H$_1$, CO, AND PLANCK/IRAS DUST PROPERTIES IN THE HIGH LATITUDE CLOUD COMPLEX, MBM 53, 54, 55 AND HLCG 92–35. POSSIBLE EVIDENCE FOR AN OPTICALLY THICK H$_1$ ENVELOPE AROUND THE CO CLOUDS

Yasuhiro Fukui$^{1}$, Ryuji Okamoto$^{1}$, Ryoei Kaji$^{1}$, Hiroaki Yamamoto$^{1}$, Kazufumi Torii$^{1}$, Takahiro Hayakawa$^{1}$, Kengo Tachihara$^{1}$, John M. Dickey$^{2}$, Takeshi Okuda$^{1,3}$, Akio Ohama$^{1}$, Yutaka Kuroda$^{1}$, and Toshihisa Kuwahara$^{1}$

$^{1}$ Department of Physics, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan; fukui@ap.nagoya-u.ac.jp
$^{2}$ University of Tasmania, School of Maths and Physics, Private Bag 37, Hobart, TAS 7001, Australia
$^{3}$ National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

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ABSTRACT

We present an analysis of the H$_1$ and CO gas in conjunction with the Planck/IRAS submillimeter/far-infrared dust properties toward the most outstanding high latitude clouds MBM 53, 54, 55 and HLCG 92–35 at $b = -30^\circ$ to $-45^\circ$. The CO emission, dust opacity at 353 GHz ($\tau_{353}$), and dust temperature ($T_d$) show generally good spatial correspondence. On the other hand, the correspondence between the H$_1$ emission and the dust properties is less clear than in CO. The integrated H$_1$ intensity $W_{HI}$ and $\tau_{353}$ show a large scatter with a correlation coefficient of $\sim 0.6$ for a $T_d$ range from 16 K to 22 K. We find, however, that $W_{HI}$ and $\tau_{353}$ show better correlation for smaller ranges of $T_d$ every 0.5 K, generally with a correlation coefficient of 0.7–0.9. We set up a hypothesis that the H$_1$ gas associated with the high $T_d$ $\geq 21.5$ K is optically thin, whereas the H$_1$ emission is generally optically thick for $T_d$ lower than 21.5 K. We have determined a relationship for the optically thin H$_1$ gas between atomic hydrogen column density and $\tau_{353}$, $N_{HI}(\text{cm}^{-2}) = (1.5 \times 10^{20}) \cdot \tau_{353}$, under the assumption that the dust properties are uniform and we have applied this to estimate $N_{HI}$ from $\tau_{353}$ for the whole cloud. $N_{HI}$ was then used to solve for $T_d$ and $\tau_{HI}$ over the region. The result shows that the H$_1$ is dominated by optically thick gas having a low spin temperature of 20–40 K and a density of 40–160 cm$^{-3}$. The H$_1$ envelope properties derived by this method do not rule out a mixture of H$_1$ and H$_2$ in the dark gas, but we present indirect evidence that most of the gas mass is in the atomic state.

Key words: ISM: clouds – ISM: individual objects (MBM 53, 54, 55 and HLCG 92-35) – radio lines: ISM

Online-only material: color figures

1. INTRODUCTION

The neutral interstellar medium (ISM) consists of H$_1$, H$_2$, and possibly “dark gas,” which is believed to be undetectable in line emission of H$_1$ or CO (Grenier et al. 2005; Planck Collaboration et al. 2011b). The H$_1$ emission at a 21 cm wavelength and the CO emission at 2.6 mm offer tools for probing atomic and molecular hydrogen. The CO clouds have a low kinetic temperature of 10–100 K with a density above 1000 cm$^{-3}$ as derived by analyses of multi-J CO transitions (e.g., Castets et al. 1990). The CO intensity is converted into molecular column density by an $X_{CO}$ factor, which is empirically determined by assuming dynamical equilibrium of the CO clouds, dust properties measured in extinction and/or far-infrared emission, and comparison with gamma rays created by proton–proton collisions via neutral pion decay (e.g., Blitz et al. 2007; Fukui & Kawamura 2010; Bolatto et al. 2013). On the other hand, the physical parameters of the H$_1$ gas have been rather ambiguous, mainly because the H$_1$ emission has a single observed quantity, intensity as a function of velocity, for two independent variables, spin temperature $T_d$ and H$_1$ optical depth $\tau_{HI}$, which does not allow us to determine each of these observationally. The H$_1$ consists of warm and cold components (for a review see Kalberla & Kerp 2009; Dickey & Lockman 1990). The mass of the H$_1$ gas having a spin temperature higher than $\sim 100$ K is measurable at reasonably high accuracy under an optically thin approximation, while the cold component, having a spin temperature of 20–80 K is measured by comparing the absorption and emission H$_1$ profiles only where background continuum sources are available (Dickey et al. 2003; Heiles & Troland 2003). It is notable that some recent works on TeV gamma-ray supernova remnants show that the cold H$_1$ gas which is not detectable in CO at a $1\sigma$ integrated intensity level of $\sim 1$ K km s$^{-1}$ (Fukui et al. 2012) is responsible for the gamma-rays via collision between cosmic-ray protons and interstellar protons (Fukui et al. 2012; Fukui 2013; Fukuda et al. 2014). However, the observed sample of cold H$_1$ is limited and further efforts are still needed to better constrain the physical properties of cold H$_1$.

Recent progress in measuring the infrared and submillimeter emission over the whole sky has been remarkable. These observations are strongly motivated by the aim to precisely measure the cosmic microwave background (CMB) radiation and its polarization. In particular, the Planck collaboration released a whole sky distribution of dust temperature $T_d$ and dust opacity $\tau_{353}$ at 5 arcmin resolution which was achieved through sensitive measurements of the dust emission above 100 GHz in the Galactic foreground. Five papers by the Planck collaboration presented comparisons between CO and dust emission (Planck Collaboration et al. 2011b, 2011c, 2011d, 2011e, 2011f). These studies derived basic physical relationships between neutral gas and dust emission and concluded that dark gas (Grenier et al. 2005) occupies 15% of the ISM, where the H$_1$ emission is assumed to be optically thin. Similar studies on 21 cm H$_1$ emission include Lee et al. (2012) and Planck Collaboration et al. (2011a).

The high latitude molecular clouds MBM 53, 54, 55 and HLCG 92–35 are one of the largest cloud systems in the sky at a Galactic latitude of $-30^\circ$ to $-45^\circ$ with only minor
background components (Magnani et al. 1985). The distance of the cloud system is determined to be 150 pc (Welty et al. 1989). Yamamoto et al. (2003) used the NANTEN 4 m telescope to observe $J = 1$–0 transitions of $^{12}$CO, $^{13}$CO, and C$^{18}$O and mapped the molecular distribution. The velocity of the MBM 53, 54, 55 and HLCG 92–35 clouds is mainly in the range from $-11$ km s$^{-1}$ to $0$ km s$^{-1}$ for CO. The half-power beam widths were 2.6–2.7 arcmin and their grid spacings were 4 or 8 arcmin for $^{12}$CO and 2 arcmin for $^{13}$CO and C$^{18}$O. They also identified associated H$_{2}$ gas at 36 arcmin resolution and discussed that the H$_{2}$ gas is being converted into H$_{2}$ under the dynamical effect of a nearby shell driven by stellar winds. Gir et al. (1994) studied and identified the associated H$_{1}$, while their coverage was limited to $\sim 1/2$ of the area studied by Yamamoto et al. (2003). For reference, this region is rich in high latitude clouds including a far-infrared looplike structure in Pegasus; Yamamoto et al. (2006) observed this loop in CO ($J = 1$–0) lines. MBM 53, 54, 55 and HLCG 92–35 clouds show no sign of active star formation and are an ideal target for studying detailed ISM properties under the general interstellar radiation field (ISRF). The regions of the MBM 53, 54, 55 and HLCG 92–35 clouds and the Pegasus loop have also been used to test CO component separation in analysis of the CMB emission (Ichiki et al. 2014).

In order to better understand the detailed physical properties of the local ISM, we have undertaken new CO ($J = 1$–0) observations of MBM 53, 54, 55 and HLCG 92–35 with the on-the-fly (OTF) mode of the 2.6 arcmin beam of the NANTEN2 4 m telescope as part of the NANTEN Super CO survey (=NASCO), which is aiming to cover 70% of the sky. By using the H$_{1}$ data set at 4 arcmin resolution from the GALFA archive data, we have compared the CO and H$_{1}$ with the Planck/IRAS dust properties. In this paper, we present the first results from this detailed comparison. Section 2 describes the observations, Section 3 gives the results and analysis, and Section 4 presents conclusions. Another paper, which deals with dust emission covering the whole sky, will be published separately (Fukui et al. 2014) and is complementary to the present paper.

2. OBSERVATIONAL DATASETS

In this study, we used NANTEN2 CO data, GALFA H$_{1}$ data, the dust emission data measured by Planck/IRAS, and the 1.4 GHz radio continuum data. All the data are gridded to 1 arcmin, smaller than the angular resolutions of these data sets.

2.1. CO Data

$^{12}$CO ($J = 1$–0) and $^{13}$CO ($J = 1$–0) emissions were obtained by the NANTEN2 4 m millimeter/submillimeter telescope of Nagoya University, which is installed at an altitude of 4865 m in northern Chile. Observations of the $^{12}$CO ($J = 1$–0) and $^{13}$CO ($J = 1$–0) lines were simultaneously conducted in several sessions from 2011 November to 2013 January and cover about 75 deg$^{2}$. Only observational parameters of $^{12}$CO ($J = 1$–0) are described below. The front end was a 4 K cooled Nb Superconductor–Insulator–Superconductor (SIS) mixer receiver and the double-sideband system temperature was $\sim 200$ K including the atmosphere toward the zenith. The spectrometer was a digital Fourier transform spectrometer with 16,384 channels, providing a velocity resolution of $0.2$ km s$^{-1}$. All observations were conducted using an OTF mapping technique with a 2.6 arcmin main beam at a 1 arcmin data sampling. Each spatial area of $1^\circ \times 1^\circ$ was mapped several times in different scanning directions to reduce scanning effects using a basket-weave technique (Emerson & Graeve 1988). These OTF data were reduced into FITS data cubes with the original IDL software. The rms noise fluctuations in $^{12}$CO ($J = 1$–0) spectra after the basket-weave technique was applied were $\sim 1.2$ K per channel in the main beam temperature, $T_{mb}$. The CO data are smoothed to a 5 arcmin spatial resolution in order to be compared with the H$_{1}$ and Planck/IRAS data sets. The final rms noise fluctuations are $\sim 0.6$ K per channel in a 5 arcmin smoothed beam. The pointing was checked regularly using planets and the applied corrections were always smaller than 20 arcsec. The standard sources M17 SW and Ori KL were observed for intensity calibration. The CO intensity is integrated over a velocity range of $-12$ km s$^{-1}$ to $+2$ km s$^{-1}$.

2.2. H$_{1}$ Data

Archival data sets of the GALFA-H$_{1}$ survey are used (Peek et al. 2011). The survey was conducted on the Arecibo Observatory 305 m telescope and the angular resolution of the data is 4 arcmin. The rms noise fluctuations of the H$_{1}$ data are $\sim 0.25$ K per channel in $T_{mb}$. The H$_{1}$ data are also smoothed to a 5 arcmin resolution, and the rms noise fluctuations of the final H$_{1}$ spectra are 0.2 K per channel for the 5 arcmin beam. The H$_{1}$ intensity is spread over a velocity range from $-49$ km s$^{-1}$ to $+17$ km s$^{-1}$, while most of the H$_{1}$ emission is between $-25$ km s$^{-1}$ and $+12$ km s$^{-1}$.

2.3. Planck/IRAS Data

Archival data sets of the optical depth at 353 GHz ($\tau_{353}$) and dust temperature ($T_{d}$) were obtained by fitting 353, 545, and 857 GHz data of the first 15 months observed by the Planck satellite and 100 micron data measured by the IRAS satellite. Both sets of data have angular resolutions of 5 arcmin. For details, see the Planck Legacy Archive (PLA) explanatory supplement (Planck Collaboration 2013).

2.4. Radio Continuum Data

For the 1.4 GHz radio continuum background, we use the CHIPASS data (Calabretta et al. 2014) for the region at $\delta (J2000) < 25^\circ$ and the data described in Reich (1982) and Reich & Reich (1986) for the region at $\delta (J2000) \geq 25^\circ$. Their spatial resolutions are 14.4 arcmin and 35 arcmin, respectively. Although these data have lower angular resolutions than the others analyzed in the study, the peak radiation temperature of the continuum data shows small variations from $\sim 3.4$ K to $\sim 4.9$ K except for the area within $\sim 30$ arcmin of the quasar 3C 454.3, which happens to be located near the CO clouds (e.g., Abdo et al. 2011). We used these lower resolution data by excluding the area around 3C 454.3.

2.5. Masking

In the present analysis, the local ISM toward the cloud system is approximated by a single layer. This is consistent with the velocity of the H$_{1}$ being peaked at around 0 km s$^{-1}$, and generally a single velocity component is dominant. In order to eliminate possible sources of contamination, we further applied the following masking. These masked areas are listed in Table 1 (see also Figure 7).

1. The areas showing CO emission higher than 1.1 K km s$^{-1}$ ($\sigma$) are masked in order to exclude the contribution of the CO-emitting molecular gas.
2. The two regions where there is a secondary H i peak outside the velocity range from \(-25 \text{ km s}^{-1}\) to \(+12 \text{ km s}^{-1}\) are masked at \((\ell, b) \approx (81.5, -33.0), (85.6, -33.8)\). Generally, these secondary peaks show an intensity comparable to that of the main H i peak.

3. Regions with high \(T_d\) indicating localized heating by stars, etc., are masked by referring to the IRAS point source catalog, etc. The most extended region of such high \(T_d\) is located toward 3C 454.3, although the origin of the high \(T_d\) is not known.

4. The six regions where the H i data are missing are masked.

### Table 1

| Position | Area | Object Name | Remark |
|---------|------|-------------|--------|
| \(\ell\) (deg) | \(b\) (deg) | (deg\(^2\)) | |
| 79.1 | -41.8 | 1.1 | ... | a |
| 81.5 | -29.3 | 6.5 | ... | a |
| 81.5 | -33.0 | 6.0 | ... | a |
| 85.6 | -33.8 | 6.4 | ... | b |
| 86.1 | -38.2 | 13.1 | 3C 454.3 | c |
| 92.2 | -38.9 | 0.3 | ... | a |
| 98.3 | -35.1 | 1.0 | ... | a |
| 99.1 | -41.6 | 13.1 | ... | a |
| 99.4 | -30.1 | 0.7 | ... | a |

80.58 | -32.47 | 8.5 x 10^{-2} | IRAS 22221+1748 | Infrared source |
82.42 | -30.16 | 8.5 x 10^{-2} | 33 Peg | Double or multiple star |
83.37 | -32.25 | 8.6 x 10^{-2} | Mrk 306 | Galaxy |
83.46 | -32.39 | 8.6 x 10^{-2} | HD 213618 | Star |
84.67 | -32.34 | 8.7 x 10^{-2} | HD 214128 | Star |
84.73 | -32.31 | 8.7 x 10^{-2} | NGC 7316 | Galaxy |
86.05 | -33.18 | 8.6 x 10^{-2} | Mrk 308 | Seyfert galaxy |
86.09 | -33.57 | 8.6 x 10^{-2} | BD+19 4992 | Star |
87.46 | -29.73 | 8.6 x 10^{-2} | NGC 7339 | Radio galaxy |
93.53 | -40.35 | 8.7 x 10^{-2} | RAFGL 3068 | Variable star |
93.91 | -40.47 | 8.7 x 10^{-2} | NGC 7625 | Interacting galaxies |
97.29 | -32.52 | 8.6 x 10^{-2} | IC 5298 | Seyfert 2 galaxy |
98.88 | -36.55 | 8.6 x 10^{-2} | NGC 7678 | Active galaxy nucleus |
99.24 | -35.40 | 8.6 x 10^{-2} | NGC 7673 | Emission-line galaxy |
99.32 | -35.49 | 8.6 x 10^{-2} | NGC 7677 | Galaxy in pair of galaxies |

Notes. Columns 1 and 2 give the positions of each mask and Column 3 gives their areas. Column 4 indicates object names located at the center of each mask. Remarks on each masked area are listed in Column 5. Details on these masked areas are described in Section 2.5.

* The H i data is missing.
* There are secondary H i peaks outside the velocity range from \(-25 \text{ km s}^{-1}\) to \(+12 \text{ km s}^{-1}\).
* Abdo et al. (2011).
* While this object is not listed in the IRAS point source catalog, \(T_d\) is locally high around this object.

### 3. RESULTS

Figure 1 shows four panels that present CO, H i, and Planck/IRAS dust properties. Figure 1(a) shows the CO \((J = 1–0)\) velocity integrated intensity distribution, \(W_{\text{CO}}\) (K km s\(^{-1}\)). Figure 1(b) shows an overlay of H i and CO where we confirm the associated H i in previous works (Gir et al. 1994; Yamamoto et al. 2003). \(W_{\text{HI}}\) (K km s\(^{-1}\)) is the intensity of H i integrated from \(-49 \text{ km s}^{-1}\) to \(+17 \text{ km s}^{-1}\). Figure 1(c) presents an overlay of \(\tau_{353}\) and CO. The comparison shows good correspondence between them within the CO contours, whereas the correspondence of H i with \(\tau_{353}\) seems less clear than in the case of CO.

We note that \(\tau_{353}\) is significantly extended beyond the lowest CO contour 3.4 K km s\(^{-1}\) (3σ). Figure 1(d) shows an overlay of \(T_d\) and CO. The lowest \(T_d\) ~ 16 K is clearly associated with CO, and \(T_d\) increases up to \(\sim 22\) K outside the CO clouds.

Figure 2(a), where masking in Section 2.5 is applied, shows an average H i spectrum over the region in Figure 1, and Figure 2(b) shows the H i integrated intensity over the same longitude range where \(^{12}\text{CO}\) \((J = 1–0)\) intensity is superposed by black contours. Figure 2(a) indicates that most of the H i emission is in the range from \(-25 \text{ km s}^{-1}\) to \(+12 \text{ km s}^{-1}\), which is determined by the 10% level of the average H i spectrum, and the H i emission from \(-25 \text{ km s}^{-1}\) to \(+12 \text{ km s}^{-1}\) has a single component, which includes 89% of the H i integrated intensity.

The remaining 11% of the H i emission is mainly on the negative velocity side at \(V_{\text{LSR}} < -25 \text{ km s}^{-1}\). In order to eliminate possible contamination of the H i at \(V_{\text{LSR}} < -25 \text{ km s}^{-1}\) we shall adopt the H i velocity range from \(-25 \text{ km s}^{-1}\) to \(+12 \text{ km s}^{-1}\) in the following analysis and call this the main H i cloud. This velocity range includes the H i which has been suggested to be associated with the CO clouds (Gir et al. 1994; Yamamoto et al. 2003) and more details are given in Appendix A on the H i velocity channel distributions (Figure 10).

In the following, \(\tau_{353}\) and \(W_{\text{HI}}\) denote those quantities for the whole velocity range and \(\tau_{353}\) and \(W_{\text{HI}}\) for the main H i cloud only. The excluded velocity ranges from the main H i cloud have very weak H i intensity of \(\lesssim 30 \text{ K km s}^{-1}\) (Figure 2(b)) and it is likely that this H i is optically thin. \(W_{\text{HI}}\) is calculated from \(W_{\text{HI}}\) by subtracting the H i integrated intensity at \(V_{\text{LSR}} < -25 \text{ km s}^{-1}\) and \(V_{\text{LSR}} > +12 \text{ km s}^{-1}\). By adopting the relationship between \(\tau_{353}\) and \(W_{\text{HI}}\) in the optically thin limit (see below), \(\tau_{353}\) is calculated from \(\tau_{353}\) by subtracting a fraction of \(\tau_{353}\) in proportion to \((W_{\text{HI}} - W_{\text{HI}}\text{main})/W_{\text{HI}}\), which corrects for the emission due to the velocity range excluded from H i main. The details of the subtraction are given in Appendix B.

Figures 3(a) and 4(a) show scatter plots between \(W_{\text{HI}}\) and \(\tau_{353}\) for the main H i cloud and for the whole H i velocity span, respectively, in the region with masking (Section 2.5.). We note that Figures 3 and 4 show the same trend, as described below, indicating that the subtraction has a minor effect on the results as expected from the weakness of the subtracted H i intensity. The scattering is fairly large with correlation coefficients of \(\sim 0.6\) in both plots (Figures 3(a) and 4(a)). Since \(W_{\text{HI}}\) is supposed to be a good measure of the total H i in the optically thin approximation, \(\tau_{353}\) should be highly correlated with \(W_{\text{HI}}\) if the H i is optically thin and if gas and dust are well mixed with uniform properties. The large scatter suggests that the dust properties may vary significantly and/or that the optically thin approximation for the H i gas may not be valid.

In Figures 3(b), (c), 4(b), and (c), we indicate \(T_d\) for every 0.5 K interval at each point in Figures 3(a) and 4(a). We made least-squares fits between \(W_{\text{HI}}\) (main) and \(\tau_{353}\) (main) by linear regression for each \(T_d\) range. Since the number of data points becomes less for the highest \(T_d\), the fitting accuracy becomes worse for higher \(T_d\). In particular, for \(T_d > 21.5\) K, the number of points becomes much less than for the others; here we assume that the intercept is zero and determine only the slope. The slopes \(k\) (K km s\(^{-1}\)), intercepts, and correlation coefficients are listed in Table 2. We note that the correlation coefficient is around 0.7–0.9 for \(T_d\) higher than 18 K. This clearly shows that the correlation strongly depends on \(T_d\) and becomes better for smaller \(T_d\) ranges; generally speaking, the slope becomes steeper and the intercept smaller with increasing \(T_d\).
Figure 1. (a) Velocity-integrated intensity map of $^{12}$CO($J = 1–0$) in the galactic coordinates. The integrated LSR-velocity range is from $-12$ km s$^{-1}$ to $+2$ km s$^{-1}$. The contours are drawn every $7.9$ K km s$^{-1}$ from $3.4$ K km s$^{-1}$. The bounding box shows the observed area. (b)–(d) are spatial distributions of the velocity-integrated intensity of the H$_i$($W_{HI}$), the optical depth at 353 GHz ($\tau_{353}$), and the temperature of the cold dust ($T_d$), respectively. The contours of CO and the bounding boxes are the same as in (a). The integrated velocity range of the $W_{HI}$ in (b) is from $-49$ km s$^{-1}$ to $+17$ km s$^{-1}$. The effective beam sizes are 5 arcmin for the four panels. (A color version of this figure is available in the online journal.)

Figure 5(a) shows a scatter plot of $T_d$ and $\tau_{353}$(main) and clearly indicates a significant decrease of $T_d$ with $\tau_{353}$(main). A similar result where the dust temperature increases with decreasing gas column density was recently found by the Planck Collaboration (Planck Collaboration et al. 2014a, 2014b).

Figure 5(b) shows a scatter plot of $W_{CO}$ and $\tau_{353}$(main) in the area observed in CO. This shows a positive correlation with a correlation coefficient of $\sim 0.7$, while the dispersion is large. The solid line in (b) represents a relationship $\tau_{353}$(main) = $[(1.8 \pm 0.8) \times 10^{-7}] \cdot W_{CO}$ (K km s$^{-1}$) + $[(8.4 \pm 5.0) \times 10^{-7}]$, which is the result of a least-squares fit to the data with $W_{CO} \geq 3\sigma$.

4. ANALYSIS

From the behavior in Figure 3, we infer that for the highest $T_d$, the optically thin approximation of H$_i$ is valid, whereas for lower $T_d$, the approximation becomes worse due to the large H$_i$ optical depth. Equation (1) is used to estimate $N_{HI}$ for the optically thin part in Figure 3,

$$N_{HI} (\text{cm}^{-2}) = (1.823 \times 10^{18}) \cdot W_{HI} \text{ (K km s}^{-1})\text{,}$$

and the relationship between $\tau_{353}$(main) and $N_{HI}$(main) is estimated for the optically thin regime at $T_d \geq 21.5$ K;

$$N_{HI}$(main) (cm$^{-2}$) = $(1.5 \times 10^{26}) \cdot \tau_{353}$(main),

where $1.5 \times 10^{26}$ is calculated by a product of $1.823 \times 10^{18}$ in Equation (1) and the slope $k = (8.47 \times 10^{7}$ K km s$^{-1}$) for $T_d > 21.5$ K in Table 2.

Relation (2) holds as long as the dust properties are uniform, allowing us to calculate $N_{HI}$(main) from $\tau_{353}$(main). Then the coupled Equations (3) and (4) in the following are used to
We estimate the errors in the velocity range but with the masking described in Section 2.5 applied. Solve for $T_i$ and $\tau_{H1}(\text{main})$, where $N_{H1}(\text{main})$ is calculated from $\tau_{353}(\text{main})$ by Equation (2),

$$W_{H1}(\text{main}) (K \text{ km s}^{-1}) = [T_i (K) - T_{bg} (K)] \cdot \Delta V_{H1} (K \text{ km s}^{-1}) \cdot [1 - \exp(-\tau_{H1}(\text{main}))],$$

$$\tau_{H1}(\text{main}) = \frac{N_{H1}(\text{main}) (\text{cm}^{-2})}{1.823 \times 10^{18} \cdot \frac{1}{T_i (K)} \cdot \frac{1}{\Delta V_{H1} (\text{km s}^{-1})}},$$

where $\Delta V_{H1}$, the H1 linewidth, is given by $W_{H1}(\text{main})$/peak H1 brightness temperature and $T_{bg}$ is the background continuum radiation temperature (see Section 2.4.) including the 2.7 K cosmic background radiation (Fixsen 2009). $\tau_{H1}(\text{main})$ is the H1 optical depth averaged over the H1 velocity width $\Delta V_{H1}$, which ranges from 8 km s$^{-1}$ to 30 km s$^{-1}$ with a median at $\sim$14 km s$^{-1}$. Note that Equation (4) is valid not only for small $\tau_{H1}$ but also for any positive value of $\tau_{H1}$. Figure 6 shows the two relationships in the $T_i$--$\tau_{H1}(\text{main})$ plane for four typical values of $T_i \simeq 20$ K (a), 40 K (b), 60 K (c), and 80 K (d). We estimate the errors in $T_i$ as shown in Figure 6 from the 1$\sigma$ noise level of the H1 and $\tau_{353}(\text{main})$ data. We find that the equations give reasonable solutions with small errors for lower $T_i$, whereas they cannot give a single set of $T_i$ and $\tau_{H1}(\text{main})$ for $T_i$ higher than $\sim$70 K, where the error bars in $T_i$ become uncomfortably large. In Figure 6, we estimate the error ranges as follows: (a) $T_i \simeq 20^{+4}_{-2}$ K, $\tau_{H1}(\text{main}) \simeq 1.06^{+0.28}_{-0.29}$, (b) $T_i \simeq 40^{+13}_{-6}$ K, $\tau_{H1}(\text{main}) \simeq 0.84^{+0.29}_{-0.29}$, (c) $T_i \simeq 60^{+126}_{-20}$ K, $\tau_{H1}(\text{main}) \simeq 0.31^{+0.21}_{-0.22}$, and (d) $T_i \simeq 80^{+\infty}_{-59}$ K, $\tau_{H1}(\text{main}) \simeq 0.16^{+0.20}_{-0.16}$. In the optically thin limit, the two equations become essentially the same, and can be satisfied by an infinite number of solutions, either a combination of large $T_i$ and small $\tau_{H1}(\text{main})$ or of small $T_i$ and large $\tau_{H1}(\text{main})$. Only the lower limit for $T_i$ and the upper limit of $\tau_{H1}(\text{main})$ are constrained.

Figure 7(a) shows the distribution of $T_i$, Figure 7(b) the distribution for $\tau_{H1}(\text{main})$, and Figure 7(c) the distribution of $\tau_{353}(\text{main})$. Several specific areas are masked as described in Section 3 and also masked where the estimated $T_i$ is greater than 70 K. In Figure 7(a), $T_i$ is mostly lower than 50 K. We also find that $\tau_{H1}(\text{main})$ becomes large in many of the data points. The results for estimated $T_i$ and $\tau_{H1}(\text{main})$ are plotted in Figure 8 with a superposition of Equation (3) for $T_i$ from 10 K to
the intercept is zero in this case. The data are fitted by least-squares method.

\[(K \text{ km s}^{-1}) (K \text{ km s}^{-1})\]

\[\text{values of the slope and intercept of the best fit linear relationship between}
\]

\[N \leftrightarrow 100 \text{ K with } \tau_{353}(\text{main}). \text{ We see saturation of } W_{H_1}(\text{main}) \text{ becomes}
\]

\[\text{important for lower } T_s, \text{ and the slope for a given } T_s \text{ decreases}
\]

Figure 4. Same as Figure 3 but integrated velocity range of the H\(_1\) is from 

\[-49 \text{ km s}^{-1} \text{ to } +17 \text{ km s}^{-1}\] and \(\tau_{353}\) is the total value.

(A color version of this figure is available in the online journal.)

Figure 5. (a) Correlation plot between \(T_d\) and \(\tau_{353}(\text{main})\) in the area shown in

\[\text{Figure 7(c). The contours represent the 90\%, 70\%, 50\%, 30\%, \text{ and 10\% levels}
\]

\[\text{of the CO data (3 K km s}^{-1}) \text{ and the solid line represents a relationship}
\]

\[\tau_{353}(\text{main}) = [1.8 (0.8) \times 10^{-6}] \cdot W_{CO}(\text{K km s}^{-1}) + [8.4 (5.0) \times 10^{-6}]
\]

\[\text{which is the result of a least-squares fit to the data with } W_{CO} > 3\sigma. \text{The dotted}
\]

\[\text{line is } \tau_{353}(\text{main}) = (1.8 \times 10^{-6}) \cdot W_{CO}(\text{K km s}^{-1}) + (2 \times 10^{-5}) \text{ (see text).}
\]

with decreasing \(T_s\) due to saturation. This result is consistent with \(T_s\) estimated from comparisons between H\(_1\) emission and absorption toward radio continuum sources, which show that cold H\(_1\) clouds of 20–40 K are common (Dickey et al. 2003; Heiles & Troland 2003). Their spatial coverage is, however, much smaller than the present coverage, 100 deg\(^2\). Possible hints of optically thick H\(_1\) are also found in the literature (Strasser & Taylor 2004; Dickey 2010).

5. PHYSICAL CONDITIONS IN THE H\(_1\) GAS

5.1. \(T_d\) and \(T_s\)

The present analysis offers evidence for a significant fraction of cold H\(_1\) gas in the region. The analysis shows typical physical parameters for the optically thick H\(_1\) gas as follows: \(N_{H_1}(\text{main}) = 4 \times 10^{20} \sim 1.5 \times 10^{21} \text{ cm}^{-2}\), H\(_1\) number density \(n_{H_1} = 40–160 \text{ cm}^{-3}\) for a cloud line-of-sight depth of 3 pc, and \(T_s = 20–40 \text{ K}\). The gas kinetic temperature of the H\(_1\) is determined by heating due to the ISRF and cooling mainly by the C\textit{ii} line (e.g., Wolfire et al. 1995) and is in a range of 10–100 K for a column density higher than \(2 \times 10^{20} \text{ cm}^{-2}\) (e.g., Goldsmith et al. 2007). Since the radiative transition rate, the Einstein \(A\) coefficient, of the 2\(1\) cm line is small, \(\sim 3 \times 10^{-15} \text{ s}^{-1}\), the 2\(1\) cm transition is well thermalized by collisional excitation for a density higher than \(\sim 10 \text{ cm}^{-3}\) (e.g., Liszt 2001; Sato & Fukui 1978). \(T_s\) is exactly in equilibrium with the gas kinetic temperature in the dense H\(_1\) gas. On the other hand, \(T_d\) is determined by the balance between the ISRF heating and thermal radiation of dust grains and is generally in a range from 15 K to 25 K in the H\(_1\) gas. \(T_d\) and \(T_s\) should show a correlation since heating is commonly due to the ISRF, where \(T_d\) variation is much smaller than that of \(T_s\) due to the strong temperature dependence.
dependence of the dust cooling, as \((T_d)^6\) (e.g., Draine 2011). For \(A_V\) more than 1 mag, \(T_d\) becomes less than 60 K (e.g., Goldsmith et al. 2007) and \(T_d\) shows a significant decrease to 17 K, which corresponds to \(T_d\) within the CO clouds (Figure 1). The present results on \(T_d\) and \(\tau_{\text{HI}}\) (main) are therefore consistent with the thermal properties of the ISM. It is possible that \(T_d\) is affected by the local radiation field in addition to the general ISRF. The distribution of \(T_d\) shown in Figure 1(d) indicates that in the northwest of the CO clouds \(T_d\) tends to be higher than in the southeast. This may be due to the excess radiation field of the OB stars in the Sco OB2 association which are located 100–200 pc away from the present clouds (see Tachihara et al. 2001).

An \(X_{\text{CO}}\) factor converting \(W_{\text{CO}}\) into \(N_{\text{HI}}\) is estimated from a comparison of CO and \(\tau_{\text{353} \text{(main)}}\) (Figure 5(b)). A least-squares fit for \(W_{\text{CO}}\) greater than 3.4 K km s\(^{-1}\) (above the 3\(\sigma\) noise level) yields \(\tau_{\text{353} \text{(main)}} = (1.8 \pm 0.8) \times 10^{-6} \cdot W_{\text{CO}} \text{(K km s}^{-1}) + (8.4 \pm 5.0) \times 10^{-8}\). Here we adopt \(W_{\text{CO}}\) greater than 3\(\sigma\) by considering that an \(X_{\text{CO}}\) factor is conventionally estimated for \(A_V \gtrsim 2–3\) mag (e.g., Bell et al. 2006). The offset of \(8.4 \times 10^{-6}\) in \(\tau_{\text{353} \text{(main)}}\) in the above relationship is interpreted as due to the contribution of the \(\text{H}_2\), and the \(X_{\text{CO}}\) factor is calculated from the slope \(1.8 \times 10^{-6}\) in the relationship and the coefficient in Equation (2) as \(X_{\text{CO}} = N_{\text{HI}} / W_{\text{CO}} = (1.5 \times 10^{26} / 2) \times 1 \times 8 \times 10^{-6} = 1.3 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})\) with a typical dispersion of \(\pm 40\%\), which is somewhat smaller than that estimated elsewhere, \((2–3) \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})\) (e.g., Bertsch et al. 1993). Numerical simulations suggest that the \(X_{\text{CO}}\) factor is relatively uniform in regions of high visual extinction where CO is intense (Inoue & Inutsuka 2012; Glover & Mac Low 2011; Bell et al. 2006). This difference may be possibly ascribed to the large contribution of cold HI gas which was not taken into account previously and should be confirmed by a careful analysis of more sample clouds. We note that we see a small number of points in Figure 5(b) which show higher \(\tau_{\text{353} \text{(main)}}\) for a given \(W_{\text{CO}}\) on the right of the dotted line and above the dashed line. These may correspond to molecular gas with slightly less CO abundance than the majority, suggesting a younger chemical evolutionary stage (Yamamoto et al. 2003) and can be characterized by a higher \(X_{\text{CO}}\) factor.

5.2. Alternative Ideas

The above interpretation assumes that all the neutral gas outside the CO is purely atomic. This interpretation is consistent with the present analysis including only \(\text{H}_1\) as shown by the fit of the line radiation transfer equation and estimated \(T_i\) and \(\tau_{\text{HI}}\) (main) (Figure 7). We shall test if an interpretation based on CO-free \(\text{H}_2\) is possible as an alternative, which was advocated for a giant molecular cloud having a total mass of \(10^5–10^6 \text{ M}_\odot\) by Wolfire et al. (2010) and was discussed in the first Planck paper (Planck Collaboration et al. 2011b). \(\tau_{\text{353} \text{(main)}}\) is a sum of the dust opacity in both the \(\text{H}_1\) and \(\text{H}_2\) gas. If CO-free \(\text{H}_2\) is dominant, \(\text{H}_2\) may account for most of the \(\tau_{\text{353} \text{(main)}}\) instead of \(\text{H}_1\). The observed value of \(W_{\text{HI}}\) (main) poses a strict lower limit on \(N_{\text{HI}}\) (main) and it is not probable that \(\text{H}_2\) dominates \(\text{H}_1\). The majority of the data points have \(T_i \sim 30\) K (Figure 8) and a lower limit for their \(\text{H}_1\) column density is given by the optically thin limit. For instance, for points having \(W_{\text{HI}}\) (main) = 250 K km s\(^{-1}\), \(N_{\text{HI}}\) (main) at \(T_i \sim 30\) K is 0.85 \times 10\(^{21}\) cm\(^{-2}\) whereas \(N_{\text{HI}}\) (main) in the optically thin limit is 0.45 \times 10\(^{21}\) cm\(^{-2}\) corresponding to \(\sim 50\%\) of 0.85 \times 10\(^{21}\) cm\(^{-2}\), and for points having \(W_{\text{HI}}\) (main) = 200 K km s\(^{-1}\), \(N_{\text{HI}}\) (main) at \(T_i \sim 30\) K is 0.6 \times 10\(^{21}\) cm\(^{-2}\) whereas \(N_{\text{HI}}\) (main) in the optically thin limit is 0.35 \times 10\(^{21}\) cm\(^{-2}\) corresponding to \(\sim 60\%\) of 0.6 \times 10\(^{21}\) cm\(^{-2}\). This suggests that the cold gas typically has an \(\text{H}_2\) abundance of 50\% or less over most of the region outside of the CO clouds. Direct UV absorption measurements of \(\text{H}_2\) abundances on the line of sight toward NGC 7469 (\(t = 83:10, b = -45:47\)) show \(N_{\text{HI}} = 4.7 \times 10^{19} \text{ cm}^{-2}\) and \(N_{\text{HI}} = 3.9 \times 10^{20} \text{ cm}^{-2}\) (Gillmon et al. 2006), indicating that the hydrogen is about 90\% atomic. It is worth noting that other lines of sight at intermediate latitudes observed by FUSE and Copernicus (summarized by Rachford et al. 2009) show similarly low molecular fractions unless the total H column density, \(N_{\text{HI}} + N_{\text{HI}} \gtrsim 10^{21} \text{ cm}^{-2}\), lending support for the conclusion that \(\text{H}_1\) is dominant. Finally, we note that the

![Figure 6](image-url)
timescale for H₂ formation is generally as long as 10⁷ yr for a typical density of 100 cm⁻³ (Hollenbach et al. 1971). The cloud lifetime is, however, smaller than ~10⁶ yr as estimated from the crossing time at latitudes higher than 10° for a typical cloud size of several parsecs and a line width of 15 km s⁻¹ (Yamamoto et al. 2003, 2006). This suggests that the present cloud is too young to form significant H₂. Another possibility is that the dust properties may be considerably different in the region, as has been explored by the Planck collaboration (Planck Collaboration et al. 2014a). We shall defer exploration of this possibility until a full account of the study is opened to the community.

5.3. Mass of the H I Envelope

We estimate the total mass of the clouds in the region under study. We estimate the total system mass including H₁, H₂, and H₂ (40% of hydrogen in mass) to be ~1.3 × 10⁵ M☉ by using the sum of τ₃⁵³(main) above 5 × 10⁻⁶ under Equation (2) applied to both H₁ and H₂ (Figure 7(c)). The typical ratio of the opacity-corrected case to the optically thin case is estimated to be 2.7 toward areas without CO emission, showing that the opacity correction has a significant impact. The mass of the H₁ gas in the masked areas is interpolated to be ~9.0 × 10² M☉ by using the average N₃⁵₃(main) ~ 1.3 × 10²¹ cm⁻² in the regions without masking and corresponds to ~7% of the total system mass above. On the other hand, the molecular mass is estimated to be ~1.2 × 10³ M☉ by applying the present X₁CO factor (=1.3 × 10²¹ cm⁻³ (K km s⁻¹)) to the CO emission. Here we integrated the CO emission above the 3σ noise fluctuations of 3.4 K km s⁻¹ in the integrated intensity in the 5 arcmin smoothed beam. By subtracting this mass from the total system mass, we obtain ~1.2 × 10⁵ M☉ as the total mass of the H₁ envelope. We thus find that the H₁ envelope has a total mass ~10 times larger than the mass of the H₂ clouds probed by CO. Note that in Gir et al. (1994) the mass of the H₁ envelope was calculated as ~3 × 10³ M☉, which is smaller than the present result. This difference may be attributed to the fact that (1) the area they used for the calculation corresponds to ~1/2 of that used in our calculation, and (2) they assumed that all the H₁ gas is optically thin.

We conclude that the H₂ clouds traced by CO are surrounded by massive, optically thick H₁ envelopes possibly containing 50% of the mass of the H₁ envelope. This is consistent with the H₁ envelope being ~10 times larger than the mass of the CO-emitting regions. We shall defer exploration of this possibility until a full account of the study is opened to the community.
It is generally known that small clouds having a mass less than $\sim 1000 M_\odot$ cannot be gravitationally bound due to the large virial mass as compared with the CO luminosity mass (e.g., Yonekura et al. 1997; Kawamura et al. 1998). The H\textsc{i} envelope may have a deep influence on cloud dynamics. The average density of the H\textsc{i} is 100 cm$^{-3}$ and the velocity width is 15 km s$^{-1}$. The dynamical pressure of H\textsc{i}, $\rho v^2$ (density) $\times$ (velocity dispersion)$^2$ is nearly equal to that of the H$_2$ gas and the pressure exerted by the H\textsc{i} envelope is able to confine the H$_2$. The H\textsc{i} envelope may help to stabilize small H$_2$ clouds yet it is perhaps true that the whole system, including the H\textsc{i} envelope, is not gravitationally bound because of the large velocity dispersion of the H$_2$ and some dynamically transient states, like those in colliding H\textsc{i} flows, must be invoked to explain the cloud dynamics (e.g., Hartmann et al. 2001).

### 5.4. Relation to the Dark Gas

Recent analyses of gamma-ray maps and the Planck data show evidence for dark gas which is not seen in CO or H\textsc{i} emission (Grenier et al. 2005; Planck Collaboration et al. 2011b). These analyses did not consider the H\textsc{i} opacity effect and assumed that H\textsc{i} is completely optically thin. The present study has shown that the H\textsc{i} optical depth effect is important in this region and an upward correction of the cloud mass by a factor of $\sim 2$ on average is required. A significant fraction of the relatively dense H\textsc{i} gas may therefore be masked by saturation of the 21 cm line, and the cold H\textsc{i} gas is a viable candidate for the dark gas. This possibility deserves further exploration by including a much larger fraction of the sky. We note that the present analysis is applicable in a $\tau_{353}$ (main) range of $2 \times 10^{-6}$ to a few $\times 10^{-5}$. Therefore, the behavior of the H\textsc{i} outside this range has yet to be explored separately.

### 6. CONCLUSIONS

We have made a comparison of H\textsc{i}, CO, and the Planck dust properties in a complex of high latitude clouds MBM 53, 54, 55 and HLCG 92–35. Our conclusions from this study are as follows.

The H\textsc{i} intensity shows a poor correlation with dust opacity with a correlation coefficient of $\sim 0.6$. We interpret that this is caused by the effect of the optical depth on 21 cm H\textsc{i} emission. We present a method for estimating the spin temperature and the optical depth of the H\textsc{i} emission which couples the equation of line radiation transfer and the expression for the H\textsc{i} optical depth by assuming that dust properties do not change significantly in the region, where the $\tau_{353} (\text{main})$ is limited to the range $3 \times 10^{-6}$ to $2 \times 10^{-5}$. We have analyzed about $8 \times 10^5$ data points smoothed at 5 arcmin resolution and successfully estimated $T_s$ and $\tau_{353} (\text{main})$. Most of the points have $T_s$ in the range from 20 K to 40 K and $\tau_{353}$ (main) is in the range from 0.2 to 4. This indicates that saturation due to a large H\textsc{i} optical depth provides a reasonable explanation of the suppressed H\textsc{i} intensity in regions with large dust opacity. The $T_s$ distribution is consistent with previous results estimated from absorption measurements toward radio continuum sources while in this paper, the spatial coverage is continuous, covering a much larger area than continuum source absorption measurements. If the present results are correct, this suggests that optically thick H\textsc{i} is more significant than previously assumed in the literature. The typical physical parameters of the cold H\textsc{i} are density 40–160 cm$^{-3}$, $T_s = 20–40$ K and $N_{\text{H}_1} (\text{main}) = 4 \times 10^{20}–1.5 \times 10^{21}$ cm$^{-2}$. The $X_{\text{CO}}$ factor to convert $W_{\text{CO}}$ into $N_{\text{H}_2}$ has been estimated to be $1.3 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$). The CO clouds are associated with a massive dense cold H\textsc{i} envelope having $\sim 1.2 \times 10^4 M_\odot$ compared with the CO cloud mass of $\sim 1.2 \times 10^3 M_\odot$. Another possibility, that the dust properties may vary significantly, is being explored currently by the Planck collaboration and should be considered in depth as a future step. Finally, it is an obvious
task to extend this method to the whole sky to see if cold \texttt{H}\textsubscript{i} is common and dominant in the local interstellar space around the Sun.

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APPENDIX A

Figure 10 shows five \texttt{H}\textsubscript{i} velocity channel distributions from $V_{\text{LSR}} = -45 \text{ km s}^{-1}$ to $+32 \text{ km s}^{-1}$. The main \texttt{H}\textsubscript{i} cloud toward the CO emitting clouds is seen from $-12.7 \text{ km s}^{-1}$ to $-0.3 \text{ km s}^{-1}$ (panel (b)) as noted by Gir et al. (1994). The main feature is outstanding in the \texttt{H}\textsubscript{i} intensity having 200 \text{K} km s$^{-1}$ in the integrated intensity. In this velocity channel, we see additional \texttt{H}\textsubscript{i} features; one is located $\sim 5^\circ$ west of the main cloud and is elongated in a similar direction and with a similar length to the main cloud (called West1 \texttt{H}\textsubscript{i}), and the other is in the north of the main cloud peaked at $(l, b) \sim (100^\circ, -31^\circ)$ (North \texttt{H}\textsubscript{i}). West1 \texttt{H}\textsubscript{i} seems to be linked with the northern tip of the CO clouds. We also find an additional feature (West2 \texttt{H}\textsubscript{i}) peaked at $(l, b) \sim (90^\circ, -37^\circ)$ which may be extended to the west up to $l \sim 80^\circ$.

In $V_{\text{LSR}}$ from $-25.0 \text{ km s}^{-1}$ to $-12.7 \text{ km s}^{-1}$ (panel (a)), we see two features; one of them corresponds to North \texttt{H}\textsubscript{i} in position and the other to West2 \texttt{H}\textsubscript{i}. In addition, the \texttt{H}\textsubscript{i}, North \texttt{H}\textsubscript{i}, and several smaller peaks along the southern rim of the main cloud, seem to be surrounding the CO, as noted by Yamamoto et al. (2003, see also their Figure 6).

In the velocity from $-0.3 \text{ km s}^{-1}$ to $+12.0 \text{ km s}^{-1}$ (panel (c)), we see the \texttt{H}\textsubscript{i} feature corresponds to West1 \texttt{H}\textsubscript{i} and the \texttt{H}\textsubscript{i} in the north shows an intensity depression surrounding the CO, suggesting a physical association with the CO.

In the other extreme velocity range from $-45.0 \text{ km s}^{-1}$ to $-25.0 \text{ km s}^{-1}$ (panel (d)) we find the main peak at $(l, b) \sim (87^\circ, -38^\circ)$ shows an elongation similar to West2 \texttt{H}\textsubscript{i}. The \texttt{H}\textsubscript{i}
may be possibly linked with West2, while it was not included in the present analysis.

We summarize the above that the H\textsc{i} in the three panels (a)–(c) is likely associated with the main cloud within a volume having a size in the order of the main H\textsc{i} cloud, 30–40 pc, at a distance of 150 pc.

**APPENDIX B**

\(\tau_{\text{353}}\) (main), which is the main component of \(\tau_{\text{353}}\), is calculated as follows.

1. First we use slope derived by least-squares fits between \(W_{\text{HI}}\) and \(\tau_{\text{353}}\) by linear regression for \(T_d > 21.5\) K in Figure 4(b).
2. By using the slope derived from (1) \(\tau_{\text{353}}\) is calculated by
   \[\tau_{\text{353}} = \tau_{\text{353}} - W_{\text{HI}}(\nu_{\text{LSR}} < -25 \text{ km s}^{-1}, +12 \text{ km s}^{-1} < \nu_{\text{LSR}})/(\text{slope}).\]
3. We estimate a new slope again by the same manner as (1) between \(W_{\text{HI}}\) (main) and \(\tau_{\text{353}}\).
4. \(\tau_{\text{353}}\) is calculated by the same manner as (2) but by using \(\tau_{\text{353}}\) and the slope derived by (3).
5. We iterate (3) and (4) until the value of the slope becomes converged.

After five iterations the best estimate of the slope \(k\) converged to \(8.34 \times 10^7\) K km s\(^{-1}\) with the relative variation less than 10\(^{-4}\).

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