THE EFFECTS OF IONIZING RADIATION ON STAR FORMATION IN MOLECULAR CLOUDS

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ABSTRACT. The gravitational stability of molecular cloud clumps before and after the onset of massive star formation is discussed. We suggest that the most massive clumps are magnetically supercritical but gravitationally stabilized by the hydromagnetic turbulence caused by FUV photoionization-regulated low-mass star formation in their interiors. The ionizing radiation of an O star can trigger star formation in initially sub- and supercritical clumps.

1. Initial Clump Stability

Giant Molecular Clouds (GMCs) are observed to be clumpy, with most of the molecular mass in clumps of much higher than mean density. Individual clumps within GMCs have been mapped and cataloged in the Rosette (Blitz 1987), Ophiuchus (Loren 1989), and M17 SW (Stutzki and Güsten 1990) molecular clouds. The observed highly supersonic (but presumably sub-Alfvénic) internal turbulence and the strong magnetic field are believed to be of comparable importance in supporting a clump against gravitational collapse (Myers and Goodman 1988). It follows that the magnetic critical mass of a clump, M_Φ (Mouschovias and Spitzer 1976), is approximately equal to its Jeans mass, M_J (including thermal and turbulent contributions): $M_\Phi \simeq M_J$. The most massive clumps (that contain a large fraction of the total mass) within a molecular cloud are observed to be close to virial equilibrium, whereas the smaller clumps have masses far below their virial masses. Since a clump that is in virial equilibrium is also close to its gravitational critical mass, $M \simeq M_{cr} \simeq M_\Phi + M_J$ (McKee 1989), it follows that virialized, magnetic, turbulent clumps are magnetically supercritical, i.e., $M > M_\Phi$. Thus the magnetic field alone cannot support such clumps against gravitational collapse; the turbulent support is crucial.

This poses an interesting problem: The turbulent energy in a magnetically supercritical clump is dissipated in 2 to 10 free-fall times (typically $10^6 - 10^7$ yr)(McKee 1989). Unless this energy is constantly replenished by some internal source, the clump will slowly contract and eventually collapse. If a significant fraction of their mass is turned into stars when the supercritical clumps collapse, the resulting star formation rate for molecular clouds would exceed the values implied from observations (e.g., McKee 1989) by an order of magnitude.

We propose that the magnetically supercritical clumps are kept gravitationally stable over the lifetime of a GMC through a photoionization-regulated equilibrium: the continuous dissipation of the turbulent energy is offset by the steady injection of energy through the winds of newly formed stars in the clumps' interior. The balance between dissipation and star formation is regulated by the fact that star formation (via ambipolar diffusion)

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can only proceed in the interior fraction of the clumps that is shielded from the diffuse interstellar FUV radiation, where the gas ionization and thereby the ambipolar diffusion rate is dominated by cosmic rays. Excessive star formation would cause the clump to expand, thereby allowing the FUV radiation to penetrate deeper into the clump, which reduces the star formation rate again. This self-regulating equilibrium yields star formation rates and clump column densities that are consistent with observations. The onset of massive star formation will eventually disperse the clumps and the GMC (for a detailed model, see Bertoldi and McKee [in preparation]). McKee (1989) has shown that a similar mechanism can explain the moderate star formation rates in GMCs as well as their observed mean extinctions.

2. Induced Star Formation

The idea that star formation is somehow triggered by external events has received serious consideration for more than a decade. Recent observations (Reipurth 1983; Nakano *et al.* 1989; Sugitani *et al.* 1989, [these proceedings]; Duvert *et al.* 1990; Bally [these proceedings]) established that cometary-shaped, photoevaporating clumps in the vicinity of massive stars frequently show signs of active star formation, suggesting that the dynamical effects of the massive stars' ionizing radiation may be quite efficient in triggering star formation in the exposed neutral clumps. We have investigated this question and here describe our preliminary results (for a detailed discussion, see Bertoldi, McKee and Klein [in preparation]).

When a massive star is born in a clumpy molecular cloud, the dynamical effects of its ionizing radiation will implode the clumps that are exposed to the star's ionizing radiation (Klein *et al.* 1983; Bertoldi 1989a,b). During this ***radiation-driven implosion*** a fraction of a given clump's initial mass is evaporated off the ionization front that embraces the clump; the remaining mass is compressed to high density and accelerated away from the star; the imploded clump will settle into an cometary-shaped quasi-equilibrium configuration (***equilibrium cometary cloud:*** ECC) that is characterized by the pressure balance between the (magnetic) neutral gas and the ionization front (Bertoldi and McKee 1990).

Before the exposure to a massive star's ionizing radiation, the molecular cloud clumps may be presumed stable against gravitational collapse, so that their masses are smaller than each clump's gravitational critical mass, $M_{cr} \simeq M_J + M_\Phi \simeq 2M_\Phi$. Magnetically supercritical ($M > M_\Phi$) clumps require significant kinetic (turbulent) support, whereas magnetically subcritical clumps ($M < M_\Phi$) are sufficiently stabilized by their magnetic fields.

As discussed above, a magnetically supercritical clump can be stabilized by the self-regulating input of turbulent energy from the clump's intrinsic low-mass star formation. The dynamical effects of its sudden exposure to ionizing radiation can induce the gravitational collapse of a magnetically supercritical clump as the rocket effect accelerates it and thereby strips off the embedded young low-mass stars that provided for the clump's internal turbulent energy support; deprived of the young stars and star-forming cores, the clump's equilibrium is severely disturbed. Due to the steady acceleration of the clump, any newly formed low-mass stars that could provide for the turbulent support are rapidly ejected from the clump. Furthermore, the mean density of the clump is increased, which enhances the energy dissipation. These effects, taken together, are likely to gravitationally destabilize the clump in a dissipation time.

The smaller, magnetically subcritical clumps are initially supported by their magnetic fields. They can form stars only via the slow, self-gravity driven ambipolar diffusion of the neutral gas through the magnetic field to the point where the clump, or a density enhance-

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ment within it, becomes magnetically supercritical and collapses. When a subcritical clump is imploded and slowly evaporates as an ECC, the ambipolar diffusion rate in its interior can be significantly enhanced and a central core could eventually become magnetically supercritical and collapse. The timescale for ambipolar diffusion is directly proportional to the fractional ionization of the molecular gas, which in turn is governed by both the photoionization by the FUV radiation of the ionizing star and cosmic ray ionization. Close to the surface of an ECC, the photoionization of the chemically nonreactive metals by the FUV radiation dominates the gas ionization, whereas in the deep interior, the cosmic ray ionization of H_2 dominates; here the ionization will be a function of the gas density. The compressive effect of the photoevaporation enhances the clump density and can thereby reduce the gas ionization to such an extent that the ambipolar diffusion timescale is significantly reduced. In certain cases star formation is thereby enhanced in photoevaporating clumps.

We conclude that the efficiency of induced star formation in the clumpy environment of a newly formed ionizing star mostly depends on the clumps' magnetic field and the upper mass cutoff of the clump mass distribution; star formation can be induced easily if the most massive clumps are initially magnetically supercritical, which seems to be the case in the observed molecular clouds in which the clump structure has been resolved. The massive, magnetically supercritical clumps will be the most vulnerable to a rapid triggering of (possibly massive, self-propagating) star formation.

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