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Observations of Winds, Jets, and Turbulence Generation in GMCs

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Abstract. Protostellar outflows can inject sufficient mass, momentum, and kinetic energy into their parent star-forming clumps to dramatically alter their structure, generate turbulence, and even to disrupt them. Outflows represent the lowest rung on a 'feedback ladder' consisting of increasingly powerful mechanisms which kick-in if star formation escalates towards the production of more massive stars, higher efficiency, and larger clusters. Outflow feedback may dominate turbulence generation and cloud disruption on the scale of cluster-forming clumps having dimensions up to a few parsecs. Outflows inject energy and momentum on a wide-range of length-scales from less than 0.01 pc to over 30 pc. However, they fail by several orders of magnitude to inject sufficient momentum and kinetic energy to drive turbulent motions on the size and mass-scales of GMCs. Injection from higher rungs on the feedback ladder or momentum injected by Galactic-scale processes are needed to power the observed turbulence on the 10 to 100 pc scales of GMCs.

Keywords. stars: formation, ISM: jets and outflows, ISM: Herbig-Haro objects

1. Introduction

Protostellar jets and outflows produce the visual-wavelength shocks known as Herbig-Haro (HH) objects (Reipurth & Bally 2001). As jets entrain and accelerate surrounding molecules, they become visible as molecular outflows. When they break out into the atomic or ionized interstellar medium, they may become visible as externally irradiated flows. Because most forming and young stars produce bipolar jets and outflows, they are abundant with hundreds examples located within 1 kpc of the Sun.

Protostellar outflows have profound impacts on the star formation environment. Their terminal shocks probe the ambient medium. The most distant shocks from a source provide information about the density, velocity structure, ionization state, and chemical composition of the impacted region. In the absence of massive stars, momentum and energy injection by jets can be the dominant source of turbulence generation and cloud disruption. Thus, outflows in low- to intermediate-mass star forming regions may dominate star formation feedback and self-regulation.

2. The Feedback Ladder

Protostellar outflows represent the lowest rung in the *Feedback Ladder* of self-regulating star formation. In molecular cloud clumps and cores where only low-mass stars are forming, outflows may be the dominant agent of energy injection and feedback. Low-mass stars have long pre main-sequence contraction time-scales ranging from one to many tens of Myr during which they have cool photospheres and K and M spectral types. Thus, while their X-rays may penetrate deep into their parent clouds, the bulk of their

Table 1. The Proto-Stellar Feedback Ladder

Type of Feedback	Mechanism	Most Massive Star
Outflows	Momentum Injection	$<$ few $M_\odot$)
X-rays	Ionization & Heating	All stellar masses
FUV ($>$ 912A)	Cloud surface heating	$>\sim$ 3 $M_\odot$)
EUV ($<$ 912A)	Ionization of H	$>\sim$ 8 $M_\odot$)
Stellar Winds	Expansion of Wind-bubble	$>\sim$ 20 $M_\odot$)
Supernovae	Impact of Blast Waves	$>\sim$ 8 $M_\odot$)
Radiation Pressure	$P \sim L/c$	Massive clusters

luminosity is an inefficient heater of gas more than a few hundred AU from the star. The luminosity produced by accretion and nuclear energy sources will only impact the immediate environment of low-mass proto-stars. On the other-hand, outflows from even the lowest mass young stellar objects (YSOs) can propagate over distances of more than a parsec.

Observations show that outflows tend to be collimated into bipolar structures. Outflows in isolated globules forming one or only a few stars tend to have long-lasting stable orientations. While they may push-away portions of the cloud along the poles of their accretion disks, they are unlikely to have much impact in the plane of the disk where the outflow is blocked. Examples of relatively isolated YSOs with steady orientations forming in small cores include B335, HH34, and HH 46/47.

The situation in regions forming clusters of low-mass YSOs may be different. Observations show that in clusters, the orientations of disks and outflows are random. Thus, most portions of the cloud will be impacted by outflows. Examples of such regions include the NGC 1333 region in the Perseus Molecular Cloud (Bally *et al.* 1996) and the 'Gulf of Mexico' region in the North America and Pelican Nebula complex (W80 = NGC 7000; see Figure 1).

If outflow kinetic energy and momentum injection rates are comparable to or greater than the dissipation rate of turbulence and consequent accretion onto YSOs (or their disks and envelopes), outflows can regulate or even terminate star formation by blowing-out the gas. On the other hand, if outflow feedback is less efficient, then dissipation in the clump will allow accretion onto proto-stellar seeds to continue. However, as stars grow in mass, the power of their outflows (momentum injection rates) tend to increase.

If outflows fail to stop star-fomation in a given region, star formation will continue until a more powerful feedback mechanism intervenes. The next rung of the ladder is non-ionizing UV (FUV) radiation. As one or more stars reach masses of a few $M_\odot$, their Kelvin-Helholtz contraction time-scales ($\approx$ pre main-sequence time-scale $\sim GM^2/R_*$) become short compared to their accretion time-scales ($\sim M/\dot{M}$). Such stars quickly develop hot photospheres with spectral types ranging from early F, A, to late B that radiate much of their luminosity in the far-UV between 912 and about 2,000 Angstroms. FUV radiation is an efficient heater of cloud surfaces by means of the grain photo-electric emission and molecular hydrogen dissociation followed by re-formation. Depending on the incident fluxes, such *photon dominated regions* (PDRs) can reach temperatures of 10^2 to nearly 10^4 K which correspond to sound-speeds of 2 to 10 km s^{-1}. The expansion of the heated gas in a PDR is a potent mechanism for injecting momentum and kinetic energy into a cloud by means of the FUV-dominated rocket effect. As moderate-mass (2 to 8 $M_\odot$) stars form, the momentum injected by FUV radiation can dominate feedback. Examples of such regions include NGC 2023 in Orion, NGC 7023 in Cepheus, and the infrared reflection nebulae surrounding late B stars in the ρ-Ophiuchus dark clouds.

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Low-mass young stars are highly variable X-ray sources with luminosities ranging from $L_x \sim 10^{27}$ to 10^{31} ergs in the 0.2 to 10 keV range (Feigelson & Montmerle 1999). Hard radiation can penetrate most of the column density of typical molecular clouds. Although an insignificant global heat source, the penetrating power of X-rays results in ionization throughout the volume of a star-forming GMC. Such radiation can alter the chemistry and heat the local environments of YSOs and is a form of feedback. X-ray luminosity of young star tends to increase with the stellar mass.

If outflows and FUV fail to halt star formation, it will continue until stars having masses greater than about 8 $M_\odot$ (spectral type earlier than B3) form that produce radiation which can ionize hydrogen. Such stars produce HII regions with temperatures of about 10^4 K and effective sound speeds of 10 to 15 km s^{-1}. When the sound speed is greater than the gravitational escape speed at the ionization front, the plasma expands. Thus, under most conditions, photo-ionization will halt star formation in the region by first dissociating molecules in a PDR, then ionizing the resulting atoms. While expanding HII regions certainly halt star formation in the immediate vicinity of UV sources, there is evidence that many parsecs from the UV source, ionization fronts may trigger star formation. Examples of ionization-driven blow-out, and possible triggering of star formation in adjacent clouds include the Orion Nebula and NGC 1977 in Orion A, NGC 2024 in Orion B, the M17 complex in Sagittarius, and the W3, W4, and W5 in Cassiopeia.

Main-sequence stellar winds increase in power with stellar mass, and can contribute to feedback by generating mega-Kelvin bubbles that contribute to HII region expansion and feedback.

In high-mass and high density clumps where the escape speed is comparable to or greater than the sound speed in photo-ionized gas, the expansion of HII regions and their tendency to stop star formation may be curtailed. In extremely massive and dense clouds such as in GMCs near the Galactic center and in starburst galaxies such as M82 and the Antennae, ionization may not halt star formation. Stars can continue to form

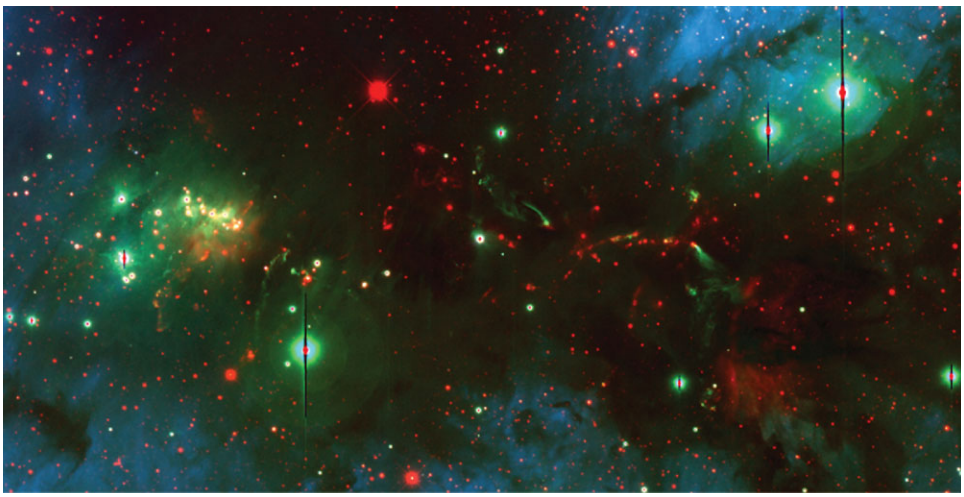

Figure 1. A color image showing dozens of protostellar outflows bursting out of the "Gulf of Mexico" region located directly in front of the W80 (NGC 7000) HII region in Cygnus. The image shows λ 2.12 μm H_2 emission (red) superimposed on λ 0.6563 μm Hα (blue), and $\lambda\lambda$ 0.6716/0.6731 μm [SII] (green). The λ 2.12 μm image was obtained by J. Bally and G. Stringfellow in November 2009 with the NEWFIRM wide-field infrared camera on the Mayall 4 meter telescope on Kitt Peak. The Hα and [SII] images were obtained by Bo Reipurth using the SUPRIME camera at the prime-focus of the Subaru 8.4 meter telescope on Mauna Kea.

and grow despite the presence of massive stars whose ionization fronts remain trapped by gravity (Keto 2002; Keto 2003). As Lyman continuum luminosity increases, HII region may break-out and halt star formation. But, if HII regions remain trapped, the next rung on the feedback ladder will be reached when stars with M >100 $M_\odot$ explode as supernovae about 3 Myr after formation.

In super-star-cluster forming clouds birthing thousands of O stars, even supernovae may not halt continued star birth. In such environments, most of the gas can be converted into stars, raising the star formation efficiency to near 100%. As the gas depletes by forming stars, the left-overs of the cloud may eventually be blown out by ionization, stellar winds, supernova explosions, and radiation pressure (Krumholz & Matzner 2009).

3. Jets, Herbig-Haro Objects, and Molecular Outflows

Protostellar outflows are traced by radiative shock waves at near-UV, visual, and infrared wavelengths, or by high-velocity line-wings on sub-mm to mm wavelength emission lines. Shocks form where faster ejecta slams into slower material with supersonic speeds. Collision velocities less than about 60 km s^{-1} excite visual-wavelength forbidden transitions such as [OI] and [SII], and the 1.26 and 1.64 μm transitions of [FeII] if the medium is weakly ionized, and the 2.12 μm and mid-IR lines of H_2 if the medium is molecular. Velocities >60 km s^{-1} dissociate and ionize hydrogen. Charge exchange and collisional

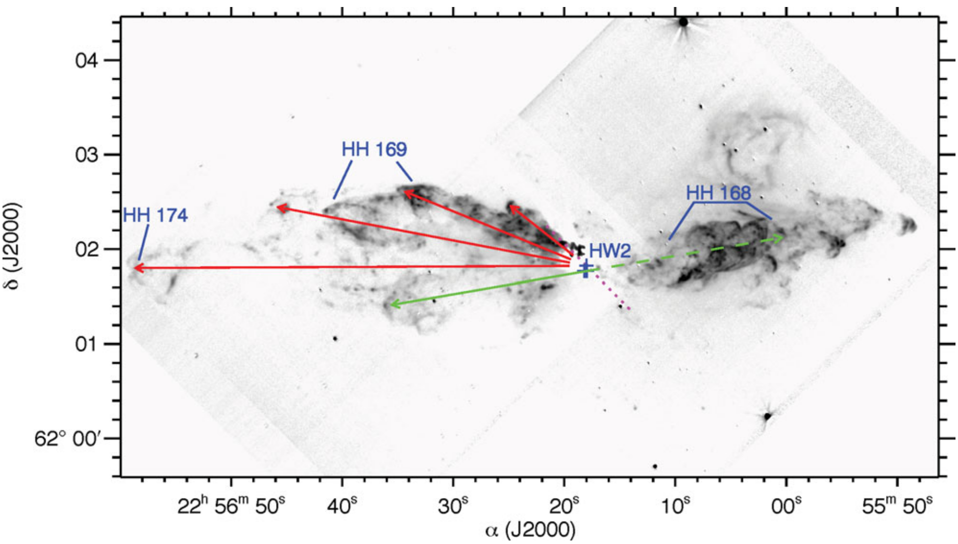

Figure 2. Continuum-subtracted 2.12 μm H_2 emission in the 10^4 $L_\odot$ Cep A outflow complex. The successive orientations of a suspected precessing jet from the $\sim$ 15 $M_\odot$ protostar HW2 are indicated by red arrows; the position of HW2 is marked with the upper blue cross. The oldest (eastward) ejection powers HH 174 to the east. The next two ejections may be responsible for HH 169. The current orientation of the radio jet emerging from HW2 is at position angle (PA) = 45^o, indicated by the dashed magenta line. Cunningham *et al.* (2009) proposed that HW2 and its disk captured a moderate-mass companion into an eccentric orbit inclined with respect to the disk. The companion passes through the disk twice during each orbit, triggering a mass accretion and ejection event. The inclined orbit causes the disk to precess. These two effects combine to produce a pulsed, precessing jet. HH 168, and the HH bows at far right (dashed green line), trace an outflow from HW3c or HW3d (marked with the lower blue cross) along the green axis. A faint H_2 bow marks the eastern lobe of this flow. A collision between the two flows may be responsible for the bright HH 168 complex. Taken from Cunningham, Moeckel, & Bally (2009).

excitation at the shock form thin zones that radiate only in hydrogen recombination lines, producing "Balmer filaments". In fast shocks, the thin (about one mean-free-path) Balmer filament is followed by a thicker layer of fully ionized hydrogen and highly ionized trace elements. Most near-UV, visual, and near-IR radiation produced by a shock emerges from the zone where recombining hydrogen and trace elements radiate away the heat generated by the shock. This layer tends to have and extended tail with temperatures of order 10^4 K set by the $\sim 1 - 3$ eV energy gaps of the visual and near-IR wavelength forbidden transitions of the most common species such as [OI], [OIII], [NII], [SII], and [FeII]. In this region, at most only one Hα photon can be produced by each recombining H atom because collisions do not have sufficient energy to excite the n=2, 3, or higher energy levels of H. Once hydrogen recombines, the low electron density insures that trace ions have long lifetimes. Thus, the few eV forbidden transitions of common ions can be excited thousands of times by collisions before they recombine. These forbidden emission lines can be as bright or brighter than Hα. Shocks speeds higher than about 300 km s^{-1} can sometimes be detected in X-rays and in the non-thermal radio continuum.

The structure, velocity field, and symmetries of outflows provide powerful diagnostics of protostellar accretion and interactions between members of multiple star systems and star clusters. The structure and kinematics of protostellar outflows point to large variations in jet ejection velocities and mass-loss rates of the source YSOs. The giant, parsec-scale outflows trace mass-loss histories over time-scales comparable to YSO accretion times. Protostellar jets are variable in mass-loss rate, ejection velocity, degree of collimation, and orientation over time-scales ranging form years to millennia. The close-connection between accretion and mass-loss implies that accretion onto YSOs is episodic.

Jets and winds transfer momentum and entrain their surroundings by means of shocks. Species such as CO probe the mass and radial velocity of swept-up, entrained gas, but only where the flow interacts with the molecular cloud. Most molecular transitions (and 21 cm emission from HI) are excited by collisions at low (~ 10 K) temperatures and do not require shocks to be observable. These transitions trace the total amount of entrained mass and the momentum injected into the parent cloud by an outflow over its lifetime.

As jets blow-out of their parent clouds, they entrain atomic gas or ionized plasmas from their surroundings. Because densities tend to be lower than the parent cloud, these swept-up layers are more difficult to observe. They can occasionally be seen in the 21 cm transition of HI, but diffuse Galactic HI emission produces a strong and structured background, making outflow-entrained HI difficult to detect (e.g. Russell *et al.* 1992). When outflows propagate in UV-rich environments, the external radiation field can render the outflow visible. Such 'irradiated jets' and 'irradiated outflows' are especially common in OB associations such as Orion and in HII regions such as the Orion Nebula (Bally & Reipurth 2001; Bally *et al.* 2006.)

4. The Impacts of Outflows

While HH objects and near-IR [FeII] and H_2 emission trace currently active shocks in great detail, the determination of the overall impacts of outflows are better determined from sub-mm and mm molecular line observations. The statistical properties of about 400 molecular outflows were reviewed by Wu *et al.*(2004) and Wu *et al.*(2005). They found the following correlations: The outflow force (momentum injection rate) scales as $log\ \dot{P} = (-4.92 \pm 0.15) + (0.65 \pm 0.043) log\ L_{bol}$ with a correlation coefficient of 0.72 where L_{bol} is the bolometric luminosity of the source in Solar units and $\dot{P}$ is in units of $M_{\odot}$ km s^{-1} yr^{-1}. The outflow force is between 3 to 5 orders of magnitude greater than

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radiation pressure at L_{bol} =1 $L_{\odot}$, but decreases to 1 to 3 orders of magnitude greater than L_{bol}/c at L_{bol} =10^6 $L_{\odot}$. Thus, winds and jets can't be powered by radiation. The outflow mechanical luminosity (in Solar units) scales as $log\ L_{mech} = (-1.98 \pm 0.14) + (0.62 \pm 0.04) log\ L_{bol}$ with a correlation coefficient of 0.69. While the mechanical luminosity is nearly comparable to the bolometric luminosity at L_{bol} =1 $L_{\odot}$, it is 2 to 4 orders of magnitude lower at L_{bol} =10^6 $L_{\odot}$. The outflow mass-loss rate (in $M_{\odot}$ yr^{-1}) scales as $log \dot{M} = (-5.57 \pm 0.096) + (0.50 \pm 0.03) log L_{bol}$ with a correlation coefficient of 0.73. The outflow mass (in $M_{\odot}$ units) scales as $log\ M = (-1.04 \pm 0.08) + (0.56 \pm 0.02) log\ L_{bol}$ with a correlation coefficient of 0.78. Outflow masses range from $\sim 0.001 - 1$ $M_{\odot}$ at L_{bol} =1 $L_{\odot}$, they increase to $10 - 10^3$ $M_{\odot}$ at L_{bol} =10^6 $L_{\odot}$. There is also a trend toward poor collimation at high luminosity. The 'dynamical ages' range from 10^3 to 10^6 years with a mean at about 5×10^4 years. Although the 'noise' in these correlations is 1 to 2 orders of magnitude, the range in luminosity is 6 orders of magnitude.

The dynamic ages of outflows from massive stars may be shorter than outflows from low-mass stars because of their rapid evolution. Once ionizing radiation breaks out of their gravitation well, UV radiation will enter the outflow cavity and erase the molecular outflow signatures. Multiplying the momentum injection rate by a typical dynamic age of 5×10^4 years implies that YSOs with L_{bol} = 1, 100, 10^4, and 10^6 $L_{\odot}$ inject about

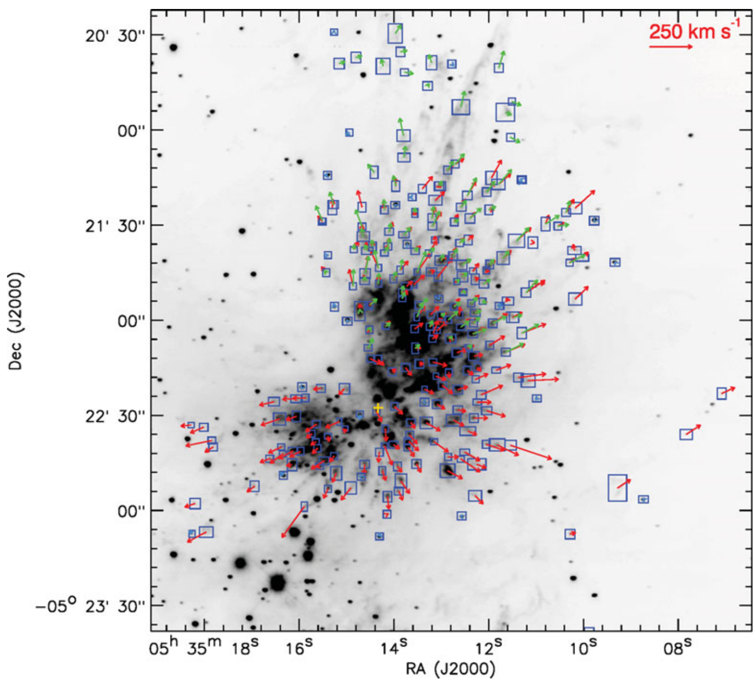

Figure 3. The explosive Orion BN/KL outflow imaged in 2.12 μm H_2 emission in December 2004 (Cunningham 2006). This outflow has dynamic age of about 500 to 1,000 years, has a kinetic energy of order 10^{47} to 10^{48} ergs, and a momentum of about 190 $M_{\odot}$ km s^{-1}. It may have been triggered by the dynamic ejection of at least three massive stars; the Becklin-Neugebauer (BN) object, radio source I, and infrared source n (Gomez 2008; Zapata 2009). The Trapezium stars which ionize the Orion Nebula are located in the lower-left corner of the image. Red and green arrows denote proper motion measurements based on comparison of the 2004 data with two different prior-epoch images, from September 1992 (Allen & Burton 1993 and January 1999 (Kaifu 2000), respectively. Blue boxes indicate features with proper motion measurements. Arrow lengths indicate velocities according to the scale at upper right, and are equivalent to 122-year motions. The yellow cross marks apparent point of origin of the ejected massive stars.

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0.6, 12, 240, and 4,700 $M_{\odot}$ km s^{-1} of momentum respectively. Taking into account a possible decreasing lifetime for massive-star outflows, the momenta scale as L_{bol}^{α} with $\alpha = 0.5 \pm 0.2$.

Ages and sizes deduced from mm/sub-mm observations are lower bounds because CO (and similar) emission is confined to the extent of the parent clouds. In most cases, optical outflows extend far beyond associated CO flows. For example, the HH 111 outflow only is a few arcminutes long in CO; but at visual wavelengths, it can be traced for nearly a degree to HH 113 and HH 311 (Reipurth, Bally, & Devine 1997). Other examples include HH 1/2, HH 34, HH 46/47. The most extreme example is the nearly 30 pc long outflow marked by HH 131 in Orion (Wang *et al.* 2005) powered from L1641N more than 2.5 degrees (18 pc) away.

Observations of YSOs reveal evolutionary trends (Reipurth & Bally 1991; Wu *et al.* 2004, 2005; Wang *et al.* 2005). The youngest, most embedded protostars (Class 0 or young Class I objects) drive slower (10 to 100 km s^{-1}) flows predominantly traced by CO, SiO, and shocked H_2. These flows tend to be dense with n(H_2) $\sim 10^4$ to over 10^7 cm^{-3}, have mass-loss rates of order 10^{-6} to more than 10^{-5} $M_{\odot}$ yr^{-1}, and high mechanical luminosities. Weak masers in species such as H_2O are occasionally seen. Bright maser emission is generally associated only with high-mass protostars. More evolved Class I YSOs tend to drive faster jets dominated by HI and low-ionization potential metals rendered visible by their forbidden lines, have lower densities around 10^2 to 10^4 cm^{-3}, and higher speeds in the range 100 to 400 km s^{-1}. Class II YSOs (classical T-Tauri stars) tend to have much fainter and lower mass-loss rate jets. Thus, as YSOs age, their jets become faster, but have lower densities, mass-loss rates, and momenta.

Outflows in forming clusters may regulate the evolution of their parent clump. NGC 1333 region in the Perseus Molecular Cloud contains approximately 150 YOSs formed within the last Myr that drive hundreds of individual shocks and dozens of outflows; many are bursting out of the parent clump (Walawender *et al.* 2008). Long-since faded, older outflows may be responsible for dozens of cavities in the cloud (Quillen *et al.* 2005). Bally *et al.* (1996) estimated that the mean time between the passage of a supersonic shock in a typical location in NGC 1333 is 10^4 to 10^5 years. Outflow feedback may be responsible for sculpting the cloud and may inject sufficient energy and momentum to maintain a quasi-balance between star formation and turbulent energy dissipation. Surveys of HH objects (Walawender *et al.* 2005) and outflows (Arce *et al.* 2010) over the entire Perseus cloud show that while outflows may self-regulate star formation on parsec scales, they would require 10 to 100 collapse time-scales to supply the observed motions on the 30 pc scale of the entire cloud.

The two nearest massive star forming complexes are in Orion and Cepheus. Figure 2 shows the $L \approx 2 \times 10^4$ $L_{\odot}$ Cepheus A (Cep A) region in the near-infrared (Cunningham, Moeckel, & Bally 2009). The most luminous object HW2 appears to be a 15 $M_{\odot}$ protostar which has trapped its ionizing radiation. It appears to power a pulsed, precessing jet, possibly caused by a moderate-mass companion captured into a non-coplanar (with the HW2 disk), eccentric orbit around HW2.

Figure 3 shows the spectacular BN/KL outflow emerging from OMC1 behind the Orion Nebula, the closest (414 $\pm$ 7 pc) site of on-going massive star formation with $L_{bol} \approx 10^5$ $L_{\odot}$. The explosive outflow may be a consequence of the dynamic decay of a system of massive stars 500 years ago (Zapata *et al.* 2009). This flow has a momentum of 190 $M_{\odot}$ km s^{-1} and kinetic energy of order 10^{47} ergs (uncertain by at least an order of magnitude). Over its dynamic age of $\sim 10^3$ years, it has impacted a region about 0.1 pc in extent.

The most powerful and massive outflows are found in massive star and cluster forming regions. The HII region and associated cluster, DR21 in Cygnus, powers a giant outflow with a mass of about 3,000 $M_\odot$ (Russell *et al.* 1992). It may be powered by ionizing radiation which ablates gas from adjacent dense clouds. The plasma flows through a recombination front to produce a powerful neutral flow detected by means of its 21 cm HI emission.

Outflows sculpt their parent clouds by creating cavities and accelerating the displaced gas. Combined effects of variations in jet/outflow mass-loss-rates, ejection velocities, degree of collimation and outflow orientation, and clustering result in generation of chaotic cloud structures and velocity fields. Outflows inject energy and momentum on a range of length-scales form less than 0.01 to 30 pc. Numerical simulations of the impacts of outflows on cloud structure, kinematics, and star formation have been conducted by Carroll *et al.* (2010), Nakamura & Li (2007), and Wang *et al.* (2010). These studies do not incorporate the full range of length, energy, and momentum scales of observed outflows. The absence of bumps in observed power-spectra of cloud turbulence (Padoan *et al.* 2009) in star forming clouds may indicate that outflow injection occurs on length-scales extending over many orders of magnitude.

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