SIMPLE THINGS WE DON'T KNOW ABOUT MOLECULAR CLOUDS

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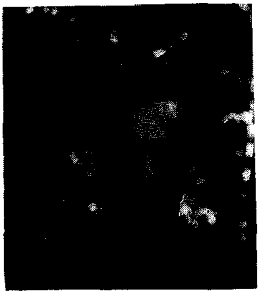

ABSTRACT

One of the ideas that most astronomers working in the interstellar medium take for granted is that Giant Molecular Clouds, as a whole, are gravitationally bound. In the following article this assertion is examined and it is concluded that the available evidence is surprisingly weak. Three arguments are discussed in detail: star formation, the virialization of clouds, and the internal pressures of clouds, all of which are found to be wanting. The importance of knowing whether GMCs are gravitationally bound is of fundamental importance in knowing whether gravity plays *any* role in their formation.

There are a number of fundamentally important things regarding Giant Molecular Clouds (GMCs) about which we are astonishingly ignorant. For example, we know very little about the distribution of angular momentum among the GMCs, and how this quantity varies as a funtion of galactic radius (see *e.g.* Blitz 1993). We are only beginning to get a detailed quantitative picture of the internal structure of GMCs. Surprisingly, as will be shown below, we really don't have any hard evidence that GMCs as a whole are bound by gravity.

That GMCs are gravitationally bound seems to have been taken as such a well established fact, that there is the only one work I am aware of that challenges the prevailing view (Maloney 1988). However, it is worth reexamining this question to see how well established the idea really is. Part of the motivation for looking at this question once again is to understand how clouds form and evolve. The detailed structure of a cloud is the result of the various forces that act on it, and it is important to know whether or not gravity is one them.

There are three fundamental arguments that GMCs are bound by gravity. Each of these is discussed below.

1. STAR FORMATION

The star formation argument goes as follows. Star formation is known to take place in GMCs. If the clouds form stars that are bound by gravity, then how could the stars form if the clouds themselves are not similarly bound? The basic flaw in this argument is that an entire cloud need not be bound for part of it to become self-gravitating and form stars. In fact, there is increasing evidence that at least some stars form in molecular clouds that are not themselves bound.

The star formation argument, invoked explicitly and implicitly for more than 20 years, gave rise to the realization that if GMCs are bound, the efficiency of star formation in GMCs must be low. If this were not the case, the mass of molecular gas in the Milky Way would imply a star formation rate much higher than observed (Zuckerman and Palmer 1974). This in turn led to the question, if molecular clouds are gravitationally bound, and if star formation is so inefficient, what prevents the clouds from collapsing; what holds GMCs up? Turbulence, it was realized, would dissipate too rapidly, and because there are no internal energy sources away from the sites of star formation, *something* has to be holding the clouds up if they are bound. This problem has never been solved to everyone's satisfaction.

Consider, on the other hand, the molecular clouds found at high galactic latitude (HLCs), most of which were shown by Magnani *et al.* (1985 - MBM) to be far from being gravitationally bound. The clouds have velocity dispersions far in excess of what is needed to bind them, a result confirmed by an independent study of Keto and Myers (1986). Observations of the molecular emission (MBM), the dust emission (Weiland *et al.* 1986), and the extinction (Magnani and de Vries 1986), confirm that the luminous masses are well enough known that given the observed velocity dispersions, they HLCs as a group cannot remain coherent entities for more than a few million years.

Nevertheless, some of the HLCs harbor star formation. For the most part, these are ones that have been previously classified as dark clouds by Lynds (1962). Examples are MBM MBM 12, the darkest part of which was catalogued as L1457/8, MBM 18, also catalogued as L1569, and MBM 20 also catalogued as L1642. There is known star formation in these clouds (MBM; Magnani personal communication), but MBM find that these clouds have insufficient mass to keep them bound by factors of 30 – 100. Apparently, star formation does occur in entities that are not in themselves bound, and an entire cloud need not be bound for a part of it to form a star.

In a study aimed at investigating the properties of the denser regions within the HLCs, Turner *et al.* (1989) found that many of the dense knots identified by Magnani *et al.* (1988) are sufficiently massive that the knots are gravitationally bound. Although there has been some controversy regarding this assertion (*e.g.* van Dishoeck 1992), molecules that are normally thought to be high density tracers are frequently found in molecular clouds where the mean extinction is considerably less than 1 mag (refs). In these regions, the expected H_2 column density implies extinctions considerably higher than what is inferrerd from star counts, suggesting that small dense regions can form which may be gravitationally bound even though the cloud as a whole is not. Therefore, not only is there star formation in clouds that do not appear to be bound, but bound clumps, a necessary precursor of star formation, also may have been detected in the HLCs.

2. THE VIRIAL THEOREM

That GMCs are gravitationally bound is implicit in the use of the virial theorem to determine the CO/H_2 conversion factor in the Milky Way. It is worth looking into the details of what is done in order to clarify how the results relate to the question of the boundedness of GMCs.

We start out with the ***assumption*** that GMCs obey the virial theorem. Thus:

$$2T = V.$$

which already introduces a factor of 2 uncertainty, because the clouds need not be virialized to be bound. Under the assumption that the clouds have an r^{-2} density profile,

$$\sigma_v{}^2 = GM/R.$$

where σ_v is the three dimensional velocity dispersion of the gas in a cloud. Now, $R = r\theta$, where r is the distance to the cloud, and θ is the mean angular radius of the cloud. M is obtained from the CO derived mass, M_{CO}. Observationally,

$$M_{CO} = \alpha < T_A > \sigma_v r^2 \theta^2$$

where

$$\alpha < T_A > \sigma_v = N(H_2).$$

Here, $< T_A >$ is the mean peak antenna temperature (corrected for atmospheric opacity and various antenna efficiencies) of the CO line in the cloud, and α is a constant in which the mean I(CO)/N(H_2) ratio is buried (I(CO) is the observed line strength of the J = 1-0 transition of CO).. Combining these terms, we obtain,

$$\sigma_v = \alpha T_A r \theta.$$

Because the variables on the right hand side as well as σ_v can all be obtained from observation, α can be obtained from a linear regression of the variable quantities. On the other hand, α, and hence the ratio I(CO)/N(H_2) may be obtained by other means, such as the extinction method (Dickman 1978), or from gamma-ray and CO surveys (Bloemen *et al.* 1986). All are fundamentally different methods of obtaining α, and the variation of published values has been more than a factor of 5. Although, the most extreme values are rejected by most observers, few would argue that α is known to better than a factor of 2 in the Milky Way, and probably exhibits a variation with radius at least that large. Another way of saying this is that if α as derived from application of the virial theorem is in error by only a factor of 2, a cloud, or an ensemble of clouds can be unbound even though it may appear to be gravitationally bound. For it to be *known* whether GMCs are gravitationally bound, the value of α needs to be known to better than a factor of two, an assertion with which many observers would feel uncomfortable.

It is worth noting that values derived from the application of the virial theorem tend to be higher than the others, suggesting that agreement can be obtained if one relaxes the assumption that $2T = V$. That is, if the clouds obey the relation $T = V$, the values of α derived from the three basic methods are in much closer agreement. The condition that the gravitational and kinetic energies are equal is one that may be characterized as gravitational neutrality. That is, clouds are gravitationally neutral if a small addition of kinetic energy will make them expand, but otherwise the clouds will neither expand, nor collapse with the energies they have. Note that gravitational neutrality is really an *average* condition over a molecular cloud, and need not be strictly true everywhere within a cloud. In other words, a clump within a cloud may be collapsing to form a star without violating the gravitational neutrality of the cloud as a whole. In that way, the cloud may be forming stars even if the cloud as a whole is not bound, or even expanding.

It seems that in the absence of some other arguments, the most commonly cited evidence that GMCs are gravitationally bound is in fact quite weak. Let us now examine what I have always believed to be the strongest argument in favor of molecular clouds being gravitationally bound.

3. THE INTERNAL PRESSURE

The structure of molecular clouds has long been known to be clumpy. From the work of Blitz *e.g.* (1978, 1980, 1993), we find that the volume averaged density of GMCs is one to two orders of magnitude less than the densities inferred from the CO emitting regions, implying that the volume filling fraction of the molecular emission is only a few percent of the volume of the cloud as a whole. This is confirmed by detailed maps of the GMCs which show numerous velocity components that correspond to the individual clumps within a cloud. Observations of the clumps can give a measure of both the density, temperature and velocity dispersion of the clumps, and therefore the pressure within a clump. It has long been known that the pressure within a typical clump of which a GMC is comprised is far larger than the pressure of the general interstellar medium as a whole. If the pressure within a typical GMC is an order of magnitude larger than the interstellar medium in which it is embedded, then it would seem that either all GMCs are expanding (an unpalatable conclusion), or that the pressure is due to the self gravity of the GMC, and the GMCs are therefore gravitationally bound.

Consider first the hydrostatic pressure of the ISM due to the gravity of the stars in the disk. This pressure can be written

$$P_{ISM} = 2\pi G \Sigma'_g \rho_* h_g$$

where Σ'_g is the gas surface density of the disk projected onto the plane, ρ_* is the density of stars in the midplane, and h_g is the gas scale height. Putting in the best values for these quantities gives a value of $P_{ISM}/k = 2 \times 10^4$ K cm^{-2}. For a GMC in hydrostatic equilibrium, the internal pressure is

$$P_{GMC} = 2\pi G {\Sigma_g}^2.$$

where Σ_g is the gas surface density of a GMC. Putting in the best values for the surface density from CO measurements one obtains that $P_{GMC}/k = 2 - 8 \times 10^5$ K cm^{-2}, at least an order of magnitude larger than the value for P_{ISM}. No error in the geometry of a cloud, or in the measured CO/H_2 ratio could make these two values agree.

Now let us look at the actual pressure within a clump. That pressure can be written

$$P_{CLUMP} = n m_{H_2} {\sigma_v}^2,$$

where n is the volume density of molecules, and σ_v is the three dimensional velocity dispersion of the gas. If we take a typical value of $n = 10^3$ (see *e.g.* Williams and Blitz 1994), and σ_v of 0.5 km s^{-1} in one dimension from measured line widths, we find that $P_{CLUMP}/k = 2 \times 10^5$ K cm^{-2}, a value commensurate with the hydrostatic pressure of the cloud as a whole. Apparently, the clumps are in pressure equilibrium with the with the hydrostatic pressure of the GMC in which it is found. On the other hand, the pressure is indeed at least an order of magnitude greater than that of the general interstellar medium.

But does this necessarily mean that the clouds are gravitationally bound? Consider the possibility that the reason we have clouds in the first place is that they only form in regions of enhanced interstellar pressure. Such regions are found in spiral arms, or in places where the there are large swept up volumes such as supershells (Heiles 1979). It is not difficult to imagine situations where the pressure is temporarily larger than the mean for the disk. Furthermore, because the GMCs take up such a small volume of the galactic disk (0.001 – Blitz 1978), these regions of higher pressure do not necessarily affect the overall pressure balance of the disk. Eventually, such high pressure regions will equalize their pressure on an acoustical timescale. Assuming that the pressure is carried primarily by the HI, a lower limit to this time scale is equal to a typical diameter of a cloud (which we may take as 50 pc), and an HI velocity dispersion of 3-5 $\mathrm{km\,s^{-1}}$. This gives a crossing time of 1-2 $\times 10^7$ y. HI envelopes arond clouds are typically much larger than the clouds themselves and contain similar masses (Blitz 1993). If the region of enhanced pressure is identified with the HI envelopes, the pressure equalization time is more in the range of 2-6 $\times 10^7$ y, a value quite close to the lifetime of GMCs estimated by Blitz and Shu (1980) and by Bash *et al.* (1977). That is, if GMCs form preferentially in high pressure regions and are gravitationally neutral, then the lifetime of the clouds is consistent with the star formation timescales of the clouds, and other measures of GMC ages. As long as gravitationally neutral clouds can form bound regions that give rise to OB associations, then the high pressures found in the clumps may simply be a remnant of the conditions under which the clouds formed, and need not be an indication that, as a whole, they are gravitationally bound.

Are we then to conclude that GMCs are *not* gravitationally bound? I think it is premature to draw that conclusion, but we should conclude, on the other hand that the evidence that GMCs are gravitationally bound is surprisingly weak. It will be important to look into this matter much more deeply and with much closer scrutiny.

4. THE RELEVANCE FOR CLOUD FORMATION

On the surface, it would seem that the discussion above is all about a factor of two, the difference between whether a cloud is gravitationally neutral, or whether a cloud is virialized and thus fairly tightly bound. While this is in some sense true, the consequences are actually far more fundamental. If all GMCs are gravitationally bound, then gravity *must* play an important role in how GMCs form in a galaxy. We must in turn look to gravitational instabilities such as the disk instability investigated by Toomre (1964) and applied by Kennicutt (1989) to understand both GMC formation and star formation in disks. On the other hand, if GMCs are gravitationally neutral, then clouds may form independently of any gravitational instability; it may be that what separates a GMC from the surrounding gas may simply be a matter of a phase transition. The process of star formation, or the formation of clusters is then reduced to a local one: we must look primarily for instabilities within a cloud rather than within a disk. The formation of individual stars is a very local process, but where stars form in a galaxy may in principle have nothing to do with gravity.

In any event, we must conclude that the argument that GMCs are bound because stars form within them is a very weak one. We must find evidence beyond that which is presently available to evaluate the boundedness of GMCs.

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