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Synthetic observations of star formation and the interstellar medium

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ABSTRACT

Synthetic observations are playing an increasingly important role across astrophysics, both for interpreting real observations and also for making meaningful predictions from models. In this review, we provide an overview of methods and tools used for generating, manipulating and analysing synthetic observations and their application to problems involving star formation and the interstellar medium. We also discuss some possible directions for future research using synthetic observations.

1. Part 1. introduction and scope

1.1. What is a synthetic observation?

In this paper, we review the growing field of synthetic observations, with a particular focus on star formation and the interstellar medium (ISM). It therefore makes sense to begin by describing what we mean by a "synthetic observation". The majority of astronomy and astrophysics has been driven by the detection and manipulation of photons. That we can learn so much from light alone owes much to the fact that its nature is fundamentally determined by the conditions (temperature, density, velocity and composition) of the emitting source and its interaction with any intervening material. The photons we detect carry this information with them, and from them we can infer much about the source of the photons and the foreground material. However, doing so can be a serious challenge.

There are means of comparing a theoretical model with observations that do not directly account for the details of photon emission from the system. For example, consider a numerical simulation of a molecular cloud collapsing to form stars. In this instance, one might compare the population of stars formed in the model with the observed initial mass function (IMF) or binary fraction (e.g. Bate, 2012). Although this comparison relates a theoretical and an observed quantity, it would not be considered a synthetic observation. Comparisons of this kind are extremely useful, but do have limitations, particularly if one wants to learn about the properties of the gas and dust, rather than the properties of discrete objects such as stars or planets.

In practice, if we want to compare observations of the gas and the dust in a particular astrophysical system (e.g. a molecular cloud) with theoretical predictions for the behaviour of that system, we need to concern ourselves with the details of photon emission and absorption.[1] Because observations are generally limited in terms of resolution and sensitivity, and moreover give us information on projected quantities (column densities, line-of-sight velocities etc.), rather than the full three-dimensional distributions, deriving information on the underlying physical state of the system can be challenging and can produce ambiguous results. It is therefore often much better to compute the expected observational properties of the theoretical model in a way that can be compared as closely as possible with real observations. Therefore, ***we define a synthetic observation to be a prediction, based on theoretical models, of the manner in which a particular astrophysical source will appear to an observer***. Most commonly, we are interested in observing sources in emission, and the majority of our review deals with this case. However, in some circumstances (e.g. extinction mapping of molecular clouds), it is more interesting to observe the source in absorption, by looking at its effect on the light from a background

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[1] In principle, one could also produce synthetic observations of non-photon signals, such as gravitational waves or direct detection of cosmic rays, but this is outside of the scope of this review.

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object or collection of objects and so theoretical predictions of absorption maps should also be considered to be synthetic observations.

1.2. Why synthetic observations?

As we have already mentioned, there are quantities such as the stellar IMF that can be generated by theoretical models and compared with observational data to test the accuracy and predictive capability of the model, without us ever having to generate a synthetic observation. One might therefore ask whether synthetic observations add value beyond providing an image that looks similar to the observed data (particularly when using the same colour scheme). However, we argue here that there are many important reasons why one might want to generate a synthetic observation. These include:

1. *Observational limitations/complexity*. Since the optical depth of the ISM is highly frequency dependent and different lines probe different ranges of density and temperature, observations of only one or a few tracers do not provide us with all of the information available within a theoretical model. Furthermore, real observations are subject to other processes such as noise, resolution constraints and interferometric effects that may be significantly different to the limitations of a numerical model. The ISM is also geometrically complex and evolves on timescales beyond the human experience. Observers are therefore limited to a restricted view of a single snapshot in time. Comparing theoretical models directly with observations without accounting for these effects may therefore be misleading (indeed in practice even our example of measuring the IMF or binary fractions directly from a model might yield different results to the values an observer would infer when studying the same system, e.g. Koepferl et al., 2017b). For example, the filamentary nature of much of the dense ISM has only been resolved in recent years, particularly with *Herschel* (e.g. André et al., 2010; Molinari et al., 2010a; Arzoumanian et al., 2011; Palmeirim et al., 2013), despite being a feature of numerical models for some time (e.g. Monaghan, 1994; Clark and Bonnell, 2005; Bate, 2009). Synthetic observations of the *Herschel*, pre-*Herschel* and perhaps also future instrumentation view of star-forming clouds may all yield distinct characteristics.
2. *Observing mode/time estimates*. Synthetic observations are an incredibly useful tool for estimating the observational parameters (e.g. choice of mode, time) required to detect a given system. In particular, for highly oversubscribed facilities such as ALMA, where only around 30 per cent of proposals were successful in cycle 4[2], a synthetic observation demonstrating that t minutes of observing time using antenna configuration y really is essential to achieve the science goals adds valuable weight to a proposal.
3. *Test observational diagnostics*. Synthetic observations allow us to test diagnostics that are used by observers in controlled situations where the exact conditions (temperature, density, velocity, etc.) of the model are known. For example, running observational pipelines on synthetic data and checking the accuracy of the inferences. They can also be used to improve existing techniques and to develop new diagnostics.
4. *Bespoke models for direct interpretation of real observations*. Synthetic observations can be used to interpret real observations of specific systems (so called backwards modelling). This use is particularly prevalent in the protoplanetary disc community, where the structure and kinematics are readily parameterised (e.g. Williams and Best, 2014), but is also used by the star formation/ISM community. For example, the Orion Bar PDR (Pellegrini et al., 2009; Andree-Labsch et al., 2017), Sgr B2 (Lis and Goldsmith, 1990; Schmiedeke et al., 2016) and Taurus Molecular Cloud 1 (TMC-1; see e.g. Gratier et al., 2016) are just a few targets that have been the subject of bespoke modelling. A challenge with such modelling is that there can be degeneracies between the model, observations and reality. Large numbers of calculations may therefore be required.
5. *Additional predictive power*. Synthetic observations offer numerical modellers additional predictive power. For example kinematic signatures that might be detected in emission line profiles, or the spatial distribution of different emission sources.
6. *Astrochemical probes*. Astrophysical systems act as laboratories for astrochemists to study the microphysics in extremes of density and temperature. Probing the composition of such a system requires computing the emission properties to compare with observations.
7. *Designing new telescopes*. Synthetic observations can model and accurately predict the capabilities of new and forthcoming instruments in any wavelength regime. Such application is vital for guiding the development of (potentially very expensive) new equipment and also for developing and testing data processing pipelines.

Some members of the community refer to a theoretical model as having some ingredients, with synthetic observations acting as the “taste test” between theory and reality (Goodman, 2011).

Clearly then, synthetic observations have a broad range of uses. Given their ever increasing application across astrophysics this usefulness is being recognised.

1.3. Types of synthetic observation

Our definition of a synthetic observation in 1.1 is somewhat generous in the sense that it permits simple measures of the emissivity to be considered a synthetic observation. In practice there are many layers of complexity that can be woven into a synthetic observation (which will be explored in more detail throughout this review). For now we define three basic classes of synthetic observation, although as we will see, the boundaries between these classes are not always clear:

1. *A simple emissivity measure*. The output of some microphysically simple model describing an astrophysical scenario (be it parametric or dynamical) is assumed to have the correct conditions (density, temperature) to inform an analytic computation of the emissivity. An example of this type is the free-free radio continuum emissivity, which is a simple function of the temperature and electron density only and so can be estimated without any detailed radiative transfer. This class requires some simple consideration of the microphysics but comes at almost no additional computational cost.
2. *Detailed microphysics and radiative transfer*. This involves a more robust computation of the abundance and level population of the emitting species. Typically, this requires a solver for the chemical state of the gas/dust, and/or a treatment of radiation transfer to determine the level populations or the dust temperature. Radiative transfer is also used to produce the resulting synthetic observable (e.g. an image or spectrum). An example would be explicitly computing the ionisation state of species in an H II region using a photoionisation code, which coupled with the temperature and density can be used to compute, for example, forbidden line emission. Often, the detailed microphysical state of the system is determined in a post-processing step applied to a dynamical simulation with a more approximate model for the chemistry and for the thermal behaviour. In reality the dynamics, microphysics and radiative transfer (and magnetic fields) are all interlinked and modelling this inter-dependency is at the frontier of modern capabilities (Haworth et al., 2016).
3. *Inclusion of instrumentational effects*. This class extends either of the prior two to include observational/instrumentational effects such as noise, beam size convolution and interferometric filtering (e.g. see Koepferl and Robitaille, 2017).

[2] https://almascience.eso.org/documents-and-tools/cycle4/c04-proposal-review-process.

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