RCW49 at Mid-IR Wavelengths: A GLIMPSE from the Spitzer Space Telescope


ABSTRACT

The luminous, massive, star formation region RCW49, located in the southern Galactic plane, was imaged with the Infrared Array Camera (IRAC) on the Spitzer Space Telescope as part of the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) program. The IRAC bands contain polycyclic aromatic hydrocarbon (PAH) features at 3.3, 6.2, 7.7, and 8.6 μm as well as the Br α line. These features are the major contributors to the diffuse emission from RCW49 in the IRAC bands. The Spitzer IRAC images show that the dust in RCW49 is distributed in a network of fine filaments, pillars, knots, sharply defined boundaries, bubbles, and bowshocks. The regions immediately surrounding the ionizing star cluster and WR stars are evacuated of dust by stellar winds and radiation. The IRAC images of RCW49 suggest that the dust in RCW49 has been sculpted by the winds and radiation.
from the embedded luminous stars in the inner 5' (inner ~6 pc) of the nebula. At projected angular radii $\phi > 5'$ from the central ionizing cluster, the azimuthally averaged infrared intensity falls off as $\sim \phi^{-3}$. Both high resolution radio and mid-IR images suggest that the nebula is density-bounded along its western boundary. The filamentary structure of the dust in RCW49 suggests that the nebula has a small dust filling factor and, as a consequence, the entire nebula may be slightly density bounded to H-ionizing photons.

Subject headings: HII regions, interstellar dust, stars:Wolf-Rayet, ISM:structure, infrared:ISM

1. Introduction

Luminous, HII regions (i.e., massive star formation regions) play a major role in galaxies by: illuminating and ionizing the ambient interstellar medium (ISM); driving turbulence and sculpting the structure of gas and dust via stellar winds and supernovae explosions; and enriching the ISM via supernovae explosions and processed stellar wind particles. Massive star formation is a key to galaxy morphology and the structure and energetics of the ISM in galaxies. NGC3247, usually referred to as RCW49 (Rogers, Campbell, & Whiteoak 1960), is a large, optically visible, and luminous HII region located in the southern Galactic plane at $l=284.3^0$, $b= -0.3^0$. The HII region is ionized by the compact cluster Westerlund 2 (hereafter W2), which contains at least a dozen OB stars, five of which are O7V stars, one is an O6V, and two are WR stars (Moffat & Vogt 1975; Moffat, Shara, & Potter 1991, hereafter MSP; and Carraro & Munari 2004). The two WR type stars are WR20a (WN7) and WR20b (WN6:h) (van der Hucht 2001).

RCW49 has been detected at X-rays from 0.2-4.5 Kev by Hertz (1983), Hertz & Grindlay (1984) and Goldwurm, Caraveo, & Bignami (1987) and from 0.1-2.4 Kev by Belloni & Mereghetti (1994). Both X-ray point sources and extended emission have been reported. RCW49 has also been observed in molecular and atomic line surveys of OH (Caswell 1997; 1998), CH$_3$OH (Caswell 1997), H$_2$O (Batchelor et al. 1980), H$_2$CO (Caswell & Haynes 1987; Whiteoak & Gardner 1974), and H109α and/or H110α lines (Wilson et al. 1970; Caswell & Haynes 1987). It has also been imaged in the radio continuum by Goss & Shaver (1970); Shaver & Goss (1970); Haynes, Caswell, & Simons (1978; 1979); and, Whiteoak & Uchida (1997; hereafter WU97).

The distance to RCW49 is uncertain. MSP report a luminosity distance to the cluster of 7.9 kpc, however, other investigators have reported distances of 2.3 kpc (Manchester et al.
1970; Brand & Blitz 1993; and WU97), and 5.0 kpc (Westerlund 1960; Manchester, Goss, & Robinson 1969; Caswell & Haynes 1987). The radio recombination lines toward RCW49 have a radial velocity of \( \sim 0 \text{ km s}^{-1} \) (Wilson et al. 1970; Caswell & Haynes 1987) indicating a kinematic distance of about 4.2 kpc, but peculiar motions of \( \pm 10 \text{ km s}^{-1} \) would place the nebula anywhere from \( \sim 2.2 \) to \( \sim 5.8 \) kpc. Carraro & Munari (2004) report a photometric distance of 6.4\( \pm 0.4 \) kpc, similar to 5.75 kpc quoted by van der Hucht (2001) for the WR star 20a. We will adopt the far kinematic distance of 4.2 kpc based on the HI 21 cm absorption line profile (Goss et al. 1972; McClure-Griffiths et al. 2001) toward RCW49 which shows deep absorption out to the tangent point velocity of \( -29 \text{ km s}^{-1} \). Until the discrepancy between the photometric and kinematic distances are resolved, the distance must be considered to be uncertain by \( \sim \pm 2 \) kpc. At a distance of 4.2 kpc, 1 arcsec corresponds to 0.020 pc.

A key issue that we will address in this paper is the morphology of dust associated with RCW49. An associated issue is the ionization source of the Warm Ionized Medium (WIM), the layer of diffuse ionized hydrogen above and below the Galactic plane, often referred to as the Reynolds Layer.

2. Observations and Data Reduction

The data reported here were obtained on 2003 Dec. 23, with the Infrared Array Camera (IRAC; Fazio et al. 2004) on the Spitzer Space Telescope. IRAC has four wavelength bands centered at 3.6, 4.5, 5.8, and 8.0 \( \mu \text{m} \) (hereafter [3.6], [4.5], [5.8], and [8.0], respectively), each of which has a field of view (FOV) of \( \sim 5.2' \times 5.2' \). All four bands are observed simultaneously. The [3.6] and [5.8] FOVs are coincident on the sky and the [4.5] and [8.0] FOVs are coincident, but the center positions of the two pairs are offset by 6.73'. The pixel size in all four bands is \( \sim 1.22'' \). The full-width at half-maximum of the point spread functions were 1.63'', 1.70'', 1.85'', and 1.94'' at [3.6], [4.5], [5.8], and [8.0], respectively. More information on the IRAC camera is available from Fazio et al. (2004) and at http://ssc.spitzer.caltech.edu/ost/.

GLIMPSE is a fully sampled survey of the inner two thirds of the Galactic plane (\( l=\pm 10^\circ \) to \( 65^\circ \), \( b= \pm 1^\circ \); total area \( \sim 220 \) square degrees) in all four IRAC bands. This program is described in detail by Benjamin et al. (2003). The GLIMPSE program was validated using early observations taken using precisely the same observing strategy that will be used by GLIMPSE. We will refer to these data as the Observing Strategy Validation (OSV) data. The OSV\(^1\) covered an area of about 1.7''\( \times 0.7'' \) centered on RCW49. The area was imaged using half-frame steps in one telescope coordinate and slightly less than a frame offset in the

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\(^1\)All 20 AORs of the OSV data have program identification number (PID) 195
perpendicular direction. Every point in the OSV area was observed a minimum of ten times. A total of 1648 frames per IRAC band, each exposed for 1.2 s, were mosaicked to form the final images. The minimum total exposure time per pixel was 12 s and the total observing time was 10 hours.

The calibrated data from the Spitzer Science Center (SSC pipeline version S9.01) were processed through the GLIMPSE pipeline reduction system (Benjamin et al. 2003; Whitney et al. 2004). Point sources were extracted from each frame using a modified version of DAOPHOT (Stetson 1987) and the individual frames at a given band were mosaiced using MONTAGE\(^2\) (http://montage.ipac.caltech.edu) to produce an image of the entire field at each band.

3. Spitzer Mid-Infrared Images of RCW49

In Figure 1, upper panel, we show a three-color ([3.6], [5.8], & [8.0]) image of RCW49 with various nebular and stellar features indicated. In the lower panel of Fig. 1, we show a three-color (J, H, K) 2MASS\(^3\) image of RCW49 for comparison. There is a striking difference between the faint, diffuse emission at J, H, and K bands and the bright, diffuse, highly structured emission in the IRAC bands. At J, H, and K, the diffuse emission is primarily a combination of scattered light from the W2 cluster and Br\(\gamma\) line emission. Only faint traces of the diffuse emission seen in the IRAC bands are apparent at J, H, and K bands. In the IRAC bands, the diffuse emission is produced primarily by polycyclic aromatic hydrocarbon (PAH) features and Br\(\alpha\) line emission, which we discuss below.

In Figure 2, we show two sets of three-color images centered on RCW49 composed of subsets of the OSV data (~360 frames per band). The top panels show the entire nebula; the lower panels are zoomed-in by a factor of two centered on the W2 cluster. We assign blue to the shortest wavelength band, green to the intermediate band, and red to the longest wavelength band. The left panels are composites of the [3.6], [4.5], & [5.8] bands; and the right panels are composites of the [3.6], [5.8], & [8.0] bands. These color combinations were chosen to highlight particular properties of the images described below. The same general

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features are seen in both of the three-color images, but there are important differences in the details that we discuss below. IRAC [3.6], [5.8], and [8.0] bands each contain (PAH) emission features; 3.3 μm in the [3.6] band, 6.2 μm in the [5.8] band, and 7.7 and 8.6 μm features in the [8.0] band (Draine 2003). These features are excited by UV radiation and as a consequence become bright in the neighborhood of a hot star if it is embedded in or surrounded by dust. Small dust grains can also be stochastically heated by absorption of UV radiation and reradiate at mid-IR wavelengths.

IRAC [4.5] contains the bright hydrogen recombination line Br α (4.05μm). The integrated radio continuum emission from RCW49 was used to predict a Br α flux within ~20% of the non-stellar flux observed in the [4.5] band integrated over RCW49. We conclude that Br α dominates the extended emission in IRAC [4.5] toward bright HII regions.

Colors intermediate between red and green in Figs. 1 and 2 indicate a combination of Br α line emission ([4.5] band) and PAH emission ([3.6], [5.8] and [8.0] bands) throughout RCW49. The reddish shades in Figure 2 indicate the distribution of warm dust emitting primarily in the 6.2 μm PAH feature in the [5.8] band (all panels of Fig. 2) and the 7.7 and 8.6 μm PAH features in the [8.0] band (right panels of Fig. 2). Main sequence stars with photospheres hotter than ~1000 K appear blue in IRAC colors, except for the most reddened ones, and are brightest at [3.6] and [4.5]. All IRAC images of RCW49 show basically the same features and extents, but their brightness are quite different. The diffuse emission systematically and sharply increases from [3.6] to [8.0] (see Fig. 3). Also, the [4.5] band (dominated by Br α) shows the same general features seen in the other bands (dominated by PAH features), although they seem to be less sharply defined in [4.5].

The dust features that produce the bright, diffuse emission associated with RCW49 show a number of interesting properties. The major features are illustrated in Fig. 3 which shows profiles at each IRAC band of the azimuthally averaged intensity as a function of projected angle φ from W2. Among these is the core of the W2 cluster inside a radius of φ ~10", a dust evacuated region out to φ ~60", a bright shell of swept-up dust and gas at φ ~100", and a region of constant or slightly decreasing intensity between φ ~150" to ~300". We refer to the radius at φ ~300" as the "transition boundary", beyond which the mean intensity decreases with projected radius as ~ φ⁻³. The region between 150" and 300" we refer to as the plateau. These features are illustrated in Fig. 3 and are apparent in Figs. 1 & 2. The φ⁻³ dependence of the azimuthally averaged intensity on projected distance from the W2 cluster is consistent with optically thin emission reradiated by dust with emissivity \( \varepsilon_d \propto n_d/r^2 \) where \( n_d \) is the space density of dust, \( r \) is the three-dimensional distance from the center of W2, and \( r^{-2} \) accounts for the geometrical dilution of the radiation field from the W2 cluster. We assume that \( n_d \propto r^{-2} \), so that \( \varepsilon_d \propto r^{-4} \) resulting in a φ⁻³ dependence of
the azimuthally averaged intensity, as observed.

The angular diameter (to the background level) of the dust emission from RCW49 in the IRAC bands is \( \sim 33' \times 18' \) \( \sim 40 \times 22 \) pc for a distance of 4.2 kpc). The major axis has a position angle of \( \sim 340° \)\( \sim 20° \) of N). By comparison, the MOST 843 MHz image of WU97 has a bright emission core of diameter 12', but emission filaments are detected as far as 30' to the W and 1° to the NE of W2. Thus the total extent of the IRAC images are somewhat larger than the radio core diameter, but smaller than the extent of some of the radio filaments. Clearly, some H-ionizing photons extend well beyond the near to mid-IR images of RCW49 in the directions where the radio filaments are observed (W and NE). The radio and mid-IR images show that dust either coexists with ionized gas, or is embedded in neutral gas clumps intimately mixed with ionized gas (i.e., as a matrix of radio continuum from interclump regions and PAH from clumps) in RCW49.

The transition boundary is apparent in Figs. 1 & 2 as a ring of eroded dust pillars that point toward the W2 cluster. The pillars appear to have been sculpted by the winds and radiation from the massive stars in the cluster and may represent remnants of Rayleigh-Taylor instabilities or dense cloud cores possibly containing embedded low-mass protostars like those in M16 (Hester et al. 1996; Scowen et al. 1998). The intensity interior to \( \phi \sim 300° \) does not follow any simple analytic function with radius as it does outside this region. The average intensities systematically increase from [3.6] to [8.0] (see Fig. 3). The integrated flux densities of diffuse emission (i.e., measured on images in which point sources have been extracted) in the [3.6]-[8.0] bands are: 233 Jy, 221 Jy, 860 Jy, and 3246 Jy, respectively, which quantitatively shows the large increase in diffuse emission in the [5.8] and [8.0] bands relative to the [3.6] and [4.5] bands. The diffuse flux densities in bands [5.8] and [8.0] have been reduced by factors of \( \sim 0.63 \) and \( \sim 0.69 \), respectively, as per SSC calibration recommendations.

The brightest emission, both at radio continuum and at mid-IR wavelengths, lies between the core of the W2 cluster and WR20b. WU97 postulated that this region has been compressed by shocks from both sides by winds from the W2 cluster and WR20b. In this region, a pattern of narrow, bright, wavy filaments are apparent (see Fig. 1); the filaments are most clearly defined in IRAC [5.8]. A medium that is shocked and compressed from two sides (see Vishniac 1994; Blondin and Marks 1996; Garcia-Segura & Franco 1996) will produce wavy structures known as "Vishniac instabilities".

One of the most striking aspects of the images shown in Fig. 2 is the complex, filamentary structure of the dust distribution in RCW49. The index of the spatial separation spectrum, \( n \) \( \propto k^{-n} \) where \( P(k) \) is the Fourier transform of the two-point correlation function of intensities at separation 1/k) varies between 1.8 and 1.4 for spatial scales ranging from 1.2"
to 40" within boxes 40" on a side distributed over the face of the nebula. The mean value of \( n \) is consistent with a spectral index of 1.67, the value associated with turbulence in the diffuse interstellar medium. The striking feature about the size scales of dust structures in RCW49 is their presence down to our resolution limit (~0.03 pc), although most of the power is in larger scale structures.

The IRAC images of RCW49 suggest that little of the volume is occupied by dusty material. Most of the diffuse features seen in the [5.8] band (mostly a dust tracer) are also seen in the [4.5] band (mostly an H\(^+\) tracer via Br \( \alpha \) emission). The feature boundaries do not seem quite as sharply defined at [4.5] as they are at [5.8], although this is difficult to quantify because of the large difference in brightness at the two bands.

The network of thin filaments, pillars, and sharp boundaries hints that the nebula may be slightly density-bounded. H-ionizing radiation propagates \( \geq 30'/ W \) of W2 (direction where radio ring A is disrupted) and at least 1° to the NE of W2 as shown by radio continuum filaments. To establish quantitatively the rate at which UV radiation escapes is impossible without more and deeper photometry of the stellar content of the W2 cluster. The UV photon luminosity required to ionize the nebula is \( \sim 5.7 \times 10^{50} (D(\text{kpc})/4.2\text{kpc})^2 \text{s}^{-1} \) based on the 5GHz flux density of Goss & Shaver (1970). The five O7V, one O6V, and two WR stars listed by MSP, Moffat & Vogt (1975), and Carraro & Munari (2004) can provide most of the UV flux required for ionization, assuming the stellar photon fluxes of Vacca, Garmany, & Shull (1996) and a distance of 4.2 kpc. There may, of course, be additional B-stars and possible O-stars that are hidden at visible wavelengths by extinction; the average extinction is \( A_V \sim 5 \text{ mag} \) (Carraro & Munari 2004), but the youngest stars could have much larger local extinctions. Whitney et al. (2004) have found \( \sim 300 \) highly reddened protostar candidates in RCW49, indicating that star formation is an ongoing process in RCW49. Until all the optically obscured stars are identified and their spectral types determined, we cannot establish the fraction of ionizing flux that escapes the nebula. Because the radial velocity of RCW49 is \( \sim 0 \text{ km s}^{-1} \), H\( \alpha \), HI 21 cm, and CO gas lying above or below (in latitude) RCW49 is confused with local ionized and neutral gas. Consequently, we have been unable to determine the ionization state of gas located above or below RCW49, which might give some indication of leakage of UV from the nebula. Improving this estimate is important because ionization of the Reynolds Layer (the diffuse ionized layer of hydrogen above and below the Galactic plane, Reynolds, Scherb, & Roesler 1973) could be accounted for if only \( \sim 15\% \) of the UV photons from OB stars in the disk of the Galaxy escape into the lower halo (Reynolds 1984). This is a small fraction and to determine if density boundedness at this level occurs will require an accurate census of hot stars in the cluster, stellar atmosphere model UV fluxes accurate to \(< 15\% \), and an accurate determination of the fraction of ionizing UV absorbed by dust in the nebula. GLIMPSE will identify any optically obscured candidate
OB stars from which a better estimate of the total stellar UV photon flux can be determined.

4. Summary and Conclusions

The Spitzer/IRAC observations of RCW49 (NGC3247) have revealed that:

- Dust coexists with ionized gas in RCW49, or else is embedded in neutral gas intimately mixed with ionized gas.
- At radii less than ~5' from the W2 cluster, the dust has been sculpted by stellar winds and radiation.
- At radii greater than ~5' from the W2 cluster, the mean intensity at [3.6]-[8.0] decreases with projected angle as $\phi^{-3}$, consistent with optically thin emission, dust emissivity proportional to the space density of dust, dust density decreasing with true distance from the W2 cluster as $r^{-2}$, and the radiation field decreasing as $r^{-2}$ as expected for geometrical dilution.
- Dust is distributed in a complex network of thin filaments, pillars, sharp boundaries, and knots suggesting that the dust filling factor is small. The size scales of dust structures has a spectrum index similar to that of turbulence in the interstellar medium with structure present down to our resolution limit (~0.03 pc).

The observations described here and by Whitney et al. (2004) and Mercer et al. (2004) demonstrate that the GLIMPSE program has great potential to reveal the distributions of dust and stars in the inner Galaxy from which the number and locations of spiral arms, the Galactic stellar scale length, and properties of massive star formation can be determined. GLIMPSE also has a high probability for serendipitous discoveries.

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Fig. 1.— Top: A three-color ([3.6],[5.8], & [8.0]) image of RCW49 with various features referred to in the text indicated by labeled arrows. Scaling is logarithmic and units are in MJy/str for Figs. 1 & 2. Bottom: A three-color (J, H, & K) 2MASS image of RCW49 with a similar field of view as shown in the upper panel of Figure 1. The minimum and maximum values for all three bands are 0.5 and 700 MJy/str.
Fig. 2.— A montage of three-color images of RCW49. *Left panels* Top: A wide-field image showing the total extent of RCW49 at [3.6], [4.5], & [5.8]. The minimum values displayed for each band are, respectively, 1.5, 3, and 5 MJy/sr. The maximum values are 700 for all images in Figure 2. Bottom: A zoomed-in version of the above image centered on the Westerlund 2 cluster. The minimum values for each band are 2, 6, and 10. *Right panels* The same as the left panels except the IRAC bands are [3.6], [5.8], & [8.0]. Top: Minimum values for each band are 1, 10, and 14. Bottom: Minimum values are 1.5, 10, 20.
Fig. 3.— The projected azimuthally averaged radial profiles of the emission from RCW49 centered on the Westerlund 2 cluster. The dotted curves are power laws of slope -3. The two vertical dashed lines indicate the inner swept up shell at angular radius $\phi \sim 100''$ and the second one at $\phi \sim 300''$ indicates the transition boundary beyond which the mean brightness decreases as $\sim \phi^{-3}$. The central wavelengths of the IRAC bands, in microns, are indicated in square brackets. The intensity of the [3.6] band is divided by 10 and [4.5] is divided by 2. The $\phi^{-3}$ dependence flattens at $\sim 1000$ arcsec because the intensity merges with the background.