Column Density Maps of the I-GALFA H I Survey: Evidence for Dark Gas?

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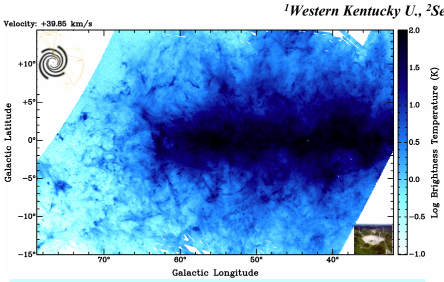


Figure 1. Neutral atomic hydrogen (H I) gas 21cm line emission from interstellar clouds, knots, and filaments extending up to 500 parsecs above and below the Galactic plane (I-GALFA; Gibson et al. 2012). Many features are cold and may contain dark gas -- either narrow-line, opaque H I emission or molecular hydrogen (H_2) gas without visible carbon monoxide (^{12}CO) 2.6mm emission. Top left: plan-view schematic map of Arecibo Galactic plane coverage; I-GALFA is in the 1st quadrant, to lower right of center.

Overview

Gas in galactic disks, including our own, occurs in a wide range of temperatures and densities, most of which are unsuitable for star formation. Somehow, diffuse atomic clouds are collected into colder, denser molecular clouds that can collapse under their own gravity. Molecular condensation is not directly observable, and the gas itself is often "dark" to standard probes like optically thin H I 21cm emission or the ^{12}CO 2.6mm line. However, the presence of dark gas can be inferred from infrared dust emission in excess of what is expected for the observed H I and CO content. We have mapped apparent H I column densities in the Inner-Galaxy Arecibo L-band Feed Array (I-GALFA) survey, which covers a 1600 deg^2 region at 4-arcminute resolution in the first Galactic quadrant. We compare these "naïve" H I columns to others derived from *Planck* first-release CO and dust maps and NE2001 model dispersion measures to identify a number of areas with potentially significant dark gas. We discuss whether optically thick H I or CO-free H_2 is more likely to dominate the dark column, and we consider the effects of possible biases on our results.

Figure 2. H-atom column density maps. *Top to bottom, left column:* H II from the NE2001 model (Cordes & Lazio 2002), I-GALFA H I for optically thin emission; H I with Strasser & Taylor (2004) correction; H_2 from *Planck* DR-1 CO for $2X_{CO} = 3.6\text{x}10^{20}$ (Dame et al. 2001); H II + H I and H II + H I + $2H_2$ sums for thin and corrected H I. *Center:* Total gas from *Planck* DR-1.1 $E_{B\text{-}V}$ and $X_{EBV} = 5.8\text{x}10^{21}$ (Bohlin et al. 1978); gas/dust column ratios and gas-dust column differences for thin and corrected H I; inferred dark columns for total gas, H I only, and H_2 only. *Right:* Same using *Planck* DR-1.2 $E_{B\text{-}V}$.

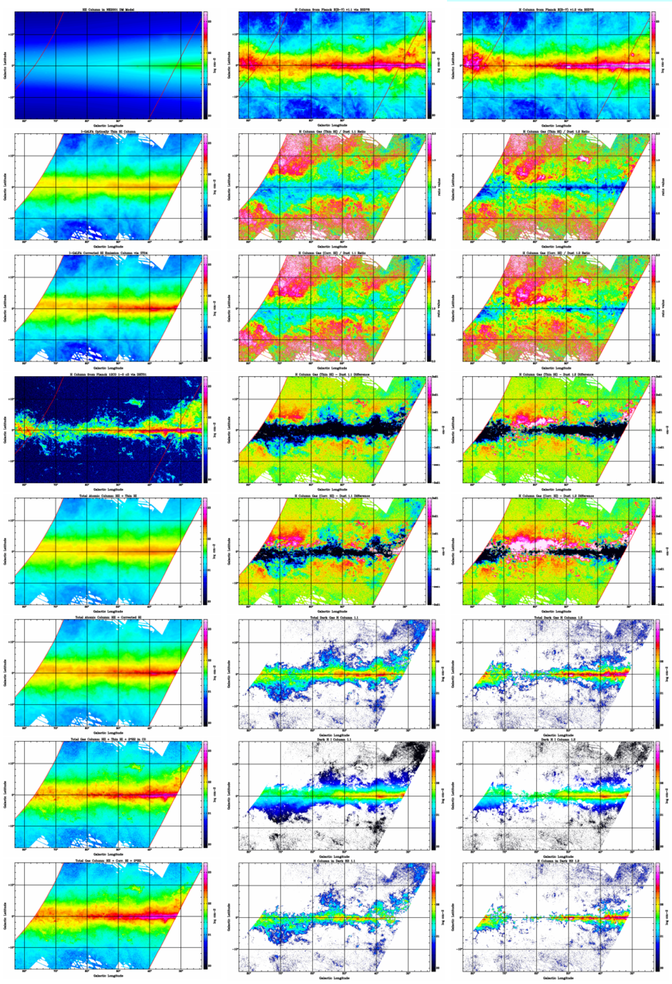
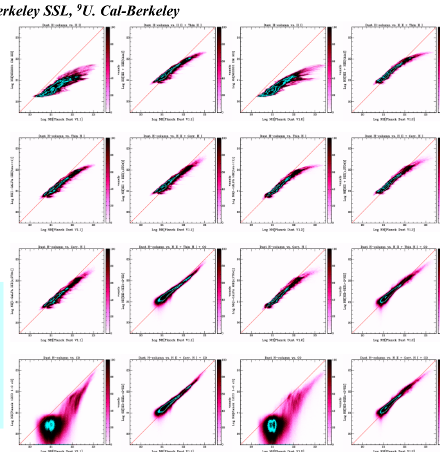


Figure 3. Scatter density plots of gas column tracers vs. total column from *Planck* $E_{B\text{-}V}$, with contours at 3 and 9 times the maximum plotted density.



Results, Caveats, and Future Work

- If standard conversion factors are used with the NE2001 H II, I-GALFA optically thin H I, and *Planck* CO and $E_{B\text{-}V}$ data, up to 50% of the total column in some regions near the Galactic plane is implied to be dark gas.
- The Strasser & Taylor (2004) correction is only statistical but reduces the dust-gas discrepancy near the plane significantly, so much of the dark column is probably optically thick H I, but the implied dark H I and H_2 components vary considerably with position. Although dark H I appears spatially smoother than the dark H_2, it is scaled off the relatively smooth integrated H I emission, and the actual dark H I may be more structured. The NE2001 model has little small-scale structure but is consistent with only a negligible dark H II column.
- The total column vs. position implied by the dust varies significantly between the *Planck* data releases 1.1 and 1.2 (March and December 2013), so individual dark gas features shown here should be treated with caution and reevaluated for future data releases. However, both available versions show more dark gas at lower Galactic longitudes, consistent with prior, lower-resolution results further from the plane (Fig. 4).
- Many positions show "excess" gas, implying the dust column is underestimated. The *Planck* dust columns are fitted to the dust thermal emission spectral energy distribution (SED) assuming a single temperature population, but if other temperatures are present, the SED fit can underestimate the dust optical depth, e.g., with a small warm grain component (Fig. 5), or with cold grains shielded deep within H_2 clouds (Wagle et al. 2014).
- We are experimenting with least-squares fits of the column difference between gas and dust tracers to see if the standard column conversion parameter values are the best choice (e.g., see Liszt 2014). But these may further underestimate the dark component, since it is not constrained unless conversion values are assumed.

Figure 4. All-sky dark gas maps for comparison from *Planck* infrared excess (top; Planck collaboration 2011), *COBE* infrared excess, and *EGRET* γ-ray excess (middle, bottom; Grenier et al. 2005).

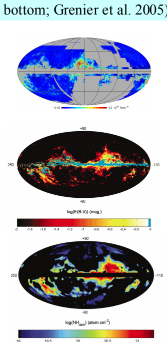
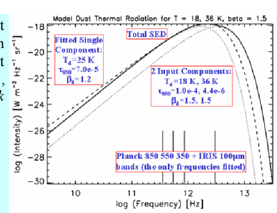


Figure 5. Example of isothermal fit to dust model with 2 temperature components, which results in an underestimate of the total dust column if the fit is only constrained at 850, 550, 350, and 100 μm, as is done for *Planck* (see Planck collaboration 2013).

Isothermal case: $I_\nu = \tau_\nu B_\nu(T_d)$, where $\tau_\nu = \tau_{\nu_0} (\nu/\nu_0)^{\beta_d}$

General case: $I_\nu = \sum_i^N I_{i,\nu} = \sum_i^N \tau_{0,i} (\nu/\nu_0)^{\beta_{d,i}} B_\nu(T_{d,i})$



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