky motion (from left to right) over 10,000 yr and has position angle uncertainty of about 15°. The orientation of the candidate BS implies a velocity vector toward the lower left of Figure 3, while the proper-motion data imply a velocity that is toward the lower right.

Figure 13 shows that BS 3 is detected with certainty only at [24] and longer wavelengths, with a marginal detection at [3.6] and [4.5]. The stellar SED is well fit by an early-B giant (\(T_{\text{eff}} = 25,000\) K, \(R = 10 R_\odot\)), consistent with its spectral type, at a distance of 1.6 kpc with an extinction \(A_V = 1.0\) mag. Curiously, HD195229 has a much lower extinction than the rest of the stars in Cyg OB2 (4–6 mag), requiring either that this star is seen through a local minimum in the obscuring dust, or that HD 195229 is actually on the near side of a heavy veil of extinction that enshrouds most of Cygnus X.

The lack of similarity between the [24] appearance and the theoretical shape in Figure 14, coupled with the misalignment between the proper motion and putative BS morphology, casts doubt on a BS interpretation. We categorize the nature of this nebula as ambiguous.

3.4.4. BS Candidate 4 and Star 4 (G79.4171+1.2703)

BS candidate 4 resembles BS 1, having no detectable emission at the IRAC bandpasses and a lima-bean morphology at [24]. Note the edge-brightened cloud to the right of the BS, suggesting illumination by the (presumed) early-B star powering the nebula. The central star is the faintest in our sample at optical and IR wavelengths and Figure 12 suggests a very large extinction of \(A_V > 12\). Its \(K\)-band magnitude is similar to the central star of BS 2, so it is probable that this is also an early-B star, if located at a similar distance. There is no literature identification for this star, so we give it a designation according to its Galactic coordinate, G79.4171+1.2703.

We note that the putative BS nebula points away from Cyg OB2 and in the direction of the H\textsc{ii} region IRAS20264+4042, located toward the upper right from Star 4 in Figure 1. This star-forming region is also identified as the radio source DR7
(Downes & Rinehart 1966) and the host of the ultracompact H II region G79.320+1.313 (Kurtz et al. 1994). While it is possible that outflows from this SF region are responsible for the high relative velocities leading to the production of the putative BS (as shown for BSs in M17 and RCW 49 by Povich et al. 2008), a careful search for other similarly oriented BSs around IRAS20264+4042 revealed none. Odenwald & Schwartz (1993) report a $^{12}$CO detection for IRAS20264+4042 at $V_{LSR} = -42 \text{ km s}^{-1}$, corresponding to a kinematic distance of 6–7 kpc inferred from the Clemens (1985) Galactic rotation curve. However, Dutra & Bica (2001) and Le Duigou & Knödlseder (2002) suggest distances of 1.1 and 1.6 kpc, respectively, based on near-IR photometry. At such a distance, the $K = 11.3$ mag of the central star, coupled with an implied extinction of $A_K \sim 1.5$ mag would correspond to an early- to mid-B star. At the larger (but, we contend, less probable) distance of 6.5 kpc, the apparent magnitude would be consistent with an O9V or similar. Given the abundance of early-type stars at the nearer distance of Cyg OB2, we prefer to adopt a kinematic distance of 1.6 kpc with an implied extinction of $A_V = 19$ mag.

Star 6 is one of only three detected at [24], suggesting the presence of a dusty shell or disk associated with the star, since we would not expect to detect the stellar photospheres at [24] or [70]. Figure 13 shows that the flux from the star at [24] is greater than the nebular flux and continues to rise beyond 24 μm. These characteristics suggest that Star 6 is a pre-main-sequence object with a very high extinction of $A_V = 19$ mag.

BS candidate 6 exhibits strong emission at both IRAC and MIPS bandpasses in Figure 6. It lies within a complex of diffuse emission that may constitute a small H II region. The central star is extremely red, and Figure 12 suggests an extinction approaching $A_V = 18$. Accordingly, there is no literature identification or spectral type available, so we designate it by its Galactic coordinates, G80.7657+0.4963.

Though the nebular component of object 6 is strong at the IRAC and MIPS bandpasses, the central star is the faintest in the sample at IRAC bandpasses. While there is no spectral information on Star 6, if we assume it is at 1.6 kpc the 2MASS SED is well fit by a mid-B dwarf ($T_{\text{eff}} = 15,000 \text{ K}$, $R = 3 R_\odot$) with a very high extinction of $A_V = 19$ mag.

BS candidate 6 exhibits strong emission at both IRAC and MIPS bandpasses in Figure 6. It lies within a complex of diffuse emission that may constitute a small H II region. The central star is extremely red, and Figure 12 suggests an extinction approaching $A_V = 18$. Accordingly, there is no literature identification or spectral type available, so we designate it by its Galactic coordinates, G80.7657+0.4963.

3.4.6. BS Candidate 6 and Star 6 (G80.7657+0.4966)

BS candidate 6 exhibits strong emission at both IRAC and MIPS bandpasses in Figure 6. It lies within a complex of diffuse emission that may constitute a small H II region. The central star is extremely red, and Figure 12 suggests an extinction approaching $A_V = 18$. Accordingly, there is no literature identification or spectral type available, so we designate it by its Galactic coordinates, G80.7657+0.4963.

Though the nebular component of object 6 is strong at the IRAC and MIPS bandpasses, the central star is the faintest in the sample at IRAC bandpasses. While there is no spectral information on Star 6, if we assume it is at 1.6 kpc the 2MASS SED is well fit by a mid-B dwarf ($T_{\text{eff}} = 15,000 \text{ K}$, $R = 3 R_\odot$) with a very high extinction of $A_V = 19$ mag.

BS candidate 6 exhibits strong emission at both IRAC and MIPS bandpasses in Figure 6. It lies within a complex of diffuse emission that may constitute a small H II region. The central star is extremely red, and Figure 12 suggests an extinction approaching $A_V = 18$. Accordingly, there is no literature identification or spectral type available, so we designate it by its Galactic coordinates, G80.7657+0.4963.

Though the nebular component of object 6 is strong at the IRAC and MIPS bandpasses, the central star is the faintest in the sample at IRAC bandpasses. While there is no spectral information on Star 6, if we assume it is at 1.6 kpc the 2MASS SED is well fit by a mid-B dwarf ($T_{\text{eff}} = 15,000 \text{ K}$, $R = 3 R_\odot$) with a very high extinction of $A_V = 19$ mag.

BS candidate 6 exhibits strong emission at both IRAC and MIPS bandpasses in Figure 6. It lies within a complex of diffuse emission that may constitute a small H II region. The central star is extremely red, and Figure 12 suggests an extinction approaching $A_V = 18$. Accordingly, there is no literature identification or spectral type available, so we designate it by its Galactic coordinates, G80.7657+0.4963.
3.4.7. BS Candidate 7 and Star 7 (A37)

BS candidate 7 has the largest angular extent of any of our targets, covering nearly 5° in Figure 8. It is detected only at [24] and [70]. The central star appears to be A37 in the notation of Comerón et al. (2002). Hanson (2003) determined a spectral type of O5V(f), making it the most energetic and massive in our sample. The presence of a BS associated with this star is noted by Gvaramadze & Bomans (2008) on the basis of images from the MSX mission. The angular distance between the star and BS apsis is the largest in our sample, ~70°, or 0.53 pc projected separation.

The SED of Star 7 in Figure 13 is consistent with an O5V star \( (T_{\text{eff}} = 40,000 \, \text{K}, R = 11 \, R_\odot) \) and \( A_V = 5 \, \text{mag} \) if placed at a distance of 2.1 kpc, slightly larger than the nominal distance to Cyg OB2, although the line-of-sight depth along the Cygnus-X complex is likely to be ~few hundred pc (Odenwald & Schwartz 1993).

The excellent agreement between the [24] morphology and the theoretical shape leads us to classify this as a probable BS. The orientation of the BS indicates a motion toward the left in Figure 8, roughly tangent to the vector toward Cyg OB2. This suggests that the origin of A37 lies somewhere outside of Cyg OB2.

3.4.8. BS Candidate 8 and Star 8 \((G77.75168+1.9047)\)

BS candidate 8 is visible at both IRAC and [70] bandpasses. Figure 9 shows that this object lacks the classical arc morphology and symmetry of the other BSs, warranting an ambiguous classification. It resembles a partial shell or bubble. The WIRO spectrum of this star obtained 2009 September 16 is consistent with a B2V–B3V having a heliocentric radial velocity of 2 km s\(^{-1}\). The spectrum of this star obtained 2009 September 16 is consistent with a B2V–B3V having a heliocentric radial velocity of 2 km s\(^{-1}\), making it the most energetic and massive in our sample. The presence of a BS associated with this star is noted by Gvaramadze & Bomans (2008) on the basis of images from the MSX mission. The angular distance between the star and BS apsis is likely to be ~few hundred pc (Odenwald & Schwartz 1993).

The SED of Star 7 in Figure 13 is consistent with an O5V star \( (T_{\text{eff}} = 40,000 \, \text{K}, R = 11 \, R_\odot) \) and \( A_V = 5 \, \text{mag} \) if placed at a distance of 2.1 kpc, slightly larger than the nominal distance to Cyg OB2, although the line-of-sight depth along the Cygnus-X complex is likely to be ~few hundred pc (Odenwald & Schwartz 1993).

The excellent agreement between the [24] morphology and the theoretical shape leads us to classify this as a probable BS. The orientation of the BS indicates a motion toward the left in Figure 8, roughly tangent to the vector toward Cyg OB2. This suggests that the origin of A37 lies somewhere outside of Cyg OB2.

3.4.9. BS Candidate 9 and Star 9 \((G76.8437+0.1231)\)

BS candidate 9 is a compact nebula with detected emission only at [5.8] and inward. The central star is clearly seen as a point source in Figure 10. The stellar SED of Star 9 is difficult to ascertain, since there is no 2MASS counterpart to the point-like source detected at the mid-IR IRAC bands. The mid-IR flux rises steeply with wavelength, consistent with a heavily enshrouded source. The [4.5] flux lies below the expectations of a simple interpolation between the [3.6] and [5.8] bands. This has become a classic signature of material dominated by emission from large molecules (e.g., PAHs; Draine & Li 2007), which are largely absent in the [4.5] band. The nebular morphology does not bear a strong resemblance to the classical BS shape. These characteristics are consistent with a young (class I?) protostar (Kenyon et al. 1993), and we designate this object as a probable YSO.

3.4.10. BS 10 and Star 10 \((GG77.0511−0.6092)\)

BS 10, pictured in Figure 11, is a small, narrow filament with strong emission in the IRAC bands, and a low ratio of far-IR to mid-IR flux in the final panel of Figure 13. The stellar source is identified only by its Galactic coordinates, GG77.0511−0.6092. Because it has similar 2MASS colors and magnitudes as many of the other BS stars, we consider it to be a probable late-O or early-B star at the distance of Cyg OB2.

The near-IR SED of Star 10 is consistent with an early-B star \( (T_{\text{eff}} = 25,000 \, \text{K}, R = 5 \, R_\odot) \) with \( A_V = 6 \) at a distance of 1.6 kpc. The IRAC points lie in excess of the photosphere, consistent with hot dust and emission from PAHs. The morphology of the [8.0] nebula appears irregular, while the [24] nebula is similar to the classical BS morphology. We classify this object as ambiguous.

3.4.11. BD+43°3654

Comerón & Pasquali (2007) present proper motions and MSX IR images of the O4If star BD+43°3654, originally identified as a probable runaway by van Buren & McCray (1988) on the basis of a probable BS seen with IRAS. They compute a distance of 1450 pc and propose that BD+43°3654 was ejected from Cyg OB2 1.6 Myr ago, not long after its birth. Gvaramadze & Bomans (2008) propose that BD+43°3654 is a blue straggler, formed from the merger of two stars and ejected from Cyg OB2 during a binary–binary encounter. They invoke the high proper-motion pulsars B2020+28 and B2021+51 as the descendants of the other two stellar participants in this 4-body interaction.

We cross-correlated the WISE spectrum of BD +43°3654 with an OSi model atmosphere, which yielded a heliocentric radial velocity of \( V_{\text{LSR}} = -66.2 \pm 9.4 \, \text{km s}^{-1} \). This is considerably more negative than the \( V_{\text{LSR}} = -10 \, \text{km s}^{-1} \) mean velocity of O stars in Cyg OB2 (Kiminki et al. 2007), and therefore BD+43°3654 would qualify as a runaway on the basis of its radial velocity alone. Its motion in the plane of the sky is 39.8 ± 9.8 km s\(^{-1}\) (Comerón & Pasquali 2007) at the assumed distance. Combining this with our radial velocity measurement, we calculate the heliocentric space velocity of BD+43°3654 to be 77 ± 10 km s\(^{-1}\).

3.5. Summary of Classifications and Statistics of Runaways in Cygnus X

The BS candidates presented here comprise a mixed bag of phenomena. Objects 2, 5, and 7 (and BD +43°3654) are most likely to be genuine BSs powered by runaway stars on the basis of having early spectral types and nebular morphologies most similar to the classical BS appearance. However, none of stars 2, 5, or 7 have remarkable radial velocities. Objects 1, 3 (the high proper-motion star HD195299), 4, and 10 are ambiguous, having nebular morphologies less similar to the classical BS shape, but, nevertheless, appear to be early-type stars. Objects 6, 8, and 9 have central stars with excess IR emission, suggesting circumstellar material. Stars 6 and 9 also have high extinction and/or SEDs that rise toward longer wavelengths, consistent with their being YSOs hosting disks or circumstellar envelopes. The nebula associated with Star 6 shows evidence for being the head of a gaseous pillar being ablated by radiation from the direction of Cyg OB2. Hence, objects 6, 8, and 9 are the least likely to be high velocity runaway stars.

\(^7\) BD+43°3654 lies outside the area of the Spitzer Legacy Survey of the Cygnus-X Complex, so we do not discuss this object in detail or present figures.
In a magnitude-selected sample of 195 bright O stars, Gies & Bolton (1986) found that 16 (8%) could be classified as runaways either on the basis of radial velocities (6; 3%), proper motions (5; 2.5%), or extreme distance from the Galactic Plane (5; 2.5%). By contrast the radial velocity survey of 146 Cyg OB2 stars by Kiminki et al. (2007) did not find any runaways. The Spitzer Cygnus X Legacy Survey covers a much larger region (~23 deg^2) than the sample of core Cyg OB2 members studied by (Kiminki et al. 2007; ~0.35 deg^2), which was selected from the optical imaging survey of Massey & Thompson (1991). The ratio of areas in these two surveys is roughly 65, so one might conclude that the number of early-type stars in Cygnus X is as many as 146 x 65 = 9500. However, the earliest and most massive stars appear to be contained within the core Cyg OB2 region covered by Massey & Thompson (1991), so that this is a gross overestimate. We very conservatively adopt that the Spitzer Cygnus X Legacy Survey includes ~600 OB stars earlier than B2, or about 4 times the number of OB stars surveyed by Kiminki et al. (2007). In this region we find only three candidates for runaways—four if BD +43°3654 is included. At face value, this is 3/600 = 0.5%. Of course, high space velocities are a necessary but not a sufficient condition for the formation of BSs. van Buren et al. (1995) found that 58 out of 188 high velocity stars evince BSs at IRAS sensitivity levels, and of these, 25 have well resolved structure. We expect that Spitzer would detect even fainter and smaller BSs. If we assume that 1/4 of runaway stars produce BSs visible at Spitzer sensitivity levels and that 8% of all OB stars are runaways, we would expect to find on the order of 12 BSs in the Cygnus X region. Why do we detect so few?

We identify only three probable BS runaways, and perhaps only one of these (BS 2) has an orientation suggesting an origin near Cyg OB2. It is certainly possible that most of the runaways, like BD +43°3654, could fall outside the survey area if they have high space velocities and were probable ejected from the Association very early in its formation. Stars with a tangential velocity of 30 km s^{-1} would travel beyond the boundaries of the Spitzer Cygnus X Legacy Survey (~26 pc diameter) in about 0.5 Myr—a small fraction of the 2–4 Myr age of Cyg OB2. Dynamical ejection scenarios wherein N-body interactions in close multiple systems expel stars would predict this—that most of the runaways are produced early in the formation of a young massive star cluster and have already traveled beyond the immediate cluster vicinity. Supernova ejection scenarios, on the other hand, predict that the start of the ejection process is delayed several Myr (until the explosion of the most massive stars), and then it continues at a constant or increasing rate as stars from lower-mass OB binaries complete their evolution. Although the arguments are mostly qualitative, our findings would seem to be more consistent with the dynamical ejection scenario.

4. BOW SHOCKS AND LABORATORIES

Baranov et al. (1971) first articulated the theoretical basis for momentum-driven BSs in the context of the solar wind termination shock. The theory of stellar wind BSs has since been further refined in papers by van Buren & McCray (1988), van Buren et al. (1990), Wilkin (1996), Wilkin (2000) and simulated numerically by Comerón & Kaper (1998). A BS forms at a radial distance $R_0$ where the momentum flux from the stellar wind material of density $\rho_w$ and velocity $V_w$ is equal to the momentum flux from the ambient medium of density $\rho_a$ moving at $V_a$ relative to the star. The relative velocity may be the result either of a “runaway” star moving at high speed or a bulk flow of the ISM, such as an outflow from a young star-forming region. Hence,

$$\frac{1}{2} \rho_w V_w^2 = \frac{1}{2} \rho_a V_a^2.$$  

The density of the stellar wind can be expressed as

$$\rho_w = \frac{M_w}{4 \pi R_0^2 V_w},$$  

where $M_w$ is the stellar mass loss rate. It follows that the standoff distance of the BS is

$$R_0 = \sqrt{\frac{V_w M_w}{4 \pi \rho_a V_w^2}}.$$  

$R_0$ can be measured directly from the BS images, assuming that all of the stars are located at the adopted distance of Cyg OB2. Technically, only the projected separation, $R_0 \cos i$, can be measured, but in order to observe a BS morphology, the viewing angle cannot be far from $i = 0^\circ$ so that $\cos i$ is not far from unity. Adopting a mean ISM gas mass per H atom of $\mu = 2.3 \times 10^{-24}$ g means that $\rho_a$ can be expressed in terms of the ambient number density: $\rho_a = \mu \rho_i$. Stellar wind speeds and mass loss rates have proved difficult to measure and may be even more uncertain than previously believed (Puls et al. 2008; Fullerton et al. 2006). As an estimate of the mass loss rates and wind velocities for stars in our sample, we adopt the values tabulated by Mokiem et al. (2007) for early-type stars. Equation (3) can then be rearranged to yield the relative motion between the star and ambient medium,

$$V_a = \frac{V_w M_w}{4 \pi R_0^2 \mu n_a^{-1/2}}.$$  

In practice, it is difficult to calculate the star’s velocity, $V_a$, relative to the surrounding medium because the quantities on the right-hand side are poorly known, especially the density of the ambient medium, $n_a$. By adopting published estimates for the stellar mass loss rates and wind velocities, we can at least make an estimate of the product $V_a n_a^{1/2}$, similar to the approach of Povich et al. (2008). In keeping with the precedent established in van Buren & McCray (1988) and Povich et al. (2008), we write the mass loss rate in units of $10^{-6} M_\odot$ yr^{-1} as $M_{w, -6}$, the stellar wind velocity in units of $10^8$ cm s^{-1} as $V_{a, 8}$ and the ambient medium density in units of $10^3$ cm^{-3} as $n_{a, 3}$. The relative star–ISM velocity is then

$$V_a = 1.5 \left( \frac{R_0}{\text{pc}} \right)^{-1} \left( V_{a, 8} M_{w, -6} \right)^{1/2} n_{a, 3}^{-1/2} [\text{km s}^{-1}].$$  

Given the uncertainties in stellar mass loss rates and wind velocities for stars later than about B0, we compute and tabulate derived parameters only for the five objects in our sample with the most reliable spectroscopic types, objects 1, 3, 5, 7, and 11 (BD+43°3654). Table 3 tabulates the adopted stellar wind velocities, mass loss rates (from the works of Repolust et al. 2004, Mokiem et al. 2005, Martins et al. 2005, Crowther et al. 2006, as summarized in Mokiem et al. 2007), standoff distances, $R_0 \cos i$, along with the product $V_a n_{a, 3}^{1/2}$. The standoff distances of 0.11–1.8 cos $i$ pc are consistent with those found for the BSs in Povich et al. (2008). The derived values for $V_a n_{a, 3}^{1/2}$ lie in the
range 0.2 to as much as 30—broadly consistent with the values from the (Povich et al. 2008) stars. For typical ISM densities of \( n_{\text{a,3}} = 0.1\text{--}1.0 \), the implied stellar speeds are few \( \times 10 \text{ km s}^{-1} \), consistent with the expected speeds of runaway stars.

### 4.1. A Novel Measure of Stellar Mass Loss Rates

Because stellar mass loss rates are probably the most uncertain parameter in Equation (5) above, we invert the approach taken by Povich et al. (2008) and exploit the phenomenon to yield an estimate of the mass loss rates for the central stars. Inverting Equation (5) yields the mass loss rate of the star as a function of the relative motion between the star and ISM, the ambient density, the stellar wind speed, and the standoff distance,

\[
M_{w,-6} = \frac{0.67[R_0 (\text{pc})]^2[V_{w,8} (\text{km s}^{-1})]^2 n_{\text{a,3}}}{V_{w,8}}. 
\]  

(6)

\( R_0 \) is readily observed from the BS images, assuming a 1.6 kpc distance to Cygnus X and assuming \( \cos i \approx 1 \). We assume a minimum star–ISM speed of \( V_w = 30 \text{ km s}^{-1} \) for runaway stars (Gies & Bolton 1986), and we adopt the stellar wind speeds of Mokiem et al. (2007) which, for our sample of O5–B0 stars, range from 3000 km s\(^{-1} \) to \( \sim 800 \text{ km s}^{-1} \) \( (V_{w,8} = 3 \text{ to } 0.8) \). The ambient number density, \( n_{\text{a,3}} \), is difficult to measure directly, but may be estimated from \( n_{\text{a,3}} \), the post-shock density within the luminous BS nebulae. For strong, highly supersonic shocks, \( n_{\text{a,3}} \approx 4 n_{\text{a,3}} \) (Landau & Lifshitz 1987). Without knowing the Mach number of each individual case, we adopt \( n_{\text{a,3}} = 2 n_{\text{a,3}} \), and consider the uncertainties to be factors of 2–4. We estimate \( n_{\text{a,3}} \) by fitting the BS SEDs in Figure 13 with the dust/PAH models of Draine & Li (2007) which give the dust emissivity per H nucleon as a function of the radiation field intensity, parameterized as a multiple, \( U \), times the mean interstellar radiation field of \( U_{\text{ISRF}} = 2.3 \times 10^{-2} \text{ erg s}^{-1} \text{ cm}^{-2} \) (Mathis et al. 1983). We made the motivated assumption that the BS luminosity stems from reprocessed photons from the central star rather than thermalized mechanical energy from the stellar wind (R. Benjamin 2009, private communication). The appropriate choice of model radiation field intensity, \( U \), is then the ratio of the flux from the central star at the standoff distance over the mean interstellar field, estimated as,

\[
U = \frac{R_0^2 \sigma T_0^4}{R_0^2} U_{\text{ISRF}}^{-1},
\]  

(7)

where \( R_0 \) is the stellar radius, \( T_0 \) is the effective stellar temperature, and \( \sigma \) is the usual Stefan–Boltzmann constant. The postshock number density can then be estimated as

\[
n_{\text{a,3}} = 10^{-3} \frac{N}{V},
\]  

(8)

where \( V \) is the BS volume which we estimate by approximating the BSs as hollow cones at a known distance, \( D \), and \( N = L_{\text{obs}}/L_0 \), the ratio of the observed luminosity at a given bandpass to the theoretical luminosity per nucleon in the Draine & Li (2007) models. Effectively, \( n_{\text{a,3}} \) is found empirically because it is the scale factor by which we multiply the Draine & Li (2007) models to match the observed SED. Because \( V \propto D^3 \) and the inferred luminosity \( L_{\text{obs}} \propto D^2 \), our estimate for \( n_{\text{a,3}} \) varies as \( D^{-1} \), inversely with the adopted distance.

Draine & Li (2007) parameterize the model SEDs in terms of a maximum and minimum radiation field incident on the dust, \( U_{\text{max}} \) and \( U_{\text{min}} \). While dust in the typical ISM is exposed to a range of intensities, we expect that material in the BSs is irradiated by a single intensity dictated by the stellar luminosity and standoff distance. Therefore, we adopt the models with \( U_{\text{max}} = U_{\text{min}} \equiv U \), where \( U \) is chosen according to Equation (7). Figure 13 of Draine & Li (2007) shows that the flux ratio \( [24]/[70] \) is sensitive to \( U \) over the range \( 1 < U < 10^3 \), and we make use of this sensitivity in fitting the BS SEDs below. We adopt the models appropriate to Milky Way dust and leave the PAH fraction, \( q_{\text{PAH}} \), as a free parameter. Larger values of \( q_{\text{PAH}} \) raise the flux in the IRAC bandpasses where PAH emission is strong, but have no effect on the SED at [24] and [70].

Dotted lines in Figure 13 show illustrative dust models that provide reasonable fits to the mid- and far-IR data. The slope of the SED between [24] and [70] allows us to guess the approximate value for \( U \) without any prior knowledge of the stellar luminosity or \( R_0 \). Interestingly, the values for \( U \) in each case calculated from Equation (7) are generally within factors of 2–3 of the initial guess. This correspondence serves as a kind of corroborating evidence that the BSs are, in fact, powered by the radiant energy from their central stars. The fits of the models to the data in Figure 13 are done by eye to maximize the agreement at [24] and [70] by adjusting \( n_{\text{a,3}} \), and then the parameter \( q_{\text{PAH}} \) is varied to achieve a best fit at the IRAC bands. The models provide reasonably good fits to the data for objects 3, 5, and 8. In other cases, the overall fit is poor at the IRAC bandpasses because the model PAH features are too weak, even for the maximum model \( q_{\text{PAH}} \), or too weak, even for the minimum model \( q_{\text{PAH}} \). We take these discrepancies as indications that PAHs may be destroyed in the BSs (former case; objects 1, 4, and 7), and that PAH excitation may be elevated and dominate the SED in some objects (latter case; objects 2 and 6). The adopted values for \( U \) and \( n_{\text{a,3}} \) appear in each panel.

Armed with estimates of the ambient number densities, \( n_{\text{a,3}} = 1/2 n_{\text{a,3}} \), we proceed to calculate mass loss rates, \( M_{w,-6} \), using the method outlined above. Again, we consider only the four objects with the most reliable spectroscopic types where the BS nature is more likely to be correct. Table 4 summarizes the relevant parameters adopted for each of objects (2, 5, 7, 11). Derived mass loss rates vary from \( < 0.18 \times 10^{-6} M_\odot \text{ yr}^{-1} \) for the early-B star (Star 2) to \( \sim 1 \times 10^{-6} M_\odot \text{ yr}^{-1} \) for the O9V star (Star 5), to \( \sim 3 \times 10^{-6} M_\odot \text{ yr}^{-1} \) for the O5V star (A37). The O4If star BD+43°3654 stands out, having an implied mass loss rate of \( 160 \times 10^{-6} M_\odot \text{ yr}^{-1} \). This large value results from the rather large standoff distance, \( R_0 = 1.4 \text{ pc} \), implied by the MSX IR image from Comerón & Pasquali (2007). We note that we have no direct measure of the ambient ISM density for this

| No. | S.T. | \( R_0 \cos i \) (pc) | \( M_{w,-6} \) \( \times 10^{-6} M_\odot \text{ yr}^{-1} \) | \( V_{w,8} \) (km s\(^{-1} \)) | \( V_{w,8} \) \( n_{\text{a,3}} \) \( 1/2 \) |
|-----|------|-----------------------|-----------------|-----------------|-----------------|
| 2   | B1V-B3V\(^a\) | 0.07 | 0.0003–0.001 | <0.8 | <0.68 |
| 5   | O9V\(^b\) | 0.19 | 0.0003–0.1 | 0.8–1.5 | 0.12–3 |
| 7   | O5V\(^b\) | 0.53 | 0.2–0.9 | 2.8–3.2 | 2–5 |
| 11  | O4If\(^b\) | 1.4\(^c\) | 8 | 2.2 | 11 |

Notes:

\(^a\) Based on spectroscopic identification.

\(^b\) Based on the images of Comerón & Pasquali (2007) and adopted 1.6 kpc distance.

Table 3

Calculated BS Parameters for Most Reliable Objects

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object, so we have assumed the average value from the other four early-type BS stars. Results for BD+43°3654 should be regarded as particularly uncertain. These results are broadly consistent with the mean $M$ values for mid- to late-O stars estimated by Lamers & Leitherer (1993) and Fullerton et al. (2006) but a factor of several or more larger than the more recent compilation of Mokiem et al. (2007).

We consider the uncertainties on mass loss rates to be factors of 2–4, dominated by the uncertainties on $n_{e,3}$, which are of the same magnitude. The other parameters that appear in Equation (6) are likely known to $\sim$30%, so that uncertainties in the standoff distance, which enter as $R_0^2$ and $V_s^2$, do not have a major impact on the result. We present the calculation of mass loss rates in this section as an outline of a novel method without claiming that this approach is in any sense superior to other well-established techniques.

### 5. CONCLUSION

We have identified ten candidate BS nebulae and their central stars in the region surrounding Cyg OB2 on the basis of mid-IR morphologies. We provide the first spectral types and radial velocities for several stars (objects 1, 2, 5, and 8) from this survey, showing that they are late-O or early-B dwarfs. We find HD195229 to be a likely runaway on the basis of its space velocity calculated from both radial velocity measurements and Hipparcos proper motions, but the velocity vectors implied by the proper-motion data and BS orientation are nearly orthogonal.

We measure the radial velocity of the suspected runaway O4If star BD+43°3654 to be $V_{\text{helio}} = -66 \pm 4 \text{ km s}^{-1}$, supporting its runaway status. Based on the morphologies, spectral types, and SEDs, we identify three objects (6, 8, 9) as probable B-star YSOs with circumstellar material. Objects 2, 5, and 7 are probable BSs based on similarity to the theoretical shape. These stars, however, have modest radial velocities, consistent with those of other Cyg OB2 members, indicating that their motions must be predominantly tangential to the line of sight. Without proper-motion data, we are not able to confirm a runaway status or suggest an origin for these stars. The physical nature of the nebulae around stars 1, 3, 4, and 10 remains ambiguous with the current data. These nebulae may be partial shells, partial bubbles, or rims of nearby clouds illuminated by the early-type stars. As part of our analysis, we have also proposed a novel method for determining the mass loss rates for runaway OB stars using BS physics that yield reasonable, if slightly larger values for $M$ compared to more traditional methods.

We thank the time allocation committees for the WIYN and WIRO observatories for graciously allowing us the observing time that made this project possible. We also thank the National Science Foundation for support provided through the Research Experience for Undergraduates (REU) grant AST 03-53760. We also thank Heather Choi for assisting with the observing run at WIRO. Bob Benjamin and Matt Povich provided helpful feedback on early drafts of this manuscript. Chris Brunt graciously allowed us early access to the CO survey of Cyg X. Advice from an astute referee strengthened the analysis herein.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

### Facilities

WIRO, Spitzer, WIYN

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### Table 4

Derived Mass Loss Rates for Most Reliable Objects

| No. | S.T.          | $n_{e,3}$ | $M_{\dot{\psi}}$ |
|-----|---------------|-----------|-----------------|
| 2   | B1V–B3V       | 0.1       | $<0.18$         |
| 5   | O9V           | 0.1       | 0.75–1.3        |
| 7   | O5V           | 0.1       | 2.5–3           |
| 11  | O4If          | 0.1       | 160             |

Note. $^a$ Not measured; value adopted from the average of other stars.
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