THE CYGNUS LOOP’S DISTANCE, PROPERTIES, & ENVIRONMENT DRIVEN MORPHOLOGY

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ABSTRACT

The Cygnus Loop is among the brightest and best studied evolved Galactic supernova remnants. However, its distance has remained uncertain thus undermining quantitative understanding about many of its fundamental properties. Here we present moderate-dispersion spectra of stars with projected locations toward the remnant. Spectra of three stars revealed Na I λ5890,5896 Å and Ca II 3934 Å absorption features associated with the remnant’s expanding shell, with velocities ranging from −160 to +240 km s$^{-1}$. Combining Gaia DR2 parallax measurements for these stars with other recent observations, we find the distance to the Cygnus Loop’s centre is 735 ± 25 pc, only a bit less than the 770 pc value proposed by Minkowski some 60 years ago. Using this new distance, we discuss the remnant’s physical properties including size, SN explosion energy, and shock velocities. We also present multi-wavelength emission maps which reveal that, instead of being located in a progenitor wind-driven cavity as has long been assumed, the Cygnus Loop lies in an extended, low density region. Rather than wind-driven cavity walls, these images reveal in unprecedented clarity the sizes and locations of local interstellar clouds with which the remnant is interacting, giving rise to its large-scale morphology.

Subject headings: ISM: individual (Cygnus Loop) - ISM: kinematics and dynamics - ISM: supernova remnants

1. BACKGROUND

The Galactic supernova remnant (SNR) G74.0-8.5, commonly known as the Cygnus Loop or Veil Nebula, is thought to be a middle-age remnant with an estimated age of 1−2 × 10$^4$ yr. Based on extensive multi-wavelength observations, the Cygnus Loop has been most often modeled as the remnant of a supernova explosion that occurred inside an interstellar cavity likely created by a high-mass progenitor star (McCray & Snow 1979; Hester et al. 1994; Levenson et al. 1997, 1998; Miyata & Tsunemi 1999; Fang et al. 2017).

Underlying any quantitative analysis of the Cygnus Loop is uncertainty about its distance. For many decades, the most often adopted value was a kinematic investigation by Minkowski (1958). Hubble (1937) measured a proper motion of 0.03 yr$^{-1}$ for the remnant’s bright eastern and western nebulae (see Fig. 1). This value, when combined with an average radial velocity of 115 km s$^{-1}$ for the remnant’s optical filaments, led Minkowski (1958) to estimate a distance of 770 pc.

However, more recent distance estimates have ranged from 440 to 1400 pc (see review by Fesen et al. 2018). The most cited value is 540$^{+100}_{−80}$ pc by Blair et al. (2005). Although smaller than many other estimates, this distance appeared in line with a subsequent study which estimated a distance of 576 ± 61 pc to a sdO star, KPD 2055 +3111, lying in the direction of the remnant’s eastern nebulosities (Blair et al. 2009).

Because this star’s UV spectrum showed high-velocity O VI 1032 Å line absorption, Blair et al. (2009) argued the star must be behind the remnant thus limiting the remnant’s distance to less than ∼576 pc. However, Gaia DR2 data (Gaia Collaboration et al. 2018) report a parallax of 1.2610 ± 0.0013 mas and hence a distance of 793 ± 30 pc for this star (Table 1).

Other recent distance estimates have tended to favor larger values. Medina et al. (2014) used spectra of Balmer-dominated Hα filaments to estimate shock velocities of around 400 km s$^{-1}$ based on Hα emission profiles. Combined with proper motions by Salvesen et al. (2009), they deduced a distance of around 890 pc. However, a re-analysis of thermal equilibrium in a collisionless shock led to a reduction of the derived shock velocities which decreased the remnant’s estimated distance to ∼800 pc (Raymond et al. 2015).

The most recent distance estimate to the Cygnus Loop is that of Fesen et al. (2018) who suggested optical nebulosities around two stars were stellar mass-loss material interacting with the remnant’s expanding shock front and thus could be used to estimate the Cygnus Loop’s distance. A small emission-line nebula with a bow-shaped morphology centered on a M4 III star, J205601, near the remnant’s eastern nebula NGC 6992 was shown to be shock-heated with significantly higher electron densities than typically seen in the remnant’s filaments. Since distance estimates to this red giant ranged from 1.0 to 4.2...
Fig. 1.— Reproduction of the red image of the Digital Sky Survey of the Cygnus Loop. Marked are our three program stars X, Y, and Z, along with the Blair et al. (2009) sdO star (KPD 2055 +3111), and the two stars, J205601 & BD+31 4224, suspected by Fesen et al. (2018) to be physically interacting with the remnant’s shock front. North is up, East to the left.

| Star Catalog ID | RA (J2000) | Dec (J2000) | Magnitude (v) | Gaia DR2 Parallax | Gaia DR2 Distance | Location to SNR |
|----------------|-------------|-------------|--------------|-------------------|-------------------|-----------------|
| J205601        | 20:56:00.936 | +31:31:29.75 | 11.57        | 0.6334 ± 0.0661 mas | 1580 ± 180 pc     | far behind      |
| KPD 2055 +3111 | 20:57:26.889 | +31:22:52.56 | 14.12        | 1.2610 ± 0.0413 mas | 795 ± 30 pc       | behind          |
| BD+31 4224     | 20:47:51.817 | +32:14:11.33 | 9.58         | 1.3033 ± 0.0438 mas | 767 ± 27 pc       | inside          |
| Star X         | 20:56:44.629 | +30:41:14.33 | 9.51         | 1.3586 ± 0.0440 mas | 736 ± 25 pc       | just behind     |
| Star Y         | 20:55:51.948 | +31:43:27.40 | 11.25        | 1.3598 ± 0.0449 mas | 735 ± 25 pc       | just behind     |
| Star Z         | 20:52:27.557 | +31:56:29.48 | 10.73        | 1.1581 ± 0.0390 mas | 864 ± 30 pc       | far behind      |

Table 1
Stars Used to Estimate the Distance to the Cygnus Loop

a References: J205601 & BD+31 4224: Fesen et al. (2018); KPD 2055 +3111: Blair et al. (2009); X, Y, Z: this work
b TYC: Høg et al. (2000); UCAC2: Zacharias et al. (2004); HD: Henry Draper Catalogue
kpc, Fesen et al. (2018) struggled to connect this star and the nebulosity to the remnant. Gaia’s DR2 parallax of 0.6334 ± 0.0661 mas implies a distance around 1.6 kpc, placing it well behind the remnant (Table 1), leaving the origin of the bow-shaped nebulosity somewhat of a mystery.

Fesen et al. (2018) also identified a B7 V star, BD+31 4224, located along the remnant’s northwestern limb within a small arc of nebulosity in a complex region of curved and distorted filaments suggestive of a disturbance of the remnant’s shock front due to the B star’s stellar winds. Whereas Fesen et al. (2018) estimated the star’s distance to be 0.8 to 1.0 kpc, Gaia DR2 reports a parallax of 1.3033 ± 0.0438 mas implying a distance of 767 ± 35 pc (Table 1).

This distance estimate, when taken together with the Blair et al. (2009) sdO star lying behind the remnant, suggests a firm distance limit of less than 800 pc, consistent with Minkowski’s 1958 value of 770 pc. A distance ≃ 750 - 800 pc could explain the failure by Welsh et al. (2002) to detect high-velocity Na I and Ca II line absorptions associated with the remnant in several stars located along the line-of-sight to the Cygnus Loop at distances less than ~700 pc.

In light of the recent Gaia data release giving relatively accurate distances to many earlier type stars located toward the Cygnus Loop, we obtained optical spectra of several stars located between 700 and 900 pc in the remnant’s direction to search for associated high-velocity Na I and Ca II absorption features as additional clues to the remnant’s distance. Our spectral observations are described in §2, with results presented in §3. Combining these new data with prior observations, we discuss in §4 the Cygnus Loop’s likely distance and thus its true size and supernova energy. We also present multiwavelength images which reveal the remnant’s likely interactions with several local interstellar clouds leading to a re-assessment of the long assumed progenitor wind-driven cavity model. Our conclusions are summarized in §5.

2. OBSERVATIONS

Roughly two dozen stars were selected as spectroscopic program targets on the basis of Gaia determined distances between 700 and 950 pc, m_\text{bol} < 13.5, Gaia T_\text{eff} values greater than 8000 K, and projected locations within the Cygnus Loop’s optical boundaries. Many had early-type A classifications listed on SIMBAD (Wenger et al. 2000). This modest target list was viewed as sufficiently large to uncover at least a few background stars exhibiting high-velocity interstellar absorption components associated with the Cygnus Loop.

Moderate-dispersion spectra of several of these stars were observed on 2018 May 30, 31 and June 1, 2, and 3 with the 1.3m McGraw-Hill telescope at MDM Observatory located at Kitt Peak, Arizona. The data were taken using a Boller & Chivens Spectrograph (CCDS) which employs a Loral 1200 × 800 CCD detector. We used an 1800 grooves mm^{−1} grating blazed at 4700 Å to yield a wavelength coverage of 330 Å with a spectral scale of 0.275 Å per pixel. Exposure times varied from 1 − 2 × 1200 s to 2 × 3000 s depending on star brightness and wavelength coverage.

A 1.5 arcsec wide slit was used which resulted in a measured FWHM of 2.2 pixels, corresponding to a spectral resolution of 0.61 Å, providing an effective R ≃ 9700 at the Na I 5890, 5996 Å lines and R ≃ 6500 at the Ca II K 3934 Å line. Although these spectral resolutions are low relative to conventional interstellar absorption studies where R values typically exceed 30,000, this spectrograph + grating system provided velocity resolutions ≃ 30 and 45 km s^{-1} for the Na I and Ca II lines, respectively. This was judged adequate for detecting the expected high-velocity expansion filaments, in the range of 50 to 300 km s^{-1}, in the spectrum of background stars.

Standard pipeline data reduction was performed using IRAF. The spectra were bias-subtracted, cosmic-ray corrected using the L.A. Cosmic software (van Dokkum 2001), co-added, wavelength calibrated using Hg, Ne, Ar, and Xe comparison lamps, and have been corrected to local standard of rest (LSR) values. Detected interstellar Na I and Ca II line components were deblended using IRAF Gaussian fitting routines. Measured velocities have a typical uncertainties of ±5 km s^{-1}.

3. RESULTS

Although our program stars were distributed across the remnant, only three stars located in eastern half were found to exhibit high-velocity absorption components visible given our spectral resolution and S/N. Projected locations of these three stars, labeled X, Y, and Z are shown in Figure 1 along with the locations of the sdO star KPD 2055 +3111 (hereafter KPD) studied by Blair et al. (2009) and the two stars J205601 (M4 III) and BD+31 4224 (B7 V) discussed by Fesen et al. (2018). Coordinates and Gaia parallax measurements for all six stars are listed in Table 1. While we were unable to classify our three observed program stars due to our limited spectral coverage, Stars X, Y, and Z have B − V values of 0.03, 0.08, and 0.29 with Star X classified as A0 (Wenger et al. 2000).

Reduced and normalized spectra of Stars X, Y, and Z for the wavelength region around the Na I D lines at 5899.95 and 5895.92 Å are showed in Figure 2. Measured D1 and D2 absorption component velocities and equivalent widths are listed in Table 2.

The spectrum of the 9.5 mag Star X located south of NGC 6995 and IC 1340 exhibited the cleanest high-velocity absorption components, showing both red and blue absorption features. Deconvolution of the observed Na I profiles indicates high-velocity interstellar components at z = −60 and +95 km s^{-1} (Fig. 2; upper panels). With a Gaia estimated distance of 736 ± 25 pc, the detection of both red and blue shifted Na I features in this star’s spectrum implies a distance limit to the back side of the Cygnus Loop of less than ~760 pc.

Star X’s spectrum covering the Ca II K line at 3933.66 Å is shown in Figure 3. As expected due to interstellar grain destruction releasing refractory Ca atoms following SN shock passage (Routly & Spitzer 1952), the strength of the high-velocity Ca II absorption features are noticeably stronger here relative to the low-velocity interstellar features compared to that seen for Na I (Fig. 2).
The spectrum of Star Y with a projected location just west of the remnant’s bright nebula NGC 6992 also showed red and blue high-velocity interstellar components indicating it too must lie behind the remnant (Fig. 2 middle panels). Components with approximate LSR velocities of $-50, +50, \& +95$ km s$^{-1}$ are seen for both D1 and D2 lines.

With a Gaia DR2 reported distance nearly identical to that of Star X, namely $735 \pm 25$ pc, Star Y’s spectrum strengthens a maximum distance limit to the backside of the Cygnus Loop of $\approx 760$ pc. However, since both stars are located near the remnant’s eastern limb, a distance limit to the centre of the remnant must take into account the spherical curvature and any aspherical geometry of the Cygnus Loop.

Lastly, the spectrum of Star Z, a 10.7 mag late A/early F star located near the remnant’s north-central limb, showed the broadest and most complicated system of Na I absorption lines (Fig. 2 lower panels). At least five high-velocity Na I D1 and D2 absorption features are detected with velocities ranging from $-158 \pm 5$ to $+243 \pm 5$ km s$^{-1}$. Both for clarity and limited by our spectral resolution, we have chosen not to show deconvolved components for the overlapping region in between...
A previous search for high-velocity components associated with the remnant conducted by Welsh et al. (2002) likely failed due to their selection of stars with distances less than \( \sim 700 \) pc. However, spectra of stars with distance in excess of 700 pc presented in Figures 2 and 3 show clear evidence for high-velocity interstellar Na I and Ca II absorptions from the Cygnus Loop’s expanding shell.

In addition to the relatively high red and blue radial velocities detected for Na I lines in the spectra of Stars X, Y, and Z, the decreased ratio of Na I D1/Ca II K equivalent widths in Star X is consistent with these components arising from shocked gas and subsequent grain destruction in accord with the well-established Routly-Spitzer effect (Routly & Spitzer 1952; Vallerga et al. 1993). Whereas the D1/K EW ratio is 1.3 for the low velocity component in the spectrum of Star X, the D1/K ratio is only 0.36 and 0.17 for the \( -60 \) and \( +95 \) km s\(^{-1}\) components. Although we did not measure the Ca II equivalent widths for Stars Y and Z, their high-velocity Na I components are as large or larger than that seen in Star X and hence would be expected to exhibit strong high-velocity Ca II absorptions with corresponding low D1/K equivalent width ratios.

The detection of both blue and red high-velocity interstellar absorption features in the spectra of Stars X and Y with Gaia estimated distances of 735 \( \pm 25 \) pc, together with several blue and red shifted interstellar absorptions in Star Z located at 864 pc, place a firm maximum distance limit to the backside of the Cygnus Loop of 760 pc. This is consistent with the KPD star’s 793 \( \pm 30 \) pc distance which showed remnant related line absorptions in its UV spectrum implying a location behind the remnant (Blair et al. 2009). Formally, these detections allow for all distances less than 760 pc for the backside of the remnant including the \( \sim 550 \) pc estimate proposed by Blair et al. (2009). However, if the stellar wind from the B7 star, BD+31 4224, located along the remnant’s northwestern limb is truly interacting with the remnant’s expanding shock wave as argued by Fesen et al. (2018), then its Gaia estimated distance of 767 \( \pm 27 \) pc places severe constrains on the remnant’s distance.

Adopting the premise that the B7 star is interacting with the remnant, this effectively anchors the Cygnus Loop to distances within the B7 star’s parallax measurement errors; namely, the remnant’s rear hemisphere can be no closer than 740 pc, and its frontside can be no further than 794 pc. At such distances, the Cygnus Loop’s main shell diameter of 2.85 degrees implies a linear di-

### Table 2

| Star ID | Line | \( V_0 \) km s\(^{-1}\) | EW\(_0\) Å | \( V_{B1} \) km s\(^{-1}\) | EW\(_{B1}\) Å | \( V_{B2} \) km s\(^{-1}\) | EW\(_{B2}\) Å | \( V_{R1} \) km s\(^{-1}\) | EW\(_{R1}\) Å | \( V_{R2} \) km s\(^{-1}\) | EW\(_{R2}\) Å | \( V_{R3} \) km s\(^{-1}\) | EW\(_{R3}\) Å |
|---------|------|----------------|--------|----------------|----------|----------------|----------|---------------|----------|---------------|----------|---------------|----------|
| Star X  | Na I D1 | +3 | 0.17 | 0.04 | ··· | +93 | 0.05 | ··· | ··· | ··· | ··· | ··· | ··· |
|         | Na I D2 | +4 | 0.22 | 0.05 | ··· | +95 | 0.07 | ··· | ··· | ··· | ··· | ··· | ··· |
| Star Y  | Na I D1 | +2 | 0.23 | 0.07 | ··· | +55 | 0.08 | +97 | 0.05 | ··· | ··· | ··· | ··· |
|         | Na I D2 | +1 | 0.29 | 0.06 | ··· | +53 | 0.08 | +94 | 0.05 | ··· | ··· | ··· | ··· |
| Star Z  | Na I D1 | +4 | 0.21 | ··· | +83 | 0.07 | +149 | 0.05 | ··· | +243 | 0.04 |
|         | Na I D2 | +6 | 0.30 | -84 | 0.06 | -158 | 0.05 | ··· | ··· | ··· | ··· | ··· | ··· |

**Fig. 3.** — Spectra covering the Ca II line region for Stars X and Z, the D1 and D2 lines. At Star Z’s estimated distance of 864 \( \pm 30 \) pc, the detection of these many blue and red shifted Na I D1 and D2 absorption features is consistent with a maximum backside remnant distance limit of 760 pc set by Stars X and Y.

A spectrum of Star Z covering the Ca II K line is shown in Figure 3. Although our spectral resolution and S/N at 3934 Å is too low to resolve the expected individual high-velocity interstellar Ca components from the stellar Ca II absorption profile, there are hints of some components along the edges of the profile’s blue and red wings.

4. DISCUSSION

4.1. The Cygnus Loop’s Distance
The combination of the B7 star interacting with the remnant’s northwestern hemisphere and the requirement that both Stars X and Y at 735 pc must lie behind the remnant places additional constrains on the maximum and minimum distances to the Cygnus Loop’s centre of expansion. Measured from its optical emission structure, the remnant is slightly asymmetric corresponding to an ellipse in the distance verses RA plane. Figure 4 shows plots of Gaia distances verses RA for Stars X, Y, Z, plus KPD, and the B7 star. Stars that must lie behind the remnant are shown as blue squares, while the B7 star which must be inside or interacting with the backside of the remnant is shown as a red circle. The projection of the remnant, centred at 20.854 hours RA (J2000: 20:51:14), in distance vs. RA is illustrated in these four plots.

The top left panel of Figure 4 shows that an aspherical remnant at a distance of 725 pc is just barely able to intersect the B7 star at it’s Gaia shortest estimated distance, thereby setting a minimum distance to the Cygnus Loop’s centre at 725 pc. In similar fashion, the top right panel shows that this same 37 pc diameter remnant cannot be centred any farther away than ≃745 pc so as to have Stars X and Y behind the remnant’s rear shell at their maximum Gaia estimated distances.

The fortuitous situation of having two stars, namely Stars X and Y, located behind the remnant’s eastern limb at virtually the same distance (735 pc) suggests the remnant’s rear eastern hemisphere is likely to be close to this 735 pc value. However, no Cygnus Loop distance between the 725 and 745 pc limits discussed above can simultaneously fulfill the requirements that Stars X and Y lie behind a 37 pc diameter remnant at their nominal Gaia 735 pc value while still having the B7 star inside or just touching the remnant’s rear NW shell at its nominal 767 pc distance. This is illustrated in the lower left panel.

A solution is that the Cygnus Loop’s main northern shell containing its brightest nebulae is aspherical and tilted. As shown in the lower right panel of Figure 4, if...
the remnant’s eastern half is tilted toward us then the various stellar distances would be in better agreement; that is, the B7 star could lie inside the remnant’s NW limb while having Stars X and Y behind the remnant’s eastern limb.

If true, this might imply the remnant’s eastern limb expanded more rapidly towards us. Consequently the remnant’s western limb, particularly its northwestern limb, is located farther away. Specifically, an asymmetric remnant with a diameter \( \approx 37 \) pc tilted some 20 degrees allows Stars X and Y to lie behind the remnant’s eastern limb while still having the B7 star within the remnant. A mild asymmetry along our line of sight would be consistent with \textit{Suzaku} and \textit{XMM-Newton} X-ray studies of the remnant (Uchida et al. 2009).

Although larger asymmetries or tilts are possible, the remnant’s fairly circular projected morphology in its main shell of emission suggests large departures from symmetry are unlikely. Thus, adopting an effective maximum tilt of 20 degrees, the plots shown in Figure 5 suggest more realistic distance limits to the remnant. In the left panel, a 35 pc diameter remnant tilted 20 degrees whose east and west limbs match the observed Cygnus Loop’s dimensions cannot be closer than 710 pc and still have the B7 star in physical contact with the remnant. A maximum distance for a 20 degree tilt of 760 pc is shown in the right panel of this figure, where Star Y is at its maximum distance while still lying behind the remnant.

Consequently, from the analyses discussed above, we conclude the centre of the main, northern portion of the Cygnus Loop containing the majority of the remnant’s bright optical nebulae lies at a distance of 735 ± 25 pc with distances between 735 and 745 pc slightly favored based on the B7 star’s nominal 767 pc distance. Interestingly, this distance estimate is only a bit less than the 770 pc value proposed by Minkowski some 60 years ago. At 735 pc, the remnant’s angular diameter of 2.88 degrees corresponds to \( \approx 37 \) pc with an uncertainty of just a few parsecs due to the remnant’s degree of asphericity.

4.2. The Cygnus Loop’s Fundamental Properties

Assuming our distance estimate of 735 pc to the remnant’s centre and its east-west diameter of 37 pc, we list in Table 3 several basic properties of the Cygnus Loop including shock velocities in low density regions, in slightly denser regions where the shock is transitioning from non-radiative Balmer dominated filament emission to radiative, and finally in denser cloud regions. As seen in this table, we find good agreement with spectroscopically inferred shock velocities for the three different density regions using the new distance estimate.

A distance of 735 pc implies a lower SN energy of \( 0.7 \pm 0.2 \times 10^{51} \) erg than the canonical SN explosion energy of \( 1 \sim 2 \times 10^{51} \) erg. This value is similar to earlier estimates of \( E_0 = 3 \sim 7 \times 10^{50} (d_{\text{pc}}/770)^{5/2} \) erg using Minkowski’s distance of 770 pc (Rappaport et al. 1974; Falle & Garlick 1982; Ballet et al. 1984; Miyata & Tsunemi 1999). However, these previous estimates, as well as ours, do not include the remnant’s southern breakout region which would raise the \( E_0 \) value a bit, possibly close to \( 1 \times 10^{51} \) erg (see discussion in §4.4).

4.3. The Remnant’s Environment Driven Morphology

An improved knowledge about the Cygnus Loop’s distance can help our understanding about its local environment and how this has impacted the remnant’s gross morphology and emission structure. Below, we briefly review past conclusions regarding the remnant’s interstellar environment and evolution, specifically its proposed origin as a progenitor wind-blow cavity explosion. We then present multi-wavelength emission maps that offer a new look into the remnant’s interstellar environment as the origin of the remnant’s large-scale structure.

4.3.1. A Historical Prospective

As seen across many wavelengths, the Cygnus Loop’s overall morphology is far from that expected for an expanding sphere in a uniform medium. Its northern portion is dominated by bright and nearly opposing nebulae, NGC 6960 in the west and NGC 6992 & NGC 6995 in the east (see Fig. 1). In addition, there is an extensive
complex of emission filaments along it north-central region (Pickering’s Triangle) with numerous other smaller nebulae and filaments, all surrounded by a nearly complete X-ray emitting and Balmer-dominated shock front shell.

Fainter and much sparser optical, X-ray, and radio emissions extending some 90 arcminutes to the south from the remnant’s nominal centre mark a prominent rupture-like structure best seen in X-rays (Levenson et al. 1997; Aschenbach & Leahy 1999). This “blowout region” exhibits such different radio polarization properties that it has led some to propose it to be a separate SNR (Uyaniker et al. 2002; Sun et al. 2006; West et al. 2016). The idea that the Cygnus Loop is a progenitor cavity explosion goes back to the earliest X-ray studies of the remnant. The discovery by Tucker (1971) that the remnant’s X-ray inferred blast wave velocity was almost three times the velocity of the optical filaments, led McCue & Cowie (1975) to suggest the remnant’s bright optical nebulae are due to dense interstellar clouds recently hit by the blast wave.

This notion was subsequently questioned by McCray & Snow (1979), Charles et al. (1985), and Braun & Strom (1986) who viewed such a scenario as unlikely to have created “such a nicely spherical shell”. They instead suggested that the Cygnus Loop’s shape was the result of a SN explosion taking place in a largely spherical, wind-driven cavity pre-dating the SNR, produced by the SN progenitor itself. There has been considerable support for the Cygnus Loop being a cavity explosion remnant. Spectral X-ray analyses revealed evidence for a high-mass progenitor through observed enrichments of O, Ne, and Mg suggesting ejecta from a ~15 solar mass core-collapse SN. In addition, numerous model investigations have concluded that the remnant’s properties are consistent with a SN explosion inside an interstellar cavity created by the progenitor star (Hester et al. 1994; Graham et al. 1995; Levenson et al. 1998; Leahy 2003; McEntaffer & Brantseg 2011). This difference is now understood as dust destruction by the remnant’s blast wave. Obscuration caused by this cloud is readily apparent on photographic images of NGC 6960 such as those published by Ross (1931). Extinction differences around NGC 6960 have been studied by Chamberlain (1953) and Bok & Warwick (1957), with H I and CO emission maps of the region showing a good correlation with the observed optical obscuration (de Noyer 1975; Scoville et al. 1977). While an analysis of mid-infrared images of the remnant and its local interstellar environment led Arendt et al. (1992) to suggest no direct link between this western cloud and NGC 6960, a study of X-ray and optical emissions along the Cygnus Loop’s western limb led Levenson et al. (1996, 1998) to conclude the remnant was, in fact, directly interacting with this cloud.

Observations revealing an expanding shell of neutral hydrogen along the Cygnus Loop’s northeastern limb led Leahy (2003) to suggest the presence of an interstellar
cloud in this region which was given a small outward velocity by the Cygnus Loop’s progenitor star’s ionizing radiation. A similar analysis was subsequently proposed for the remnant’s southeastern limb (Leahy 2005). In both regions, interstellar clouds were proposed to be immediately adjacent to the remnant.

From a deep optical survey of the remnant’s emission structure, Levenson et al. (1998) concluded the remnant’s brightest optical emissions trace interactions of its blast wave with dense interstellar clumps. They found faint nonradiative, Balmer-dominated shock emission filaments forming a nearly circular and complete shell around the remnant’s northern region with a radius of 1.9 degrees. They argued that the remnant’s bright optical emission arising from radiative shocks are only seen where the blast wave encounters denser inhomogeneities in the local interstellar medium, and it is these interactions which dominate the remnant’s global appearance and evolution.

### 4.3.2. A Multi-wavelength Analysis

In order to investigate the interstellar environment around the Cygnus Loop, we constructed a series of multi-wavelength composite images of its neighboring regions using on-line data archives. These included Planck infrared images (Planck Collaboration et al. 2014), Wide-field Infrared Survey Explorer (WISE) data, ROSAT HRI and PSPC X-ray images, optical survey images including the Digital Sky Survey (DSS2) and the Mellinger survey (Mellinger 2009), and near UV image data from the Galaxy Evolution Explorer (GALEX) (Morrissey et al. 2007).

Figure 6 shows a roughly $12 \times 15$ degree wide composite image of the Milky Way around the Cygnus Loop covering Galactic coordinates $l = 66^\circ$ to $82^\circ$, $b = -2.8^\circ$.

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**Fig. 6.** A wide-angle composite image made from optical Mellinger RGB images, Planck 857 GHz infrared data (gray), GALEX UV images (pink) and ROSAT X-ray images (white) of the Milky Way region around the Cygnus Loop. Galactic coordinates are shown. The remnant’s brightest optical and X-ray emission features can be seen immediately adjacent to local dust clouds.
to $-15.5^\circ$, constructed from Planck 857 GHz, ROSAT PSPC, GALEX UV, and Mellinger images. This composite relates the projected locations of the remnant’s X-ray and optical emissions with interstellar dust clouds.

The image shows that the remnant, located well off the Galactic plane between Galactic latitudes $-6.9^\circ$ to $-9.8^\circ$, is situated in a broad channel largely empty of dust clouds, bounded on its western limb by a large, extended dust cloud stretching roughly from $l = 69^\circ$ to $75^\circ$. Eastern edges of this cloud coincide with the remnant’s bright western and northeastern nebulosities, namely NGC 6960 and Pickering’s Triangle. Smaller, less dense dust clouds near $l = 76^\circ, b = -9^\circ$ appear to coincide with the remnant’s eastern X-ray and optical emissions, namely NGC 6992, NGC 6995, and IC 1340.

Additional composite images showing the interstellar medium around the Cygnus Loop using WISE, GALEX, ROSAT, and Planck data are shown in Figure 7 but now in an equatorial coordinate format. The left panel shows the remnant’s ROSAT X-ray, GALEX UV and WISE infrared emissions in relation to projected locations of infrared emission from dust clouds. Especially notable is the presence of dust clouds along most of the remnant’s western limb. The appearance of the remnant’s emission relative to these clouds gives the impression that the remnant lies on the near side of these clouds. This is supported by the small extension or bulge of remnant’s X-ray emitting shock front to the west of the northern tip of NGC 6960. We also note that the remnant’s seemingly greater expansion to the north coincides with a region relatively free of significant interstellar clouds.

The other multi-wavelength composite shown in the right panel of Figure 7 reveals excellent correlation between the remnant’s bright radiative UV and optical emission nebulae and projected locations of dust clouds. This includes dust clouds all along the remnant’s bright eastern nebulosities, plus a small dust cloud coincident with the remnant’s southeastern emission knot roughly one degree south of NGC 6995 that has been studied by Fesen et al. (1992), Graham et al. (1995), and Levenson & Graham (2001).

Although there is considerable evidence for direct cloud interaction along the Cygnus Loop’s western limb (Levenson et al. 1996), there has not been previously published data pointing to specific dense clouds correlated with the remnant’s other strong X-ray/UV/optical emission features such as Pickering’s Triangle, NGC 6992 or NGC 6995. The locations of the dust clouds seen in Figures 6 and 7 greatly clarifies where and why the remnant looks the way it does across many wavelengths.

Using X-ray data and deep optical images covering the entire remnant, Levenson et al. (1998) attempted to construct a three-dimensional picture of the Cygnus Loop. They concluded that dense clouds and atomic gas together form the walls of a cavity in which the SN occurred. However, the composite images shown in Figures 6 and 7 make it clear that the “cavity” is simply a region relatively free of interstellar clouds.

We agree with Levenson et al.’s suggestion that a large cloud located along the rear of the remnant is responsible for its western limb emission since it is consistent with our distance estimate for the remnant centre vs. that of the B7 star. However, they claim that the cloud that is the cause for the bright northeastern emission is also on the far side, whereas we find evidence for the remnant’s eastern emissions to be closer than emission along the
west and northwestern limbs.

One can test the idea that projected coincidences of these dust clouds do, in fact, signal interactions of the remnant’s shock by using the new distance described above along with reddening versus distance estimates toward these clouds. Figure 8 shows 12 regions for which we obtained reddening values as a function of distance from the three-dimensional maps presented in Green et al. (2015) which utilized Pan-STARRS (Schlafly et al. 2014) and 2MASS (Skrutskie et al. 2006) photometry. Figure 8 also highlights again the projected locations of the Cygnus Loop’s optical and UV bright nebulae relative to interstellar dust clouds and its position inside a broad N-S channel largely empty of interstellar clouds.

Measured $E(B-V)$ values for 450, 550, 650, 750, 850, and 950 pc for the 12 regions marked in Figure 8 are listed in Table 4. The sharp rise of extinction around 650 to 750 pc along the remnant’s western limb (Regions 1-4) is presumably due to the molecular dust cloud the remnant is physically encountering. This rise is consistent with our derived 735±25 pc distance. In like fashion, the reddening measurements to the northwestern clouds (Regions 5 & 6) and the fainter northeastern clouds (Regions 7-9) are also consistent with distances in excess of $\approx$ 550 pc. In contrast, the reddening measurements taken for projected regions toward the centre of remnant (Regions 10-12) show reddening values that only slowly increase with distance out to 950 pc.

It should be noted that these reddening measurements support the view that the B7 star lies inside the remnant as proposed by Fesen et al. (2018). Moreover, since reddening measurements for all 12 locations are found to be relatively low (< 0.13) out to 550 pc, distances to the Cygnus Loop of less than $\approx$ 600 pc are now firmly excluded. Finally, as mentioned above and discussed by Fesen et al. (2018), the presence of some of the remnant’s shock filaments up to 30′ farther to the west of NGC 6960 (see Fig. 4 in Fesen et al. 1992) suggests the remnant lies close to the near side of the western molecular cloud.

Interaction of the remnant’s blast wave with local clouds along its eastern limb appears likely to have occurred relatively recently. Hester et al. (1986) used the presence of optical [O III] line emission behind a Balmer filament along the remnant’s eastern limb to conclude that the remnant’s shock hit a wall of denser gas a few hundred years ago. Shull & Hippelein (1991) cited X-ray emission just outside the remnant’s eastern optical emission filaments to suggest that the cloud was encountered less than 1000 yr ago.

In summary, we find that the long suspected SN progenitor generated cavity walls appear, in fact, to be simply discrete interstellar clouds in the remnant’s vicinity. Rather than invoking a low-density, progenitor wind-driven cavity, we find the remnant to be located in a broad region some eight degrees off the Galactic plane that is relatively free of interstellar clouds.

Specifically, we conclude that the remnant’s gross morphology is due to the supernova’s blast wave encounter-
ing a large molecular cloud off to its west giving rise to NGC 6960, smaller discrete clouds off to the east and northeast resulting in NGC 6992, NGC 6995, and IC 1340, and relatively dense clouds to the northwest resulting in Pickering’s Triangle and neighboring nebulae. Although X-ray abundance data suggests the Cygnus Loop is the remnant of a high-mass progenitor star, there is no need to propose a wind-driven cavity to explain the Loop is the remnant of a high-mass progenitor star, there

Although X-ray abundance data suggests the Cygnus Loop is the remnant of a high-mass progenitor star, there

The location of this secondary blowout roughly coincides with a break in the southern extent of the western molecular cloud (see Fig. 7) suggesting the blowout is at the same distance as the Cygnus Loop.

Also as can be seen in Figure 9, there is a large secondary blowout off the western side of the main blowout. The location of this secondary blowout roughly coincides with a break in the southern extent of the western molecular cloud (see Fig. 7) suggesting the blowout is at the same distance as the Cygnus Loop.

Consequently, we find no morphological evidence to support a second SNR scenario. This conclusion is strengthened by the lack of X-ray emission at a presumed interface region where two separate SNRs would be interacting. Thus we conclude, as did Ku et al. (1984), that the southern blowout is simply the result of the remnant’s shock front encountering a low density interstellar region.

5. CONCLUSIONS

While the Cygnus Loop is among the best studied Galactic supernova remnants, its distance has long been uncertain. Here we present the first detections of high-velocity interstellar absorptions of Na I and Ca II seen in the spectra of stars with projected locations within the remnant’s boundary. These detections, along with the recent discovery of a B7 star, BD+31 4224, lying either inside and/or interacting directly with the remnant’s expanding blast wave along the Cygnus Loop’s northwestern limb (Fesen et al. 2018), are used to set the most robust distance estimate to the remnant. Our findings are summarized below.

1) Moderate-dispersion spectra of three stars with projected locations toward the remnant reveal the first de-
2) We estimate the centre of the Cygnus Loop lies at a distance of $735 \pm 25$ pc based on the detection of high-velocity Na I absorptions in these three background stars, combined with the distance to the B7 star interacting with the remnant’s shock. We further find that the remnant is likely aspherical in shape, with its eastern limb nearer to us than its northwestern limb, with a diameter $\simeq 37$ pc.

3) Using our new estimated distance for the Cygnus Loop, we calculate several fundamental physical properties of the remnant which are in good agreement with inferred values reported from numerous previous studies (Table 3).

4) From inspection of multi-wavelength composite images, we find the Cygnus Loop’s morphology to be the result of its location far off the Galactic plane in a relatively low-density region in between local interstellar clouds. The interaction of the remnant’s blast wave with these clouds explains the locations of all its major optical and UV emission nebulae. Consequently, we propose that the Cygnus Loop is not a remnant inside a progenitor wind-driven, low-density cavity but rather lies in an extended, low-density region in between a dense molecular cloud to its west and northwest, with smaller clouds to its east and northeast.

5) These composite images along with deep H$\alpha$ images show no evidence supporting the notion that the Cygnus Loop’s southern blowout region is a separate SNR. Instead, the blowout is just what it appears to be: a blowout of the Cygnus Loop’s blast wave toward a low-density region largely absent of interstellar clouds.

Finally, we note the star, TYC 2688-2556-1, identified by Boubert et al. (2017) as a possible runaway former companion of the Cygnus Loop’s progenitor at estimated distances around 430 pc (Gaia DR2) is unlikely if our estimate of $\simeq 735$ pc is correct. Likewise, the pulsar wind nebula candidate discovered by Katsuda et al. (2012) in the remnant’s southern blowout region, if physically related to the Cygnus Loop, would require a transverse velocity in excess of 1200 km s$^{-1}$, quite high but still lower than their estimate of 1850 km s$^{-1}$ assuming a distance of 540 pc and an age of 10,000 yr.

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