

Cygnus OB2 at all wavelengths

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Abstract. The Cygnus X region is one of the most nearby star formation regions within our Galaxy, that is recognised by prominent emission throughout the entire electromagnetic spectrum, from radio to gamma-ray waves. The centre is populated by the peculiar stellar cluster Cyg OB2, traditionally classified as OB association, but in the light of modern data more likely the prototype of a young globular cluster within our own Galaxy. Heavily shredded by dense molecular clouds this object has been less thoroughly studied than other, more distant star formation complexes in the Milky Way. I will review our current knowledge about this object, by exposing its properties and that of its environment throughout the entire electromagnetic spectrum. Particular emphasis will be given to infrared, radio-continuum, X-ray, and gamma-ray line observations that find in Cyg OB2 a text-book case for multiwavelength studies.

1. The stellar population of Cygnus OB2

1.1. Optical surveys

The history of optical observations of Cyg OB2 starts in 1953, when Münch & Morgan first noticed a clustering of eleven blue giants in the area northeast of γ Cygni. Following this discovery, Johnson & Morgan (1954) obtained spectroscopic observations of the 11 stars, and recognised the considerable interstellar absorption towards these objects, which made them to the most heavily obscured stars that were known at that epoch. From their data, they obtained a first distance estimate of 1.5 kpc to the association, which is already close to the modern value of 1.7 kpc (e.g. Massey & Thompson 1991). Morgan et al. (1954a; 1954b) discovered seven further early type members, of which the first (Schulte 12) is the most famous object in Cyg OB2 because of its unequaled visual luminosity ($M_V \approx 10$) and large extinction ($A_V \approx 10$). Schulte (1956a) named the association VI Cygni, and in the following years, he established a list of 31 association members from his initial list of 88 suspected OB stars (Schulte 1956b; 1958).

One of the most comprehensive studies of Cyg OB2 has been undertaken by Reddish et al. (1966) who performed detailed photographic UBV investigations of the area. From star counts on their photographic plates down to a magnitude limit of $B = 16.5$, they estimated a number of ~ 400 OB stars within the association. By extending the star counts to fainter magnitudes using the Palomar Sky Survey plates, they found a total of 3000 association members, for which

however no spectral type information was available. Based on the luminosity function, they estimated an association mass between $(5.8 - 27) \times 10^3 M_{\odot}$, where the lower limit corresponds to 400 OB stars members while the upper limit assumes that all 3000 member stars were indeed of OB type. From the star counts they determined an elliptical shape for Cyg OB2 with major and minor axes of $48' \times 28'$, and they suggested that this shape might result from the rotation of the association around the minor axis which lies parallel to the galactic plane. On basis of the dimension, star numbers and total mass, Reddish et al. (1966) were also the first who suggested that Cyg OB2 may be regarded as a young globular cluster, similar to the blue globular clusters in the Magellanic Clouds.

No further extensive survey of Cyg OB2 has been performed until the early nineties, when Torres-Dodgen et al. (1991) obtained Strömgren and near-infrared photometry for about 80 stars in the association. Using the method of spectroscopic parallax, they estimated the distance of Cyg OB2 to 1.7 ± 0.2 kpc, and by the means of isochrone fitting they estimated a minimum age of 3 Myr. The first CCD photometric survey of Cyg OB2 has been undertaken by Massey & Thompson (1991) who also performed spectroscopic observations of 76 stars, thus enhancing by a factor of four the number of member stars with spectral type classification. They also determined the distance to 1.7 kpc, and they estimated the slope of the initial mass function to $\alpha = -1.0 \pm 0.3$.

1.2. Near-infrared surveys

The first survey of Cyg OB2 in the near-infrared domain has been performed by Voelcker & Elsässer (1973) who observed 80 stars in the J , H , K and L bands. Based on their observations they suggest that the stars are still located in the natal dust cloud from which they have been formed. This idea is supported by near-infrared observations of Torres-Dodgen et al. (1991) from which the authors determined a normal extinction law with a ratio of total-to-selective extinction of $R_V = 3.04 \pm 0.09$ (see also McMillan & Tapia 1977 and references therein).

Using J , H , and K_S photometric data from the 2MASS survey, Knödlseeder (2000) re-determined the morphology and stellar content of Cyg OB2 and demonstrated that previous visual surveys were heavily biased by the foreground extinction pattern. In total, he found 120 ± 20 O star members and estimated the total cluster mass to $(4 - 10) \times 10^4 M_{\odot}$. He determined the association diameter to 2° , which at a distance of 1.7 kpc converts into a radius of 30 pc. Assuming spherical symmetry, this results in an average cluster density of $0.4 - 0.9 M_{\odot} \text{ pc}^{-3}$, with a central density reaching $\rho_c = 40 - 150 M_{\odot} \text{ pc}^{-3}$. The 2MASS data indicate a relatively steep slope of the initial mass function of $\alpha = -1.6 \pm 0.1$. Taken all these parameters together, Knödlseeder (2000) confirms the suggestion of Reddish et al. (1966) that Cyg OB2 should be classified as a young globular galactic cluster.

In a recent near-infrared spectroscopic survey of 46 candidate early-type members of Cyg OB2, Comerón et al. (2002) confirmed the findings of Knödlseeder (2000). In particular, they detect $\text{Br}\gamma$ emission lines from 20 stars which is characteristic for evolved stars that experience considerable mass loss. Most of the $\text{Br}\gamma$ stars are redder than predicted by the reddening vector, indicating circumstellar dust emission that probably has been created by the mass ejections. This

Table 1. Parameters of Cygnus OB2

Centre (J2000)	$\alpha = 20^{\text{h}}33^{\text{m}}10^{\text{s}}, \delta = +41^{\circ}12'$
Distance	1.7 ± 0.2 kpc
Age	$(3 - 4) \times 10^6$ yr
Diameter	$\sim 2^{\circ}$ (~ 60 pc)
Members earlier F3V	8600 ± 1300
OB star members	2600 ± 400
O star members	120 ± 20
Total stellar mass	$(4 - 10) \times 10^4 M_{\odot}$
Central mass density ρ_0	$40 - 150 M_{\odot} \text{ pc}^{-3}$
IMF slope ,	$-1.0 \dots - 1.6$

suggestion is substantiated by the detection of H_2 and CO in some stars, which is indicative of abundant circumstellar molecular material. Comerón et al. (2002) estimate the fraction of Br γ emission line to O-type stars to 25%, which places an interesting age limit on Cyg OB2 if we assume that all these stars are indeed in their Wolf-Rayet phase. From the evolutionary model presented in Figure 3 of Knödlseeder et al. (2002), this fraction is reached at an age of 3 – 4 Myr under the assumption of coeval star formation, in agreement with findings by other methods (see Knödlseeder et al. 2002 and references therein).

1.3. Mid- and far-infrared observations

Mid- and far-infrared observations of the Cygnus region have been conducted by balloon-borne telescopes (Campbell et al. 1980 and references therein), but the most comprehensive list of infrared sources in Cyg OB2 is based on observations with the IRAS satellite (e.g. Odenwald 1989). Most of the mid- and far-infrared point sources detected in the Cyg OB2 area are either embedded early-type stars or star clusters, or young stellar objects (YSO). Many of them are associated to thermal radio continuum sources which are suggestive of H II regions. Some of the point sources have been identified with known members, suggesting warm circumstellar dust which is attributed to extensive mass loss. Examples are stars no. 5 and 12, and the putative member MWC 349 (Parthasarathy et al. 1992).

Several tens of YSOs have been found in the area of Cyg OB2 (Parthasarathy et al. 1992; Odenwald & Schwartz 1993) which may indicate that star formation is still ongoing in the association. Yet, although the density of YSOs is higher in the Cyg OB2 area with respect to adjacent sky fields, it is unclear whether the objects are indeed members of Cyg OB2 or whether they are situated in the surrounding matter, where the kinematical activity of Cyg OB2 has led to compression of the medium and possibly triggered star formation.

1.4. Peculiar stars

Cyg OB2 houses some of the hottest and most luminous stars known in our Galaxy. Stars number 7 and 22-A are the only stars of the extreme type O3 If* known in the northern hemisphere (Walborn et al. 2002). Star number 5, also known as V729 Cyg, is an evolved contact binary system formed by a O7 Ia + Ofpe/WN9 pair that undergo considerable mass loss and mass exchange

(Rauw et al. 1999). Star number 12 figures amongst the visually most luminous ($M_V \approx -10$) and at the same time most obscured ($A_V \approx 10$) stars known within our Galaxy. It seems to violate the empirical Humphrey-Davidson upper-luminosity limit, which led Massey & Thompson (1991) to the suggestion that it might be a Luminous Blue Variable (LBV) star in quiescence. Indeed, this star shows photometric and spectroscopic variability that is typical for LBV stars, and the large extinction may indicate the presence of circumstellar material that is a remain of some past episodic mass-loss outburst.

The presence of thermal and non-thermal components of radio emission in a couple of stars (numbers 8A and 9, WR 147) further indicates massive stars that undergo mass loss. Higgs et al. (1994) have identified a spherical shell in high resolution radio observations of G79.29+0.46, located at the south-western edge of Cyg OB2. They identified a central star of extreme luminosity ($M_V \sim 10$) and extinction ($A_V \sim 16$) at a distance compatible with that of Cyg OB2. More recent spectroscopy strongly supports their initial idea of G79.29+0.46 being a LBV star, which possibly is in the transition of becoming a Wolf-Rayet star (Voors et al. 2000). The observed radio and infrared shell is probably due to $\sim 14M_\odot$ of circumstellar material that have been ejected by the star (Waters et al. 1996). Yet, the distance estimate is rather uncertain, and the derived radial velocity of $V_{\text{LSR}} = -27 \text{ km s}^{-1}$ would place the object rather in the Perseus spiral arm (Voors et al. 2000).

Three Wolf-Rayet stars in the Cyg OB2 field have so far been suggested as members of the association: WR 144, 145, and 146. WR 146 is a binary star (Niemela et al. 1998) that shows non-thermal radio emission located between both components that is strongly suggestive of wind-wind collision (Dougherty et al. 2000). A similar situation has been observed in WR 147, yet it is situated slightly outside the 2° diameter association boundary, and its suggested distance of 650 pc (Morris et al. 2000) indicates a foreground object. Wind-wind collisions may also explain the high-energy gamma-ray emission from the unidentified EGRET source 3EG J2033+4118 that has tentatively been associated to star number 5 (Benaglia et al. 2001). Recently, even TeV gamma-ray emission has been observed near 3EG J2033+4118 and star number 5 (Rowell et al. 2002), indicating that particle acceleration to multi-TeV energies may take place at the shock front of the colliding wind regions.

The question of still on-going star formation in Cyg OB2 is closely related to the identification of pre-main-sequence members, and the peculiar star MWC 349A has indeed been suggested as such (Meyer et al. 2002 and references therein). MWC 349A possesses characteristics of a pre-main-sequence B[e] star, in particular a dusty rotating circumstellar disk and a bipolar outflow, yet other authors argue that it could also be a massive B[e] supergiant (e.g. White & Becker 1985). From the similarity of polarisation magnitude and position angle between MWC 349A and nearby Cyg OB2 members, Meyer et al. (2002) conclude that it is indeed part of the association.

Finally, the X-ray binary star Cyg X-3 lies in the field of Cyg OB2, yet distance estimates of about $\sim 9 \text{ kpc}$ (Predehl et al. 2000) place this object far behind the association, located either in the Perseus or the outer spiral arm.

2. The environment of Cygnus OB2

2.1. The distance problem

Studying the environment of Cyg OB2 is intimately related to the assignment of distances to adjacent structures and stellar groups which then allows to dress a three-dimensional picture of the region and to study the interplay of the various constituents. However, kinematic distance estimates in the Cygnus region are unreliable for distances below 4 kpc because the velocity gradient due to differential galactic rotation is substantially smaller than the typical velocity of streaming or expansion motions of a few 10 km s^{-1} . The only reasonably well defined distances come from spectroscopic parallax measurements towards stars, yet also here the patchy extinction pattern and the possible presence of circumstellar dust may considerably deteriorate the estimates. Although there is little doubt about the existence of a spiral arm feature in this region of the sky that is seen tangentially, part of the apparent alignment of objects along the line of sight at distances from 0.5 to 4 kpc may result from erroneous distance estimates. Thus, in order to understand the Cyg OB2 environment, estimates of distance uncertainties are crucial, and should be considered seriously.

2.2. Cygnus X

Cyg OB2 lies near the centre of an extended ($\sim 10^\circ$) radio emission structure known as Cygnus X (Piddington & Minnett 1952). Cygnus X is composed of numerous individual H II regions, which have first been listed by Downes & Rinehart (1968). Dickel et al. (1969) estimated their distance by comparing their radio-continuum intensity to the $\text{H}\alpha$ surface brightness of corresponding optical nebula, and found that most of them are situated in a narrow distance range of 1.2 – 2.4 kpc, with a typical distance uncertainty of 25%. Cong (1977) identified two molecular cloud complexes that are associated with the H II regions: the DR 21 complex east of Cyg OB2 which comprises the radio sources DR18, DR20, DR21, DR22, and DR23, and the IC1318b,c complex west of Cyg OB2 which comprises the radio sources DR6, DR9, DR12, DR13, DR15, and IC1318b,c. These complexes are perceptible at various wavelengths (radio continuum, infrared, molecular gas) as the most prominent emission regions of Cygnus X with Cyg OB2 matched in between. Distance estimates to these complexes are 1.6 ± 0.4 kpc for DR 21 (Comerón & Torra 1999) and 1.5 ± 0.4 kpc for IC1318b,c (Dickel et al. 1969), which within the uncertainties is compatible with the distance to Cyg OB2.

Véron (1965) has suggested that Cygnus X is a single giant H II region that is powered by Cyg OB2, yet the identification of individual H II regions with their exciting stars in Cygnus X indicates that there are also other ionising sources in the area. Wendker (1970) has identified a diffuse thermal radio component that constitutes $\gtrsim 50\%$ of the emission in Cygnus, which may indeed present the extended Strömgren sphere of Cyg OB2. Using an evolutionary synthesis model to predict the multi-wavelength emission of the massive star populations in the Cygnus X region, Knödseder et al. (2002) confirm this hypothesis. About 50% of the predicted ionising luminosity in the area comes from Cyg OB2 while the rest is provided by massive stars that are found in the surrounding associations and clusters. Using their predicted Lyman continuum flux of $10^{51} \text{ ph s}^{-1}$ for

Cyg OB2, and assuming an electron temperature and density of $T_e = 6000$ K and $n_e = 10 \text{ cm}^{-3}$, respectively, a Strömgren sphere with a radius of 60 pc is expected, corresponding to an angular diameter of 4° at a distance of 1.7 kpc. This is comparable to the size of the diffuse radio emission component, which shows two maxima at a distance of $\sim 2^\circ$ from Cyg OB2 that coincide with the DR 21 and IC1318b,c complexes (Wendker 1970). Interestingly, it has been suggested that the H II region observed near the mass-losing giant NML Cyg, situated at about 2.7° from the centre of Cyg OB2, results from the photoionisation of the stellar outflow by UV photons from Cyg OB2 (Morris & Jura 1983). Thus, the Strömgren sphere of Cyg OB2 may even reach a radius of ~ 80 pc.

2.3. Wind swept shells

Wind swept shells around Cyg OB2 have been searched and tentatively identified by several authors (e.g. Kaftan-Kassim 1961; Heiles 1979; Gosachinskii et al. 1999; Lozinskaya et al. 2002), yet no convincing detection has been made so far. The major difficulty in finding interstellar shells in the Cygnus region arises from the fact that for distances of up to 4 kpc, the differential galactic rotation results only in low radial velocities $|v| \lesssim 10 \text{ km s}^{-1}$, a value that is smaller than the dispersion of interstellar gas velocities ($\sim 15 \text{ km s}^{-1}$) in the Galaxy (e.g. Heiles 1979; Geballe et al. 1999). Consequently, all the matter of the local spiral arm piles-up in a narrow radial velocity interval which completely blends the possible signature of an expanding shell.

Lozinskaya et al. (2002) estimate the mechanical luminosity of Cyg OB2 to a few $10^{39} \text{ erg s}^{-1}$ during the past 2 million years. Assuming a typical initial density of 100 cm^{-3} , in agreement with measurements of immersed molecular clumps in Cyg OB2 by Gredel & Münch (1994), the size of a bubble created by the winds of Cyg OB2 should amount to 63 pc, with a bubble shell velocity of 19 km s^{-1} (Weaver et al. 1977). At a distance of 1.7 kpc, this should result in a shell diameter of 4° , comparable to the estimated size of the Strömgren sphere. Indeed, the DR 21 and IC1318b,c complexes lie at the approximate location of the hypothesised wind blown shell, and the numerous compact radio sources, YSOs, and embedded young clusters that are found in these complexes (Le Duigou & Knödlseeder 2002) suggest that Cyg OB2 may have triggered star formation in their interiors.

2.4. The Cygnus X-ray superbubble

The Cygnus X-ray superbubble has been discovered by Cash et al. (1980) as an uncomplete ring of soft X-ray emission $13^\circ \times 18^\circ$ in diameter surrounding the Cygnus X region. The morphology of the X-ray emission is shaped by heavy foreground extinction due to the Great Cygnus Rift, and the underlying source could in reality present a nearly uniform emission morphology (Cash et al. 1980; Uyaniker et al. 2001).

The origin of the Cygnus X-ray superbubble is still a puzzle, and the protagonists split into two groups who either suggest a single superbubble formed by Cyg OB2 or a superposition of numerous sources that are superimposed along the line of sight of the local spiral arm. Cash et al. (1980), belonging to the first group, suggested that a series of 30 – 100 supernovae exploding over a period

of 3 – 10 Myrs in a former stellar generation of the Cyg OB2 association may have created the structure. Yet, there is no evidence for the existence of such a former generation of stars in Cyg OB2, and Abbott et al. (1981) proposed that the combined stellar winds from Cyg OB2 members may have formed the bubble during the last 2 million years. On the other hand, Bochkarev & Sitnik (1985) summarise arguments against the single superbubble scenario and argue that the X-ray emission results from discrete sources in the various OB associations and clusters that are found in the Cygnus region. In particular, the X-ray superbubble seems to be elongated along the galactic plane which is contrary to the expectation for an expanding bubble which should expand more easily perpendicular to the galactic disk. Hence, similar to the reasoning for the Cygnus X radio emission, the superbubble is probably a result of the superposition of various objects along the line of sight, yet a major contribution from the stellar wind activity of Cyg OB2 members is expected.

2.5. Gamma-ray line emission

Prominent 1.809 MeV gamma-ray line emission has been reported from the Cygnus X region based on observations of the COMPTEL telescope (del Rio et al. 1996; Plüschke et al. 2002). The 1.809 MeV gamma-ray line arises from the decay of ^{26}Al , a radioactive isotope with a mean lifetime of about one million years. ^{26}Al is mainly produced during the core hydrogen burning phase in massive stars, and is subsequently ejected by stellar winds (in particular during the LBV and Wolf-Rayet phases) and/or supernova explosions. The presence of ^{26}Al in the Cygnus region is again a clear indicator of extensive mass loss by massive ($M > 20M_{\odot}$) stars in this area. Using an evolutionary synthesis model, Knödlseeder et al. (2002) have suggested that Cyg OB2 is indeed the dominant ^{26}Al source in the Cygnus X region. Yet, actual models fail to explain the observed 1.809 MeV line intensity, indicating possible shortcomings of nucleosynthesis calculations in massive stars that might be related to neglecting stellar rotation and/or binarity (Knödlseeder et al. 2002).

3. Galactic context

Cyg OB2 is not the only massive young star cluster that has been observed in the Milky Way. The list of such objects amounts to at least 8 clusters in the Galaxy (Table 2), and encloses the Central, Arches, and Quintuplet clusters (Figer, these proceedings), WR43 (Blum et al. 1999), W49A (Conti & Blum 2002), NGC 3603 (Moffat, these proceedings), and Westerlund 1 (Negueruela & Clark, these proceedings). These clusters are characterised by typical Lyman continuum luminosities of about 10^{51} photons s^{-1} which corresponds to an equivalent of about ~ 100 O type stars. Consequently, they are all very young, with ages of a few Myrs, and some, such as W49A, are still embedded in their natal cloud. This leads to the question why no older massive star clusters have been observed so far, with ages of say a few 10 – 100 Myrs. Probably it is observationally difficult to unveil them since the absence of ionising stars won't lead to a prominent thermal radio emission feature, optical H II region, or 1.809 MeV gamma-ray line signature, that triggered the discovery of some of the known clusters. On the other hand, at least in the galactic centre, cluster disruption time scales

Table 2. Massive young galactic star clusters.

Name	d (kpc)	age (Myr)	O stars	$\log M$	diameter (pc)
Central	8	~ 5	~ 100	4.0	2
Arches	8	2.5 ± 0.5	~ 160	4.3	0.4
Quintuplet	8	4 ± 1	~ 100	3.8	2
W43	~ 7		~ 100		5
W49A	11.4 ± 1.2	$\lesssim 2$	~ 100		15
Cyg OB2	1.7 ± 0.2	3 – 4	120 ± 20	4.6 – 5.0	60
NGC 3603	7 ± 1	~ 3	~ 50	3.7	10
Westerlund 1	1.1 ± 0.4	4 – 5		4.5 – 5.0	5

are of the order of $\lesssim 10$ Myrs (Kim et al. 1999), and at least the three known clusters in this area should disrupt within the next million years.

Some of the clusters, such as the Arches cluster, show a considerable mass segregation (Stolte et al. 2002), others do not (e.g. Cyg OB2, Knödlseher 2000). Also, the radial extent of the clusters vary by about 2 orders of magnitudes, and given that they have roughly similar mass (at least within one order of magnitude) their density varies by over 6 orders of magnitudes! This large spectrum certainly tells us something about the cluster formation process, which may have been different for the different clusters. Future multi-wavelength observations should shed more light on these clusters and their environments, and will hopefully unveil the conditions that lead to the formation of these localised starbursts within our Galaxy.

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