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Multi-wavelength modeling of the circumstellar disk of the Butterfly Star in Taurus

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Abstract

We present first results of our self-consistent multi-wavelength modeling of the Butterfly Star in Taurus. The continuum spectral energy distribution of the disk and envelope around this young stellar object as well as spatially resolved images in the range from 1 μm to 2.7 mm are taken into account. In particular, a submillimeter observation at 894 μm and a new high angular resolution 1.3 mm map obtained with the Submillimeter Array (SMA) and the Plateau de Bure Interferometer (PdBI), respectively, are considered for the first time.

1. Introduction

The Butterfly Star in Taurus is a showcase-like Class I young stellar object surrounded by a perfectly edge-on orientated circumstellar disk. Its near-infrared appearance is dominated by a totally opaque band that bisects the scattered light nebulosity. With high angular resolution studies at near-infrared to millimeter wavelengths, the Butterfly Star is an ideal target to provide insights into the change of the opacity structure due to disk evolution and early planet-forming processes, such as grain growth and dust settling.

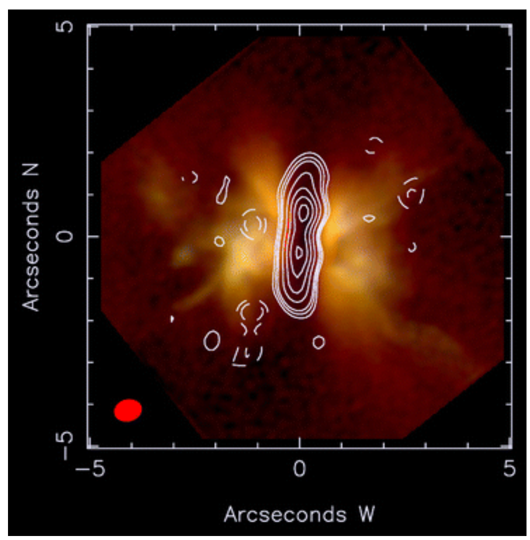

Figure 1: 894 μm map of the Butterfly Star overlaid on the near-infrared scattered-light map ([3], [7]).

2. Observations

A first model, that has been developed by Wolf et al. (2003, [6]) is based on high-resolution near-infrared images obtained with the Hubble Space Telescope camera NICMOS (see Fig. 1) and resolved 1.3 mm and 2.7 mm maps of the disk obtained with the Owens Valley Radio Observatory. While the millimeter observations are sensitive only to radiation being emitted from dust in the dense region within the disk, the near-infrared images are dominated by scattering of the stellar light on the dust in the circumstellar envelope and the disk "surface". These observations trace different physical processes in different regions of the circumstellar environment, but both are strongly related to the dust properties in the system.

In 2008, Wolf et al. ([7]) presented a spatially resolved 894 μm map of the Butterfly Star (see Fig. 1), obtained with the SMA. In comparison to the previously developed model, the predicted and observed radial brightness profiles agree well in the outer disk region but differ in the inner region with an outer radius of $80 - 120$ AU (see Fig. 2). In particular, they find

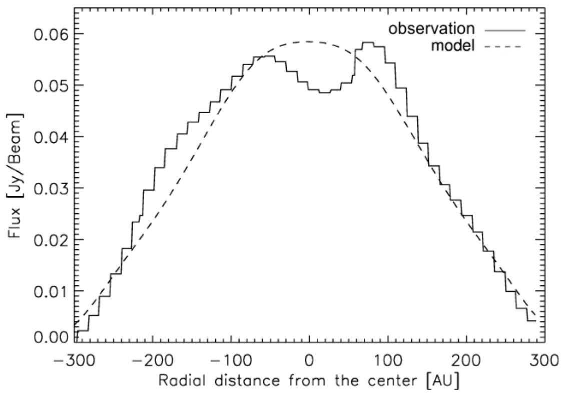

Figure 2: Radial brightness profiles at $894\,\mu$m ([7]). The dashed line shows the old model.

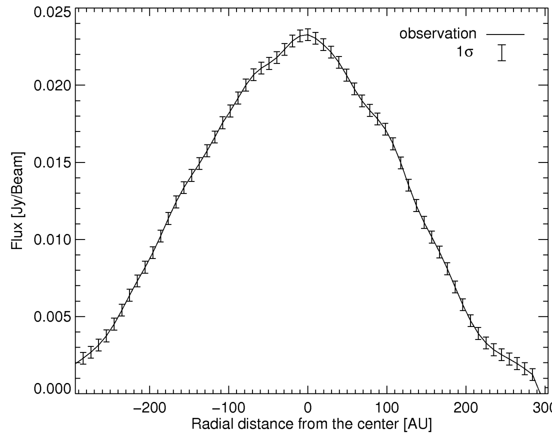

Figure 3: Radial brightness profile at 1.3 mm.

a local minimum of the radial brightness distribution at the center, which can be explained by an increasing density/optical depth combined with the decreasing vertical extent of the disk toward the center.

Recently, we obtained a new, higher resolution 1.3 mm map of the Butterfly Star using the PdBI (see Fig. 3 for the radial brightness profile). This new map confirms the prediction that the disk is optically thick at wavelengths as long as $894\,\mu$m.

3. Modeling

Our goal is to find a self-consistent model that is in agreement with all the observational data. Our modeling shows that the new 1.3 mm map supports the theory of an optical depth effect as an explanation of the local minimum in the radial brightness distribution in the submillimeter and excludes a large inner disk hole. Besides general conclusions about the global disk structure and evidence for grain growth in the disk, we also provide detailed constraints for the disk structure and dust grain properties in the inner (< 100 AU), i.e., the potential planet-forming region.

For our continuum radiative transfer simulations we use our code MC3D ([5]). It is based on the Monte Carlo method and solves the continuum radiative transfer problem self-consistently. Our multi-wavelength modeling of the unique circumstellar disk of the Butterfly Star now additionally includes the $894\,\mu$m SMA map, the new 1.3 mm PdBI map, mid-infrared observations obtained with VISIR at the Very Large Telescope, and the spectrum in the range from $3.6\,\mu$m - $8\,\mu$m and at $24\,\mu$m and $70\,\mu$m obtained with the Spitzer Space Telescope ([4]). For the fitting process of the observational data we are using an efficient fitting algorithm based on a simulated annealing technique, a Markov Chain Monte Carlo method similar to the Metropolis-Hastings algorithm ([1], [2]).

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