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PROBING THE ROLE OF PROTOSTELLAR FEEDBACK IN CLUSTERED STAR FORMATION : OUTFLOWS IN THE COLLAPSING PROTOCLUSTER NGC 2264-C.

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Abstract. We study the amount of turbulent support injected by protostellar outflows in the NGC 2264-C collapsing protocluster. Using HERA at the IRAM 30 m telescope, we took extensive maps of NGC2264-C in ^{12}CO(2–1), ^{13}CO(2–1), and C^{18}O(2–1). We found widespread high-velocity ^{12}CO emission, testifying to the presence of numerous outflows in the region. We carried out a detailed analysis of the properties of these outflows, including a quantitative evaluation of the total momentum flux injected by outflows in the protocluster. We show that protostellar feedback due to outflows doesn't provide enough energy to efficiently support the whole NGC 2264-C protocluster against global collapse.

1 Introduction

1.1 Clustered star formation and protostellar feedback processes.

It is now well established that a large fraction of young stars in giant molecular clouds form in groups and clusters rather than in isolation (e.g. Lada & Lada 2003).

Three main classes of models have been developed to link the IMF to the cluster formation process. The first one is a scenario based on turbulent fragmentation of the parent molecular cloud (e.g. Elmegreen 1997; Padoan & Nordlund 2002). This scenario produces an IMF-like core mass distribution as observed, and the IMF results primarily from the properties (e.g. power spectrum) of the turbulence. The second class of models emphasizes the role of protostellar feedback in regulating the star formation process (e.g. Norman & Silk 1980, Adams & Fatuzzo 1996). Here, the IMF is determined by the stars themselves through the collective effects of their feedback on both individual cores and the parent cloud. A third scenario exists, however, according to which interstellar turbulence plays no direct role in shaping the IMF, and the distribution of stellar masses is entirely determined by competitive accretion between already formed protostars and dynamical interactions between individual cluster members (e.g. Bonnell et al. 1998, Bate et al. 2003).

On the observational side, millimeter studies both in the continuum (Motte, André & Neri 1998) and molecular lines emission (André et al. 2007) are the best tool to study the very early phases of clustered star formation. Also, millimeter observations of molecular clouds have revealed supersonic linewidths, which are presumably due to turbulent motions. Theory suggests that turbulent motions can be treated as an additional pressure, so that supersonic turbulence increases the effective Jeans mass supported against collapse, $M_J^{eff} = (\frac{\pi}{G})^{3/2} \times \rho^{-1/2} \times c_{s,eff}^3$, where $c_{s,eff}$ is the effective sound speed (such that $c_{s,eff}^2 = c_s^2 + \frac{\langle v^2 \rangle}{3}$).

Recently, Li & Nakamura (2006) discussed the possible effects of protostellar outflows on clustered star formation. In particular, they argued that, due to its short decay time (e.g. Mac Low et al. 1998), the "interstellar turbulence" initially present in a cluster-forming cloud is quickly replaced by turbulent motions generated by protostellar outflows. The protostellar outflow-driven turbulence dominates for most of a protocluster's lifetime and acts to maintain the cluster-forming region close to overall virial equilibrium for several dynamical times, avoiding global free-fall collapse.

As the role of protostellar feedback in cluster-forming clouds is still a matter of debate, detailed studies of the dynamical effects of protostellar outflows in young protoclusters, where outflows are particularly strong and numerous, are required to fully understand the process of clustered star formation.

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1.2 Our target region : the protocluster NGC2264-C.

The NGC 2264-C protocluster is located in the Mon OB1 molecular cloud complex at a distance $d \sim 800$ pc, and has an LSR velocity of $\sim +7$ km.s^{-1}.
In 1972, Allen discovered in this region a bright embedded IR source, hereafter called IRS1, associated with IRAS 06384+0932, and also known as Allen's source. NGC 2264 has been the target of many molecular line studies, including an unbiased CO (J=1 $\rightarrow$ 0) survey for molecular outflows by Margulis et al. (1988) which revealed that IRS1 is associated with a molecular outflow, named NGC 2264-C. Also, a search for dense gas via a multitransitional CS study has been conducted, revealing molecular clumps.
Performing 30m observations with, e.g., MAMBO and HERA, Peretto et al. (2006) first completed a comprehensive mm continuum/line study of the cluster-forming clump NGC 2264-C (Peretto et al. 2006). Their 1.2 mm continuum mosaic of NGC 2264-C resolved the internal structure of the region, uncovering a total of 12 compact prestellar/protostellar cores. Their HCO^+(3–2) and CS line observations, combined with radiative transfer modelling, established the presence of *large-scale collapse motions*, converging onto the most massive core (C-MM3 with $M \sim 40\,M_\odot$, near the center of NGC 2264-C. Moreover, high-resolution PdBI observations in low-optical depth tracers of the inner part of NGC 2264-C allowed them to resolve a strong dynamical interaction in the central part of NGC 2264-C.
Detailed comparison of these 30m/PdBI observations with numerical SPH simulations of the evolution of a 1000 $M_\odot$ Jeans-unstable, isothermal clump (Peretto et al. 2007) confirms the view that NGC2264-C is an elongated clump collapsing/fragmenting along its long axis. The SPH simulations of Peretto et al. (2007) indicate that NGC 2264-C is observed at a very early stage of global clump collapse, typically $\lesssim 10^5$ yr after the start of dynamical contraction. A significant shortcoming of their present SPH simulations, however, is that they only produce the observed level of clump fragmentation when the total mass of dense ($> 10^4\,\mathrm{cm}^{-3}$) gas in the model is a factor of ~ 10 lower than in the actual NGC 2264-C clump. This pointed to the **need for extra support against gravity**, not included in the present simulations, such as support provided by magnetic fields or from feedback from protostellar outflows.
Because it is well documented and known to exhibit outflow activity, the NGC 2264-C protocluster is an ideal laboratory for probing the initial conditions of clustered star formation and evaluating the impact of outflow feedback on early protocluster evolution.

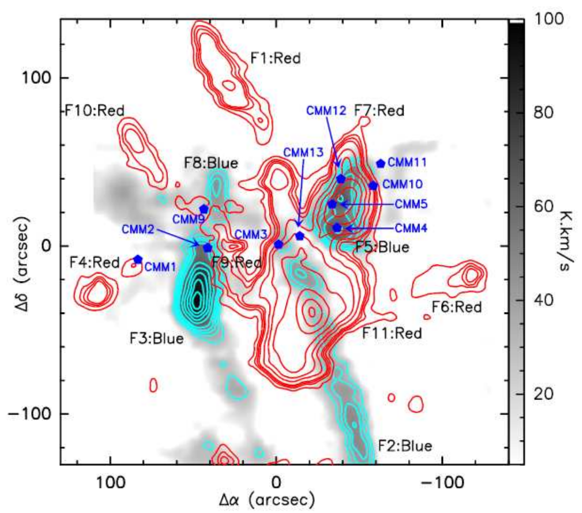

Fig. 1. ^{12}CO(2–1) map of the NGC 2264-C protocluster. The background image and blue contours show the levels of intensity integrated between -27 km/s and 2 km/s in the blue-shifted part of CO(2–1) line, from 5 to 98 K.km.s^{-1}. Red contours are levels of intensity integrated between 13 km/s and 34 km/s in the red-shifted part of the line, from 5 to 110 K.km.s^{-1}. The eleven outflows discovered are labelled by F1 to F11. Blue markers refer to the positions of millimetric peaks found (Peretto et al. 2006, 2007)

1.3 ^{12}CO(2–1) mapping of the NGC 2264-C protocluster

We thus initiated a mapping study of the outflow already detected by Margulis et al. (1988) in NGC 2264-C, with higher angular resolution and better sensitivity. Our goal was to assess the momentum injection rate due to outflows in this protocluster and examine whether outflows could affect the global dynamical evolution of the protocluster.

Observations of the ^{12}CO(2–1), $C^{18}O$(2–1) and ^{13}CO(2–1) emission lines from the NGC 2264-C protocluster were taken with the IRAM-30 m telescope between October and November 2006 using the HEterodyne Receiver

Array HERA together with the VESPA autocorrelator backend. The resulting map has a size of 3.3′ × 3.3′ (equivalent to ∼ 0.6 pc^2 at the distance of the protocluster). We detected a total of eleven sub-regions or "lobes" exhibiting high-velocity emission in the $^{12}CO(2–1)$ map (see Fig.1.). These eleven lobes are spatially distributed around the millimeter continuum cores identified by Peretto et al. (2006, 2007), and four of these lobes can be directly associated with Class 0 - like objects. Moreover, some of the outflows lobes that were found exhibit very colllimated shapes (see bipolar outflow made of F1 and F2 in Fig.1. for an example) and very high LSR velocity features (up to +33 km/s in the case of the blue-shifted lobe F10).

1.4 Momentum flux

To quantify the effective feedback of these eleven outflows on the protocluster, we led a quantitative study consisting in computing the momentum flux injected by the protostellar outflows in the region. Details about the method used can be found in Maury et al. 2008 (in prep).

Following Scoville et al. (1986) we first evaluated the gas mass carried out by each outflow independently, by integrating the excess $^{12}CO(2–1)$ emission both over the adequate velocity range, and spatially over the outflow extent (see Fig. 2.). The masses of entrained gas vary from outflow to outflow, and the total mass carried out by outflows over the whole NGC 2264-C protocluster is estimated to $37{\times}10^{-2}M_\odot$ ($\pm 5{\times}10^{-2}M_\odot$).

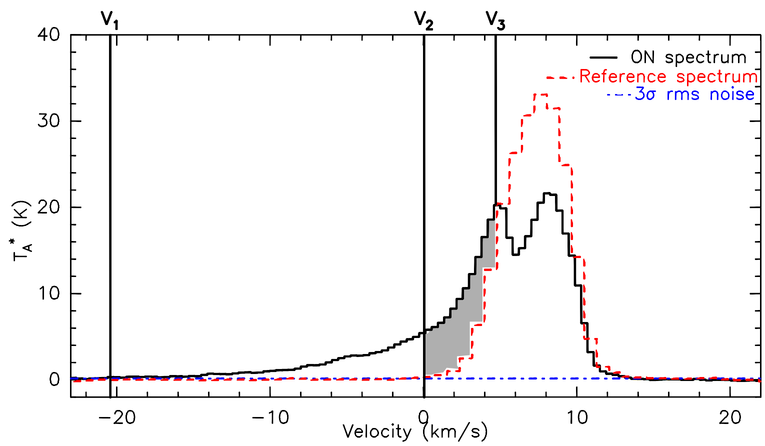

Fig. 2. Excess $^{12}CO(2–1)$ emission at blue-shifted velocities in outflow F3. The dashed spectrum represents the $^{12}CO(2–1)$ reference spectrum. The solid spectrum is extracted from the candidate outflow F3 spectra. Vertical solid lines illustrate the velocity ranges used in the computation of the outflow masses. [V_1 ; V_2] is the interval used for the calculation of the minimum mass : no emission being seen in the reference spectrum, all the emission seen in the spectrum extracted from F3 region is due to outflow. [V_2 ; V_3] is the velocity interval used to compute the additionnal outflow low-velocity mass, by integrating the $^{12}CO(2–1)$ emission corresponding to the area highlighted in grey.

We then used our mass estimates to compute the momentum flux of each outflow :
$F_{out} = M_{out} \times V_{char}/t_{dyn}$, with V_{char} the characteristic velocity of the flow (mean outflow velocity observed in the map over the entire extent of the outflow), and t_{dyn} the dynamical time of the outflow.
A correction factor for inclination of the outflow axis with the line of sight(l.o.s.) has to be taken into account when evaluating V_{char} and t_{dyn}, leading to a final inclination factor $f(i) = \frac{\sin(i)}{\cos^2(i)}$ (cf. Bontemps & al. 1996) on the momentum flux.
For each outflow, the minimum momentum flux was computed using the minimum computed value of entrained gas, and without correction for any inclination effect ($f(i) = 1$).
The maximum momentum flux of each outflow was computed by using the maximum computed value of entrained gas. Also, we assumed random outflow orientations in our dataset in this case, and therefore applied a correction factor $\langle f(i)\rangle = 2.9$ (corresponding to a mean statistic inclination angle i∼ 57.3°).

The momentum fluxes vary from outflow to outflow, and the total momentum flux injected by outflows over the whole NGC 2264-C protocluster is estimated to $10{\times}10^{-4}$ $M_\odot$.km.s^{-1}.yr^{-1} ($\pm 7{\times}10^{-4}$ $M_\odot$.km.s^{-1}.yr^{-1}).

1.5 Conclusions

We discovered eleven outflows emerging from compact Class 0-like protostellar sources in the NGC2264-C complex (see Fig. 1.). Most of them are powerful ones (if compared to Class 0 outflows studied by Bontemps & al. 1996), strengthening the idea that NGC2264-C is forming luminous intermediate-mass objects.

The maximum total force due to the eleven ^{12}CO(2–1) protostellar outflows is found to be:

$$\mathbf{F}_{out} \approx \mathbf{1.7{\times}10^{-3}\ M_{\odot}.km.s^{-1}.yr^{-1}}.$$

In order to discuss wether or not such a force applied to the NGC 2264-C protocluster has to be taken into account in the energy budget, we estimated the support needed to keep the whole protocluster (mass of ≈1600 $M_{\odot}$ in a 0.4pc radius) in hydrostatic equilibrium.
The pressure gradient needed to keep a spherical clump with a mass distibution such as $\rho(r) = \frac{a^2}{2\pi G r^2}$ and M(R=0.4pc) = 1600 $M_{\odot}$ (where a is the isothermal sound speed, and G is the gravitational constant) in hydrostatic equilibrium is:

$$\frac{dP}{dr} = -\ G\ \frac{\rho(r).m(r)}{r^2} \implies P{=}\frac{GM^2}{8\pi R^4} \quad \text{for a spherical shell of radius R.}$$

Therefore, the total force needed to balance gravity at radius $R = 0.4$ pc in the NGC 2264-C protocluster is:

$$\mathbf{F} = \frac{GM^2}{2R^2} = \mathbf{40{\times}10^{-3}\ M_{\odot}.km.s^{-1}.yr^{-1}}$$

If we compare this value to the largest force exerted by the eleven outflows on the surrounding protocluster, we conclude that the total momentum flux injected by the eleven outflows is too small by an order of magnitude to provide significant support against collapse in NGC 2264-C. One should consider either cumulative effects of outflows on a longer timescale, or numerous weaker outflows not detected in this study to bring additionnal support against gravity through protostellar outflows (Maury et al. 2008, in prep.).

We show that the energy injected by outflows into cloud turbulent motions is much too low to efficiently support the whole collapsing protocluster. We conclude that the extra support needed to explain the global dynamics of the NGC2264-C protocluster could have another origin, such as magnetic support.

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