Turbulence, clustered star formation and the rapid star formation model

Lecture 6
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Turbulence and star formation in molecular clouds

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Summary. Data for many molecular clouds and condensations show that the internal velocity dispersion of each region is well correlated with its size and mass, and these correlations are approximately of power-law form. The dependence of velocity dispersion on region size is similar to the Kolmogoroff law for subsonic turbulence, suggesting that the observed motions are all part of a common hierarchy of interstellar turbulent motions. The regions studied are mostly gravitationally bound and in approximate virial equilibrium. However, they cannot have formed by simple gravitational collapse, and it appears likely that molecular clouds and their substructures have been created at least partly by processes of supersonic hydrodynamics. The hierarchy of subcondensations may terminate with objects so small that their internal motions are no longer supersonic; this predicts a minimum protostellar mass of the order of a few tenths of a solar mass. Massive ‘protostellar’ clumps always have supersonic internal motions and will therefore develop complex internal structures, probably leading to the formation of many post-stellar condensation nuclei that grow by accretion to produce the final stellar mass spectrum. Molecular clouds must be transient structures, and are probably dispersed after not much more than 10^7 yr.
\[ \delta v \propto l^\alpha, \]
\[ \alpha = 0.65 \pm 0.01 \]
Decay of turbulence

- comparison of decay timescale in hydrodynamics simulations (no magnetic fields) to simulations including magnetic fields (magneto-hydrodynamics, or “MHD”)

FIG. 12. Decay of supersonic turbulence. The plots show the time evolution of the total kinetic energy $E_k$ in a variety of 3D numerical calculations of decaying supersonic turbulence in isothermal ideal gas with initial rms Mach number $M = 5$. Grid-based ZEUS models have $32^3$ (dotted line), $64^3$ (short-dashed line), $128^3$ (long-dashed line), or $256^3$ (solid line) zones, while the particle-based smoothed particle hydrodynamics (SPH) models have 7000 (dotted line), 50,000 (short-dashed line), or 350,000 (solid line) particles. The panels show (a) gas-dynamic runs with ZEUS, (b) gas-dynamic runs with SPH, (c) MHD ZEUS calculations with Alfvénic Mach number $A = 5$, and (d) $A = 1$ MHD runs with ZEUS, where $A = \nu_m / v_A = v_{rms} / \sqrt{4 \pi \rho |B|}$. From Mac Low et al., 1998.
ABSTRACT

We suggest that molecular clouds can be formed on short timescales by compressions from large scale streams in the interstellar medium (ISM). In particular, we argue that in the Taurus-Auriga complex, with diameters of 20-20 x 2-2 pc, most have been formed by H I flows in ≲ 3 Myr, explaining the absence of post-T Tauri stars in the region with ages ≳ 3 Myr. Observations in the 21 cm line of the H I "index" around the Taurus molecular gas show many features (broad asymmetric profiles, velocity shifts of H I relative to CO) predicted by our MHD numerical simulations, in which large-scale H I streams collide to produce dense filamentary structures. The rapid evolution is possible because the H I flows producing and disrupting the clouds have much higher velocities (5-10 km s⁻¹) than are present in the molecular gas resulting from the colliding flows. The simulations suggest that such flows can occur from the global ISM turbulence without requiring a single triggering event such as a supernova explosion.

Subject headings: ISM—clouds — ISM—evolution — stars: formation — stars: pre-main-sequence — turbulence

INTRODUCTION

It has been recognized for many years that the measured star-formation regions exhibit little evidence for stars of ages ≲ 5 Myr, even though one would expect that such "post-T Tauri stars" (PTTSs) should be more numerous than the ~1 Myr old T Tauri stars. More than a decade ago, Herbig, Vrba, & Rydgren (1988) stated that "it is a source of some unease that this large population of PTTSs has not yet been identified." Since that time, a variety of techniques, including proper motion surveys, major photometric surveys from plates, and CCD photometric selection, have been used to search for PTTSs. As outlined in §2, none of these techniques has yielded evidence for PTTSs in any significant numbers.

The lack of PTTSs, combined with the presence of newly formed stars in all substantial nearby molecular clouds, is most simply explained if molecular clouds like Taurus come together, form stars, and disperse in a few megayears. However, this simple picture causes difficulties for current theories of star formation. Since Taurus has a spatial extent of 20 pc, but the molecular gas has a velocity dispersion of only about 2 km s⁻¹, it is difficult to understand how such widely separated regions produced stars almost simultaneously, i.e., how star formation is triggered throughout the cloud on a scale shorter than the crossing (or dynamical) timescale. In principle, a simple powerful event like a supernova explosion is required for star formation in a molecular cloud over short timescales, but there is no obvious candidate for this triggering source in the case of Taurus (Elmegreen 1991).

In addition, Taurus is supposed to be the archetype for the "standard" picture of isolated, low-mass star formation, in which magnetically subcritical cloud cores collapse to form stars only after ambipolar diffusion has removed excess magnetic flux on timescales of order 10⁰ Myr (Shu, Adams, & Lizano 1987, Meschtscherou 1991, and references therein). If protostellar cloud cores are highly subcritical, the long ambipolar diffusion timescale makes it difficult to understand star formation events lasting only a few megayears. A long diffusion timescale also makes it difficult to reconcile with the existence of clouds with less than 10⁻²⁰ pc⁻¹ (van Dishoeck 1991). This is more complete, consisting of direct measurements, such as the self-gravity rate, as recognized for a long time, it essentially involves four changes to way we view the physical processes

Today the observational picture for rapid star formation has changed. We suggest that molecular clouds can be formed on short timescales by compressions from large scale streams in the interstellar medium (ISM). In particular, we argue that in the Taurus-Auriga complex, with diameters of 20-20 x 2-2 pc, most have been formed by H I flows in ≲ 3 Myr, explaining the absence of post-T Tauri stars in the region with ages ≳ 3 Myr. Observations in the 21 cm line of the H I "index" around the Taurus molecular gas show many features (broad asymmetric profiles, velocity shifts of H I relative to CO) predicted by our MHD numerical simulations, in which large-scale H I streams collide to produce dense filamentary structures. The rapid evolution is possible because the H I flows producing and disrupting the clouds have much higher velocities (5-10 km s⁻¹) than are present in the molecular gas resulting from the colliding flows. The simulations suggest that such flows can occur from the global ISM turbulence without requiring a single triggering event such as a supernova explosion.

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Rapid Formation of Molecular Clouds and Stars in the Solar Neighborhood

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ABSTRACT

We show how molecular clouds in the solar neighborhood might be formed and produce stars rapidly enough to explain stellar population ages, building on results from numerical simulations of the turbulent interstellar medium and general considerations of molecular gas formation. Observations of both star-forming regions and young, gas-free stellar associations indicate that most nearby molecular clouds form stars only over a short time span before dispersal; large-scale flows in the diffuse interstellar medium have the potential for forming clouds sufficiently rapidly and for producing stellar populations with ages much less than the lateral crossing times of their host molecular clouds. We identify four important factors for understanding rapid star formation and short cloud lifetimes. First, much of the accumulation and dispersal of clouds near the solar circle might occur in the atomic phase; only the high-density portion of a cloud’s life cycle is spent in the molecular phase, thus helping to limit molecular cloud “lifetimes.” Second, once a cloud achieves a high enough column density to form H₂ and CO, gravitational forces become larger than typical interstellar pressure forces; thus, star formation can follow rapidly upon molecular gas formation and turbulent dissipation in limited areas of each cloud complex. Third, typical magnetic fields are not strong enough to prevent rapid cloud formation and gravitational collapse. Fourth, rapid dispersal of gas by newly formed stars, passing shock waves, and reduction of shielding by a small expansion of the cloud after the first events of star formation might limit the length of the star formation epoch and the lifetime of a cloud in its molecular state. This picture emphasizes the importance of large-scale boundary conditions for understanding molecular cloud formation and implies that star formation is a highly dynamic, rather than quasi-static, process and that the low Galactic star formation rate is due to low efficiency rather than slowed collapse in local regions.

Subject headings: circumstellar matter — ISM: clouds — stars: formation — stars: pre-main-sequence

Observational Constraints on the Ages of Molecular Clouds and the Star Formation Timescale: Ambipolar-Diffusion–Controlled or Turbulence-Induced Star Formation?

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ABSTRACT

We revisit the problem of the star formation timescale and the ages of molecular clouds. The apparent over-abundance of star-forming molecular clouds over clouds without active star formation has been thought to indicate that molecular clouds are “short-lived” and that star formation is “rapid.” We show that this statistical argument lacks self-consistency and, even within the rapid star formation scenario, implies cloud lifetimes \(\approx 10\) Myr. We discuss additional observational evidence from external galaxies that indicate lifetimes of molecular clouds and a timescale of star formation of \(\approx 10^7\) years. These long cloud lifetimes, in conjunction with the rapid (\(\approx 1\) Myr) decay of supersonic turbulence, present severe difficulties for the scenario of turbulence-controlled star formation. By contrast, we show that all 31 existing observations of objects for which the line width, the size, and the magnetic field strength have been reliably measured are in excellent quantitative agreement with the predictions of the ambipolar-diffusion theory. Within the ambipolar-diffusion–controlled star formation theory, the line widths may be attributed to large-scale nonradial cloud oscillations (essentially standing large-amplitude, long-wavelength Alfvén waves), and the predicted relation between the line width, the size, and the magnetic field is a natural consequence of magnetic support of self-gravitating clouds.