A Chain of Dark Clouds in Projection Against the Galactic Center

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(Received 2007 May 2; accepted 2008 November 21)

Abstract

In a J, H, and Ks band survey of the Galactic center region over an area of 2° × 5°, we have found many dark clouds among which a distinguished chain of dark clouds can be identified with a quiescent CO cloud. The distances of J H Ks clouds are estimated to be 3.2–4.2 kpc, corresponding to the Norma arm, by our new method for determining the distances to dark clouds using the cumulative number of stars against the J – Ks color. By adopting these estimated distances, the size and total mass of the cloud are estimated to be ∼70 pc in length and 6 × 10⁴ M☉, respectively. Three compact H II regions exist in the cloud, indicating that star-forming activities are going on at the cores of the quiescent CO cloud on the spiral arm.

Key words: ISM: clouds

1. Introduction

The central region of our Galaxy suffers large interstellar extinction, and images taken toward the Galactic center (GC) in the optical wavelength are generally featureless star fields with few stars. Since the discovery of an infrared source corresponding to the GC by Becklin and Neugebauer (1968), the GC region has been extensively observed in the infrared, where interstellar extinction is smaller by one order of magnitude than in the optical wavelength. Following the larger-scale near-infrared (NIR) surveys of 2MASS (Skrutskie et al. 2006) and DENIS (Epchtein et al. 1994), which have given a general view of the Galactic structure, we carried out a J, H, and Ks band survey of the 2° × 5° region centered on the GC with a 2 mag deeper sensitivity and a 2-times finer resolution than those of 2MASS. In the course of the survey, we found numerous dark clouds silhouetted against the dense star fields.

Toward the GC, the existence of many molecular clouds is well known from radio observations (Morris & Serabyn 1996 and references therein). Their locations in the line of sight are uncertain, but part of them, located on this side of the GC, should appear as dark clouds in near-infrared images. However, the correspondence of near-infrared dark clouds to radio molecular clouds has not been studied well.

The distances to dark/molecular clouds are crucial in discussing the physical parameters associated with them. In radio observations, the kinematic distances to molecular clouds are often derived from their radial velocities on the assumption that each cloud follows the circular Galactic rotation. However, since the Galactic rotation is perpendicular to our line of sight to the GC, we cannot determine the distance to the molecular cloud. Moreover, noncircular components, such as expanding rings, complicate the distance determinations.

Sofue (2006) proposed a method for determining the distance of CO cloud in the direction of GC from the gradient in the l–v diagram, and determined the distance of CO cloud toward the GC. This method is powerful for determining the distance to armlike structures, which extend long in the l direction, but is unsuited for small CO clouds, because the velocity gradient is not determined well.

In this paper, we report on a chain of dark clouds found in our near-infrared survey, which positionally and morphologically agrees with a velocity component of $2CO (J = 1-0)$ observed with the Nobeyama radio telescope (Kawamura et al. 1998).

A new method for determining the distances to dark clouds from a diagram of J – Ks color and cumulative star number is presented, and the resultant distance to the chain of dark clouds is estimated.

2. Observation

2.1. NIR Data

Our near-infrared survey toward the 2°(b) × 5° (l) region of the Galactic center was carried out in 2002–2004. The observation was made with Simultaneous three-color InfraRed Imager for Unbiased Survey (SIRIUS), a simultaneous imager in the J ($\lambda = 1.26 \mu m$), H ($\lambda = 1.63 \mu m$), and Ks ($\lambda = 2.14 \mu m$) bands covering an area of 7.7′ × 7.7′ with a pixel scale of 0.′45 on the InfraRed Survey Facility (IRSF) 1.4 m telescopes at Sutherland, South Africa. The details of the instrument are described in Nagashima et al. (1999) and Nagayama et al. (2003). We observed in total 891 7.7′ × 7.7′ fields centered on the GC, with 10 times of 5 s exposure.
The reduction of near-infrared array images was performed with IRAF (Imaging Reduction & Analysis Facility). Each image, after subtraction of the average dark frame, was divided by the normalized flat-field image. Then, the thermal-emission pattern, the fringe pattern due to OH emission, and the slope pattern seen in the HAWAII arrays were subtracted from each frame with a median sky frame. The photometry for point sources was performed with the DAOPHOT package in IRAF (Stetson 1987), and calibrated with the standard star 9172 in Persson et al. (1998). The 10 magnitude limiting magnitudes for the $J$, $H$, and $K_S$ bands were 17.1, 16.6, and 15.6 mag, respectively, and stars brighter than 10 mag in all the three bands were saturated. More details concerning our data reduction and photometry are described in Nishiyama et al. (2005).

2.2. CO Data

$^{12}$CO ($J = 1-0$, 115.271202 GHz) observations over the area $-15 \leq l \leq 15$ and $-0.6 \leq b \leq +0.6$ were carried out from 1995 February to April, and from 1996 March to May with the 45 m telescope of Nobeyama Radio Observatory by Oka et al. (1998). The spatial resolution of the telescope was $15\arcsec$ and the grid spacing was $30\arcsec$, resulting in an actual resolution on a map of $34\arcsec$. The details of the observation are described in Oka et al. (1998). We reprocessed the data and the acquired 88 velocity channel maps covering a velocity range of $V_{LSR} = -220$ to $+220$ km s$^{-1}$, integrated over successive 5 km s$^{-1}$ widths.

3. Comparison between NIR Images and CO Maps

We examined positional and morphological counterparts between the dark clouds seen in our survey and the $^{12}$CO emission. Comparing our NIR images with the velocity-channel maps of the $^{12}$CO observation, we found the filamentary high-intensity edge of $^{12}$CO contours in the channel map (ch-48, $V_{LSR} = +15$ to $+20$ km s$^{-1}$) correlates well with a chain of dark clouds. In figure 2, we show $^{12}$CO intensity maps of ch-48 together with the adjacent channels (ch-47 and ch-49). A filamentary structure extends from $(l, b) \sim (-0.4, -0.2)$ to $(l, b) \sim (-0.4, -0.5)$ in the map of ch-48. Of particular interest is that the small velocity-width and velocity-gradient are confined within a single channel or a range less than 5 km s$^{-1}$.

For further comparison, we made a contour map of $I(l,h)-[I(l-0.5,h)+I(l+0.5,h)]/2$ superposed on the number density of stars brighter than 14.5 mag in the $K_S$ band (figure 2), in which the shape of the $^{12}$CO contour conforms with an area with few stars in both positional and morphological senses. Therefore, the $^{12}$CO cloud seen only in ch-48 and the chain of dark clouds are presumably identical.

4. Determination of the Distance to the Chain of Dark Clouds

4.1. A New Method for Determining Distances to Dark Clouds

The determination of distances to dark clouds holds the key to a discussion of their physical properties, such as the real size and mass. We will demonstrate that the cumulative number of stars bluer than a certain $J - K$ color, $N(J - K)$, is a good indicator of the distances to dark clouds. Provided that the interstellar extinction and reddening increase monotonously with the distance in the line of sight, the observed $J - K$ color of a star depends on the distance to it. Therefore, the profile of $N(J - K)$ against various $J - K$ is determined by the extinction in the line of sight and, conversely, we can estimate the extinction distribution along the line of sight from the $N(J - K)$ profile.

The number of stars to be observed can be predicted by using an infrared model of the Galaxy (Wainscoat et al. 1992). We add an artificial screen with an extinction, $A_{K_S}$, at distance $D$ as a dark cloud, besides the general interstellar extinction, $A_{K_S}$, in the model. Here, we assume that the thickness of dark clouds along the line of sight is thin enough compared with the galactic scale; the thickness of the screen is zero in our calculation. We then calculate $N(J - K)$ to be observed with our actual limiting magnitude $F = 16.0$ and $K_S = 15.0$. The details of calculation are described in the Appendix.

Figure 3 shows predicted $N(J - K)$ toward $(l, b) = (-0.2, -0.3)$ against $A_{K_S}$. First, we discuss the case that the cloud is a complete screen, and we cannot detect stars behind the cloud. In figure 3a, the 11 lines ($D = 1.0$ to 6.0 kpc with...
a step of 0.5 kpc) are shown, together with the line without a screen. The thick top line represents the case of no-screen with only interstellar extinction, while the 11 other lines are the case where the cloud is a complete screen with $A_{K_{dc}} = \infty$ in addition to interstellar extinction. In these cases, only foreground stars contribute to $N(J - K_{s})$.

The $N(J - K_{s})$ profile with the complete screen increases in the same way as the no-screen $N(J - K_{s})$ profile at small $J - K_{s}$, because of the foreground stars, but are detached from the no-screen line, beginning with the case of the nearest distance, $D$. Because the detached points are different in each value of $D$, we can determine $D$ by comparing the predicted and observed detached points. After being detached from the no-screen line, the increase of $N(J - K_{s})$ stops at $N_{fg}$, the number of stars that are detectable in our observation. $N_{fg}$ is uniquely determined for $D$ in the cases of completely obscuring clouds.

Next, we discuss the case where the cloud does not completely obscure the stars behind. In this case, a certain number of stars behind the cloud are detected, reddened by the additional extinction of the cloud. Figure 3b shows the case of $D = 2$ kpc with $A_{K_{dc}} = 0, 0.2, \cdots, 0.9, 1.0, 1.2, 1.5, \text{and} \infty$ mag. As described in figure 3a, $N(J - K_{s})$ with $A_{K_{dc}} = 0$ stays at $N_{fg}$ because background stars are undetectable. In the case of $A_{K_{dc}} = 1.0$ mag, all background stars are reddened by about 1.0 mag in $J - K_{s}$, $A_{K_{dc}} = 0.494 E(J - K_{s})$, Nishiyama et al. 2007. Therefore, the increase of the $N(J - K_{s})$ with $A_{K_{dc}} = 1.0$ stops at $N_{fg}$ at $J - K_{s} = 1$, but $N(J - K_{s})$ increases again from $J - K_{s} = 3$ due to the contribution of background stars. Because the different $A_{K_{dc}}$ gives the different width of $J - K_{s}$ stopping at $N_{fg}$, we can determine $A_{K_{dc}}$ from it.

As we described using figures 3a and 3b, the $N(J - K_{s})$ profiles reflect $D$ and $A_{K_{dc}}$, respectively. Therefore, we can determine $D$ and $A_{K_{dc}}$ by comparing the observed $N(J - K_{s})$ with the templates parameterized by $D$ and $A_{K_{dc}}$.

Figure 4 shows simplified templates to determine $A_{K_{dc}}$ and $A_{K_{dc}}$ for $(I, D) = (-0.3, -0.3)$, a total of 13 lines for the cases of no-screen (interstellar extinction only) and combination of $A_{K_{dc}}$ (0.5 and 1.0 mag) and $D$ (1, 2, 3, 4, 5, and 6 kpc) is shown. Because the lines with various combinations of $A_{K_{dc}}$ and $D$ are well separated from each other, we can assign a unique pair of $A_{K_{dc}}$ and $D$ for the observed $N(J - K_{s})$ profile of dark clouds.

4.2 Comparison of Our Method with the Wolf Diagram

In the Wolf diagram, a traditional method for estimating the distances to dark clouds, a cumulative number of stars observed brighter than magnitude $m$, $N(m)$, is adopted instead of $N(J - K_{s})$. The distance to the dark cloud is estimated from the apparent magnitude where the $N(m)$ profile for the dark cloud is detached from that for the comparison field. In reality, however, the detached point is very ambiguous due to the large dispersion in the absolute magnitudes of the stars, as pointed out by Trumpler and Weaver (1953).

By contrast, the intrinsic color of stars in the near-infrared tends to be similar among almost all spectral types; the $J - K$ of dwarfs and giants lies between 0.0 and 1.0 (Wainscoat et al. 1992). The color excess $E(J - K)$ due to the interstellar reddening is also expected to be about 0.4 mag at the distance of the GC. Thus, the large change of $E(J - K)$ compared with the ambiguity of intrinsic $J - K$ of stars enables us to determine...
the best-fit AK of 0.2 mag and 0.1 kpc, respectively. The model lines with the observed of the Galaxy model toward the GC region, we compared (DC1 to DC8) (figure 5). In order to confirm the reliability of the dark clouds, two reference fields (RF1 and RF2) and eight dark clouds were searched for the best-fit variables, AK, D, and N. We calculated N(J − KS) without a screen (interstellar extinction only). A possible reason that the fittings for RF1 and RF2 are worse than those for the dark-cloud regions is the uncertainty of the model for the inner galaxy, which becomes insignificant when dark clouds are present.

The results for DC1–DC8, summarized in table 1, show convergence to a specific distance of 3.2–4.2 kpc. Presumably, these dark clouds lie on a single chain of molecular clouds at a distance of ~4 kpc with an extinction range of $AK_{DC} \sim 0.4$ to 1.0 mag. The interstellar extinction in front of the clouds, $A_I$, is estimated to be 0.4 to 0.5 mag from a model calculation. Most of the dark clouds previously studied are nearby, and the foreground extinction is negligibly small. In contrast, the dark clouds studied in this paper are significantly farther, and therefore the cumulative interstellar extinction is comparable to $A_I$.

The CO cloud discussed in this paper was also identified with $V_{LSR} = 21$ km s$^{-1}$ and $dv/dl = 5.1$ km s$^{-1}$ deg$^{-1}$ (Sofue 2006). Its distance was derived to be 4.7 kpc for $R_0 = 8.0$ kpc, which is now 4.4 kpc for $R_0 = 7.5$ kpc, which is a slightly larger value than ours.

The distance 3.2–4.2 kpc is halfway between the GC and the Sun ($R_0 = 7.5$ kpc). According to a summary of previous studies of the galactic structure (Vallée 2008), three arms, Sagittarius—Carina, Scutum—Crux, and Norma arms, intervene between the Galactic center and the Sun. In figure 1 of Vallée (2008), these three arms cross the line of sight to the GC at approximately 0.8, 2.8, and 4.0 kpc from the Sun, respectively. It is reasonable that the dark/molecular cloud is located around the Norma arm, and rotates around the GC with a noncircular velocity component of $V_{LSR} \sim +20$ km s$^{-1}$.

The 4 kpc molecular ring (Clemens et al. 1988; Nakanishi & Sofue 2006) is also known as a component, crossing the line of sight to the GC. However, Vallée (2008) claimed that the 4 kpc molecular ring is just an assemblage of starting segments of the four spiral arms, and we therefore leave it out of consideration.

5. Discussion

We estimated the projected length of the chain of dark clouds to be ~70 pc, and the typical thickness of the filaments is as thin as 0.1, or about 7 pc, located at ~30 pc off from the Galactic plane. The gaseous filaments are themselves divided into finer structures, and several high-intensity knots are seen on the ridge of the CO contours. By integrating the CO excess in figure 2, the mass of each ridge is estimated to be an order of $10^4 M_\odot$, and the total mass for the entire CO cloud is $\sim 10^4 M_\odot$. If we assume the depth to be identical with the apparent thickness (7 pc) and combined with a length of 70 pc, this total mass yields a molecular gas density on the order of $18 M_\odot$ pc$^{-3}$ or $4 \times 10^7$ H$_2$ cm$^{-3}$. This is a typical density for normal galactic clouds.

In the three high-intensity knots, we found four NIR sources (SF1-A, SF1-B, SF2, and SF3), with extents of 0.1 to 0.4 or 0.2–0.8 pc at 4 kpc. Their pseudo color images and positions are shown in figure 7 and table 2. Mid-infrared sources (MSX-PSC: Egan & Price 1996) are associated with all of them. OH, H$_2$O, and/or CH$_3$OH masers (SIMBAD; Caswell & Haynes 1983; Caswell et al. 1983; Menten 1991) are also associated with SF1-A, SF1-B, and SF3 with $V_{LSR} = +15$ to +23 km s$^{-1}$, quite consistent to $V_{LSR}$ of CO. Both their...
6. Summary

We have found a number of dark clouds in our near-infrared survey in the direction of the Galactic center region over an area of $2^\degree \times 5^\degree$. From the morphological resemblance between the infrared image and the CO cloud, we have identified a chain of dark clouds located around the Norma spiral arm with a single CO molecular cloud lying at a distance of $\sim$4.0 kpc. The chain of dark clouds harbors compact H II regions at the cores of the clouds in the CO spiral arm.

We wish to thank the staff of the South African Astronomical Observatory for their kind support during our observation and Dr. H. Okuda for his careful reading of the manuscript. The IRSF/SIRIUS project was financially supported by the Sumitomo foundation and Grants-in-Aid for Scientific Research on Priority Areas (A) (No. 10147207 and No. 10147214) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT). This work is supported by a Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the MEXT. IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy.
Fig. 6. Cumulative star-number histogram against $J - K_S$ toward two reference fields (RF1 and RF2) and eight dark clouds (DC1–8) are drawn. The dashed line indicates the predicted number from the Galaxy model. For RF1 and RF2, they are calculated with no screen (interstellar extinction only). For DC1–8, the best-fit combinations of the $D$ and $A_{K_S, DC}$ are drawn. The best-fit parameters are written at the bottom in each panel.
Table 1. Positions of DC1–8 and RF1-2.

<table>
<thead>
<tr>
<th>ID</th>
<th>$l$ (°)</th>
<th>$b$ (°)</th>
<th>$D$ (kpc)</th>
<th>$A_{K_s, DC}$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC1</td>
<td>0.250</td>
<td>-0.450</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>DC2</td>
<td>0.100</td>
<td>0.465</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td>DC3</td>
<td>0.025</td>
<td>0.445</td>
<td>3.2</td>
<td>0.8</td>
</tr>
<tr>
<td>DC4 (SF3)</td>
<td>-0.200</td>
<td>-0.445</td>
<td>3.8</td>
<td>0.6</td>
</tr>
<tr>
<td>DC5 (SF2)</td>
<td>-0.290</td>
<td>-0.400</td>
<td>4.2</td>
<td>0.4</td>
</tr>
<tr>
<td>DC6 (SF1)</td>
<td>-0.395</td>
<td>-0.225</td>
<td>3.6</td>
<td>0.8</td>
</tr>
<tr>
<td>DC7</td>
<td>-0.095</td>
<td>-0.305</td>
<td>4.0</td>
<td>0.8</td>
</tr>
<tr>
<td>DC8</td>
<td>+0.185</td>
<td>-0.315</td>
<td>4.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 2. Positions of SF1-A, SF1-B, SF2, and SF3.

<table>
<thead>
<tr>
<th>ID</th>
<th>$l$ (°)</th>
<th>$b$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF1-A</td>
<td>359.615</td>
<td>-0.244</td>
</tr>
<tr>
<td>SF1-B</td>
<td>359.654</td>
<td>-0.241</td>
</tr>
<tr>
<td>SF2</td>
<td>359.716</td>
<td>-0.374</td>
</tr>
<tr>
<td>SF3</td>
<td>359.970</td>
<td>-0.456</td>
</tr>
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</table>

Appendix. The Galaxy Model: Stellar Populations with Interstellar Extinction

The numbers of stars detectable in the $J, H,$ and $K_s$ bands have been estimated on the basis of the Galaxy model of Wainscoat et al. (1992). It comprises geometrically and physically realistic representations of the Galactic disk, bulge, halo, spiral arms, and a molecular ring. They represent each of the distinct Galactic components by space densities of 87 spectral-type stars with scale heights and absolute magnitudes $B, V, J, H, K, 12, \text{and} 25 \mu m$. Our calculations three components, an exponential disk, a bulge, and a molecular ring, were taken into account. We adopted 7.5 kpc as $R_0$, the distance between the GC and the Sun (Eisenhauer et al. 2005; Nishiyama et al. 2006b), instead of 8.5 kpc used in Wainscoat et al. (1992), which leads to a reduction factor of 0.88 for the associated parameters. We also took only 29 spectral types of main sequences and giants from table 2 of Wainscoat et al. (1992) into consideration.

The stellar flux is subject to the general interstellar extinction. The amount of general interstellar extinction between the Sun and distance $AD_{obj}$, is calculated as

$$A_{D_{obj}} = \frac{\int_0^{D_{obj}} \nu \exp\left(-\frac{r}{h_x}\right) \exp\left(-\frac{|z|}{h_z}\right) dD}{\nu_{GC}} \quad (A1)$$

Here, $r$ and $z$ are the distance from the Galactic center on the Galactic plane and that from the Galactic plane; $h_x$ and $h_z$ are the scale lengths of $r$ and $z$, adopting 3080 pc and 100 pc, respectively. And $\nu_{GC}$ is the amount of extinction per unit length at the Galactic center, which was obtained as follows.

First, we obtained the averaged extinction of red clump stars in the RF1 and RF2 ($A_{K_s, obj} \equiv 1.7$ and 1.2, respectively) and assumed each of them to be the total amount of general interstellar extinction to the Galactic center ($D_{obj} \equiv 7.5 \text{kpc}$). The details of the method for obtaining the extinction are described in Nishiyama et al. (2005). Next, we substituted $A_{D_{obj}} = 1.7$ in the direction of RF1 and 1.2 in RF2 into equation (A1), and derived $\nu_{GC} = 0.76$ for RF1 and 0.71 for RF2. We adopted 0.73 mag kpc$^{-1}$, the average of the above two values, as $\nu_{GC}$ in this work.

We calculated the apparent magnitude of 29 spectral types of stars every 10 pc bin along the given line of sight, and integrated the star number detectable by the given limiting magnitude and color ($J \leq 16$ and $K_s \leq 15, 85\%$ detection rate of artificial stars in the most crowded region of our observation) over the distance of 20 kpc. We consider their sum to be the total number of stars to be detected.

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