Identifying Primordial Substructure in NGC 2264 with the *Spitzer* Space Telescope

PAULA S. TEIXEIRA[1,2], CHARLES C. LADA[1], ERICK YOUNG[3], AND MASSIMO MARENGO[1]

[1]Smithsonian Astrophysical Observatory, Cambridge, MA USA, [2]University of Lisbon, Portugal, and [3]Steward Observatory, AZ, USA

email: pteixeira@cfa.harvard.edu clada@cfa.harvard.edu eyoung@as.arizona.edu mmarengo@cfa.harvard.edu

UNIVERSIDADE DE LISBOA

Abstract

We present new results on the massive young cluster NGC 2264 based on the analysis of data acquired from the *Spitzer* Space Telescope. The MIPS (Multiband Imaging Photometer for *Spitzer*) has enabled us to identify the most recent episodes of star formation in NGC 2264. In particular, the 24 μm data combined with submillimeter observations from Wolf-Chase (2003) indicate that the most recent star formation events have occurred primarily within dusty filaments of dense gas in the central regions of the complex. These observations provide interesting constrains for theoretical models of collapsing molecular clouds. Additional IRAC (Infrared Array Camera) and near-infrared JHK 2MASS data has enabled us to assemble spectral energy distributions which help elucidate the natures of the deeply embedded sources and confirm their extreme youth and status as protostellar objects.

NGC 2264

NGC 2264 is a young cluster in the Monoceros (Mon) OB1 complex, associated with a giant molecular cloud. It is located at 800 pc (Dahm & Simon 2005) and there are numerous evidences of ongoing star forming activity in the cluster. These consist of a plethora of molecular outflows (Margulis et al. 1988; Williams & Garland 2002) and Herbig-Haro objects (Reipurth et al. 2004). Lada & Lada (2003) classify NGC 2264 as a hierarchically structured cluster. It is currently understood that hierarchical structure is a tell tale sign of the influence of turbulence of the gas and dust that collapsed into stars (e.g. Elmegreen et al. 2000). We aim to explore the star formation history in NGC 2264 and thereby understand its structured nature. *Spitzer* has allowed us to probe the embedded population, and in doing so has revealed a curious clustering of young stellar objects (YSOs). We present here results on the study of this region in NGC 2264 which we refer to as the "Spokes".

Observations and Data Reduction

The IRAC (Infrared Array Camera) and MIPS (Multiband Imaging Photometer for *Spitzer*) data were obtained through the GTO programs 37 and 58, respectively. IRAC is an imaging camera operating at four wavelengths, 3.6, 4.5, 5.8, and 8.0 μm, while the MIPS data are comprised of imaging in three broad spectral bands centered nominally at 24, 70, and 160 μm. NGC 2264 was observed in two epochs, with two dithers of 0.6 and 12 s of exposure time for each frame. The total mosaiced area corresponds to $\sim 0.7° \times 1.2°$. The IRAC data were reduced using the *Spitzer* Science Center pipeline, while the MIPS data were reduced through the pipeline developed at the University of Arizona. After source extraction with SExtractor software, we used the usual IRAF routines to perform aperture photometry.

The Spokes Cluster

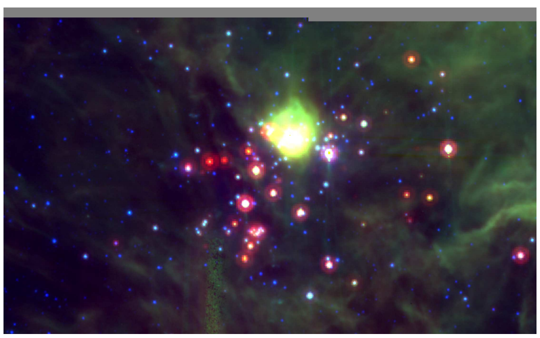

Figure 1: False color image of the Spokes region (Teixeira et al. (2005). The color coding corresponds to red of 24 μm, green of 8.0 μm, and blue of 3.6 μm. The image shows unusual linear spatial alignments of the brightest 24 μm sources. The central saturated source is IRAS 06382+0939 (IRAS 12).

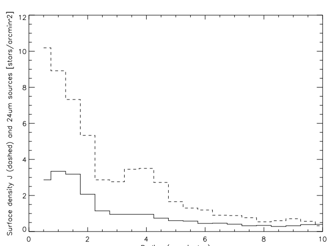

Figure 2: Comparison of the surface density radial profiles of sources detected in the 24 μm MIPS band (solid line) and the 2MASS J-band (dashed line)(Teixeira et al. (2005).

Figure 1 shows bright 24 μm sources that seem to be arranged in two/three arms that extend from IRAS 12, resembling "wheel spokes". By building radial surface density profiles, shown in Figure 2, we find that the distribution of the 24 μm sources is indeed more structured than the population detected at shorter wavelengths. We note that Allen's source is situated approximately 5′ from the center of the Spokes cluster, which accounts for the second peak in the J-band radial profile.

We also find sub-clustering within the Spokes cluster itself: there exists a dense agglomeration of sources 2.3′ southeast of IRAS 12. We are able to resolve the sources within this sub-cluster in bands 1 and 2 of IRAC, unfortunately this is not possible for the rest of our data due to resolution. Counting 10 sources detected at 4.5 μm within a radius of 12.5″(0.05 pc), we find the stellar number density of this sub-cluster to be 2.2×10^5 pc^{-3}.

From Figure 3 we see that this sub-cluster of the Spokes is coincident with a core of strong dust emission at 850 μm (and 450 μm, see Wolf-Chase, 2003). Margulis et al. (1998) observed a large CO outflow in this region. Williams & Garland (2002) detect a deep, redshifted absorption dip in their HCO^+ spectra of this core, interpreted as an infall signature.

Star Formation within Filamentary Structures

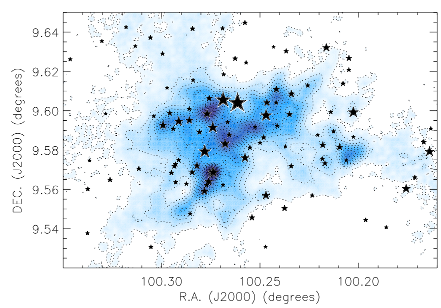

Figure 3: Comparison of the spatial locations of 24 μm MIPS sources with dust emission at 850 μm (JCMT SCUBA data courtesy from Wolf-Chase et al. (2003)). The greyscale and contours represent the submillimeter detections (contours range from 0 to 2 in steps of 0.1 Jy/beam), while the stars mark the position of the sources detected at 24 μm with MIPS. The sizes of the stars are proportional to their magnitude, having the brightest 2.0 magnitudes and the faintest 12.0 magnitudes.

Spectral Energy Distributions

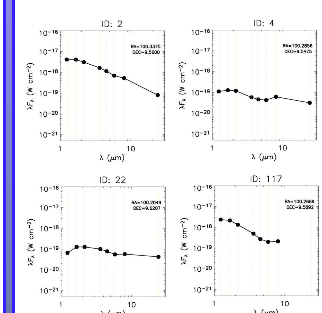

Figure 4: Examples of spectral energy distributions (SEDs) of sources in our catalogue that present excess emission in at least one of the IRAC and MIPS bands. Objects with IDs 4 and 22 are Class I sources, showing a typical SED of sources that are located within the dusty filaments, the other two objects are Class II sources and represent the SEDs of sources surrounding the filaments.

The SEDs are a useful tool in assessing the evolutionary stage of the YSO. The majority of the sources that are located within the dusty filaments present SEDs with a positive (or flat) slope. On the other hand, the sources in the immediate surroundings, areas with less dust emission, show typical T Tauri star SEDs.

Conclusions

- We find that the MIPS 24 μm data is the better tracer of the distribution of the youngest population in NGC 2264.
- These protostars are spatially coincident with dense and dusty filaments.
- Spectral energy distributions show that these highly embedded protostars are Class I sources, while the population in the immediate surroundings of the dusty filaments are Class II/Class III sources detected primarily with IRAC.
- Within the Spokes region we identify a dense sub-cluster with IRAC data, that is coincident with a bright 24 μm detection and strong submillimeter emission at both 450 and 850 μm. It could also be the engine of the CO outflow observed by Margulis et al. (1988).
- We begin to see a separation of the protostellar population, as the distribution of the YSOs still display the spatial configuration of the parental molecular cloud from which they formed.

References

- Dahm, S. E. & Simon, T. 2005, AJ, 129, 829
- Elmegreen, B. G., Efremov, Y., Pudritz, R. E. & Zinnecker, H. 2000, Protostars and Planets IV, 179
- Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
- Margulis, M., Lada, C. J., & Snell, R. L. 1988, ApJ, 333, 316
- Reipurth, B., Yu, K., Moriarty-Schieven, G., Bally, J., Aspin, C., & Heathcote, S. 2004, AJ, 127, 1069
- Teixeira, P. S., Lada, C. J., Young, E., Marengo, M. et al. 2005, in preparation
- Williams, J. P. & Garland, C. A. 2002, ApJ, 568, 259
- Wolf-Chase, G., Moriarty-Schieven, G., Fich, M. & Barsony, M. 2003, MNRAS, 344, 809

ACKNOWLEDGMENTS

P. Teixeira acknowledges support from the Fundação para a Ciência e Tecnologia (FCT) Programa Operacional Ciência Tecnologia Inovação (POCTI) do Quadro Comunitário de Apoio III, graduate fellowship SFRH/BD/13984/2003, Portugal.

This work is based on observations made with the *Spitzer* Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

†Address for correspondence: Harvard-Smithsonian Center for Astrophysics 60 Garden Street, M.S. 72 Cambridge, MA 02138, USA