Astro2020 Science White Paper

Twelve Decades: Probing the Interstellar Medium from kiloparsec to sub-AU scales

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

Primary thematic area: Resolved Stellar Populations and their Environments
Secondary thematic area: Multi-Messenger Astronomy and Astrophysics

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After a decade of great progress in understanding gas flow into, out of, and through the Milky Way, we are poised to merge observations with simulations to build a comprehensive picture of the multi-scale magnetized interstellar medium (ISM). These insights will also be crucial to four bold initiatives in the 2020s: Gravitational Waves (GWs), Fast Radio Bursts (FRBs), cosmic B-mode, and the Event Horizon Telescope (EHT).

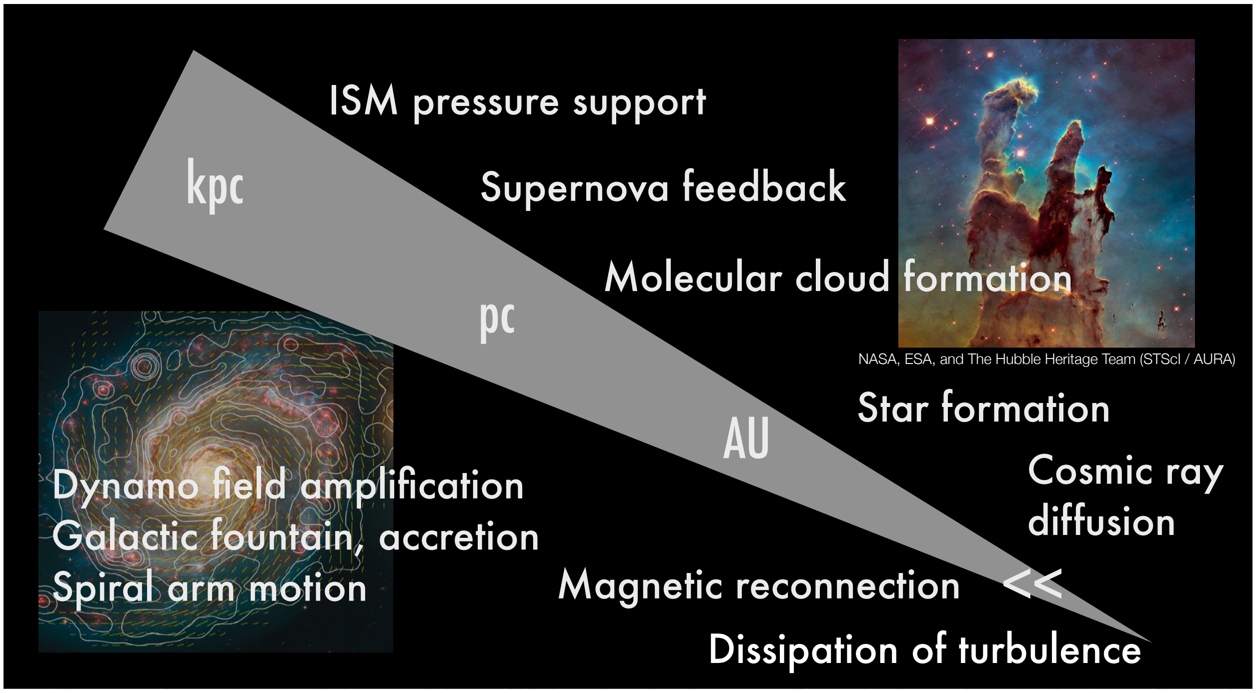


Figure 1: The interstellar medium (ISM): from spiral arms to star formation (design: S.E. Clark; image of M51: [1])

Introduction The interstellar gas gives birth to stars and receives their remains. Stellar ejecta both enrich it chemically and energize it by heating, ionizing and stirring. Thus, as illustrated in Figure 1, large-scale motions from supernovae create turbulence in the plasma, which in turn competes with gravitational contraction. Though recent advances in indirect probing methods have revealed a cascade in energy over 12 decades in scale, many basic questions remain about the turbulence in both the neutral and ionized phases of the interstellar medium (ISM). We highlight this exciting and wide-ranging science here.

A Decade of Challenge

- Develop a multi-scale understanding of the ISM beyond the power spectrum.
- Incorporate magnetic structure throughout, focusing on scale-dependent dimensionality.
- Link insights probed by different tracers (including radio and optical polarization, pulsar dispersion and scintillation, Hα emission, Faraday rotation, H I emission and absorption, and extinction) on radically different scales.
- Follow the energy flow from large-scale stirring to small-scale heating and cooling.
- Focus on a dynamical ISM and understand size-dependent timescales.
- Use the Milky Way as a guide to extragalactic and intergalactic gas.

Support Large-scale Projects

- Mitigate ISM effects and detect long-wavelength gravitational waves with a Pulsar Timing Array (PTA).
- Add key propagation insights to interpret Fast Radio Bursts (FRBs).
- Use neutral hydrogen mapping to better constrain the polarized light foreground, making a cosmic B-mode detection possible.
- Provide crucial scatter-broadening corrections for the Event Horizon Telescope (EHT).

Probing the Structure and Energetics of the ISM

Without a deep, consistent, multi-scale understanding of the ISM and its magnetic field we do not truly know how the Milky Way works. If we do not fully grasp the flow of gas into, out of, and through the Milky Way, we fall short in understanding the development of other galaxies over cosmic time. The problems continue to cascade throughout astrophysics. While the past decade yielded great advances in our understanding of the ISM, driven by exciting new observations and a much tighter connection between data and magnetohydrodynamic (MHD) simulations, our insights are still relatively siloed and partial.

As one example, in Figure 2a we see multi-tracer evidence for a 3-D Kolmogorov, augmented by recent *in situ* measurements of plasma density from the Voyager 1 spacecraft [2, 3, 4]. There is enhanced power near the kinetic scales (e. g. Larmor and inertial scales). This strongly suggests a turbulent energy cascade over twelve decades in scale that is terminated by dissipation at these small scales. However, there is a disconnect between a pervasive turbulent plasma and the presence of highly localized plasma concentrations that cause extremely anisotropic radiowave scattering or refraction (e. g. [5]). Pulse broadening increases strongly with distance, indicating that radiowave scattering grows very rapidly toward the inner Galaxy and is widely distributed. This is a problem that needs a solution. Recent Voyager 1 measurements suggest turbulence in our local region near the Sun. Such localized concentrations of turbulent plasma on ~ 1 AU scales combine the two concepts — appearing as spatially intermittent turbulence — but what are the energy sources? There is no good explanation for the driver of a pervasive turbulence, nor is there an accepted mechanism for containing the thermal pressure implied in localized plasma concentrations. MHD simulations with the needed fidelity and resolution are just arriving (e. g. Figure 2b) and will provide crucial clues for solving this puzzle.

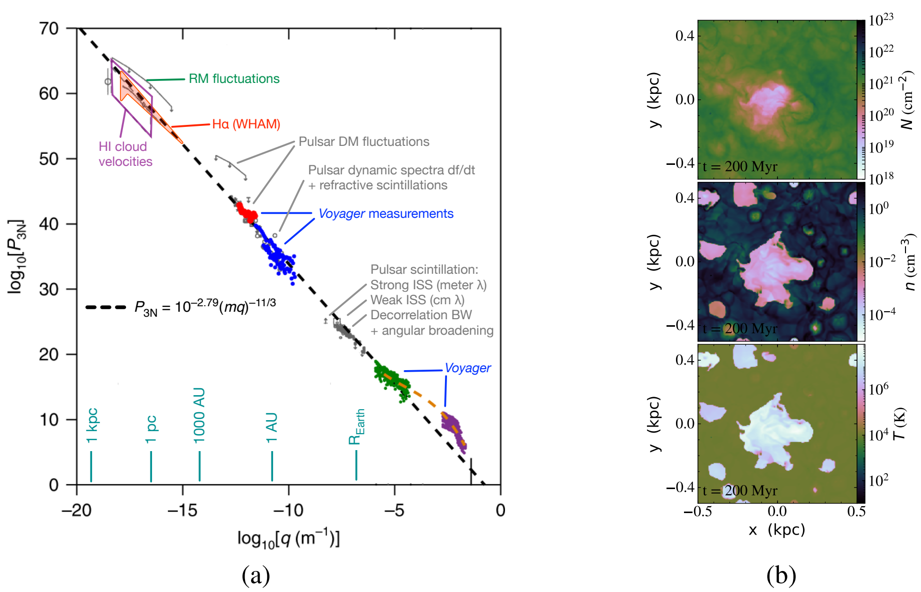


Figure 2: a) Multi-probe evidence for a Kolmogorov spectrum in plasma density, augmented recently from Voyager 1 data [2, 3, 4]. It implies a turbulent cascade over 12 decades in scale with a slight bump at the highest wavenumbers. b) Images from a multi-phase ISM simulation. Pinkish-white areas, some of which may be analogous to the Local Bubble, are cavities blown by supernovae [6].

Requirements to Achieve Scientific Goals

The last ten years have produced many surprises in our study of the gas in the Milky Way: fibers of neutral hydrogen stretching for tens of parsecs, aligned by the local magnetic field (Figure 3a); dense networks of magnetic field gradient (Figure 3b); sheets of ionized gas intercepting pulsar signals every hundred parsecs or so; compact plasma lenses of unknown origin affecting quasar and pulsar radio signals and possibly linked to FRBs. A comprehensive understanding of neutral and ionized gas in the Galaxy is within reach over the next decade as observations and simulations converge on a picture of turbulent, magnetized flows that yield abrupt density variations in the particular, but average, over long enough path lengths, into statistically stable turbulence cascades.

In other white papers we will highlight specific projects and facilities that will accelerate this rapid progress. Here, we focus on the rich interlinked *science* that requires us to understand magnetized gas dynamics over at least twelve orders of magnitude in spatial size[1].

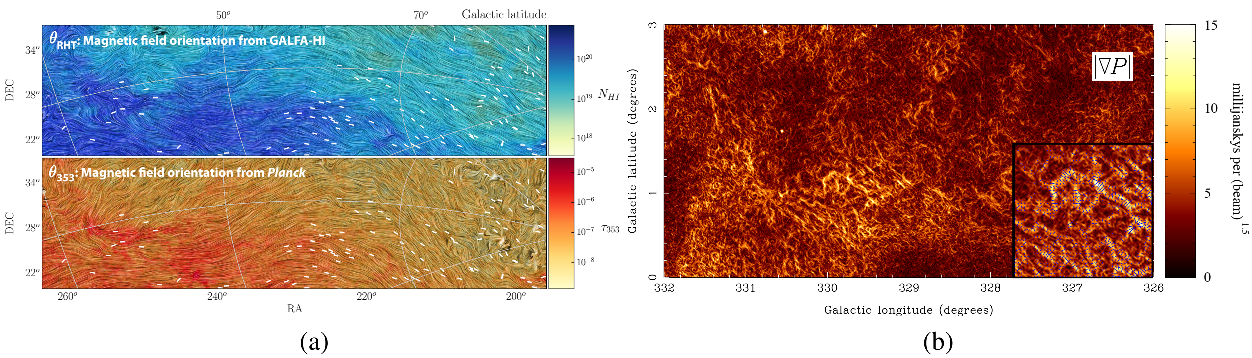


Figure 3: a) Magnetic fiber orientation from GALFA-HI data compared with *Planck* polarized dust emission [7]. b) Gradient image of linear polarization, $|\nabla P|$, for an 18-deg^2 region of the Southern Galactic Plane Survey [8].

On the one hand there is evidence for a cascade of turbulent waves over an astonishing twelve decades in scale size. On the other hand, both in the neutral gas and in ionized hydrogen, discrete structures abound that can be explored through a variety of techniques.

What will provide science breakthroughs in the 2020s? The rapidly increasing sophistication of MHD modeling is starting to be up to the task by carefully incorporating the relevant physical processes and scales (e.g. [6, 9, 10, 11, 12, 13]). There is also promising work in developing statistical comparisons between these models and observations (e.g. [14, 15, 16]). However, linking the sub-AU scales on which turbulence dissipates to the Galactic scales on which it is driven remains a major numerical challenge. This will need to be coupled with continued observations that delve further into the structure of the different phases of the ISM and their interfaces.

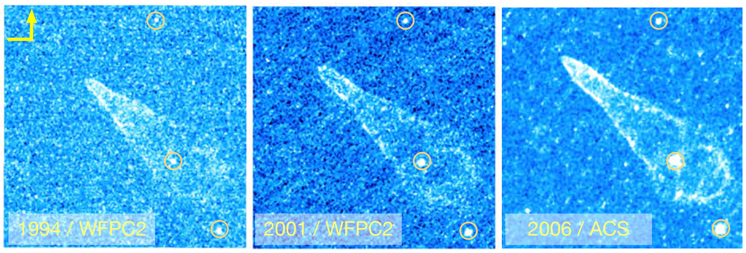
The current generation of single-dish 21-cm surveys (GALFA-HI, HI4PI) is unlikely to be superseded for a while, which is most relevant to the diffuse, high-latitude ISM. However, the plane will be surveyed by interferometers, e.g. GASKAP. There will, however, be a major advance in the next decade in HI spin temperature measurements with SKA and its pathfinders

[1] For comparison, twelve orders of magnitude in ocean size scale runs from the largest ocean waves ($\sim$ 30m) to the size of an atom!

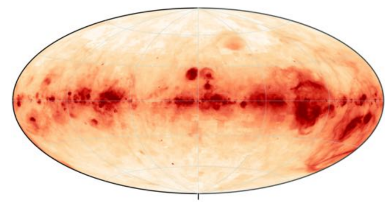
[17]. An increase in the number of HI Zeeman measurements of the field strength of similar proportions is possible (see the accompanying white paper by S.E. Clark and C. Heiles).

If molecular clouds form at the interfaces of streams of warm gas, we need to understand how those streams form and interact [17, 18, 19, 20].

As shown in Figure 4 we have a rich set of diagnostics at our disposal to explore the ISM. Bow-shock nebulae provide a nearly perfect *in situ* probe of the gas being ionized by pulsar ram



(a)



(b)

Figure 4: a) *HST* imaging of the time evolution of the tip of the Guitar nebula, an Hα bow shock nebula produced by the supersonic motion of the pulsar B2224+65, provides an *in situ* probe of structure in the interstellar medium. Image is 15$''$ in size, and structure on 0.1$''$ scales corresponds to length scales $\sim$ 80 AU [21]. b) WHAM Sky Survey [22, 23], showing all-sky Hα emission from the WIM and H II regions.

pressure[21]. Targeted Hα observations[24] have begun to yield new ISM structures on arcsecond scales as well as constraints on warm neutral medium filling fractions. Additionally, the IPHAS[25] and VPHAS[26] surveys continue to image the Hα distribution down to 1 arcsecond along the Galactic plane, using 2–4 m optical telescopes. The all-sky WHAM view of Hα emission emphasizes the dynamic and multi-scale nature of the ionized gas [22, 23].

High-cadence pulsar timing provides a wealth of scientific dividends beyond the primary goals of probing neutron star physics and gravitational wave science. As shown in Figure 5, the rapid space velocities of pulsars (typically 100's of km/s) scan through the ISM and uncover unexpected and unexplained structure in the parsec – AU range. Greater observing bandwidths will also increase the range of spatial scales probed by multipath progagation [27]. Continuing improving VLBI capabilities can resolve scattering screens [28] and thus improve small-scale ISM measurements.

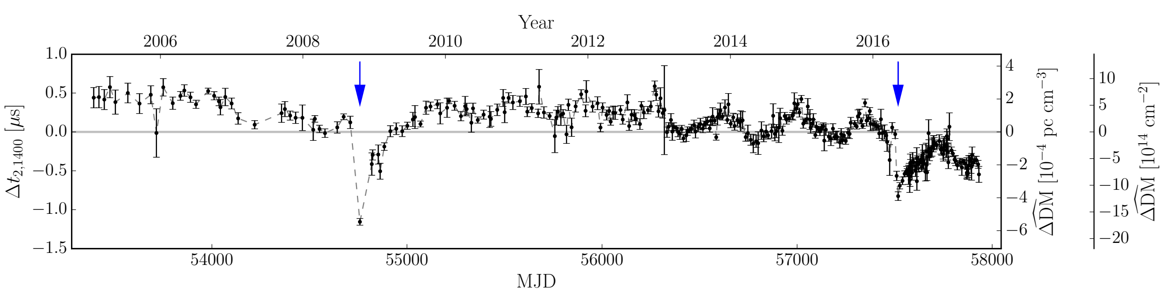


Figure 5: Two chromatic timing events in the millisecond pulsar J1713+0747 presumably caused by discrete ISM structures [29].

Additional Science Dividends

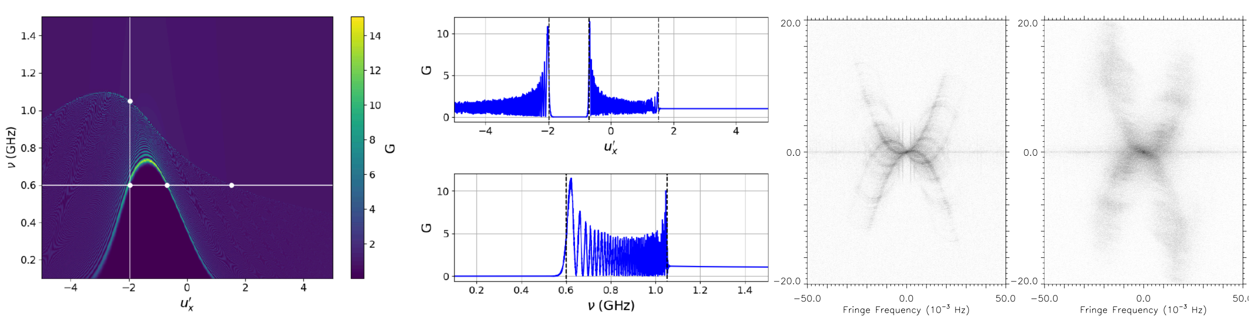
In addition to core science goals, ISM studies will benefit astrophysics in at least two other ways.

First, the ISM is a serious foreground for several decade-long efforts: i) opening another gravitational wave window using a PTA, ii) unlocking the secrets of FRBs, iii) detecting a cosmic B-mode signal, and iv) imaging the Milky Way's central black hole with the EHT. Proof-of-concept has been produced for mitigating foreground effects. Now, we must develop robust implementation strategies, a 10-year effort in some cases.

Second, several high-cadence monitoring projects (PTAs, pulsar and FRB searches) produce a wealth of information about the ISM. Synoptic telescopes like CHIME, HIRAX and DSA2000 will produce high-cadence, multifrequency data sets on many objects (pulsars and FRBs), yielding important ISM information. In the case of PTAs, high-precision ionized column densities and scatter-delay measurements are made weekly or biweekly. Figures 5 and 6 show some of the unexpected events that have occurred or may appear in this rich data set, which will grow to about 100 sight lines through the Galaxy in the 2020s, sampled as often as daily. The ability to detect and rapidly follow up on ISM events will complement other synoptic monitoring efforts such as the LSST.

Summary

Surprises from the last ten years emphasize that the ISM is a multi-scale medium threaded with tangled and ordered magnetic fields that dominate its dynamics in many cases. Continued support of this science in the next ten years will **yield crucial payoffs for US and international astrophysics:** from the interaction with star formation, not discussed here; through the gas dynamics of the Milky Way including numerous episodes of large-scale infall and expulsion; and by the feedback mechanisms associated with supernovae and powerful stellar winds. Knowing the full energy budget of the Milky Way leads to clear insights about external galaxies and galaxy assembly through cosmic time. In addition, the science sketched here provides crucial support to some key initiatives of the 2020s.



(a) (b)

Figure 6: a) Intensity disturbance due to lens intercept[30] b) Secondary spectra for the pulsar B1737+13 taken 6 days apart[5].

References

[1] Andrew Fletcher, R Beck, A Shukurov, E M Berkhuijsen, and C Horellou. Magnetic fields and spiral arms in the galaxy M51. *MNRAS*, 412(4):2396–2416, April 2011.

[2] J. W. Armstrong, B. J. Rickett, and S. R. Spangler. Electron density power spectrum in the local interstellar medium. *Astrophys. J.*, 443:209–221, 1995.

[3] A. Chepurnov and A. Lazarian. Extending the Big Power Law in the Sky with Turbulence Spectra from Wisconsin Hα Mapper Data. *Astrophys. J.*, 710:853–858, Feb 2010.

[4] K. H. Lee and L. C. Lee. Interstellar turbulence spectrum from *in situ* observations of voyager 1. *Nature Astronomy*, 3:154–159, 2019.

[5] D. A. Hemberger and D. R. Stinebring. Time Variability of Interstellar Scattering and Improvements to Pulsar Timing. *Astrophys. J.*, 674:L37–L40, 2008.

[6] Alex S. Hill, Mordecai-Mark Mac Low, Andrea Gatto, and Juan C. Ibáñez-Mejía. Effect of the Heating Rate on the Stability of the Three-phase Interstellar Medium. *Astrophys. J.*, 862:55, Jul 2018.

[7] S. E. Clark, J. Colin Hill, J. E. G. Peek, M. E. Putman, and B. L. Babler. Neutral Hydrogen Structures Trace Dust Polarization Angle: Implications for Cosmic Microwave Background Foregrounds. *Phys. Rev. Lett.* , 115:241302, Dec 2015.

[8] B. M. Gaensler, M. Haverkorn, B. Burkhart, K. J. Newton-McGee, R. D. Ekers, A. Lazarian, N. M. McClure-Griffiths, T. Robishaw, J. M. Dickey, and A. J. Green. Low-Mach-number turbulence in interstellar gas revealed by radio polarization gradients. *Nature* , 478:214–217, Oct 2011.

[9] Blakesley Burkhart, A. Lazarian, I. C. Leão, J. R. de Medeiros, and A. Esquivel. Measuring the Alfvénic Nature of the Interstellar Medium: Velocity Anisotropy Revisited. *Astrophys. J.*, 790:130, Aug 2014.

[10] Clare L. Dobbs. The interstellar medium and star formation on kpc size scales. *Mon. Not. R. Astron. Soc.*, 447:3390–3401, Mar 2015.

[11] Blakesley Burkhart and A. Lazarian. The Phase Coherence of Interstellar Density Fluctuations. *Astrophys. J.*, 827:26, Aug 2016.

[12] Chang-Goo Kim and Eve C Ostriker. Three-phase Interstellar Medium in Galaxies Resolving Evolution with Star Formation and Supernova Feedback (TIGRESS): Algorithms, Fiducial Model, and Convergence. *ApJ*, 846(2):133, September 2017.

[13] Ka Ho Yuen, Junda Chen, Yue Hu, Ka Wai Ho, A. Lazarian, Victor Lazarian, Bo Yang, Blakesley Burkhart, Caio Correia, Jungyeon Cho, Bruno Canto, and J. R. De Medeiros. Statistical Tracing of Magnetic Fields: Comparing and Improving the Techniques. *Astrophys. J.*, 865:54, Sep 2018.

[14] Blakesley Burkhart, Alex Lazarian, and Bryan M Gaensler. Properties of Interstellar Turbulence from Gradients of Linear Polarization Maps. *ApJ*, 749(2):145, April 2012.

[15] Claire E. Murray, Snežana Stanimirović, Chang-Goo Kim, Eve C. Ostriker, Robert R. Lindner, Carl Heiles, John M. Dickey, and Brian Babler. Recovering Interstellar Gas Properties with Hi Spectral Lines: A Comparison between Synthetic Spectra and 21-SPONGE. *Astrophys. J.*, 837:55, Mar 2017.

[16] C A Herron, Blakesley Burkhart, Bryan M Gaensler, G F Lewis, Naomi M McClure-Griffiths, G Bernardi, E Carretti, M Haverkorn, M Kesteven, S Poppi, and Lister Staveley-Smith. Advanced Diagnostics for the Study of Linearly Polarized Emission. II. Application to Diffuse Interstellar Radio Synchrotron Emission. *ApJ*, 855(1):29, March 2018.

[17] N. M. McClure-Griffiths, S. Stanimirovic, C. Murray, D. Li, J. M. Dickey, E. Vazquez-Semadeni, J. E. G. Peek, M. Putman, S. E. Clark, M. A. Miville-Deschenes, J. Bland-Hawthorn, and L. Staveley-Smith. Galactic and Magellanic Evolution with the SKA. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, page 130, Apr 2015.

[18] Javier Ballesteros-Paredes, Enrique Vázquez-Semadeni, Aina Palau, and Ralf S. Klessen. Gravity or turbulence? - IV. Collapsing cores in out-of-virial disguise. *Mon. Not. R. Astron. Soc.*, 479:2112–2125, Sep 2018.

[19] Paul C. Clark, Simon C. O. Glover, Ralf S. Klessen, and Ian A. Bonnell. How long does it take to form a molecular cloud? *Mon. Not. R. Astron. Soc.*, 424:2599–2613, Aug 2012.

[20] Fabian Heitsch, Andreas Burkert, Lee W. Hartmann, Adrianne D. Slyz, and Julien E. G. Devriendt. Formation of Structure in Molecular Clouds: A Case Study. *Astrophys. J.*, 633:L113–L116, Nov 2005.

[21] S. Chatterjee and J. M. Cordes. Smashing the Guitar: An Evolving Neutron Star Bow Shock. *Astrophys. J.*, 600:L51–L54, Jan 2004.

[22] L. M. Haffner, R. J. Reynolds, S. L. Tufte, G. J. Madsen, K. P. Jaehnig, and J. W. Percival. The Wisconsin Hα Mapper Northern Sky Survey. *Astrophys. J. Supp. Ser.*, 149:405–422, December 2003.

[23] L. M. Haffner, R. J. Reynolds, G. J. Madsen, A. S. Hill, K. A. Barger, K. P. Jaehnig, E. J. Mierkiewicz, J. W. Percival, and N. Chopra. Early Results from the Wisconsin H-Alpha Mapper Southern Sky Survey. In R. Kothes, T. L. Landecker, and A. G. Willis, editors, *The Dynamic Interstellar Medium: A Celebration of the Canadian Galactic Plane Survey*, volume 438 of *Astronomical Society of the Pacific Conference Series*, page 388, December 2010.

[24] S. Brownsberger and R. W. Romani. A Survey for Hα Pulsar Bow Shocks. *Astrophys. J.*, 784:154, April 2014.

[25] G. Barentsen, H. J. Farnhill, J. E. Drew, E. A. González-Solares, R. Greimel, M. J. Irwin, B. Miszalski, C. Ruhland, P. Groot, A. Mampaso, S. E. Sale, A. A. Henden, A. Aungwerojwit, M. J. Barlow, P. J. Carter, R. L. M. Corradi, J. J. Drake, J. Eislöffel, J. Fabregat, B. T. Gänsicke, N. P. Gentile Fusillo, S. Greiss, A. S. Hales, S. Hodgkin, L. Huckvale, J. Irwin, R. King, C. Knigge, T. Kupfer, E. Lagadec, D. J. Lennon, J. R. Lewis, M. Mohr-Smith, R. A. H. Morris, T. Naylor, Q. A. Parker, S. Phillipps, S. Pyrzas, R. Raddi, G. H. A. Roelofs, P. Rodríguez-Gil, L. Sabin, S. Scaringi, D. Steeghs, J. Suso, R. Tata, Y. C. Unruh, J. van Roestel, K. Viironen, J. S. Vink, N. A. Walton, N. J. Wright, and A. A. Zijlstra. The second data release of the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS DR2). *Mon. Not. R. Astron. Soc.*, 444:3230–3257, November 2014.

[26] J. E. Drew, E. Gonzalez-Solares, R. Greimel, M. J. Irwin, A. Küpcü Yoldas, J. Lewis, G. Barentsen, J. Eislöffel, H. J. Farnhill, W. E. Martin, J. R. Walsh, N. A. Walton, M. Mohr-Smith, R. Raddi, S. E. Sale, N. J. Wright, P. Groot, M. J. Barlow, R. L. M. Corradi, J. J. Drake, J. Fabregat, D. J. Frew, B. T. Gänsicke, C. Knigge, A. Mampaso, R. A. H. Morris, T. Naylor, Q. A. Parker, S. Phillipps, C. Ruhland, D. Steeghs, Y. C. Unruh, J. S. Vink, R. Wesson, and A. A. Zijlstra. The VST Photometric Hα Survey of the Southern Galactic Plane and Bulge (VPHAS+). *Mon. Not. R. Astron. Soc.*, 440:2036–2058, May 2014.

[27] J M Cordes, R M Shannon, and D R Stinebring. Frequency-dependent Dispersion Measures and Implications for Pulsar Timing. *ApJ*, 817(1):16, January 2016.

[28] Mikhail V. Popov, Norbert Bartel, Carl R. Gwinn, Michael D. Johnson, Andrey Andrianov, Evgeny Fadeev, Bhal Chandra Joshi, Nikolay Kardashev, Ramesh Karuppusamy, Yuri Y. Kovalev, Michael Kramer, Alexey Rudnitskiy, Vladimir Shishov, Tatiana Smirnova, Vladimir A. Soglasnov, and J. Anton Zensus. PSR B0329+54: substructure in the scatter-broadened image discovered with RadioAstron on baselines up to 330 000 km. *Mon. Not. R. Astron. Soc.*, 465:978–985, Feb 2017.

[29] M. T. Lam, J. A. Ellis, G. Grillo, M. L. Jones, J. S. Hazboun, P. R. Brook, J. E. Turner, S. Chatterjee, J. M. Cordes, T. J. W. Lazio, M. E. DeCesar, Z. Arzoumanian, H. Blumer, H. T. Cromartie, P. B. Demorest, T. Dolch, R. D. Ferdman, E. C. Ferrara, E. Fonseca, N. Garver-Daniels, P. A. Gentile, V. Gupta, D. R. Lorimer, R. S. Lynch, D. R. Madison, M. A. McLaughlin, C. Ng, D. J. Nice, T. T. Pennucci, S. M. Ransom, R. Spiewak, I. H. Stairs, D. R. Stinebring, K. Stovall, J. K. Swiggum, S. J. Vigeland, and W. W. Zhu. A Second Chromatic Timing Event of Interstellar Origin toward PSR J1713+0747. *Astrophys. J.*, 861:132, Jul 2018.

[30] Gianfranco Grillo and James Cordes. Wave asymptotics and their application to astrophysical plasma lensing. *arXiv e-prints*, page arXiv:1810.09058, Oct 2018.

[31] Dieter Breitschwerdt, Miguel A. de Avillez, and Verena Baumgartner. Modeling the Local Warm/Hot Bubble. In Randall K. Smith, Steven L. Snowden, and K. D. Kuntz, editors, *American Institute of Physics Conference Series*, volume 1156 of *American Institute of Physics Conference Series*, pages 271–279, Aug 2009.

[32] A Chepurnov and Alex Lazarian. Extending the Big Power Law in the Sky with Turbulence Spectra from Wisconsin Hα Mapper Data. *ApJ*, 710:853, February 2010.

[33] J. E. G. Peek, Brian L. Babler, Yong Zheng, S. E. Clark, Kevin A. Douglas, Eric J. Korpela, M. E. Putman, Snežana Stanimirović, Steven J. Gibson, and Carl Heiles. The GALFA-H I Survey Data Release 2. *The Astrophysical Journal Supplement Series*, 234:2, Jan 2018.

[34] S. E. Clark, J. E. G. Peek, and M. E. Putman. Magnetically Aligned H I Fibers and the Rolling Hough Transform. *Astrophys. J.*, 789:82, Jul 2014.