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SELECTED FIRST RESULTS FROM THE GLIMPSE SURVEY

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RESUMEN

El Relevamiento del Plano Galáctico Infarrojo de Legado Extraordinario (GLIMPSE, por las siglas en inglés) brinda una visión completamente nueva de nuestra galaxia asi como gran riqueza de nuevos resultados científicos. En esta reseña reporto cuatro nuevos resultados de GLIMPSE. El primero es la distribución estelar de la Vía Láctea interior y sus implicaciones para la distribución galáctica a gran escala, especialmente en cuanto a la presencia y propiedades de la barra central. El segundo es la ley de enrojecimiento en el infrarrojo intermedio derivado en tres diferentes direcciones en el plano galáctico. El tercero es el descubrimiento de más de 250 objetos estelares jóvenes (YSOs), la presencia de varios choques entre vientos estelares en colisión y otros fenómenos energéticos en la región de formación masiva RCW49. El cuarto es una muestra de dos casos de formación estelar provocada de entre los numerosos ejemplos de este fenómeno en el relevamiento GLIMPSE. El catálogo estelar GLIMPSE y su archivo ya se encuentran disponibles en el Centro Científico de Spitzer.

ABSTRACT

The Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) is giving us an entirely new view of our Galaxy and providing a wealth of new scientific results. In this review I will report on four early results from GLIMPSE. One is the stellar distribution in the inner Milky Way and its implications for large-scale galactic structure, especially, the presence and properties of the central bar. Two is the mid-infrared reddening law derived toward three different directions in the galactic plane. Three is the discovery of more than 350 young stellar objects (YSOs), the presence of several colliding stellar wind shocks, and other energetic phenomena in the massive star formation region RCW49. Four is a visual illustration of triggered star formation toward two of numerous examples of this phenomenon in the GLIMPSE survey. The GLIMPSE stellar catalog and archive are available now at the Spitzer Science Center.

Key Words: **DUST, EXTINCTION — GALAXIES: SPIRAL — GALAXY: STRUCTURE — STARS: FORMATION**

1. INTRODUCTION

The Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) is a fully sampled survey of the inner Milky Way from $|l| = 10°–65°$ (both sides of the Galactic center) and $b = \pm 1°$; 220 square degrees with resolutions $< 2''$. This area was imaged twice at 3.6, 4.5, 5.8, and 8.0 μm using the Infrared Array Camera (IRAC) on board the *Spitzer Space Telescope*. Due to space limitations, I will discuss only four results from this extraordinary survey that is providing an entirely new view of our Galaxy and its stellar and dust content. I will discuss: 1) the distribution of stars in longitude l, latitude b, and magnitude m in the survey area; 2) the near to mid-infrared interstellar reddening law; 3) the massive star formation region RCW49; and 4) evidence for stimulated star formation. It was difficult to narrow the discussion to only these topics because this survey continues to reveal numerous other very interesting results.

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2. THE STELLAR DISTRIBUTION IN THE INNER GALAXY

The highly reliable ($\geq 99.5\%$) GLIMPSE Point Source Catalog (hereafter Catalog) contains over 30 million stars and the GLIMPSE Point Source Archive (hereafter Archive) contains over 47 million stars. The selection requirements for a star to appear in the Catalog and Archive are discussed in detail in the GLIMPSE Quality Assurance document and the GLIMPSE Data Products Description.[2]

The Catalog and Archive provide powerful databases for analyzing large-scale Galactic structure as traced by stars. They uniformly and completely sample the inner Galactic plane to well-defined limits at wavelengths where extinction is significantly reduced, allowing us to see deeper into the inner disk. They take advantage of $< 2''$ angular resolutions to extract individual stars and provide a very large sample of stars, permitting very good

[2]Both documents will soon be available at http://www.astro.wisc.edu/sirtf/docs.html.

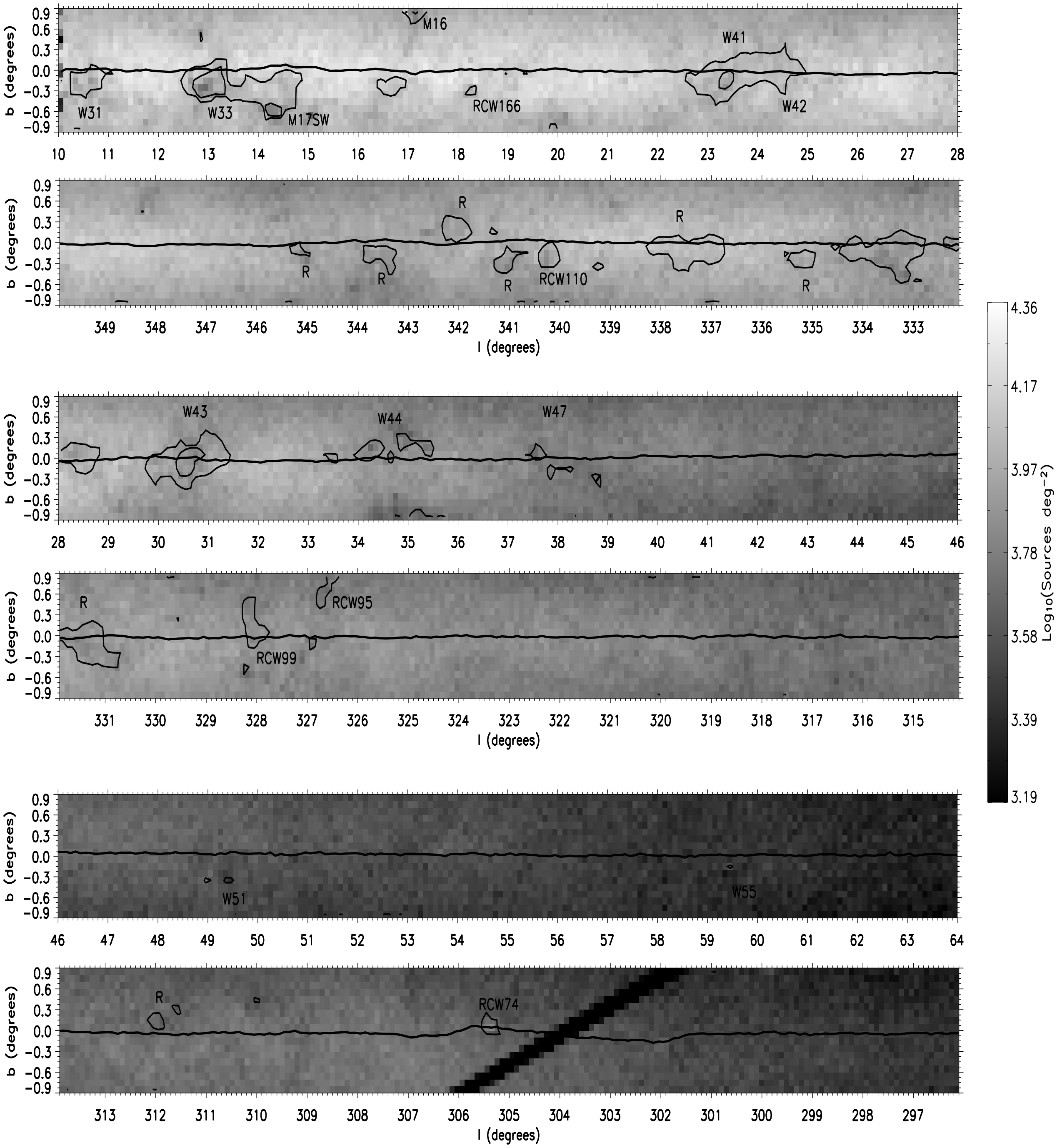

Fig. 1. Log of the number of stars/deg^2 at 4.5 μm from the GLIMPSE Catalog in the magnitude range 6.5 to 12.5 as a function of galactic latitude and longitude. Sources are binned into $0.1^\circ \times 0.1^\circ$ pixels. Each pixel contains from 10^3 to $> 10^4$ stars. The horizontal line near latitude $b = 0^\circ$ is the stellar weighted mid-plane which varies by $\leq 0.05^\circ$ from $b = 0^\circ$. The contoured regions with labels are regions of decreased star counts which also correspond to known massive star formation regions/massive molecular cloud complexes and a class of very red mid-IR stars. These regions clearly show that extinction, even at mid-IR wavelengths, is important in the inner Galaxy. The most prominent feature is the pronounced asymmetry between the north ($l = 10^\circ$ to $\sim 30^\circ$) and south ($l = 35^\circ$ to $\sim 330^\circ$); the north has about 25% more stars than the south in this longitude range.

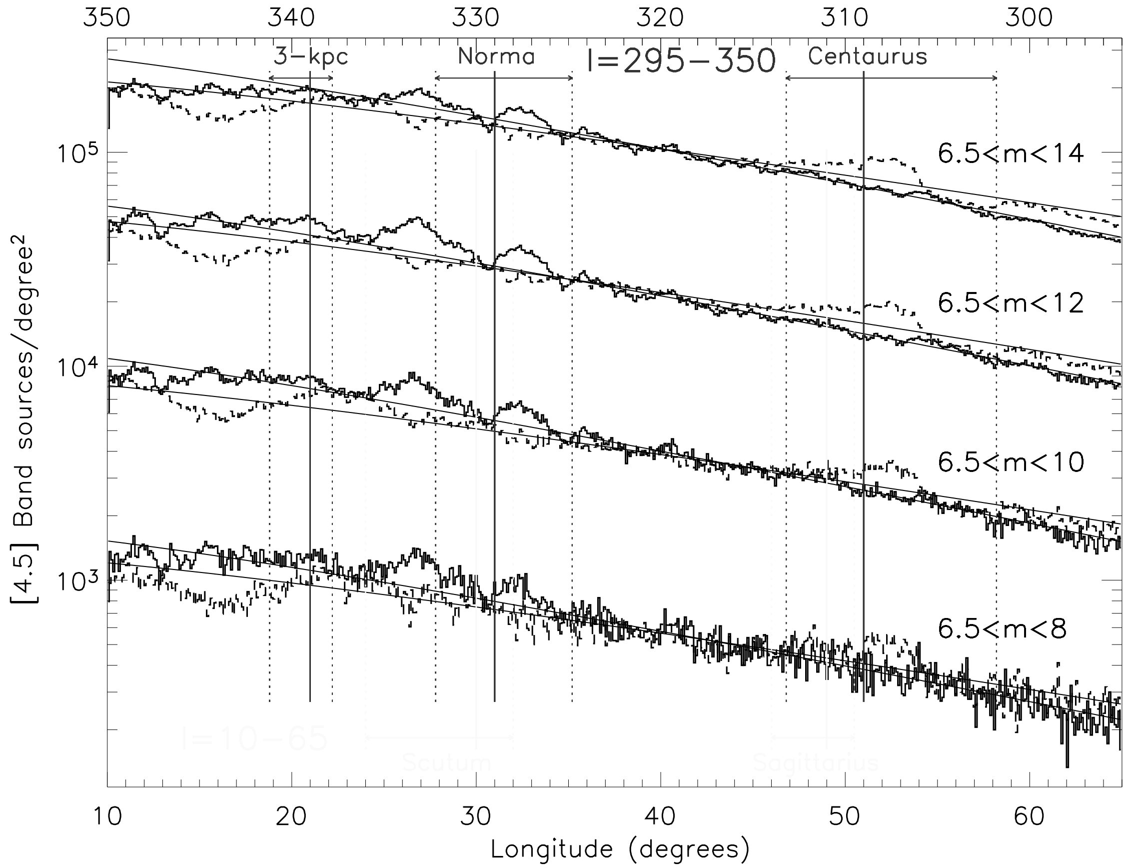

Fig. 2. The average number of stars/deg^2 as a function of longitude in both the northern (solid curves, lower axis) and the southern (dashed curves, upper axis). The average source densities were obtained by binning the stars into strips of 0.1 deg in longitude by 1.8 deg in latitude. Four mag ranges are shown. Regions where spiral arm tangencies have been identified by other tracers are indicated by vertical solid and dotted lines. The curves can be fit quite accurately by both exponential and Bessel functions for $l > 30°$.

statistics. When combined with the 2MASS data, the Catalog and Archive provide spectral energy distributions sampled at seven wavelengths between 1 and 8 μm. In the following, I will summarize our determination of the stellar distribution in the inner Galaxy, the details of which are given by Benjamin et al. (2005).

Figure 1 shows the distribution of all stars in the Catalog in the magnitude range of 6.5 to 12.5 at 4.5 μm. This range is fainter than the nonlinear threshold of the detectors and substantially brighter than the 5σ detection limit ($\sim$ 14th mag). The average number of stars of all magnitudes in each $0.1° \times 0.1°$ bin is $\sim$ 1400 Catalog and $\sim$ 2200 Archive. As Figure 1 shows, there are $\sim$ 25% more stars at longitudes 10° to $\sim$ 29° than at the corresponding angular distances from the center in the south (350° to 331°). The continuous line near $b = 0°$ is the source-count weighted latitude distribution, which is a measure of the departure from symmetry above or below the Galactic plane. This only varies between $b = \pm 0.05°$, implying a highly symmetric stellar distribution about $b = 0°$. The contours in Figure 1 show the distribution of $\sim 40,000$ unusually red ($m_K - m_{[8]} \geq 3.0$) stars that also coincide with bright radio continuum sources (i.e. massive star formation regions and/or massive molecular clouds). These unusual stars could be red either because they are seen through large, optically thick molecular clouds or because they are YSOs deeply embedded in optically thick infalling circumstellar envelopes. Either way, it is clear that they trace regions of high infrared opacity where GLIMPSE stellar number counts are depressed.

It was found that the number counts with longitude can be accurately fit by a modified Bessel function or an exponential function at angular distances of 35°–65° from the galactic center. The best esti-

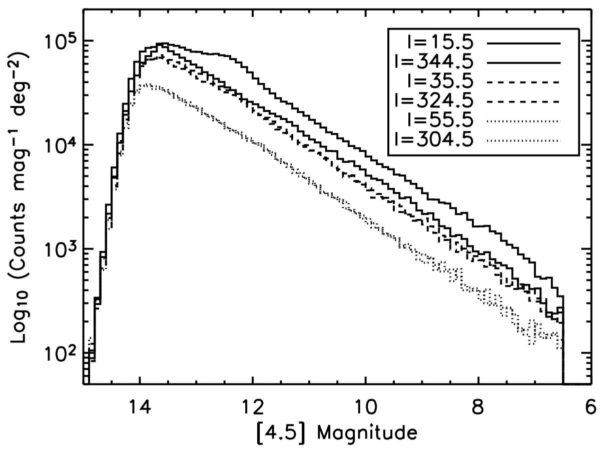

Fig. 3. The number of stars as a function of magnitude at 4.5 m for pairs of sight lines equidistant from the galactic center. The outer galaxy ($l = 55.5°$ and $304.5°$, dotted curves) and middle galaxy ($l = 35.5°$ and $324.5°$, dashed curves) have about the same amplitude and slopes. The inner galaxy ($l = 15.5°$ and $324.5°$, solid curves) clearly shows that the south (lower solid curve) has fewer stars at all magnitudes than the north (upper solid curve). The north also has a prominent bump at ~ 12.2 mag.

mates for the angular and linear stellar scale lengths from our data are $20° \pm 2°$ and 3.4 ± 0.5 kpc (north) and $26° \pm 3°$ and 4.3 ± 0.5 kpc (south). Several longitude intervals ($l \sim 26°$, 32–33°, and 307–308°) show stellar enhancements of $\sim 20\%$ above the exponential fit. It is suggested that these probably correspond to stellar spiral arm tangencies (possibly the "3-kpc arm", the Scutum arm, and the Centaurus arm) that are close to but not exactly coincident with tangencies traced by H I and CO. No evidence for stellar tangencies at the Sagittarius and Norma arms are evident. Finally, inside $|l| = 22°$ there appears to be a deficit of stars relative to that predicted by the modified Bessel function fit at higher longitudes. These points are apparent in Figure 2.

In Figure 3, the number of sources is plotted as a function of magnitude for three north/south pairs of directions equidistant from the Galactic center. Here we see that in the magnitude range of 6.5 to ~ 13.8, the directions 55.5° and 304.5° have the same number of stars at all magnitudes, as do the directions 35.5° and 324.5°. However, at 15.5° (and other directions for $l < 23°$) there are more stars at all magnitudes in the north than at the same angular distance from the center in the south. There is also a "hump" at $l = 15.5°$ and other longitudes interior to $\sim 29°$ at magnitudes ~ 12 to ~ 13.0 that is not seen in the south. To determine where the stars are lo-

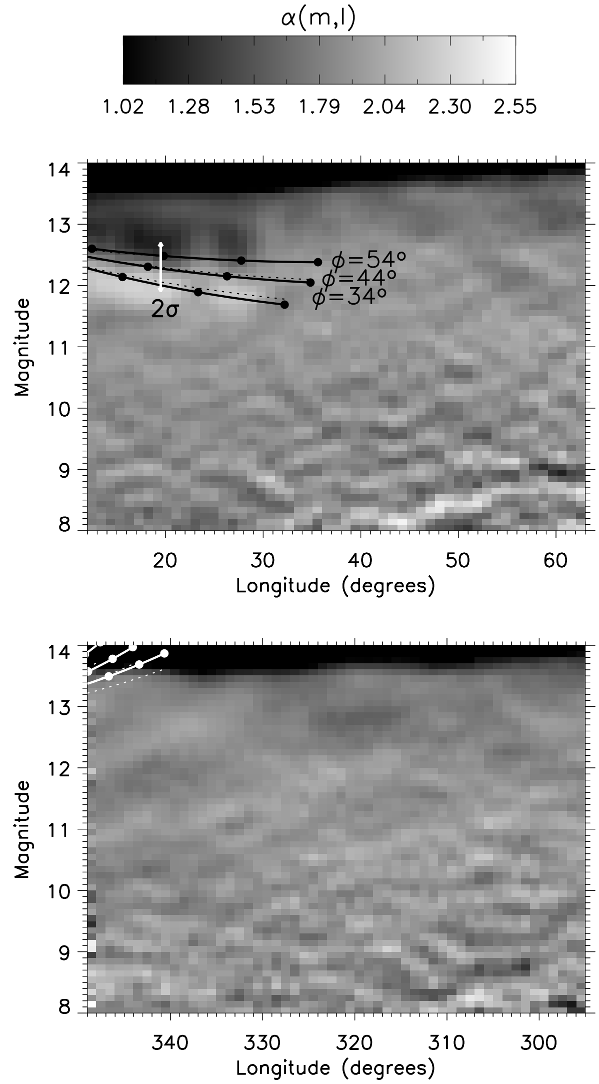

Fig. 4. The power law slope α of stars as a function of apparent mag and galactic longitude. The position of the ~ 12 mag hump seen towards $l = 15.5°$ in Fig. 3, is seen here to vary systematically in both mag and longitude. The dispersion of the bump is about 1 mag. The locus of mag and longitude of a model bar consisting of stars of absolute magnitude $M_{4.5} = -2.25$, foreground extinction of $A_{4.5}(r) = 0.05$ mag/kpc and three different orientations ϕ of the bar relative to the galactic center-sun line. The dots indicate radii of 3, 4, and 5 kpc along the bar. The lower panel shows that the bar is for the most part beyond our detection limit.

cated that contribute to the "hump," we plotted the gradients of the 15.5° curve in Figure 3 as a function of magnitude and longitude, as shown in Figure 4.

We find that the hump population extends from our inner boundary of 10° to $\sim 29°$, the stars have

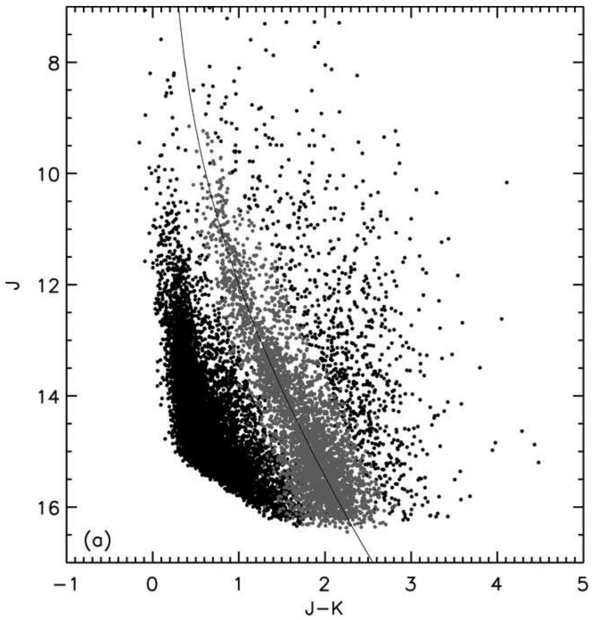

Fig. 5. A color-magnitude diagram (J vs J-K) showing dwarf (black dots) and red clump giant (gray dots) field stars near longitude $l = 284°$. The solid curve is the locus of red clump giants (RCGs). By selecting the RCGs, Indebetouw et al. (2005) determined A_J/A_K, the absolute extinction with distance (J mag/kpc), and color excess ratios from near- to mid-IR color-color plots. From the A_J/A_K and near- to mid-IR color excess ratios the interstellar extinction law was derived.

an apparent magnitude ~ 12.5 at 4.5 μm with a dispersion (FWHM) of about 1 mag. The average mag also systematically becomes fainter with decreasing longitude. The simplest interpretation of these data is a central bar of radius 4.4 kpc with an inclination of 44° to the line joining the Sun to the galactic center. It appears to be traced primarily by K III stars with an average absolute magnitude −2.16 at 4.5 μm.

3. THE MID-INFRARED REDDENING LAW

The mid-infrared interstellar reddening law is essential to understand and interpret the data produced by infrared satellites such as *COBE/DERBE, ISO, MSX,* and *Spitzer*. The mid-IR interstellar reddening law was determined by Lutz et al. (1996) toward the Galactic center using *ISO* data. Indebetouw et al. (2005) used the much more extensive data from 2MASS and GLIMPSE to color-select red clump giants from which they were able to determine the general interstellar reddening law in three arbitrary directions ($l = 42°$, 284°, and toward the massive star formation region RCW49). The red

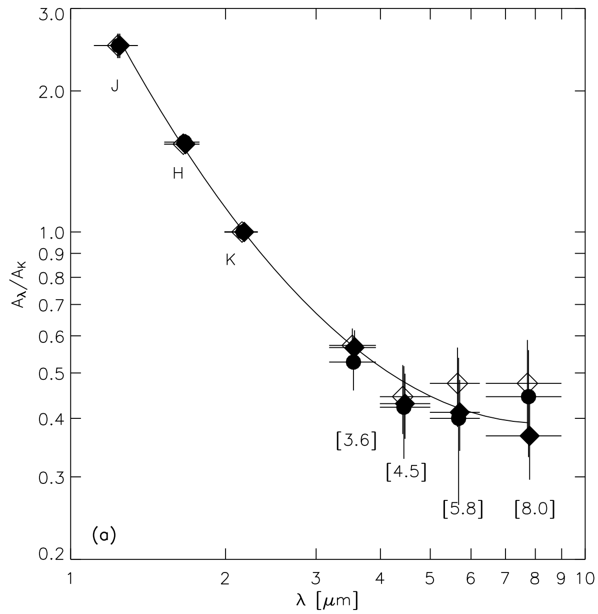

Fig. 6. The interstellar extinction law calculated for three directions in the disk of the galactic plane (Indebetouw et al. 2005). The symbols are for sightlines along $l = 284°$ (solid diamonds), 42° (open diamonds), and toward RCW49 (solid circles). Note the almost wavelength independent extinction from ~ 4.5 to 8.0 μm.

clump giants (RCGs) are easily distinguished from field main-sequence stars in the near infrared (NIR), as shown in Figure 5. Since the intrinsic magnitudes of the RCGs are known and have a relatively narrow dispersion, it was possible to determine the ratios A_J/A_K, A_J/kpc, A_K/kpc, and color excess ratios $E_{\lambda-K}/E_{J-K} = (A_\lambda - A_K)/(A_J - A_K)$ from which the extinction law A_λ/A_K was determined. The resulting interstellar extinction law is shown in Figure 6. The best analytic fit to the NIR-MIR reddening law from GLIMPSE is

$$\begin{aligned} log[A_\lambda/A_K] &= 0.61(\pm 0.04) - 2.22(\pm 0.17)\log(\lambda) \\ &\quad +1.21(\pm 0.23)[\log(\lambda)]^2 \end{aligned}$$

where λ is in μm (Indebetouw et al. 2005). Note that from about 4.5 to 8.0 μm the extinction appears to be almost independent of wavelength.

4. RCW49

RCW49 is a large massive star formation region lying at a distance of ~ 4 kpc in the southern Galactic plane. It is ionized and heated by the compact stellar cluster Westerlund 2 (W2). It also contains two Wolf-Rayet stars (WR20a,b). Two papers have

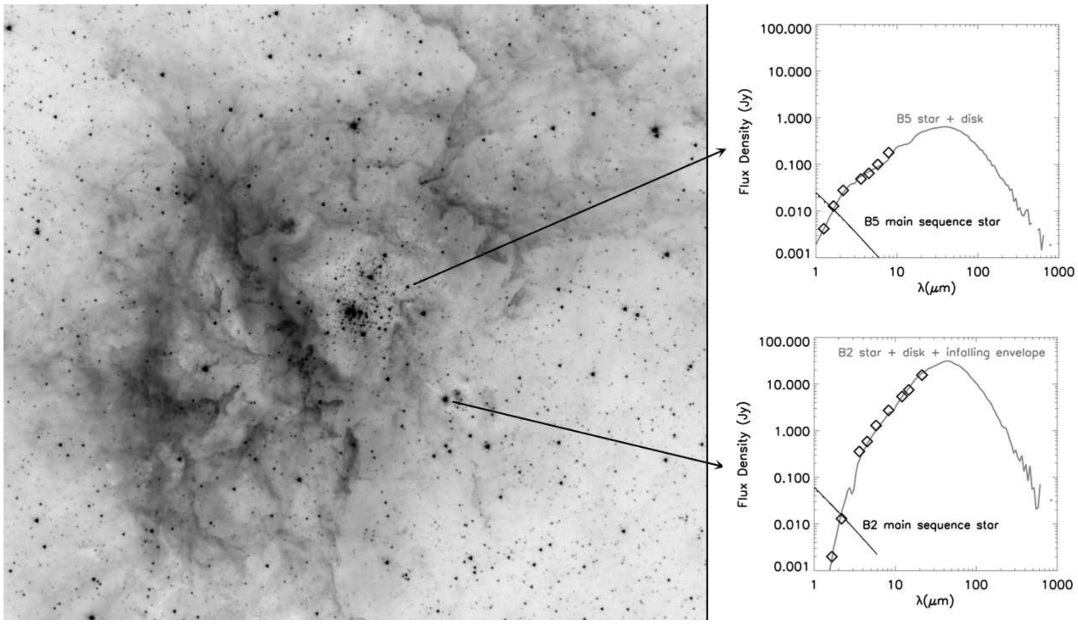

Fig. 7. A GLIMPSE grayscale image of the massive star formation region RCW49. The arrows indicate two stars whose spectral energy distributions have been fit by YSO models at different stages of evolution. The data in the upper panel is best fit by a B5 V star plus an accretion disk; the data in the lower panel is best fit by a B2 V star with an accretion disk plus a large envelope that is feeding the disk. The symbols are observed points and the curve is the model. The lower panel represents a protostar at an earlier stage of evolution than the star in the upper panel.

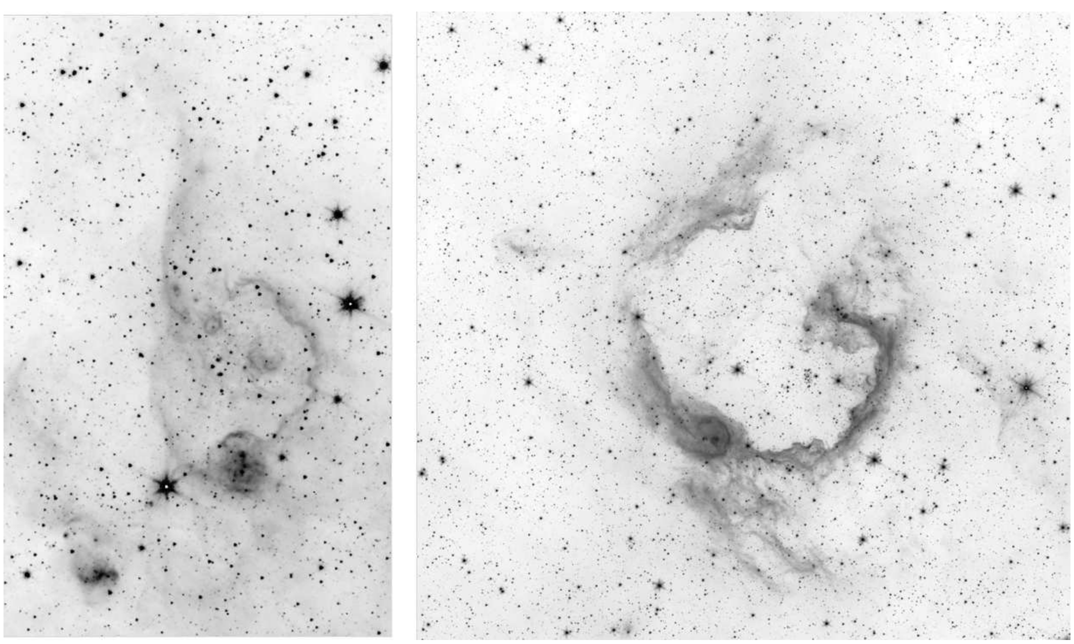

Fig. 8. Images of two dust bubbles in the GLIMPSE survey. Both strongly suggest formation of a younger generation of stars by compression and cooling of ambient gas due to the expansion of a bubble driven by the winds and radiation pressure of an older generation of stars. The appearance of small bubbles on the periphery and within a projected larger bubble is suggestive of stimulated or triggered star formation. Hydrodynamic models that would support this supposition are planned.

been published by the GLIMPSE team on this region. Churchwell et al. (2004) discussed the general morphology of the dust and ionized gas associated with RCW49. It was shown that within a radius of ~ 5 arcmin, dust emission is greatly reduced due to the action of stellar winds and radiation from W2 and the WR stars which has evacuated the dust and filled this cavity with stellar wind-shocked, low density but very hot gas. Even though the dust emission is quite chopped up by stellar wind action, outside this radius of ~ 5 arcmin the azimuthally averaged emission falls off in all IRAC bands as r^{-3}, consistent with the average density falling off as r^{-2} and dust emissivity proportional to density. It was also found that in the ionized region, as determined from radio continuum, the Brα line is a major contributor to IRAC band 2 emission. Whitney et al. (2004) showed that there are more than 350 young stellar objects (YSOs) associated with RCW49. It was shown that Monte Carlo radiative transfer models of YSOs in various early stages of evolution fit the observed SEDs quite well, as illustrated in Figure 7. The IRAC images of RCW49 also revealed at least two bow shocks produced by colliding stellar winds. Bow shocks have also been detected in several massive star formation regions. Colliding stellar wind shocks are likely to be a general feature of young massive star formation regions.

5. STIMULATED (TRIGGERED) STAR FORMATION

Rings (presumably bubbles seen in projection) are very common morphologies observed in the GLIMPSE survey. This is also true in the MSX survey. GLIMPSE provides a view of these structures with about ten times the spatial resolution and about 100 times the sensitivity of MSX and reveals very fine filamentary structures, pillars, and sharp inner boundaries of the bubbles. Many of the bubbles seen by GLIMPSE are too small to be resolved as bubbles by MSX.

Several bubbles in the GLIMPSE survey show compelling evidence for triggered or stimulated star formation by an earlier generation of stars. The winds and radiation of these stars compress the surrounding ambient interstellar medium, initiating collapse of quasi-stable, pre-existing molecular clumps (Cyganowski et al. 2004; Povich et al. 2004). Figure 8 shows two examples of large bubbles that have smaller bubbles within or on their periphery in which several, presumably younger, stars are apparent at 3.6 and 4.5 μm. Model fits to both the older and younger generations of stars are being calculated to demonstrate that the stars in the small peripheral bubbles are indeed younger than those responsible for producing the larger bubble and are consistent with the size of the bubbles for which they are responsible. This is work in progress and will be reported in a later communication. If these morphological structures prove to be what they appear, they will clearly demonstrate that stimulated star formation is an important mode of star formation that will have to be included in the global star formation rate in the Milky Way and other spiral galaxies.

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