Constraining the halo size from possible density profiles of hydrogen gas of Milky Way Galaxy

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Outline

- Cosmic Rays (CRs).
- Motivation and components needed for the work.
- Possible density profiles of hydrogen gas of Milky Way Galaxy.
- Results.
- Summary & Conclusions.
Cosmic Rays (CRs)

Origin of cosmic rays?

nucleus + X → π + X

π⁰ → γγ

π⁺ → μ + ν

μ → e + νν

apparent source direction

charged particle
The large error on halo height \((z_t)\) or the vertical height of CR diffusion region is an important source of uncertainty in case of CR propagation.

Previous calculations:
\begin{itemize}
  \item a) \(1 \text{kpc} \lesssim z_t \lesssim 10 \text{kpc}\) \(\text{(^{10}\text{Be}/^{9}\text{Be measurement}) (A. W. Strong et al., Ann. Rev. Nucl. Part. Sci. 57, 285 (2007)).}\)
  \item b) \(z_t = 8^{+8}_{-7} \text{kpc}\) (with semi analytical codes; gas density \(\sim 1 \text{ cm}^{-3}\)) \((A. \ Putze \ et \ al., \ Astron. \ Astrophys. \ 516, \ A66 \ (2010)).\)
  \item c) \(z_t = 5.4 \pm 1.4 \text{kpc}\) (Bayesian analysis + GALPROP) \((R. \ Trotta \ et \ al., \ ApJ \ 729, \ 106 \ (2011)).\)
  \item d) \(z_t \gtrsim 2 \text{kpc}\) (DRAGON code) \((G. \ D. \ Bernardo \ et \ al., \ JCAP \ 03 , \ 036 \ (2013)).\)
\end{itemize}
A realistic model of Galactic magnetic field is needed as it directly affects the CR propagation.

For the estimation of halo height $^{10}\text{Be}/^{9}\text{Be}$ and $\text{B}/\text{C}$ are important.

$^{10}\text{Be}/^{9}\text{Be} \propto \sqrt{D(E_k)/z_t}$ and $\text{B}/\text{C} \propto z_t/D(E_k)$ with $z_t$, $E_k$ and $D(E_k)$ being the halo height, kinetic energy and energy dependent diffusion coefficient, respectively (A. W. Strong et al., Astron. Astrophys. 534, A54 (2011)).
Basic components of the work

- Density profiles of hydrogen gas:
  a) Molecular ($H_2$),
  b) Atomic/Neutral (HI) and
  c) Ionized (HII).

- Diffusion Reacceleration and Advection of Galactic cosmic rays: an Open New code (DRAGON) (G. D. Bernardo et al., Astropart. Phys. 34, 274 (2010), C. Evoli et al., JCAP 02, 015 (2017))
  (https://github.com/cosmicrays/DRAGON)

- A plain diffusion model is considered. The diffusion coefficient is,

$$D(\rho, z) = \beta^n D_0 \left( \frac{\rho}{\rho_0} \right)^\delta \exp \left( \frac{Z}{Z_t} \right), \quad (1)$$
GMF model: Pshirkov type (M. S. Pshirkov et al., ApJ 738, 192 (2011)) with disc, halo and turbulent components. Their corresponding normalization are denoted as $B_0^\text{disc}$, $B_0^\text{halo}$ and $B_0^\text{turbulent}$, respectively. Turbulent component is more important for CR propagation than the other two components (G. D. Bernardo et al., JCAP 03, 036 (2013)).

$D(z)^{-1} \propto B^\text{turbulent}(z) \propto \exp\left(-z/z_t\right)$ (G. D. Bernardo et al., JCAP 03, 036 (2013)).

Theoretical modeling of the propagation of Galactic cosmic ray electrons and positrons to fit their observed flux, their synchrotron emission and its angular distribution gave a relation between $B_0^\text{turbulent}$ and $z_t$ (G. D. Bernardo et al., JCAP 03, 036 (2013)).

To avoid boundary effects, transport equations are solved assuming $L = 3z_t$, where, $L$ is the vertical boundary (G. D. Bernardo et al., JCAP 03, 036 (2013)).
Density Profiles: Case #1

\[ n_{H_2}(r, z) = n_{CO}(r, z) \times X_{CO} \ cm^{-3}, \]  

(2)

L. Bronfman et al., ApJ 324, 248 (1988); M. Ackermann et al., ApJ 750, 03 (2012).

\[ n_{HI}(r, z) = Y(r) f(z) \ cm^{-3}, \]  

(3)

M. A. Gordon and W. B. Burton, ApJ 208, 346 (1976); J. M. Dickey and F. J. Lockman, Ann. Rev. Astron. Astrophys. 28, 215 (1990); P. Cox et al., A& A 155, 380 (1986).

\[ n_{HII}(r, z) = (0.025 \ cm^{-3}) \times \exp \left[- \left( \frac{|z|}{1.0 \ kpc} \right)\right] \exp \left[- \left( \frac{r}{20.0 \ kpc} \right)^2\right] \]

\[ + (0.20 \ cm^{-3}) \times \exp \left[- \left( \frac{|z|}{0.15 \ kpc} \right)\right] \exp \left[- \left( \frac{r - 4.0 \ kpc}{2.0 \ kpc} \right)^2\right]. \]  

(4)

J. M. Cordes et al., Nature 354, 121 (1991).
K. Ferriere et al., A& A 467, 611 (2007).

For $r \lesssim 3$ kpc:

$$n_{H_2}(r, z) = n_{H_2}^{CMZ} + n_{H_2}^{disk}. \quad (5)$$

$$n_{HI}(r, z) = n_{HI}^{CMZ} + n_{HI}^{disk}. \quad (6)$$

$$n_{HI}(r, z) = (8.0 \text{ cm}^{-3}) \times \left\{ \exp \left[ -\frac{x^2 + (y - y_3)^2}{L_3^2} \right] \times \exp \left[ -\frac{(|z| - z_3)^2}{H_3^2} \right] \right. \right.$$  

$$\left. + 0.009 \times \exp \left[ -\left( \frac{r - L_2}{L_2/2} \right)^2 \right] \sech^2 \left( \frac{|z|}{H_2} \right) \right.$$  

$$\left. + 0.005 \left[ \cos \left( \frac{\pi}{2L_1} \right) u(L_1 - r) \right] \times \sech^2 \left( \frac{|z|}{H_1} \right) \right\}, \quad (7)$$

where, $u$ is the unit step function, $y_3 = -10$ pc, $z_3 = -20$ pc, $L_3 = 145$ pc, $H_3 = 26$ pc, $L_2 = 3.7$ kpc, $H_2 = 140$ pc, $L_1 = 17$ kpc and $H_1 = 950$ pc.
K. Ferriere, ApJ 497, 759 (1998).

For $r > 3$ kpc:

$$n_{H_2}(r, z) = \frac{(0.5 \times 0.58 \text{ cm}^{-3})}{(2.9 \text{ kpc})^2} \times \exp \left[ - \frac{(r - 4.5 \text{ kpc})^2 - (4.0 \text{ kpc})^2}{(2.9 \text{ kpc})^2} \right] \left( \frac{r}{8.5 \text{ kpc}} \right)^{-0.58} \times \exp \left[ - \left( \frac{z}{0.081 \text{ kpc}} \right)^2 \left( \frac{r}{8.5 \text{ kpc}} \right)^{-1.16} \right].$$

(8)

$$n_{H\text{II}}(r, z) = \frac{(0.0237 \text{ cm}^{-3})}{(37.0 \text{ kpc})^2} \exp \left[ - \frac{r^2 - (8.5 \text{ kpc})^2}{(37.0 \text{ kpc})^2} \right] \exp \left( - \frac{|z|}{1.0 \text{ kpc}} \right) + \frac{(0.0013 \text{ cm}^{-3})}{0.150 \text{ kpc}} \times \exp \left( - \frac{|z|}{0.150 \text{ kpc}} \right) \times \exp \left[ - \frac{(r - 4.0 \text{ kpc})^2 - (4.5 \text{ kpc})^2}{(2.0 \text{ kpc})^2} \right].$$

(9)
\[ n_{\text{HI}}(r, z) = \frac{(0.340 \text{ cm}^{-3})}{(\alpha_h(r))^2} \times \left\{ 0.859 \exp \left[ -\left( \frac{z}{(0.127 \text{ kpc})\alpha_h(r)} \right)^2 \right] + 0.047 \times \exp \left[ -\left( \frac{z}{(0.318 \text{ kpc})\alpha_h(r)} \right)^2 \right] + 0.094 \exp \left[ -\left( \frac{|z|}{(0.403 \text{ kpc})\alpha_h(r)} \right) \right] \right\} \]

\[ + \frac{(0.226 \text{ cm}^{-3})}{(\alpha_h(r))} \times \left\{ \left[ 1.745 - \frac{1.289}{\alpha_h(r)} \right] \times \exp \left[ -\left( \frac{z}{(0.127 \text{ kpc})\alpha_h(r)} \right)^2 \right] \right. \]

\[ + \left. \left[ 0.473 - \frac{0.070}{\alpha_h(r)} \right] \times \exp \left[ -\left( \frac{z}{(0.318 \text{ kpc})\alpha_h(r)} \right)^2 \right] \right) \]

\[ + \left[ 0.283 - \frac{0.142}{\alpha_h(r)} \right] \times \exp \left[ -\left( \frac{|z|}{(0.403 \text{ kpc})\alpha_h(r)} \right) \right] \right\} \]  

(10)

where,

\[ \alpha_h(r) = 1.0, \text{ For, } r \leq 8.5 \text{ kpc} \]

\[ = \frac{r}{8.5 \text{ kpc}}, \text{ For, } r > 8.5 \text{ kpc}. \]  

(11)
Sayan Biswas and Nayantara Gupta, arXiv:1802.03538v3 [astro-ph.HE] (2018).
For $r \lesssim 3 \text{ kpc}$:
In this region, the expressions of $n_{\text{H}_2}(r,z)$, $n_{\text{HI}}(r,z)$, and $n_{\text{HII}}(r,z)$ are considered same as the expressions for Case #2 in $r \lesssim 3 \text{ kpc}$.

For $r > 3 \text{ kpc}$:
In this region of interest, we have constructed our desired density profiles with the radial ($n_j(r)$) and vertical ($n_j(z)$)) distributions in the following way

$$n_j(r,z) = N_{0j} n_j(r) n_j(z) \text{ cm}^{-3},$$

where, $j$ (=$\text{H}_2$, HI, HII) denotes the particular component of hydrogen gas. Here, $N_{0j}$ is the normalization constant that can be evaluated as, $N_{0j} = 1/n_j(z=0)$. Vertical distributions are obtained from R. Feldmann et al., ApJ 763, 21 (2013).
a) For $3 \text{ kpc} < r < 10.4 \text{ kpc}$

$$n_j(r, z) = N_0 j(r, 0) n_j(z) \text{ cm}^{-3}, \quad (13)$$

where, $n_j(r, 0)$ is obtained from Case #2 in $r > 3 \text{ kpc}$.

b) For $r \gtrsim 10.4 \text{ kpc}$

In this region, the density distributions of molecular, atomic and ionized components of hydrogen gas are obtained by using the following relation $n_H(r) - n_{\text{HII}}(r) = 2n_{\text{H}_2}(r) + n_{\text{HI}}(r)$. We also assumed that $n_{\text{H}_2}(r) = n_{\text{HI}}(r) = \left( n_H(r) - n_{\text{HII}}(r) \right)/3$.

$n_H(r)$: M. J. Miller and J. N. Bregman, ApJ 800, 14 (2015).

$n_{\text{HII}}(r)$: R. Feldmann et al., ApJ 763, 21 (2013).
Sayan Biswas and Nayantara Gupta, arXiv:1802.03538v3 [astro-ph.HE] (2018).
Results (Sayan Biswas and Nayantara Gupta, arXiv:1802.03538v3 [astro-ph.HE] (2018)): Fitted parameters, Case 1

| Model/Parameter             | Option/Value       |
|----------------------------|--------------------|
| $R_{\text{max}}$           | 20.0 kpc           |
| $L$                        | 6.0 kpc            |
| Gas density type           | Case #1            |
| Source Distribution        | Ferriere           |
| Diffusion type             | Exp (see Eq. (1))  |
| $D_0$                      | $2.0 \times 10^{28}$ cm$^2$/s |
| $\rho_0$                   | 3.0 GV             |
| $\delta$                   | 0.54               |
| $z_t$                      | 2.0 kpc            |
| $\eta$                     | -0.40              |
| $v_A$                      | 0.0                |
| Magnetic field type        | Pshirkov           |
| $B_0^\text{disc}$          | $2.0 \times 10^{-6}$ Gauss |
| $B_0^\text{halo}$          | $4.0 \times 10^{-6}$ Gauss |
| $B_0^\text{turbulent}$     | $9.65 \times 10^{-6}$ Gauss |
| First injection slope ($\alpha_0$) | 2.32               |
| Position of first break (rigidity) | 330 GV             |
| Second injection slope ($\alpha_1$) | 2.20               |
Fitted CR spectra, Case 1

All the observed data are taken from cosmic ray database: D. Maurin, F. Melot, and R. Taillet, A& A 569, A32 (2014).

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| Model/Parameter                        | Option/Value                      |
|---------------------------------------|-----------------------------------|
| $R_{\text{max}}$                      | 20.0 kpc                          |
| $L$                                   | **6.6 kpc**                       |
| Gas density type                      | Case #2                           |
| Source Distribution                   | Ferriere                          |
| Diffusion type                        | Exp (see Eq. (1))                 |
| $D_0$                                 | $2.9 \times 10^{28}$ cm$^2$/s     |
| $\rho_0$                              | 3.0 GV                            |
| $\delta$                             | 0.54                              |
| $z_t$                                 | **2.2 kpc**                       |
| $\eta$                                | -0.40                             |
| $v_A$                                 | 0.0                               |
| Magnetic field type                   | Pshirkov                          |
| $B_0^{\text{disc}}$                   | $2.0 \times 10^{-6}$ Gauss        |
| $B_0^{\text{halo}}$                   | $4.0 \times 10^{-6}$ Gauss        |
| $B_0^{\text{turbulent}}$              | **9.30 \times 10^{-6}** Gauss     |
| First injection slope ($\alpha_0$)    | 2.32                              |
| Position of first break (rigidity)    | 330 GV                            |
| Second injection slope ($\alpha_1$)   | 2.20                              |
### Fitted parameters, Case 3

| Model/Parameter                  | Option/Value           |
|---------------------------------|------------------------|
| $R_{\text{max}}$                | 20.0 kpc               |
| $L$                             | 18.0 kpc               |
| Gas density type                | Case #3                |
| Source Distribution             | Ferriere               |
| Diffusion type                  | Exp (see Eq. (1))      |
| $D_0$                           | $1.8 \times 10^{29}$ cm$^2$/s |
| $\rho_0$                        | 3.0 GV                 |
| $\delta$                       | 0.54                   |
| $z_t$                           | 6.0 kpc                |
| $\eta$                         | -0.40                  |
| $v_A$                           | 0.0                    |
| Magnetic field type             | Pshirkov               |
| $B_0^{\text{disc}}$             | $2.0 \times 10^{-6}$ Gauss |
| $B_0^{\text{halo}}$             | $4.0 \times 10^{-6}$ Gauss |
| $B_0^{\text{turbulent}}$        | $6.62 \times 10^{-6}$ Gauss |
| First injection slope ($\alpha_0$) | 2.32                   |
| Position of first break (rigidity) | 330 GV              |
| Second injection slope ($\alpha_1$) | 2.20                  |
Variation of halo-height with density profiles to fit experimental data

| Case | Density profile | $z_t$ (kpc) | $D_0$ (cm$^2$/s) | $z_t/(D_0/10^{28})$ kpc/cm$^2$/s |
|------|-----------------|-------------|-----------------|-----------------------------------|
| 1    | #1              | 2           | $2.0 \times 10^{28}$ | 1.0                               |
| 2    | #2              | 2.2         | $2.9 \times 10^{28}$ | 0.76                              |
| 3    | #3              | 6           | $1.8 \times 10^{29}$ | 0.33                              |
Our prime objective is to study the effect of density profiles of hydrogen gas on halo-height of Milky Way Galaxy.

Study of possible density profiles of molecular, atomic and ionized component of hydrogen gas. The chosen density profiles are characteristically different from each other.

Such density profiles are implemented in the DRAGON code to study the propagation of CRs.
$^{10}\text{Be}/^{9}\text{Be}$, B/C, proton, helium, and antiproton are fitted with observed data.

We observed that $z_t/D_0$ value decreases with increase in the target gas density.

We have obtained that $z_t$ value is in the range of 2-6 kpc for our chosen density profiles of hydrogen gas.

We need more observational and theoretical studies in future to determine density profiles uniquely.
THANK YOU