

The link between solenoidal turbulence and slow star formation in G0.253+0.016

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Abstract. Star formation in the Galactic disc is primarily controlled by gravity, turbulence, and magnetic fields. It is not clear that this also applies to star formation near the Galactic Centre. Here we determine the turbulence and star formation in the CMZ cloud G0.253+0.016. Using maps of 3 mm dust emission and HNC0 intensity-weighted velocity obtained with ALMA, we measure the volume-density variance $\sigma_{\rho/\rho_0} = 1.3 \pm 0.5$ and turbulent Mach number $\mathcal{M} = 11 \pm 3$. Combining these with turbulence simulations to constrain the plasma $\beta = 0.34 \pm 0.35$, we reconstruct the turbulence driving parameter $b = 0.22 \pm 0.12$ in G0.253+0.016. This low value of b indicates solenoidal (divergence-free) driving of the turbulence in G0.253+0.016. By contrast, typical clouds in the Milky Way disc and spiral arms have a significant compressive (curl-free) driving component ($b > 0.4$). We speculate that shear causes the solenoidal driving in G0.253+0.016 and show that this may reduce the star formation rate by a factor of 7 compared to nearby clouds.

Keywords. Galaxy: centre, ISM: clouds, magnetic fields, stars: formation, turbulence

1. Introduction

Rathborne *et al.* (2014, 2015) showed that G0.253+0.016 is a dense turbulent cloud in the central molecular zone (CMZ). However, so far it has been unclear what drives this turbulence and whether that turbulence plays a role in controlling the low star formation rate (SFR) seen in G0.253+0.016 and in the CMZ as a whole (Longmore *et al.* 2013;

et al. 2009; Carroll *et al.* 2010; Wang *et al.* 2010; Cunningham *et al.* 2011; Plunkett *et al.* 2013, 2015; Offner & Arce 2014; Federrath *et al.* 2014). The 2nd category (which we refer to as “Dynamics” in Figure 1) includes accretion (such as accretion onto a galaxy) and gravitational collapse (Hoyle 1953; Vázquez-Semadeni *et al.* 1998; Klessen & Hennebelle 2010; Elmegreen & Burkert 2010; Vázquez-Semadeni *et al.* 2010; Federrath *et al.* 2011; Robertson & Goldreich 2012; Lee *et al.* 2015), the magneto-rotational instability (MRI) (Balbus & Hawley 1991; Piontek & Ostriker 2004, 2007; Tamburro *et al.* 2009), spiral-arm compression (Dobbs & Bonnell 2008; Dobbs *et al.* 2008), cloud-cloud collisions (Tasker & Tan 2009; Benincasa *et al.* 2013), and shear. While different drivers can play a role in different environments, Kruijssen *et al.* (2014) found that most of these drivers are not sufficient to explain the turbulent velocity dispersion in the CMZ, but some of them can.

A critical consideration is that the majority of turbulence drivers (e.g., supernova explosions, high-mass stellar winds, and accretion) primarily drive compressible (curl-free) modes, so we refer to these as “compressive drivers”. By contrast, solenoidal (divergence-free) modes can be generated directly by shear and the MRI (so we call them “solenoidal drivers”). The key aspect here is that the density probability distribution function (PDF) depends critically on the driving. Federrath *et al.* (2008, 2010); Price *et al.* (2011); Molina *et al.* (2012); Konstandin *et al.* (2012); Nolan *et al.* (2015); Federrath & Banerjee (2015) showed that the variance (width) of the density PDF is given by

$$\sigma_{\rho/\rho_0} = b \mathcal{M} (1 + \beta^{-1})^{-1/2}, \quad (1.1)$$

with the turbulent Mach number $\mathcal{M} = \sigma_v/c_s$ (the ratio of velocity dispersion and sound speed), plasma β (the ratio of thermal and magnetic pressure), and the turbulence driving parameter b , which smoothly varies from $b = 1/3$ for purely solenoidal driving to $b = 1$ for purely compressive driving (Federrath *et al.* 2010).

The theoretical models and simulations in Federrath & Klessen (2012) demonstrated that the SFR depends on b , with compressive driving producing up to an order of magnitude higher SFRs than solenoidal driving. Thus, our goal is to determine whether the driving of turbulence in G0.253+0.016 is primarily solenoidal or compressive. We do this by measuring σ_{ρ/ρ_0} , \mathcal{M} , and β , and inverting Equation (1.1) to solve for b . Finally, we use our measurement of b to predict the SFR in G0.253+0.016 and to contrast this to the SFR in Milky Way clouds located in the Galactic disc rather than the Galactic Centre.

2. Results

The main results and methods of this work are published in Federrath *et al.* (2016). Here we summarise the main results concerning the driving mode of the turbulence in G0.253+0.016 and its implications for the SFR.

Figure 2 shows the H₂ column density and the HNC0 intensity-weighted velocity in G0.253+0.016. In order to isolate primarily turbulent motions in the cloud, we have subtracted the large-scale velocity gradient seen across G0.253+0.016 (Rathborne *et al.* 2015). From the two maps in Figure 2, we compute the column density PDF and the turbulent velocity PDF shown in Figure 3, respectively. We find $\sigma_{\eta} = 0.34 \pm 0.02$ (as reported by Rathborne *et al.* 2014) for the log-normalised column density contrast $\eta = \ln(N/\langle N \rangle)$ and the 1D velocity dispersion $\sigma_{v,1D} = 3.9 \pm 0.1 \text{ km s}^{-1}$, both in the plane of the sky. Using temperature measurements from Ginsburg *et al.* (2016), we find sound speeds $c_s = 0.60 \pm 0.15 \text{ km s}^{-1}$, leading to the 3D turbulent Mach number, $\mathcal{M} = 11 \pm 3$ in G0.253+0.016.

In order to apply Equation (1.1) to solve for the turbulence driving parameter b , we

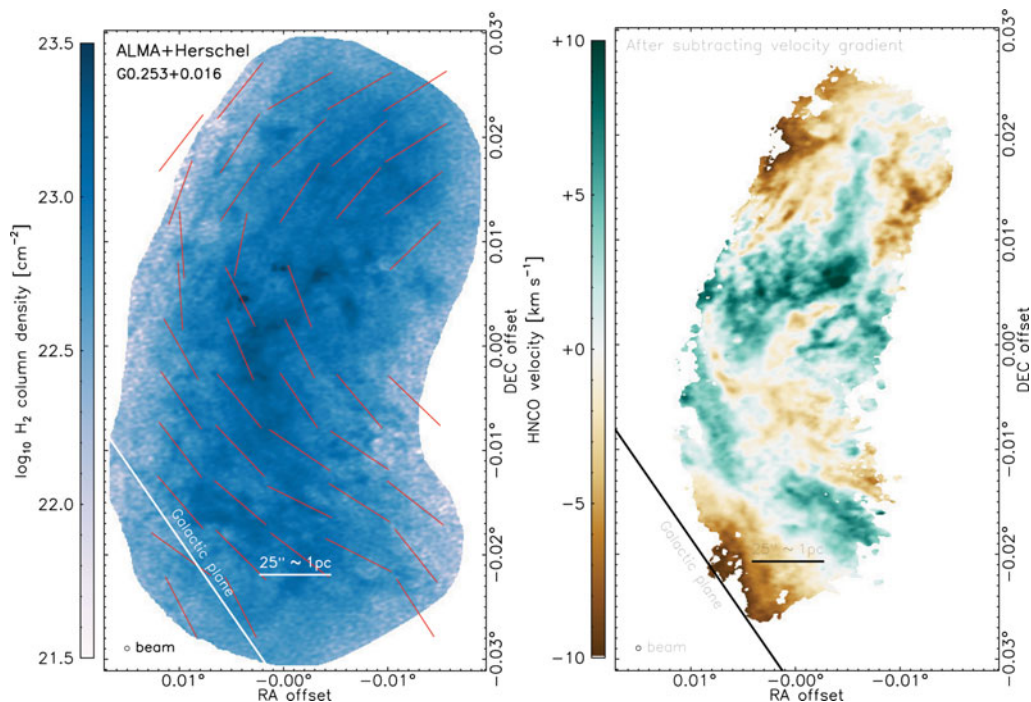


Figure 2. Left-hand panel: H_2 column density map of G0.253+0.016 from combined ALMA+*Herschel* data (Rathborne *et al.* 2014). The direction of the large-scale magnetic field from polarisation measurements obtained in Dotson *et al.* (2010) and Pillai *et al.* (2015) is shown as red pseudo vectors. Right-hand panel: HNC0 intensity-weighted velocity of G0.253+0.016 after subtraction of the large-scale velocity gradient across the cloud. The gradient-subtracted map primarily depicts the turbulent motions in the plane of the sky. Both maps are in equatorial coordinates with the (0,0) offset position in right ascension (RA) and declination (DEC) being 17:46:09.59, $-28:42:34.2$ J2000, respectively.

need to convert the column-density variance σ_η to the volume-density variance σ_{ρ/ρ_0} . We use the technique developed in Brunt *et al.* (2010b,a) (see also Kainulainen *et al.* 2014) and find $\sigma_{\rho/\rho_0} = 1.3 \pm 0.5$. Finally, we need an estimate for the turbulent (unordered) magnetic-field plasma β parameter. We use the ordered magnetic field measurement from Pillai *et al.* (2015) (see polarisation pseudo vectors in Figure 2) and run magneto-hydrodynamical turbulence simulations with this ordered field and the measured \mathcal{M} . From the simulations, we determine the unordered, turbulent plasma $\beta = 0.34 \pm 0.35$ entering Equation (1.1).

Combining our measurements of σ_{ρ/ρ_0} , \mathcal{M} , and β and propagating the uncertainties, we find $b = 0.22 \pm 0.12$ in G0.253+0.016, indicating solenoidal driving of the turbulence. We interpret this driving to be the result of strong shearing motions in the CMZ (Krumholz & Kruijssen 2015, Kruijssen *et al.*, in prep.). This is in stark contrast to the driving parameter inferred for typical clouds in the Galactic disc and spiral arms of the Milky Way. Currently available measurements for Taurus (Brunt 2010), GRSMC43.30-0.33 (Ginsburg *et al.* 2013) and IC5146 (Padoan *et al.* 1997) all show $b > 0.4$ with typical values of $b = 0.5$, thus exhibiting a significant compressive driving component, in contrast to the CMZ cloud G0.253+0.016.

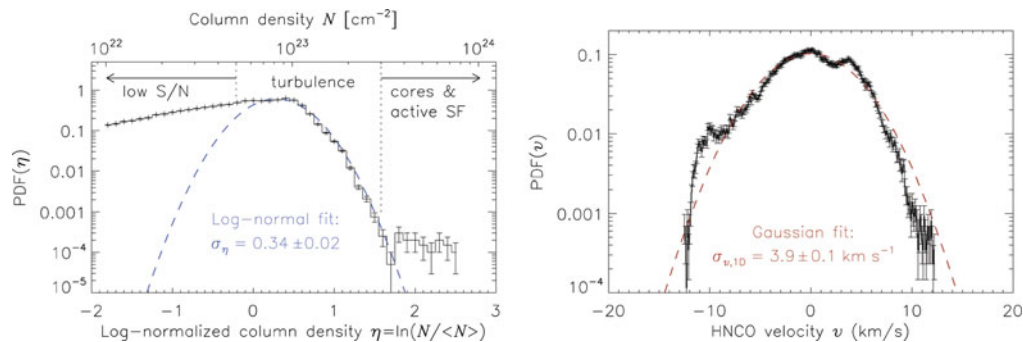


Figure 3. Left-hand panel: column density PDF of the map shown in the left-hand panel of Figure 2, for the log-normalised column density contrast $\eta = \ln(N/\langle N \rangle)$. A log-normal fit (dashed line) in the turbulence-dominated regime gives $\sigma_\eta = 0.34 \pm 0.02$ (Rathborne *et al.* 2014). Right-hand panel: HNC velocity PDF of the map shown in the right-hand panel of Figure 2. From a Gaussian fit, we measure the 1D turbulent velocity dispersion $\sigma_{v,1D} = 3.9 \pm 0.1 \text{ km s}^{-1}$.

3. Implications for the SFR

Using our measurements of b , \mathcal{M} , and β , we find a predicted SFR = $(1.1 \pm 0.8) \times 10^{-2} M_\odot \text{ yr}^{-1}$, based on the theoretical multi-freefall models of the SFR summarised in Federrath & Klessen (2012). If we used a turbulence driving parameter $b = 0.5$ (as measured for clouds in the Galactic disc and spiral arms), we would find a 7 times higher SFR. This shows that the driving of the turbulence is a critical parameter for star formation and may significantly contribute to explaining the low SFRs in G0.253+0.016 and possibly in the entire CMZ.

References

- Arce, H. G., Borkin, M. A., Goodman, A. A., Pineda, J. E., & Beaumont, C. N. 2011, *ApJ*, 742, 105
- Balbus, S. A. & Hawley, J. F. 1991, *ApJ*, 376, 214
- Balsara, D. S., Kim, J., Mac Low, M., & Mathews, G. J. 2004, *ApJ*, 617, 339
- Banerjee, R., Klessen, R. S., & Fendt, C. 2007, *ApJ*, 668, 1028
- Benincasa, S. M., Tasker, E. J., Pudritz, R. E., & Wadsley, J. 2013, *ApJ*, 776, 23
- Breitschwerdt, D., de Avillez, M. A., Fuchs, B., & Dettbarn, C. 2009, *SSRv*, 143, 263
- Brunt, C. M. 2010, *A&A*, 513, A67
- Brunt, C. M., Federrath, C., & Price, D. J. 2010a, *MNRAS*, 405, L56
- . 2010b, *MNRAS*, 403, 1507
- Carroll, J. J., Frank, A., & Blackman, E. G. 2010, *ApJ*, 722, 145
- Cunningham, A. J., Frank, A., Carroll, J., Blackman, E. G., & Quillen, A. C. 2009, *ApJ*, 692, 816
- Cunningham, A. J., Klein, R. I., Krumholz, M. R., & McKee, C. F. 2011, *ApJ*, 740, 107
- de Avillez, M. A. & Breitschwerdt, D. 2005, *A&A*, 436, 585
- Dobbs, C. L. & Bonnell, I. A. 2008, *MNRAS*, 385, 1893
- Dobbs, C. L., Glover, S. C. O., Clark, P. C., & Klessen, R. S. 2008, *MNRAS*, 389, 1097
- Dotson, J. L., Vaillancourt, J. E., Kirby, L., *et al.* 2010, *ApJ*, 186, 406
- Elmegreen, B. G. & Burkert, A. 2010, *ApJ*, 712, 294
- Elmegreen, B. G. & Scalo, J. 2004, *ARAA*, 42, 211
- Federrath, C. & Banerjee, S. 2015, *MNRAS*, 448, 3297
- Federrath, C. & Klessen, R. S. 2012, *ApJ*, 761, 156
- Federrath, C., Klessen, R. S., & Schmidt, W. 2008, *ApJ*, 688, L79
- Federrath, C., Roman-Duval, J., Klessen, R. S., Schmidt, W., & Mac Low, M. 2010, *A&A*, 512, A81

- Federrath, C., Schrön, M., Banerjee, R., & Klessen, R. S. 2014, *ApJ*, 790, 128
- Federrath, C., Sur, S., Schleicher, D. R. G., Banerjee, R., & Klessen, R. S. 2011, *ApJ*, 731, 62
- Federrath, C., Rathborne, J. M., Longmore, S. N., *et al.* 2016, *ApJ*, accepted (arXiv:1609.05911)
- Ginsburg, A., Federrath, C., & Darling, J. 2013, *ApJ*, 779, 50
- Ginsburg, A., Henkel, C., Ao, Y., *et al.* 2016, *A&A*, 586, A50
- Goldbaum, N. J., Krumholz, M. R., Matzner, C. D., & McKee, C. F. 2011, *ApJ*, 738, 101
- Gritschneider, M., Naab, T., Walch, S., Burkert, A., & Heitsch, F. 2009, *ApJ*, 694, L26
- Hennebelle, P. & Falgarone, E. 2012, *A&A Rev.*, 20, 55
- Hoyle, F. 1953, *ApJ*, 118, 513
- Johnston, K. G., Beuther, H., Linz, H., *et al.* 2014, *A&A*, 568, A56
- Kainulainen, J., Federrath, C., & Henning, T. 2014, *Science*, 344, 183
- Klessen, R. S. & Hennebelle, P. 2010, *A&A*, 520, A17
- Konstandin, L., Girichidis, P., Federrath, C., & Klessen, R. S. 2012, *ApJ*, 761, 149
- Kruijssen, J. M. D., Longmore, S. N., Elmegreen, B. G., *et al.* 2014, *MNRAS*, 440, 3370
- Krumholz, M. R. & Kruijssen, J. M. D. 2015, *MNRAS*, 453, 739
- Krumholz, M. R., Matzner, C. D., & McKee, C. F. 2006, *ApJ*, 653, 361
- Lee, E. J., Chang, P., & Murray, N. 2015, *ApJ*, 800, 49
- Lee, E. J., Murray, N., & Rahman, M. 2012, *ApJ*, 752, 146
- Longmore, S. N., Bally, J., Testi, L., *et al.* 2013, *MNRAS*, 429, 987
- Mac Low, M.-M. 1999, *ApJ*, 524, 169
- Mac Low, M.-M. & Klessen, R. S. 2004, *RvMP*, 76, 125
- Mac Low, M.-M., Klessen, R. S., Burkert, A., & Smith, M. D. 1998, *PhRvL*, 80, 2754
- Matzner, C. D. & McKee, C. F. 2000, *ApJ*, 545, 364
- McKee, C. F. 1989, *ApJ*, 345, 782
- McKee, C. F. & Ostriker, E. C. 2007, *ARAA*, 45, 565
- Molina, F. Z., Glover, S. C. O., Federrath, C., & Klessen, R. S. 2012, *MNRAS*, 423, 2680
- Nakamura, F. & Li, Z. 2008, *ApJ*, 687, 354
- Nolan, C. A., Federrath, C., & Sutherland, R. S. 2015, *MNRAS*, 451, 1380
- Norman, C. & Silk, J. 1980, *ApJ*, 238, 158
- Offner, S. S. R. & Arce, H. G. 2014, *ApJ*, 784, 61
- Padoan, P., Federrath, C., Chabrier, G., *et al.* 2014, *Protostars and Planets VI*, 77
- Padoan, P., Jones, B. J. T., & Nordlund, A. P. 1997, *ApJ*, 474, 730
- Peters, T., Banerjee, R., Klessen, R. S., & Mac Low, M. 2011, *ApJ*, 729, 72
- Peters, T., Banerjee, R., Klessen, R. S., *et al.* 2010, *ApJ*, 711, 1017
- Pillai, T., Kauffmann, J., Tan, J. C., *et al.* 2015, *ApJ*, 799, 74
- Piontek, R. A. & Ostriker, E. C. 2004, *ApJ*, 601, 905
- . 2007, *ApJ*, 663, 183
- Plunkett, A. L., Arce, H. G., Corder, S. A., *et al.* 2015, *ApJ*, 803, 22
- . 2013, *ApJ*, 774, 22
- Price, D. J., Federrath, C., & Brunt, C. M. 2011, *ApJ*, 727, L21
- Rathborne, J. M., Longmore, S. N., Jackson, J. M., *et al.* 2014, *ApJ*, 795, L25
- . 2015, *ApJ*, 802, 125
- Robertson, B. & Goldreich, P. 2012, *ApJ*, 750, L31
- Scalo, J. M. & Pumphrey, W. A. 1982, *ApJ*, 258, L29
- Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, *ApJ*, 508, L99
- Tamburro, D., Rix, H.-W., Leroy, A. K., *et al.* 2009, *AJ*, 137, 4424
- Tasker, E. J. & Tan, J. C. 2009, *ApJ*, 700, 358
- Vazquez-Semadeni, E., Canto, J., & Lizano, S. 1998, *ApJ*, 492, 596
- Vázquez-Semadeni, E., Colín, P., Gómez, G. C., Ballesteros-Paredes, J., & Watson, A. W. 2010, *ApJ*, 715, 1302
- Wang, P., Li, Z.-Y., Abel, T., & Nakamura, F. 2010, *ApJ*, 709, 27