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J. E. Tohline

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Star formation in the early Universe

By J. E. Tohline
Yale University Observatory, Box 2023, *Yale Station,*
New Haven, Connecticut 06520, *U.S.A.*

Introduction

Recent three-dimensional fluid dynamic numerical calculations have been performed to study the gravitational fragmentation of Jeans unstable gas clouds as they undergo dynamic collapse. So far the results of these numerical experiments have been applied to discussions of star formation in gas clouds whose densities and temperatures are representative of conditions in the galactic disk, but the results have important implications with regard to theories of galaxy formation and star formation in the early Universe as well. The numerical experiments and their general results are briefly reviewed in the following section; a few comments concerning the implications these results have on star formation in the early Universe are made in the last section.

The numerical experiments

The three-dimensional fluid dynamic calculations on which the following discussion is based are described in detail by Tohline (1978, 1980). A numerical program was written to follow the self-gravitating collapse of a rotating gas cloud, including the effects of gas pressure gradients. A cylindrical grid of resolution (34, 16, 34) in (R, θ, z) was used; the rotation axis was aligned with the Z-axis of the coordinate grid; the only geometric symmetry assumed was reflexion through the equatorial plane of the cloud. In this initial investigation the gas clouds were constrained to be isothermal both in space and time; magnetic fields and viscous forces were ignored. The initial *basic* models were uniform in density and uniformly rotating, and had no motion in in the meridional, R–Z planes, allowing unique definition by the two parameters α (the ratio of thermal energy to the absolute value of the gravitational potential energy) and β (the ratio of the rotational kinetic energy to the absolute value of the gravitational potential energy). The magnitude of α ($\lesssim 1$) tells how close the model is to pressure equilibrium, or equivalently how many Jeans masses are enclosed in the initial cloud; the magnitude of β ($\lesssim 0.3$) tells how close the cloud is to centrifugal balance. To test the susceptibility of each model to fragmentation, I perturbed the *basic* model by embedding two density-enhanced ‘blobs’ on opposite sides of the rotation axis – in the angular coordinate, the perturbation introduced a pure $m = 2$ mode into the cloud's density structure. The density and velocity structure of the clouds were analysed throughout their dynamic collapse; damping or amplification of asymmetries in the structure were recorded as well as the tendency for long wavelength perturbations to distribute their energy into smaller wavelengths.

Briefly the results of the numerical experiments can be summarized as follows: an isothermal gas cloud that collapses from a Jeans unstable configuration will only fragment *during* its dynamic collapse if perturbations in the initial cloud structure, themselves, enclose more than a Jeans mass of material.† Density fluctuations initially smaller than a Jeans mass undergo pressure damping and do not subsequently grow in amplitude during the dynamic collapse of a cloud even though the classical Jeans length decreases in proportion to the square root of the increasing cloud density. This empirical conclusion implies: (1) a gas cloud that initially encloses N Jeans masses can be induced to fragment into at most N pieces during its collapse (in practice, the number of pieces will be substantially smaller than N); (2) a cloud near the Jeans limit ($\alpha \approx 1.0$) which, by definition, initially encloses little more than one Jeans mass of gas, will not undergo fragmentation during its dynamic collapse. This finding is in contrast to the picture of fragmentation suggested by the earlier analytical work of Hoyle (1953) and Hunter (1962), which concerns the growth of perturbations in a collapsing, *pressure-free* gas cloud.

The numerical calculations do indicate that once a gas cloud has collapsed to a denser, 'quasi-static' configuration – that is, a configuration that is no longer evolving on a dynamic time scale but which, because other forces have grown in importance, is at least temporarily supported against gravitational collapse (centrifugal forces were the crucial balancing mechanism in these calculations) – it may finally experience the growth of small wavelength perturbations.

Larson (1978) has simulated three-dimensional gas dynamics with a particle code and his results support these conclusions. He found that a gas cloud could fragment as a result of small amplitude random perturbations in the initial cloud structure, but in all cases the number of fragments that formed and the fraction of the total cloud mass that went into each fragment was directly related to the number of Jeans masses in the initial cloud. Larson also found (private communication) that significant growth of perturbations, and hence noticeable fragmentation of the cloud, did not occur until *after* the entire gas cloud had completed its initial dynamic collapse and was adjusting to a long-lived, rotationally balanced configuration.

IMPLICATIONS

These isothermal models are of course idealized, but the pressure damping observed in these models alters considerably the predictions concerning the fragmentation of gas clouds that have, until now, been based primarily on pressure-free analyses. If, at the time when radiation and matter decoupled in the early Universe, there was indeed a spectrum of density fluctuations in which the minimum Jeans mass was *ca.* 10^5–$10^6\ M_\odot$, our numerical experiments indicate that fragmentation on a smaller mass scale than this would not have occurred until after at least one free-fall time,

$$\tau_{\mathrm{ff}} = (\tfrac{3}{32}\pi/G\rho_0)^{\frac{1}{2}},$$

as determined by the density, ρ_0, in the initial fluctuations. Because these massive clouds would not have undergone spontaneous gravitational fragmentation during their collapse, they each would have formed a single, supermassive object unless forces due to rotation or magnetic fields stopped the collapse before it reached stellar densities. Supermassive objects which formed directly from Jeans unstable fragments in the early Universe would have initially permeated the Universe in a fairly uniform fashion; subsequent clustering of the objects, occurring in a dissi-

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† It should be noted here that this was a necessary, but not sufficient, condition. One case was examined in which perturbations, initially Jean's unstable, eventually succumbed to damping by the gas flow involved in the overall collapse of the gas cloud and as a result did not lead to fragmentation.

pationless fashion, should have left these objects more uniformly distributed in Space than any stellar population that formed from gas at later times.

Even if rotation prevented a supermassive cloud from collapsing to a single object, the numerical studies indicate that fragmentation of the rotationally flattened spheroid would have produced a small number of gas blobs of relatively large mass. One would have to follow the collapse, rotational flattening and subsequent fragmentation of these blobs through many generations before obtaining what we would normally term 'stellar mass' fragments. Such a stepwise fragmentation process would undoubtedly produce some stars at *all* masses, making it highly unlikely that the initial mass function of stars in the early Universe was skewed entirely to very low mass objects.

Our numerical experiments also indicate that in a general sense, gravitational fragmentation of isolated massive gas clouds is a 'difficult' process that is relatively slow and inefficient at producing large numbers of objects of stellar mass. It seems likely that bursts of star formation will only occur when a gas cloud is induced by some external agent to form stars (e.g. collisions between gas clouds).

In summary, it is highly unlikely that star formation processes in the early Universe (during 1–2 τ_{ff} after the time, t_0, when matter and radiation decoupled) produced a significant number of stars with masses as small as the stars that currently dominate the observable stellar mass function ($M \lesssim 30\ M_\odot$). Fragmentation processes make it much more unlikely that a large stellar population consisting of *only* very low mass, low luminosity stars ($M < 0.5\ M_\odot$) formed during this time. It is plausible, however, that a generation of supermassive stars ($M \approx 10^5$–$10^6\ M_\odot$) formed directly from Jeans unstable density perturbations that were present in the Universe at time t_0. I therefore support the idea that the 'unseen' massive halos around galaxies and the component of clusters that is responsible for observed large mass:light ratios are made up of the dark remnant of supermassive stars, and not of objects of very low mass.

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