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The modelling of feedback in star formation simulations

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ABSTRACT

I review the current state of numerical simulations of stellar feedback in the context of star formation at scales ranging from the formation of individual stars to models of galaxy formation including cosmic reionisation. I survey the wealth of algorithms developed recently to solve the radiative transfer problem and to simulate stellar winds, supernovae and protostellar jets. I discuss the results of these simulations with regard to star formation in molecular clouds, the interaction of different feedback mechanisms with each other and with magnetic fields, and in the wider context of galactic- and cosmological-scale simulations.

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1. Introduction and scope of this review

The formation of stars is arguably the most important process in astrophysics, impacting virtually every theoretical and observational subfield. Despite its prominence and decades of intensive study, there is still much about star formation that is not understood. One reason for this slow progress is the fact that the conversion of gas to stars is a non-linear process. There are a variety of reasons for this, such as the non-linearity of the self-gravitational forces which lead to the collapse of individual stars, but the issue of most interest here is that the rate of star formation is influenced by stars themselves via feedback.

There are many other phenomena that affect the rate and morphology of star formation, such as mergers between galaxies (e.g. Hopkins et al., 2013; Whitmore et al., 2010), collisions between molecular clouds (e.g. Furukawa et al., 2009; Tasker and Tan, 2009) or the passage of spiral shocks through galactic discs (e.g. Bonnell et al., 2013; Meidt et al., 2013). However, while a given star-forming region may or may not have experienced these particular perturbations, feedback from the stars themselves is, by definition, *always* present, and it is this broad range of processes that are the focus of this review

Stellar feedback has been invoked, with varying degrees of success, to solve a wide range of issues and problems in astrophysics, including the slow and inefficient star formation observed in molecular clouds and on galactic and cosmological scales, the triggering of star formation, the formation of disc galaxies and the suppression of excess dwarf galaxy formation in cosmological simulations. A glance at almost any image from *HST*, *Spitzer*, *Herschel*, *WISE* and many ground-based images reveals that the structure of the ISM is riddled with bubbles, shells, pillars and outflows, none of which can be explained without invoking feedback. Since one of the main purposes of astrophysical simulations is to help explain what is observed in the Universe, it is clear that feedback is a critical component of such simulations, and of any general model of star formation.

More specifically, this is a review of *numerical simulations of feedback*. A self-gravitating pure-hydrodynamics problem would already be of sufficient complexity to require the use of high-dimensional computer simulations. The inclusion of additional physical processes, particularly the transfer of radiation, only makes the problem more complex and the necessity of using simulations all the greater. However, progress in this field is very rapid and the existence of a varied set of mutually-interacting feedback processes has resulted in a bewildering number of recent studies. A timely summary will therefore be of benefit to specialists and non-specialists alike. In this review, the fundamental physical processes will be only briefly rehearsed; a detailed overview can be found in Krumholz et al. (2014). The spotlight will instead fall on the algorithms that have been written to model them, and of simulations which have been performed including them, and what we have learned from these simulations. Numerical studies of feedback have a long and rich history (e.g. Garcia-Segura and Franco, 1996; Tenorio-Tagle, 1979; Tenorio-Tagle et al., 1985; Yorke et al., 1989). No single review could encompass all this work, and this article will concentrate on articles published for the most part in the last 10 years, and on two- or three-dimensional simulations.

Although feedback in the galactic context will be discussed, this review deals with *stellar* feedback and, despite its evident importance, AGN feedback will not be covered. Interested readers are referred to Fabian (2012). Similarly, since we are here concerned with the connection between stellar feedback and star formation, the focus will be on feedback from low- and intermediate-mass proto- and pre-main stars, and on O-stars, whose entire life-cycle is comparable to the lifetimes of GMCs. Planetary nebulae and feedback from accretion onto compact objects will not be examined, and readers are instead directed to Balick and Frank (2002).

For the most part, this review also does not cover feedback from Population III stars, an area of research which has grown substantially in recent years, and which is eloquently reviewed by Greif (2015).

Magnetic fields are not commonly regarded as a type of feedback and will not receive dedicated attention here. However, the presence of a magnetic field will likely alter the response of a fluid to some or all of the feedback mechanisms under consideration and several authors have performed simulations including both feedback and magnetic fields. This work will be discussed, but the algorithms used to model the magnetic field will not be described.

The structure of this article is as follows. Section 2 gives a brief introduction to the major feedback mechanisms, namely photoionisation, stellar winds, supernovae, accretion heating, radiation pressure and protostellar jets. Section 3 briefly introduces the major classes of astrophysical hydrodynamics codes – particle-based schemes such as SPH, grid-based schemes such as AMR, and the new generation of moving-mech codes. Section 4 surveys the algorithms used for modelling radiation transport, winds, supernova and jets. Section 5 discusses the science which has been done with the codes described in Section 4 with reference to particular astrophysical problems, including the fragmentation and destruction of molecular clouds and the formation and evolution of spiral and dwarf galaxies. Section 6 contains a short summary and outlook for the future.

2. Brief introduction to stellar feedback physics

Stellar feedback involves the insertion of matter, momentum and energy from stars into the surrounding fluid, from which the stars may also still be accreting gas. In terms of material, momentum and energy emitted *per star*, massive OB-type stars far outweigh their lower-mass brethren in importance. In clouds where there are no O-stars (either because the cloud mass is too small to support massive star formation, or because there has not been time for O-stars to form), feedback from low- and intermediate-mass stars in the form of jets and outflows and the conversion of gravitational potential energy to heat are dominant processes. On larger lengthscales and longer timescales, encompassing the formation and evolution of galaxies