A WISE Survey of Star Formation in Nearby Molecular Clouds

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Abstract

During the last decade, sensitive mid-infrared observations obtained by the Spitzer Space Telescope significantly increased the known population of Young Stellar Objects (YSOs) associated with nearby molecular clouds. With such a census, recent studies have derived star formation rates and efficiencies in the different environments. Given the small Spitzer coverage of some of these clouds, relative to their extended regions, these YSO populations may represent a limited view of star formation in these regions. We are taking advantage of mid-infrared observations from the recent NASA Wise-Field Infrared Survey Explorer (WISE) mission, which provides an all-sky view and therefore full coverage of the nearby clouds, to assess the degree to which their currently known YSO populations may be under-representative of the extended, more complete populations. By extending the well established classification method developed by Spitzer Legacy teams to archived WISE observations, we are assembling a more complete census of YSOs associated with these clouds. This WISE survey is discussed, and initial results are presented.

Motivation

Evans et al. (2009) compiled the results of the Cores-to-Disks (c2d) Spitzer survey into a synthesis of typical star-formation properties of the nearby molecular clouds, including star-formation rates and efficiencies as well as estimates of the lifetimes of the early Class I and Flat stages relative to the lifetimes of the Class II stage. That study presented a nice review of the literature concerning the method of comparing the populations of the YSOs at various stages to estimate the lifetimes (or the "half lifes" of the stages), the assumptions involved, and previous results, which were primarily based on small numbers of YSOs. The lifetimes are referenced to that of the Class II stage, which Evans et al. concluded 2 ± 1 Myr is the best estimate. Considering the large molecular clouds observed by c2d, as a whole set, the number of Class I YSOs relative to Class II is ~0.27, implying the lifetime of the Class I stage is ~0.5 Myr, assuming young stars evolve in the same manner, independent of mass, and assuming star formation in the clouds has been continuously occurring long enough for it to populate the full scale of the Class II stage. In reality, these assumptions are likely not the case, but this approach is the natural first step.

Heiderman et al. (2010) extended the study to include all of the large molecular clouds observed by the c2d and Gould Belt (GB) Spitzer surveys. The star formation rates of these clouds vary considerably, from ~0.5 – 3 $M_\odot$ Myr^{-1} for the Auriga North, Chamaeleon III, and Scorpius clouds to the more procreating clouds, such as Perseus and Serpens-Aquila, with rates of ~100 – 400 $M_\odot$ Myr^{-1}. **When comparing some of the star formation rates listed in Table 1 of Heiderman et al., one cannot help but question the degree to which some of these rates reflect observational or methodological biases rather than intrinsic characteristics of the clouds.** For example, the star formation rate of the main part of the Auriga cloud was found to be 42.7 ± 23 $M_\odot$ Myr^{-1}, while part of the same filament, Auriga North, was determined to have a significantly different rate of 0.50 ± 0.27 $M_\odot$ Myr^{-1}. The only reason these regions were separated was due to the limited time available for observing. **Do these regions truly have starkly different intrinsic star-formation properties, or are such differences at least somewhat affected by the limited coverage?**

Given the large range of star formation rates, as well as striking images such as those in Figure 1, of large populations of YSOs in some extended clouds (e.g., Perseus; Jørgensen et al. 2006) while others appear relatively more quiescent (e.g., Musca), it is certainly believable that intrinsic differences among the clouds exist that regulate the degree of star formation. While it is clear that YSOs, especially those of earlier classes, are closely associated with dense gas (e.g., Enoch et al. 2007; Enoch et al. 2008), many of the Spitzer images with identified YSO populations tantalize us by showing these populations (even the early Class I populations) with spatial distribution that suggest they continue beyond the Spitzer-covered fields. **What else is beyond the boundaries of these Spitzer-covered fields?**

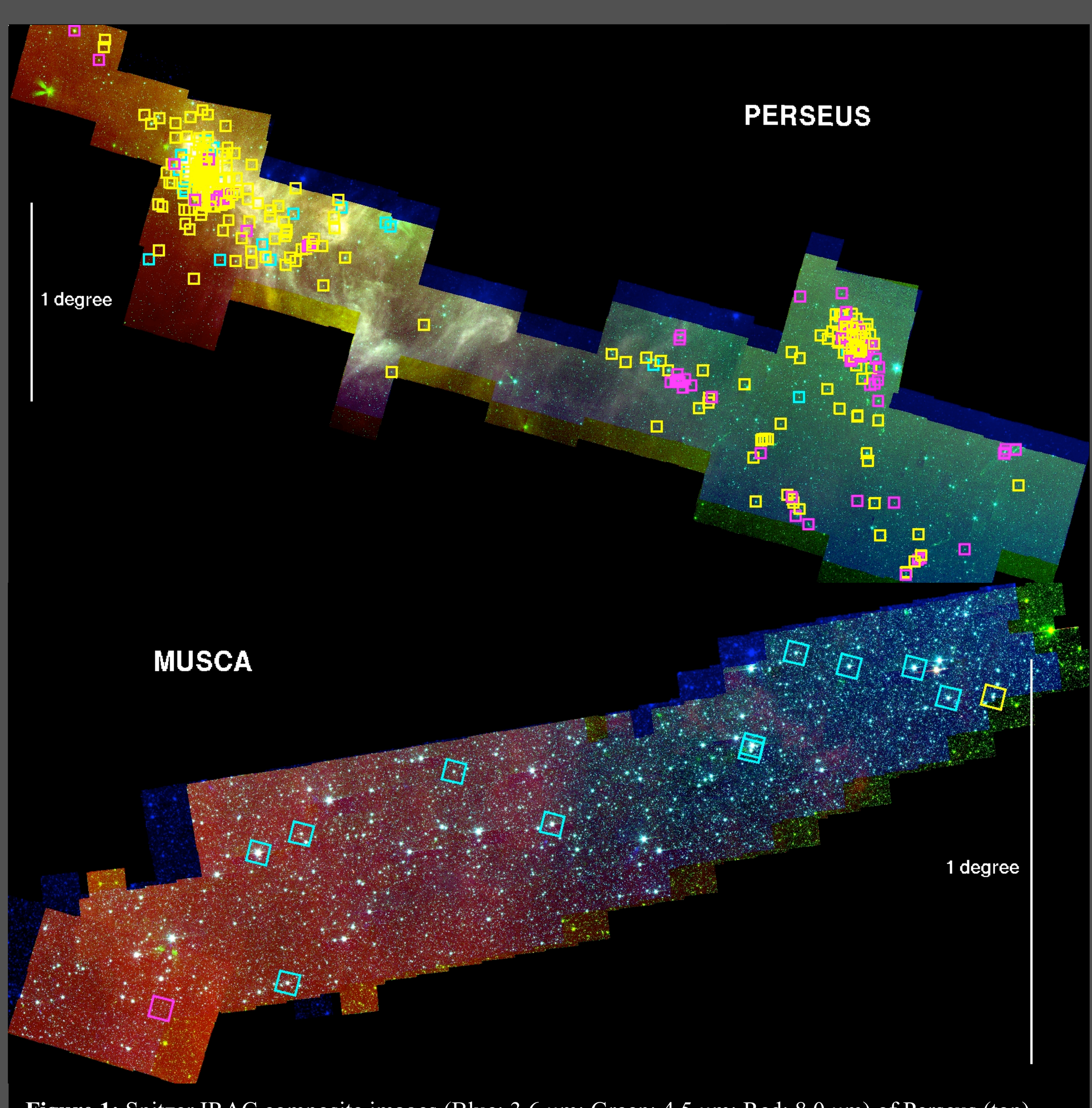

Figure 1: Spitzer IRAC composite images (Blue: 3.6 μm; Green: 4.5 μm; Red: 8.0 μm) of Perseus (top) and Musca (bottom) clouds covered by the c2d and GB surveys. YSOs identified with these Spitzer data are shown by the small magenta (Class I), yellow (Flat and Class II), and cyan (Class III) squares.

YSO Identification Based on WISE

In order to obtain a clearer view of the likely YSOs associated with nearby molecular fields, we are taking advantage of the all-sky coverage of the WISE mission and have extended to the WISE data the classification scheme developed by the c2d team for Spitzer data (e.g., Harvey et al. 2007). The critical Spitzer color-magnitude and color-color diagrams, as well as their WISE analogs, are shown in Figure 2 for the Perseus molecular cloud. For WISE, we have shifted the critical regions in the color-magnitude and color-color diagrams based on inspection of the relative distributions of extincted stars, YSOs, and likely galaxies, which were classified by the Spitzer observations. For example, comparing the WISE ([4.6]-[12], [4.6]) and the Spitzer ([4.5]-[8.0], [4.5]) color-magnitude diagrams (top left plots in Figure 2), it is clear that the distributions extend to redder colors in the WISE diagram as the wavelength baseline is greater and the 12-μm band overlaps the well known 9.8-μm silicate absorption band. In addition, the WISE observations are not as deep as the Spitzer observations, as evident by comparing the vertical distributions in these diagrams. Thus, in extending this color-magnitude criterion to WISE, we shifted the dashed lines toward brighter [4.6] and redder [4.6]-[12] colors.

With a working version of the classification scheme extended to the WISE data, the primary challenge currently is to filter the WISE data to remove photometry discrepant from the deeper Spitzer photometry. In comparing Spitzer and WISE photometry, there are significant numbers of spurious detections and flux discrepancies, particularly in the 12-μm and 22-μm WISE bands. As shown in Figure 3, these discrepancies can be 1-4 magnitudes, even for sources with apparently reliable photometry based on their low WISE- and Spitzer-cited photometric uncertainties. We believe the source of the discrepancy may be an improper background subtraction for some sources observed toward regions of nebulosity. We are experimenting with methods to remove such discrepant photometry, based primarily on radial flux profiles constructed from aperture photometry available from the WISE archive. Since our goal is to study star formation in regions not covered by Spitzer, we must develop a method based solely on the WISE data. Figure 3 summarizes results from our current filtering method.

Once our WISE-data-filtering method has undergone more extensive testing, we will identify the YSO populations in the extended regions of Perseus shown in Figure 4, as well as in the extended regions of other nearby molecular clouds.

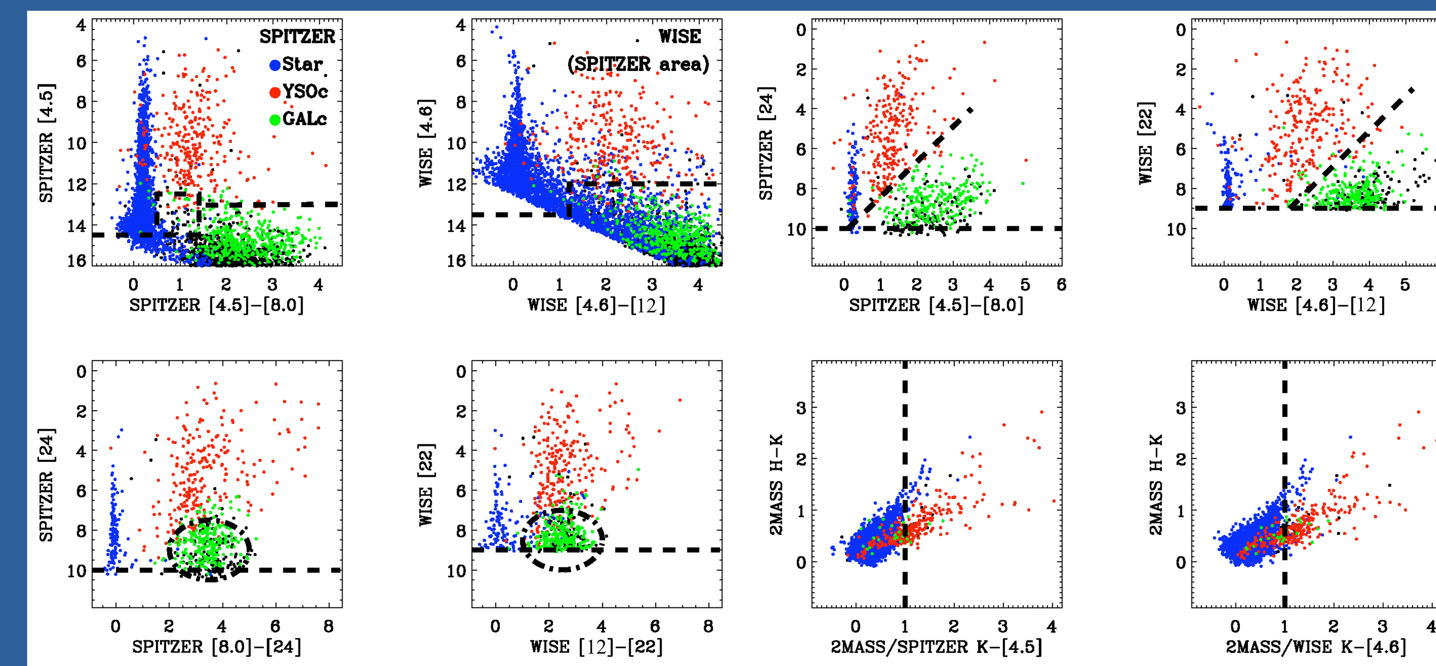

Figure 2: Spitzer diagrams used by the c2d and GB teams to identify YSOs, and the same diagrams extended to WISE photometry. Critical regions are identified by the dashed lines, ellipses, and squares. The data points included on these diagrams correspond to Perseus Spitzer sources, where sources classified as Star, YSOc, and GALc are identified by the blue, red, and green symbols, respectively.

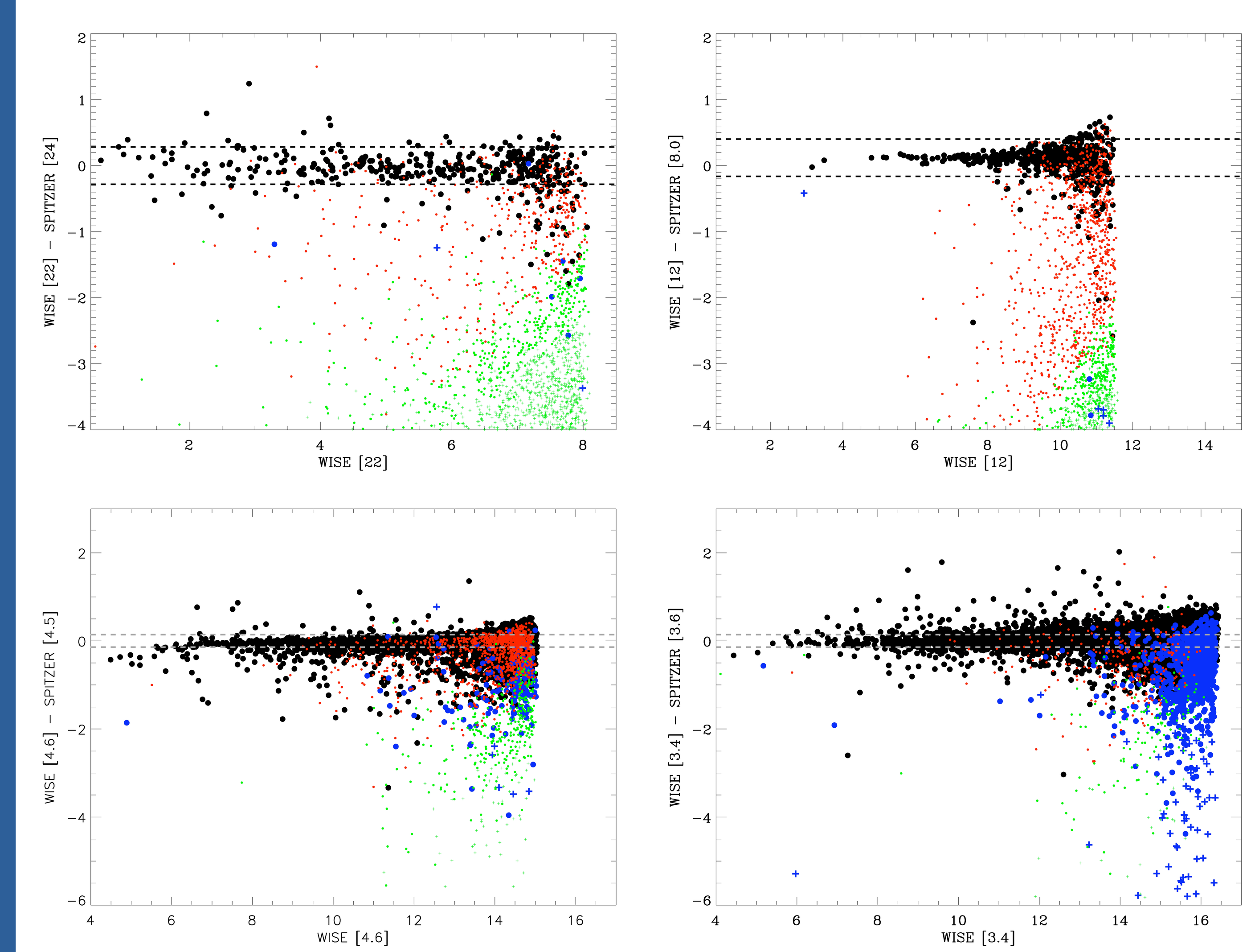

Figure 3: Comparison of WISE photometry with that of Spitzer. Larger (black, blue) symbols show WISE data accepted by our WISE-selection criteria, while smaller (red, green) symbols show the rejected WISE data. All 22-μm and 12-μm WISE data plotted are those with WISE photometric errors less than 0.20 mag; the 4.6-μm and 3.4-μm WISE data are those with WISE photometric errors less than 0.10 mag. Black and red dots represent data with similarly reliable Spitzer photometry, while the blue and green dots represent Spitzer photometry with greater uncertainties. Plus signs indicate Spitzer upper limits. Our WISE-selection criteria remove most of the WISE-discrepant data.

Acknowledgements

This research is funded in part by the NASA Astrophysics Data Analysis Program, grant NNX13AF246. This project will use the all-sky WISE data, supplemented with all-sky 2MASS data, to characterize and study the star-formation efficiencies in nearby molecular clouds by including extended regions not covered by deeper Spitzer surveys. Source classifications and extinction maps, similar to those produced by the c2d and GB Spitzer teams, will be produced by this project and may be made available to the community through the NASA Infrared Science Archive (IRSA).

References

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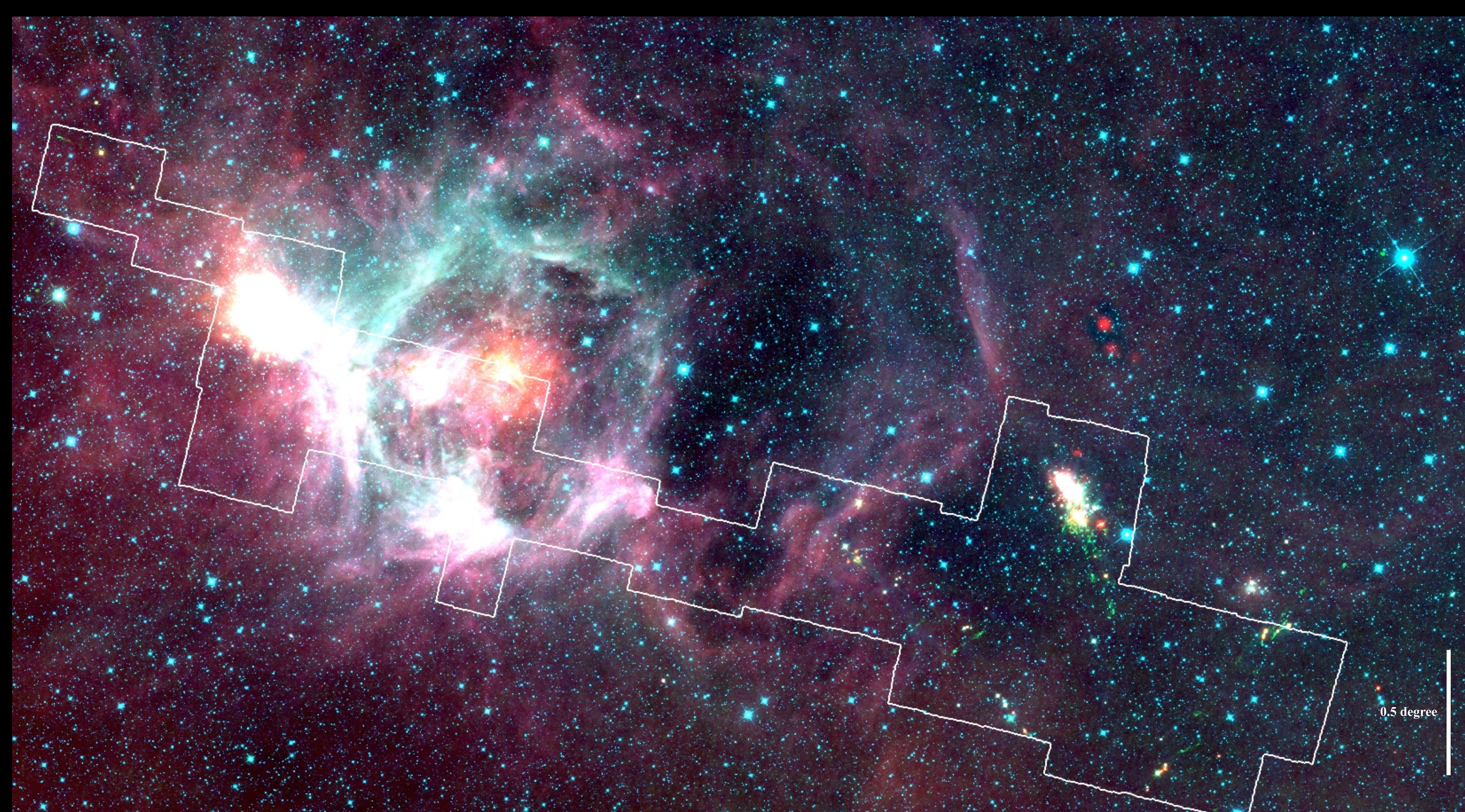

Figure 4: WISE composite image (Blue: 3.4 μm; Green: 4.6 μm; Red: 22 μm) of the region around the Perseus molecular cloud. That portion covered by c2d with Spitzer is indicated by the white contour.