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FRAGMENTATION OF ELONGATED CYLINDRICAL CLOUDS

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RESUMEN

Usando simulaciones hidrodinámicas tridimensionales estudiamos la fragmentación de nubes moleculares uniformes, isotérmicas y alargadas, las cuales están rotando alrededor de un eje perpendicular a la dirección de su alargamiento. Argumentamos que este proceso puede resultar en la formación de estrellas binarias y múltiples. Este nuevo método en la producción de estrellas binarias puede explicar sistemas binarios de gran separación, con grandes excentricidades y diversas razones de masas. Para números de Jeans, J_0, (la razón de energías de amarre a energías térmicas) relativamente bajos, se forma un sistema binario simple. Para mayores valores de J_0, fragmentación múltiple ocurre entre los fragmentos binarios, formándose así un sistema múltiple. Esta fragmentación adicional espontánea es inducida por la rotación. El añadir una componente del momento angular paralela al eje de alargamiento, complica este escenario. Para J_0 pequeño, aun se forma un sistema binario simple. Para J_0 mayor la fragmentación múltiple ya no ocurre entre los fragmentos binarios, pero a cambio los mismos fragmentos binarios pueden fragmentarse a través de un estado de barra intermedio, o a través de un estado de disco intermedio.

ABSTRACT

Using 3D hydrodynamical simulations, we study the fragmentation of uniform, isothermal, elongated molecular clouds, which are slowly rotating around an axis perpendicular to their elongation. We argue that this process could result in the formation of binary and multiple stars. This new method for forming binary stars can explain widely separated binaries with large eccentricities and various mass ratios. At relatively low Jeans numbers J_0 (the ratio of the binding energies to thermal energies), a simple binary system is formed. For higher J_0, multiple fragmentation occurs between the binary fragments, forming a multiple system. This spontaneous additional fragmentation is induced by rotation. The addition of an angular momentum component parallel to the axis of elongation complicates this scenario. At low J_0, a simple binary is still formed. At higher J_0, multiple fragmentation no longer occurs between the binary fragments but instead the binary fragments themselves can fragment through an intermediary bar stage, or through an intermediary fragment-disk stage.

Key words: HYDRODYNAMICS — ISM: CLOUDS — ISM: KINEMATICS AND DYNAMICS — STARS: FORMATION

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1. INTRODUCTION

Bastien (1983) and Rouleau & Bastien (1990) showed that, for sufficiently high J_0, the collapse of elongated clouds with uniform density and temperature naturally break into two fragments of equal mass. These fragments rapidly collapse on themselves to form protostars, and on a longer timescale move toward each other along the axis of the cloud. If the simulations were pursued further, the fragments would eventually collide and merge at the center of the cloud. Zinnecker (1991) suggested that clouds could be initially rotating about an axis perpendicular to their elongation. Such rotation would provide sufficient angular momentum to form the binary.

To test this idea, we performed 3D hydrodynamical simulations using a Smooth Particle Hydrodynamics (*SPH*) code. Clouds were parametrized by there length L, ratio of length to diameter L/D, initial Jeans number J_0, and by the parameters $\beta_\perp$ and $\beta_{||}$, where β is the ratio of rotational kinetic energy to binding energy, and the subscripts $\perp$ and $||$ refer to the rotation perpendicular and parallel to the axis of the cloud, respectively. The cloud length, in all cases, was 0.45 pc, while $\beta_\perp$ and $\beta_{||}$ were in the range $0-0.3$ in accordance with observations (see, e.g., Goldsmith & Arquilla 1985). We used an isothermal equation of state for pure molecular hydrogen at a temperature of 10 K.

2. THE FORMATION OF BINARY SYSTEMS

With a nonzero $\beta_\perp$, flat, disk-like envelopes form around the two binary fragments. At the minimum fragment separation, these disks can be close enough for tidal interaction to be important. This interaction decreases the fragments' relative velocities. The disks themselves are strongly disrupted, their rotation being prograde relative to the orbit. A familiar spiral structure forms in the disks (indicating the presence of gravitational torques), and the outer arms (located the farthest from the center of the binary) can have enough relative velocity to escape the fragment carrying away some angular momentum.

All simulations produced at least a binary system. The binaries are characterized by an initially high orbital eccentricity (0.44 to 0.8) and maximum separations of 0.01 tp 0.1 pc. These results are in good agreement with observations of wide binaries (Duquennoy & Mayor 1989). For a given angular velocity, the clouds with larger L/D produce smaller orbital eccentricities. In such cases, the initial separation of the fragments is larger, yielding smaller ratios of radial to transverse velocities. Lowering the rotation for a given L/D reduces the angular momentum, thus producing larger eccentricities, unless separation at closest approach is small enough for allowing dissipative effects to reduce the eccentricity. Finally, the eccentricities increase with the J_0, as the larger gravitational pull on the fragments increases their radial velocities.

3. THE FORMATION OF MULTIPLE SYSTEMS

For higher J_0 the cloud collapses primarily towards the major axis (see Bastien 1983). When this happens, the matter between the two binary fragments can itself fragment if initial perturbations are present (Bastien *et al.* 1991). Fragmentation between the binary seems to occur spontaneously due to the rotation for $L/D = 2$ and $J_0 = 3 - 4$. This is illustrated on Figure 1 for a cloud of mass $12.4 M_\odot$. One minor fragment survived an interaction with one of the major fragment's disk (1a–1d), while the other disk formed a low mass companion with a mass ratio of 0.28 (1c–1e). Another minor fragment formed at the cloud's center and eventually encountered this binary system (primary and low mass companion), forming a triple system (1e–1f). This triple system bound as it is to a binary system forms a quintuple system. The binary is composed of a major fragment ($2.7 M_\odot$) and a companion ($1.47 M_\odot$), whereas the triple system is composed of a major fragment ($3.0 M_\odot$) and two companions ($1.02 M_\odot$ and $0.83 M_\odot$). Disk fragmentation occurs only when the companion is itself a binary or multiple system. The disks were never observed to fragment when the system was a simple binary. This could indicate that the presence of an oscillating gravitational field amplifies the $m = 1$ instability such that fewer orbits are required, or that this instability is generated by the binary companion.

4. DOUBLE ROTATION: MODES OF FRAGMENTATION

The collapse of clouds with nonzero $\beta_{||}$ largely resembles that of clouds with $\beta_{||} = 0$. However, the binary fragments come out in various shapes, depending on the values of $\beta_{||}$ and J_0. The fragment's shapes can be either spheroidal with surrounding disks, bar-shaped, or toroidal. Further fragmentation can occur depending on the type of fragment. Bar fragmentation occurs for larger values of $\beta_{||}$ and J_0. In some cases the central

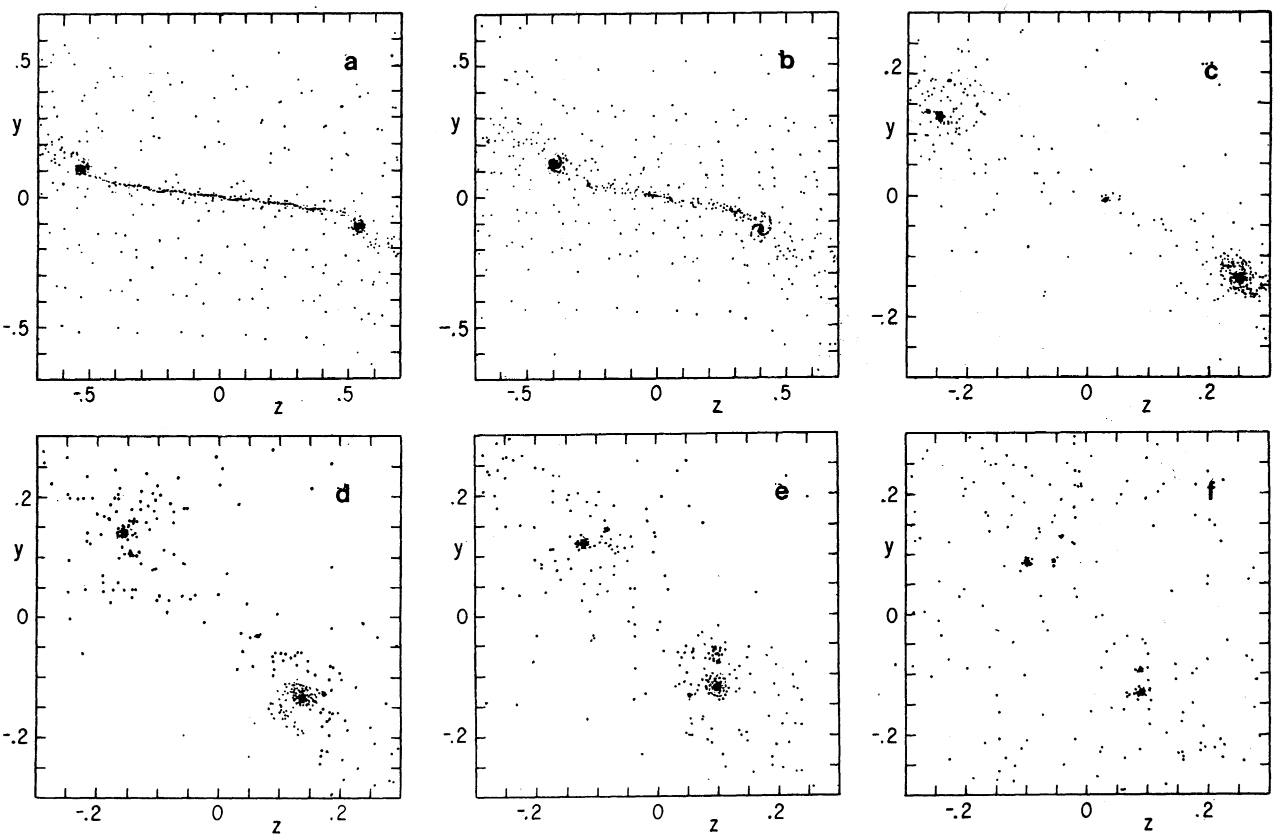

Fig. 1. — Fragmentation of a rotating elongated cloud, leading to the formation of a quintuple system. From Bonnell *et al.*, The Astrophysical Journal, 377, 553 (1991).

region of the bar evolves into a single fragment, while the extremities evolve into a spiral pattern that turns into a disk. In some other cases the bar fragments directly into 2 components. The spiral arms are also observed to fragment. This happens at higher values of J_0 when the bar forms one condensation but not at its center. Disk fragmentation occurs for intermediary values of $\beta_{\|}$ and J_0. This disk fragmentation is due to the residue non-axisymmetric material from an unsuccessful bar fragmentation. The toroidal shaped fragments themselves fragment directly into multiple components. The value of $\beta_{\perp}$ determines whether or not the binary fragments will have time to interact before fragmenting. Such interaction (collision or tidal disruption) also leads to subfragmentation. Figure 2 shows schematically the location of these various fragmentation modes in the $J_0 - \beta_{\|}$ phase space. A small nonzero value of $\beta_{\perp}$ (a few percent) is assumed.

5. SUMMARY OF FRAGMENTATION MODES REAVELED BY THE SIMULATIONS

1) *PRIMARY MODE*, designates the fragmentation of the parent cloud.

Binary Fragmentation: The parent cloud fragments into two condensations, called *Binary Fragments*, located at each end of the cloud.

No Fragmentation: Occurs when the Jeans number is too small. A single condensation forms in the center of the cloud.

Evaporation: Occurs for even smaller Jeans numbers. The cloud is gravitationally unbound.

2) *SECONDARY MODES*, designates the subsequent fragmentation of the Binary Fragments or their surrounding.

No Fragmentation: The system remains a binary.

Fragment Dissipation: One of the binary fragment is dissipated by tidal interaction.

Spindle Fragmentation: A fragment forms in the bridge connecting the Binary Fragments. Occurs only for very small $\beta_{||}$.

Disk Collision: The Binary Fragments collide in the center of the cloud.

Bar Fragmentation: A bar-shaped Binary Fragment fragments in two subcondensation. This mode is very similar to the Binary Fragmentation of the parent cloud itself.

Bar-Arm Fragmentation: A fragment forms inside a spiral arm surrounding a bar-shaped Binary Fragment.

Disk Fragmentation: A $m = 1$ instability in the disk surrounding a Binary Fragment results in the formation of a companion.

Toroidal Fragmentation: Occurs only when the rotation parallel to the axis of the cloud is differential instead of solid body.

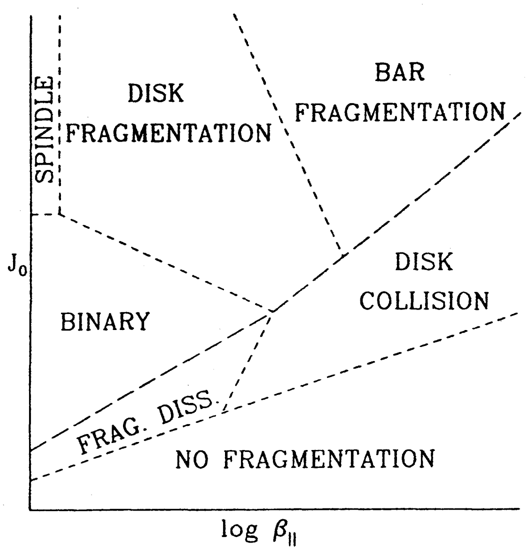

Fig. 2. — Schematic representation of the location of the fragmentation modes in the $J_0 - \beta_{||}$ phase space. From Bonnell *et al.*, The Astrophysical Journal, 400, 579 (1992).

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