SF2A 2025
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APE: PROVIDING PHYSICAL CONDITIONS FOR CHEMICAL MODELS AND SYNTHETIC OBSERVATIONS

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Abstract. Chemical models and synthetic observations are of paramount importance to interpret and predict observations. Coupled together they offer a great opportunity to increase our understanding of the processes involved in star formation. The new publicly available Analytical Protostellar Environment (`APE`*) code has been designed for this purpose. It allows simulations and synthetic observations to be performed at low computational cost, providing a powerful approach to interpret and predict observations. `APE` uses a semi-analytical model describing dynamically the formation and the evolution of the protostar and its environment from the onset of the prestellar collapse to the end of the Class I stage. It includes the central object, the envelope, the protoplanetary disk and the outflow, and is interfaced with publicly available codes such as `Nautilus`, `RADMC-3D` and `Imager`, allowing to produce chemical abundance maps, emission maps and synthetic observations.

Keywords: Methods: analytical, Methods: numerical, Stars: protostars, Stars: formation, Protoplanetary disks, ISM: molecules, Astrochemistry

1 Introduction

The study of star formation requires the combination of dynamical, physical and chemical processes occurring over a wide range of spatial and temporal scales. Observations with current facilities such as ALMA or NOEMA provide increasingly detailed information on the physical structure and chemical composition of protostars and protoplanetary disks. However, interpreting these data remains challenging, as it requires connecting the observed signatures with the underlying physics and chemistry of the system.
While magnetohydrodynamics (MHD) simulations provide detailed descriptions, they remain computationally expensive. Analytical and semi-analytical approaches, in contrast, allow for fast exploration of parameter space. To address this need, we developed the **Analytical Protostellar Environment (`APE`*)** code (Marchand et al. 2025a), designed to facilitate the production of chemical abundance maps and synthetic observations.

2 APE general description

`APE`* is a semi-analytical model describing dynamically the formation and evolution of a protostar and its environment, including the envelope, the central object, the disk, and the outflow. The collapse starts from a critical Bonnor-Ebert sphere, for which analytical prescriptions are used to compute density and velocity profiles. The model then describes the collapse and the temporal evolution of the system. Dust grain growth is also included to provide consistent opacities for radiative transfer. The full description of the code is presented in Marchand et al. (2025a).
The code can be run on standard laptops with very low computational cost. `APE` is provided with interfaces to work with the 3 phase gas-grain chemical code `Nautilus` (Ruaud et al. 2016), the radiative transfer code `RADMC-3D` (Dullemond et al. 2012) and the `Imager`† package of `Gildas`‡. `APE` can be used through three different modes:

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*`https://bitbucket.org/pmarchan/ape_code`
†`https://imager.oasu.u-bordeaux.fr/`
‡`http://www.iram.fr/IRAMFR/GILDAS`

2.1 Snapshot mode

The snapshot mode generates 2D maps of density, temperature, velocity fields and dust size-distribution at a given time. This mode uses a 2D grid in spherical coordinates, assuming a cylindrical symmetry and a symmetry with respect to the mid-plane of the disk. These snapshots can be used as direct input for `RADMC-3D` or as initial conditions for `Nautilus`.

2.2 Particle mode

The particle mode follows the history of an individual particle throughout the collapse, providing time-dependent trajectories, velocities, densities, temperatures and visual extinction. This mode is particularly suited for coupling with chemical codes such as `Nautilus`.

2.3 Grid of particles

Snapshot and particle modes can be combined to reconstruct the full history of an entire snapshot. In this approach, a map is generated similarly to the snapshot mode, with a particle assigned to each grid cell. `APE` then traces the trajectories of these particles backward in time. The resulting density and temperature histories can then be used with a chemical modeling code (such as `Nautilus`) to generate maps of chemical abundances.

3 Applications and studies

`APE` has been used to study the evolution of complex organic molecules during star formation (Marchand et al. 2025b). We also modeled the chemical impacts of luminosity outbursts in protostellar envelopes (Espagnet et al. in prep.), especially those on complex organic molecules (COMs). Furthermore, we have investigated potential biases in protostellar observations through the use of synthetic observations (Marchand et al. in prep.). Figure 1 shows the different steps used in Marchand et al. (2025a) to produce synthetic observations that can be compared to the observations of IRAS04302+2247 in Podio et al. (2020). These applications illustrate the versatility of `APE` in bridging physical evolution, chemistry, and observations.

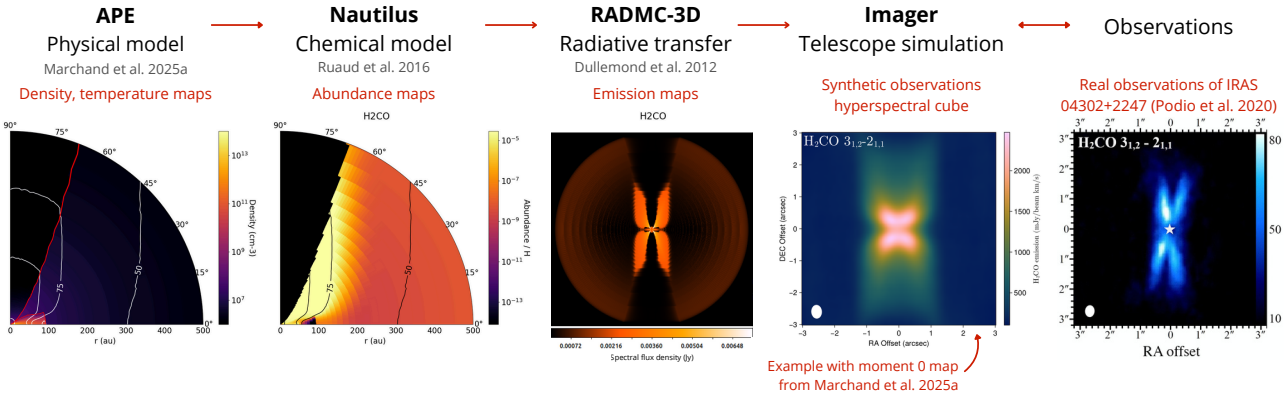

Fig. 1. Different steps used in Marchand et al. (2025a) to produce synthetic observation corresponding to observations of H_2CO in IRAS04302+2247 (Podio et al. 2020).

4 Conclusions

`APE` is a fast and flexible semi-analytical code that provides physical conditions of protostellar systems and facilitates the production of chemical studies and synthetic observations. Thanks to its modular design and interfaces with widely used codes, it enables an efficient exploration of parameter space and direct comparison with observations.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Chemtrip, grant agreement 949278).

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