Small Ionized and Neutral Structures: A Theoretical Review

Steven R. Spangler\textsuperscript{1} and Enrique Vázquez-Semadeni\textsuperscript{2}

\textsuperscript{1}Department of Physics and Astronomy, University of Iowa, \textsuperscript{2}Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México

Abstract. The workshop on Small Ionized and Neutral Structures in the Interstellar Medium featured many contributions on the theory of the objects which are responsible for “Tiny Scale Atomic Structures” (TSAS) and “Extreme Scattering Events” (ESE). The main demand on theory is accounting for objects that have the high densities and small sizes apparently required by the observations, but also persist over a sufficiently long time to be observable. One extensively-discussed mechanism is compressions by transonic turbulence in the warm interstellar medium, followed by thermal instabilities leading to an even more compressed state. In addressing the requirements for overpressured but persistent objects, workshop participants also discussed fundamental topics in the physics of the interstellar medium, such as the timescale for evaporation of cool dense clouds, the relevance of thermodynamically-defined phases of the ISM, the effect of magnetic fields, statistical effects, and the length and time scales introduced by interstellar processes.

1. Introduction

The SINS meeting was dominated by an interesting and often disconnected mix of observational reports on “small scale” structure in various interstellar environments, and theoretical works attempting to explain such observed structures. Interestingly, there was a wider variety in the kinds and physical properties of the structures reported observationally than in the theoretical approaches presented as potential models. This article includes a review of the theoretically-significant results presented at the SINS workshop. For reference, we first recall observational results that pose the challenge for the theoretical studies.

2. Classes of Compact Structure

Small-scale structure was reported to be observed in all three of the diffuse ionized, atomic and molecular components of the interstellar medium (ISM), although the physical properties of the structures in each component are as varied as the environments in which they are found (see the observational review by Heiles & Stinebring in this volume). Even the very notion of “small” differs strongly from one field to another. The features are primarily distinguished by their observational signatures.
2.1. Dense Regions of Ionized Gas

In the diffuse ionized gas, small-scale structures are inferred from radio scintillation effects, such as large flux density variations of compact radio sources or pronounced “fringing” in the dynamic spectra of pulsars. A more subtle observational indicator is a host of effects suggesting that additional fluctuations in plasma density are needed above and beyond the Kolmogorov spatial power spectrum which has become canonical. Comments addressing the existence of such excess power were made in the presentations by Barney Rickett and Dan Stinebring.

Deducing physical properties of these ionized enhancements is not so straightforward, and more model-dependent than for the atomic and molecular components, but the results that are available give densities $\sim 10 \, \text{cm}^{-3}$, sizes $\ll 1 \, \text{AU}$, and filling factors $\sim 0.1$ (Rickett’s talk).

The so-called Extreme Scattering Events (ESEs) are, well, more extreme, with estimated densities in the range $300-10^5 \, \text{cm}^{-3}$, and diameters of $0.06-0.38 \, \text{AU}$ (Clegg, Fey, and Lazio 1998). The structures responsible for ESE could be more extreme versions of the structures responsible for the ubiquitous pulsar scintillation arcs, which also seem to involve discrete, identifiable clouds rather than a continuum of turbulent fluctuations (Stinebring’s talk).

2.2. “Tiny scale atomic structure” (TSAS): High Density Neutral Atomic Gas

Most of the presentations dealt with observations of measurable changes in the neutral hydrogen column density over small angular distances on the sky. Interpreted at face value, these features would correspond to small ($\sim 10-100 \, \text{AU}$ in size) regions of greatly enhanced gas density (see Crystal Brogan’s talk). Characteristic values of the gas density would be $\sim 10^5 \, \text{cm}^{-3}$ as opposed to $\sim 0.5 \, \text{cm}^{-3}$ for the typical Warm Neutral Medium (WNM), or $\sim 50 \, \text{cm}^{-3}$ for the Cold Neutral Medium (CNM). Even with the assumption of low neutral hydrogen temperatures of $\sim 50 \, \text{K}$, these regions would then exceed the typical pressure in the neutral medium by $\sim 3$ orders of magnitude. The filling factor of TSAS is, however, very low, $\sim 0.001$.

2.3. Small-scale structure in molecular gas

While attention at this workshop concentrated on the CNM, WNM, and DIG (Diffuse Ionized Gas) components of the interstellar medium, small-scale molecular structures were also reported at the conference by Andreas Heithausen, with typical densities $\sim 10^3-10^4 \, \text{cm}^{-3}$, temperatures $\sim 10-20 \, \text{K}$, sizes $\sim 100-5000 \, \text{AU}$, and masses $\sim 0.1-1 \, M_{\odot}$. Such masses are much smaller than their virial masses ($\sim 1M_{\odot}$), implying that these structures cannot be gravitationally bound, and must be formed or confined by some form of pressure (possibly ram pressure). Edith Falgarone and Pierre Hily-Blant further pointed to tiny molecular clouds in which the HCO$^+$ abundances are much higher than those expected in steady-state models and in which abundance ratios vary wildly, suggesting a very dynamical state. Edith interpreted these data in terms of turbulence-induced chemical reactions leading to HCO$^+$, resulting from localized heating caused by turbulent dissipation.
2.4. Theoretical challenges

The main theoretical challenge in understanding these structures is that, if they are true density enhancements, then they are strongly overpressured with respect to the ambient ISM pressure, and, naively, they should either not be there, or disperse quickly. Possible explanations presented at the meeting included persistent turbulent production of transient structures, geometrical effects, or statistical observational projection effects. In §4 we summarize these possibilities.

If the structures are really small-scale density and pressure enhancements in the ISM, then the challenge is to understand how one can generate such large excursions out of a medium with typical densities between \( \sim 0.1 \text{ cm}^{-3} \) (the Diffuse Ionized Gas or DIG) and \( \sim 1 \text{ cm}^{-3} \) (the WNM). For the scintillation features in ionized gas, the fact that this gas is ionized removes any possibility of the pressure being reduced by a low gas temperature.

3. Basic Theoretical Descriptions of the Interstellar Gas

Since the warm ISM is characterized by a transonic velocity dispersion, theoretical explanations for the SINS as actual density enhancements rely on transonic turbulence in a cooling, magnetized medium. There are basic questions about how one theoretically describes the gas that comprises the interstellar medium, and different descriptions may be necessary for the different phases. Ellen Zweibel discussed the large variety of spatial scales that arise in the gas due to viscosity, resistivity, and collisions between ions and neutrals. In addition, there are still remaining basic physics issues about how one describes the true viscosity in a magnetized, collisionless plasma. The ESE structures occur on (very roughly) the ion-neutral collisional scale in the DIG, i.e. the scale that corresponds to the wavelength of an Alfvén wave with a frequency equal to the ion-neutral collision frequency. Perhaps such fundamental plasma scales define the sizes of TSAS and ESE phenomena.

The study of turbulence in plasmas is also highly relevant to the small structures in the interstellar medium, since the phenomena we observe probably grow out of the general turbulence field. If this is the case, we need to fully understand some of the topics discussed by Alex Lazarian, Stanislav Boldyrev and Joanne Mason, such as the location and extent of the inertial subrange and dissipation range of the turbulence, and the relationship between different turbulence variables, like density and magnetic field.

The interstellar medium may provide a new arena for the study of plasma turbulence. Much of plasma turbulence theory has depended on spacecraft observations of the solar wind for data support. While this theory-observation link has proven fruitful, other turbulent media in astrophysics might differ in important ways. Solar wind turbulence at 1 AU is dynamically young, nearly collisionless, and describable by a simple energy equation. The interstellar medium is different in each of these categories, so the lessons learned from studies of the solar wind might not be applicable here. Another specific difference, which might illuminate fundamental differences, is in the presence or absence of compressibility. In solar wind turbulence, the density fluctuations are small relative to those of magnetic field and flow velocity. The ISM, on the other hand, is characterized by a range of densities and temperatures spanning many orders
of magnitude, and its cooling properties render it highly compressible and even thermally unstable in the range \(8000 \text{ K} \gtrsim T \gtrsim 500 \text{ K}\).

4. Theoretical interpretations

4.1. Numerical results

A number of investigators presented numerical simulations of dynamical compressions at moderate Mach numbers \(\mathcal{M} \lesssim 2\) (Enrique Vazquez-Semadeni, Patrick Hennebelle) or global transonic turbulence in the WNM (Adriana Gazol), subject to thermal bistability (e.g., [Field et al. 1963]), showing that in principle a population of small-scale, high-density, high-pressure objects can be transiently formed in such flows. The basic principle is that the transonic compressions in the WNM nonlinearly trigger thermal instability, causing a phase transition to a cold, dense phase ([Hennebelle & Pérault 1999]). Since the total (thermal + ram) pressure is higher than the thermal pressure of the WNM \(P_{\text{WNM}}\) alone, the cold cloudlets end up at pressures higher than \(P_{\text{WNM}}\) as well ([Vázquez-Semadeni et al. 2006]). Moreover, the compressed layers develop turbulence (e.g., [Vishniac 1994; Walder & Folini 1998; Koyama & Inutsuka 2002; Heitsch et al. 2005; Vázquez-Semadeni et al. 2006]) and, since they are much colder than the WNM \(T \lesssim 50 \text{ K}\), this turbulence is strongly supersonic, so that the flow there is highly compressible and the highest-density structures are transient.

In the simulations, pressures up to \(P \sim 10^5 \text{ K cm}^{-3}\) and densities up to \(n \sim 10^3\) are readily reached (see Adriana’s and Patrick’s contributions). It is noteworthy that structures of a given high density (e.g., \(n \sim 300 \text{ cm}^{-3}\)) can span roughly two orders of magnitude in thermal pressure \((10^4\text{-}10^6 \text{ K cm}^{-3})\), indicating that dense cloudlets can exist at both high and low temperatures. Presumably, the warmer ones are those that have not had time to cool down yet, and are probably in the process of doing so. For example, a cloudlet at \(n \sim 3000 \text{ cm}^{-3}\) and \(P \sim 10^6 \text{ K cm}^{-3}\) is at a temperature \(T \sim 300\text{ K}\) and cooling strongly. It is already much cooler than the WNM, but not yet at the temperatures characteristic of the CNM or the molecular gas. This suggests that indeed these structures are transient, in particular the warmer ones.

In principle, then, dense, overpressured, small-scale structures (both cold and warm) can be generated in such flows. Patrick reported densities up to \(n \gtrsim 10^4 \text{ cm}^{-3}\) and pressures up to \(P \lesssim 10^6 \text{ K cm}^{-3}\) in 2D simulations with a resolution of 10000 grid points per dimension, down to scales of hundreds of AU. This appears very close to explaining the physical conditions of individual structures reported by the atomic and molecular observations. However, in order to determine whether the mechanism can account for the entire population of structures, detailed statistical comparisons are necessary. Adriana reported 7% of the mass being at \(n \gtrsim 100 \text{ cm}^{-3}\), although Patrick warned that this fraction seems to depend on resolution. In general, it is necessary to measure this fraction, as well as the filling factors, as a function of the threshold density used to define the clumps in the simulations in order to compare in detail with the observations. This should allow a quantitative determination of whether the mechanism of transient, out-of-equilibrium density fluctuations by transonic turbulence in the WNM can account for the population statistics of these objects,
and not only the existence of a few such objects in isolation. Other means of comparison based on the energy and density spectra as derived taking into account projection effects were outlined by Alex Lazarian.

If comparisons prove to be statistically correct, then the mechanisms can be considered viable in principle, although much higher resolution and the inclusion of the relevant microphysical processes will still be needed for the simulations to reach the scales of the ionized structures responsible for radio scintillation. On the other hand, if the simulations do not produce these structures in sufficient numbers, then it may be necessary to explain the remainder of the observed structures by other mechanisms, such as those discussed below in §§4.4 and 4.5.

4.2. Implications for the Significance of Phases of the Interstellar Medium

Much of the fundamental theoretical description of the interstellar medium has been based on the concept of phases arising from thermodynamic equilibrium. The identification of the cold and warm phases of the interstellar medium with portions of the equilibrium $P(\rho)$ relationship dates back nearly 40 years (Field et al. 1969) and is appealing because of its physical simplicity. However, there is presently a controversy, expressed indirectly at this meeting by the (sometimes loud!) discussions between Patrick Hennebelle and Enrique Vázquez-Semadeni, as to whether these concepts are meaningful, or if the real interstellar medium is always so far from thermodynamic equilibrium as to make those concepts invalid. The physics of the actual ISM is probably a mixture of these concepts. In regions of strong turbulent mixing, the interfaces between the equilibrium phases may be blurred, the flow being more similar to a density continuum than to a two-phase medium. Conversely, in more quiescent regions, thermal instability may be free to act and generate two-phase structure. Indeed, the simulations show both kinds of situations, with CNM clu dlets sometimes surviving for long times relatively unperturbed, and some others rapidly dispersing away back into the diffuse gas.

In regions where two-phase structure is present, studies of clump evaporation are relevant, and were presented by Jonathan Slavin, Inoue San and Nagashima San, with reports of typical evaporation timescales $\sim 1$ Myr. However, since the small-scale structures that are the subject of this conference are generally agreed to be strongly overpressured, it is expected that their lifetimes are determined by a dynamical formation and re-expansion process, with the characteristic timescale being their turbulent crossing time, which is generally much shorter than the evaporation time. In regions where two-phase structure is present, the development of thermal instability may also generate moderate turbulence (Inutsuka & Koyama’s poster).

One disappointment in the workshop was the lack of a more vigorous and extensive discussion about the relationship (if any) between the atomic and ionized entities. Barney Rickett and Mark Walker are to be complimented as progressives in this respect. In coming to an eventual understanding of these objects, it will be helpful to know if the radio propagation effects are caused by the ionized outer envelopes of the clouds responsible for TSAS, or if we are dealing with entirely distinct structures that reside within the CNM or WNM on one hand, and the DIG on the other.
4.3. The Role of the Magnetic Field

The proper primitive equations for study of the interstellar medium are the equations of magnetohydrodynamics, not just hydrodynamics. The interstellar medium is permeated by a magnetic field with a magnitude of 3-5 \( \mu \)G, resulting in a plasma \( \beta \) (defined as the square of the ion-acoustic to Alfvén speed ratio) of less than 1. The magnetic field pressure and tension play a dynamic role in the interstellar medium, and cannot be ignored.

Several presentations illustrated the role played by interstellar magnetism. Alex Lazarian discussed some intrinsically magnetic effects, such as the generation of density fluctuations by MHD waves even at scales smaller than the viscous scales. Adriana Gazol presented results from simulations of thermally bistable, magnetized turbulent flows indicating that in this case a population of cold regions of low density (i.e., very low thermal pressure) supported by magnetic pressure exists in the flow. The question then comes down to how much variation in \( nk_B T \) can be mechanically balanced by \( \frac{1}{c} \vec{J} \times \vec{B} \). The value of \( \frac{B^2}{8\pi} \) for \( B = 5 \mu \)G is \( 10^{-12} \) dynes/cm\(^2\), corresponding to an \( nT \) product of \( 7.2 \times 10^3 \) K/cm\(^3\). Large variations in the magnetic energy density could therefore balance variations of several thousand (cgs units) in the dimensional quantity \( nT \).

It is widely believed that, due to flux freezing, the magnetic field should be enhanced together with the density fluctuations. However, both observations (e.g., Crutcher 1999; Heiles & Troland 2003, Crystal Brogan’s talk at this meeting) and numerical simulations of MHD turbulence (e.g., Passot et al. 1995; Padoan & Nordlund 1999; Ostriker et al. 2001) show otherwise. The magnetic field strength appears to be in general uncorrelated with the density, except perhaps at the highest densities. In his talk, Enrique Vázquez-Semadeni recalled a proposed explanation for this phenomenon (Passot & Vázquez-Semadeni 2003) based on the fact that the different modes of nonlinear MHD waves (so called “simple” waves) are characterized by different scalings of the field strength with density, so that in a turbulent medium the field strength at a given point does not directly depend on the density, but on the (random) history of wave passages through that point. It had been previously shown already (Hennebelle & Pérault 2000) that compressions of a thermally bistable medium oblique to the magnetic field up to a certain angle (that depends on the Mach number of the compression) can induce a transition to the dense phase without increasing the field, because the latter re-orient the motions along itself, and the matter can slide freely along the field. Thus, the lack of correlation is to be expected even in ideal MHD situations.

4.4. Geometry effects?

In addition, and in some sense prior to this, we must be certain that the observations really indicate relatively isotropic regions of enhanced density, rather than highly anisotropic regions such as sheets, which are fortuitously aligned with the line of sight. This possibility was first discussed by Carl Heiles in 1997. In this case, the implied volume densities and pressures would not be as extreme as the face-value implications of the observations. Statistical analyses are again necessary to determine whether the chance alignment of the structures is sufficient to account for the observed frequency of the phenomenon.
4.5. TSAS and ESE as Statistical Fluctuations?

A. Deshpande proposed an explanation for TSAS and ESE that contrasts greatly with all of the other presentations, which attribute these phenomena to compact, overdense gaseous structures in the interstellar medium. Desh contends that the observations of large differences in the optical depth on two lines of sight separated by a distance \( x_0 \) are not due to “clouds” with physical sizes \( x_0 \), but rather to the statistics of the optical depth structure function in a medium with a spatial power law in neutral hydrogen density. Desh emphasized that the optical depth structure function at a spatial lag \( x_0 \) (essentially what is being measured) is not determined solely by structures with size \( x_0 \), but in general contains contributions from density structures on all scales. Desh’s presentation drew largely on previous results (Deshpande 2000) for the TSAS discussion. He also claimed that a similar reasoning would apply to path integrals through the ionized ISM which produces ESE and other strong scintillation phenomena. This last contention is not obvious because optical depth is directly describable as a stochastic integral, but scintillation phenomena must be described by wave propagation through a random medium.

Desh’s proposal is controversial because it differs so substantially from the commonly-held view that TSAS, ESE, and related phenomena are due to discrete and extraordinary structures in the interstellar medium. In contrast, Desh suggests that the observations are essentially statistical fluctuations resulting from a medium with a wide range of spatial scales. If he is correct, the highly dense, overpressured objects which attracted so much discussion in this meeting would be nonexistent, or at least possess much less extreme properties. This disturbing prospect should motivate the workshop participants (and others) to explore the mathematics of optical depth differences in a turbulent medium, and scrutinize their data for independent evidence of high pressures and densities in the ISM, or alternatively, indications that such extremes are absent.

5. Future Research Directions

One of the useful features of a workshop like this is the guidance it can provide for future research investigations, the construction of new instrumentation, and the development of new computer codes. The following are the issues which we think should attract the attention of the community in the next five years or so.

- As discussed by Dave Meyer, the upgrade to the HST should permit measurements of column density variations to more, and more closely-spaced stars, including binaries and globular clusters that have not been observed until now. This development will give us our best chance to visualize the features responsible for spatially-variable absorption.

- Future developments in radio astronomy would help in improving our understanding of both the TSAS and ESE phenomena. The Expanded Very Large Array (EVLA) in the short term, and the Square Kilometer Array (SKA) in the long term will allow measurements of hydrogen absorption along more lines of sight to extragalactic radio sources and pulsars.
• The presentations and discussions at this meeting indicated that simulators should try and quantify the population statistics of the small-scale density structures in the simulations. They should analyse their simulations so as to produce numbers on filling factors and mass fractions as a function of density threshold. Extraction of information on clump lifetimes would also be of interest. All of this information can help us decide if highly transient, overpressured “clouds” in the simulations are compatible with the statistics on lines of sight occupied by TSAS and ESE.

• A turbulent plasma is characterized by more than density and its variations. The more interesting fluid variables are flow velocity, magnetic field, vorticity, and the like. Optical and radio observers should be encouraged to “get sophisticated” and think about ways in which observations might yield new fluid variables such as vorticity.

• A related appeal (which was brought up in the group discussion at the end of the meeting) is for simulators to develop diagnostics which would permit a more direct comparison with observations. One way would be to calculate path integrals through their simulations, or at a more advanced level, spectral line profiles. Such diagnostics would facilitate the conversation between observers and theorists, and provide information the observers need. As Jim Cordes said, speaking of the relationship between the scattering measure (defined as the path integral of the turbulence parameter \( C_2^2 \) (proportional to the variance of the density fluctuations)) and the emission measure, “if you have emission measure, you can turn off the scattering measure, but you can’t have a scattering measure and turn off the emission measure”.

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