GALFA Science Highlights

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Since the beginning of this year several projects aiming at studying Galactic HI with ALFA have been undertaken or are in progress, a few smaller ones have even been completed. These projects address outstanding and diverse questions in the field of Galactic astronomy, cover regions of varying size, and are slowly building up the 'jigsaw puzzle' of the whole Galactic sky visible from Arecibo, at the angular resolution of $\sim$ 3.4 arcmin. We summarize here several interesting scientific results that are already emerging from these studies.

1 What drives the Forbidden-Velocity Wings?

Large-scale (ℓ,v) diagrams of HI 21-cm line emission in the Galactic plane usually show small high-veloctiy bumps protruding from their surroundings. Since those wing-like features are at forbidden velocities, i.e., at velocities beyond the maximum or minimum values permitted by the Galactic rotation, we call them "Forbidden-velocity wings (FVWs)". Fig. 1 (a) is a (ℓ,v) diagram at $b = 4°$. The wing-like feature at $\ell \sim 39$ and [80 km s$^{-1} \lesssim v_{\rm LSR} \lesssim$ 130 km s^{-1}] and the one at $\ell \sim 83$ and [30 km s$^{-1} \lesssim v_{\rm LSR} \lesssim$ 70 km s^{-1}] in Fig. 1 (a) are the examples of FVWs. We suspect that they are the sites where Galactic dynamical events, for example, supernova explosions, stellar winds, or collisions of high-velocity clouds, which could accelerate their surrounding gas, have occurred. We have searched for the FVWs using the Leiden-Dwingeloo HI survey and the Southern Galactic Plane Survey data, and identified about 90 FVWs in the Galactic plane ($| b | \leq 13°$) (Kang 2004, Kang et al. 2004). We compared this catalog of FVWs with those of supernova remnants, high-velocity coulds, and nearby galaxies, and found that about 85% are not coincident with those known objects. The natures of most FVWs are not known yet.

During last January and Febuarary, for 15 days, we carried out commensal observations using the ALFA receiver covering areas including 3 FVWs in the inner Galaxy. Two of them showed shell-like features. FVW39.0+4.0 (Fig. 1, b) is an $\sim 1°$-sized shell of $v_{\rm exp} \gtrsim\sim$ 55 km s^{-1}. As it goes to higher velocities, it becomes fainter and finally disappears, so that its endcap is not seen. Its systematic velocity seems to be less than 73 km s^{-1}. Its distance from the Sun would be less than 5.0 kpc or greater than 8.3 kpc. If it is located in the Sagittarius-Carina arm, the kinetic energy of the HI shell would be $\sim 1.2 \times 10^{50}$ erg or $\sim 1.0 \times 10^{51}$ erg, depending on whether it is at close ($\sim$ 3.3 kpc) or distant ($\sim$ 9.8 kpc) part of the arm. It doesn't have any known OB type stars inside and could be an old supernova remnant. FVW40.0+0.5 (Fig. 1, c) shows center-filled complex of filamentary structures. Since it shows a roughly circular shape, it could possibly be part of an endcap of a larger shell. FVW44.5−2.0 (Fig. 1, d) shows a single clump-like

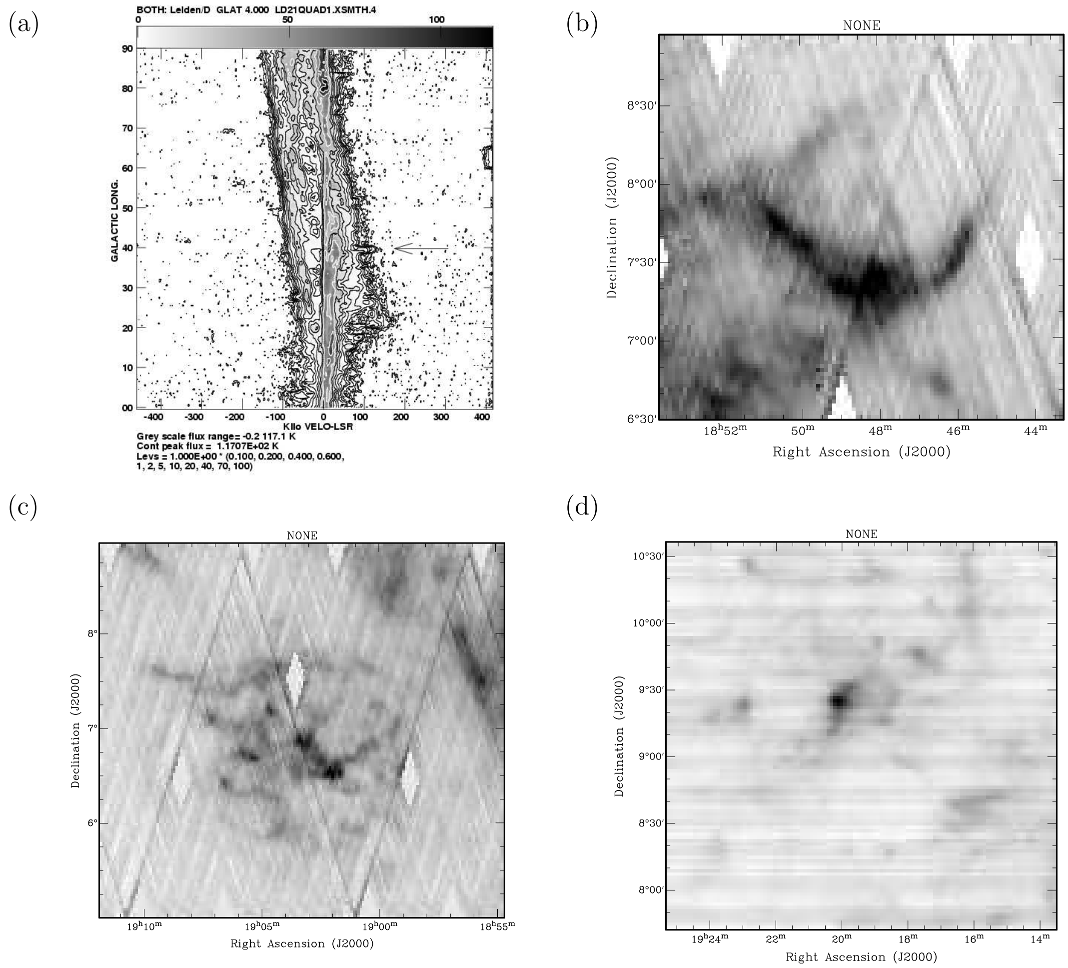

Figure 1: (a) Large-scale (ℓ, b) diagram at $b = +4°$using LD data. Arrow near the center indicates faint extended bump of FVW39.0+4.0. (b) Arecibo image of FVW39.0+4.0 integrated over velocities between $v_{\rm LSR}$ =73 km $s^{-1}$and 130 km s^{-1}. (c) Image of FVW40.0+0.5 integrated from $v_{\rm LSR}$ =−79 km $s^{-1}$to −114 km s^{-1}. (c) Image of FVW44.5−2.0 integrated from $v_{\rm LSR}$ =+90 km $s^{-1}$to +110 km s^{-1}. (Image courtesy: Ji-hyun Kang and Bon-Chul Koo)

structure from 110 km $s^{-1}$to 90 km s^{-1}, and then connects to a complicated filamentary structure at lower velocities. It seems to be similar to the halo cloud of (Lockman 2002) in the sense that it exists near the tangent velocity and shows a clump-like structure. These are only three of 26 FVWs observable at Arecibo. The future ALFA survey of the Galactic plane will reveal the nature of FVWs.

2 Halo HI clouds in the Galactic outback

One of the very first GALFA observations targeted the region of the Galactic Anti-center, which is well know to harbor a wealth of high velocity gas. The most striking feature in these observations is a large number of discrete, small HI clouds located at velocities distinctly separated from that of the bulk of HI gas in the Galactic disk, yet not very anomalous from the velocity range permitted by the Galactic rotation. An example of this phenomenon is shown in Fig. 2 — 3 small HI clouds are easily noticeable in this Galactic longitude–velocity diagram, located at the velocity of about –20 km s^{-1}. The velocity profile shown at the bottom of this figure was obtained through the center of the cloud in the middle, at $l = 187.07°$and $b = 18.00°$. While we are still searching GALFA datasets for a more complete census of similar clouds, their typical properties are: an angular size of 5–10 arcmin, a velocity line-width of about 5 km s^{-1}, and a peak HI column density of 2×10^{19} cm^{-2}. Clearly, some of these clouds are very cold.

Clouds with similar properties have been discovered in the inner Galaxy with the Green Bank Telescope (Lockman 2002), suggesting that most of the mass of the lower Galactic Halo could be in the form of small, discrete HI clouds. It is believed that these clouds are a result of the Galactic Fountain — buoyant outflows from the star forming regions that bring hot gas from the Galactic disk into the Halo. The hot gas eventually starts to cool and condense into small clouds, which then rain back into the disk. ALFA observations, together with the recent observations of several regions in the outer Galaxy obtained with the Effelsberg telescope (Kalberla et al. 2004), show that the clumpy Halo structure may not be restricted only to the inner Galaxy but could be a wide-spread phenomenon. The origin of the Halo clouds in the Galactic outback is harder to understand though. The effects of the Galactic Fountain in the outer Galaxy are expected to be more severe than in the inner Galaxy. Due to a larger rotation velocity clouds are expected to lag back significantly behind the bulk of the disk gas. Yet, we find that they still primarily follow the main disk features. Other mechanisms for the formation of these clouds clearly need to be considered.

3 GALFA Discovers Massive Ultra-high Velocity Cloud

The GALFA consortium has begun mapping and imaging various regions of the Galactic sky. Fortuitously, one of these regions contained an unexpected and un-cataloged high-velocity cloud (HVC). This, though, is no ordinary HVC. With Galactic standard of rest (GSR) velocities approaching –300 km $s^{-1}$and a mass of $\sim 2000\ M_{\odot}(D_k pc)^2$, this is very nearly the fastest HVC ever seen, and dwarfs all other known clouds in this ultra-high velocity range.

Fig. 3 shows the HI column density and the velocity field of this cloud. The morphology is very suggestive of an infalling cloud. The cloud has shredded streamers at reduced velocities pulling off the main body of the cloud, perhaps having been sheared off by interaction with ambient halo gas (i.e. ram pressure stripping). The cloud also has a somewhat 'head-tail' or even cometary shape, suggestive of infall, towards the galactic plane (up, in the plot, Fig. 3).

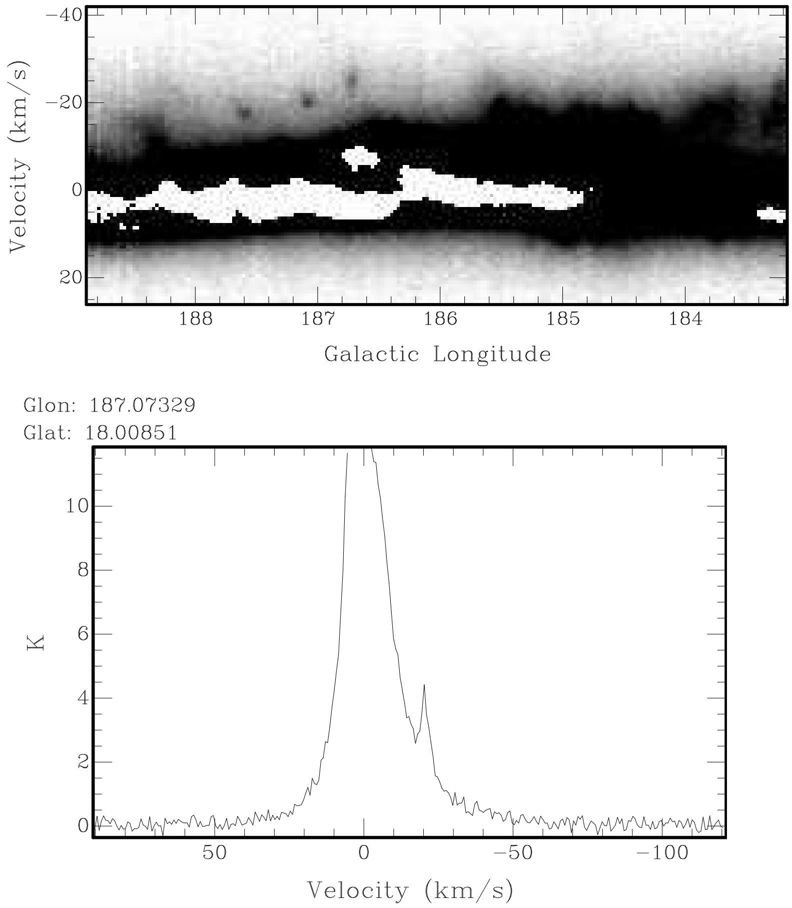

Figure 2: (top) A longitude-velocity diagram at b=18 degrees from the recent GALFA observations. Three small Halo clouds, at l 187 degrees are noticeable with the LSR velocity of about -20 km/sec. All pixels with the brightness temperature higher than 10 K have been masked out to enhance weaker features in the figure. (Bottom) An HI spectrum through the center of the small cloud at l=187 degree and v=-20 km/sec. (Image courtesy: Snezana Stanimirovic and Mary Putman).

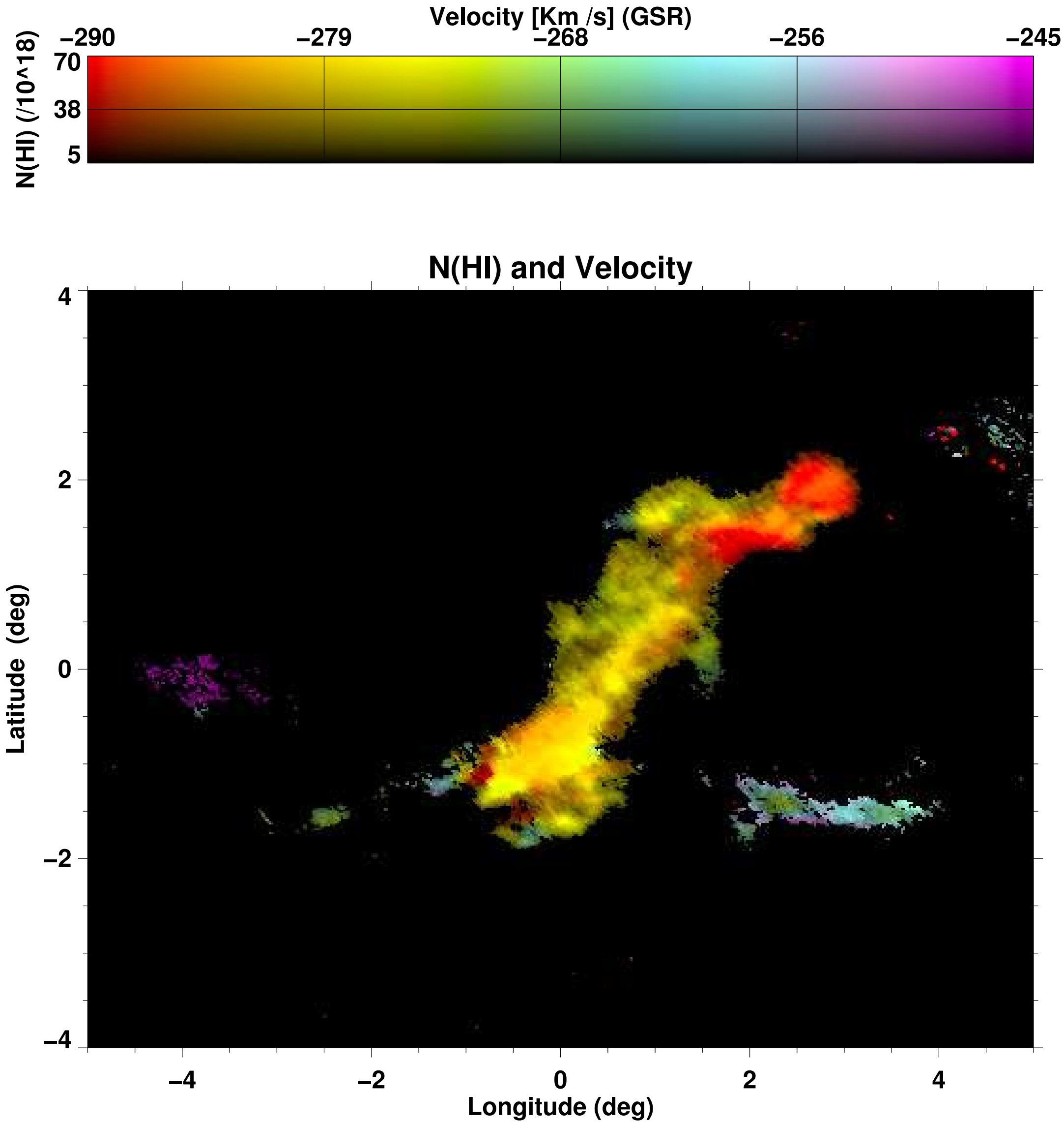

Figure 3: The HI column density distribution and the velocity field of the massive HVC at the extreme negative velocity end of the range 'allowed' for HVCs. (Image courtesy: Josh Goldston and Carl Heiles)

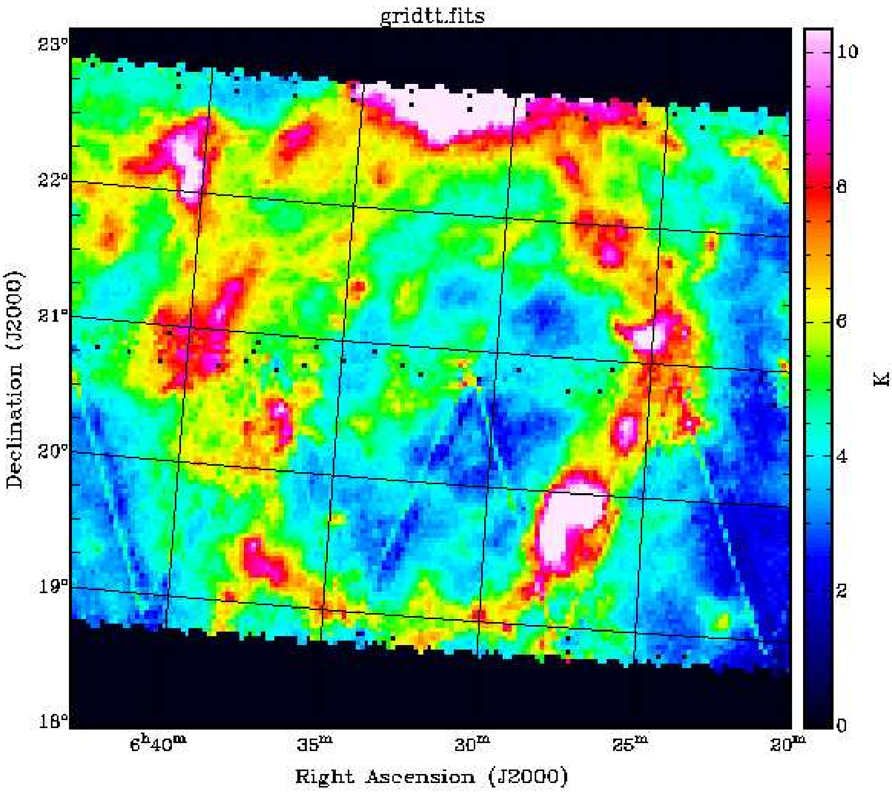

Figure 4: A large shell in the Galactic Anti-center recently mapped with ALFA. (Image courtesy: Kevin Douglas, Eric Korpela)

A cloud with these characteristics puts stiff constraints on models of HVC origin. A compact, low-mass cloud at this velocity could be explained by chance kinetic interactions, but a coherent cloud of this scale requires a robust explanation. Were this cloud to be falling directly onto the plane, it would have an infall velocity of nearly 450 km s^{-1}. Since this number is comparable to the escape speed from the solar neighborhood, any model that proposes to generate HVC velocity by infall, whether it be an accretion model or a fountain model, must contend with a massive body entering the galaxy at free-fall, even as we see it being ablated (and therefore presumably arrested) by ambient gas. It seems that Milky Way gravity alone cannot account for this monster HVC.

4 Large Shell in the Galactic Anti-center

Prior to the installation of ALFA, the SETHI survey, consisting of Arecibo L-band data originally taken for SETI@home, had been scanning the Arecibo sky since 1999. With the SETHI data, Korpela et al. 2004 detected what appears to be a series of interlocking shells in a region close to the Galactic plane, near the anticenter $[(l, b) = (192, 6)]$. This region was recently mapped with ALFA. Fig. 4 shows a huge shell structure, at the velocity of –18 km/sec, having a diameter of almost 4 degrees. These observations were made using a "modified basketweave" technique, because of the region's declination being close to 18

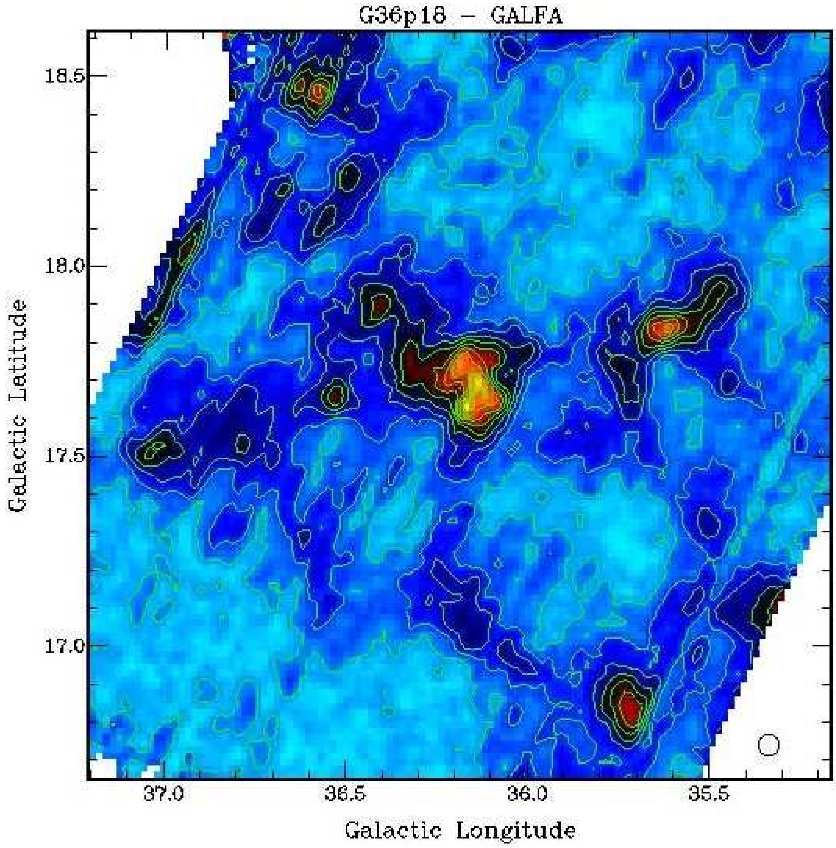

Figure 5: The HI column density image of the Galactic cloud G36.18 obtained with ALFA. (Image courtesy: Erik Muller)

degrees, making transit observations unfavourable. A technique was devised where the region would be scanned at an hour angle of 1 hr, and the azimuth of the Gregorian would be wagged while keeping the zenith angle constant, instead of the usual method which reverses the roles of these angles. Furthermore, test observations prior to the observing run showed that beam rotation occurs during modified basketweave runs, so the region was split into two adjacent strips in an effort to limit beam rotation by covering a smaller declination range.

5 Small-scale HI structure of Galactic clouds

Several Galactic HI clouds, previously observed with the Green Bank Telescope (GBT), have been recently observed with ALFA. Fig. 5 shows an HI image of one of the target clouds. While being unresolved at the GBT's angular resolution of 9 arcmin, with Arecibo's resolution of 3 arcmin the cloud breaks into several HI clumps, which are embedded in a more diffuse emission. A more technical aim of this project is to compare HI images obtained with ALFA with the images obtained with the GBT and and the Very Large Array to study the influence of the ALFA sidelobes on the mapped power distribution. In addition, as

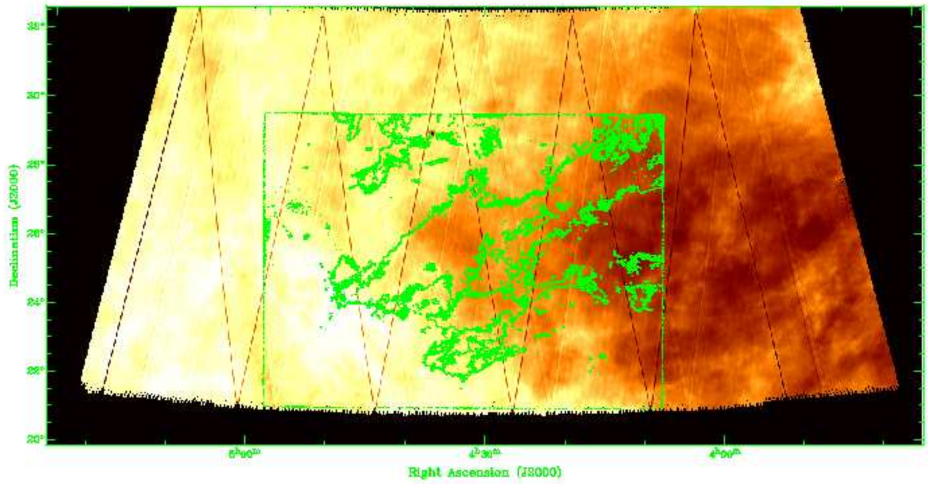

Figure 6: The HI column density image of the Taurus molecular cloud obtained recently with ALFA. (Image courtesy: Marko Krco, Hector Arce and Paul Goldsmith)

this project employs a drift-and-chase mode, it is suceptable to effects resulting from the elongation of the beams on the sky, which would otherwise impose a directional structure bias in all maps of the extended emission. A secondary objective for this project is to investigate the benefits to be gained from artificially defocusing the beam shape, to force it to return to a circular shape and thereby removing any directional biases, albeit at the expense of spatial resolution. This project was one of the very first ones to employ commensal observing capabilities with two independent back-end systems, the GALFA spectrometer and the more traditional WAPP system.

6 How do molecular clouds form?

All stars are formed deep inside molecular clouds. One of the current enigmas lies in the formation and evolution of molecular clouds, specifically the conversion from atomic to molecular gas. Until recently, studies of the relationship between the atomic and molecular gas were limited to observations of individual small clouds. The enhanced capabilities of ALFA currently allows the observation of the neutral hydrogen in and surrounding large molecular clouds spanning several hundreds of square degrees on the sky. In July of 2005 GALFA mapped about 300 square degrees of the Taurus Molecular Cloud (TMC) complex yielding the largest high-resolution 21cm map of a star forming region, while using less than 40 hours of observing time. This map provides clues that will allow us to tackle long standing questions in star formation theory.

Figure 6 shows an integrated intensity HI map of our region over a velocity range of 0 - 10 km s^{-1}. The overlaid contours represent the borders of significant 13CO emmission obtained from a recent FCRAO map. The HI Narrow Self-Absorption (HINSA) feature allows us to measure the HI content of individual dense clumps in the cloud, and, in combination with molecular line data, allows us to determine the chemical ages of the clumps. Most of the dark regions in the map which correspond with significant CO emmision exhibit HINSA features. This will yield significant insight into the formation mechanisms of the TMC and similar star forming regions. Studying the warm, externally heated, HI in the molecular cloud halo will allow us to better understand the physical and chemical conditions of the transition region between the neutral and molecular gas. A cursory look at the HI distribution in this region immediately shows us a wide variety of environments ranging from diffuse gas, and pre-stellar dark clouds, to newly formed stars. This shows us that the different portions of the TMC complex are in various stages of evolution. In short, we now have our first complete high-resolution, high-sensitivy head-to-toe guide to star formation in a giant molecular cloud complex.

References

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