1997RMxAC...6..195B

RevMexAA (Serie de Conferencias), **6**, 195–197 (1997)

EQUILIBRIUM AND PHOTOIONIZATION REGULATED STAR FORMATION

Frank Bertoldi[1] and Christopher F. McKee[2]

RESUMEN

Se propone un modelo global para la formación de estrellas de baja masa en nubes moleculares gigantes (GMC), regulado por la fotoionización debida al campo externo de radiación FUV. Sólo los fragmentos más masivos pueden formar estrellas a una tasa significativa, en donde se equilibra la energía inyectada por los vientos con la disipada por la turbulencia. El aumento en la presión o el flujo FUV externos puede desestabilizar a estos fragmentos magnéticos supercríticos y disparar la formación de estrellas masivas y de cúmulos estelares. Las regiones con "starbursts" tienen presiones mayores, P, de manera que sus GMCs tienen densidades superficiales mayores, $N \propto P^{1/2}$. La tasa de formación estelar se escala con $N^{1/2}$ y es mayor que las GMCs típicas.

ABSTRACT

A global model for low-mass star formation in giant molecular clouds (GMCs) is proposed according to which star formation proceeds at a rate that is determined by the photoionization through external FUV radiation. Only the most massive, self-gravitating clumps in a GMC may form stars at a significant rate. These clump may assume an equilibrium configuration in which the star formation rate (SFR) is such that the turbulent dissipation is just offset by the energy injected by the winds of the embedded young stars. A sudden rise in external pressure or the incident FUV flux can cause the instability of these magnetically supercritical clumps and can thereby lead to the formation of massive stars and of dense star clusters. Starburst regions have higher pressures, so that the GMCs within them have higher surface densities, $N \propto P^{1/2}$. Consequently, their SFR, which scales with $N^{1/2}$, is higher than in typical GMCs.

Key words: **ISM: GENERAL — STARS: FORMATION**

1. INTRODUCTION

How do stars form in the Galaxy, and how do the formation mechanisms in regions of Galactic low- and high-mass star formation differ from those in regions we call starbursts? To address this question, we must quantitatively understand how stars form in GMCs, and in particular, how the physical state of a cloud regulates the rate at which stars form in it. In starburst regions the total SFR per unit volume is high compared with typical regions of star formation in spiral disks. Apparently, large quantities of dense gas are quickly accumulated in a small region, and when certain conditions are met, these clouds convert much of their mass into stars in a time $10^7 - 10^8$ yr, short compared with typical galactic evolution times, but similar to the formation timescales in Galactic star forming regions. The basic mechanism of star formation may not differ in starbursts and Galactic star forming regions, starburst may just be regions under extreme conditions. It may thus be instructive to apply quantitative models of star formation such as the one presented here to such regions.

2. STARS FORM AS CLUSTERS IN MASSIVE MOLECULAR CLUMPS

In the Galaxy, stars form in and from GMCs, agglomeration of dense molecular gas clumps with masses up to several $10^3 M_\odot$. Recent IR surveys of nearby molecular clouds reveal that most of the young stars are located in compact clusters associated with massive, dense clumps (see Bertoldi & McKee 1996). In fact, it appears that the formation of compact clusters is the dominant mode of star formation. In the Orion B, Rosette, Ophiuchus, Taurus-Auriga and the Perseus molecular clouds, the clumps in which star formation is occurring are the most massive substructures within the respective cloud. These $300 - 3000\ M_\odot$ clumps appear to be breeding low-mass stars on timescales of 1 to 10 Myr.

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[1] Max-Planck-Institut für Extraterrestrische Physik, 85740 Garching, Germany; fkb@mpe-garching.mpg.de.

[2] Departments of Physics and of Astronomy, University of California, Berkeley, CA 94720, USA.

3. LOW-MASS STAR FORMATION IS REGULATED BY THE GAS IONIZATION

Low-mass stars are believed to form in molecular clumps through the gradual contraction of magnetically supported (i.e., subcritical) condensations ($1 - 10\ M_{\odot}$, 0.1pc cores) to the point of gravitational collapse. The contraction rate depends on the drag between the neutrals and ions (ambipolar diffusion; AD) and its timescale is given by the ionization fraction, x_e, which depends on the gas density and its shielding from the FUV radiation: $t_{\rm AD} \simeq 10^{14} x_e$ yr (Mouschovias 1976; Nakano 1984). In the outer layers of a massive, centrally condensed clump, FUV photoionization dominates the ionization. The ionization level in the center is due to cosmic rays and is low enough to allow a significant rate of AD. The SFR therefore depends on the central clump opacity: small clumps ($M \lesssim 100\ M_{\odot}$) have too high a level of ionization for the gas to drift through the B-field at any significant rate; no star formation is possible in such clumps. To estimate the SFR in a massive clump, we assume that the average growth rate of cores is given by the average rate of AD in a clump of mass M:

$$\frac{M}{t_{*\rm AD}} = \int_M t_{\rm AD}^{-1}(x_e)\ dM\ . \tag{1}$$

We compute the ionization structure and the star formation timescale, $t_{*\rm AD}$, in self-gravitating clumps (Bertoldi & McKee 1997). We compare our results with an observed star forming clump, with a mass of 410 $M_{\odot}$ and $\bar{A}_V \simeq 8$ mag, in NGC 2024. For a standard Habing UV field at the clump surface, we would predict $t_{*\rm AD} \approx 15 - 20$ Myr. With more than 300 stars formed, the clump has converted about 1/4 of its initial mass into stars, and if the SFR has been constant in time, it should have commenced 5 Myr ago at a rate of $3 - 4 \times 10^{-5}\ M_{\odot}{\rm yr}^{-1}$. A SFR of this magnitude ($4 \times 10^{-5}\ M_{\odot}{\rm yr}^{-1}$) was estimated for the Perseus clusters IC 348 (Lada & Lada 1995) and NGC 1333 (Lada et al. 1996). For NGC 1333, $\bar{A}_V \approx 7-10$ mag and $M \approx 450\ M_{\odot}$, and we predict $t_{*\rm AD} \simeq 15$ Myr and $\dot{M}_* \simeq 3 \times 10^{-5}\ M_{\odot}{\rm yr}^{-1}$, in good agreement with what is observed. Thus, the SFR predicted by ambipolar diffusion regulation can well explain the observed rates. However, what sets the observed column densities of the star forming clumps?

4. THE MEAN CLUMP EXTINCTION IS SET BY THE GMC PRESSURE

Most molecular clouds with masses above $10^3\ M_{\odot}$ are strongly self-gravitating. This is true for GMCs as a whole, but also for the largest clumps within them. Since these clouds live for much longer than a free-fall time, they must be in approximate virial equilibrium: $3(\bar{P} - P_0)V_{cl} + \mathcal{M} + W = 0$, where $\bar{P}$ is the mean total gas pressure, P_0 the surface pressure, V_{cl} the cloud volume, $\mathcal{M}$ the net magnetic energy, and W the gravitational energy. It is convenient to define a gravitational pressure by $W \equiv -3\bar{P}_G V_{cl}$, so that for $\mathcal{M} \ll |W|$, the virial equation writes $\bar{P} \simeq P_0 + \bar{P}_G$: the mean pressure is the sum of the surface pressure and the one due to self-gravity. The gravitational pressure is proportional to the square of the cloud's column density, $\bar{P}_G \propto N^2$. Since the surface pressure on the clumps is comparable to the mean pressure in the GMC, which is $\propto N_{\rm GMC}^2$, the clumps have $N_{cl} \gtrsim N_{\rm GMC}$. Strongly self-gravitating clumps have $\bar{P} \simeq \bar{P}_G \gtrsim 2P_0$; for example, a singular isothermal sphere has $\bar{P} = 3P_0$. Since the mean pressure in a clump cannot be much greater than the surface pressure, we expect $N_{cl} \simeq (1-2)N_{\rm GMC}$, which appears to be well supported observationally (Bertoldi & McKee 1992). We thus find that the surface density of the massive clumps is approximately set by the surface density of the GMC that embeds them; the latter is given by the GMC evolutionary state.

5. SELF-REGULATING STAR FORMATION

For a given pressure, the clump size is given by its kinetic energy, $\mathcal{T}$, which depends on the dissipation rate and the energy input through external waves or internal stirring by the winds of young stars. A self-gravitating massive clump will adjust its size according to the value of $\mathcal{T}/|W|$: if the dissipation rate exceeds the gain, the clump loses kinetic support and contracts, but it expands if the energy increases. Since the SFR in a massive clump is set by its extinction or size, we may envision a self-regulating mechanism (cf., Norman & Silk 1980; McKee 1989; Franco 1991), in which star formation in a clump proceeds at such a rate that the dissipation of turbulent energy is just offset by the energy gain due to the winds of newly formed stars. Elsewhere (Bertoldi & McKee 1996) we argue that the SFR for which the winds of YSOs can balance the clump's dissipation is approximately $M/t_{*eq} = M\bar{N}_{22}/50$ Myr, assuming that about half the wind momentum remains in the clump. By equating the SFR required for dynamical equilibrium, $M/t_{*eq}(\bar{N})$, with the SFR due to AD, $M/t_{*\rm AD}(\bar{N}, M)$, we can solve for the equilibrium column density of a clump of a given mass. The derived column and the resulting SFR are consistent with those observed in typical star forming clumps. It can also account for the global SFR in the Galaxy, $\simeq 3M_{\odot}{\rm yr}^{-1}$, if about one sixth (half of all GMCs, and about 1/3 of the mass in clumps within each is actively forming stars) of the total molecular mass $\simeq 2 \times 10^9\ M_{\odot}$ in the Galaxy is forming stars at the equilibrium rate.

GMCs form via large-scale gravitational instabilities of the clumpy gas layer in the Galaxy, and contract as they dissipate their turbulent energy on timescales of several 10^7 yr. Star formation commences when the pressure and surface density in a GMC has grown to an extent that the most massive clumps are dense and opaque enough to allow AD at a significant rate (McKee 1989). Star formation is terminated after massive stars begin to form; through their strong radiation and winds they disperse the clumps in which they form, and eventually the GMC.

6. GMCS AND THEIR MASSIVE CLUMPS ARE MAGNETICALLY SUPERCRITICAL

Magnetic fields play a significant role in the support of molecular clouds. A cloud threaded by a field B and flux $\Phi = \pi R^2 B$ can be supported against collapse as long as its mass is smaller than the magnetic critical mass, $M_\Phi \propto \Phi$. If kinetic energy also contributes to a cloud's support, it is stable when $M < M_\Phi + M_J$, where M_J is the turbulent Jeans mass. B-field measurements (Crutcher et al. 1993) and virial arguments (Myers & Goodman 1988; Bertoldi & McKee 1992) indicate that the magnetic and kinetic energies in a GMC or its clumps are in equipartition, so that the observed supersonic velocities reflect the Alfvén speed, and $M_J \simeq M_\Phi$. A strongly self-gravitating cloud with $M \simeq M_J + M_\Phi$ is "magnetically supercritical", i.e., the B-field alone cannot support it against gravitational collapse —turbulent support is crucial. If low-mass star formation proceeds in such a clump, the kinetic energy drops quickly and it becomes unstable. Low-mass star formation is therefore life-supporting for the massive clumps.

7. MASSIVE STARS FORM WHEN MASSIVE CLUMPS BECOME GLOBALLY UNSTABLE

Massive stars apparently always form in tight associations, suggesting that the stars formed synchronously; otherwise the first one to form would have destroyed the surrounding dense gas clump before the other stars would have had a chance to collapse. Since the timescales for low-mass star formation in the massive clumps are much longer than the clump's destruction time by an O star, massive stars are unlikely to form via slow ambipolar diffusion. Since the most massive clumps are magnetically supercritical, it is suggestive that massive stars form when such a clump becomes globally unstable and collapses in a dissipation time, $\approx 10^6$ yr. A massive clump becomes unstable when its kinetic energy dissipates more rapidly than it is replenished by the young stars that form within the clump. Such a dissipation instability may occur when a clump in equilibrium is compressed and the dissipation rate, which increases with density, rises enough that the clump loses kinetic support before a sufficient number of stars form to offset the higher dissipation rate. The SFR increases as a reaction to a higher clump density and opacity only after a delay comparable to the ambipolar diffusion time. If the dissipation time of the clump is shorter, the clump may reach a state of global instability and may collapse to a cluster of massive (and low-mass) stars. A sudden increase of the FUV flux would lower or terminate low-mass star formation in an equilibrium clump. As a consequence, the clump would contract until its density and opacity is high enough for AD to proceed. However, the mean to surface pressure ratio cannot be arbitrarily high, and stable equilibria may not be possible if the FUV flux exceeds a certain value. In this case, the clump would also become globally unstable. We suggest that massive star clusters such as the Orion Trapezium, NGC 3603, or R136 are results of global collapses of magnetically supercritical clumps. Starbursts are regions where massive clumps within a high-pressure and strong FUV environment are breeding stars in dynamical equilibrium over timescales of 1 – 10 Myr, and where some of them collapse to form massive stars in timescales of order 1 Myr. Since the pressure in starburst regions is higher than in typical GMCs, the GMCs and their clumps will be at a higher surface density, $\bar{N} \propto \bar{P}^{1/2}$. As a consequence, the SFR will also be higher: $t_{*eq} \propto \bar{N}^{-1} \propto \bar{P}^{-1/2}$.

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