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DYNAMIC STAR FORMATION

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RESUMEN

Argumentamos que es necesario entender cómo se forman las nubes a fin de entender las condiciones iniciales que conducen a la formación estelar. Los flujos a gran escala que barren el gas interestelar forman las nubes, mismas que proceden inmediatamente al colapso global. Simultáneamente, estos flujos sufren varias inestabilidades, formando los grumos protoestelares, los cuales se contraen más rápidamente, procediendo a una rápida y local, aunque distribuida formación estelar, antes de que el colapso global domine.

ABSTRACT

We argue that it is necessary to understand how clouds form to understand the initial conditions leading to star formation. Large-scale flows that sweep up gas in the interstellar medium form clouds, which immediately start their global collapse. At the same time, such flows are subject to various instabilities which can form protostellar clumps that contract faster, proceeding to a rapid, local but distributed star formation before global collapse dominates.

Key Words: ISM: clouds — stars: formation — stars: pre-main sequence

1. A SCENARIO FOR MOLECULAR CLOUD FRAGMENTATION

For some time the low rate of star formation in the Milky Way was attributed to the retarding effects of magnetic fields, which permitted protostellar cores to collapse only when ion-neutral drift (i.e., ambipolar diffusion) removed enough magnetic flux for gravity to take over (e.g., Shu, Adams, & Lizano 1987). However, stellar populations within molecular clouds have low ages, and few molecular clouds of significant mass harbor no young stars (Hartmann, Ballesteros-Paredes, & Bergin 2001; Ballesteros-Paredes & Hartmann 2007). Instead, the low rate of star formation is due to *inefficient production*; molecular clouds are dispersed (mostly by the energy input of massive stars) before a significant fraction of the gas can be converted into stars. The result is that star formation is a highly time-dependent, dynamic process.

The rapidity with which star formation occurs after molecular cloud formation from atomic gas in the solar neighborhood (Bergin et al. 2004) suggests that one should look to the cloud formation process to understand fragmentation. We have argued that the assembly of molecular clouds generally occurs through large-scale supersonic flows in the interstellar medium, which can explain why stellar population ages are often smaller than lateral crossing times (Ballesteros-Paredes, Hartmann, & Vazquez-Semadeni 1999). Working within this paradigm, we have been investigating the formation of substructure in post-shock gas due to various instabilities (Heitsch et al. 2005, 2006, 2008). In particular, we find that both the non-linear thin shell instability (NTSI) and the Kelvin-Helmholtz instability (KHI) can be triggered if the flow is not perfectly normal to the shock front, or if there are small perturbations in the shock front. These in turn can produce density concentrations which are strongly amplified by thermal instability and cooling, until gravity becomes important and core collapse proceeds.

Figure 1 shows a time sequence of the process envisaged to produce protostellar cores. Small initial perturbations grow through NTSI and KHI, and then are amplified by thermal instability and rapid cooling. The result is a series of small dense clumps that have the potential to form protostars rapidly upon the cloud achieving local densities and average surface densities sufficient to form H_2 and CO.

The dense knots of gas mostly are formed along a partial "ring" or slightly curved filament. This structure is the result of the so-called "edge effect" (Burkert & Hartmann 2004). Finite massive clouds, especially if flattened, tend to have non-linear gravitational accelerations near their edge which cause material to pile up. To avoid immediate ring formation in the simulation shown in Figure 1, we decreased the densities of the elliptical flows proceeding

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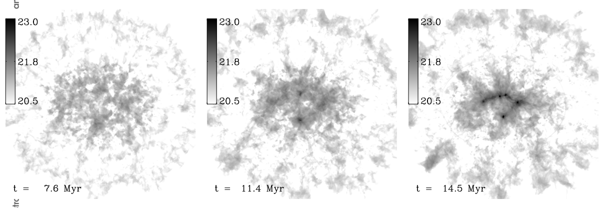

Fig. 1. Time evolution of the collision of two identical, supersonic flows of atomic gas. The flows have an elliptical cross-section, and the interface between the flows is slightly perturbed with long wavelengths to start the instabilities. The column densities (gray scale) are shown from the direction along the flows.

from center to edge; even so, a remnant of the edge effect is present, eventually producing a ring-shaped structure.

2. GLOBAL GRAVITATIONAL COLLAPSE

Note also that the dense clumps and filament are collapsing toward the center. Burkert & Hartmann (2004) emphasized that massive molecular clouds are generally subject to global gravitational collapse — a feature which is *not* seen (and cannot be seen) in simulations with periodic boundary conditions. In the slow formation, long cloud lifetime scenario, supersonic turbulence is needed to keep clouds from collapsing, leaving them in a quasi-equilibrium state. However, numerical simulations show that supersonic turbulence decays rapidly (e.g. Mac Low et al. 1998; Stone, Ostriker, & Gammie 1998; Ostriker, Gammie, & Stone 1999), so unless the turbulence is continuously regenerated, collapse is likely somewhere. In the rapid star formation picture, support is unnecessary as long as the cloud is dispersed sufficiently rapidly by stellar energy input. The resulting infall velocities, only $\sim 2^{1/2}$ larger than equilibrium, are consistent with observations.

To illustrate the potential effects of global gravitational collapse, in Figure 2 we show the time evolution of a gravitationally collapsing, rotating sheet. The development of dense filaments results from the edge effect, with a particularly massive region near one end. The resulting morphology bears a striking resemblance to the structure of the dense gas of the Orion A molecular cloud. Furthermore, the edge effect with particular focusing at the densest end of the cloud provides a natural mechanism for collecting a large mass of gas to form the Orion Nebula Cluster. Finally, the entire evolution of this isothermal simulation, when scaled to the current length ~ 40 pc and mass $\sim 10^5\ M_\odot$ of the Orion A cloud, takes only 1.7 Myr, consistent with the typical ages

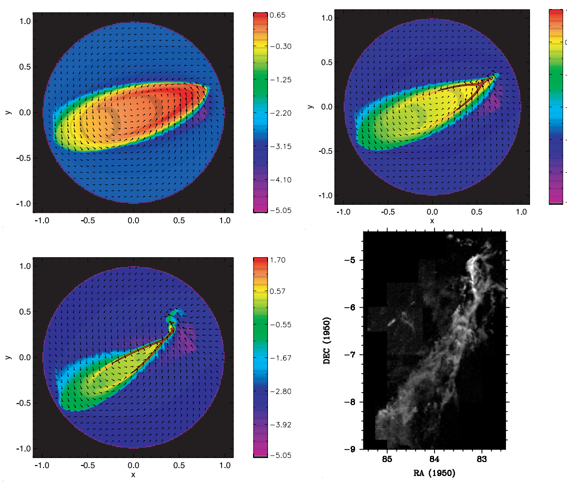

Fig. 2. Surface densities in a simulation of the gravitational collapse of an initially elliptical, isothermal sheet. The sheet initially has a smooth increase of surface density toward one end, and is set into uniform rotation. The sheet contracts gravitationally, with filaments resulting from the edge effect, and a concentration of mass toward the initially dense end of the sheet. The final structure bears a striking resemblance to the morphology of the ^{13}CO gas in the region, as mapped by Bally et al. (1987). (From Hartmann & Burkert 2007).

of stars $\lesssim 1$ Myr in the region. The conclusion is that global gravitational effects must be treated in any attempt to understand the structure and evolution of star-forming clouds.

REFERENCES

Ballesteros-Paredes, J., & Hartmann, L. 2007, RevMexAA, 43, 123

Ballesteros-Paredes, J., Hartmann, L., & Vázquez-Semadeni, E. 1999, ApJ, 527, 285

Bally, J., Stark, A. A., Wilson, R. W., & Langer, W. D. 1987, ApJ, 312, L45

Bergin, E. A., Hartmann, L. W., Raymond, J. C., & Ballesteros-Paredes, J. 2004, ApJ, 612, 921

Burkert, A., & Hartmann, L. 2004, ApJ, 616, 288

Hartmann, L., & Burkert, A. 2007, ApJ, 654, 988

Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. A. 2001, ApJ, 562, 852

Heitsch, F., et al. 2005, ApJ, 633, L113

_________. 2006, ApJ, 648, 1052

_________. 2008, ApJ, 674, 316

Mac Low, M.-M., Klessen, R. S., Burkert, A., & Smith, M. D. 1998, Phys. Rev. Lett., 80, 2754

Ostriker, E. C., Gammie, C. F., & Stone, J. M. 1999, ApJ, 513, 259

Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23

Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, ApJ, 508, L99