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DISTANCE DETERMINATION TO THE MOLECULAR CLOUDS IN THE GALACTIC ANTI-CENTER REGION

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ABSTRACT

We conducted a deep CCD observations in V band to obtain stellar density distribution and to determine the distances toward two molecular clouds with anomalous velocity in the Galactic anti-center region. Star count method based on the linear programming technique was applied to the CCD photometric data. We found two prominent peaks at distances of around 1.4 and 2.7 kpc. It is found that the first peak coincides well with stellar density enhancement of B8-A0 stars and the second one with the outer Perseus arm. The effect of the choice of the luminosity function is discussed. The stellar number density distribution is used to derive the distances to the molecular clouds and the visual extinctions caused by the clouds. We found that two molecular clouds are located almost at the same distance of about 1.1 ± 0.1 kpc, and the peak extinctions caused by the clouds are about 2.2 ± 0.3 mag in V band.

Key words : Galaxy: structure-ISM: cloulds-ISM: dust, extinction

I. INTRODUCTION

The Galactic anti-center region of (l, b)=(178.°0~186.°0, 3.5~6.°0) was recently mapped with a sampling rate of 3' in the transition of ^{12}CO J=1–0 line using the Taeduk Radio Astronomy Observatory (TRAO)'s 14-m radio telescope (Lee et al. 1999). During the survey (Galactic Anti-Center CO Survey: GACCOS), Lee et al. (1999) found several peculiar molecular clouds with anomalous velocity of about −20 km s^{-1}, and mapped these clouds with higher sampling rate of 1' for further investigation (Lee et al. 2000). In order to study the physical properties of these peculiar molecular clouds, their distances should be determined. However, distance determination of a dark cloud in the Galactic center or anti-center region is always difficult because the kinematic distance using Galactic rotation curve cannot be estimated. The star count method of Bok (1937) is particularly important to establish the distance to a molecular cloud when other distance indicators are absent. We thus made a deep CCD photometry toward these peculiar molecular clouds, and applied the star count method based on the *linear programming* (*LP*) technique recently developed by Kim (1999).

In Section II, CCD observations and data reduction procedure are briefly described, and Wolf diagrams for program and reference fields are presented. In Section III, we explain very briefly the basic principle of the *LP* based star count method for finding stellar number density distribution and effect of choice of two luminosity functions on the resulting stellar density function is discussed. Subsequent application of the star count method using the Wolf diagram to find the cloud distance and extinction is also demonstrated. In Section IV, we summarize the results.

II. CCD OBSERVATIONS

The CCD observations were made using the Bohyunsan Optical Astronomy Observatory (BOAO)'s 1.8 m

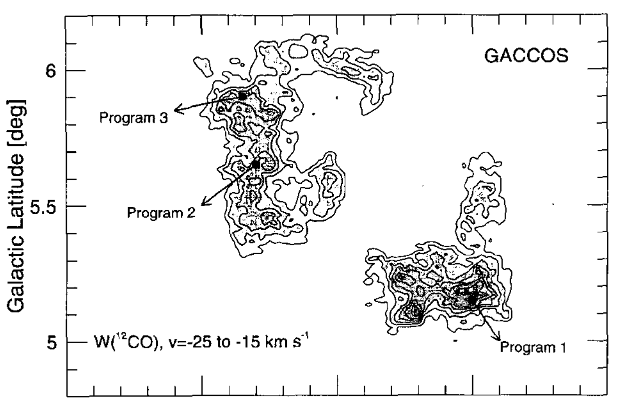

Fig. 1. The program fields are indicated as filled squares on the ^{12}CO J=1–0 intensity map integrated from −25 to −15 km s^{-1}. The contour level starts from 1.0 K km s^{-1} with an interval of 1.5 K km s^{-1}. (Courtesy: Lee et al. 2000).

Table 1. CCD Observations Summary

Field	Galactic Coordinates		Exposure (seconds)		Filter
	l (deg)	b (deg)	long	short	
Reference	178.80	5.30	300	10	V
Program 1	180.00	5.15	300	10	V
Program 2	180.80	5.65	300	10	V
Program 3	180.85	5.90	300	10	V

telescope equipped with a CCD camera at the Ritchey-Chretien F/8 focus in November 1999. The CCD camera used is a SITe AR-coated 2048 × 2048 pixel array whose plate scale is 0."34/pixel. The sky area covered by a single frame is about 11.'6 × 11.'6. The seeing was about 2" on average. We selected the reference fields by using both of the ^{12}CO map and POSS prints so that they are close to the cloud but free of ^{12}CO emission. Three program fields were selected on the peaks of ^{12}CO emission, and are indicated as filled squares on the ^{12}CO integrated intensity map in Fig. 1. Each frame was exposed twice; at first with long exposure and then with short exposure to enhance the dynamic range of the photometry. Only the standard V filter was used for all exposures. The CCD observations are summarized in Table 1.

The preprocessings including bias subtraction and flat fielding were performed using the IRAF's CCDRED package. Stars were identified using DAOFIND task in DAOPHOT package, and the instrumental magnitudes were obtained from PSF (point spread function) photometry. The instrumental magnitudes were transformed into the standard visual magnitudes of the SAAO system (Menzies et al. 1991), by observing 11 stars in SA93, SA94, SA99, and SA114. The atmospheric extinction effect was removed by deriving primary extinction coefficient which is compensated for small variation depending on time and V-I color of the standard stars. Five frames for standard stars were taken during the observations. The limiting apparent magnitude at 300 second exposure was about 21.0 magnitudes in V band.

Stars in each magnitude bin were counted and each counts were converted into counts per square degree.

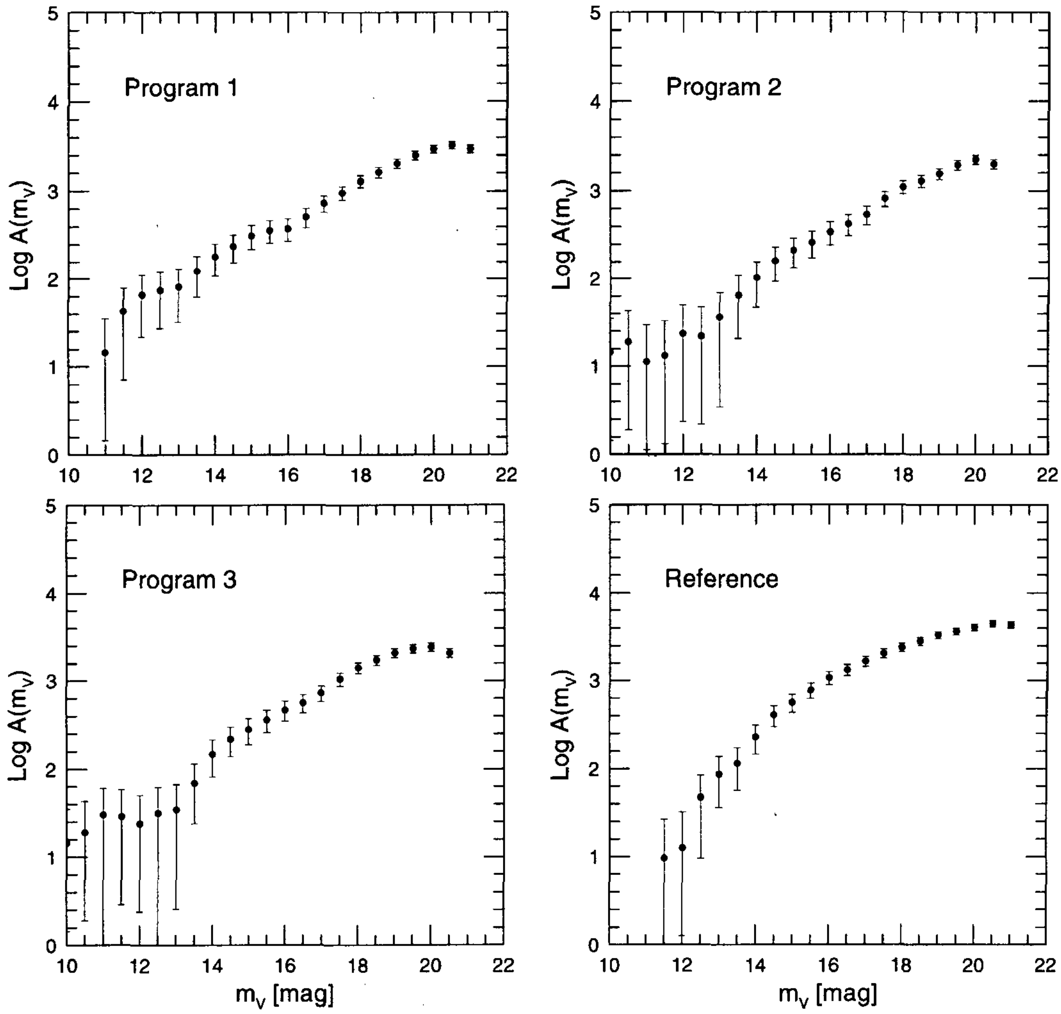

Fig. 2. Wolf diagrams for the program fields 1, 2, 3 and reference field. $A(m_V)$ is the number of stars per square degree in unit magnitude interval. The vertical bars on the open circles denote the statistical uncertainties involved in the counts.

The resulting Wolf diagrams in the program fields 1, 2, 3 and the reference field are shown in Fig. 2. Length of the vertical bar on the filled circle represents the uncertainty corresponding to the statistical fluctuation in the count. The statistical uncertainty associated with a count of N stars in a reseau element is taken as $\sqrt{N}$ assuming the fluctuation in count follows the Poisson statistics.

III. STAR COUNT METHOD FOR THE DISTANCE DETERMINATION

(a) General Formulation for Star Counts

Suppose that a dark cloud is located at a distance r_0 and causes an extinction of E magnitudes. The number of stars $A(m)$ observed in an apparent magnitude interval $(m-1/2)$ and $(m+1/2)$ is given by

$$A(m) = \int_0^\infty \Phi(M) f(M;\, R, z) D(r) r^2 dr, \qquad (1)$$

where $\Phi(M)$ denotes the luminosity function with M being absolute magnitude, $f(M;\, R,\, z)$ is the position dependency of luminosity function in cylindrical coordinates, and $D(r)$ is the stellar number density distribution in units of the corresponding number density in the solar neighborhood. In Eq. (1), the apparent magnitude m is related to the absolute magnitude M, the general interstellar extinction $a(r)$, and the extinction due to the cloud E by

$$M = m+5-5\log r - a(r) - \mu E,$$

where μ=0 for the foreground stars ($r \leq r_0$) and μ=1 for the background stars ($r > r_0$). The left hand side of Eq. (1) is obtained from the photometry of CCD image. Counts of the stars in a field of an arbitrary size are normalized to the corresponding numbers in 1°×1° field.

In order to solve Eq. (1) for cloud distance r_0 and the cloud extinction E, one must at first know the stellar number density distribution $D(r)$. To derive $D(r)$, we need to count stars in the unobscured region (E=0) close to the program field which is called the reference field. The reference field should be carefully chosen so that the stellar number density distribution can be assumed to be the same as that of the program field. Similar to the case of the program field, the count at the reference field $A_r(m)$ is given by

$$A_r(m) = \int_0^\infty \Phi(M) f(M;\, R, z) D(r) r^2 dr, \qquad (2)$$

where M is m+5–5log r–$a(r)$. The integral equation [Eq. (2)] is then solved for $D(r)$ from the counts at the reference field.

Once $D(r)$ is obtained, Eq. (1) can be solved for the unknowns r_0 and E from the counts at the program field. The $\Phi(M)$ and $D(r)$ at program field are assumed to be the same as those for the reference field.

(b) *LP* Algorithm for Stellar Density Function

In order to solve for $D(r)$, we follow the exact step described by Kim (1999). The integral in Eq. (2) for reference field is replaced by a summation over concentric shells centered on the sun:

$$A_r(m_k) = \sum_{i=1}^{i_{\max}} \Phi(M_k) f(M_k;\, R_i, z_i)\, D(r_i) r_i^2 \Delta r_i, \qquad (3)$$

with $M_k = m_k + 5 - 5\log r_i - a(r_i)$. Here Δr_i is thickness of i-th shell, R_i and z_i are cylindrical coordinates of the center of the i-th cell. The concentric shells are taken uniformly from the sun with radii,

$$r_i = 0.1,\ 0.2,\ 0.3,\ ...,\ 10.0 \text{ kpc}.$$

Since the stars at large distances are too faint to be detected with the CCD camera, it is in practice enough to extend the summation only up to $i_{\max} = 100$. The problem is to search for the most plausible stellar number density distribution, which fits the observed Wolf curve for reference field optimally.

In order to transform Eq. (3) to an *LP* problem, a variable $R(m_k)$ is introduced which represents the fractional residual at each magnitude interval centered on m_k at reference field. The $R(m_k)$ is expressed as

$$R(m_k) = 1 - A_r^c(m_k)/A_r(m_k),\ k = 1,\ 2,\ ...,\ k_{\max},$$

where $A_r^c(m_k)$ denotes the calculated count in unit magnitude interval centered on m_k at reference field as given by the right hand side of Eq. (3). The index k needs to be extended up to the limiting magnitude $m_k = m_{\lim}$. The problem is to find a density function $D(r_i)$ that minimizes the weighted sum of absolute fractional residuals,

$$S = \sum_{k=1}^{k_{\max}} w_k |R(m_k)|. \qquad (4)$$

The absolute expression in the above equation can be removed with suitable constraints. That is, the problem is equivalent to find $D(r_i)$ that minimizes the weighted sum of $R'(m_k)$'s,

$$S' = \sum_{k=1}^{k_{\max}} w_k R'(m_k), \qquad (5)$$

satisfying the following constraints:

$$A_r^c(m_k)/A_r(m_k) - R'(m_k) \leq 1 \ (k = 1,\ 2,\ ...,\ k_{\max}), \qquad (6)$$

$$A_r^c(m_k)/A_r(m_k) + R'(m_k) \geq 1 \ (k = 1,\ 2,\ ...,\ k_{\max}), \qquad (7)$$

$$D(r_1) = 1, \qquad (8)$$

$$D(r_i) > 0 \ (i = 2,\ 3,\ ...,\ i_{\max}), \qquad (9)$$

where $R'(m_k)$ represents $|1 - A_r^c(m_k)/A_r(m_k)|$ and w_k is a suitably defined weighting function. Eq. (5) is the objective function or cost equation that we should minimize. Any set of values $D(r_i)$ that satisfies all of the constraint

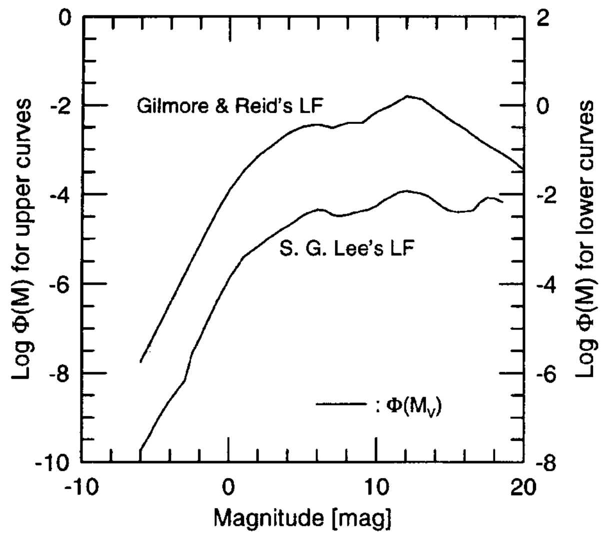

Fig. 3. The luminosity functions of Gilmore & Reid (1983) and Lee (1997) are shown as a function of the absolute magnitude. Gilmore's luminosity function is a composite of three independent studies of Miller & Scalo (1979) for the range $-6 \leq M_V < 2$, of Wielen (1974) for the range $2 \leq M_V \leq 10$, and of Gilmore & Reid (1983) for the range $M_V > 10$.

equations [Eq. (6)-Eq. (9)] is called a feasible solution. A feasible solution that minimize the cost equation is called the optimal feasible solution, which we are looking for. Further details of the *LP* algorithm for stellar density function can be found in Kim (1999).

The luminosity functions we used are shown in Fig. 3. We adopt two luminosity functions of Gilmore & Reid (1983) and Lee (1997) for comparison. Both luminosity functions were derived from disk stars in the solar neighborhood.

The general interstellar extinction law $a(r)$ should also be known *a priori*. However, it is very difficult to know its exact distribution along a line of sight. One thus assumes the general extinction law as a linear function of radial distance with a form $a(r) = k \cdot r$ for simplicity. The proportional constant k is also known to vary from direction to direction. For the k value toward the Galactic anti-center direction, we take $k = 0.8$ mag/kpc from FitzGerald (1968) and Lucke (1978).

For the function $f(M;\ R,\ z)$, we adopt the galaxy model of Bahcall & Soneira (1980) which consists of disk and halo components;

$$f(M;\ R,\ z) \propto \exp\left[-\frac{z}{H(M)} - \frac{(R-R_0)}{h}\right],$$

where R and z are distance and height in cylindrical coordinates. The halo component needs not to be considered here because we are studying outer region of the Galaxy. The scale length h of 3.5 kpc used by Bahcall & Soneira (1980) to be too large according to recent studies. Robin et al. (1992) found 2.5 kpc from optical

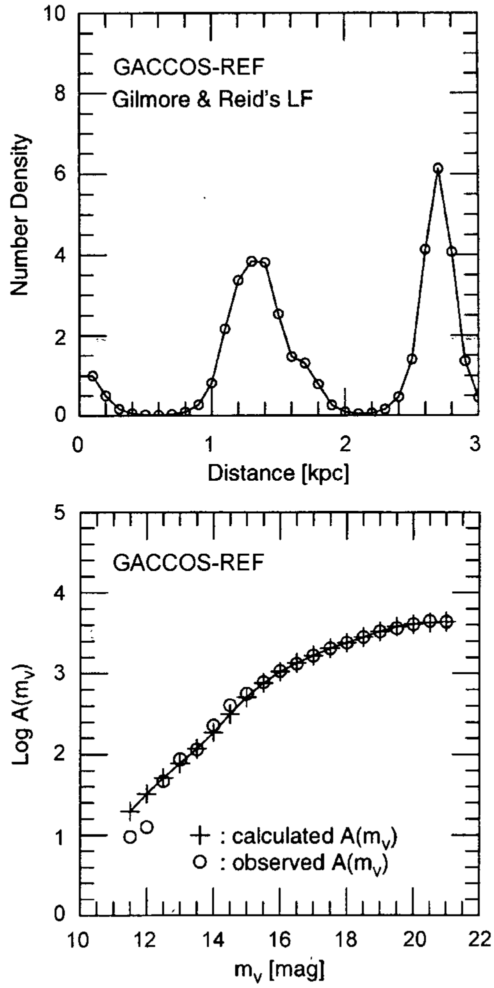

Fig. 4. Stellar density function toward the Galactic anti-center molecular cloud using the luminosity function of Gilmore & Reid (1983). A linear general interstellar extinction law with a proportional constant of 0.8 mag/kpc was assumed. Upper panel shows stellar density function which fits the observation best. Lower panel shows the fit. The observed Wolf curve is denoted by open circles and the calculated one by crosses.

study, and Ruphy et al. (1996) obtained even smaller value of 2.3 ± 0.2 kpc from near-infrared study. In this study a value of 2.5 kpc is taken for h. The distance of the sun from Galactic center R_0 is taken as 8 kpc. For the scale height $H(M)$, the following relation from Bahcall & Soneira (1980) is used.

$$\frac{H(M_V)}{[pc]} = 90.0,\ M_V \leq 2.3$$
$$= 87.0\ M_V - 110.1,\ 2.3 < M_V < 5.0$$
$$= 325.0,\ M_V \geq 6.0$$

The resulting $D(r)$ using both luminosity functions are presented in Figs. 4 and 5, respectively. The derived stellar number density distribution toward the reference field shows two prominent peaks at distances of around 1.4 and 2.7 kpc. Although the peak densities and shapes are slightly different from each other, general trends

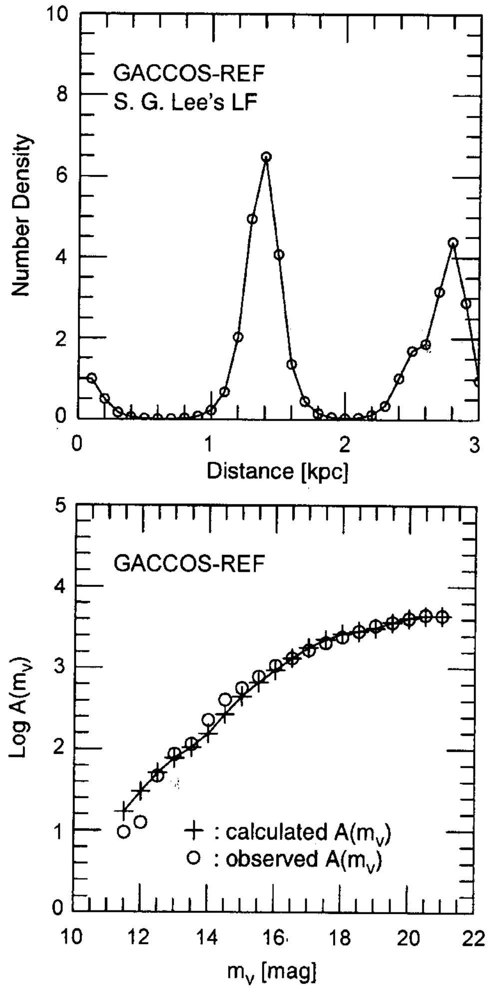

Fig. 5. Stellar density function toward the Galactic anti-center molecular cloud using the luminosity function of Lee (1997). All notations indicate the same as in Fig. 4.

resemble each other remarkably. This fact indicates that the stellar density function toward the Galactic anti-center region depends insensitively on the choice of the luminosity function. The first peak at around 1.4 kpc corresponds roughly to the stellar density enhancement of B8-A0 stars (Mihalas & Binney 1981), and the other one to the wellknown outer Perseus arm.

(c) Cloud Distance and Extinction

Assuming that $\Phi(M)$, $f(M;\ R,\ z)$ and $D(r)$ are all the same as those for the reference field, Eq. (1) can be solved for the unknowns, r_0 and E, from the counts at the program field. Similar to the case for reference field [Eq. (3)], we replace the integral equation. Eq. (1), by a summation. The count in the presence of a cloud, $A(m_k)$ is expressed in the same form as the right hand side of Eq. (3)

$$A(m_k)=\sum_{i=1}^{i_{\max}} \Phi(M_k)f(M_k;\ R_i,\ z_i)D(r_i)r_i^2\Delta r_i, \qquad (10)$$

except that M_k is expressed as

$$M_k = m_k+5-5\log\ r_i-a(r_i)-\mu E.$$

The only difference between Eq. (10) and Eq. (3) is M_k involving the parameter μ. In case E=0 or $r_0=\infty$, $A(m_k)$ becomes identical to $A_r(m_k)$.

In order to find r_0 and E, we utilized the modified Wolf diagram of Hong & Sohn (1989), and a χ^2-fitting method to minimize the arbitrariness. We define

$$\chi^2=\sum_{k=1}^{k_{\max}} w_k\cdot(\Delta m_k-\Delta\tilde{m}_k)^2,$$

where Δm_k and $\Delta\tilde{m}_k$ are defined in such a way that

$$A(m_k) = A_r(m_k-\Delta m_k),$$

and

$$A^c(m_k;\ r_0,\ E) = A_r(m_k-\Delta\tilde{m}_k).$$

Series of modified theoretical Wolf curves are calculated for a hypothetical cloud with a given set of (r_0, E) grid points. By comparing the theoretical Wolf curve at each set of (r_0, E) with the observed one, we calculate a suitably defined error which is a weighted sum of deviations at each magnitude m_k. The optimal cloud distance and extinction is the (r_0, E) pair where the weighted sum of deviations has its local minimum.

The resulting χ^2 maps by using the luminosity function of Gilmore & Reid (1983) are shown as contour plots in Fig. 6, and the best fit theoretical Wolf curves corresponding to the optimal points are shown in Fig. 7. The same things with the luminosity function of Lee (1997) are shown in Fig. 8 and Fig. 9.

The optimal sets of r_0 and E are listed in Table 2 for both luminosity functions. The distances of the two peculiar clouds are found to be at almost the same distance of about 1.1 ± 0.1 kpc, with the visual extinctions of about 1.9 to 2.6 ± 0.3 mag. The error was simply the difference among results with various fitting methods.

IV. SUMMARY AND CONCLUSION

We conducted a deep CCD observations in V band to obtain the stellar density distribution toward two molecular clouds with an anomalous velocity in the Galactic anti-center region. A star count method based on the linear programming technique was adopted for the distance determination, because the kinematic distance

Table 2. Cloud Distance and Visual Extinction

Field	r_0 (kpc)		E (mag)	
Program 1	1.2 ± 0.1	1.1 ± 0.1	2.0 ± 0.3	2.0 ± 0.3
Program 2	1.1 ± 0.1	1.0 ± 0.1	2.6 ± 0.3	2.3 ± 0.3
Program 3	1.1 ± 0.1	1.0 ± 0.1	1.9 ± 0.3	1.9 ± 0.3

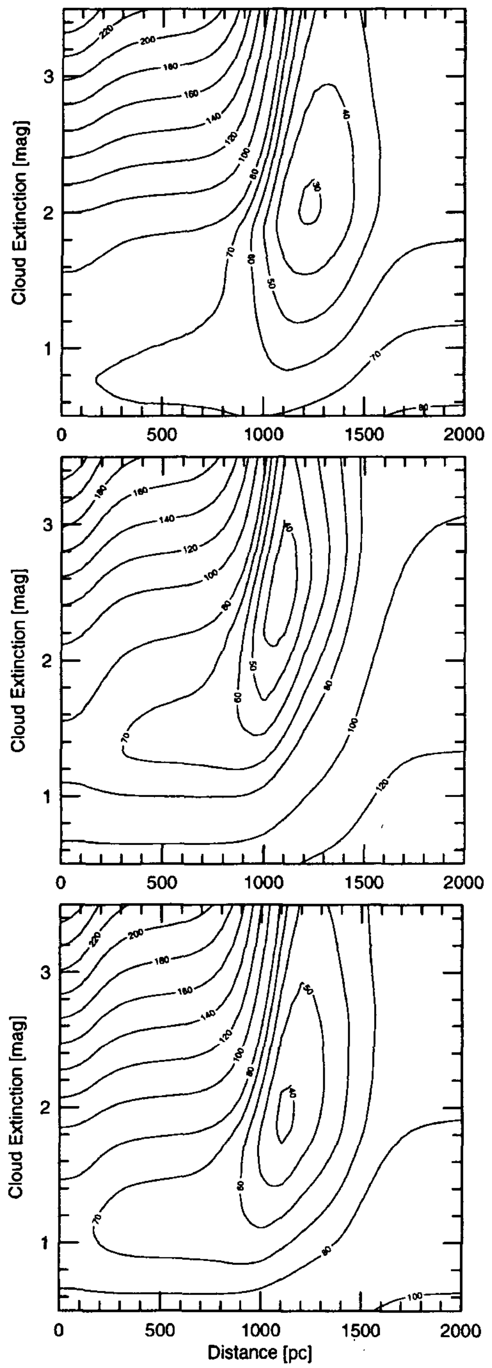

Fig. 6. Contour maps of weighted sum of deviations of the modified theoretical Wolf curve from the observed one for the three program fields. The luminosity function of Gilmore & Reid (1983) was used. The optimum points are found at $r_0 = 1.2$, 1.1 and 1.1 ± 0.1 kpc and $E = 2.0$, 2.6 and 1.9 ± 0.3 mag, respectively.

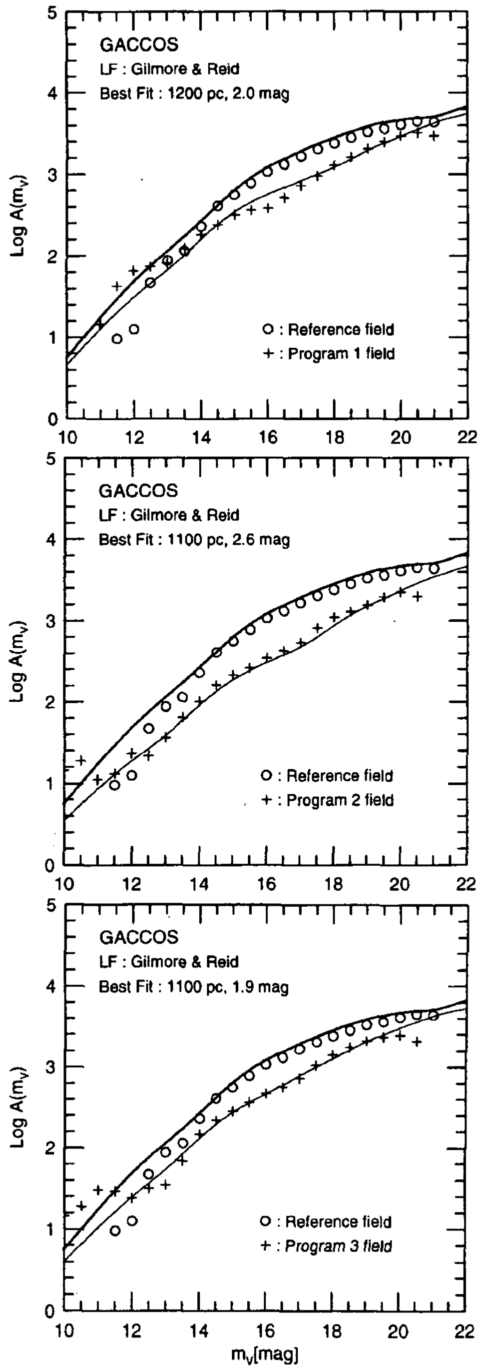

Fig. 7. Theoretical Wolf diagrams with and without hypothetical cloud. The open circles denote the observed counts at reference field. Thick line represents a best fit to the open circles. The crosses are the observed counts at program field. Thin line is the theoretical Wolf curve calculated at the optimal points in Fig. 6.

using Galactic rotation curve is invalid in this direction. The effect of the choice of the luminosity function was examined by applying two different luminosity functions to the same set of data. Although the peak densities and shapes are slightly different from each other, they resemble each other remarkably. This fact indicates that the stellar density function toward the Galactic anti-center region depends insensitively on the choice of the luminosity function.

The stellar density function shows two prominent peaks at distances of around 1.4 and 2.7 kpc. It is found that the first peak coincides well with stellar density enhancement of B8-A0 stars and the second one with the outer Perseus arm. The stellar density function is

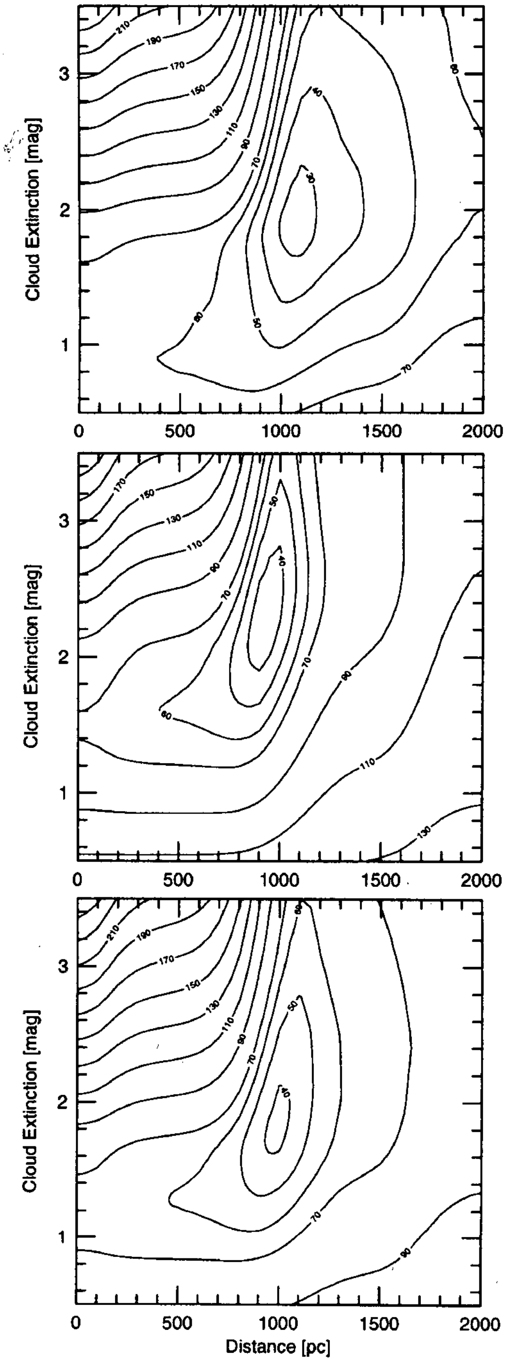

Fig. 8. Contour maps of weighted sum of deviations of the modified theoretical Wolf curve from the observed one for the three program fields. The luminosity function of Lee (1997) was used. The optimum points are found at $r_0 = 1.1$, 0.95 and 1.0 ± 0.1 kpc and $E = 2.0$, 2.3 and 1.9 ± 0.3 mag, respectively.

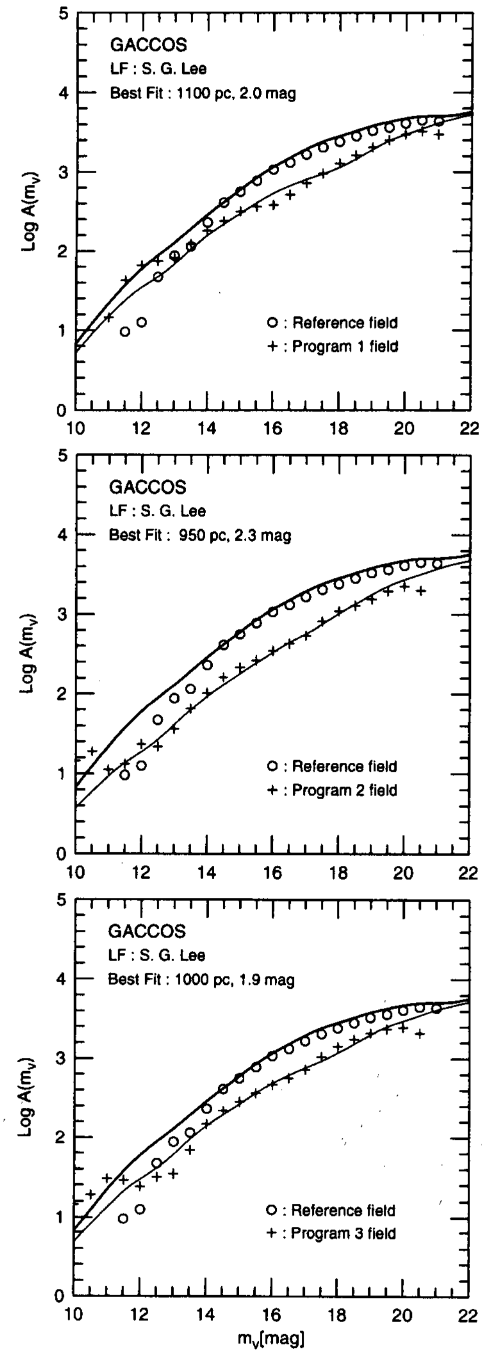

Fig. 9. Theoretical Wolf diagrams with and without hypothetical clouds. The open circles denote the observed counts at reference field. Thick line represents a best fit to the open circles. The crosses are the observed counts at program field. Thin line is the theoretical Wolf curve calculated at the optimal points in Fig. 8.

further used to derive the distances to the molecular clouds and the visual extinctions caused by the clouds. For this, we utilized the modified Wolf diagram with χ^2-fitting method to minimize the arbitrariness. We found that the two molecular clouds are located at almost same distances of about 1.1 ± 0.1 kpc from us, and the peak extinctions caused by the clouds are about 2.2 ± 0.3 mag in V band.

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