Triggered Star Formation in a Turbulent ISM
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Dynamical processes in star forming regions: feedback and turbulence generation

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Abstract. Young stellar objects (YSOs) inject large amounts of momentum and kinetic energy into their surroundings. Feedback from low mass YSOs is dominated by their outflows. However, as stellar mass increases, UV photo-heating and ionization play increasingly important roles. Massive stars produce powerful stellar winds and explode as supernovae within 3 - 40 Myr after birth. While low-mass protostellar feedback can drive turbulence in cloud cores and even disrupt the star forming environment, feedback from massive stars plays important roles in the generation of cloud structure and motions in the entire ISM.

Keywords. stars: formation, stars: winds and outflows, ISM: kinematics and dynamics, turbulence

1. Introduction

Chaotic and turbulent motions are ubiquitous in the ISM. On galactic ($\sim$ 10 kpc) scales, turbulence can be driven by many processes, including infall from outside the Galaxy, gravitational forces exerted by tidal effects of nearby galaxies or mass concentrations within the galactic disk such as spiral density waves, and processes such as swing amplification, or magneto-rotational instability in the galactic disk (see the various reviews in this volume). While these sources inject energy and momentum into the ISM, convergent flows, vorticity, and dissipation into heat result in the decay of turbulent motions.

It is remarkable that ISM density structure, velocity fields, and turbulence can be characterized by simple power laws on scales ranging from many 10s of kpc to well under 1 pc. On scales larger than the scale-height of the Galactic disk near the Sun, about 100 pc, the disk gas is effectively 2 dimensional while on smaller scales this, disk gas is 3 dimensional. Why is there no break observed in the power-law relationships describing motions and structure in the ISM near 100 pc? Furthermore, why is there no signature of the transition from gravitationally unbound motions in the disk to gravitationally bound molecular clouds and cores? One possible reason is that motions in the ISM may not trace a simple cascade of energy, momentum, and vorticity from a single scale where it is driven to small scales where it is dissipated. Instead, motions may be driven on many scales and such injection may smear out the breaks expected where the flows change dimensionality or become dominated by self-gravity.

In star forming regions, energy and momentum injected by forming stars may dominate all other sources. Most stars are born from dense cloud cores in giant molecular clouds in transient open clusters and in expanding OB associations. Protostellar outflows and UV radiation churn and tend to disrupt parent molecular clouds. UV radiation, winds, and supernovae form superbubbles whose expansion sweeps up the surrounding ISM into shells or rings of denser gas. The roughly 8 $M_{\odot}$ B3 stars, the least massive to explode as type II supernovae and to produce significant amounts of ionizing radiation, have main-sequence lifetimes of order 30 – 40 Myr. Thus, an OB association or star cluster containing O and early B stars will actively power the expansion of the surrounding ISM and sweep-up shells on this time-scale. After the last supernova, the shell will coast and decelerate. Such superbubbles grow to sizes raging from 100 to over 1,000 pc, comparable to or larger than the typical thickness of the gas layer in galactic disks. They tend to sweep-up rings of dense gas within the galactic plane that become sheared by galactic differential rotation. McCray & Kafatos (1987) found that such rings fragment into self-gravitating clouds with masses or order 10^5 $M_\odot$ in 20 to 50 Myr.

2. Feedback

2.1. *Low-mass star forming regions*

When only low mass stars form, protostellar winds, jets, and bipolar outflows are the only viable form of feedback. Highly collimated jets with steady orientations and velocity tend to blow out of their parent clouds and don't couple energy and momentum efficiently to their surroundings. However, observations show that most YSO jets are surrounded by wide cavities and bipolar outflows that impact a relatively large volume in their surroundings.

Observations of Herbig-Haro (HH) objects show that jets are variable in ejection velocity, degree of collimation, and orientation (e.g. Reipurth & Bally 2001); these processes widen cavities. Ejection velocity variations produce shocks where fast flow elements catch-up to slower moving gas. Pressure gradients in the post-shock layers transform some of this velocity difference into motion orthogonal to the jet axis, resulting in the sideways splashing of ejecta. Examples of such "internal working surfaces" include chains of shocks along the axes of HH1/2 (Bally *et al.* 2002), HH34 (Reipurth *et al.* 2002), HH 26/47 (Hartigan *et al.* 2005), and HH 111 (Reipurth *et al.* 2001; Hartigan *et al.* 1999). Larger bow shocks with higher side-way motions tend to be located downstream from these knotty jets. Low-velocity CO flows and reflection nebulae trace entrained molecular gas and the walls of cavities excavated from the parent cloud by such variable jets. In some flows such as HH 46/47, Spitzer Space Telescope images trace these cavity walls by means of H_2 emission (Noriega-Crespo *et al.* 2004).

In the 40 $M_\odot$ L1551 region, a half-dozen outflows criss-cross the cloud. The most luminous YSO, the binary system L1551-IRS5 drives twin jets toward a large cavity lit by reflected starlight and HH objects (Moriarty-Schieven *et al.* 2006; Stojimirović *et al.* 2006). This flow has blown completely out of the L1551 cloud as evidenced by HH objects seen beyond the cloud edge along a line-of-sight containing many background galaxies (Devine *et al.* 1999). The momentum and kinetic energy budgets of the L1551 cloud are dominated by outflows.

While our attention tends to be drawn to the spectacular jets, many YSOs show only marginal evidence for collimated outflows. Forbidden line emission and absorption in many YSO spectra show clear evidence for winds with relatively wide opening angles. Jets also tend to be surrounded by lower density, wide angle winds (e.g. Reipurth & Bally 2001). Wide angle flows tend to generate wide outflow cavities from which ambient material has been displaced and accelerated.

In clustered star forming environments and multiple star systems, outflows can experience forced precession. A companion or passing star in a non co-planar orbit can torque a disk, leading to jet orientation changes. Observationally, such interactions result in outflows that exhibit S-shaped (in case of a uniform precession rate) or Z-shaped point symmetry (if the disk orientation is changed abruptly by a passing star on either a hyperbolic or eccentric orbit). Examples include HH 198 in the L1228 cloud (Bally *et al.* 1995), IRAS 20126+4104 (Cesaroni *et al.* 1997; Shepherd *et al.* 2000), and IRAS 03256+3055 in the NGC 1333 region in the Perseus cloud (Hodapp *et al.* 2005), and Cepheus A (discussed below).

Typical YSOs lose mass at rates ranging from $\dot{M} = 10^{-7}$ to 10^{-5} $M_\odot$ yr^{-1} at velocities ranging from 50 to over 300 km s^{-1}. These flows accelerate the surrounding cloud in momentum-conserving isothermal shocks at rates of order $\dot{P} = 5 \times 10^{-6}$ to 3×10^{-3} $M_\odot$ yr^{-1} km s^{-1}. If a cloud such as L1551 contains 10 outflows at any one time and each lasts 10^5 years, the total momentum transferred to the surrounding ISM is roughly $\dot{M}V\tau \approx 0.5$ to 300 $M_\odot$ km s^{-1}.

The observed ^{13}CO line-widths (away from outflows) in clouds such as the 1 to 2 pc diameter L1551 are around 0.5 to 1.0 km s^{-1}, corresponding to an $M_{1551}V$ product of 20 – 40 $M_\odot$ km s^{-1} (Larson 1981). Class 0 low-mass YSOs drive flows near the upper end of the mass-loss-rate quoted above for a time-scale of order few 10^4 years, followed by decreasing outflow power over the next 10^6 years as the forming stars evolve through the Class I phase to become classical T Tauri stars (Class II and III YSOs; Reipurth & Bally 2001). Thus, depending on the mass spectrum of YSOs and the star formation history of a particular core, outflows can play roles ranging from insignificant to dominant in the cloud momentum budget. The former case corresponds to clouds with low rates of star formation and little feedback while the latter corresponds to small clusters of stars in which the combined action of multiple YSO outflows tends to disrupt the cloud and terminate star formation. In low-mass star-forming regions, wide-angle winds and outflow cavity widening by jets with variable speeds and orientations increases the coupling of outflow momentum and kinetic energy to the surrounding ISM.

2.2. *Larger clusters and moderate mass star forming regions*

The rate at which random motions are generated by protostellar feedback in molecular clouds is difficult to determine with any degree of reliability. Even rough estimates require complete mapping of entire molecular clouds in tracers such as the optically-thin CO isotopes and dense gas tracers such as CS and/or HCO^+, assays of the YSO population in the cloud, sensitive multi-transition CO surveys for bipolar molecular outflows, and deep narrow-band imaging of shock tracers such as Hα, [SII], and the near-IR lines of [FeII] and H_2.

For many clouds in the Solar vicinity, surveys are becoming available at visual wavelengths (e.g. Reipurth *et al.* 2004; Walawender *et al.* 2005b; Bally *et al.* 2006b), and in CO (e.g. the "ancient" Bell Labs CO J=1-0 surveys of Orion A, B, and Perseus: Bally *et al.* 1987; Walawender *et al.* 2005; the FCRAO surveys of Perseus: Ridge *et al.*2006; the Molecular Ring: Jackson *et al.* 2006; and the Outer Galaxy: Brunt & Heyer 2002; Heyer, Carpenter, & Snell 2001).

The CO and visual wavelength surveys of the Perseus molecular cloud (Miesch & Bally 1994; Walawender *et al.* 2004; 2005b) provide an excellent example. The 10^4 $M_\odot$ Perseus cloud, located at a distance of roughly 300 pc contains over a dozen dense cloud cores (Enoch *et al.* 2006; Hatchell *et al.* 2005) several of which are actively forming clusters of several hundred low to intermediate mass stars. The cloud contains the 2 –5 Myr old cluster, IC 348 near its eastern end and the NGC 1333 region, perhaps the most active site of active star formation within 300 pc of the Sun (Quillen *et al.* 2005). About 150 YSOs have formed in NGC 1333 and several dozen are driving outflows into their surroundings. In the Spitzer IRAC near-IR images (Jorgensen *et al.* 2006), and in narrow-band Hα and

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[SII] images (Bally *et al.* 1996; Walawender *et al.* 2005b), the cloud is confusion-limited in shocks.

The analyses of Bally *et al.* (1996), Walawender *et al.* (2005b), and Quillen *et al.* (2005) indicate that the energy and momentum released by the dozens of outflows in the NGC 1333 cluster generate a sufficiently large $\dot{M}V$ product to drive the observed cloud motions, perhaps even enough to disrupt the cloud and to eventually stop star formation. Interestingly, Walsh *et al.* (2006) find evidence that gas is falling into this cluster at a rate of about $\dot{M} \approx 10^{-4}$ $M_{\odot}$ yr^{-1} with a speed of about a half to one km s^{-1}. The accretion rate is comparable to the overall star formation rate. However, for mass ejection rates from stars of order 10% or more of the accretion rate, and outflow speeds of 100 km s^{-1}, the $\dot{M}V$ product associated with this infall is lower than that generated by outflows.

Walawender *et al.* (2005b) present a complete narrow-band survey of the entire Perseus cloud, finding 150 currently active shocks that trace over 50 individual outflows. In addition to the virulent NGC 1333 region, several other cloud cores drive multiple outflows into their surroundings: Barnard 1 (Walawender *et al.* 2005a), the HH 211 region associated with the "Flying Ghost Nebula" located southwest of the older IC 348 cluster of several hundred young stars (Walawender *et al.* 2006), L1448 (Wolf-Chase *et al.* 2001), and L1455 (Bally *et al.* 1997). Additionally, Perseus contains isolated YSOs whose outflows impact adjacent cloud cores (e.g. L1451; Walawender *et al.* 2004).

Walawender's 2005b analysis of the entire Perseus cloud concludes that the turbulent momentum content of the entire Perseus cloud, after subtraction of the overall velocity gradient, is about an order of magnitude larger than the supply rate of momentum generated by outflows. Thus, protostellar outflows may not be able to sustain the observed level of turbulence in the entire cloud. However, on scales of one to a few parsecs, comparable to the size of the cluster forming cores, outflows *do* generate sufficient energy and momentum to self-regulate star formation, stop infall, and disrupt the cloud. However, Walawender *et al.* cautions that most measurements of outflow momentum rely of the detection of shocks, an estimate of the rate at which they process cloud gas, or the analysis of their entrained mass. These measurements are uncertain by about an order of magnitude due to to unknown excitation conditions, poorly constrained extinction corrections, and the non-linear physics of shocks. It is possible that we have not yet detected all of the momentum conveyed by outflows to their surroundings.

The Perseus results provide a natural explanation for why most stars form in clusters: Multiple simultaneous outflows may be required to generate enough outward pressure to stop or even reverse infall. The birth of dozens to hundreds of young stars can produce sufficient feedback to counter the effects of decaying turbulence and self-gravity.

The 2×10^4 $L_{\odot}$ Cepheus A region (D $\sim$ 700 pc) provides another example of multiple outflows emerging from a region forming several early B stars along with a cluster of low mass YSOs. The most massive YSO, HW2, contains a radio continuum jet (Garay *et al.* 1996; Curiel *et al.* 2006), a luminous cluster of masers (Torrelles *et al.* 2001), a massive cirucmstellar disk (Patel 2005), and a spectacular, collimated outflow that appears to be precessing (Cunningham 2006). Deep H_2 images show that over the last 5,000 years, HW2 produced a series of eruptions about every 10^3 years. The orientation of each successive eruption changed by about 15°. The oldest and most distant shock in this system is due east of HW2; the younger and closer shocks are located at smaller position angles. Today, the jet is oriented northeast at PA $\sim$ 45°. Cunningham (2006) proposed that a moderately massive companion star in a highly eccentric, non-coplanar orbit with a period of about 10^3 years triggers episodic accretion/mass-ejection events during periastron passages during which the disk orientation is abruptly changed. The

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resulting precession provides an excellent example of how a single flow can impact a large portion of a parent cloud.

2.3. *Massive star forming complexes*

The Orion star forming complex illustrates how massive stars dominate star formation feedback. The vicinity of the 10^5 $L_\odot$ Orion Nebula contains several thousand mostly low-mass stars along with about dozen massive ones. The most massive star is the 30 $M_\odot$ θ^1Ori C (see O'Dell 2001 for a review). In addition to the powerful outflows bursting out of the luminous but embedded YSOs in the OMC1 and OMC-1S cloud cores, dozens of low-mass young stars within the HII region also drive jets (Bally 2006a and references therein). However, the momentum injection rate of these outflows pales in comparison to the momentum generated by photo-ionization. The main ionization front at the interface between the Orion A cloud and HII region loses mass at a rate of about 10^{-4} $M_\odot$ yr^{-1} and vents to the southwest at a speed of about 20 km s^{-1}. The advance of the D-type I-front into the molecular cloud must deliver a comparable amount of momentum to the surrounding neutral gas. It is clear that once massive stars are born, their UV radiation, stellar winds, and terminal supernova explosions dominate the energetics of the surrounding ISM.

3. Conclusions

While downward cascades of turbulent energy may dominate the kinematics and structure of the general ISM, in star forming regions, injection by local sources is more important. In dark clouds, and those portions of giant molecular clouds giving birth to only low-mass stars, protostellar winds and jets dominate stellar feedback. A variety of processes such as velocity variability, orientation changes, and wide-angle winds contribute to the widening of outflow cavities to increase the efficiency of the coupling of outflow momentum to the chaotic motions and disruption of the cloud. In clusters, the random orientations of outflows, and dynamical interactions between stars, increases this coupling. However, when massive stars form, their UV radiation, winds, and terminal supernovae explosions dominate momentum and energy injection.

Quantitative measures of the momentum injection rates and feedback from forming stars are just now becoming available. In clustered regions of star formation, these rates appear to dominate all other sources, including the decay of turbulent energy from larger scales. While star formation feedback dominates on the scale of a few parsecs, on the scale of entire GMCs such as the Perseus molecular cloud, turbulent motions must originate form larger scales or be driven by self-gravity. In Orion and Perseus, superbubbles and shells powered by previous generations of stars may feed chaotic motions and structure of molecular gas.

I speculate that multi-scale injection from a variety of processes is responsible for the universality of the power-laws that characterize turbulent motions and density structure in the ISM. The inclusion of momentum injection on scales ranging from one to hundreds of parsecs will tend to flatten these power-laws by adding excess kinetic energy and creating density structures that would otherwise be less evident. Such additional sources may erase the expected breaks where the turbulent cascades transition from two to three dimensions and where self-gravity becomes important.

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Discussion

HEYER: 1: Lack of break in structure function is due to resolution and dynamic range of analysis. 2. Outflows need to be widely distributed to affect and drive turbulence in

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the FULL cloud. It is difficult to imagine that outflows can generate near-coherent large scale shear component observed in CO maps.

Bally: Josh Walawender demonstrated (in his PhD thesis; see Walawender *et al.* 2005) that in the Perseus molecular cloud energy and momentum injection dominates turbulent decay on scales of about one parsec *in regions where stars are forming*. Outflows may fail by more than an order of magnitude on the scale of the entire cloud (20 pc). I suspect that motions on these large scales may be driven by the nearby Per OB2 association by a combination of shear flow uv-induced photo-ablation, and winds from stars and supernovae.

Nakamura: Recently, Li and I did numerical simulations of turbulent magnetized clouds, including effects of protostellar outflows and we found that dynamic interaction between magnetic field and outflows is important to generate supersonic turbulence because outflows generate large amplitude Alfven and MHD waves that transform outflow motions into turbulent motions. So, my question is, is there any evidence showing interaction between magnetic field and outflows in your observations.

Bally: Possibly, Observations of the L1551 cloud and the outflow from Barnard 5 IRS1 reveal ridges of emission parallel to the outflow axis but located in the molecular cloud well outside the boundaries of the outflow cavity. These density and very low velocity perturbations may have been formed by some sort of perturbation, induced by the outflow, propagating through the cloud. Might these be your MHD or Alfven waves?

Zinnecker: Since I am blamed to be the bad boy before lunch, I want to make up for it and be the good guy after lunch by advertising that John Bally together with Bo Reipurth, just published a popular book on "The Birth of Stars and Planets", which you can see upstairs in the booth of Cambridge University Press! (Do I get a free copy now?)

Bally: Yes. Some of the images I used in this presentation are shown in our book.

Mac Low: Matzner (2002) made a quantitative argument for outflows supporting small molecular clouds, but HII regions supporting larger ones.

Bally: Outflows are an important feedback mechanism only when massive stars are absent. A and late B stars come to dominate feedback by soft uv photo-heating of PDRs. O stars inject much more energy through the propagation of their ionisation fronts. So I completely agree – massive stars and their uv dominate feedback when they are present – typically in larger, more massive star-forming regions.