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Tidal forces as a regulator of star formation in Taurus

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ABSTRACT

Only a few molecular clouds in the solar neighbourhood exhibit the formation of only low-mass stars. Traditionally, these clouds have been assumed to be supported against more vigorous collapse by magnetic fields. The existence of strong magnetic fields in molecular clouds, however, poses serious problems for the formation of stars and of the clouds themselves. In this Letter, we review the three-dimensional structure and kinematics of Taurus – the archetype of a region forming only low-mass stars – as well as its orientation within the Milky Way. We conclude that the particularly low star formation efficiency in Taurus may naturally be explained by tidal forces from the Galaxy, with no need for magnetic regulation or stellar feedback.

Key words: stars: formation – ISM: clouds – ISM: kinematics and dynamics – galaxies: kinematics and dynamics.

1 INTRODUCTION

Few nearby molecular clouds (e.g. Taurus, Chamaeleon I and II) are observed to form only low-mass stars. Assuming a universal initial mass function, the lack of high-mass young stars in these regions indicates a low overall star-forming rate compared with clouds-like Orion where both low- and high-mass stars are actively being formed. Traditionally, the clouds forming only low-mass stars have been assumed to be supported against more vigorous collapse by magnetic fields. In such a scheme, stars can form only after substantial magnetic flux has been removed locally via ambipolar diffusion (e.g. Shu, Adams & Lizano 1987). The Taurus Molecular Cloud (TMC) is often cited as the archetype for this picture of isolated, low-mass star formation.

There are, however, some difficulties with this scenario. On one hand, strong magnetic fields ought to prevent the formation of molecular clouds by large-scale compressions in the first place (Hartmann, Ballesteros-Paredes & Bergin 2001). In addition, there is a problem with the synchronization of star formation along large distances. While molecular clouds have dynamical time-scales of the order of 10–20 Myr, most active star-forming regions (i.e. those still containing molecular gas) have populations with ages $\leq$3 Myr (Hartmann et al. 2001). The lack of old stars associated with molecular clouds (the so-called post-T Tauri problem, see Herbig 1978; Herbig, Vrba & Rydgren 1986) has been explained in terms of rapid assembling of molecular clouds by large-scale flows, which may be able to trigger star formation over large regions almost simultaneously. Such a rapid assembling of molecular clouds and synchronized events of star formation over large distances require magnetic fields to *not* be dominant (Hartmann et al. 2001).

Moreover, the ambipolar diffusion time-scale is not unique. It depends, among other parameters, on the ionization fraction, which in turn depends on the precise local shielding conditions. Differences in the degree of ionization and magnetic field intensities should introduce an unobserved spread of at least several Myr in the onset of star formation. This brings us back to the post-T Tauri problem (Ballesteros-Paredes & Hartmann 2007).

Different numerical work has examined the picture of rapid molecular cloud assembling from different points of view and found it to be a viable mechanism (see Ballesteros-Paredes et al. 2007, and references therein). An important difficulty, however, is the low star formation efficiency observed in actual molecular clouds, compared with those reported in simulations. As discussed by Heitsch & Hartmann (2008), most simulations are performed in closed boxes, with no stellar energy feedback. In such a situation, the amount of mass in collapsed objects after one crossing time is usually large, with values between 10 and 30 per cent, depending on the mass and the level of turbulence of the model (Klessen, Heitsch & Mac Low 2000; Vázquez-Semadeni et al. 2003; Vázquez-Semadeni, Kim & Ballesteros-Paredes 2005). In comparison, typical values of the star formation efficiency observed in molecular clouds are only a few per cent (Myers et al. 1986). When feedback from massive stars is included in the simulations, the measured efficiencies are significantly smaller (Passot, Vázquez-Semadeni & Pouquet 1995), suggesting that massive stars are a key ingredient in regulating the

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efficiency of star formation (see also Ballesteros-Paredes 2004, and references therein).

In regions where no massive stars are formed, however, a different mechanism is clearly required. And since magnetic regulation brings a number of additional problems, it is worth looking for alternative possibilities.

Recently, Ballesteros-Paredes et al. (2009, hereafter Paper I) have analysed the complete gravitational content of molecular clouds within a given spiral galaxy. They write the total gravitational energy of a molecular cloud, W, as follows

$$W = -\frac{1}{2}\int_V \rho\Phi_{\rm cl}{\rm d}V - \int_V x_i\rho\frac{\partial\Phi_{\rm ext}}{\partial x_i}{\rm d}V, \qquad (1)$$

where ρ is the density, $\Phi_{\rm cl}$ is the gravitational potential due to the mass of the cloud, i.e. the mass inside its volume V, $\Phi_{\rm ext}$ is the gravitational potential due to the mass outside the cloud, and x_i is the ith component of the position vector. The first term on the right-hand side is the gravitational energy $E_{\rm grav}$, while the second term is the energy due to the mass outside of the cloud, which we call the tidal energy. This second term may cause a compression or a disruption of molecular clouds, depending on their size, position and orientation within the host galaxy. Thus, tidal interactions may play a significant role in the overall stability of molecular clouds, and, therefore, on the efficiency of star formation within them.

In this Letter, we investigate the role that tidal interactions might play in the regulation of star formation in the TMC. In Section 2, we examine the three-dimensional structure and the orientation of Taurus within the Milky Way using recent data. We then calculate the relative contribution of self-gravity and tidal interactions for such a configuration (Section 3) and discuss our results in Section 4. The conclusions are given in Section 5.

2 THREE-DIMENSIONAL STRUCTURE OF TAURUS

In CO maps, the TMC extends for about 10° on the sky, with filaments that have aspect ratios between 5:1 and 10:1 (e.g. Goldsmith et al. 2008). It has a total molecular mass between 10^4 and $\sim 2.4 \times 10^4\,{\rm M}_\odot$ (Goldsmith et al. 2008), and is located roughly towards the Galactic anticentre (at $l \sim 170°$–$176°$) but at a Galactic latitude of −15° to −16°. Recent multi-epoch VLBA observations have provided distances to several young stars located across the TMC complex with accuracies better than 1 per cent (corresponding to absolute errors of ∼0.5–1 pc) (Loinard et al. 2005, 2007; Torres et al. 2007, 2009). The obtained distances range from about 160 pc for HP Tau, near the eastern edge of the complex at $(l, b) \sim (175°, -16°)$ (Torres et al. 2009), down to about 130 pc for the closest stars, Hubble 4 and HDE 283572, in the western part of the TMC at $(l, b) \sim (170°, -15°)$ (Torres et al. 2007). This situation is quite unlike that in the core of Ophiuchus (Loinard et al. 2008a) or the Orion nebula (Menten et al. 2007) where different stars are found at very similar distances.

The properties mentioned above indicate that it is appropriate to model the TMC as a $10^4\,{\rm M}_\odot$ elongated filament (a prolate spheroid) centred at a distance of 145 pc from the Sun in the direction $(l, b) = (172\overset{\circ}{.}5, -15°)$ (see Fig. 1 for a schematic view). This places the TMC about 37.5 pc below the Galactic plane. The long axis of the spheroid was taken to be of 32.37 pc long and, assuming an angular width for the cloud of about 5°, the short axes are 5 pc in length. The density of the spheroid was taken to be constant; for our choice of parameters, its value is $n = 405\,{\rm cm}^{-3}$.

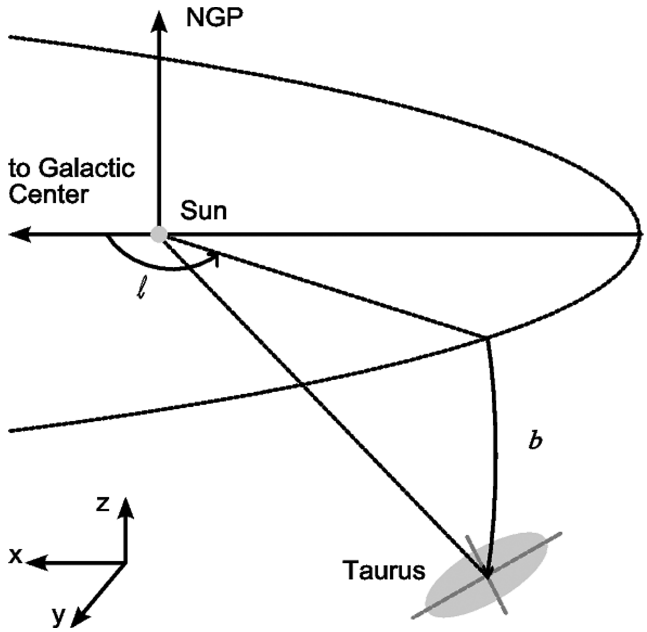

Figure 1. Schematic view of the TMC, according to the distances and positions reported by Loinard et al. (2005, 2007), Torres et al. (2007) and Torres et al. (2009).

We performed an energetics analysis similar to that presented in Paper I, but with one important difference. In our previous work, every parcel of the test cloud had a velocity given by the circular velocity. As most nearby star-forming cloud, however, the TMC has a substantial peculiar velocity (Torres et al. 2009). Therefore, although the calculation of the tidal energy $W_{\rm ext}$ is performed in the standard of rest of the centre of the spheroid, the effective potential must involve the peculiar velocities of the filament. In order to account for those velocities, we calculated the components of the peculiar velocities (u, v, w) using radial velocities from the CO observations (Ungerechts & Thaddeus 1987, see also figs 2 and 3 in Ballesteros-Paredes et al. 1999), and the proper motions of the stars reported by Torres et al. (2007, 2009). We note that the proper motions have been determined with a very good accuracy (±0.15 mas yr^{-1} in the worst case). However, since the line profile of the gas has some spread around the maximum intensity, we have used radial velocities (express relative to the local standard of rest) ranging from 5 to 5.5 km s^{-1} near the eastern edge of the cloud, and from 5.5 to 6 km s^{-1} for the western part.

3 RESULTS

As in Paper I, the gravitational potential used to calculate the tidal energy $W_{\rm ext}$ includes a Galactic axisymmetric background potential that represents a bulge, a flattened disc and a massive halo, and a bisymmetric potential describing a logarithmic spiral pattern. Our choice of parameters describing this potential reproduces, in particular, the Oort constants, the rotation curve and the local escape velocity (see Pichardo et al. 2003, and references therein). The exact position of the TMC with respect to the Galactic stellar spiral arms is not well known. Thus, we have calculated the ratio between the tidal and the gravitational energy, $W_{\rm ext}/E_{\rm grav}$, as a function of galactocentric angle, θ (Fig. 2). The different curves are the results of our calculations assuming a slightly different radial velocities, in order to account for the scatter in the CO emission (see Section 2).

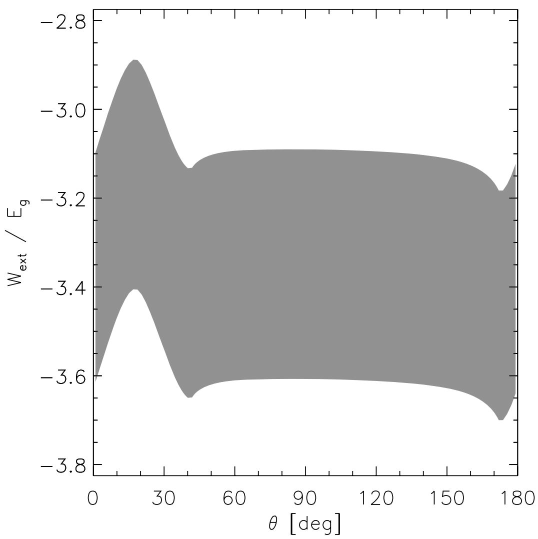

Figure 2. $W_{\mathrm{ext}}/E_{\mathrm{grav}}$ ratio for an elongated spheroid at the position and orientation, and with the kinematical properties of the TMC as a function of galactocentric angle θ. The shadded area covers the range of radial velocities at the extrema of the spheroid (see Section 2).Since the potential is bisymmetric, we plot the results only for the range $\theta \in [0^\circ, 180^\circ]$.

Since the ratio $W_{\mathrm{ext}}/E_{\mathrm{grav}}$ scales with density as $1/\rho$ (see Paper I for details), it is straightforward to scale it to a different total mass.

Fig. 2 shows some important points. First of all, the ratio $W_{\mathrm{ext}}/E_{\mathrm{grav}}$ is always negative, with values between -3 and -3.6 (shaded region), depending on the detailed velocity field assumed for the cloud. This indicates that the tidal energy W_{ext} acts against the gravitational energy, i.e. by trying to disrupt the cloud. Secondly, for this configuration, the tidal energy is larger than the gravitational energy for any azimuthal angle. Thirdly, even close to the spiral arms ($\theta \sim 15^\circ$ in our figure), an elongated cloud highly aligned with the galactocentric radius will also be disrupted.

We have performed the same calculations for smaller clumps at the same position, but with different aspect ratios, densities and sizes. Our results indicate that for smaller and denser regions, the situation is reversed and the gravitational energy exceeds the tidal energy by factors of 10 to 10^5, depending on the properties of the clumps/cores. The situation considered in these calculations corresponds to individual clumps within the TMC, such as Heiles Cloud 2, or Lynds 1495 (see Goldsmith et al. 2008, for details) or to individual dense cores like TMC-1C or Lynds 1517.

This means that if the volume filling factor of the gas is smaller than unity, the small, compact, dense fragments will collapse, but the cloud as a whole will not. By disrupting the cloud, tidal forces prevent global collapse.

4 DISCUSSION

As mentioned in Section 1, magnetic fields and massive stars have been the usual mechanisms invoked to explain the low efficiency of star formation observed in star-forming regions. In the case of Taurus, feedback by massive stars clearly cannot be invoked since there are no such stars. Large magnetic fields, on the other hand, are difficult to reconcile with the synchronized star formation observed in molecular clouds in the solar neighbourhood.

About 10 yr ago, it was proposed that molecular clouds, in general, and Taurus, in particular, could be produced by converging large-scale flows (Ballesteros-Paredes, Hartmann & Vázquez-Semadeni 1999), explaining how star formation can occur simultaneously in dynamically disconnected regions. Hartmann et al. (2001) pointed out that the interstellar gas in the solar neighbourhood becomes gravitationally unstable at the same time that it becomes molecular, and typical magnetic fields are not strong enough to inhibit rapid molecular cloud and star formation. More recently, different authors have reported that turbulent motions may have a gravitational origin (Burkert & Hartmann 2004; Ballesteros-Paredes 2006; Hartmann & Burkert 2007; Vázquez-Semadeni et al. 2007; Field, Blackman & Keto 2008; Heitsch & Hartmann 2008). This revived the idea originally proposed by Goldreich & Kwan (1974) that the supersonic linewidths have a gravitational origin. In particular, Vázquez-Semadeni et al. (2007) showed that collapsing clouds develop a 'virial' type relationship,[1] in which kinetic and gravitational energies are within a factor of 2 of each other. Moreover, Heitsch & Hartmann (2008) have found that, although molecular clouds and their substructures are formed by colliding turbulent flows, some degree of gravitational contraction must occur along the direction perpendicular to the collision of the streams to allow molecular cloud and star formation.

All the work mentioned above suggest that molecular clouds must be, to some degree, in a state of global collapse that typical magnetic fields cannot detain. In this situation, magnetic support cannot be invoked to regulate star formation, and massive stars are seemingly the only agents able to keep the star formation efficiency at a reasonably low value. But what regulates star formation in clouds, like Taurus, which do not harbour massive stars?

The results of the previous section allow us to propose a solution. Like every known large molecular cloud, the TMC has a mass much larger than its Jeans mass, so it could be collapsing vigorously. Because of it position and orientation within the Milky Way, however, it appears to suffer significant large-scale tidal disruptions. This ought to prevent global collapse and limit the efficiency of star formation. Note, however, that tidal disruption is irrelevant at small scales (see Section 3), so lateral collapse (Heitsch & Hartmann 2008) and star formation can proceed in dense cores (as is indeed observed).

According to our results, what defines whether a given molecular cloud develops a large or a small star formation rate is its particular position and orientation in the Galaxy. It would be interesting to test this proposal with other regions of star formation. According to Hartmann & Burkert (2007), Orion has a large degree of global collapse. Our results would then suggest that this complex should not be very elongated along the galactocentric radius. Existing observations in the region of the Orion Nebula (Menten et al. 2007) are consistent with this idea, but the distance to young stars spread over a more extended area will have to be measured to test our prediction. Another region where this proposal could be tested is Ophiuchus, where low- and intermediate-mass stars are present. Although precise distances have been measured for this region (Loinard et al. 2008a), the three-dimensional structure is still not well constrained because of possible confusion with background stars (Loinard et al. 2008b). Perseus would also be an interesting region to study because, like Taurus, it appears to have a filamentary structure. Again, however, an accurate distance is only known for one part of the complex (NGC 1333; Hirota et al. 2008).

[1] It has been proposed to call it 'energy equipartition' relationship, rather than virial relationship, since observations do not allow us to distinguish between energy equipartition and true virial balance (Ballesteros-Paredes 2006).

5 CONCLUSIONS

Our analysis of the full gravitational content of the TMC, i.e. considering not only the gravitational energy, but also the tidal contribution from the Galaxy, indicates that TMC must be suffering significant tidal disruption. This suggests that, unlike other clouds (e.g. Orion see Hartmann & Burkert 2007), TMC is not found in a state of global collapse, explaining thus why it only forms low-mass stars. Small-scale collapse within the complex, on the other hand, is permitted. Such local collapse enhances the formation of molecular gas from H I, and accounts for the rapid formation of stars (Heitsch & Hartmann 2008).

Our result could be tested further if multi-epoch observations similar to those obtained in Taurus by Loinard et al. (2007) and Torres et al. (2007, 2009) are performed for different star-forming regions exhibiting different efficiencies. Such observations are currently underway.

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REFERENCES

Ballesteros-Paredes J., 2004, Ap&SS, 289, 243
Ballesteros-Paredes J., 2006, MNRAS, 372, 443
Ballesteros-Paredes J., Hartmann L., 2007, Rev. Mex. Astron. Astrofis., 43, 123
Ballesteros-Paredes J., Hartmann L., Vázquez-Semadeni E., 1999, ApJ, 527, 285
Ballesteros-Paredes J., Klessen R. S., Mac Low M., Vázquez-Semadeni E., 2007, in Reipurth B., Jewitt D., Keil K., eds, Protostars and Planets V. Univ. Arizona Press, Tucscon, p. 63
Ballesteros-Paredes J., Gómez G. C., Pichardo B., Vázquez-Semadeni E., 2009, MNRAS, 393, 1563 (Paper I)
Burkert A., Hartmann L., 2004, ApJ, 616, 288
Field G. B., Blackman E. G., Keto E. R., 2008, MNRAS, 385, 181
Goldreich P., Kwan J., 1974, ApJ, 189, 441
Goldsmith P. F., Heyer M., Narayanan G., Snell R., Li D., Brunt C., 2008, ApJ, 680, 428
Hartmann L., Burkert A., 2007, ApJ, 654, 988
Hartmann L., Ballesteros-Paredes J., Bergin E. A., 2001, ApJ, 562, 852
Heitsch F., Hartmann L., 2008, ApJ, 689, 290
Herbig G. H., 1978, in Mirzoyan V., ed., Problems of Physics and Evolution of the Universe. Acad. Sci. Armenian SSR, Yerevan, p. 171
Herbig G. H., Vrba F. J., Rydgren A. E., 1986, AJ, 91, 575
Hirota T. et al., 2008, PASJ, 60, 37
Klessen R. S., Heitsch F., Mac Low M.-M., 2000, ApJ, 535, 887
Loinard L., Miodusewski A. J., Rodriguez L. F., Gonzalez R. A., Rodriguez M. I., Torres R. M., 2005, ApJ, 619, L179
Loinard L., Torres R. M., Mioduszewski A. J., Rodriguez L. F., González-Lópezlira R. A., Lachaume R., Vàzquez V., Gonzáléz E., 2007, ApJ, 671, 546
Loinard L., Torres R. M., Mioduszewski A. J., Rodríguez, L. F., 2008a, ApJ, 675, L29
Loinard L., Torres R. M., Mioduszewski A. J., Rodríguez L. F., 2008b, in Jin W.-J., Platais I., Perryman M. A. C., eds, Proc. IAU Symp. Vol. 248, A Giant Step: From Milli- to Micro-Arcsecond Astrometry. Cambridge Univ. Press, Cambridge, p. 186
Menten K. M., Reid M. J., Forbrich J., Brunthaler A., 2007, A&A, 474, 515
Myers P. C., Dame T. M., Thaddeus P., Cohen R. S., Silverberg R. F., Dwek E., Hauser M. G., 1986, ApJ, 301, 398
Passot T., Vázquez-Semadeni E., Pouquet A., 1995, ApJ, 455, 536
Pichardo B., Martos M., Moreno E., Espresate J., 2003, ApJ, 582, 230
Shu F. H., Adams F. C., Lizano S., 1987, ARA&A, 25, 23
Torres R. M., Loinard L., Mioduszewski A. J., Rodríguez L. F., 2007, ApJ, 671, 1813
Torres R. M., Loinard L., Mioduszewski A. J., Rodríguez L. F. 2009, ApJ, submitted
Ungerechts H., Thaddeus P., 1987, ApJS, 63, 645
Vázquez-Semadeni E., Ballesteros-Paredes J., Klessen R. S., 2003, ApJ, 585, L131
Vázquez-Semadeni E., Kim J., Ballesteros-Paredes J., 2005, ApJ, 630, L49
Vázquez-Semadeni E., Gómez G. C., Jappsen A. K., Ballesteros-Paredes J., González R. F., Klessen R. S., 2007, ApJ, 657, 870

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