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Feedback through molecular outflows

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Abstract. Molecular outflows are believed to occur during the formation of all stellar objects, and provide an insight into not only the forming star, but also the environment in which it develops. Discovered before their prediction, they are now a major topic of study for both observers and theoreticians, yet a great deal about them is still unknown. With cataloguing proceeding apace, more detailed studies of individual outflows can lead to both specific and statistical understanding of their significance on a larger scale. Here we provide a brief overview of the feedback produced by these outflows, and a short introduction to some recently initiated research into their composition and its development.

Keywords : Stars: formation – ISM: jets and outflows – ISM: kinematics and dynamics

1. Introduction

It is widely accepted as truth that the outflows generated during early star formation play a crucial role in the development process. The large kinetic energy in the outflow is assumed to be a result of the need to extract rotational energy from the central object. These outflows commonly consist of a highly collimated, fast jet, that provides at least part of the driving energy for a much wider, uncollimated and slower moving wind(Garatti et al. 2008), with the characteristics of both changing with the age of the driving source. Younger objects are believed to produce dense, relatively slow and molecular jets that entrain a large amount of material, converting to lighter, faster atomic jets as they age and the surrounding environment clears (Bontemps et

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al. 1996). While these attributes are well catalogued, their production, lifespan and content are still poorly understood as well as their larger impact on the environment in which they form.

With a large number of molecular outflows now known, and that number ever increasing (Davis et al. 2009), we increasingly understand that the outflows are not only significant for the forming star, but also for the cloud in which they form. These occur over a large range of scales. Outflows can develop into the well known multiple-parsec long chains of Herbig Haro objects, but are believed to form from the inner regions of the accretion disc, which may be just a few astronomical units across. The feedback they provide can be broadly divided into kinetic, with the transferal of energy and resulting morphological changes, and chemical, altering the chemistry in the warm, dense regions around the protostar and the larger molecular cloud.

2. Kinetic feedback

It has been believed for some time that the primary resistive force supporting molecular clouds against self-gravitational collapse is provided by supersonic turbulence(Klessen et al. 2000). The source of this turbulence is a contentious issue, with arguments for hierarchical gravitational collapse(Field et al. 2008), external turbulence in the ISM of the same sort that formed the molecular cloud initially(Mac Low & Klessen 2004), and kinetic feedback from protostellar outflows.

The nature of the kinetic feedback that would be provided by an outflow is itself unclear. The impact of the jet into the medium, and its entrainment of material as it passes through, will necessarily deposit a significant amount of energy. However, it is not only the quantity of energy that is deposited that matters, but the manner in which it is transferred. If the transfer is sufficiently supersonic, then it may be sufficient to support a forming cluster(Li & Nakamura 2006), or even to regenerate the entire region through outflows alone(Matzner 2007). However, doubts exist as to whether this is possible. Highly supersonic jets entrain little material, and much of the turbulence imparted by it may remain subsonic(Banerjee et al. 2007).

As well as simple kinetic transfer from the output impacting upon and entraining the surrounding medium, the cavities in the cloud left by jets and outflows once they cease may provide a source of turbulence(Cunningham et al. 2006:Quillen et al. 2005). These “fossil cavities” will collapse and generate turbulence within the cloud, though again the quantity that will be supersonic and the timescale over which it will remain so, is unclear. This turbulence will, however, be contributed at a different time to that of the jet. The cavities will not immediately collapse upon the cessation of the jet, as expansion will be continuing. If the jet can therefore provide a relatively short-lived but high intensity injection of supersonic momentum, the subsequent cavity collapse may provide a considerable, though much lower intensity addition over an extended period. The combined effect may be to inject a considerable quantity of turbulence into the local region, and in areas of high star formation could provide the dominant source of turbulence.

Our knowledge of the expansion and entrainment of outflows is limited by our knowledge of their formation. The source of the outflow itself is greatly debated, the thick cocoon of dust that surrounds a protostar occluding the vast majority of information that can be gathered in that region. Most research in the field supports the concept of the launching being related to magnetic field effects, though the specific relation is still disputed. Theories differ on the strength of magnetic field required, how the magnetic field interacts between the protostar, accreting material and outflow, and how the field changes during the collapse of a cloud into a core. Measurements of the magnetic field strength in molecular clouds is possible with radio astronomy, producing measurements of the changing field between the core and its surrounding envelope (Crutcher et al. 2009), but relatively few observations have been made.

Beyond the launch, the kinetics of an outflow itself is still relatively undefined. Outflows are frequently simulated as a smooth jet entraining material from a homogeneous environment, but we know reality is not so simple. Large scale features such as the well known string of Herbig Haro objects that make up the HH34 "superjet" can be attributed to large, periodic velocity variations in the outflow (Raga & Noriega-Crespo 1998). However, increasingly high resolution images of outflows show that the large structures are themselves fragmented. Dense knots labelled in previous images as single objects are resolved into groupings of smaller objects, which may themselves be unresolved clusterings. This may be caused by further small velocity variations and a minor precession in the source. Alternatively, the medium through which they travel may retain a sufficiently chaotic structure from the original cloud turbulence to provide a potential source for these small scale disruptions.

As we observe young stellar objects in finer resolution and our simulations grow increasingly accurate, it has become clear that stars rarely form as isolated bodies. A multiple body system that is producing an outflow is likely to display a precession, increasing the volume of material that it interacts with, and reducing the energy input of any individual region. When an isolated disc can fragment into a collection of numerous small bodies, capable of entering orbits unaligned to the original plane(Stamatellos & Whitworth 2009), the local environment of the jet launching region may include material travelling in orbits unaligned to the main accretion disc. This material could therefore enter the outflow from a random direction, producing alterations in the flow velocity, density, temperature and composition.

3. Chemical feedback

Observations of highly collimated H_2 jets are well known (Dionatos et al. 2009), yet conditions within the jet are not favourable for its formation. H_2 is observed travelling at over 100 km s^{-1}, yet is known to dissociate in shocks at much lower velocities (Smith 1994). The source of the jet will be hot, dense and irradiated, implying that molecules in accreted material would not survive to the jet launching. The molecules should therefore be introduced to the outflow at a point post-launching.

Ideas for the molecular loading of the jet include entrainment of slowly accelerated molecular material as the jet "turns on" (Lim et al. 2002) and the formation of molecules within the jet itself, as it rapidly cools in a dense region just after launching (Glassgold et al. 1991). The former of these seems largely dependent on the kinetic characteristics. The latter can be greatly influenced by the presence of interstellar dust, the resultant gas-grain interactions greatly enhancing the formation of H_2 and a wide variety of other molecular species. Despite this importance, and the many ongoing studies currently devoted to investigating and quantifying the rate and results of these interactions , the dust content in outflows and jets is poorly understood (Podio et al. 2009). The dust itself can be destroyed by heat and shocks, grow by freezing the gas into icy mantles, and the impact on molecular formation rates may rely as much on the size and type of grains that are present as the mass.

Outflows could therefore play a significant role in the development of dust-based chemistry within a cloud. Visible densities of various elements will be affected by their capture or release from the icy mantles, or disruption of the dust itself. Complex organic molecules have been observed in the outflows from low-mass stars (Arce et al. 2008), and this is attributed to their release from the grain mantles on which they formed during shocks. Recycling of the dust mantles could then lead to a source for the complex chemistry observed around protostars, and their release in an outflow return increasingly complex chemistry to the cloud as a whole.

Our predictions of chemical development within outflows are limited by our knowledge of their composition. A jet is normally assumed to be launched as a warm, ionic gas, that then slowly cools into a neutral atomic gas. The rate at which this cooling occurs and the gas neutralises are unknown. If the features are correct, cooling to temperatures of less than 100 K could occur rapidly, within hundreds or even tens of AU, yet jet material is rarely observed at such low temperatures. Collimated molecular hydrogen has been observed at hundreds of degrees in outflows from the youngest sources, though this may be warm, shocked material surrounding a cooler core (Dionatos et al. 2009).

The chemical evolution of a jet could therefore be largely decided within a very small distance from the driving engine, contained and hidden within the dense dust envelope. The combination of density, temperature and dust at the base of the launching jet and in its close environment will drive chemistry on a timescale much smaller than will be found anywhere else within the outflow. Adding in the effects of any turbulence within the envelope and the momentum imparted by the launching process, it may result that the dominant features of an outflow are defined by processes occurring within the first few AU. With our observations of this potentially crucial region inhibited by extinction and limited by resolving power, and simulations largely focusing on much greater scales, there is still much to be learnt.

4. Upcoming research

To begin investigating structures that may be found in the dense activity at the base of young outflows, we will produce models of the early development of a central jet within the inner envelope, beyond the point of collimation. A simulation space covering a region tens of AUs in size will be explored through the use of 2- and 3-dimensional hydrodynamic and magnetohydrodynamic simulations, generated with a Eulerian mesh based code that includes a chemical network to trace the molecular evolution. This will allow study of entrainment and acceleration of material by the jet within the inner core, and any chemical evolution that occurs within and around the jet in this dense, hot environment.

These simulations will attempt to explain the observed high velocity molecules and whether they can be attributed to material that has been entrained and accelerated without a dissociative shock, or to in situ formation along the jet path. They will also show the transfer of kinetic energy from the jet into the surrounding molecular material and how changing parameters of the jet impact upon the larger molecular outflow. Through variation of the atmospheric characteristics, we ultimately hope to better understand the impact on outflows produced by stars forming in multiple systems with dynamic envelopes, as opposed to the idealised, isolated and symmetric objects more commonly modelled.

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