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disksurf: Extracting the 3D Structure of Protoplanetary Disks

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Software

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Summary

`disksurf` implements the method presented in Pinte et al. (2018) to extract the molecular emission surface (i.e., the height above the midplane from which molecular emission arises) in moderately inclined protoplanetary disks. The Python-based code leverages the open-source `GoFish` (Teague, 2019) package to read in and interact with FITS data cubes used for essentially all astronomical observations at submillimeter wavelengths. The code also uses the open-source `detect_peaks.py` routine from Duarte & Watanabe (2021) for peak detection. For a given set of geometric parameters specified by the user, `disksurf` will return a surface object containing both the disk-centric coordinates of the surface as well as the gas temperature and rotation velocity at those locations. The user is able to 'filter' the returned surface using a variety of clipping and smoothing functions. Several simple analytical forms commonly adopted in the protoplanetary disk literature can then be fit to this surface using either a chi-squared minimization with `scipy` (Virtanen et al., 2020) or through an Monte-Carlo Markov-Chain approach with `emcee` (Foreman-Mackey et al., 2013). To verify the 3D geometry of the system is well constrained, `disksurf` also provides diagnostic functions to plot the emission surface over channel maps of line emission (i.e., the emission morphology for a specific frequency).

Statement of need

The Atacama Millimeter/submillimeter Array (ALMA) has brought our view of protoplanetary disks, the formation environment of planets, into sharp focus. The unparalleled angular resolution now achievable with ALMA allows us to routinely resolve the 3D structure of these disks; detailing the vertical structure of the gas and dust from which planets are formed. Extracting the precise height from where emission arises is a key step towards understanding the conditions in which a planet is born, and, in turn, how the planet can affect the parental disk.

A method for extracting a 'scattering surface,' the emission surface equivalent for small, sub-micron grains was described in Stolker et al. (2016) who provided the `diskmap` package. However, this approach is not suitable for molecular emission, which traces the gas component of the disk and has a strong frequency dependence due to Doppler shifting from the disk rotation. Pinte et al. (2018) presented an alternative method that could account for this frequency dependence and demonstrated that this could be used to trace key physical properties of the protoplanetary disk, namely the gas temperature and rotation velocity, along the emission surface. An example script was provided with this publication demonstrating the algorithm: https://github.com/cpinte/CO_layers.

While the measurement of the emission surface only requires simple geometrical transformations, the largest source of uncertainty arises through the handling of noisy data. As more works perform such analyses, for example Teague et al. (2019), Rich et al. (2021), and Law et al. (2021), the need for an easy-to-use package that implements this method was clear. Such a package would facilitate the rapid reproduction of published results, enable direct comparisons between numerical simulations and observations (Cataldi et al., 2021; Schwarz et al., 2021), and ease benchmarking between different publications. `disksurf` provides this functionality, along with a tutorial to guide users through the process of extracting an emission surface. The code is developed in such a way that as the quality of observations improve, the extraction methods can be easily refined to maintain precise measurements of the emission surface.

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