Infrared Photometric Properties of 709 Candidate Stellar Bowshock Nebulae

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Abstract

Arcuate infrared nebulae are ubiquitous throughout the Galactic Plane and are candidates for partial shells, bubbles, or bowshocks produced by massive runaway stars. We tabulate infrared photometry for 709 such objects using images from the Spitzer Space Telescope, the Wide-field Infrared Explorer, and the Herschel Space Observatory (HSO). Of the 709 objects identified at 24 or 22 μm, 422 are detected at the HSO 70 μm bandpass. Of these, only 39 are detected at HSO 160 μm. The 70 μm peak surface brightnesses are 0.5–2.5 Jy arcmin−2. Color temperatures calculated from the 24 to 70 μm ratios range from 80 to 400 K. Color temperatures from 70 to 160 μm ratios are systematically lower, 40–200 K. Both of these temperature are, on average, 75% higher than the nominal temperatures derived by assuming that dust is in steady-state radiative equilibrium. This may be evidence of stellar wind bowshocks sweeping up and heating—possibly fragmenting but not destroying—interstellar dust. Infrared luminosity correlates with standoff distance, R0, as predicted by published hydrodynamical models. Infrared spectral energy distributions are consistent with interstellar dust exposed to either single radiant energy density, \( U = 10^3–10^7 \) (in more than half of the objects) or a range of radiant energy densities \( U_{\text{min}} = 25 \) to \( U_{\text{max}} = 10^3–10^9 \) times the mean interstellar value for the remainder. Hence, the central OB stars dominate the energetics, making these enticing laboratories for testing dust models in constrained radiation environments. The spectral energy densities are consistent with polycyclic aromatic hydrocarbon fractions \( q_{\text{PAH}} \lesssim 1\% \) in most objects.

Key words: catalogs – HII regions – ISM: bubbles – stars: massive – surveys

Supporting material: machine-readable tables

1. Introduction

Infrared nebulae exhibiting distinctive circular, elliptical, or arc-like morphologies reveal a host of astrophysical phenomena that sculpt the Galactic interstellar medium. Massive stars or star clusters may blow wind- and photon-driven bubbles (Castor et al. 1975; Weaver et al. 1977), which may grow to galactic scales if injected with sufficient energy (Heiles 1979; Mac Low & McCray 1988). Individual massive stars or evolved stars ejecting may carve smaller bubbles on \(<a \) few parsec scales. Churchwell et al. (2006, 2007) compiled a catalog of nearly 600 interstellar bubbles discovered in mid-infrared 3.6–8.0 μm images of the Galactic Plane obtained during the Spitzer Space Telescope (SST) Galactic Legacy Infrared MidPlane Survey Extraordinary program (GLIMPSE; Benjamin et al. 2003; Churchwell et al. 2009) conducted with the Infrared Array Camera (IRAC; Fazio et al. 2004). Worldwide volunteers identified hundreds more using these images as part of the Zooniverse Milky Way Project (Simpson et al. 2012) citizen science project. This wealth of identifications has led to the discovery of new star clusters and evolved stars, and to a better understanding of the structure and evolution of the Milky Way. Bubbles may develop an asymmetric, elliptical, or arcuate appearance in the presence of a density gradient in the ambient medium or a relative motion between the energy source and interstellar matter (ISM); in the latter case, a stellar bowshock nebula is formed (Wilkin 1996, 2000).

Infrared nebulae with arcuate morphologies may reveal the presence of a high-velocity massive star when the \( >1000 \) km s\(^{-1}\) stellar wind shocks the ambient ISM, generating a distinctive bowshock feature. Gull & Sofia (1979) studied the bowshock (first seen in H\( \alpha \)) preceding the high-velocity O9.2IV star ζ Oph. Brown & Bomans (2005) discovered eight H\( \alpha \) bowshocks using modern H\( \alpha \) sky surveys. However, H\( \alpha \), X-ray, and radio free–free emission are expected to be several orders of magnitude fainter than the far-infrared dust emission, making the latter the most observable bowshock signature (Meyer et al. 2014, 2016). van Buren & McCray (1988) and van Buren et al. (1995) cataloged dozens of far-infrared bright bowshocks associated with known massive and high-proper-motion stars thought to be “runaways” (Blauw 1961). Deliberate searches for bowshock nebulae preceding high-velocity stars yielded a few dozen more candidates (e.g., Gvaramadze & Bomans 2008; Kobulnicky et al. 2010; Peri et al. 2012; Gvaramadze et al. 2013; Sexton et al. 2015). Hypervelocity stars (Hills 1988; Kenyon et al. 2008) populate the extreme end of the runaway spectrum, but such objects may not support bowshocks (Brown et al. 2005; Meyer et al. 2014). Bowshocks have also been associated with high-mass X-ray binaries (Gvaramadze et al. 2011), pulsars (Wang et al. 2013), red (Noriega-Crespo et al. 1997; Gvaramadze et al. 2014a) and blue (Gvaramadze et al. 2014b) supergiants, and the A-type star δ Vel (Gáspár et al. 2008). Thus, arcuate nebulae appear to be associated with different types of systems and different physical phenomena. Peri et al. (2012, 2015) concluded that only 10%–15% of high-proper-motion massive stars showed evidence of bowshocks in Wide Field Infrared Explorer (WISE; Wright et al. 2010) mid-infrared images. The accumulating evidence suggests that early-type stars and high space velocities are neither necessary nor sufficient conditions for the formation of prominent bowshocks at infrared wavelengths. Huthoff & Kaper (2002) compared the velocities and ambient interstellar densities of OB stars producing...
bowshocks and those lacking bowshocks, concluding that interstellar density plays a larger role than space velocity or stellar spectral type in creating an observable nebula. This conclusion is supported by hydrodynamical simulations of Comeron & Kaper (1998) and Meyer et al. (2016), who explored how a range of stellar and ISM properties combine to produce a variety of bowshock morphologies or no visible nebula at all. Mildly supersonic space velocities, strong stellar winds, and high ambient interstellar densities $n > 0.1 \text{ cm}^{-3}$ result in the most pronounced bowshock nebulae.

Kobulnicky et al. (2016) conducted a extensive visual examination covering hundreds of square degrees within the infrared Galactic Plane surveys made by the $SST$ GLIMPSE and MIPS/AL (Carey et al. 2008) programs and other wide-area $SST$ programs, including the Spitzer Legacy Survey of the Cygnus-X Complex (Beerer et al. 2010) and the Spitzer Mapping of the Outer Galaxy (SMOG; Carey et al. 2008). Data from the four-band all-sky $WISE$ survey within several degrees of the Plane were also used to cover portions not observed by $SST$. They tabulated 709 arcuate nebulae discovered either at the $SST$ 24 $\mu$m or $WISE$ 22 $\mu$m bandpasses along with positional and photometric data on the central prominent star located along the symmetry axis of each object. Figure 2 of Kobulnicky et al. (2016) plots the spatial distribution of the objects along the Galactic Plane. In about 15%–25% of the objects, the nebulae were located within or pointed toward a nearby H II region, leading the authors to designate a class of “in situ” bowshock candidates following Povich et al. (2008), where a localized flow of ambient material impinges upon an otherwise low-velocity massive star. Chick et al. (2017) obtained optical spectra for ~60 of the central stars and found that 85% were O- or early-B type stars, strengthening the evidence that these nebulae are frequently bowshocks associated with hot stars and likely constitute genuine bowshocks.

In this contribution we present aperture photometry and spectral energy distributions (SEDs) for the 709 bowshock candidates cataloged by Kobulnicky et al. (2016). Their infrared SEDs and derived dust temperatures provide insight regarding the heating mechanisms of the nebulae (i.e., shocks versus radiative heating). SEDs can also be used to infer the dust grain size distribution and presence or absence of polycyclic aromatic hydrocarbons (PAHs). Section 2 describes the photometry procedure employed to measure fluxes from the 3.6 $\mu$m $SST$ or 3.4 $\mu$m $WISE$ bandpasses through the Herschel Space Observatory (HSO) Photoconductor Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) 70 and 160 $\mu$m bands. This section includes two tables containing the photometric measurements available in machine-readable format. Section 3 presents an analysis of the photometric properties, infrared colors, and inferred dust temperatures. Section 4 presents an analysis of SEDs in comparison to interstellar dust models. Section 5 compare the sizes and luminosities of the nebulae published by hydrodynamical simulations of bowshock nebulae, yielding some inferences concerning the densities of the ambient interstellar medium.

2. Aperture Photometry

Data sets for aperture photometry of 709 infrared nebulae included the $SST$ 3.6, 4.5, 5.8, and 8.0 $\mu$m (i.e., the IRAC I1, I2, I3, I4 bands) mosaics and 24 $\mu$m Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) produced by the GLIMPSE team covering the GLIMPSE, MIPS/AL, SMOG, and Cyg-X survey regions. The telescope beam size at these bands is 1".66, 1".72, 1".88, 1".98 and 6" FWHM, respectively.5 For targets in the second and third Galactic quadrants not covered by $SST$ programs, we use the all-sky $WISE$ atlas images at 3.4, 4.6, 12, and 22 $\mu$m (i.e., W1, W2, W3, and W4 bands), which have beam sizes of 671.

5 http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook, http://irsa.ipac.caltech.edu/data/SPITZER/docs/mips/mipsinstrumenthandbook
For each object we drew a crescent-shaped polygon encompassing the extent of the infrared nebula as seen in the SST 24 \(\mu\)m images or WISE 22 \(\mu\)m images, as these were the bandpasses used to first identify the candidate bowshocks. In just a few cases, SST 24 \(\mu\)m data were not available in regions nominally covered by IRAC and MIPS. In these cases, we substituted WISE 22 \(\mu\)m photometry. These exceptions are G018.2660−00.2988, G284.0765−00.4323, G287.4071−00.3593, G287.6131−01.1302, G287.6736−01.0093, and G288.1505−00.5059. In seven cases (G015.0749−00.6461, G015.0812−00.6570, and G015.1032−00.6489 in the M17 region, and G284.2999−00.3359, G284.3011−00.3712, and G284.3400−00.2827 in the Westerlund 2/RCW49 region, and G287.4389−00.6132) the angular size of the object was too small and the background levels too high to carry out meaningful photometric measurements. Otherwise, apertures were drawn to avoid the bright central stars that are typically prominent at wavelengths \(<8\ \mu\)m and are occasionally detected at longer wavelengths. We also measured the approximate angular height, \(H\), and radius, \(R\), of each nebula as an indication of its aspect ratio. Figure 1 shows a three-color image of the G026.1473−0.0420 object (object 123 from the catalog of Kobulnicky et al. 2016) with the source polygon outlined in green along with angular height and radius markers overlaid in white. Blue, green, and red depict the 24, 70, and 160 \(\mu\)m data from SST, HSO, and HSO, respectively. This object shows good morphological similarity at all three pictured wavebands, but is most prominent at 24 and 70 \(\mu\)m (blue and green). The complexity of the field surrounding the source and the adjoining bright (unrelated?) 160 \(\mu\)m emission to the lower left of the source illustrates the difficulty of determining appropriate source and background regions within the Galactic Plane. Figure 2 depicts another “typical” object, G026.5272+0.3808, using the same color scheme as Figure 1, but without the marker overlays. This source is detected at 24 and 70 \(\mu\)m, which show excellent morphological agreement, but it is not detected at 160 \(\mu\)m. A photometric measurement was deemed a detection only if the morphology at a given bandpass showed a close resemblance to that at 24 \(\mu\)m. In many cases, this was a judgment call on the part of the lead author, as the Galactic Plane exhibits a variety of unrelated structures, especially at 160 \(\mu\)m, where fields are heavily mixed with foreground and/or background emission. Defining the shape and extent of the polygonal aperture is unavoidably a subjective process because the nebulae often lie in regions of high, structured background emission that overlap the foreground. In many cases, this was a judgment call on the part of the lead author, as the Galactic Plane exhibits a variety of unrelated structures, especially at 160 \(\mu\)m, where fields are heavily mixed with foreground and/or background emission. Defining the shape and extent of the polygonal aperture is unavoidably a subjective process because the nebulae often lie in regions of high, structured background emission that overlap the

\[\text{http://irsa.ipac.caltech.edu/frontpage/}\]

\[\text{http://irsa.ipac.caltech.edu/data/SPITZER/docs/mips/instrumenthandbook/}\]

\[\text{http://wise2.ipac.caltech.edu/docs/release/allsky}\]

\[\text{http://ds9.si.edu/site/Home.html}\]

\[\text{HISO atlas images are in Jy \text{pixel}^{-1}}\] so no conversion after summation is needed. SST images are in \(\text{M}\)\text{Jy sr}^{-1} so the conversion factor is \(10^4\ \text{Jy M}\text{Jy}^{-1} \times 206265^2 \text{sr arcsec}^{-2} \times S \text{arcsec}^{-2} \text{pixel}^{-1}\), where \(S\) is the pixel size in arcseconds appropriate to each mosaicked image. either 1\(\prime\)2 or 2\(\prime\)4. For WISE the conversion from the native units of DN to Jy is specific to each band, as given in the header of WISE atlas images; the conversions used here are 1.935 \times 10^{-10}, 2.705 \times 10^{-10}, 2.905 \times 10^{-10}, and 5.227 \times 10^{-10} for bands W1, W2, W3, and W4, respectively.

\[\text{http://irsa.ipac.caltech.edu/allsky/}\]
Table 1

| ID   | Name           | R.A. (2000) | Decl. (2000) | Radius (arcsec) | Height (arcsec) | $F_{70}$ (Jy) | $F_{24}$ (Jy) | $F_{160}$ (Jy) | Peak$_{70}$ (Jy arcmin$^{-2}$) | $T_{24/70}$ (K) | $T_{70/160}$ (K) |
|------|----------------|-------------|--------------|-----------------|-----------------|---------------|---------------|-----------------|----------------------|----------------|----------------|
| 1    | G000.1169−00.5703 | 17 48 07.70 | −29 07 55.5  | 38              | 44              | −0.074        | −0.150        | −0.086          | 8.730                 | 28.300         | −22.000        | 126.5 | 92 | −99 |
| 2    | G000.3100−01.0495 | 17 50 27.59 | −29 12 46.8  | 16              | 25              | −0.258        | −0.149        | −0.114          | 0.041                 | 0.453          | 0.450          | 24.6  | 132| −99 |
| 3    | G001.0563−00.1499 | 17 48 41.78 | −28 06 37.8  | 13              | 21              | −0.139        | −0.120        | −0.230          | 0.710                 | 13.305         | 39.000         | 372.6 | 95 | −99 |
| 4    | G001.2588−00.0780 | 17 48 53.40 | −25 53 59.7  | 17              | 19              | −0.065        | −0.375        | −0.062          | 0.108                 | 1.023          | 3.910          | 355.0 | 89 | −99 |
| 5    | G003.5118−00.0470 | 17 53 56.10 | −25 56 50.3  | 12              | 23              | −0.055        | −0.038        | −0.020          | 0.010                 | 0.273          | −0.400         | −99.9  | −99| −99 |
| 6    | G003.7391+00.1425 | 17 53 43.26 | −25 39 19.2  | 11              | 17              | −0.086        | −0.061        | −0.059          | 0.025                 | 0.370          | 1.300          | −6.400 | 56.2| 90 | −99 |
| 7    | G003.8417−01.0440 | 17 58 30.64 | −26 09 49.1  | 13              | 13              | 0.103         | 0.106         | 0.496           | 1.311                 | 0.830          | 21.700         | 179.3  | 61 | 80 |
| 8    | G004.3087+00.2222 | 17 54 41.61 | −25 07 25.6  | 10              | 12              | −0.083        | −0.250        | −0.056          | 0.093                 | 0.609          | 4.700          | 2.400  | 59.8| 76 | 77 |
| 9    | G004.7315−00.3875 | 17 57 57.62 | −25 03 53.6  | 9               | 10              | −0.017        | −0.015        | −0.017          | 0.015                 | 0.391          | 3.300          | −4.800 | 45.7| 75 | −99 |
| 10   | G004.8449−00.9309 | 18 00 17.51 | −25 14 47.7  | 9               | 13              | −0.195        | −0.114        | −0.079          | 0.054                 | 0.259          | −0.100         | −2.300 | −99.9| −99| −99 |
| 11   | G005.5941+00.7335 | 17 55 36.25 | −25 45 21.8  | 9               | 11              | −0.116        | −0.076        | −0.032          | 0.086                 | 0.758          | 0.500          | −0.200 | 14.1| 158| −99 |
| 12   | G005.6985−00.6550 | 18 01 06.15 | −24 21 34.4  | 16              | 19              | −0.048        | −0.030        | −0.052          | −0.116                | 1.795          | −1.100         | −3.300 | −99.9| −99| −99 |
| 13   | G006.2977−00.2012 | 18 00 40.59 | −23 36 50.7  | 17              | 15              | −0.089        | −0.064        | −0.029          | 0.060                 | 1.065          | 7.500          | −1.100 | 123.0| 77 | −99 |
| 14   | G006.3600−00.1846 | 18 00 44.92 | −23 33 06.3  | 7               | 10              | −0.034        | −0.188        | −0.024          | −0.054                | 0.318          | −5.700         | −1.000 | −99.9| −99| −99 |
| 15   | G006.8933+00.0743 | 18 00 55.27 | −22 57 36.9  | 14              | 12              | −0.080        | −0.053        | −0.101          | −0.122                | 2.274          | 7.100          | −1.000 | 80.8 | 93 | −99 |
| 16   | G007.5265−00.2652 | 18 03 33.49 | −22 34 38.3  | 4               | 6               | −0.109        | −0.072        | −0.024          | −0.019                | 0.266          | −0.400         | −1.300 | −99.9| −99| −99 |
| 17   | G008.3690+00.0239 | 18 04 15.53 | −21 42 05.7  | 23              | 16              | −0.164        | −0.131        | −0.131          | 0.189                 | 3.254          | 1.800          | −6.400 | 112.5| 172| −99 |
| 18   | G009.0177+00.1410 | 18 05 11.21 | −21 04 43.3  | 15              | 17              | −0.052        | −0.033        | −0.030          | −0.005                | 0.226          | −0.330         | −2.000 | −99.9| −99| −99 |
| 19   | G009.6852−00.2025 | 18 07 51.86 | −20 39 48.8  | 7               | 10              | −0.026        | −0.017        | −0.010          | −0.027                | 0.111          | −0.070         | −0.700  | −99.9| −99| −99 |
| 20   | G010.1395−00.0350 | 18 08 10.89 | −20 11 06.4  | 21              | 17              | −0.038        | 0.033         | 0.157           | −0.496                | 1.137          | 3.700          | −1.900 | 84.4 | 92 | −99 |

Note. Typical flux uncertainties are 25% in each band. Negative flux values indicate non-detections with 1σ upper limits given by $-1\times$ the listed value. (1) ID from Kobulnicky et al. (2016); (2) generic identifier by galactic coordinates; (3) right ascension; (4) declination; (5) nebula angular radius in arcsec; (6) nebula angular height in arcsec; (7)−(11) flux in Jy at SST 3.6/4.5/5.8/8.0/24 μm bands; (12) and (13) flux in Jy at HSO 70/160 μm bands; (14) peak surface brightness above local background at 70 μm in Jy arcmin$^{-2}$; (15) and (16) color temperature derived from the 24/70 μm and 70/160 μm measurements, respectively.

(This table is available in its entirety in machine-readable form.)
Table 2  
WISE and HSO Photometry of Candidate-bowshock Nebulae

| ID   | Name          | R.A. (2000) | Decl. (2000) | Radius (arcsec) | Height (arcsec) | \( F_{14} \) (Jy) | \( F_{22} \) (Jy) | \( F_{24} \) (Jy) | \( F_{70} \) (Jy) | \( F_{160} \) (Jy) | Peak\( _{70} \) (Jy arcsec\(^{-2} \)) | \( T_{22/70} \) (K) | \( T_{70/160} \) (K) |
|------|---------------|-------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|----------------------------|-----------------|-----------------|
| 13   | G006.2812+23.5877 | 16 37 09.54 | −10 34 01.5  | 173             | 404             | 6.250           | 7.995           | 51.320          | 343.77         | 246.700         | 61.550                  | 9.8             | 158             |
| 39   | G013.4900+01.6618 | 18 08 46.51 | −16 25 56.9  | 108             | 92              | −0.675          | −0.677          | 3.406           | 21.43          | −99.999         | −99.999                  | −99.9           | −99             |
| 54   | G015.0813−00.6570 | 18 05 58.84 | −14 11 53.0  | 101             | 91              | −0.113          | −0.472          | 3.298           | 28.89          | −99.999         | −99.999                  | −99.9           | −99             |
| 64   | G016.8993−01.1152 | 18 25 38.90 | −14 45 05.7  | 53              | 39              | −0.265          | −0.403          | 4.194           | 20.76          | −99.999         | −99.999                  | −99.9           | −99             |
| 66   | G016.9848+01.7482 | 18 15 23.97 | −13 19 35.3  | 102             | 127             | 0.368           | 0.509           | 9.384           | 52.45          | −99.999         | −99.999                  | −99.9           | −99             |
| 154  | G031.1096+03.6457 | 18 35 08.21 | +00 02 34.8  | 30              | 28              | 0.053           | 0.048           | 0.184           | 0.79           | −99.999         | −99.999                  | −99.9           | −99             |
| 240  | G045.9397+03.2506 | 19 03 40.72 | +13 03 11.5  | 17              | 18              | −0.010          | −0.005          | −0.005          | 0.01           | −99.999         | −99.999                  | −99.9           | −99             |
| 272  | G050.9339+03.0747 | 19 13 48.34 | +17 24 15.5  | 16              | 21              | −0.008          | −0.004          | −0.005          | 0.03           | −99.999         | −99.999                  | −99.9           | −99             |
| 298  | G059.9225−01.9671 | 19 51 08.28 | +22 49 53.9  | 13              | 13              | 0.024           | 0.020           | 0.037           | 0.14           | −99.999         | −99.999                  | −99.9           | −99             |
| 310  | G061.8355+02.9452 | 19 36 31.44 | +26 56 30.2  | 25              | 25              | −0.015          | −0.008          | −0.001          | 0.06           | −99.999         | −99.999                  | −99.9           | −99             |
| 313  | G063.5153−01.4433 | 19 57 17.76 | +26 10 49.2  | 13              | 23              | −0.007          | −0.004          | 0.035           | 0.02           | −99.999         | −99.999                  | −99.9           | −99             |
| 315  | G064.0602+01.6348 | 19 46 39.32 | −28 13 23.2  | 35              | 73              | −0.077          | −0.009          | −0.007          | 0.25           | −99.999         | −99.999                  | −99.9           | −99             |
| 316  | G064.7582+00.2889 | 19 53 30.15 | +28 08 20.1  | 8               | 10              | −0.001          | −0.003          | −0.008          | 0.06           | −99.999         | −99.999                  | −99.9           | −99             |
| 317  | G067.1370−00.6744 | 20 02 57.58 | +29 39 49.9  | 29              | 24              | −0.008          | −0.005          | 0.031           | 0.03           | −99.999         | −99.999                  | −99.9           | −99             |
| 318  | G073.2946−01.6939 | 20 22 56.66 | +34 14 20.3  | 21              | 19              | −0.001          | −0.002          | 0.016           | 0.01           | −99.999         | −99.999                  | −99.9           | −99             |
| 319  | G073.3536+02.5872 | 20 05 38.06 | +36 39 37.3  | 5               | 151             | −0.002          | −0.002          | −0.020          | 0.13           | −99.999         | −99.999                  | −99.9           | −99             |
| 320  | G073.6200+01.8522 | 20 09 25.91 | +36 29 19.1  | 37              | 24              | −0.056          | −0.065          | 0.089           | 2.98           | 6.480          | −2.610                  | 7.0             | 110             |
| 321  | G074.1929+00.9964 | 20 14 33.30 | +36 29 48.6  | 8               | 9               | −0.001          | −0.020          | 0.021           | 0.12           | −99.999         | −99.999                  | −99.9           | −99             |
| 322  | G074.3117+01.0041 | 20 14 51.09 | +36 35 59.7  | 21              | 25              | −0.002          | −0.001          | 0.020           | 0.51           | 1.600          | −1.020                  | 3.5             | 100             |
| 323  | G075.1730−00.5064 | 20 23 50.71 | +36 24 26.4  | 13              | 7               | 0.023           | 0.031           | 0.155           | 0.89           | −99.999         | −99.999                  | −99.9           | −99             |

Note. Typical flux uncertainties are 25% in each band. Negative flux values indicate non-detections with \( 1\sigma \) upper limits given by \( -1 \times \) the listed value. (1) ID from Kobulnicky et al. (2016); (2) generic identifier by galactic coordinates; (3) right ascension; (4) declination; (5) nebula angular radius in arcsec; (6) nebula angular height in arcsec; (7)-(10) flux in Jy at WISE 3.4/4.6/12/22 \( \mu \)m bands; (11) and (12) flux in Jy at HSO 70/160 \( \mu \)m bands; (13) peak surface brightness above local background at 70 \( \mu \)m in Jy arcmin\(^{-2} \); (14) and (15) color temperature derived from the 22/70 \( \mu \)m and 70/160 \( \mu \)m measurements, respectively.

(This table is available in its entirety in machine-readable form.)
fluxes tabulated here can be regarded as 25% low, on average, but the fraction will vary with the size of aperture used. Use of larger apertures was deemed inappropriate because of the increasing errors introduced by inclusion of unrelated background and foreground emission.

Figure 3 displays the ratio of nebula radius to height (i.e., the aspect ratios) versus height. A small random Gaussian offset with $\sigma = 1$ arcsec has been added to each point to prevent overlap of data points at common integer values. Heights range from $3''$ in the most compact cases to over $200''$ (off scale). Average radius-to-height ratios near unity indicate that most objects are approximately circular, but values range from 0.5 to 2.0. These ratios are consistent with the nebulae being either partial bubbles, partial elongated bubbles, or bowshocks, which would be morphologically indistinguishable from partial non-circular bubbles except under the most favorable signal-to-noise ratios and dynamic range of the image. Additional data, such as infrared SEDs, would allow a bowshock to be distinguished from a bubble, given that the latter usually display bright PAH emission in the $SST$ 8 $\mu$m or WISE 12 $\mu$m bandpasses where soft UV radiation from a central star excites large molecules in a surrounding molecular cloud (e.g., Churchwell et al. 2006).

The columns of Table 1 record the identification number for each object (1) using the numeration of Kobulnicky et al. (2016), its generic designation in galactic coordinates (2), the right ascension (3) and declination (4) of the nominal central star given by Kobulnicky et al. (2016), measured radius (5) and height (6) in arcseconds, as illustrated in Figure 1, fluxes in Jy in the $SST$ 3.6, 4.5, 5.8, 8.0, and 24 $\mu$m bandpasses (columns 7–11), the fluxes in Jy in the $HSO$ 70 and 160 $\mu$m bandpasses (12, 13), and the peak 70 $\mu$m surface brightness above background levels in Jy arcmin$^{-2}$ (14). A value of $-99.999$ indicates that no measurement was available because either the source was not covered by the survey at this bandpass, or because in a few cases, the angular size of the source is smaller than a few arcseconds and is too small for measurement. A $-99.9$ in column 14 giving the peak surface brightness indicates that the source is not detected in the $HSO$ 70 $\mu$m bandpass. Negative values for fluxes designate $-1$ times the approximate $1\sigma$ upper limits for non-detections. Column 15 gives the calculated color temperature as derived from the 24 $\mu$m $SST$ and 70 $\mu$m $HSO$ photometric measurements. Column 16 gives the calculated color temperature as derived from the 70 $\mu$m and 160 $\mu$m $HSO$ photometric measurements. The first 20 lines of Table 1 appear in the journal article to provide guidance as to its form and content. The entire contents are available in the electronic edition as a machine-readable table. Table 2 records the same information as Table 1, but for the objects having four-band WISE photometry instead of five-band $SST$ photometry. The first 20 lines of Table 2 appear in the journal article to provide guidance as to its form and content. The entire contents are online available as a machine-readable table.

Table 3 presents a summary of the detection frequencies for each bandpass for the objects having $SST$ and $HSO$ photometry. The first column of the top row indicates that 617 objects are identified as candidate bowshock nebulae on the basis of

9 Objects detected in the $SST$ surveys are, of course, covered by the WISE all-sky survey as well, but $SST$ data are used preferentially, if available, owing to the smaller beam size.
SST 24 \( \mu m \) detections. The second column of the top row indicates that 399 of these also have detections at the HSO 70 \( \mu m \) bandpass. The last column of the top row indicates that only 35 of these 339 are further detected in the HSO 160 \( \mu m \) bandpass. A detection at 160 \( \mu m \) always implies a detection at 70 \( \mu m \). The second row reports detections at the SST 8.0 \( \mu m \) bandpass in conjunction with detections at longer wavelengths. The number 106 in the first column is the number of objects detected at both 24 and 8.0 \( \mu m \). The number 90 in the second column is the number that are further detected at 70 \( \mu m \). The final column shows that only 20 objects are detected at 8.0 \( \mu m \) and all three longer wavelengths. The bottom row of Table 3 reports the number of objects detected at 3.6 \( \mu m \) and successively longer wavelengths. Thirty-two objects are detected at 3.6 \( \mu m \) and at all longer SST wavelengths. Only 26 have detections at 3.6 \( \mu m \)

10 All but 7 of the 709 Kobulnicky et al. (2016) objects are detected at either SST 24 \( \mu m \) or WISE 22 \( \mu m \). Exceptions are numbers 51, 52, 53—in the M17 star-forming region—400, 401, 402—in the RCW 49 star-forming region—and 408—in the Carina star-forming region—which are identified on the basis of SST 8.0 \( \mu m \) or shorter wavelength images.

Figure 6. Three-color 160/70/24 (or 22) \( \mu m \) images in red, green, and blue, respectively, of four nebulae: the canonical runaway star and bow-shock nebula \( \zeta \) Oph (upper left), BD+43 3654 (upper right), G045.1952+00.7420 (lower left), and G331.6579+00.1308 (lower right).
through 70 μm, and only 8 are detected at all bandpasses from 3.6 μm through 160 μm.

Table 4 reports detection frequencies for objects measured in the WISE and HSO survey images. The first column of the top row (85) designates the number of catalog objects detected exclusively in the WISE 22 μm data. The second and third columns give the number of objects further detected at 70 μm and 160 μm (23 and 4, respectively). The middle row lists the number of objects detected at the WISE 12 μm bandpass, and successively longer wavelengths. A detection at 22 μm is almost always accompanied by a detection in the 12 μm bandpass, which includes both PAH and hot dust contributions. The bottom row gives the number of detections at the WISE 3.4 μm bandpass along longer wavelengths. Only 12 objects are detected at 3.4 μm through 22 μm; 2 of these have 70 μm detections, and only 1 has a 160 μm detection.

3. Infrared Color Analysis

Photometric measurements at two or three bandpasses—available for the majority of this sample—enable calculation of the infrared colors and color temperatures. We undertake this type of analysis first in Section 3.1 as a means of characterizing the ensemble properties of a large number of bowshock nebula candidates. For objects where the temperature, radius, and distance of the central illuminating star is known, more sophisticated types of analyses are possible. These include comparisons of the expected steady-state dust temperatures and radiant energy densities in the nebulae to the temperatures and energy densities implied by fitting interstellar dust models to the SEDs. We evaluate these additional diagnostics in Sections 3.2 and 3.3 for a subsample of 20 nebulae having well-characterized central stars.

3.1. IR Colors

Ratios of infrared fluxes provide constraints on the properties of the emitting material, including dust temperatures. Figure 4 shows a color–color diagram for the 115 nebulae detected at the HSO 70 μm band and SST 24 and 8 μm (upward pointing triangles; 92 objects) or WISE 22 and 12 μm (downward pointing triangles; 23 objects). SST and WISE objects exhibit a high degree of overlap, together forming a band that stretches from the upper left (high 70/24 μm and low 24/8 μm ratios) to the lower right (low 70/24 μm and high 24/8 μm ratios). The WISE targets lie preferentially in the upper half of the SST objects. The solid curve illustrates the colors of a blackbody denoted by filled circles every 25 K from 75 K at the upper right to 400 K at the lower left. The dashed curve illustrates the colors of a modified blackbody (Sν ∝ ν^βBν(T)) with β = 1 over the same range. That the distribution of points runs orthogonal to the blackbody curves is an indication that the objects are not well characterized as single-temperature dust in the majority of cases. If anything, the modified blackbody shows poorer agreement with the data than the simple blackbody. A star and diamond denote the colors of the canonical bowshock nebulae associated with the runaway stars ζ Oph and BD+43 3654. A hexagon and octagon denote colors of G045.1952+00.7420 and G331.6579+00.1308, as indicative of other bright objects in our sample. Typical photometric uncertainties are about 0.2 dex on each axis. Most of the points lie to the upper left of the blackbody curve, indicating that their color temperatures inferred from the F_70/F_24 ratios are considerably cooler than those indicated by the F_24/F_8 (or F_22/F_12) ratios. This discrepancy may result from a contribution from very large molecules (i.e., PAHs) or an anomalously large population of small, hot, non-thermally heated grains emitting in the SST IRAC 8 μm and WISE 12 μm bandpasses. Such an effect would lower the F_24/F_8 ratio and shift points horizontally to the left of the blackbody curve. For this reason, the F_70/F_24 ratio is likely to be a more reliable indicator of the dust temperature. However, most points lie several orders of magnitude to the left of the blackbody fiducial, making it unlikely that excess contribution from PAHs is (solely) the cause. Emission from dust at multiple temperatures within an extended dust and gas nebula likely plays a role.

Figure 5 plots the log of the F_160/F_70 ratios versus log of the F_70/F_24 ratios for the 36 SST objects and 4 WISE objects having data. Symbols are the same as in Figure 4. As in Figure 4, the majority of points lie to the upper left of the blackbody curve. In these bandpasses, PAHs are not present, so another cause is required to explain the distribution in this color space. One possible explanation is, again, an excess of very small non-thermally heated grains that contributes disproportionately at the 24/22 μm bands, shifting points to the left of the blackbody curve. Another possibility is a multi-temperature dust structure. The apparent excess of F_70 relative to F_24 in Figure 4 and excess of F_160 relative to F_70 in Figure 5 would be consistent with the majority of sources showing increased contributions from cool dust at longer wavelengths. Infrared morphologies provide some support for this interpretation.

Figure 6 displays four examples of the 160/70/24(22) μm morphologies in red, green, and blue, respectively, for the four objects plotted with magenta symbols in the preceding color–color diagrams. The upper left panel is the bowshock associated with the O9.21V star ζ Oph (object 13). It spans more than 10′ on the sky but has high-quality measurements from HSO and WISE data owing to its high Galactic latitude (+23°) and, therefore, relative lack of foreground/background contamination. With a HIPPARCOS parallax of 8.91 mas, its implied distance of 112 pc makes ζ Oph the nearest known bowshock. Consequently, its nebular appearance is highly resolved into wispy filaments better seen in mid-infrared WISE bandpasses.11 This object, plotted as a magenta star, lies near the blackbody curve in Figures 4 and 5.

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11 e.g., https://www.nasa.gov/mission_pages/WISE/news/wise20110124.html.
Somewhat smaller in angular size is the nebulae associated with the O4If star BD+43 3654 (upper right; object 344). This object is prominent at 22 μm (blue) but less distinct at the HSO band-passes. At Galactic latitude +2°3, it also suffers from less background confusion than a typical Galactic Plane source, but it is located near the extended Cygnus-X star-forming complex at a probable distance of 1.3–1.5 kpc (Rygl et al. 2012; Kiminki et al. 2015), which contributes to unrelated line-of-sight emission. This object, plotted as a diamond, lies far from the blackbody curve in Figure 4 but near the modified blackbody curve in Figure 5. G045.1952+0.7420 (lower left; object 238) illustrates the common circumstance that an 24 μm arcuate nebula has 70 and 160 μm counterparts showing significantly different morphologies. Azimuthal variations in dust temperature and density seem likely in objects such as this. This object, plotted as a hexagon, lies far from the blackbody curve in Figure 4 but very near the blackbody curve in Figure 5. G331.6579+0.1308 (lower right; object 582) exemplifies another pattern noted in about 10%–15% of objects. The prominent 24 μm arc is accompanied by 70 and 160 μm features that are offset spatially to the exterior of the arc.

This object, plotted as a hexagon, lies near the blackbody curve in Figure 4 and somewhat farther from the blackbody curve in Figure 5.

The morphology in the lower right panel of Figure 6 might result when a stellar wind-driven bowshock is encountering a molecular cloud or region of higher density. Such an arrangement provides a possible explanation of why only 10% of runaway stars produce detectable infrared bowshocks (Peri et al. 2015). Perhaps a sufficiently high dust density or a density gradient is required to produce the requisite surface brightness to be detected amidst the high background levels in the Plane. For example, if ζ Oph, with a peak 70 μm surface brightness of 9 Jy arcmin−2, were placed in the Plane where our typical objects have surface brightnesses of tens to hundreds of Jy arcmin−2, it would likely go unnoticed and be undetectable. At 22 μm the ζ Oph bowshock nebula has a surface brightness of 1.9 Jy arcmin−2, which may be considered typical of our sample where values range from 0.6 to over 20 Jy arcmin−2. Figure 7 shows a histogram of

Figure 8. Histogram of color temperatures determined from 24 to 70 μm measurements (left) and histogram of color temperatures determined from 70 to 160 μm measurements (right). The long tail toward higher dust temperatures in the left panel is plausibly the result of an overabundance of small stochastically heated grains emitting at 24 μm.

Figure 9. Color temperatures derived from 70 to 160 μm measurements vs. those from 24 to 70 μm measurements. Filled large symbols are the same objects as in Figure 4.

Figure 10. Color temperatures derived from 24 to 70 μm measurements vs. radiation energy density parameter, U. The solid and dashed line show the predicted relationships from Draine (2011) for silicate and graphite dust, respectively.
| ID | Name            | Alt. name            | Sp.T. | $T_{\text{eff}}$ | $R_s$ | D   | $R_0$ | $R_0$ | $U$ | $T_{\text{sS}}$ | $T_{22/70}$ | $T_{70/160}$ | $F_{IR}$ | $L_*/L_{\odot}$ |
|----|-----------------|----------------------|-------|------------------|-------|------|-------|-------|-----|----------------|-------------|-------------|----------|----------------|
| 13 | ζ Oph           | G006.2812+23.5877    | O9.2IV | 31000            | 7.2   | 0.14 | 29    | 0.02  | 1.7 x 10^4 | 123          | 158          | 240       | 6.4 x 10^-8 | 1110      |
| 67 | NGC 6611 ESL 45 | G017.0826+00.9744    | O9V   | 31500            | 7.7   | 1.99 | 7.5   | 0.07  | 1.6 x 10^4 | 82           | 842          | ...       | 5.8 x 10^-6 | 8.4       |
| 329| KGK 2010 10     | G077.0505-00.6094    | O7V   | 35500            | 9.3   | 1.32 | 10    | 0.06  | 4.6 x 10^4 | 98           | 131          | ...       | 5.1 x 10^-6 | 440       |
| 331| LS II+39 53     | G078.2869+00.7780    | O7V   | 35500            | 9.3   | 1.32 | 25    | 0.18  | 7.3 x 10^3 | 72           | 195          | ...       | 5.3 x 10^-9 | 430       |
| 338| CPR2002A10      | G078.8223+00.0959    | O9V   | 31500            | 7.7   | 1.32 | 23    | 0.15  | 3.8 x 10^3 | 65           | 110          | ...       | 6.9 x 10^-9 | 160       |
| 339| CPR2002A37      | G080.2400+00.1354    | O5V   | 41500            | 11.1  | 1.32 | 70    | 0.45  | 2.6 x 10^3 | 61           | 120          | ...       | 6.0 x 10^-9 | 1100      |
| 341| KGK2010 1       | G080.8621+00.9749    | B2V   | 20900            | 5.4   | 1.32 | 20    | 0.13  | 4.7 x 10^2 | 46           | 126          | ...       | 1.9 x 10^-9 | 43        |
| 342| KGK2010 2       | G080.9020+00.9828    | B2V   | 20900            | 5.4   | 1.32 | 10    | 0.06  | 1.9 x 10^3 | 58           | 70           | 69        | 6.0 x 10^-10 | 140       |
| 344| BD+43 3654      | G082.4100+02.3254    | O4IV  | 40700            | 19    | 1.32 | 193   | 1.24  | 9.1 x 10^2 | 51           | 98           | 174       | 5.0 x 10^-8 | 350       |
| 368| KM Cas          | G134.3552+00.8182    | O9.5V | 30500            | 7.4   | 2.00 | 14    | 0.13  | 3.7 x 10^3 | 64           | 96           | ...       | 1.4 x 10^-10 | 2400      |
| 369| BD+60 586       | G137.4203+01.2792    | O7.5V/O8III | 34400       | 8.9   | 2.00 | 73    | 0.71  | 3.2 x 10^2 | 43           | 81           | 148       | 1.4 x 10^-9 | 640       |
| 380| HD 53367        | G225.7092-01.9008    | B0Ive | 30000            | 7.4   | 0.26 | 15    | 0.02  | 1.8 x 10^3 | 124          | 183          | ...       | 3.3 x 10^-9 | 5400      |
| 381| HD 54662        | G224.1685-00.7784    | O7V   | 35500            | 9.4   | 0.63 | 71    | 0.22  | 4.2 x 10^3 | 66           | 82           | ...       | 4.4 x 10^-9 | 2300      |
| 382| FN CMa          | G224.7096-01.7938    | B2la  | 17600            | 30    | 0.93 | 101   | 0.45  | 5.8 x 10^2 | 47           | 100          | ...       | 3.2 x 10^-9 | 980       |
| 406| HD 92607        | G287.1148-01.0236    | O8IV+O9V | 33400      | 8.5   | 2.30 | 16    | 0.18  | 4.1 x 10^3 | 66           | 230          | ...       | 1.9 x 10^-9 | 300       |
| 407| HD 93249        | G287.4071-00.3593    | O9III | 33400            | 13.6  | 2.30 | 7.8   | 0.09  | 3.1 x 10^4 | 92           | 141          | ...       | 6.3 x 10^-9 | 160       |
| 409| HD 93027        | G287.6131-01.1302    | O9.5IV | 30500            | 7.4   | 2.30 | 7.4   | 0.08  | 9.9 x 10^3 | 76           | 229          | ...       | 7.6 x 10^-10 | 330       |
| 410| HD 305536       | G287.6736-01.0093    | O9.5V+? | 30500       | 7.4   | 2.30 | 3.7   | 0.04  | 3.9 x 10^4 | 96           | 102          | ...       | 1.1 x 10^-9 | 220       |
| 411| HD 305599       | G288.1505-00.5059    | B0Ib  | 25000            | 30    | 2.30 | 4.2   | 0.05  | 2.3 x 10^3 | 128          | 106          | ...       | 4.0 x 10^-10 | 5100      |
| 413| HD 93683        | G288.3138-01.3085    | O9V   | 31500            | 7.7   | 2.30 | 15    | 0.17  | 2.9 x 10^3 | 62           | 123          | ...       | 1.0 x 10^-9 | 360       |
μm surface brightness for our sample. Values range from 3 to 300 Jy arcmin$^{-2}$. The detectability limit is usually around 0.02 Jy pixel$^{-1}$ or 7 Jy arcmin$^{-2}$ in the HSO$^{70}$ images, but in some favorable sightlines, factors of two lower are possible. For some objects that are just marginally detected, a value of 3.5 Jy arcmin$^{-2}$ is a typical value, representing a rough lower limit to detectability.

3.2. Dust Temperatures

Figure 8 (left panel) shows a histogram of color temperatures calculated by fitting a blackbody to the 24 (or 22) and 70 μm data for the 422 objects having measurements at those two bandpasses. The distribution is approximately Gaussian with a mean of 147 K, an rms of 78 K, and a long tail toward higher temperatures as large as 500 K. Figure 8 (right panel) shows a histogram of color temperatures for the 40 objects having both 70 and 160 μm HSO measurements. Nearly all the objects cluster between 25 and 100 K, with a few outliers up to 300 K. Figure 9 plots the 70/160 μm color temperatures versus the 24/70 μm color temperatures. The vast majority of objects lie to the right of the 1:1 relation, and there is no significant correlation. We interpret this to mean either that the 160 μm measurements are unreliable, sampling unrelated foreground or background material, or that the arcuate nebulae are intrinsically multi-temperature structures, as might be expected in the presence of a density gradient such as at the edge of a molecular cloud. This discrepancy could also result from a population of small, hot, semi-stochastically heated grains elevating the 24 μm fluxes and skewing the fitted color temperature upward toward higher values; such a scenario would be indistinguishable from the multi-temperature hypothesis on the basis of only three broadband measurements. Images presented above show that the 160 μm emission is sometimes offset from the 24 μm emission, lending credence to the idea of multiple temperature components. Shocks may also fragment dust grains producing a population of stochastically heated very small grains radiating strongly in the 24 μm band.

The nebula associated with ζ Oph (plotted as a magenta star) has one of the highest 70/160 μm color temperatures in the sample. Its 70/160 μm color temperature is 240 K versus a 24/70 μm temperature of 158 K. We believe this is largely the result of the large angular size of the source (over 400'' in diameter) that makes the photometry, particularly at 160 μm, very sensitive to the adopted background level. The BD +43 3654 nebula (magenta diamond) also lies above the 1:1 line, plausibly for similar reasons. Although it is considerably smaller at an angular diameter of about 120'', it lies close to the Plane in a confused region near the Cygnus OB2 star-forming complex. The G045.1952+00.7420 nebula (hexagon) has very similar color temperatures from both diagnostics. The G331.6579+00.1308 nebula lies below the line, along with...
the majority of the objects. It has a $24/70 \mu m$ temperature of 126 K and $70/160 \mu m$ temperature of 64 K. As illustrated by the lower right panel of Figure 6, this object has an extended area of $160 \mu m$ emission just outside the arcuate region defined by $24 \mu m$ emission. Inclusion of this perhaps unrelated material would lower the derived color temperature. The majority of objects in Figure 9 are probably affected by a similar circumstance. We consider the $70/160$ color temperatures to be less reliable and/or less diagnostic than the temperatures $24/70$ color temperatures, even allowing for the possibility of small stochastically heated grains affecting the $24 \mu m$ bandpass.

4. SED Modeling

Detailed modeling of the SEDs is possible for a few objects where the properties of the central stars ($T_{\text{eff}}, R_*$) are known and distances to the objects are also well constrained so that the standoff distance, $R_0$, between the star and nebula is also known. The star must also have at least two, and preferably three or more, photometric measurements. Table 5 lists 20 objects that meet these criteria. Columns 1–3 give the target ID number used in this work and in Kobulnicky et al. (2016) along with the common name and identifier in Galactic coordinates. Column 4 gives the spectral type and luminosity class as listed in the literature or, in a few cases, from our own spectroscopy (Chick et al. 2017). Column 5 is the adopted effective temperature, $T_{\text{eff}}$, from the assigned spectral type and luminosity class using the theoretical effective temperature scale of Martins et al. (2005). Column 6 is the corresponding stellar radius, $R_*$, in solar radii. Column 7 lists the adopted distance, $D$, to each source in kpc. For the majority of the objects in Table 5 distances are estimated through their association with a star cluster or molecular cloud of known distance, measured from main-sequence color–magnitude diagram fitting, or from radio very long baseline interferometry parallax measurements toward masers.\footnote{Spectrophotometric distance estimates toward the remainder of our sample are possible but considerably more uncertain owing to difficulties in assessing accurate spectral types and luminosity classes, reddening, and binarity. We defer this analysis to a future work.} Instances include NGC 6611 at 1.99 kpc (Hillenbrand et al. 1993), the W3/4/5 star-forming complex at 2.00 kpc (Xu et al. 2006), the Cygnus-X complex/Cygnus OB2 at 1.32 kpc (Rygl et al. 2012; Kiminki et al. 2015), and the Carina star-forming complex at 2.3 kpc (Allen & Hillier 1993). The remainder are sufficiently close to have optical parallax measurements (HIPPARCOS; Perryman et al. 1997).

Columns 8–9 list the standoff distance of the nebulae, $R_0$, from the central star in arcsec and pc, respectively. From these data we compute in Column 10 the radiation density parameter, $U$, at the location of the nebula. $U$ is defined in Draine & Li (2007, DL07) as the ratio of the radiant energy density (in erg cm$^{-3}$) due to the star to the mean interstellar radiant energy density estimated by Mathis et al. (1983).
MMP83),

\[
U = \frac{u_a}{u_{\text{MMP83}}} = \frac{R_a^2 \sigma T_a^4 / (R_a^2 c)}{0.0217 \text{ erg s}^{-1} \text{ cm}^{-2} / \text{c}}.
\]  

(1)

Draine & Li (2007) use this dimensionless ratio, \( U \), as a parameter characterizing the radiant energy density in their grid of model dust emissivities. For the objects in Table 5, these values range from several \( \times 10^2 \) to \( 2 \times 10^5 \), indicating that the central stars dominate the radiant energy density at the locations of the nebulae. From these basic data, it is straightforward to compute the steady-state temperature of dust, \( T_{SS} \), in the nebulae if radiant heating from the central star were the dominant heat source. Adopting the Draine (2011) Equation (24.19) for the temperature approximation of silicate grains in the size range \( a \ll 0.1 \mu m \),

\[
T_{SS} (K) = 16.4 \left( a / 0.1 \mu m \right)^{-1/15} U^{1/6},
\]

(2)

(where \( a \) is the grain size, taken to be 0.1 \( \mu m \)) for silicate dust.\(^{13} \) \( T_{SS} \) is relatively insensitive to errors in \( R_a \) or \( R_0 \) (derived from the adopted distance), given that \( T_{SS} \) scales weakly with both quantities. \( R_0 \) is a lower limit on the star-nebula separation since the inclination angle of the vector from star to nebula apex is unknown. Nevertheless, the inclination angle is likely to be near 90\({}^\circ\) owing to selection biases that would work against detection of bowshocks viewed at small inclination angles. Furthermore, most dust within the nebula lies at distances \( > R_0 \) from the star, given the approximately parabolic bowshock shape, making the derived \( T_{SS} \) a firm upper limit.

Columns 12 and 13 of Table 5 are the color temperatures derived from the 24/70 or 70/160 \( \mu m \) ratios. Figure 10 plots the log of derived 24/70 \( \mu m \) color temperatures versus log \( U \). The solid line shows the relation predicted by Draine (2011), Equation (24.19), which is appropriate to silicate dust, while the dashed line shows the prediction for graphite dust. It is immediately apparent that the predicted steady-state dust temperatures are lower than the measured color temperatures by factors of 1.1–3, with a mean ratio of 1.76. We interpret this as evidence that the infrared nebulae are not merely interstellar material sculpted and heated radiantly by the central star. Evidently, these nebulae require an additional source of heating, such as shock heating from the stellar wind mechanical energy. The discrepancy between the 24/70 \( \mu m \) color temperatures and steady-state dust temperatures could also be explained by invoking a population of anomalously small grains with \( a \ll 0.1 \mu m \), but given the \( a^{-1/15} \) dependency, increasing the dust temperature by 30% would require a large deviation from the interstellar grain size distribution adopted in Draine (2011). Such a preponderance of small grains, if confirmed, would support the idea of grain fragmentation in the stellar wind bowshocks. Mid-infrared spectroscopy of the nebula in conjunction with dust models including excess populations of small grains could potentially allow confirmation of a variance from the interstellar grain size distribution.

Column 14 of Table 5 contains the total flux, of the nebula \( (RIR, \text{ in erg s}^{-1} \text{ cm}^{-2}) \) estimated by integrating a blackbody fit.
to the 24 (or 22) and 70 μm data points over the range 1–300 μm. As demonstrated below, a blackbody provides a reasonable fit to the overall SED at wavelengths longer than 22 μm in most cases. Column 15 contains the ratio of stellar luminosity to nebular luminosity, \( L_{\text{IR}}^*/L_{\text{IR}} \). \( L_{\text{IR}}^* \) is calculated using the adopted \( R^* \) and \( T_{\text{eff}} \). Luminosity ratios range from 8 to 5100, with typical values of several hundred. Apparently, the dust in the nebulae intercepts and reradiates a small fraction of the stellar luminosity. There is no correlation between \( *L_{\text{IR}}/L_{\text{IR}} \) and the standoff distance, \( R_0 \), as might be expected if larger standoff distances result in the nebulae intercepting and reradiating a smaller fraction of the stellar luminosity.

4.1. SEDs of Sources with 160 μm Detections

Knowledge of the radiation field can be used in conjunction with the Draine & Li (2007) interstellar dust models to infer the properties of dust in the subsample of well-characterized bowshock nebula candidates. The grid of Draine & Li (2007) is parameterized in terms of three variables: dust exposed to a minimum radiant energy density \( U_{\text{min}} \), a maximum radiant energy density \( U_{\text{max}} \), and a fraction of PAH molecules by mass \( q_{\text{PAH}} \). We use the models appropriate to Milky Way dust and metallicity. Figure 11 plots the infrared SEDs for the four objects from Table 5 that have 160 μm HSO measurements. Points show photometric data at WISE 12 and 22 μm, SST 24 μm, and HSO 70 and 160 μm bandpasses. Typical photometric uncertainties are 0.2 dex. Black solid curves are best-fitting blackbodies, with labels in each panel indicating the temperature. The blackbody curves fit the data well in the upper two panels, but fail to produce enough flux at the 12 μm bandpass in the lower two panels. Dashed red curves are DL07 dust models with a constant \( U \), selected to be the nearest model match appropriate to the central star’s luminosity and the nebula’s standoff distance, as listed in Table 5. The model curves are normalized to the 70 μm point. The dash–dotted green curves are DL07 dust models with a range of radiation energy density between \( U_{\text{min}} \) and \( U_{\text{max}} \), again normalized to 70 μm. Values of \( U_{\text{min}} \) and \( U_{\text{max}} \) are labeled in the plots. All models have the minimum PAH fraction of \( q_{\text{PAH}} = 0.47\% \) by mass. Figure 11 shows that the fixed-\( U \) models are generally a poor representation of the data compared to the variable-\( U \) models. The latter, which include a contribution from large molecules (PAHs), provide a better fit to the 12 μm data than either the blackbody model or the single-\( U \) DL07 models. Given that the DL07 models have at least three free parameters (\( U_{\text{min}}, U_{\text{max}}, \) and PAH fraction), we do not perform a fit to the data points, but instead show the model curves as illustrative examples. In these four examples, all of which are hot stars with a high implied radiant energy density at the location of the nebula, the SEDs are most consistent with minimal or no PAH content, as might be expected if shocks act efficiently to destroy large molecules.

Figures 14. Spectral energy distributions for four additional nebulae from Table 5, as in Figure 12.

\[^{14}\text{Draine & Li (2007) also consider linear combinations of dust heated by a single } U \text{ and dust heated by a range of } U, \text{ via their parameter } \gamma, \text{ specifying the fraction of dust mass exposed to each radiant energy density. Given the limited number of photometric data points available in our study, we do not include this additional free parameter in our model comparisons.}\]
4.2. SEDs of Sources at Shorter Wavelengths

Additional photometric data at shorter wavelengths can further help constrain the dust properties. Figure 12 depicts the SEDs for four nebulae (ζ Oph and KGK2010 2, as in Figure 11) plus two additional objects from Table 5. The data points include the 70 μm and 24 or 22 μm measurements, plus the next two shorter bandpasses, either SST 5.8 and 8.0 μm or WISE 4.5 and 12 μm. Models are normalized to the 24 or 22 μm data points. Notations follow those in Figure 11. In three of the four cases, the single-U DL07 dust model of the appropriate U from Table 5 (red) cannot simultaneously fit the 70 μm data point and the shortest wavelength points. Similarly, the blackbody curve in three of the four cases significantly underpredicts the flux at the shortest wavelengths, which is expected to contain PAH or very hot dust contributions. Generally, the variable-U models (green) match the short-wavelength data better, but also overpredict the 70 μm flux. Notably, the required PAH contribution for KGK2010 2 (upper right panel) is the maximum included in the DL07 model grid at 4.5%, as shown by the high 8.0 to 24 μm flux ratio. ζ Oph is also better with a PAH fraction of qPAH = 3.19%. The other two objects seemingly require no or minimal PAH contribution. NGC6611 ESL 45 is noteworthy for having the highest 24/70 μm ratio in our sample and correspondingly the highest implied color temperature at 842 K. The best-fitting multi-U models typically have $U_{\text{min}} = 25$ and $U_{\text{max}}$ of $10^3$ to $10^5$. For this object, the single-U model provides the best fit.

Figure 13 show an additional four SEDs from Table 5 with notation as in Figure 12. The best-fitting models are similar, with a minimal PAH fraction and $U_{\text{min}} = 25$ and $U_{\text{max}}$ of $10^3$ to $10^5$. The models with a range of radiant intensities reproduce the data in three of the four panels well. In the two panels in the right column, the single-U models also reproduce the data as well as the variable-U models. In the lower left panel, neither of the DL07 models provides a good fit to the data. The simple blackbody fit to the two longest-wavelength data points approximating the data for all four objects reasonably well.

Figure 14 shows another four SEDs from Table 5 with notation as in Figure 12. The best-fitting variable-U models are similar, with a minimal PAH fraction and $U_{\text{min}} = 25$ and $U_{\text{max}}$ of $10^3$ to $10^5$. In three of four cases, the single-U models fit the data better than the variable-U models. In general, the simple blackbody curve fits the two longest-wavelength data points are also reasonable approximations of the overall SEDs.

4.3. SEDs of Sources with Strong 8 μm Detections

Although most nebulae are not detected at 8 μm or shorter, those that have short-wavelength measurements can be used to yield insights regarding the PAH content of the nebula. Figure 15 plots the SST 3.6, 4.5, 5.8, 8.0, and 24 μm measurements and HSO 70 μm measurement for four sources with suitable data as black stars. The generic source name and fitted 24/70 μm blackbody (solid black line) temperature are labeled in the upper left. As in previous SED figures, the green dotted curve shows a DL07 dust model with a range of radiant
energy densities and the minimum PAH fraction (0.47%). The SED in the upper right panel is G026.1437–0.0420, pictured in Figure 1. In two of the four panels, the green curve fits the long-wavelength points reasonably well, while in the other two panels, the blue curve provides a better match to the data. In all but the lower left panel, the green curve underpredicts the flux at the shortest two wavebands. The red curve is a model with the same range of $U$, but for a larger PAH fraction, as labeled in each panel. In all cases, a very small increase in PAH content is sufficient to reproduce the 3.6 and 4.5 μm fluxes, but begins to overpredict the 8 μm fluxes. The blue curve is a model with a single radiant energy density ($U = 1 \times 10^4$, as typical of stars described in previous subsections) and a variable PAH content. This model fits the long-wavelength data better than the variable-$U$ models in two of the four panels. It is similar to the red curve in its ability to predict the short-wavelength data, often overpredicting the 8 μm flux when the PAH fraction exceeds 1.12% (the second lowest model available in the DL07 grid). Figure 16 shows SEDs for four additional sources, as in Figure 15. Here, the blue single-$U$ curve reproduces the long-wavelength data better than the variable-$U$ models in all four panels. Similar to the four sources in Figure 15, a small PAH fraction of $q_{PAH} = 0 \%-2\%$ reproduces the short-wavelength fluxes better than the minimum PAH models. PAH fractions larger than this overpredict the 8 μm fluxes, and in some cases, even the minimum PAH fraction models overpredict the 8 μm fluxes. In seven of the eight sources, the fluxes are monotonically falling at short wavelengths; only G332.7156+00.5673 shows an upturn, perhaps due to very hot dust or contamination from foreground/background stellar sources along the sightline to the nebula. We conclude that of the nebulae with detections at short wavelengths, single-$U$ models fit the data better than models with a range of radiation energy densities, and models with minimal PAH content are most consistent with the data.
5. Inferences Regarding the Ambient ISM Density

Meyer et al. (2014) conduct a series of hydrodynamical simulations of bowshocks generated by main-sequence stars ranging from 10 to 40 \( M_\odot \) and red supergiants from 10 to 20 \( M_\odot \). Their Figure 24 presents the predicted correlation between bowshock luminosity and bowshock volume in three different tracers, including the infrared continuum most relevant here. Figure 17 plots infrared luminosity versus different tracers, including the infrared continuum most relevant here. Figure 17 plots infrared luminosity versus different tracers, including the infrared continuum most relevant here. Figure 17 plots infrared luminosity versus different tracers, including the infrared continuum most relevant here. Figure 17 plots infrared luminosity versus different tracers, including the infrared continuum most relevant here.

\[
R_0 \propto \sqrt{\frac{M v_\infty}{n_\alpha v_\star}},
\]

where \( M \) is the mass-loss rate, \( v_\infty \) is the stellar wind velocity, \( n_\alpha \) is the ambient ISM density, and \( v_\star \) is the star’s space velocity. It is generally accepted that \( v_\infty \) and \( v_\star \) are known to factors of two or better. Some combination of smaller \( M \) and larger \( n_\alpha \) are apparently needed to reduce \( R_0 \) by a factor of 10, as required to reconcile the data with the models.

We infer from this discrepancy that the typical ambient interstellar densities in our sample may be as much as factors of 100 higher than the 0.57 cm\(^{-3}\) used in the Meyer et al. (2014) simulations. ISM densities higher by factors of \( \pm 3-5 \) would be consistent with values of \( 2-3 \) cm\(^{-3}\) determined in a few well-studied bowshock nebulae such as \( \alpha \) Orionis (Ueta et al. 2008) or \( \zeta \) Oph (Gull & Sofia 1979). This low detection rate is a consequence of being on the Rayleigh–Jeans tail of the blackbody spectrum and the complex emission from foreground/background structures in the Galactic Plane.

2. Only a small fraction (178 objects; 25%) are detected at \( SST \) \( 8 \) \( \mu m \), where PAH emission often dominates the emission, or lie at shorter wavelengths. This suggests that PAH contributions are not generally present in these nebulae, a conclusion supported by comparing ISM dust models to a subset of well-measured objects.

3. Spectral energy distributions peak in the 12–70 \( \mu m \) range, in agreement with the hydrodynamical simulations of Meyer et al. (2016).

4. Color temperatures derived from 70/160 \( \mu m \) ratios are systematically cooler than those from 24/70 \( \mu m \) ratios. We infer from this that either the 160 \( \mu m \) measurements are contaminated by unrelated background/foreground emission (appears likely in some cases), that the nebulae are intrinsically multi-temperature dust structures, as might be expected if a bowshock is being driven into a higher-density structure such as a molecular cloud, or that the 24/22 \( \mu m \) bandpasses contain a disproportionate contribution from very small stochastically heated dust grains.

5. In a subset of 20 objects with well-determined distances, sizes, stellar effective temperatures, and stellar radii, we find that the radiative energy density from the star at the location of the nebula is \( 10^{2-3} \) higher than that of the ambient interstellar radiation field, indicating that the early-type stars dominate the energetics of the nebulae. Both of the infrared color temperatures are hotter, by 76% on average, than the nominal steady-state dust temperature if the dust were in radiative equilibrium, consistent with shocks or additional heating sources in these nebulae.

6. Among the 20 well-characterized objects, we find no correlation between the ratio of stellar-to-nebular luminosity and the standoff distance, \( R_0 \). There is a weak correlation between infrared luminosity and \( R_0^3 \), as predicted by numerical simulations of Meyer et al. (2014). However, the data are offset toward smaller \( R_0 \) compared to the simulations. We infer that ambient ISM densities in the vicinity of bowshocks are higher by factors of \( \sim 100 \) or stellar mass-loss rates are lower by factors of \( \sim 100 \), or some combination thereof, relative to the values adopted in the simulations.

7. Analysis of the SEDs for 20 well-characterized objects shows that the shortest wavebands (8 or 12 \( \mu m \)) rarely have fluxes high enough to require significant PAH contributions. Most SEDs are consistent with DL07 dust spectra having a constant radiative energy density (single-\( U \) models) or a range of radiative intensity from \( U = 25 \) to \( U = 10^3 \) or \( 10^4 \) times the ambient interstellar radiation field for a minority of the objects. In about half the cases, the single-\( U \) models provide better fits to the 8–70 \( \mu m \) data, while the variable-\( U \) models appear to provide better fits to the small number of objects with 24–160 \( \mu m \) photometry. In nearly all cases, the models with minimal PAH content provide the best fits, indicating that PAH...
contribution to most candidate bowshock nebulae is small. Even in sources with strong 8 μm detections (Figures 15 and 16), a small increase in the PAH fraction to $q_{PAH} = 1\%–2\%$ appears sufficient to reproduce the short-wavelength 3.6–5.8 μm data. This is substantially smaller than the median $q_{PAH} = 4.1\%$ for nearby galaxies (Dale et al. 2017) and does not vary, on average, by more than half a percent as a function of galactocentric radius, with $q_{PAH}$ dropping slightly at smaller radii; see Sandstrom et al. (2013). Taken together, these trends are consistent with shocks or UV radiation fragmenting large dust grains and large molecules within the nebulae to the point where PAHs are not a dominant component of the infrared SEDs.

Additional spectroscopic observations, both optical and infrared, are needed to characterize the central stars of these nebulae and enable a more comprehensive analysis of the energy balance and physical properties in a large sample of arcuate candidate-bowshock nebulae. Because the radiation field is convincingly dominated by a single hot star, these objects make enticing laboratories for studying the effects of UV radiation on dust properties and for testing models of dust emission against the data. Sensitive optical or infrared spectroscopy may be able to detect diagnostic fine-structure or forbidden lines that could be used as shock tracers or density indicators. Unfortunately, the surface brightnesses of the nebulae are all below the detection thresholds of airborne infrared instruments on SOFIA, but some objects are shock tracers or density indicators. Unfortunately, the surface brightnesses of the nebulae are all below the detection thresholds of airborne infrared instruments on SOFIA, but some objects are

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