The Final Session - 10 Questions, 10 Responses

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Abstract.
The final session in the workshop was chaired by the graduate students and post-doctoral fellows. Ten questions were presented to the workshop members for discussion. The questions are reproduced here, along with a summary of the ensuing discussion.

1. The ideal statistic to characterize ISM structure - What are its desirable properties? Does physical theory predict its existence?

An ideal statistic does not exist; it requires a universality in the ISM on all scales and between all phases, which does not occur. However, we can define the desirable properties of analysis tools in general.

Without knowledge of the 3-dimensional distribution of matter, the statistic must be robust against projection effects. The statistic would also have to be robust against noise. The question "What do you want to know" determines the nature of the statistics which characterize a problem.

When interpreting observations, well understood physical processes do not necessarily give rise to easy-to-understand physical features. In other words, there is not a one-to-one correspondence between cause and effect. A statistic describing a process is different from one describing a class of objects. Be aware that the peculiarities of different telescopes and different spectral regimes can yield false correlations between the two.

2. Why is filamentary structure prevalent in the Galaxy?

Gravity acting alone creates spheres. Collapse into sheets is moderated by internal "pressures": rotation, magnetic fields, and turbulence. The intersection of sheets will be brighter than the surroundings, and appear to be filamentary.

There is no reason to expect sheets to be flat. Sheets are seen to contain ripples. Non-uniform sheets have been observed in young SN remnants. Sheets of vorticity can be Kelvin-Helmholtz unstable, and can collapse into filaments.

Edge-on sheets can, in principle, be distinguished observationally from filaments. The edge-on view of a sheet will have brighter emission (higher column density) at a given velocity than a filament.

There are structures in the ISM that require a sheet-like morphology, because if we invoke a filament-like morphology we derive unacceptably high values of density and pressure. Are there then examples of "true" filaments, or are all observed filaments merely the result of projection? Herbig-Haro objects and jets are certainly examples of elongated structures, if not bona fide filaments.

3. Magnetic reconnection - How? On what time scales? How relevant is it compared to other heating?

Magnetic reconnection occurs where the magnetic field strength approaches zero near a field reversal. For example, consider two anti-parallel lines of field: any collapse will bring the lines together and the magnetic field adds to zero ("reconnects"). Astrophysically, one needs a quickly moving gas for reconnection to occur. This effect has been documented in the solar atmosphere. One progresses from X-shaped field lines to a four-leafed clover geometry, where the magnetic field at the cross-over point of the "X" has reconnected and added to zero field strength. Very little of the magnetic energy is lost to reconnection ($\sim 5\%$).

4. What astrophysics will emerge from modeling turbulence?

The observed Galactic chemical distribution is probably due to the turbulent transport ("mixing") of matter throughout the ISM.

One fundamental problem in the theory of the ISM is that we don't know the relationship between fluctuations in density and velocity within a cloud. Ultimately, we wish to derive all of the observed properties of the medium, such as temperature and magnetic field strengths.

Current modeling of the ISM is in 2-D, however our observations are of projections of 3-D structure. Modeling results and observations compare favourably. In the case of a compressible fluid, the 2-D simulations resemble the 3-D situation due to the one-dimensional nature of shocks. Computing limitations restrict the usefulness of 3-D simulations.

Simulations are not "classical" experiments - in an experiment the laws of physics are always obeyed. Models include only the physics that we put into them, and compromises are made. Statistical study of the results help quantify the effects of these compromises and improve the modeling.

5. What are the boundaries at which turbulence becomes dominant over large-scale shocking for structure formation?

The question is posed badly. A shock is an object, while turbulence is a concept. There is no physical distinction between the two. Turbulence creates objects such as sheets, filaments and vortices. Shocks interact with these.

A shock wave propagating through a uniform medium has a steady flow and is not turbulent. The interaction of expanding bubbles with each other gives rise to turbulence. If roughly 20% of the ISM by volume is comprised of freely expanding stellar winds, then perhaps this portion can be characterized by smooth flow; the rest is turbulent.

Compressibility is not a necessary property for a fluid to be turbulent. A curved shock wave will produce vorticity, and a shock propagating from a "straight" to a curved density field will produce vorticity.

To assess the impact of turbulence, leave it out as a first approximation! The McKee-Ostriker model successfully reproduced the observational data at the time, such as column densities. Today the observational picture has changed, along with our attitude towards it. Instead of looking at individual objects, we now want to understand those data as a unified whole. Can the turbulent models make accurate predictions? Turbulence is only one process, albeit an important one, which shapes what we see in the ISM.

6. How relevant are 2-D versus 3-D simulations of the ISM?

The currently available computing resources force us to make a compromise between spatial resolution and physical area. We sacrifice the third dimension of spatial information to enhance the other 2 dimensions. This situation could be disastrous in an incompressible fluid but should be fairly close to reality in the compressible case due to the 1-D nature of shocks. We are, however, missing instabilities if we work in 2-D since the filaments cannot undergo twisting.

Results should always be tested by increasing the resolution by a factor of two and rechecking the solution for convergence. Without this process, the model results are as irrelevant as observations which don't report or quantify noise statistics.

7. How important is dust in the ISM? Models do not use full radiative transfer - how is cooling handled?

Dust contributes only about 0.1% of the baryonic mass of the Galaxy. However, 30% of the luminosity of the Galaxy is from dust in the IR. Dust reprocesses UV radiation. Dust transfers energy via photoelectric emission to the neutral gas, and heats the CNM to 100 K. Grains acting as charge carriers only have a significant effect in dense molecular cloud cores. Molecular hydrogen forms on the surface of dust grains. Also, metals deplete onto dust surfaces, removing coolants from the surrounding medium.

In typical simulations the full theory of radiative transfer is not incorporated due to the immense complications required. To first order, the inclusion of dust is not handled rigorously.

In order to handle cooling, many simulations impose an equation of state, or parameterize density and temperature. The simplest radiative transfer treatment is the isothermal approximation, where no heating or cooling is required. There are also codes which attempt to incorporate chemical processes.

8. Is the gas pushing the magnetic field or vice versa?

The interstellar medium is not a quiescent environment. Supernova explosions are frequent, and they sweep up both gas and magnetic fields and inject kinetic energy into the ISM.

If there is energy equipartition on all scales then there is a complex interplay occurring. The gas flow pushes the field lines, but they resist this push and deviate the flow. In a weak field case, the gas flow compresses and strengthens the field; in a strong field case the magnetic field will channel the gas motions and expand into equipartition. The magnetic field acts as a pressure.

9. How does the ISM modulate the formation of molecular clouds? How do supershells appear in this picture?

We do not completely understand how molecular clouds form. Consider time scales - does the instability operate on shorter timescales than turbulence in the cloud? Giant molecular clouds (GMC's) are often associated with supershells. But while GMC's limit the extent of superbubbles, GMC's are not actually formed from material collected by the expanding supershell. Studies of GMC's in face-on galaxies quantify the influence of spiral arms (e.g., Elmegreen).

Molecular gas is created in spatially large regions. Since molecular hydrogen is easily destroyed by absorption of (sub-ionizing) Lyman-band photons, self-shielding is an important factor. Knowledge of both (1) the total column density of H_2 (assume steady state), and (2) the radiation field, will yield an estimate of the formation rate. One would therefore like to be able to trace atomic gas on large scales down to molecular gas on small scales, taking into account destructive processes like photodissociation.

10. What is a dynamo? What sort of turbulence is needed? Where does the random field come from?

In a region of large scale shear (e.g., differential rotation), magnetic fields will be amplified by gas motions. The shearing motions will stretch and wind up a radial field into an azimuthal field. Coriolis forces will produce helical motions which further deform the field. This stretching and amplifying of the field is the basis for the dynamo, but it requires an initial seed field. The origin of these seed fields is unknown but they may be extragalactic.

Magnetic fields will not grow indefinitely; there is an equilibrium strength where the dynamo process will quench itself. The disk of our Galaxy appears to have reached this state with the magnetic, thermal and cosmic ray pressures being similar in strength.

The stability criterion is what determines which dynamo mode (axisymmetric or bisymmetric) will dominate. The random component of the magnetic field is probably created through the same set of instabilities. Streaming instabilities from cosmic rays can also contribute to the random component.

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