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THE IMPACT OF GIANT STELLAR OUTFLOWS ON THEIR CLOUDS

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RESUMEN

Discutimos los resultados de nuestro estudio detallado del impacto de dos flujos protoestelares gigantes (HH 300 y HH 315) sobre sus nubes moleculares maternas. Nuestros resultados muestran que ambos flujos han modificado las distribuciones de densidad y velocidad de sus nubes maternas a distancias en escalas de parsecs a partir de su origen. También compilamos y estudiamos una muestra de 5 (dos de nuestro estudio y tres de la literatura) flujos moleculares gigantes y sus nubes huéspedes. Los datos de nuestra pequeña muestra indican que un flujo molecular gigante "típico" en una nube molecular relativamente pequeña (masa menor que unos $80\,M_\odot$) tiene una energía cinética comparable a (o mayor que) la energía turbulenta y la energía de ligada gravitacional de la nube materna. Por lo tanto, vemos que en algunos casos un solo flujo protoestelar gigante puede tener un efecto profundo sobre la evolución y destino de su nube materna.

ABSTRACT

We discuss the results of our detailed study of the impact of two giant protostellar outflows (HH 300 and HH 315) on their parent molecular clouds. Our results show that both of these outflows have modified their respective parent clouds' density and velocity distributions at parsec-scale distances from their source. We also compile and study a sample of 5 (two from our study and three from the literature) giant molecular outflows and their host clouds. The data from our small sample indicate that a "typical" giant molecular outflow in a relatively small molecular cloud (mass less than about $80\,M_\odot$) has a kinetic energy comparable to (or larger than) the turbulent energy and the gravitational binding energy of its parent cloud. Thus, in some cases a single giant protostellar outflow may have a profound effect on the evolution and fate of its parent cloud.

Key Words: **ISM: CLOUDS — ISM: JETS AND OUTFLOWS — STARS: FORMATION**

1. INTRODUCTION

Recent wide-field optical and near-infrared observations of star-forming regions have shown that giant (parsec-scale) protostellar outflows exist and that they are common (e.g., Reipurth, Bally, & Devine 1997; Stanke, McCaughrean, & Zinnecker 2000). The huge size of a giant protostellar outflow enables it to entrain molecular cloud material at distances of a parsec or more from its protostar. Thus, a giant outflow has the potential to have a major impact on its parent molecular cloud.

In order to study the effect of giant protostellar outflows on their surroundings, we extensively mapped two giant outflows and their host molecular clouds, in more than one molecular emission line. The two giant protostellar outflows observed were HH 300 and HH 315, both discovered by Reipurth et al. (1997). The HH 300 flow is driven by the protostar IRAS 04239+2436, located in the B18w dark cloud in Taurus, and has a projected length of about 1.2 pc. The HH 315 flow, driven by the protostar PV Cephei, is 2.6 pc long.

We observed the molecular gas immediately surrounding the giant HH flows using the ^{12}CO(2–1) line, in order to study the molecular outflow morphology and kinematics. In addition, we observed the ^{12}CO(1–0) and ^{13}CO(1–0) lines of a larger extent of the gas surrounding the HH flows, in order to study the outflows in context with their parent molecular cloud and their surroundings. With these observations we studied the effects the outflows have on the structure and kinematics of the ambient cloud on large scales. In addition, we were able to use the $J = 1$–0 lines to correct for the ^{12}CO velocity-dependent opacity, which is extremely important for obtaining accurate estimates of the outflow physical parameters (e.g., Arce & Goodman 2001).

2. HH 300 AND HH 315

Our estimate of the molecular outflow mass shows that both HH 300 and HH 315 have been able to entrain and accelerate enormous amounts of molecular gas, creating giant molecular outflows of 4 and $7\,M_\odot$, respectively. In addition, each of the two molecular outflows has a momentum and a kinetic energy on the order of $10\,M_\odot\,\mathrm{km\,s^{-1}}$ and 10^{45} erg, respectively. In both cases the kinetic energy is comparable to both the gravitational energy and the turbulent energy of their respective parent clouds.

In addition, our results show that both giant HH flows have a major impact on their surroundings

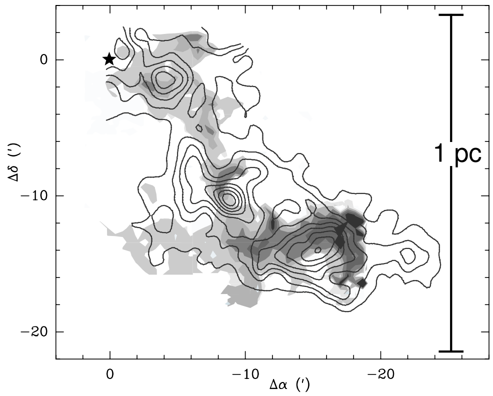

Fig. 1. ^{12}CO(1–0) integrated intensity map of the HH 300 redshifted molecular outflow lobe, superimposed on a grayscale map of the ^{13}CO line width (FWHM). Darker tones show regions of wider ^{13}CO spectra. Coordinate offsets are given with respect to the outflow source position (star symbol). From Arce & Goodman (2001).

up to distances of about 1 pc away from the outflow source. For example, our ^{13}CO(1–0) observations show that HH 300 has been able to affect the velocity distribution of its parent cloud. Figure 1 shows that the ^{13}CO velocity width is greater near the flow axis and near regions of peak CO outflow emission. This is evidence that the widening of the ^{13}CO line is due to the outflow-cloud interaction. Thus, it is clear that the HH 300 outflow is modifying the velocity distribution of its parent cloud's medium-density gas (traced by the ^{13}CO line) at parsec-scale distances from the source.

The impact of HH 315 on its environment is even more dramatic. The blue-shifted lobe of the HH 315 flow has been able to push a substantial amount of gas north of the outflow source, piling it in a dense shell-like structure, surrounding the outflow lobe, which we detect in ^{13}CO(1–0) (see Arce & Goodman 2002). The morphology, velocity and momentum of the ^{13}CO shell are all consistent with it being formed by the (momentum-conserving) entrainment of cloud molecular gas, by the HH 315 flow. Moreover, from the position-velocity diagram of the ^{12}CO line it is evident that there is a velocity gradient in the ambient cloud gas along the same direction as the flow (Arce & Goodman 2002). Thus, our results indicate that the HH 315 flow is drastically affecting its parent cloud's velocity and density distribution, at parsec-scale distances from the source.

3. A QUANTITATIVE COMPARISON

It would not be wise to make a general statement on the effects of giant protostellar outflows on their clouds based only on our detailed study of HH 300 and HH 315. Therefore, we decided to compare our results with the results of other observations of giant protostellar outflows.

We searched the literature for parsec-scale HH flows that have created observed giant (linear extent of 1 pc or more) CO outflows in non-crowded sites of low- to mid-mass star formation. We restricted our literature search to giant molecular outflow studies that include corrections for gas opacity when calculating the outflow's mass and/or had added the mass of the slow molecular outflow component traced by ^{13}CO (similar to our study of HH 300 and HH 315). These corrections are very important, as ignoring them may result in an underestimation of the molecular outflow mass by a factor of five to ten (see Arce & Goodman 2001; Yu, Billawala, & Bally 1999; Tafalla & Myers 1997; Moriarty-Schieven & Snell 1988). Also, we restricted our search to giant HH flows in clouds which have been mapped in ^{13}CO (similar to our study).

The search yielded only three more outflows in addition to the two we studied: (i) the L 1228 molecular outflow (Tafalla & Myers 1997) produced by the HH 199 flow, from the source IRAS 20582+7724, in the L 1228 cloud (Bally et al. 1995), (ii) the B5-IRS1 molecular outflow (Yu et al. 1999) in the B5 cloud in Perseus (Langer et al. 1989), and (iii) the L 1551-IRS5 molecular outflow in the L 1551 cloud in Taurus (Moriarty-Schieven & Snell 1988).

In Table 1 we compare the outflow kinetic energy ($E_{\rm flow}$) of each of the five outflows to their respective parent clouds' turbulent energy ($E_{\rm turb}$) and gravitational energy ($E_{\rm grav}$), in order to make a quantitative comparison of the impact of the giant outflows on their clouds. Table 1 also shows the geometric mean radius and the mass ($M_{\rm c}$) of each molecular cloud (obtained from the ^{13}CO data).

The data shown in Table 1 indicates that the L 1551-IRS1, HH 300 and HH 315 molecular outflows have kinetic energies comparable to or larger than their host clouds' turbulent energy and gravitational binding energy. The host clouds of these three giant flows are relatively small with radius and mass less than 0.8 pc and 80 $M_\odot$, respectively. On the other hand, the L 1228 and B5-IRS1 outflows, although powerful, do not have enough energy to surpass the turbulent energy or binding energy of their respective clouds—which have masses of more than 180 $M_\odot$ and radii of more than 1 pc.

It is clear that some of the molecular outflows in our small sample have kinetic energy comparable to, or larger than, the binding energy and the turbulent energy of their cloud. However, this does not imply

TABLE 1

COMPARISON OF OUTFLOW AND CLOUD ENERGETICS

Molecular Outflow	$E_{\rm flow}/E_{\rm turb}$ %	$E_{\rm flow}/E_{\rm grav}$ %	$M_{\rm esc}/M_{\rm c}$ %	Cloud Radius pc	Cloud Mass $M_\odot$
L 1228	10	10	5	1.3	181
B5-IRS1	70	10	5	2.2	790
L 1551-IRS5	5500	5500	180	0.65	38
HH 300	300	110	25	0.55	72
HH 315	1000	140	20	0.7	74

that these powerful outflows will certainly unbind their parent clouds or drive the turbulence in their host clouds. We do not know how well the kinetic energy of a molecular outflow couples to the rest of its parent molecular cloud. More theoretical and numerical studies are needed to answer this question. Thus, we cannot make any precise predictions on the parent clouds' future. However, we can state that some of the protostellar outflows are capable of injecting an amount of energy into the molecular gas comparable to their parent clouds' turbulent and gravitational energy. Therefore, they have the *potential* to help drive the turbulence in their cloud and/or to help gravitationally unbind their parent cloud (to a limited extent).

We define the "escape mass" ($M_{\rm esc}$) as the mass that could potentially be dispersed by an outflow, assuming all the outflow momentum is used to accelerate $M_{\rm esc}$ to the cloud's escape velocity, that is $M_{\rm esc} = P_{\rm flow}/v_{\rm esc}$. We note that the molecular outflows in our small sample *currently* entrain a mass lower than $M_{\rm esc}$, but by the end of the outflow stage they could easily entrain as much (or more) mass than $M_{\rm esc}$. Since we do not know how much mass will *eventually* be entrained by the outflow, we use $M_{\rm esc}$ as a measure of the *potential* disruptive effect outflows have on their cloud. The L 1551-IRS5, HH 300, and HH 315 molecular outflows have enough momentum to potentially disperse about 20% or more of their respective cloud's mass (see Table 1). This would have a disruptive effect on the cloud, since a loss of 20% of the original mass of a cloud would translate into a decrease of the gravitational potential energy to 64% of the original value. The L 1228 and B5-IRS1 outflows lie inside clouds with much more mass than the other three outflows, and so even though L 1228 and B5-IRS1 have comparable (or larger) momenta than the other three outflows, they only have the potential to eject about 5% of their respective parent clouds' mass.

4. CONCLUSIONS

The main points derived from our study are:

- The giant protostellar outflows HH 300 and HH 315 have both produced massive and energetic giant molecular outflows. Both of these outflows have modified their respective parent clouds' density and velocity distributions at parsec-scale distances from their source.
- From our limited sample we see that a "typical" giant molecular outflow in a relatively small molecular cloud (radius less than 0.8 pc, and mass less than 80 $M_\odot$) has: (i) a kinetic energy comparable to (or larger than) the turbulent energy and the gravitational binding energy of its parent cloud, and (ii) enough momentum to potentially gravitationally unbind a significant amount of cloud mass.
- Giant protostellar outflows may have a profound effect on the evolution and fate of their parent clouds.

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