Supersonic turbulence in the context of astrophysics

An example of how to conduct a literature review

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Figure 1: Sink formation along filaments in $Ma = 10$ supersonic turbulence. Simulation by C. Federrath at the Monash Centre for Astrophysics in Australia.

1 My e-mail: madams[at]pas.rochester.edu
2 Simulation snapshot borrowed from: https://www.monash.edu/moca/research/astrofluids
Hey, aren’t you a plasma person? What are you doing in our astrophysics journal club?
What happens if you deposit a supernova in a can compressed via magnetic field (Z-pinch)?
This is effectively a toy model of **Magnetic Liner Inertial Fusion** (minus the applied $B_z$)

1. The DD or DT fuel is pre-magnetized via axial field, $B_z$, via ABZ: 10-50 T
2. The fuel is pre-heated using Z-Beamlet laser (100-250eV for $C_R \sim 20-30$)
3. Compression occurs via $\mathbf{J} \times \mathbf{B}$, further heating the fuel to the point of being close to ignition

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My toy $z$-Pinch sees supersonic motion

**Figure 3:** The average and maximum $Ma$ time series featured in the simulation of $Z$-pinch compression a few slides prior. The red-shaded regions highlight supersonic regimes.
Let’s consider just the z-Pinch component of my toy model for a moment...
My toy z-Pinch (without hydrodynamic energy injection) sees supersonic motion

Figure 4: The average and maximum $Ma$ time series featured in the simulation of $Z$-pinch compression a few slides prior. The red-shaded regions highlight supersonic regimes.
But will you see instability/turbulence where the Mach number is high? Vice versa?

**Figure 5:** Same plot, but we’re gonna look at a slice somewhere in that blue interval.
But where is the Mach number high? \((t = 185 \text{ns})\)

Figure 6: A density slice at \(t = 185 \text{ ns}\) of the toy model, where on the right, a red filter is applied to indicate where supersonic Mach numbers occur in the flow.
Things would probably become really interesting if I add my Sedov solution as an energy deposition...
But let’s get a move on because you’re expecting me to talk about astrophysics
Some thoughts spurned based on what I know, and my toy model

1. Z-Pinches can be supersonic.
2. They are also wrought with the magneto-Rayleigh Taylor instability.
   2.1 To what extent does MRTI’s relatively large scale motion “cascade” to dissipative scales?
3. Sedov solutions/supernovae explosions can also be supersonic...
4. How does supersonic turbulence scale, or impact transport relevant to our pursuit in fusion (Braginskii transport)?
5. Mix????
6. Scaling????

Figure 7: The average and maximum Mach time series featured in the simulation of Z-pinch compression a few slides prior. The red-shaded regions highlight supersonic regimes.
What can I learn from other fields that have encountered this problem?
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Where does compressible turbulence occur in astrophysics?
First we need to learn some basics:
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1. What is turbulence?
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1. What is turbulence?
2. What makes it supersonic?
Background: some things we need to know...

1. Turbulence is an unsolved problem, and our best theory is still under review.
2. The best theory for turbulence was developed by Kolmogorov in the middle of the 20th century, which will be referred to as K41 in this presentation.
3. Folks couple K41 with turbulence models. There are many models that have dis/advantages.
4. Certainly folks contribute experimental observations about turbulence, but most studies are numerical. Analytic work is very difficult, and Fields Medal worthy.
5. Empirically, one can observe turbulence by tuning the Reynolds number, $Re = \frac{\rho uL}{\mu} = \frac{uL}{\nu}$. 

Figure from M. Breuer et al., Int. J. Heat and Fluid Flow 21 (2000) 186-196.
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Streaklines around a square cylinder for different Reynolds numbers (a) \( \text{Re} = 60 \); (b) \( \text{Re} = 100 \); (c) \( \text{Re} = 200 \); (d) \( \text{Re} = 300 \).
Assume we have some fluid flow that is “incompressible”

“Flow’s material density $\rho(x_i; t)$ is constant within a small volumetric chunk that moves with the flow velocity $u_i(x_i; t)$”

$$\equiv \quad “\partial_i u_i = 0”$$

$$\partial_t \rho + \partial_i (\rho u_i) = 0 \quad \text{Continuity (⋆)} \quad (1)$$

If Incompressible,

$$D_t \rho = \partial_t \rho + (\partial_i \rho) u_i$$

$$= \partial_t \rho + (\partial_i \rho) u_i + \rho (\partial_i u_i) - \rho (\partial_i u_i) \quad \text{Adding zero (⋆)}$$

$$= -\rho (\partial_i u_i)$$

$$= 0.$$
The best description we have of turbulence was developed by Kolmogorov in 1941 accompanied by numerical turbulence models.

i.e. After applying K41 to incompressible Navier-Stokes, discretize,

\[
\partial_t u_i + u_j \partial_j u_i = -\partial_i P + \partial_i \tau_{ij}(u_i, u_j) + \nu \partial_j \partial_j u_i \tag{3}
\]

where (*) you apply some model...

A zoo of Turbulence models:
LES (fails by over-estimating where laminar flow transitions), Turbulent viscosity models \((\tau_{ij} \approx -2\nu_T \langle S_{ij} \rangle\), fails w.r.t strain and rapid distortion \((\langle S_{ij} \rangle \to \infty))\), RANS, Rotta.... list goes on.
The energy rate $\epsilon$ (per unit mass) is “cascading” down a hierarchy of eddies at the same rate $\epsilon$, and is eventually removed from the system by dissipation at rate $\epsilon$.

**Figure 8:** Cartoon illustrating the turbulent/Richardson cascade for an incompressible flow based on Kolmogorov’s 1941 Theory (K41) & figure inspired by one in Frisch. Note the eddies are space-filling.

**General components of K41:**
- Zeroth law of turbulence
- K41 hypothesis
- Scale-locality, cascade assumptions
- Scaling of $u(\ell)$, $\tau(\ell)$, etc.
- Landau’s criticism of K41 ($S(\ell) = c_r \epsilon^{p/3} \ell^{p/3}$, $c_r$ is not universal)
How K41 applies to incompressible turbulence

\[ E(k) = C \epsilon^{2/3} k^{-5/3} \]

e.g. In application to Burger’s equation (reduction of INSE)

Table 2: Here is presented a table for each viscosity value listed above \( \nu = \{0.5, 0.01, 0\} \) including the velocity profile in the \( x \)-direction, the total energy per unit time, and the spectrum.

\( \nu = 0.5 \)

\( \nu = 0.01 \)

\( \nu = 0.0 \)
Problem! K41 only applies to incompressible turbulence...

So what happens if we no longer assume the fluid is “incompressible,” but rather, compressible?
What happens if we no longer assume the fluid is “incompressible”?
What happens if we no longer assume the fluid is “incompressible”?

1. Now we’d be dealing with the most general form of the NSE ($D_t \rho \neq 0$).
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3. Can’t anticipate the scaling law of $E(k) \propto k^{-5/2}$ any more, necessarily.
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4. Shocks, extreme density gradients and changes may occur. The density of a gas, or fluid, changes significantly along a streamline.
What happens if we no longer assume the fluid is “incompressible”?

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4. Shocks, extreme density gradients and changes may occur. The density of a gas, or fluid, changes significantly along a streamline.
5. This occurs due to significant changes to the velocity and pressure.
6. Thus, the Mach number, \(Ma = \frac{u}{c_s}\) becomes relevant (\(Ma > 1\)).
Where does supersonic turbulence appear in astrophysics?

We know it does manifest in an astrophysical context.
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We know it does manifest in an astrophysical context. My intuition tells me probably star formation.
Where does supersonic turbulence appear in astrophysics?

We know it does manifest in an astrophysical context. My intuition tells me probably star formation. I don’t feel comfortable confidently saying that... What if I am forgetting some other realm?
Where does supersonic turbulence appear in astrophysics?

We know it does manifest in an astrophysical context. My intuition tells me probably star formation. I don’t feel comfortable confidently saying that... What if I am forgetting some other realm? Let’s answer this question later with more confidence.
With a Literature Review to help us.
Where does one start with a literature review?

Do some academic “googling”...
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Do some academic “googling”...

Go to Web of Science, and do the following:
Where does one start with a literature review?

Do some academic “googling”...

Go to Web of Science, and do the following:

`supersonic turbulence`
Where does one start with a literature review?

Do some academic “googling”...

Go to Web of Science, and do the following:

```
Results: 2,622
(from Web of Science Core Collection)
```

Yikes... Let’s try something else instead...
Where does one start with a literature review?

Do some academic “googling”...

Go to Web of Science, and do the following:

```
[Search button]
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supersonic turbulence astrophysics
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Go to Web of Science, and do the following:

supersonic turbulence

Results: 2,622
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Yikes... Let’s try something else instead...

supersonic turbulence astrophysics

Results: 33
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Okay, much better. Still overwhelming though for a journal club...
Where does one start with a literature review?

Do some academic “googling”...

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\(^3\)...

\(^3\)No disrespect
Which of these 33 papers is the best for my interests?
Or at least be a friendly place to start?
Or even one of their citations?

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- Author institution citation network (collaborations)
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- Term citation network based off of titles and abstracts
  - Tells us the context and application of the query
So we are querying for “supersonic turbulence astrophysics”... What do we expect to know about how the publications are represented in a citation network?

After downloading the information pertinent to these 33 publications from Web of Science, we input it into some network visualization software⁴.

⁴It is called VOSViewer, developed at the University of Lieden. See: http://www.vosviewer.com/
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   - Each link has a **strength:** may indicate number of cited references between two publications (in common), number of publications two researchers have co-authored, or number of publications in which two terms occur together (co-occurrence).

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3. **Items** are grouped into **clusters**. A set of terms (community) included in the map.

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So let’s see who is behind these 33 publications from this query

supersonic turbulence astrophysics
Author citation network for 5% of authors meeting the threshold of contributing 6 documents to the field

Figure 9: The four main clusters for highly cited authors (5% of 854 authors) in the field of "supersonic turbulence." Bubble sizing scaled by number of citations, weights of lines are the number of citation occurrences between authors.
The same citation network but with the top 1% of authors meeting the threshold (18 documents)

Figure 10: Figure 10's four clusters reduce to three, resulting in nine prominent authors out of the original 44/845.
When did these 9 authors publish in this field on average?

**Figure 11:** The range of average publication year ranges from 2004 to 2014. By this metric, Mac Low is the originator, and Federrath is the pusher.
What is the institutional network of these authors, their collaborators, and people who cite them?

On the authors:

- Federrath: ANU, Monash, Lyon, Heidelberg, Wuerzburg
- Schmidt: Göttingen
- Klessen: Heidelberg
- Vazquez-Semadeni: UNAM, Texas-Austin
- Mac Low: AMNH, Princeton, Boulder
- Padoan: Barcelona, UCSD, INA, Harvard, NASA/Caltech, Copenhagen
- Norman & Kritsuk: UCSD

On Figure 12:

- Consistent with Figure 11: Mac Low is originator, Federrath is pusher.
- Knowing postdoc and PhD institutions allows you to observe author history
- By process of elimination you can find collaborators and citers
So... what are these authors talking about with regard to “supersonic turbulence”?

Figure 13: The network visualization for 105/10624 terms (1%–27 occurrences) with a relevancy score of 60% – 63 meet this threshold. After trimming we have the resultant 43 terms in three clusters.
What discussion points are popular now? What is the evolution of the field?

Avg. Pub. Year

Figure 14: The same 43 terms scored by the amount of times mentioned, and colored by their occurrence by average publication year.
What discussion points are popular now? What is the evolution of the field?

Avg. # of citations

**Figure 15:** The same 43 terms scored by the amount of times mentioned, and colored by how many citations these words get.
I know what you’re thinking...

Okay Marissa, we get it...

Did VOSViewer pay you for this?

Can you get to the actual discussion and papers and stuff now???

No they didn’t!!

But yeha... ok :/
I know what you’re thinking...

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Using citation networks to refine our literature review

客观目标：获取超音速湍流如何在天体物理学（如恒星形成）中体现的概览，并确定作者在这一背景下使用什么工具来诊断这种物理现象。

- 让我们考虑起源者（Mac Low）和推动者（Federrath）的最高引证论文。
- 去ADSABS并找到每位作者的三篇最高引证论文，例如author:"Federrath"+"supersonic turbulence"。

**Federrath**:

**Mac Low**:
Now that I have read these 6 papers, this is generally what I can tell you about the field of supersonic/compressible turbulence as adheres to star formation...
Supersonic, compressible turbulence in astrophysics

Interstellar medium (ISM)
- Mac Low & Klessen (2004)
- McKee & Ostriker (2007)
  - Controls rate of star formation triggered by gas compression in shocks
  - Star formation efficiency (SFE)
    - Elmegreen (2008), Federrath & Klessen (2013), Kainulainen et al. (2013)
  - Determines the mass distribution of stars when they are born

Galactic discs
- Gravitational instability
  - Romeo et al. (2010)
  - Hoffmann & Romeo (2012)

Early universe
- First cosmic halos contracting to form galaxies
  - Abel et al. 2002
  - Gref et al. 2008
  - Wise et al. 2008
  - Schiecher et al. 2010

Analytics of Star Formation:
- PDF of gas density
- Scaling of velocity spectrum in supersonic turbulence

Are they universal in any kind of supersonic flow? Do they depend on what is driving the turbulence?

Supernovae explosions and expanding, ionizing shells from previous cycles of star formation
- McKee (1989), Krumholz et al. (2006), Balsara et al. (2004), Breitschwerdt et al. (2009), Peters et al. (2011), Goldbaum et al. (2011), Lee et al. (2012)

Gravitational collapse and accretion of material

Galactic spiral-arm compression of HI clouds

Magneto-rotational Instability
- Piontek & Ostriker (2007), Tamburro et al. (2009)

+ Drivers of turbulence on smaller scales

For some vector field, $\mathbf{F}$ that drives the turbulence
- Solenoidal driving ($\text{div}(\mathbf{F}) = 0$)
- Compressive driving ($\text{curl}(\mathbf{F}) = 0$)
If you’re interested in this topic start here:

Control of star formation by supersonic turbulence

Mordecai-Mark Mac Low
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79th Street at Central Park West, New York, NY 10024-5192, USA

Ralf S. Klessen
Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
and UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA

Understanding the formation of stars in galaxies is central to much of modern astrophysics. However, a quantitative prediction of the star formation rate and the initial distribution of stellar masses remains elusive. For several decades it has been thought that the star formation process is primarily controlled by the interplay between gravity and magnetostatic support, modulated by neutral-ion drift (known as ambipolar diffusion in astrophysics). Recently, however, both observational and numerical work has begun to suggest that supersonic turbulent flows rather than static magnetic fields control star formation. To some extent, this represents a return to ideas popular before the importance of magnetic fields to the interstellar gas was fully appreciated. This review gives a historical overview of the successes and problems of both the classical dynamical theory, and the standard theory of magnetostatic support from both observational and theoretical perspectives. The outline of a new theory relying on control by driven supersonic turbulence is then presented. Numerical models demonstrate that although supersonic turbulence can provide global support, it nevertheless produces density enhancements that allow local collapse. Inefficient, isolated star formation is a hallmark of turbulent support, while efficient, clustered star formation occurs in its absence. The consequences of this theory are then explored for both local star formation and galactic scale star formation. It suggests that individual star-forming cores are likely not quasi-static objects, but dynamically collapsing. Accretion onto these objects varies depending on the properties of the surrounding turbulent flow; numerical models agree with observations showing decreasing rates. The initial mass distribution of stars may also be determined by the turbulent flow. Molecular clouds appear to be transient objects forming and dissolving in the larger-scale turbulent flow, or else quickly collapsing into regions of violent star formation. We suggest that global star formation in galaxies is controlled by the same balance between gravity and turbulence as small-scale star formation, although modulated by cooling and differential rotation. The dominant driving mechanism in star-forming regions of galaxies appears to be supernovae, while elsewhere coupling of rotation to the gas through magnetic fields or gravity may be important.

Accepted for publication in Reviews of Modern Physics

This review has over 1000 citations... (y. 2003)
ON THE STAR FORMATION EFFICIENCY OF TURBULENT MAGNETIZED CLOUDS

CHRISTOPH FEDERRATH\textsuperscript{1} AND RALF S. KLESEN\textsuperscript{2}

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ABSTRACT

We study the star formation efficiency (SFE) in simulations and observations of turbulent, magnetized, molecular clouds. We find that the probability density functions (PDFs) of the density and the column density in our simulations with solenoidal, mixed, and compressive forcing of turbulence, sonic Mach numbers of 3–50, and magnetic fields in the super- to the trans-Alfvénic regime all develop power-law tails of flattening slope with increasing SFE. The high-density tails of the PDFs are consistent with equivalent radial density profiles, $\rho \propto r^{-\kappa}$ with $\kappa \sim 1.5–2.5$, in agreement with observations. Studying velocity–size scalings, we find that all the simulations are consistent with the observed $v \propto \ell^{1/2}$ scaling of supersonic turbulence and seem to approach Kolmogorov turbulence with $v \propto \ell^{1/3}$ below the sonic scale. The velocity–size scaling is, however, largely independent of the SFE. In contrast, the density–size and column density–size scalings are highly sensitive to star formation. We find that the power-law slope $\alpha$ of the density power spectrum, $P_{3D}(\rho, k) \propto k^\alpha$, or equivalently the $\Delta$-variance spectrum of the column density, $\sigma^2_\Delta(\Sigma, \ell) \propto \ell^{-\alpha}$, switches sign from $\alpha \lessgtr 0$ for SFE $\sim 0$ to $\alpha \gtrsim 0$ when star formation proceeds (SFE $> 0$). We provide a relation to compute the SFE from a measurement of $\alpha$. Studying the literature, we find values ranging from $\alpha = -1.6$ to +1.6 in observations covering scales from the large-scale atomic medium, over cold molecular clouds, down to dense star-forming cores. From these $\alpha$ values, we infer SFEs and find good agreement with independent measurements based on young stellar object (YSO) counts, where available. Our SFE–$\alpha$ relation provides an independent estimate of the SFE based on the column density map of a cloud alone, without requiring a priori knowledge of star formation activity or YSO counts.

\textit{Key words:} ISM: clouds – ISM: kinematics and dynamics – ISM: structure – magnetohydrodynamics (MHD) – stars: formation – turbulence

\textit{Online-only material:} color figures
Paper I (Federrath) : Summary

Tools Used
∆-variance, sink particles, density PDF (mass and volumetric weighted, CD), Fourier power spectrum

Concepts & questions
“We want to set up these magnetized compressible turbulence simulations with sink particles and see if we can measure the SFE in them and if the statistics yield good results.”

Conclusions
“I am going to solve a spherical cow to study this one process that happens in the spherical cow.”
A comparison between grid and particle methods on the statistics of driven, supersonic, isothermal turbulence

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\textbf{ABSTRACT}

We compare the statistics of driven, supersonic turbulence at a high Mach number using FLASH, a widely used Eulerian grid-based code, and PHANTOM, a Lagrangian smoothed particle hydrodynamics (SPH) code at resolutions of up to $512^3$ in both grid cells and SPH particles. We find excellent agreement between codes on the basic statistical properties: a slope of $k^{-1.95}$ in the velocity power spectrum for hydrodynamic, Mach 10 turbulence, evidence in both codes for a Kolmogorov-like slope of $k^{-5/3}$ in the variable $\rho^{1/3}v$ as suggested by Kritsuk et al. and a lognormal probability distribution function (PDF) with a width that scales with the Mach number and proportionality constant $b = 0.33 - 0.5$ in the density variance–Mach number relation. The measured structure function slopes are not converged in either code at $512^3$ elements.

We find that for measuring volumetric statistics such as the power spectrum slope and structure function scaling, SPH and grid codes give roughly comparable results when the number of SPH particles is approximately equal to the number of grid cells. In particular, to accurately measure the power spectrum slope in the inertial range, in the absence of sub-grid turbulence models, requires at least $512^3$ computational elements in either code. On the other hand the SPH code was found to be better at resolving dense structures, giving maximum densities at a resolution of $128^3$ particles that were similar to the maximum densities resolved in the grid code at $512^3$ cells, reflected also in the high density tail of the PDF. We find SPH to be more dissipative at comparable numbers of computational elements in statistics of the velocity field, but correspondingly less dissipative than the grid code in the statistics of density-weighted quantities such as $\rho^{1/3}v$.

For SPH simulations of high Mach number turbulence, we find it important to use sufficient non-linear $\beta$-viscosity in order to prevent particle interpenetration in shocks (we require $\beta_{\text{max}} = 4$ instead of the widely used default value, $\beta_{\text{max}} = 2$).
Paper II (Federrath) : Summary

Tools Used
Comparison between SPH/PIC and AMR code comparison, convergence tests, tracer particles, RMS Mach number, density, cross section slices, CDM, PDFS, spectra, structure functions

Concepts & questions
To what extent does numerical technique impact the statistics?

Conclusions
Numerical approach comparisons are useful, this put FLASH on the forefront of these kind of studies.
Paper II (Federrath)

Figure 3. Projected column density in the reversion (SPH, left-hand panels) and r-sun grid, middle panels) calculation at a resolution of $1.25^2$ parsec by grid cells, showing the evolution over the first few dynamical times (top to bottom), together with the density contrast from the tracer particle position in the r-sun calculation using an SPH density estimate (right-hand panels). After 1 dynamical time (first row), there is a close correspondence in individual shock structure between the SPH and the grid code, while after 2 dynamical times (second row) there are similar large-scale features. However, by 3 or 4 dynamical times (third and fourth rows) only a weak correlation even between large-scale features is observed. Dense features are in general better resolved in the SPH calculations or equivalent resolution at a smaller number of particle (number of grid cells sizes, while the grid-based calculations tend to better resolve features in low density regions (see also Fig. 5). The increased resolution of shock features in the tracer particle density fields (right-hand panels) compared to middle panels) suggests a remarkable ability for the tracer particles to provide information on sub-grid scales at essentially zero additional computational cost.

3.2.2 Cross-section slices

Column density plots such as those shown in Fig. 3 in a general tend to highlight dense features, since all structures along the line of sight contribute to the projected field (which also tends to be the case in observations). The features in column density plots are therefore reflected by statistics such as the PDF (Figs 6–8) and quantities such as the maximum density (Fig. 7). However, volumetric quantities such as the volume filling factor of the material and the velocity field, reflected in statistics such as power spectra and structure functions, are better illustrated by cross-section slices. For this reason we show cross-section slices of density at the mid-plane of the computational domain ($z = 0.5$ L), showing a resolution study of the initial shock development at 3 dynamical times (Fig. 4) and a comparison of the evolved snapshots at the end of the simulation ($t/τ = 10$), showing only the highest resolution (Fig. 5). The plots show the density field using r-sun (left-hand panels) and grid cells (middle panels) in Figs 4 and 5 and for the tracer particle density field computed from the r-sun calculations (right-hand panels).

Figs 4 and 5 show clearly that the grid results are better resolved in low density regions. The resolution in the SPH calculations is concentrated towards high density regions which fill relatively little of the volume. Comparing individual shock structures in Fig. 4 shows that in general the shocks have better definition in r-sun, with the shock widths in the highest resolution reversion calculation similar to those obtained at 256$^2$ in r-sun. This is as might be expected given the relative crudeness of the shock capturing scheme (artificial viscosity) in the SPH code compared to the PPM shock capturing scheme (Colella & Woodward 1984) employed in r-sun. In the more evolved snapshot (Fig. 5), the grid results show many well-defined shock features in low density regions that are much less well resolved in the SPH calculation.

Some numerical artefacts are visible in the lowest resolution SPH calculations in the earliest snapshot ($t/τ = 4$, top-left panel) of Fig. 4 due to the "breaking" of the initial regular lattice on which the particles were placed so it is distorted by the flow. Interestingly, similar artefacts are visible – and more accentuated – in the low-resolution tracer particle plots (top-right panel). These effects are
Numerical and semi-analytic core mass distributions in supersonic isothermal turbulence

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ABSTRACT

Context. Supersonic turbulence in the interstellar medium plays an important role in the formation of stars. The origin of this observed turbulence and its impact on the stellar initial mass function (IMF) still remain open questions.

Aims. We investigate the influence of the turbulence forcing on the mass distributions of gravitationally unstable cores in simulations of isothermal supersonic turbulence.

Methods. Data from two sets of non-selfgravitating hydrodynamic FLASH3 simulations with external stochastic forcing are analysed, each with static grid resolutions of 2562, 5122 and 10242 grid points. The first set applies solenoidal (divergence-free) forcing, while the second set uses purely compressive (curl-free) forcing to excite turbulent motions. From the resulting density field, we compute the mass distribution of gravitationally unstable cores by means of a clump-finding algorithm. Using the time-averaged probability density functions of the mass density, semi-analytic mass distributions are calculated from analytical theories. We apply stability criteria that are based on the Bonnor-Ebert mass resulting from the thermal pressure and from the sum of thermal and turbulent pressure.

Results. Although there are uncertainties in applying of the clump-finding algorithm, we find systematic differences in the mass distributions obtained from solenoidal and compressive forcing. Compressive forcing produces a shallower slope in the high-mass power-law regime compared to solenoidal forcing. The mass distributions also depend on the Jeans length resulting from the choice of the mass in the computational box, which is freely scalable for non-selfgravitating isothermal turbulence. If the Jeans length corresponding to the density peaks is less than the grid cell size, the distributions obtained by clump-finding show a strong resolution dependence. Provided that all cores are numerically resolved and most cores are small compared to the length scale of the forcing, the normalised core mass distributions are close to the semi-analytic models.

Conclusions. The driving mechanism of turbulence has a potential impact on the shape of the core mass function. Especially for the high-mass tails, the Hennebelle-Chabrier theory implies that the additional support due to turbulent pressure is important.

Key words. hydrodynamics – ISM: clouds – ISM: kinematics and dynamics – methods: numerical – stars: formation – turbulence
Paper III (Federrath) : Summary

Tools Used
AMR, volume renderings of mass density, vorticity modulus, Taylor scale (using tools from incomp. turb), energy and mass density spectra, velocity structure functions, PDFs, projections

Concepts & questions
They conclude that compressible turbulence exists, but they’re looking at the incompressible tree within the compressible forest, so to speak.

- Different approaches to these questions: colliding flows, or periodic box

Conclusions
I like that they are trying to find analogs to incompressible turbulence based on simulation and statistics (e.g. power laws in the spectra)
Paper III (Federrath) : Summary

W. Schmidt et al.: Compressively driven turbulence in isothermal gas

Fig. 3. Contour plots of the mass density $\rho$ and the Mach number $M$ in the plane $z = 0$ corresponding to the top panels in Figs. 1 and 2. The rectangles show the boundaries of refined grid patches.
Paper III (Federrath) : Summary

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figures/paper3_summary}
\caption{Contour plots of the mass density $\rho$ and the Mach number $M$ in the plane $z = 0$ corresponding to the bottom panels in Figs. 1 and 2. The rectangles show the boundaries of refined grid patches.}
\end{figure}
Astronomy & Astrophysics

Turbulent velocity structure in molecular clouds

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Abstract. We compare velocity structure observed in the Polaris Flare molecular cloud at scales ranging from 0.015 pc to 20 pc to the velocity structure of a suite of simulations of supersonic hydrodynamic and MHD turbulence computed with the ZEUS MHD code. We examine different methods of characterising the structure, including a scanning-beam method that provides an objective measurement of Larson’s size-linewidth relation, structure functions, velocity and velocity difference probability distribution functions (PDFs), and the $\Delta$-variance wavelet transform, and use them to compare models and observations. The $\Delta$-variance is most sensitive to characteristic scales and scaling laws, but is limited in its application by a lack of intensity weighting so that its results are easily dominated by observational noise in maps with large empty areas. The scanning-beam size-linewidth relation is more robust with respect to noisy data. Obtaining the global velocity scaling behaviour requires that large-scale trends in the maps not be removed but treated as part of the turbulent cascade. We compare the true velocity PDF in our models to simulated observations of velocity centroids and average line profiles in optically thin lines, and find that the line profiles reflect the true PDF better unless the map size is comparable to the total line-of-sight thickness of the cloud. Comparison of line profiles to velocity centroid PDFs can thus be used to measure the line-of-sight depth of a cloud. The observed density and velocity structure is consistent with supersonic turbulence with a driving scale at or above the size of the molecular cloud and dissipative processes below 0.05 pc. Anisotropic diffusion could explain the dissipation. Over most of the observed range of scales the velocity structure is that of a shock-dominated medium driven from large scale. The velocity PDFs exclude small-scale driving such as that from stellar outflows as a dominant process in the observed region. In the models, large-scale driving is the only process that produces deviations from a Gaussian PDF shape consistent with observations, almost independent of the strength of driving or magnetic field. Strong magnetic fields impose a clear anisotropy on the velocity field, reducing the velocity variance in directions perpendicular to the field.

Key words. ISM: clouds – ISM: magnetic fields, turbulence – ISM: kinematics and dynamics – MHD
Paper IV (Mac Low): Summary

Tools Used
Larson’s relationships, MHD simulations, \( \Delta \)-variance (multidimensional wavelet transformation; Stutzki 1998), characterize total \( v_i \) distribution (PDF, line centroid), size-linewidth relations

Concepts & questions
Tested 5 different methods on an observational data set covering Polaris Flare with aid of turbulence models

Conclusions
This is an incredibly boring paper, however it is useful as it details the above mentioned techniques and statistics in order to test the Larson Relations
Turbulent driving scales in molecular clouds

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ABSTRACT

Context. Supersonic turbulence in molecular clouds is a dominant agent that strongly affects the clouds’ evolution and star formation activity. Turbulence may be initiated and maintained by a number of processes, acting at a wide range of physical scales. By examining the dynamical state of molecular clouds, it is possible to assess the primary candidates for how the turbulent energy is injected.

Aims. The aim of this paper is to constrain the scales at which turbulence is driven in the molecular interstellar medium, by comparing simulated molecular spectral line observations of numerical magnetohydrodynamic models and molecular spectral line observations of real molecular clouds.

Methods. We use principal component analysis, applied to both models and observational data, to extract a quantitative measure of the driving scale of turbulence.

Results. We find that only models driven at large scales (comparable to, or exceeding, the size of the cloud) are consistent with observations. This result applies also to clouds with little or no internal star formation activity.

Conclusions. Astrophysical processes acting on large scales, including supernova-driven turbulence, magneto-rotational instability, or spiral shock forcing, are viable candidates for the generation and maintenance of molecular cloud turbulence. Small-scale driving by sources internal to molecular clouds, such as outflows, can be important on small scales, but cannot replicate the observed large-scale velocity fluctuations in the molecular interstellar medium.

Key words. magnetohydrodynamics (MHD) – turbulence – techniques: spectroscopic – ISM: molecules – kinematics and dynamics – radio lines: ISM
Paper V (Mac Low): Summary

Tools Used

- Principal component analysis (PCA), randomly forced (Fourier space)
  MHD + self-gravity simulations w. $128^3$-grid (ZEUS-3D)

Concepts & questions

- How is the TKE injected?
- and at what scale?
- Then is there potential to amend the Larson relations/scaling laws?
- Are clouds continuously driven, or is this turbulence in a decaying state?

Conclusions

Old paper, but started using PCA and comparing between spectroscopic observations and simulation
PHYSICAL VERSUS OBSERVATIONAL PROPERTIES OF CLOUDS IN TURBULENT MOLECULAR CLOUD MODELS

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ABSTRACT

We examine the question of how well the physical properties of clumps in turbulent molecular clouds can be determined by measurements of observed clump structures. To do this, we compare simulated observations of three-dimensional numerical models of isothermal, magnetized, supersonic turbulence with the actual physical structure of the models. We begin by determining how changing the parameters of the turbulence changes the structure of the simulations. Stronger driving produces greater density fluctuations, and longer wavelength driving produces larger structures. Magnetic fields have a less pronounced effect on structure, one that is not monotonic with field strength. Aligned structures are seen only with low-density tracers and when the intensity of the field is large. Comparing different regions with the same tracers (or conversely, the same region with different tracers) can give information about the physical conditions of the region. In particular, different density tracers can help determine the size of the density fluctuations and thus the strength of the driving. Nevertheless, velocity superposition of multiple physical clumps can fully obscure the physical properties of those clumps, and short-wavelength (compared with the size of the region under analysis) driving worsens this effect. We then compare Larson’s relationships and mass spectra in physical and observational space for the same structure data set. We confirm previous claims that the mean density–size relationship is an observational artifact due to limited dynamical range in column density: it is the inevitable consequence of the presence of a lower cutoff in column density. The velocity dispersion–size relationship, on the other hand, is reproduced in both physical and observed clumps, although with substantial scatter in the derived slope, consistent with observations. Finally, we compute the mass spectra for the models and compare them to mass spectra derived from simulated observations of the models. We show that when we look for clumps with high enough resolution, both spectra converge to the same shape. This shape appears to be lognormal, however, rather than the power-law function usually used in the literature.

Subject headings: ISM: clouds — ISM: kinematics and dynamics — stars: formation — turbulence
Paper VI (Mac Low): Summary

**Tools Used**
Larson’s relationships, mass/density spectra, 18 simulations ($L, k, B, \sigma_\rho$), density fluctuations, CLUMPFIND

**Concepts & questions**
- Defining topology: clumps (cores or filaments?)
- Do obs. of emission represent real clumps in MC?
  - If obs. structure $\neq$ actual structure, are the statistical properties valid? (Larson relations, mean density size limited by dynamic range?)
  - What are the mechanisms that drive the turbulence?

**Conclusions**
Old paper, brute force, insightful questions
Other tools I came across along the way...

Comparing simulation to experiment or observation

Polaris MC, NGC-1333 MC, HII

Fractal density structure

Power spectrum of $P(\nu)$ versus $P(\rho^{1/3}\nu)$

$$\frac{de_{\text{kin}}}{dt} \propto \frac{\rho \nu^2}{t} \propto \frac{\rho \nu^3}{\ell} \equiv \text{const.}$$
Conclusions

Okay maybe I have illustrated how someone could make the literature review process less overwhelming, but systematic for their benefit/purpose.
Conclusions

What did I get out of it?
Conclusions

Now I have some tools to explore
okay we knew about PDFs, and spectra (but didn’t consider applying it to vorticity), now how to do CDMs and projections, Δ-variance, PCA, higher moment statistics

and some concepts to look out for!
The notion of different types of driving (sinusoidal, compressive), can I apply many of these questions they asked to analogs in my study?

Here is astro helping me, maybe I can help astro?
We talk about Braginskii transport, but you guys don’t....