THE NEW INTERSTELLAR MEDIUM: TRANSITORY, ANISOTROPIC, MAGNETIC, TURBULENT

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1. INTRODUCTION

1.1. Science Background

The gas disks of spiral galaxies are turbulent and inhomogeneous. On scales of a few kiloparsecs in size and a hundred million years in time, the spiral pattern in the stellar gravitational potential sweeps through the gas causing a shock, compression, and star formation (Sellwood and Balbus, 1999; Goldman, 2000). On smaller scales of several hundred parsecs and ten million years, star formation and the concomitant stellar winds and supernova remnants shred the gas, sweeping out shells and bubbles and piling up clouds, often in the shape of sheets and filaments. These shells can break out of the disk and vent hot gas into the lower halo, driving a galactic fountain that redistributes gas radially. On still smaller scales of space and time the structure and motion of the gas is more random and irregular—*turbulent* (Brunt et al., 2003; Lazarian and Pogosyan, 2000).

The kinetic energy injected must be dissipated. The accepted picture: it transfers to the upper scale length of turbulence and then cascades to smaller scales. Ultimately the energy is dissipated into microscopic motions on the smallest turbulent size scale, known as the inner scale. The dissipation scale is at least as small as 100 AU and may be as small as a few thousand kilometers. Between the inner and outer scales, the ISM structure is best described as stochastic turbulence with a power spectrum. The cascade of energy to smaller scales reflects the astrophysical processes that govern the dynamics of the gas, and in particular the motion of the gas is coupled to the magnetic field in a spectrum of magneto-acoustic waves (Passot and Vazquez-Semadeni, 2003; Ferriere et al., 1988).

Given this theoretical background, some of the relevant observational questions become: What is the topology of the ISM, and what are the filling factors of the various phases? What are the energy sources and how do they transfer energy to the turbulent cascade? Can we identify interstellar structures such as shocks, the actual agents that inject the energy to the turbulent cascade? How does interstellar gas make the transition between phases? How are the thermal phases related to the turbulent spectrum?

And on the very largest galactic scales: What is the structure of galaxy halos? What is the nature of the disk/halo interface? How much matter and energy falls on the Galaxy with High-Velocity Clouds? Is there a large-scale Galactic fountain and/or wind?

We, along with many astronomers, believe that most of the ISM is truly described as "turbulence" over small enough length scales. However, that's not the whole story: we see morphological structures that are distinctly non-fractal and these highlight currently unknown physical processes and situations. The remaining section describe ISM structures, some of which seem "turbulent" and some of which seem more like individual morphological features that lie outside the realm of scale-independent fractal turbulence.

1.2. Instrumentation

In the 21-cm line, the various scales are observationally probed by 21-cm line maps and interstellar scattering of point radio sources such as pulsars. Observational capabilities for the 21-cm line have dramatically increased as a result of the 7-feed ALFA array at Arecibo, and promise even more in the future if the Allen Telescope Array is built to its full complement of 350 telescopes. Recent advances in interstellar scattering round out the picture; they include arcs, arclets, and intra-day variables, to name a few. These are studies of time variability of point sources and, as such, require the highest sensitivity; Arecibo, with its huge collecting area, is the instrument of choice. Obtaining and synthesizing these unprecedented data into a coherent whole will *transform our understanding of the interstellar medium.*

2. THE GALACTIC ISM: TURBULENCE vs. QUASI-EQUILIBRIUM vs. MACROFLOWS

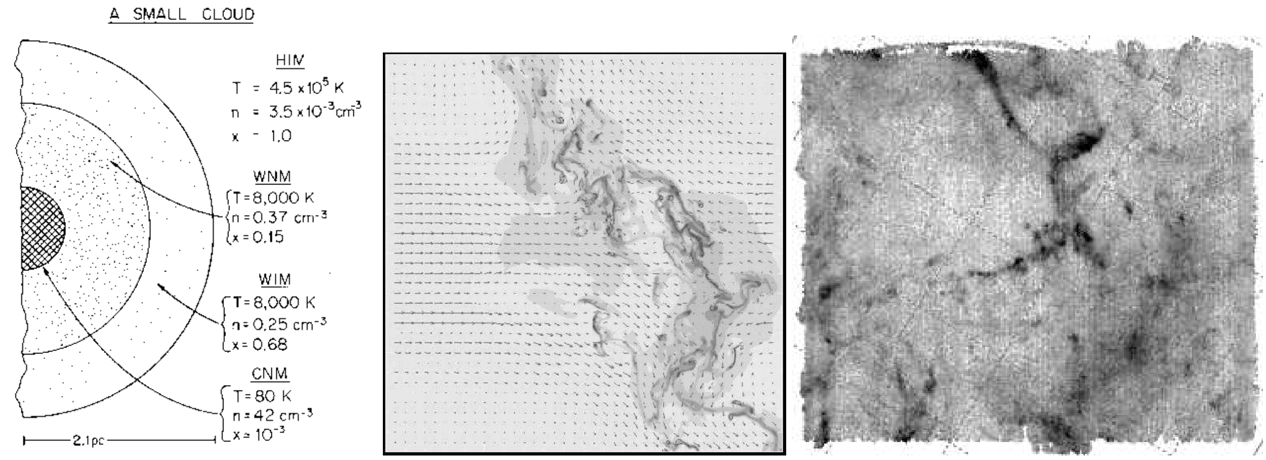

Fig. 1.— *Left:* Quasi-static model of CNM clouds (MO) in evaporative quasi-equilibrium with the surrounding HIM. *Center:* CNM "cloud" from a simulation by Hennebelle (private communication). *Right:* An observed CNM filamentary "cloud"; this image is from the Arecibo GALFA survey.

The ISM's overriding morphological trait is *anisotropy.* It tends to lie in sheets and filaments with aspect ratios that can reach hundreds to one. The right-hand panel of Figure 1 shows a hot-off-the-telescope (i.e., unpublished) Arecibo GALFA image of a twisted, writhing filament moving supersonically through its surroundings. The middle panel shows a theoretical image from a recent numerical gasdynamical simulation; to the eye, it looks—deceptively—like the data. Deceptive, because supersonic motions are rare in the simulations. In contrast, the left-hand image is from a highly regarded ISM textbook published just a few years ago (Tielens 2005), and it represents the image that rests in most astronomers' minds: a spherical cold gas core in subsonic quasi-equilibrium with a warm envelope, embedded in the HIM substrate—the classical ISM theory of McKee & Ostriker (1978; MO).

What are we to believe? The classical theory describes neither the morphology nor the kinematics. (It does pretty well in predicting global quantities like pressure, however.) Turbulence wins over quasi-equilibrium because the simulations—which are all about turbulence—do describe the morphology. Turbulence is, by nature, *fractal*—scale-invariant, so one size scale looks like another. We see plenty of evidence for fractal turbulence, which is especially easy to characterize for the small scales sampled by pulsar scintillation and related phenomenae. The right-hand panel of Figure 1 departs from this ideal fractal turbulence because its size scales are too large. It characterizes *macroscopic flows* at large length scales which, somehow, drive the turbulence by transferring their substantial energy to the smaller length scales for which the term "turbulence" applies.

How does this transfer occur? In the nearly 400 $\deg^2$ angular area covered by the Arecibo data of Figure 1, there is no indication whatsoever of interaction between this supersonic filament and the rest of the gas. The accepted picture is that filaments like this are produced by the major sources of energy input—like supernova, stellar winds, and HII regions—which originate with stars. This may or may not be true: supernova shocks begin as moving much faster and we haven't observed any transitionary objects between the highly supersonic supernova shock and the relatively modest-velocity filaments like this. Regardless of the origin, our filament should have a long period of uninhibited, almost frictionless motion because most of the ISM volume is occupied by the highly rarefied $\sim 10^6$ Kelvin HIM, through which the filament is moving subsonically.

At some point the filament must collide with the cooler, denser gas, and that's where the fun begins: the motion is supersonic for the cooler gas and the interaction should be intense. Interstellar space is full of of filaments like this. Owing to the unprecedented sensitivity and angular resolution of existing and, especially, future 21-cm line telescopes, we now overcome the classical limitation of totally inadequate angular resolution in large-area high-sensitivity surveys and can look forward to locating and studying these interactions. They are of fundamental importance because the energy transfer powers interstellar turbulence and defines the upper length scale for which the turbulence concept applies.

3. A MAMMOTH PROTOSTELLAR JET?

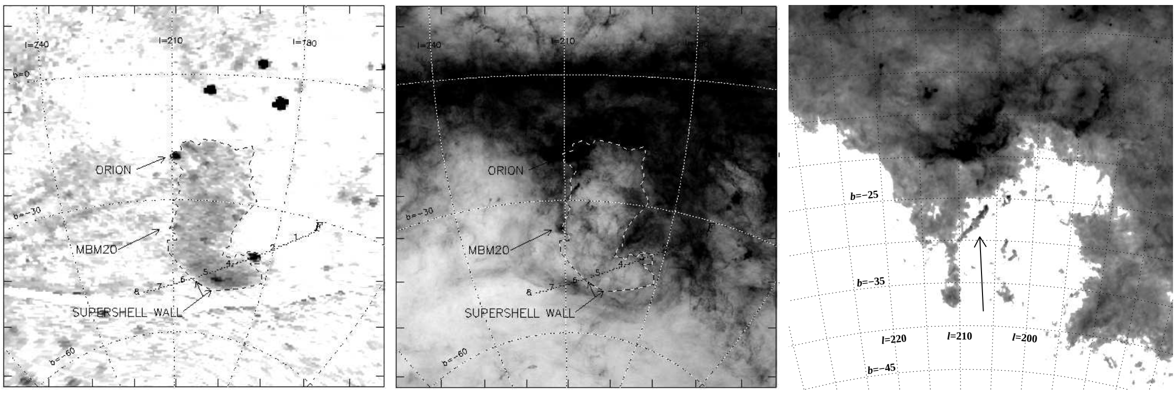

Fig. 2.— Stereographic projections of a $90° \times 90°$ area of sky centered on the Orion/Eridanus superbubble. *Left,* XM band emission from ROSAT. *Center,* heavily-stretched 100 μm IRAS image. *Right,* a severely-stretched HI image at ~ -4 km s^{-1} from LDS; the arrow points to the putative protostellar jet.

Here we describe what seems to be a mammoth protostellar jet. Whatever it is, it is a hitherto unrecognized source of energy for interstellar turbulence; the diffuse ISM's turbulence can be energized by jets, just as molecular clouds are. Figure 2 presents stereographic projections of the Orion/Eridanus superbubble region, a superb showcase for all ISM gas phases (Heiles, Haffner, & Reynolds 1999). It was probably produced by stellar winds and supernovae in the series of Orion star associations. The left panel, which exhibits the 0.75 keV emission (from ROSAT), shows that the central volume of the superbubble is full of very hot gas; the colder, denser gas that formerly occupied this space has been swept into dense shells at the periphery.

The center and right panels of Figure 2 show this swept-up gas as revealed by the IRAS 100

μm maps and the HI image at ~ -4 km s^{-1} from LDS. Near the centers of these images we encounter an intriguing region of jetlike features. We have severely stretched the right-hand image to highlight the most prominent one, marked by the arrowhead; it points roughly toward 1 o'clock with its lower corner at $(\ell, b) = (210°, -30°)$. It is resolved by IRAS and is 6.°2 long and 0.°4 across, an aspect ratio ~ 15. It is easily seen, but underresolved, in the LDS HI survey (resolution 0.6°). At $(\ell, b) = (207.6°, -27.1°)$, it has $N(HI) \approx 2.5 \times 10^{20}$ cm^{-2}, which is less than expected from the peak 100 micron IRAS diffuse emission—meaning that the remainder is H_2 or that the dust-to-gas ratio is unusually high.

The jet's velocity ranges from -2.06 km s^{-1}at the upper right to -5.15 km s^{-1}at the lower left, a change of 3.1 km s^{-1}and a gradient of 0.5 km s^{-1}per degree. If its distance is 500 pc and its length results entirely from its velocity gradient, its age is $23 \tan(i)$ Myr. Given the intense dynamical situation in the region, it is very unlikely that the filament could survive for more than a couple of Myr, which corresponds to $i = 5°$. For $i = 5°$, it is 71 pc long—and the total velocity difference along its full length is 36 km s^{-1}! If this is a protostellar jet, it is *much* larger than any other. If it is not a protostellar jet, then it might be related to the superbubble.

In either case this jet is an amazing and exotic object. Understanding this jet, together with the other smaller ones in its general vicinity, requires images of atomic and molecular gas with angular resolution comparable to IRAS. The fully-completed Allen Telescope Array is ideal for this task—and it will also provide magnetic field measurements using Zeeman splitting.

4. ISOLATED CNM BLOBS or DARK MATTER RESERVOIRS?

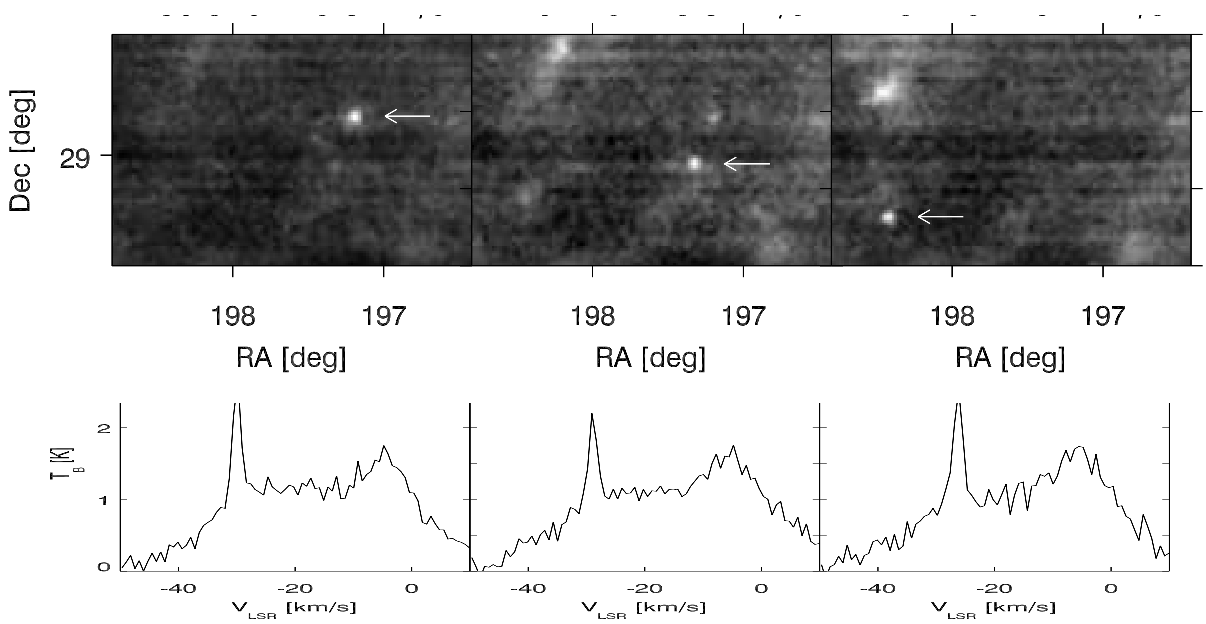

Fig. 3.— Top: Three HI blobs in the same angular field but at different velocities, marked by arrows. Bottom: their spectra.

Figure 3 shows a representative sample of isolated blobs, with images on the top and spectra on the bottom. These unpublished results are from the GALFA survey; without the unprecedented combination of surface-brightness sensitivity and angular resolution, we'd never see them—and indeed, such objects have never before been seen. We see blobs everywhere. Some look like condensations on filaments, which probably result from magneto-cooling instabilities. Some, like these, are disconnected from all other neutral gas. They have small angular diameters and are unresolved, not only with the 3.5 arcmin resolution of Arecibo but also with the 0.5 arcmin resolution of the VLA D configuration.

The lines are narrow, so the gas is cold; being isolated from other cool gas suggests that they are gravitationally bound, which requires stellar-type masses. But the HI masses are tiny, about a Jupiter mass. This situation, with a seemingly invisible confining mass, is reminiscent of the high-latitude, *isolated molecular* blobs of Heithausen (2002, 2006) and Dirsch, Richtler, & Gómez (2005), which lie nowhere near significant interstellar clouds, either atomic or molecular. Both their molecular and our atomic blobs have narrow lines, tiny measurable masses, and large virial masses—a combination that defies current concepts of interstellar matter.

These are truly mysterious objects. The molecular versions have been around for several years, but their existence is not well known or appreciated within the astronomical community. This ignorance belies their possible importance. It's conceivable that they are nothing more than neutral envelopes of cool, obscured stars, but such stars are not cataloged at these positions. An intriguing alternative: they are bound by black holes (Heithausen 2004), a possibility actually predicted (!) by Pfenniger & Combes (1993); their outer skins would be ionized by starlight enough to produce Extreme Scattering Events (Walker & Wardle 1998) and related phenomenae. The original theoretical prediction was oriented towards explaining what dark matter is, and if these blobs are held together by black holes then they are numerous enough to contribute a meaningful faction, but probably not all, of the Galaxy's dark matter.

5. TRACING THE DIFFUSE HALO WITH HIGH-VELOCITY CLOUDS or: HVCs AND THEIR EFFECT ON [the holy grail of] STAR FORMATION

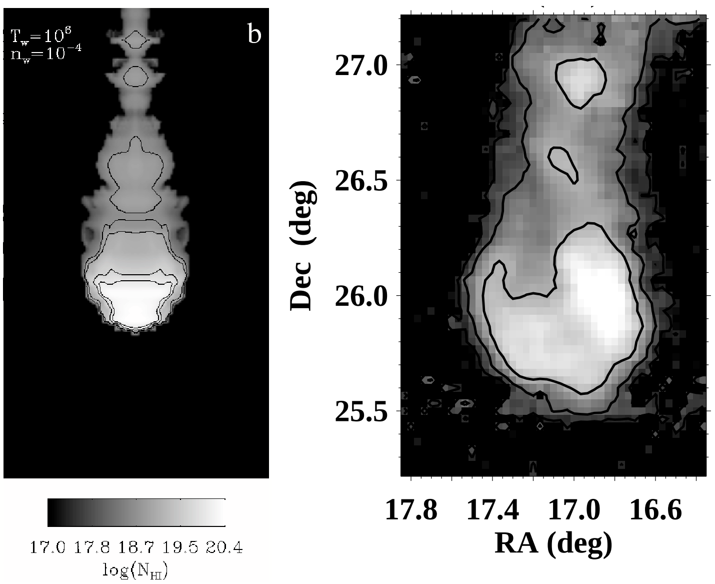

Fig. 4.— *Left:* A *simulated* head-tail cloud moving at 200 km s^{-1} through the diffuse Galactic halo with density 10^{-4} cm^{-3} (Quilis & Moore 2001); contours are $0.5, 1, 5, 10 \times 10^{19}$ cm^{-2}. *Right:* A GALFA-*observed* head-tail cloud; contours $0.3, 1, 3 \times 10^{19}$ cm^{-2}.

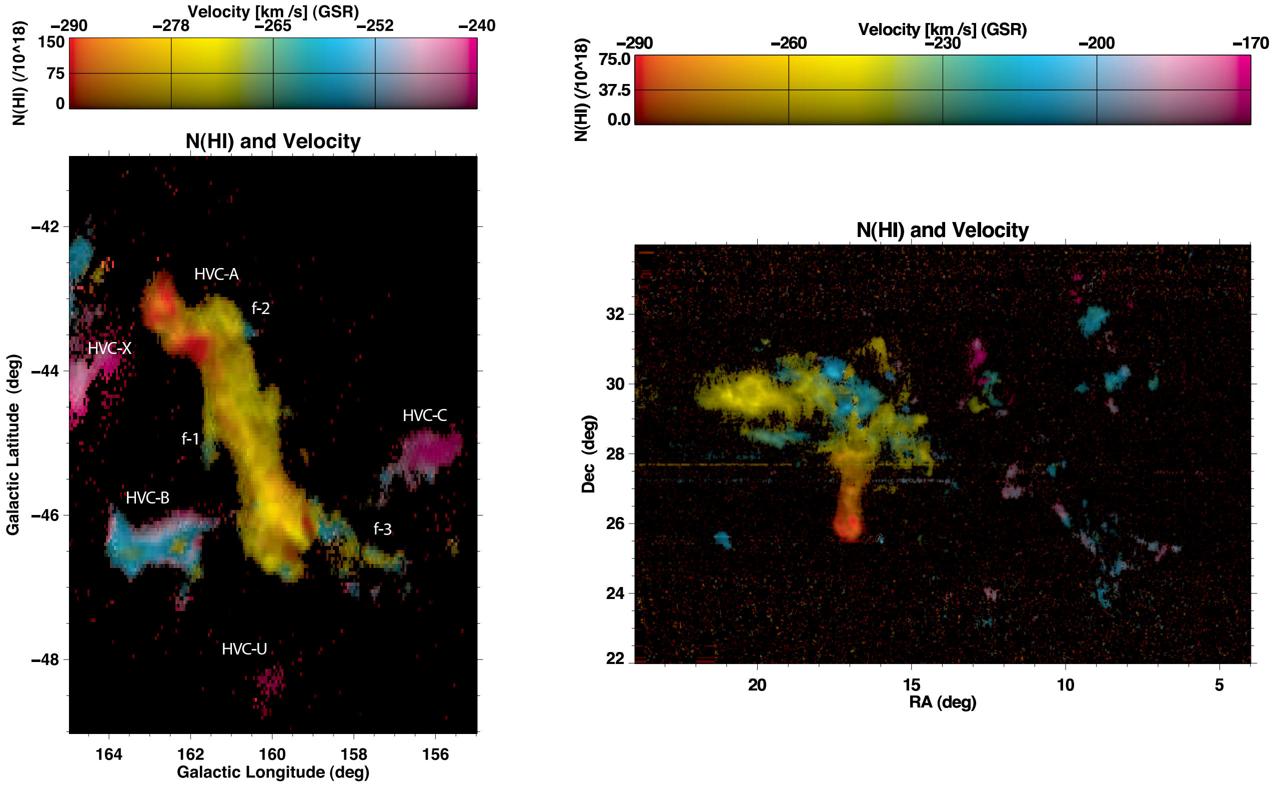

Fig. 5.— *Left:* The HVC and its shards. Color represents central GSR velocity and brightness the total column density. The labelled features were used in the hydrodynamic modelling. *Right:* The HVC showing a clear head-tail velocity difference.

Figure 4 compares theory and observation of a high-velocity cloud falling through the Galactic halo. It's hard to tell the difference! Theory says as halo clouds move through the diffuse halo medium, they form a compressed head and diffuse tail structure (e.g. Quilis & Moore 2001; Gunn & Gott 1972). The morphological details vary according to the speed and density of the cloud, and the density of the halo medium. Theory (e.g. Wolfire et al. 1995) also says that the friction between the infalling cloud and the halo also produces a core-halo structure in *velocity* space—again, just like the observations of some clouds (Figure 5, right panel). Moreover, the numerical simulations reveal stripping effects that result in slower-moving shards and fingers extending off the sides of the cloud.

Observations uniquely show this happening (Figure 5, left panel). A straightforward dynamical model for the drag on the fragments provides quantitative values for the local ambient halo density. Combining this with a hydrostatic halo model, in which density is a well-defined function of z height and Galactic radius, provides a new technique for getting HVC distances (Peek et al. 2007)—which are notoriously hard to measure.

HVC distances are important: they allow accurate estimates of mass inflow rate to the Galaxy, which relates to two key global questions about where the gas for ongoing star formation comes from: (1) at its current profligate rate of making new stars, the ISM is all used up quite rapidly without this source of replenishment; (2) the infalling clouds inject energy into interstellar turbulence, a usually ignored energy source in addition to the standard ones involving stellar winds and supernovae.

6. INSTRUMENTATION: ARECIBO AND THE ALLEN TELESCOPE ARRAY

Everything discussed above is brand new, a result of the revolutionary capability of high surface-brightness sensitivity and angular resolution afforded by the 7-feed ALFA array on the Arecibo telescope. A filled aperture provides this combination if the telescope is big enough; our experience is that the 1000-foot aperture of Arecibo is required. Another approach is aperture synthesis, which provides the necessary angular resolution—but currently there is *not a single instrument* that supplies the requisite surface-brightness sensitivity. While that's the current situation, the future will be different if the Allen Telescope Array (ATA) is built out to its full complement of 350 telescopes.

7. REFERENCES

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