Aligned Molecular Clouds towards SS 433 and L = 348:5: Possible Evidence for a Galactic “Vapor Trail” Created by a Relativistic Jet

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Abstract

We carried out a detailed analysis of the NANTEN 12CO (J = 1–0) dataset in two large areas towards SS 433 (l ~ 40°) and l ~ 348:5. In SS 433, we detected ten clouds, which are well aligned nearly along the axis of an X-ray jet emanating from SS 433 at \( V_{\text{LSR}} = 42 - 56\ \text{km s}^{-1} \). The total length of the feature is ~ 300 pc, three-times longer than that of the X-ray jet, at 3 kpc. Towards l ~ 348:5, we detected four aligned clouds at \( V_{\text{LSR}} = -80 - -100\ \text{km s}^{-1} \), nearly perpendicular to the Galactic plane. The total length of the feature is ~ 400 pc at 6 kpc. In both cases, the CO clouds are distributed at \( b \sim 1° - 5° \) and their alignments and coincidence in velocity should be rare, suggesting that they are physically associated. We present a scenario to explain these aligned clouds in which the interaction between a relativistic jet and the interstellar medium induced molecular cloud formation over the last \( 10^{5 - 6} \) yr. It is suggested that the timescale of the relativistic jet may be considerably larger, on the order of \( 10^{5 - 6} \) yr, than previously thought in SS 433. The driving engine of the jet is obviously SS 433, itself, in SS 433, although the engine is not yet identified in l ~ 348:5 among possible several candidates detected in X-rays and TeV gamma rays.

Key words: Radio lines: ISM — ISM: clouds — ISM: jets and outflows — stars: individual (SS 433)

1. Introduction

Astrophysical jets of various scales are recognized as ubiquitous phenomena in the Universe, and the physics of jets is one of the most fundamental issues in astrophysics. On stellar scales, molecular jets driven by young protostars or bipolar outflows are well-known phenomena since the 1980’s, and are believed to represent a crucial step in proto-stellar evolution (e.g., Lada 1985; Fukui 1989; Bally et al. 2005). In addition, evolved compact stellar remnants like pulsars, such as Crab pulsar, Vela pulsar, and MSH 15–52 exhibit more energetic relativistic jets with non-thermal radiation observed as pulsar-driven nebulae (e.g., Tamura et al. 1996; Weisskopf et al. 2000; Pavlov et al. 2003). Even more massive objects, black-hole candidates, such as SS 433 and GRS 1915+105, exhibit much more energetic relativistic jets whose velocity is close to the light speed (e.g., Margon & Anderson 1989; Mirabel & Rodríguez 1994). Magneto-hydrodynamical numerical simulations on these jets have been carried out by several authors, mainly in order to reproduce the jets themselves (e.g., Kato et al. 2004; Uzdensky & MacFadyen 2006). Observationally, these relativistic jets have been detected so far only through high-energy phenomena, including non-thermal radio emission and X-rays, but their interaction with the interstellar medium were very poorly known with a possible few examples in the Galaxy (e.g., Mirabel & Rodríguez 1999); we note that interactions with the much more diffuse gas are discussed concerning some of the jets in external galaxies (e.g., Oosterloo & Morganti 2005; Krause et al. 2007).

Some of the relativistic jets, whose origin is a neutron star or a black-hole, have been identified (e.g., Mirabel et al. 1992; Rodríguez et al. 1992). A superluminal source, GRS 1915+105, is a candidate for the relativistic jet interacting with the interstellar matter; Chaty et al. (2001) show that two associated IRAS point sources are located symmetrically at \( \sim 60\ \text{pc} \) on both sides of GRS 1915+105 in a straight line. It is argued that the relativistic jet from GRS 1915+105, whose velocity is estimated to be \( 0.92c \), may have interacted with the molecular clouds and possibly induced star formation.

SS 433 is an X-ray binary system consisting of a black-hole candidate or a neutron star, and is an accelerating relativistic jet whose speed is \( 0.26c \) (Margon & Anderson 1989). SS 433 is also associated with a symmetric and linear jet, as observed in X-rays. The jet is extended by about \( 1° \) in each side of SS 433, and the two lobes are called East lobe and West lobe, respectively (Kotani 1998). The length of the jet is estimated to be about \( 40\ \text{pc} \) on each side, if we adopt a distance of \( 3\ \text{kpc} \) (Dubner et al. 1998). It is also known that SS 433 is located towards the center of a supernova remnant (SNR), W50. This SNR shows a barrel-type shape in non-thermal radio continuum emission. It has features called “ears” and “wing” along the jet axis (Elston & Baum 1987), which may be due to the interaction of the SNR with the surroundings.

The interaction of the SS 433-W50 system and the surroundings has been studied by several authors. Dubner et al. (1998) studied the radio continuum emission at \( 1.4\ \text{GHz} \) and the 21 cm H I emission, and noted that the H I at \( V_{\text{LSR}} \sim 42\ \text{km s}^{-1} \) has a cavity-like shape surrounding the radio continuum emission,
which may indicate some interaction between the H I and the SNR. On the other hand, Lockman et al. (2007) suggest that SS 433–W50 interacts with H I at $V_{\text{LSR}} \sim 75 \text{ km s}^{-1}$. Safi-Harb and Güelman (1997) and Safi-Harb and Petre (1999) analyzed the X-ray data of ROSAT, ASCA, and RXTE, and discussed the interaction between the jet from SS 433 and the surroundings. Band (1987) and Band and Gordon (1989) studied far-infrared data taken with the IRAS, and discovered some knots that may be associated with the jet, providing another piece of evidence for the interaction (Wang et al. 1990). Moldowan et al. (2005) suggest that one of the infrared objects is not correlated with the X-ray emission by the Chandra observation.

SS 433 and its relationship with molecular clouds were studied by Huang et al. (1983). They claimed that the CO molecular clouds at $V_{\text{LSR}} \sim 27–36 \text{ km s}^{-1}$ may be spatially correlated with W50. On the other hand, Band (1987) notes that these clouds are located on the near side, and is not physically related to SS 433. Subsequently, Durouchoux et al. (2000) suggest that CO clouds at $\sim 50 \text{ km s}^{-1}$ located towards the overlapping region of the West lobe of the X-ray jet may be interacting with the jet, because X-ray hot spots are associated with them. Fuchs et al. (2002) observed the region with ISO and the IRAM 30 m telescope to find that some of the IRAS knots are associated with these molecular clouds. One of these knots coincides with that noted by Durouchoux et al. (2000). Lockman et al. (2007) also studied the association between the SS 433–W50 and CO clouds using the FCRAO 14 m telescope at $2^\circ \times 2^\circ$ centered on SS 433. They concluded that there are no associations between the SS 433–W50 and the CO clouds.

To summarize, the previous studies on the possible interaction between a relativistic jet and interstellar matter have shown two possible cases of such interactions, SS 433 and GRS 1915+105. It is therefore still the beginning of observations of such interactions, and theoretical studies of the interactions largely remain unexplored.

NANTEN, a 4 m mm/sub-mm telescope located in Chile, has been used to make an extensive survey of the Galactic plane in $^{12}\text{CO} (J = 1–0)$ emission at a grid spacing of $4^\prime$ at $|b| \leq 5^\circ$ and that of $8^\prime$ at $5^\circ \leq |b| \leq 10^\circ$ (for more details see e.g., Mizuno & Fukui 2004). This offers a few-times spatially finer CO images at $|b| \leq 5^\circ$ compared to the previous low-resolution CO survey (Dame, Hartmann & Thaddeus 2001). The new NANTEN CO dataset is useful to search uniformly for various phenomena towards $\pm 10^\circ$ of the Galactic plane on a large scale, including supershells and other active events (e.g., Fukui et al. 1999, 2006; Matsunaga et al. 2001).

In the present paper, we show and discuss the observational results of molecular clouds that may be associated with a relativistic jet toward SS 433 and $l \sim 348^\circ.5$, and their implications. Section 2 gives a summary of the CO dataset. Sections 3 and 4 present the main observational results for the two regions and a model is presented and discussed in section 5. Conclusions are given in section 6.

### 2. The NANTEN CO Dataset

We used the NANTEN Galactic Plane Survey dataset of the $^{12}\text{CO} (J = 1–0)$ emission (Mizuno & Fukui 2004). The coverage of the data is $220^\circ$ from $l \sim 200^\circ$ to $60^\circ$, including the Galactic center and at $|b| \leq 5^\circ$ with a grid spacing of $4^\prime$ and at $5^\circ \leq |b| \leq 10^\circ$ with a grid spacing of $8^\prime$ for the main beam width of $2.6$ in addition to selected areas of nearby clouds at $|b| \geq 10^\circ$ (e.g., Mizuno et al. 2001; Onishi et al. 2001). The total number of observed points is $\sim 1.1$ million. The velocity coverage and resolution of the data are usually from $300 \text{ km s}^{-1}$ to $-300 \text{ km s}^{-1}$ and $0.65 \text{ km s}^{-1}$, respectively. All of the observations were carried out by the position-switching technique. The telescope was equipped with a superconducting mixer receiver (Ogawa et al. 1990). The system temperature, including the atmosphere, was in a range of 250–350 K in the single side-band mode (SSB) on average towards the zenith, and the typical r.m.s. noise fluctuations of the spectral data are $\sim 0.35 \text{ K}/(0.65 \text{ km s}^{-1})$ in the absolute antenna temperature, $T_A^*$, corresponding to an integration time of a few to several seconds per point at on-position.

### 3. SS 433

#### 3.1. Large-Scale Distribution of Molecular Clouds

Figure 1 shows the $^{12}\text{CO} (J = 1–0)$ integrated intensity distribution, whose velocity range is $V_{\text{LSR}} = 40$ to $60 \text{ km s}^{-1}$ in the region of $l = 37^\circ$ to $42^\circ$ and $b = -5^\circ$ to $0^\circ$. Superposed are the H I integrated intensity distribution at a $6^\prime$ effective resolution with the Parkes 64 m telescope (McClure-Griffiths et al. 2005) and the ASCA X-ray distribution of the GIS image in the $0.7$–$10 \text{ keV}$ band (Kotani 1998). We have identified ten $^{12}\text{CO}$ clouds along the X-ray axis of SS 433 at the Galactic center and at $|b| \leq 5^\circ$ with a grid spacing of $4^\prime$ and at $5^\circ \leq |b| \leq 10^\circ$ with a grid spacing of $8^\prime$ for the main beam width of 2:6 in addition to selected areas of nearby clouds at $|b| \geq 10^\circ$ (e.g., Mizuno et al. 2001; Onishi et al. 2001). The total number of observed points is $\sim 1.1$ million. The velocity coverage and resolution of the data are usually from $300 \text{ km s}^{-1}$ to $-300 \text{ km s}^{-1}$ and $0.65 \text{ km s}^{-1}$, respectively. All of the observations were carried out by the position-switching technique. The telescope was equipped with a superconducting mixer receiver (Ogawa et al. 1990). The system temperature, including the atmosphere, was in a range of 250–350 K in the single side-band mode (SSB) on average towards the zenith, and the typical r.m.s. noise fluctuations of the spectral data are $\sim 0.35 \text{ K}/(0.65 \text{ km s}^{-1})$ in the absolute antenna temperature, $T_A^*$, corresponding to an integration time of a few to several seconds per point at on-position.

![](https://academic.oup.com/pasj/article-abstract/60/4/715/1396856/1)

**Fig. 1.** Integrated intensity map of $^{12}\text{CO} (J = 1–0)$ (black contours) superposed on the H I (gray scale), whose velocity range is $40$ to $60 \text{ km s}^{-1}$. The boundaries of SS 433-N1–SS 433-N4, and SS 433-S1–SS 433-S6 are shown by thick contour lines. The contours of the CO are illustrated every $1.8 \text{ K km s}^{-1}$, respectively. All the typical r.m.s. noise fluctuations of the spectral data are $\sim 0.35 \text{ K}/(0.65 \text{ km s}^{-1})$ in the absolute antenna temperature, $T_A^*$, corresponding to an integration time of a few to several seconds per point at on-position.
the lowest 3σ contour level in $l \sim 39°$–$41°$ and $b \sim 5°$–$-1°$. Southeast of SS 433 there are six clouds, named from SS 433-S1 to SS 433-S6 at $b \sim -3°$–$-5°$ and at $V_{\text{LSR}} \sim 42$–$45 \text{ km s}^{-1}$. Northwest of SS 433 there are four clouds, named from SS 433-N1 to SS 433-N4 at $b \sim -1°$–$-2°$ and at $V_{\text{LSR}} \sim 50$–$55 \text{ km s}^{-1}$. The observed parameters of these clouds are listed in table 1.

These ten clouds exhibit a remarkably straight distribution along the axis of the X-ray jet of SS 433. This alignment is approximated by the dashed line in figure 1, as determined by a linear-regression fit on the clouds weighted in the total CO intensity, and is expressed as $b^\circ = (63 \pm 2^\circ) - (1.65 \pm 0.05) \times l^\circ$ with a high correlation coefficient of $\sim 0.98$. This line passes almost exactly through the position of SS 433 ($l, b = (39^\circ 7, -2^\circ 2)$), as shown in figure 1. We note that the position angle of the line is $\sim 30^\circ$ in the galactic coordinate, while that of the X-ray jet is $\sim 20^\circ$, showing a small difference of $\sim 10^\circ$.

The southern clouds were discovered by the present work. Some of the northern clouds have already been observed and the interaction with the SS 433 jet has been discussed for SS 433-N1 to SS 433-N4 by previous authors (Band & Gordon 1989; Durouchoux et al. 2000; Fuchs et al. 2001; Moldovan et al. 2005).

Table 1. Physical properties of $^{12}$CO clouds.

| No.         | $l$ ($^\circ$) | $b$ ($^\circ$) | $T_R$ (K) | $\Delta V$ (km s$^{-1}$) | $V_{\text{LSR}}$ (km s$^{-1}$) | $N(H_2)$ (10$^{21}$ cm$^{-2}$) | $R$ (pc) | $M_{\text{CO}}$ ($M_\odot$) | $M_{\text{vir}}$ ($M_\odot$) | $t_{\text{cross}}$ (Myr) |
|-------------|---------------|---------------|-----------|--------------------------|-------------------------------|--------------------------------|---------|---------------------------|-----------------------------|--------------------------|
| SS 433-N1   | 39.27         | -1.60         | 4.0       | 3.1                      | 55.8                          | 3.9                            | 5.1     | 2500                      | 6000                        | 2.3                      |
| SS 433-N2   | 39.33         | -1.33         | 6.0       | 2.9                      | 53.7                          | 3.0                            | 5.5     | 3100                      | 14000                       | 1.6                      |
| SS 433-N3   | 39.47         | -1.53         | 3.3       | 1.3                      | 53.0                          | 1.5                            | 3.6     | 1300                      | 5400                        | 1.3                      |
| SS 433-N4   | 39.60         | -1.87         | 10.0      | 2.3                      | 49.4                          | 4.8                            | 3.6     | 2100                      | 5000                        | 1.4                      |
| SS 433-S1   | 40.53         | -3.53         | 3.9       | 1.4                      | 42.9                          | 1.4                            | 2.8     | 600                       | 1200                        | 1.9                      |
| SS 433-S2   | 40.53         | -3.87         | 2.7       | 2.2                      | 45.4                          | 1.4                            | 2.0     | 400                       | 6400                        | 0.5                      |
| SS 433-S3   | 40.80         | -4.13         | 2.9       | 2.4                      | 44.1                          | 1.7                            | 2.8     | 900                       | 3300                        | 1.2                      |
| SS 433-S4   | 41.13         | -4.20         | 1.8       | 3.8                      | 43.2                          | 1.5                            | 3.6     | 1200                      | 21000                       | 0.7                      |
| SS 433-S5   | 41.13         | -4.60         | 1.2       | 4.2                      | 44.8                          | 1.1                            | 2.8     | 500                       | 16000                       | 0.5                      |
| SS 433-S6   | 41.33         | -4.53         | 2.4       | 2.6                      | 42.1                          | 1.4                            | 5.6     | 2300                      | 16000                       | 1.6                      |
| MJ G348.5-N | 348.47        | 1.73          | 3.3       | 5.4                      | -95.0                         | 2.3                            | 12.5    | 14000                     | 77000                       | 2.3                      |
| MJ G348.5-S1| 348.53        | -0.80         | 1.9       | 3.4                      | -82.4                         | 1.6                            | 3.9     | 1500                      | 9700                        | 1.2                      |
| MJ G348.5-S2| 348.68        | -1.67         | 1.6       | 3.3                      | -80.0                         | 1.1                            | 5.6     | 2000                      | 12000                       | 1.7                      |
| MJ G348.5-S3| 348.67        | -2.13         | 3.2       | 4.3                      | -81.3                         | 1.3                            | 9.6     | 8300                      | 26000                       | 2.2                      |

Col. (1): Cloud name, Col. (2)–(3): Cloud peak ($l, b$) position, Col. (4): Peak temperature, Col. (5): Line width of the composite spectrum, Col. (6): Peak velocity of the composite spectrum, Col. (7): Column density of peak position, Col. (8): Radius of the molecular cloud, Col. (9): Mass of the molecular cloud, Col. (10): Virial mass of the molecular cloud, Col. (11): Crossing time of the molecular cloud.

† The distance is assumed as 3 kpc on SS 433 and 6 kpc on MJ G348.5. In details, see subsections 3.2 and 4.2.

Figure 2b shows the velocity distribution of the $^{12}$CO clouds in a position-velocity diagram superposed on the H I distribution. The position is the offset from SS 433 taken along a line tilted to the galactic plane by 45°, as indicated in figure 2a. Some of the clouds are overlapped in the figure, and the number of the clouds apparently becomes less than ten. The typical velocities of the northern clouds, SS 433-N1 to SS 433-N4, and the southern clouds, SS 433-S1 to SS 433-S6, are $\sim 53 \text{ km s}^{-1}$ and $\sim 43 \text{ km s}^{-1}$, respectively, on average. We note that the internal velocity dispersions of these clouds are as small as 2 km s$^{-1}$, while that of SS 433-S6 is $\sim 4 \text{ km s}^{-1}$. It is not certain if another cloud at an offset of $1.5°$ and $V_{\text{LSR}} \sim 50 \text{ km s}^{-1}$ is related to the present northern clouds.

Figure 3 shows a larger scale view of the region in the $^{12}$CO integrated intensity distribution in the same velocity range as in figure 1, covering 50 square degrees from $l = 35°$ to $45°$ and $b = -5°$ to $0°$. This demonstrates that there are only a few CO clouds, except for the present ones, over a volume of $\sim 500 \text{ pc}$ (in $l \times \sim 100 \text{ pc}$ in $b \times \sim 1 \text{ kpc}$ in the line of sight (in $v$)) at $b \lesssim -3°$ for an assumed distance of $\sim 3 \text{ kpc}$ (see subsection 3.2). We note that the present CO southern clouds are distributed up to $z \sim 240 \text{ pc}$, very far out from the galactic plane, whose typical scale height in CO emission is $\sim 87 \text{ pc}$ (Dame et al. 1987). The southern CO clouds located at around $4°$ are therefore very rare, and a group of such aligned clouds is quite unique. We shall hereafter assume that the ten clouds are at the distance of SS 433 because of their similar velocities and alignment.

### 3.2. Physical Parameters

The two average velocities of the CO clouds, $53 \text{ km s}^{-1}$ and $43 \text{ km s}^{-1}$, correspond to kinematic distances of 3.5 kpc and 3 kpc, respectively, for the flat rotation curve (Brand & Blitz 1993), while another kinematic distance around $\sim 10 \text{ kpc}$ is also permitted. According to previous studies, the distance to SS 433 is estimated to be $\sim 3 \text{ kpc}$ from the absorption of atomic hydrogen (van Gorkom et al. 1980) and the velocity of the cavity of atomic hydrogen (Dubner et al. 1998), $\sim 4.85 \text{ kpc}$ from six radio continuum images at two-day intervals with VLBI by Vermeulen et al. (1993) and $\sim 5.5 \text{ kpc}$ from radio continuum observations in the central part of SS 433 with VLA (Hjellming & Johnston 1981; Blundell & Bowler 2004). We shall hereafter tentatively adopt the distance to SS 433 as the smaller value, 3 kpc, which is consistent with the present kinematic distance. This gives conservative estimates of related physical...
Fig. 2. (a) Same as figure 1, but the contour levels of CO are every 10 K km s\(^{-1}\) from 3.6 K km s\(^{-1}\). (b) Position-velocity diagram of \(^{12}\)CO (\(J = 1-0\)) emission (contours) superposed on the HI (gray scale), which is integrated in the direction of the long side of the rectangle in (a). The contours of the CO are illustrated every 1.5 K from 5.5 K. The offsets are relative to the position of SS 433. (Color Online)
parameters, such as the radius and mass of the molecular clouds. If the cloud velocity is affected by motion other than galactic rotation, this estimate needs to be reconsidered.

The physical parameters of the clouds were calculated as listed in Table 1. We adopt the X factor, which is defined as $N(H_2)/W(12\text{CO})$, of $2.0 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ (Lebrun et al. 1983; Bertsch et al. 1993), in these calculations. The linewidth, mass, size, and peak $T_R$ are similar to those of nearby dark clouds (e.g., Mizuno et al. 2001; Tachihara et al. 2001). The cloud mass ranges from $10^2$ to $10^3 M_\odot$. The total molecular mass of the southern clouds amounts to $5.9 \times 10^3 M_\odot$, while that of the northern clouds is $9.0 \times 10^3 M_\odot$. The virial mass of these molecular clouds is several-times larger than this luminous mass, indicating that the molecular clouds are not gravitationally bound; this is a typical property of molecular clouds in such a low mass range (e.g., Onishi et al. 2001; Yamamoto et al. 2003, 2006). They may be confined by the ambient pressure or be transient at a timescale of $10^6$ yr, the crossing timescale as discussed in previous studies, including the above two.

### 3.3 Comparison with Radio Continuum, H I and X-Ray around SS 433

Figure 4 shows an overlay of the radio continuum distribution of W50, a supernova remnant associated with SS 433, at 4850 MHz (e.g., Condon et al. 1989) on the H I 21 cm line integrated intensity in the $V_{\text{LSR}}$ range of 40–60 km s$^{-1}$. The SNR is elongated by $2^\circ$ towards the same direction as the X-ray jet, while the width is $1^\circ$, significantly larger than the X-rays, showing a sharp intensity gradient towards the galactic plane. The northern clouds SS 433-N1, SS 433-N2 and SS 433-N3 are located towards the northern edge of the SNR, and SS 433-N4 seems to be located inside of the SNR. On the other hand, the southern clouds are separated from the SNR. Dubner et al. (1998) show that the SNR W50 is located towards a hole of the H I emission and argue that the hole may have been created by the supernova explosion. We confirm this suggestion as the H I depression towards SS 433 in Figure 4. A recent H I study in and around the SS 433-W50, reported by
Lockman et al. (2007), suggests that the H I gas at a velocity \( \sim 75 \text{ km s}^{-1} \) has interacted with the W50 from the morphology of the H I gas by new observations and its distance. The 75 km s\(^{-1}\) component of the H I gas also seems to be interacting with SS 433-W50 at the upper part of the W50. However, here we use the H I data at \( V_{\text{LSR}} \sim 40-60\text{ km s}^{-1} \) because the velocity of the present molecular clouds is \( \sim 40-60\text{ km s}^{-1} \), and these are not associated with the H I at \( V_{\text{LSR}} \sim 75\text{ km s}^{-1} \).

We find in figures 1 and 3 that the southern CO clouds are located towards a H I protrusion peaked at \((l, b) \sim (40\text{°}9, -3\text{°}9)\), where the present CO clouds are distributed within a H I contour of 410 K km s\(^{-1}\). Figure 2b shows that the CO velocity agrees with the H I velocity at an offset of \(-1\text{°} - 3\text{°}\). These results suggest that the southern CO clouds and the H I are physically associated. In figure 2b the northern clouds also seem to be associated with the H I at the offset of \(0\text{°}5-1\text{°}\), while the H I velocity is slightly larger by a few km s\(^{-1}\) than the CO velocity.

The H I mass of the protrusion towards \(39\text{°} \leq l \leq 41\text{°}4\) and \(-3\text{°}4 \leq b \leq -5\text{°}\) within a contour level of 410 K km s\(^{-1}\) is estimated to be \(51000 M_\odot\) by using the conventional factor of the H I intensity into mass, \(1.8 \times 10^{18}\text{ cm}^{-2}/(\text{K km s}^{-1})\). The total molecular mass of the southern CO clouds is \(\sim 3900 M_\odot\), corresponding to about one tenth of that of H I.

The ASCA X-ray distribution shown in figure 1 clearly indicates the two lobes of the X-ray jet, the West and East lobes, respectively. SS 433-N4 is located towards the West lobe and SS 433-N1 and SS 433-N3 also show some overlapping with this lobe. This may suggest some interaction between them, as already noted by Durouchoux et al. (2000). SS 433-N2 is somewhat far from the other clouds and its physical association with the X-ray lobe may not be certain. We note that the field of view of the X-ray observations towards the lobe is limited to the three fields centered on SS 433 covering regions within \(\sim 1\text{°}\) of SS 433. Thus, the distribution of X-rays outside the area remains to be uncovered.

4. Linearly Aligned Molecular Clouds Perpendicular to the Galactic Plane towards \(l \sim 348\text{°}5\)

4.1. Large-Scale Molecular Distribution

In the course of a detailed analysis of the \(^{12}\text{CO}\) dataset, we have discovered an unusual aligned distribution of CO clouds toward \(l \sim 348\text{°}5\). Figure 5 shows an integrated intensity distribution of \(^{12}\text{CO}\) \((J = 1-0)\) emission, whose velocity range is from \(V_{\text{LSR}} = -100 \text{ to } -70 \text{ km s}^{-1}\) in the region of \(347\text{°} \leq l \leq 350\text{°}\) and \(-3\text{°} \leq b \leq 3\text{°}\). Four clumpy clouds located at \(b \sim 1\text{°}7, -0\text{°}8, -1\text{°}7, \) and \(-2\text{°}1\) are aligned nearly perpendicular to the Galactic plane where most of the intense CO emission is confined at \(|b| \leq 0\text{°}5\). We shall tentatively assume the physical association of the four clouds in the following, and name the group of southern and northern clouds as MJ G348.5 (= molecular jet at \(l = 348\text{°}5\)). We hereafter call the four components MJ G348.5-N, MJ G348.5-S1, MJ G348.5-S2, and MJ G348.5-S3, respectively, as labeled in figure 5. We note the separations between the northern and southern tips of the molecular clouds MJ G348.5-N and MJ G348.5-S3, and the Galactic plane is nearly \(\sim 2\text{°}\), respectively. A linear-regression fit to the four clouds, shown in figure 5 by a dashed line, with integrated intensity weighting yields the relationship \(b''(\circ) = (-13.67 \pm 1.63) \times l(\circ) + (4765.69 \pm 566.64)^{(\circ)}\) with a correlation coefficient of \(\sim 0.89\), which passes through the Galactic plane at \(l = 348\text{°}5\), and is nearly perpendicular to the Galactic plane at an angle between the line and the Galactic plane of \(\sim 86\text{°}\). The apparent largest separation of MJ G348.5-S3 from the Galactic plane is \(\sim 2\text{°}\). The \(V_{\text{LSR}}\) of the southern three components is \(\sim -82 \text{ km s}^{-1}\) and that of the northern one is \(\sim -95 \text{ km s}^{-1}\), as shown in figure 6a. We note that the two clouds, MJ G348.5-N and MJ G348.5-S3,

![Galactic Longitudes](https://example.com/galactic_longitudes.png)
exhibit the largest dispersion of $\sim 7 \text{km s}^{-1}$ (see figures 6b and 6c), while the other clouds, MJ G348.5-S1 and MJ G348.5-S2, show smaller velocity dispersions of $\sim 3 \text{km s}^{-1}$.

We further note that another cloud is located at $l \sim 347.7$ and $b \sim 1.6$ at a LSR velocity of $\sim -83.0 \text{km s}^{-1}$. This cloud is also unusual at such high latitude and large LSR velocity.

We come back to this feature later in a comparison with the HI and in the discussion section.

Figure 7 shows a larger scale view of the region in the $^{12}$CO integrated intensity distribution in the same velocity range as in figure 5, covering 200 square degrees from $l = 339^\circ$ to $359^\circ$ and $b = -5^\circ$ to $5^\circ$. This demonstrates that there are only a few CO clouds, except for the present ones over a volume of $\sim 2 \text{kpc}$ in $l$ and $0.4 \text{kpc}$ in $b$ in the line of sight in $v$ at $|b| \leq 3^\circ$ for a kinematic distance of $\sim 6 \text{kpc}$, as derived below. The CO clouds located at more than $\pm 1.5$ in Galactic latitude are very rare, and a group of such clouds aligned in a straight line is unique, as in the case of SS 433. We further note that the present CO clouds are distributed to $z \sim 240 \text{pc}$, very far out of the typical CO scale height of the CO emission, $\sim 87 \text{pc}$ (Dame et al. 1987).

### 4.2. Physical Properties of the Molecular Clouds

The averaged $V_{\text{LSR}}$ of MJ G348.5-S1, MJ G348.5-S2, and MJ G348.5-S3 is $\sim -82 \text{km s}^{-1}$, corresponding to a kinematic distance of $5.9 \text{kpc}$ or $10.8 \text{kpc}$, and that of MJ G348.5-N of $\sim -95 \text{km s}^{-1}$ corresponds to $6.1 \text{kpc}$ or $10.5 \text{kpc}$, respectively, if we assume a flat rotation curve (Brand & Blitz 1993). We tentatively adopt the smaller averaged value, $\sim 6 \text{kpc}$, hereafter, since it gives conservative estimates of the cloud parameters, noting that the kinematic distance may include a large uncertainty toward this direction near the center. For instance, the kinematic distance changes from $5.7 \text{kpc}$ to $6.0 \text{kpc}$ for a velocity difference of $+5 \text{km s}^{-1}$, a typical velocity dispersion in HI clouds. The alignment of the three southern molecular clouds is remarkably good over a length of $\sim 200 \text{pc}$ with a width of $\sim 10 \text{pc}$ at $6 \text{kpc}$. The location of the northern
cloud, MJ G348.5-N, is fairly symmetric to MJ G348.5-S3 with respect to the plane.

The relevant observed and derived physical parameters of the present clouds are summarized in Table 3. The peak temperature and line width of the $^{12}$CO emission of the four molecular clouds are 1.6 to 3.3 K and 3.3 to 5.4 km s$^{-1}$, not much different from those of the typical CO clouds, whose average density and kinetic temperature are $n$(H$_2$) $\sim$ 10$^2$ cm$^{-3}$ and $T_k$ $\sim$ 10 K (see for typical nearby dark clouds, e.g., Mizuno et al. 2001; Tachihara et al. 2001). The range of mass of each CO cloud is from $1.5 \times 10^3$ to $1.4 \times 10^4$ M$_\odot$ by adopting the X factor $N$(H$_2$)/$W$($^{12}$CO), of $2.0 \times 10^{20}$ cm$^{-2}$/K km s$^{-1}$ (Bertsch et al. 1993). In total, the molecular mass in the four clouds is estimated to be $2.6 \times 10^4$ M$_\odot$. They share similar dynamical properties with those in SS 433, as mentioned in subsection 3.2.

### 4.3. Comparison with the HI

Figures 8a and 8b show two velocity channel maps of $^{12}$CO superposed on the distribution of the 21 cm H I line emission integrated in the corresponding velocity ranges. The effective H I resolution is 16$''$ with the Parkes 64 m telescope (McClure-Griffiths et al. 2005). The strong H I emission at $b > 1^\circ$ is the Galactic-disk emission. At $b > 1^\circ$ we are able to identify the H I features associated with the present CO clouds. Towards MJ G348.5-N at $b < 1^\circ$, an isolated H I cloud is found in figure 8a. This H I cloud, having a size of $\sim 50$ pc $\times$ $\sim 30$ pc at 60 K km s$^{-1}$, is elongated in a similar direction to the CO distribution from NW to SE tilted to the Galactic plane by $\sim 45^\circ$. Towards the southern three

### Table 2. List of supernova remnants and high-energy sources toward MJG348.5 in the galactic plane.*

| Name | Positions | Type of source | Wavelength of detection | Associated objects |
|------|-----------|----------------|-------------------------|--------------------|
| G348.5+0.1 (CTB37A)$^*$ | $l = 348\text{'}39$, $b = 17\text{'}14\text{''}6.0$ | SNR | Radio-Conti. (90cm) | CTB 37A |
| G348.5−0.0$^*$ | $l = 348\text{'}60$, $b = 17\text{'}15\text{''}26.0$ | SNR | Radio-Conti. (90cm) | CTB 37B |
| G348.7+0.3 (CTB37B)$^*$ | $l = 348\text{'}65$, $b = 17\text{'}13\text{''}55.1$ | SNR | Radio-Conti. (90cm) |
| 3EG J1714−3857$^*$ | $l = 348\text{'}04$, $b = 17\text{'}14\text{''}5.4$ | $\gamma$-ray | $\gamma$-ray ($E > 100$ MeV) |
| H.E.S.S. J1713−381$^*$ | $l = 348\text{'}65$, $b = 17\text{'}13\text{''}58.2$ | $\gamma$-ray | $\gamma$-ray ($E > 100$ GeV) |
| 1RXS J17132.8−390553$^*$ | $l = 348\text{'}83$, $b = 17\text{'}13\text{''}12.8$ | X-ray | X-ray |
| 1RXS J171551.8−385843$^*$ | $l = 348\text{'}23$, $b = 17\text{'}15\text{''}51.9$ | X-ray | X-ray |
| 1RXS J171557.7−385152$^*$ | $l = 348\text{'}33$, $b = 17\text{'}15\text{''}57.7$ | X-ray | X-ray |
| 1RXS J171354.4−381740$^*$ | $l = 348\text{'}56$, $b = 17\text{'}13\text{''}54.4$ | X-ray | X-ray |

* Sources within $1^\circ$ from $(l, b) = (348\text{'}5, 0\text{'}0)$ are listed.

$^*$ Hartman et al. (1999)

| Name | Positions | Type of source | Wavelength of detection | Associated objects |
|------|-----------|----------------|-------------------------|--------------------|
| G348.5+0.1 (CTB37A)$^*$ | $l = 348\text{'}39$, $b = 17\text{'}14\text{''}6.0$ | SNR | Radio-Conti. (90cm) | CTB 37A |
| G348.5−0.0$^*$ | $l = 348\text{'}60$, $b = 17\text{'}15\text{''}26.0$ | SNR | Radio-Conti. (90cm) | CTB 37B |
| G348.7+0.3 (CTB37B)$^*$ | $l = 348\text{'}65$, $b = 17\text{'}13\text{''}55.1$ | SNR | Radio-Conti. (90cm) |
| 3EG J1714−3857$^*$ | $l = 348\text{'}04$, $b = 17\text{'}14\text{''}5.4$ | $\gamma$-ray | $\gamma$-ray ($E > 100$ MeV) |
| H.E.S.S. J1713−381$^*$ | $l = 348\text{'}65$, $b = 17\text{'}13\text{''}58.2$ | $\gamma$-ray | $\gamma$-ray ($E > 100$ GeV) |
| 1RXS J17132.8−390553$^*$ | $l = 348\text{'}83$, $b = 17\text{'}13\text{''}12.8$ | X-ray | X-ray |
| 1RXS J171551.8−385843$^*$ | $l = 348\text{'}23$, $b = 17\text{'}15\text{''}51.9$ | X-ray | X-ray |
| 1RXS J171557.7−385152$^*$ | $l = 348\text{'}33$, $b = 17\text{'}15\text{''}57.7$ | X-ray | X-ray |
| 1RXS J171354.4−381740$^*$ | $l = 348\text{'}56$, $b = 17\text{'}13\text{''}54.4$ | X-ray | X-ray |

### Table 3. Physical parameters of SS 433.

| Velocity$^*$ | Mass flow rate$^*$ | Momentum$^*$ | Kinetic power$^*$ | Timescale$^*$ |
|--------------|-------------------|--------------|-------------------|--------------|
| $0.26c$      | $1.5 \times 10^{-7}$ | $1.2 \times 10^{-2}$ | $1.1 \times 10^{46}$ | $2 \times 10^{4}$ |

$^*$ Margon & Anderson (1989)

$^*$ Marshall et al. (2002)

$^*$ (Velocity) $\times$ (Mass flow rate)

$^*$ Zealey et al. (1980)

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**Fig. 8.** Integrated intensity channel maps of $^{12}$CO($J = 1$–0) (black and white contours) superposed on that of H I (gray scale and black dashed contours). MJ G348.5-N, MJ G348.5-S1, MJ G348.5-S2 and MJ G348.5-S3 are shown by black solid contours. The velocity ranges of both CO and H I data in (a) and (b) are $-100$ to $-85$ km s$^{-1}$ and $-85$ to $-70$ km s$^{-1}$, respectively. The contours of CO and H I are illustrated every 2.1 K km s$^{-1}$ from 4.2 K km s$^{-1}$ and every 15 K km s$^{-1}$ from 15 K km s$^{-1}$, respectively. (Color Online)
Fig. 9. Channel maps of the longitude–velocity diagram from 2°53 to −2°53, except within ±0°33 every 0°2 in Galactic latitude. The velocity of H I and CO was smoothed at a resolution of 1 km s$^{-1}$. The range of the galactic latitude is shown in the upper side of each channel map. The gray-scale and dashed contours are H I, and the solid contours are CO. MJ G348.5-N, S1, S2, and S3 appear to the channel maps of (d) and (e), (f), (p) and (q), and (r) and (s), respectively. The contour levels of CO and H I are illustrated every 1.5 K from 2.0 K and every 2.0 K from 4.0 K, respectively. (Color Online)
clouds, MJ G348.5-S1, MJ G348.5-S2, and MJ G348.5-S3, we can see that a protrusion of the H I emission is extended at \(l \sim 348.5^\circ\) up to \(b \sim -2^\circ 4\). MJ G348.5-S2 is associated with part of the H I protrusion towards \(l \sim 348.6^\circ\) and \(b \sim -1^\circ 7\) at a contour level of \(\sim 135\) K km s\(^{-1}\). This H I emission has a size of \(\sim 100\) pc \(\times \sim 60\) pc at the H I contour level of \(105\) K km s\(^{-1}\) elongated to the Galactic plane by \(\sim 45^\circ\) from NE to SW. The H I protrusion is also identified in figure 6(a) in a velocity range from \(-90\) K km s\(^{-1}\) to \(-75\) K km s\(^{-1}\) at a H I contour level of \(\sim 85\) K. In addition, MJ G348.5-S3 is associated with the southern extension of the H I protrusion towards \(l \sim 348.6^\circ\) and \(b \sim -2^\circ 0\) (figure 8b), which is identified at \(V_{LSR} \sim -80\) K km s\(^{-1}\) in figure 6a. These spatial and velocity extents of the H I emission are to be regarded as the lower limits by considering the possible more extended H I features at lower intensity levels.

We have further inspected the H I distribution in detail. Figure 9 shows longitude-velocity diagrams of the H I superposed on the CO in \(b \sim 2^\circ 5^\circ\) to \(-2^\circ 5^\circ\), except for the area within \(\pm 0.5^\circ\) where contamination is strong. The CO emission is clearly associated with H I in panels (d), (e), (l), (p), (q), (r), and (s) of figure 9, confirming that the H I is associated with MJ G348.5-S3. The H I associated with MJ G348.5-S3 is not clearly resolved, but the upper limits of the line width and the radius of the H I associated with MJ G348.5-S3 are roughly estimated to be \(\sim 5\) K km s\(^{-1}\) and \(\sim 6.8\) pc at 6 kpc, respectively, yielding the crossing time of H I, \(\sim 2.3 \times 10^6\) yr, similar to that of the molecular cloud, MJ G348.5-S3. The mass of the associated H I both in the southern protrusion and in the northern cloud is estimated to be \(\geq 25000\) \(M_\odot\) at an H I integrated intensity level of \(100\) K km s\(^{-1}\), which is about two thirds of the total mass of the four molecular clouds. Here, we used the conventional relationship to convert the H I intensity into mass \(1.8 \times 10^{18}\) cm\(^{-2}\) (K km s\(^{-1}\)) by assuming optically thin H I emission.

We note that the CO cloud towards \(l \sim 347^\circ 7\) and \(b \sim 1^\circ 6\) at a LSR velocity of \(-83\) K km s\(^{-1}\) shows a H I counterpart. This cloud is clearly associated with H I, as can be seen in panels (e) and (f) of figure 9. Figure 8 also shows this H I cloud in panel (b). We further note that an H I protrusion is seen towards \((l, b) = (347^\circ 5, -1^\circ 4)\) of figure 8, which could be a possible counterpart in the south. The real physical association of these clouds is still uncertain compared with MJ G348.5 clouds.

To summarize, the H I distribution superposed in the position-velocity diagrams (figures 6a and 9) and in the sky (figures 8a and 8b) suggest that H I gas is physically associated with the four molecular clouds.

### 4.4. High-Energy Objects in the Galactic Plane

Energetic sources are not associated towards the individual molecular clouds, but toward the Galactic plane at \(l \sim 348^\circ 5\), the point of crossover between the straight line defined by these molecular clouds (subsection 4.1) and the Galactic plane; there are several energetic sources already confirmed by observations of non-thermal radio emission, X-rays and \(\gamma\)-rays, as summarized in table 2. In figure 5, the positions of the known supernova remnants, SNR G348.5+0.1 (CTB37A), G348.5–0.0, and G348.7+0.3 (CTB37B), are indicated by crosses (e.g., Kassim et al. 1991). In addition, there are two TeV \(\gamma\)-ray sources confirmed by H.E.S.S. observations that may be associated with these SNRs or their stellar remnants, as shown in figure 15 of Aharonian et al. (2006). We note that the positional coincidence of the crossover point and these energetic sources, particularly CTB37A, is remarkably good. Other high-energy sources are identified by EGRET and ROSAT All Sky Survey (Hartman et al. 1999; Voges et al. 1999) near the three SNRs, although the positions between these sources and the three SNRs are slightly different, except for 1RXS J171354.4–381740, as shown in figure 5 (see also table 2). The relationship between molecular clouds and these energetic sources is discussed in the next section.

### 5. Discussion

#### 5.1. The Aligned Molecular Clouds

The present study has revealed remarkably well-aligned molecular clouds of \(\sim 300–400\) pc in length in the two fields of the Galaxy. The existence of the CO clouds, themselves, is rare at high \(z\) values greater than \(\sim 100\) pc. The alignments are not accidental, by considering even the rare coincidence in velocity; the several clouds on a line passing through SS 433 at \(z \sim 200\) pc strongly indicate a physical association among them, and also with SS 433. The similar features in MJ G348.5 are also very unusual, suggesting their physical association. The probability for such aligned clouds is indeed very low, as shown in the Appendix.

We here estimate the spatial and velocity dispersions of the aligned molecular clouds. In SS 433, only the southern clouds are dealt with because the northern clouds are contaminated by the galactic background emission. The 1\(\sigma\) dispersion of the displacement of the molecular clouds from the dashed line in figure 1 is around \(\sim 9.7 \pm 2.0\) pc for the intensity-weighted average. Figure 2b was used to estimate the 1\(\sigma\) velocity dispersion as \(\sim 5.0 \pm 1.0\) K km s\(^{-1}\). The same procedure was applied to the MJ G348.5 clouds, yielding a spatial dispersion of \(\sim 7.3 \pm 1.4\) pc and a velocity dispersion of \(\sim 2.2 \pm 0.3\) K km s\(^{-1}\), respectively. These small dispersions in both the cases indicate the excellent alignments in both space and velocity (table 1).

SS 433 is one of the best-studied compact objects driving a relativistic jet. The jet of SS 433 has a spatial extent of \(\sim 80\) pc in X-rays, the largest size of such a jet known to date in the Galaxy. The jet is still being accelerated near the driving source at a velocity of \(0.26c\), as determined from Doppler measurements of the H\(\alpha\) emission (Margon et al. 1979). The jet is likely to be driven by the accretion disk plus a stellar remnant that has a deep gravitational potential well of a black hole or a neutron star. The disk material is perhaps being supplied from a counterpart of the binary, an ordinary evolved star having a large envelope. On the other hand, MJ G348.5 does not have a known jet-accelerating object in the center. We first focus on SS 433 in the following, and discuss a possibility that the present clouds were created by a relativistic jet driven by a compact object, and then extend the model to MJ G348.5.

Before moving to the relativistic-jet interpretation, we consider two alternative possibilities, i.e., “protostellar bipolar outflow” and “supershell wall” to explain the aligned clouds. The known molecular outflow from young stars is several pc at most in length, nearly two orders of magnitude smaller than in the present two cases of SS 433 and MJ G348.5.
(e.g., Lada 1985; Fukui 1989; Bally et al. 2005), and exhibits broad linewidths on the order of 10–100 km s\(^{-1}\), more than an order of magnitude larger than the present linewidths. The aligned clouds are therefore quite different from the protostellar outflow. Supershells produced by massive stars via supernovae and/or stellar winds may offer an explanation for the high z distribution and the large extents of \(\sim 100\) pc. The known molecular supershells are indeed characterized by a few 100 pc radius (Fukui et al. 1999; Yamaguchi et al. 1999; Matsunaga et al. 2001), but the straight distribution of the present clouds is hard to be reconciled with part of an expanding shell that should show non-uniform curved patterns in space and velocity typical of shells. We do not further discuss the supershell interpretation.

5.2. The Relativistic-Jet Model

5.2.1. Scenario

The origin of the molecular clouds towards the SS 433 region is explained as follows. The relativistic jet, whose expanding velocity is a few tens % of the light speed, part of which is observed as an X-ray jet, interacted with H\(\text{I}\) gas peaked towards \(l, b = (40^\circ 9, -3^\circ 9)\). The interaction with the jet agitated the pre-existent H\(\text{I}\) gas dynamically, and heated it up significantly. The kinetic power of the SS 433 jet, \(\sim 1.1 \times 10^{46}\) erg yr\(^{-1}\), is in fact huge (table 3); we shall tentatively assume that very hot gas, such as observed in the X-ray jet, is created via the interaction since no detailed calculations on the process are found in the literature. A natural consequence of the interaction is a cylindrical expanding shock front compressing the gas, which leads to the formation of molecular clouds around the jet axis. The measured velocity and spatial dispersions of the clouds given in table 1 indicate that the typical expansion velocity and the radius of the expanded cylinder are 2–5 km s\(^{-1}\) and 7–10 pc, respectively. The timescale is then roughly estimated to be a few Myr by dividing the radius by the velocity. This offers an explanation on the straight distribution of the present southern CO clouds. The spatial coincidence of the southern CO clouds with the H\(\text{I}\) protrusion over a length of \(\sim 60\) pc is consistent with this scenario, because the background atomic gas is a necessary condition to form molecular clouds. The observed clumped CO distribution may be due to the initial density inhomogeneities in H\(\text{I}\), which is not yet resolved with the present scenario, because the background atomic gas is the shock-compressed H\(\text{I}\) gas. A similar process may have taken place in the north to form the northern clouds where the higher H\(\text{I}\) density exists near the galactic plane. The southern jet is extended by at least \(\sim 150\) pc, while the northern jet can be traced up to \(\sim 50\) pc. This asymmetry may be ascribed to increased deceleration near the galactic plane.

The length of the observed X-ray jet indicates that the jet has a momentum large enough to travel over at least \(\sim 40\) pc. The present scenario implies that the relativistic jet of SS 433 has an actual full extent of \(\sim 150\) pc on the southern side, significantly larger than the known size of the X-ray jet. We note that the X-ray observations by Kotani (1998) does not cover the area of the present southern clouds at \(b\) less than \(-2^\circ\) and the X-ray observations yet remain to be extended towards the region of the southern clouds.

In order to explain the distribution of the aligned clouds toward \(l \sim 348^\circ.5\), we argue that the same mechanism as in SS 433 is working there by assuming the existence of a relativistic jet and a compact driving engine similar to SS 433. All of the basic aspects of the interaction in SS 433 are then applicable to MJ G348.5. The background H\(\text{I}\) is also rich towards the CO clouds, which is consistent with the model. The number of the clouds, four, in MJ G348.5 is less than in SS 433. This may be due to the lower spatial resolution at 6 kpc and/or due to the difference in the initial H\(\text{I}\) distribution.

5.2.2. Timescales

We may estimate the timescale of the interaction. An obvious one is the traveling time over \(\sim 200\) pc, as given by \((150–240\) pc\)/0.26c \(\sim 3 \times 10^3\) yr. A more practical timescale of the interaction will be larger than this when we consider the concerned physical and chemical processes. A possible preliminary guess about the timescales is a crossing timescale of \(\sim 10^6\) yr for each CO cloud. This is roughly consistent with that from the ratio of the velocity and the spatial dispersions of the clouds along the jet axis, although the estimates should be crude at best, and much affected by the initial conditions in the width of the relativistic jet and fluctuations of the H\(\text{I}\) gas in both velocity and density. For instance, the jet may expand in width at 100–200 pc from the engine, causing an increase of the molecular-jet width. In such a case the timescale should be smaller than that mentioned above.

Another possible constraint is the timescale for CO formation in the H\(\text{I}\) gas via interstellar shocks, which requires \(\sim 10^5–10^6\) yr, depending on the density. Recent studies of high latitude molecular clouds associated with a shell created by stellar wind offer observational support for molecular formation by shock compression (Yamamoto et al. 2003, 2006). A theoretical study shows that the shock-produced CO clouds should have peak velocities and velocity dispersions similar to those of the ambient H\(\text{I}\) gas (see Koyama & Inutsuka 2002). The observed velocity dispersion among the CO clouds, \(\sim 2–5\) km s\(^{-1}\), seems to be consistent with this. In order to obtain a more detailed understanding of the physical processes in the interaction, we definitely need to elaborate on the physical and chemical processes in the shock, which is beyond the scope of this paper. Theoretical studies of the magneto-hydrodynamics of such an interaction have been made for protostellar jets (Shibata & Uchida 1990), and are to be extended to the relativistic jet with appropriate modifications of the physical parameters. Such studies will shed more light on the processes discussed above.

Another issue to be considered in SS 433 is the timescale of the SNR. The lifetime of W50 is generally assumed to be on the order of \(10^3\) yr (Safi-Harb & Ogelman 1997; Safi-Harb & Petre 1999), but the present model suggests that the lifetime of the SS 433 jet may be an order of magnitude larger than the assumed lifetime of the SNR. It is important to reinvestigate a possible range of the timescale of the SNR allowed under the present observed physical parameters.

5.2.3. Energetics

We shall examine the energy balance in the interaction by focusing on the SS 433 southern clouds where the interaction is more clearly identified than in the north. In table 3, the kinetic power of the southern SS 433 jet is estimated to be
$\sim 1 \times 10^{46}$ erg yr$^{-1}$ for the speed and mass flow rate derived from the Hα emission (Marshall et al. 2002). The energy deposit in the molecular gas through the interaction is roughly estimated to be $\sim 10^{46}$ erg for an assumed expansion velocity of $\sim 5$ km s$^{-1}$, the velocity dispersion among the CO clouds (table 1). This corresponds to $10^{-3}$ of the total energy of the jet if its duration is $\sim 10^5$ yr, suggesting that the energy requirement is well satisfied under the SS 433 jet properties, and that most of the deposited energy is radiated away. MJ G348.5 also has a similar expansion energy of the molecular clouds, and is explicable with the parameters of the SS 433 jet. If we take into account the atomic mass, this energy may become somewhat larger, but not by more than an order of magnitude.

5.2.4. The interaction with H I

In the present scenario, the jet should lose momentum through its interaction with the pre-existent H I gas. As long as the jet is running at a velocity close to the light speed, we expect an alignment of the formed molecular clouds along the axis because the velocity of the jet is much faster than the local turbulent motion of several km s$^{-1}$ in the undisturbed H I gas (see, e.g., figures 2b and 6a). When the deceleration becomes significant, so that the expanding speed becomes less than the local turbulent velocity of H I, the distribution of the forming clouds may become dominated by the local ambient velocity field. Large velocity dispersions are in fact seen only towards the tips of the jet, i.e., in the SS 433 south cloud (SS 433-S6), MJ G348.5-N and MJ G348.5-S3; also the magnitude of the velocity dispersion, several km s$^{-1}$, is roughly consistent with the local turbulent motion of H I. These enhanced dispersions at the tips may indicate deceleration at the end of the interaction.

In SS 433, it is somewhat unusual that the H I gas is distributed at such a high galactic latitude of $\sim -4^\circ$ prior to the interaction. We suggest that this may be due to the stellar winds by an early type star that caused a supernova explosion prior to formation of the relativistic jet. Such a gas shell is found in CO, H I and dust emission in the Pegasus loop which is driven by an early B-type star (Yamamoto et al. 2006). The H I gas in the south is perhaps part of the shell created by the stellar wind of the supernova precursor.

The mass of each molecular cloud formed by the interaction is on the order of $10^2$--$10^3 M_\odot$, and is comparable to the mass of the H I gas in a cylinder of length 10 pc and radius 10 pc, which is a typical size of molecular clouds having a density of $\sim 10$--$30$ cm$^{-3}$.

5.2.5. Tilt of the jet

It is suggested that the SS 433 jet is tilted to the line of sight by $12^\circ$ in the sense that the southern part is closer to us (Hjellming & Johnston 1981). This is qualitatively consistent with the idea that the southern clouds have smaller velocities than the northern clouds by $\sim 10$ km s$^{-1}$, while the nominal difference of $\sim 500$ pc between the northern and southern clouds in kinematic distance seems too large, where the radial velocity is perhaps affected by motion other than galactic rotation, like the expansion of the H I gas noted above. We should in addition recall that there is a small difference in the projected angle between the molecular jet and the X-ray jet by $10^\circ$. This may be ascribed to a long-term precession of the axis or, alternatively, to the relative motion of the ambient H I gas.

In MJ G348.5, the northern part has blue-shifted velocities compared to the southern part by $\sim 15$ km s$^{-1}$. This is explicable as saying that the jet axis is somewhat tilted to the line of sight in the sense that the northern part is closer to us, while we should again be cautious about the large uncertainties in the kinematic distance.

5.2.6. Candidates for the driving source in MJ G348.5

In SS 433, the driving engine is most likely SS 433, itself, located at (39$\rlap{\degree}$69, $-2^\rlap{\degree}$24) in (l, b). On the other hand, such a compact object is not uniquely identified in MJ G348.5. There are some SNRs and X-ray/$\gamma$-ray sources towards MJ G348.5 listed in the literature (see subsection 4.2). We note that the distances to the three SNRs (CTB37A, CTB37B, and G348.5--0.0) have been estimated by various methods to be $\sim 3.1$ kpc, $\sim 4.8$kpc, and $\sim 10$kpc, respectively (e.g., Caswell et al. 1975; Vermeulen et al. 1993; Reynoso & Mangum 2000). These values are different from the present kinematic distance, 6kpc, although there is a large uncertainty in the kinematic distance towards the center of the Galaxy. It should be important to make detailed observations of energetic sources in the field at radio, X-ray and $\gamma$-ray wavelengths. The present scenario suggests that the interaction occurred $\geq 10^5$ yr ago, possibly longer than the timescale of the currently observed energetic objects mentioned above, and it is also possible that the driving source of MJ G348.5 is not active now. Based on these considerations, we shall postpone discussing the driving engine until more details concerning the high-energy objects are revealed towards the center of MJ G348.5.

5.3. Further Implications

The most developed jet in the Galaxy known to date is that in SS 433 (e.g., Margon 1984; Margon & Anderson 1989; Kotani 1998). GRS 1915+105 is another possible candidate if the associations of the IRAS sources are correct (Chaty et al. 2001). Such an example, showing an elongated jet of more than 10 pc in length, is very rare, except for SS 433, and possibly GRS 1915+105 in the Galaxy. Relativistic jets observed in the X-ray or radio synchrotron emission are usually much smaller in size than the SS 433 jet. These include pulsar wind nebulae (= PWN), like Crab and radio/X-ray jets, including Cygnus X-1 (Gallo et al. 2005), and are on the order of several pc at most. The length of the jet and the physical properties of molecular clouds between SS 443 and MJ G348.5 are nearly the same, and the physical parameters of the driving source of MJ G348.5 may be similar to those of SS 433.

The present discoveries have shown the first candidates for the 400-pc-scale jet from a stellar remnant, three to five-times longer than previously known in the Galaxy. It is also noteworthy that the relativistic jet may be able to interact with the interstellar medium to form molecular clouds. The present findings have opened a new possibility to use millimeter CO emission to search for a relativistic jet from a black hole or a neutron star. The time scale of jet formation is $\sim 10^5$ yr, offering a probe for a past episode of a relativistic jet. At the moment we have only two cases of this kind of molecular jet. This is not surprising since CO surveys with high angular resolutions have rarely been made for the latitude range above 1$^\circ$ in |b| extensively (Jackson et al. 2006). High-resolution CO surveys with a large latitude coverage have a potential to
broaden our knowledge about black holes and neutron stars, and their related activities in the Galaxy.

We recall the other unusual feature shown in figure 5 towards \((i, b) \sim (347.5, 1.6)\) (see subsection 4.1). This cloud may represent a third example of this type; we note that there is a hint of an \(H\ I\) protrusion, a possible counterpart without \(CO\), below the galactic plane at \(b \sim -1^\circ\) at a similar longitude [see figure 8, \((i, b) = (347.5 - 347.7, -1.5 - 1.5)\)]. We cannot exclude a possibility that this cloud is an object similar to MJ G348.5, although the supporting evidence is still weaker than that in the other two examples at the moment.

The process in the present scenario is analogous to what is familiar as the “vapor trail” produced by a jet airplane in the Earth’s atmosphere, although the detailed mechanism of formation is obviously different; the vapor trail is solid or liquid water condensed under the influence of hot ejected matter by a jet engine. A common phenomenological property between the present jet and the vapor trail is that the remnant trail survives over a much longer time scale than that of the interaction, holding the position of the path of the interaction.

We shall propose to call the present jet a “galactic vapor trail”, because of such a similarity.

6. Conclusions

The main conclusions of the present study are summarized as follows:

1. We carried out a detailed analysis in two large areas of \(\sim 25\) square degrees around SS 433 and of \(\sim 18\) square degrees towards \(l \sim 348.5\) using the NANTEN Galactic Plane Survey \(^{12}\)CO \((J = 1-0)\) dataset. We have discovered two groups of well-aligned molecular clouds: ten molecular clouds along the X-ray jet axis of SS 433 and four molecular clouds towards \(l \sim 348.5\) over \(\sim 4^\circ\) in \(b\) with \(\sim 10^\circ\) width perpendicular to the Galactic plane.

2. We suggest that the aligned molecular clouds in the SS 433 region represent molecular gas created by the interaction between the relativistic jet and the interstellar \(H\ I\) gas. The present clouds are extended by \(\sim 150\) pc at a kinematic distance of \(3\) kpc, suggesting that the relativistic jet is more extended by a factor of about three towards the south than the X-ray jet.

3. We applied the same relativistic-jet model to the MJ G348.5 clouds in order to explain the alignment over \(\sim 100\) pc at a kinematic distance of \(\sim 5\) kpc, and suggest that the clouds were created by an interaction between the hypothetical relativistic jet and the \(H\ I\) gas. Four high-energy objects, three SNRs and a gamma-ray source in the galactic plane are considered as candidates for the driving engine, while none of them has a known relativistic jet at the moment.

4. In either case, the estimated kinetic energy of the molecular clouds is \(\sim 10^{44}\) erg, corresponding to \(\%\) of the total kinetic energy released in relativistic jet from SS 433 over \(\sim 10^5\) yr. This suggests that the energy of the relativistic jet is large enough to form such molecular clouds.

5. We suggest that the present findings open a new possibility to search for candidates of a neutron star or a black hole over more than 10-times longer timescales than the direct detection of high-energy radiation from these compact objects. We name the phenomenon as “galactic vapor trail” from the analogy with the vapor trail created by jet airplanes.

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Appendix. Probability of Aligned Clouds

Here, we give a quantitative estimate of the probability for an alignment of molecular clouds along a jet axis.

We first assume that a jet axis is defined by two clouds at lower latitude (e.g., MJ G348.5), or by the driving engine and another cloud at a lower latitude (e.g., SS 433). We then estimate the probability to find another cloud at a higher latitude on the jet axis including the agreement in velocity.

In the case of MJ G348.5, the jet axis is defined by MJ G348.5-S1 and MJ G348.5-S2, and MJ G348.5-S3 “happens” to be located on the axis at a higher latitude than 2\(^\circ\). Figure 7 illustrates that such a CO cloud, like MJ G348.5-S3 at above 2\(^\circ\), is only one in the field presented, and being very rare at both the negative and positive latitudes. The only one exception is seen at \((l, b) = (356^\circ, 2^\circ)\), which is the top of the proposed magnetic flotation loop further away in the galactic center (Fukui et al. 2006). We estimate that only one cloud, MJ G348.5-S3, is found for an area of 500 pc \(\times\) 500 pc projected on the galactic plane (figure 10a), where 500 pc corresponds to half of the projected length along the longitude as well as along the line of sight estimated from the velocity span covered, from \(-100\) km s\(^{-1}\) to \(-70\) km s\(^{-1}\), shown in figure 7.

By adopting a typical cloud size 10 pc as the size of a two-dimensional cell, we can estimate the probability to find S3 on the jet axis as being 10 pc/500 pc \(\times\) 10 pc/500 pc = 1/50 \(\times\) 1/50 \(\sim\) 4 \(\times\) \(10^{-4}\). This is actually a secure upper limit, since there is another cloud N at positive latitude, whose alignment makes the probability of MJ G348.5 even smaller.

In the case of SS 433, the jet axis is defined by two objects, SS 433 itself and, for simplicity, a set of clouds, SS 433-S1 \(-\) SS 433-S4, at \(b\) below \(-4^\circ\) that has a typical spatial dispersion of 10 pc around the jet axis (figure 10b). Another set of clouds,
SS 433-S5 and SS 433-S6, then “happens” to be located on the axis at $b$ above $-4^\circ$. Figure 3 illustrates that such a set of CO clouds, like SS 433-S5 and SS 433-S6, above $-4^\circ$ is only one in the presented field. We again estimate that a set of CO clouds is found for an area of 300 pc projected on the galactic plane (figure 10b), where 300 pc corresponds to half of that along the longitude projected on the sky as well as the depth along the line of sight estimated from the velocity span covered, from 40 km s$^{-1}$ to 60 km s$^{-1}$, shown in figure 3. By using the same argument as above, we estimate the probability to find the clouds on the jet axis to be $\frac{10}{3}$ pc/$300$ pc, shown in figure 3. By using the same argument as above, we estimate the probability to find the clouds on the jet axis to be $\frac{10}{3}$ pc/$300$ pc, shown in figure 3.

To summarize, we argue that the probability of the present aligned clouds is as small as $10^{-3}$–$3 \times 10^{-4}$.

References

Aharonian, F., et al. 2006, ApJ, 636, 777
Bally, J., Licht, D., Smith, N., & Walawender, J. 2005, AJ, 129, 355
Band, D. L. 1987, PASP, 99, 1269
Band, D. L., & Gordon, M. A. 1989, ApJ, 338, 945
Bertsch, D. L., Dame, T. M., Fichtel, C. E., Hunter, S. D., Sreekumar, P., Stacy, J. G., & Thaddeus, P. 1993, ApJ, 416, 587
Blundell, K. M., & Bowler, M. G. 2004, ApJ, 616, L159
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Caswell, J. L., Murray, J. D., Roger, R. S., Cole, D. J., & Cooke, D. J. 1975, ApJ, 45, 239
Chaty, S., et al. 2001, A&A, 366, 1035
Condon, J. J., Broderick, J. J., & Seielstad, G. A. 1989, AJ, 97, 1064
Dame, T. M., et al. 1987, ApJ, 322, 706
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
Dubner, G. M., Holdaway, M., Goss, W. M., & Mirabel, I. F. 1998, AJ, 116, 1842
Durouchoux, Ph., et al. 2000, Adv. Space Res. 25, 703
Elston, R., & Baum, S. 1987, AJ, 94, 1633
Fuchs, Y., et al. 2002, in Proc. 4th Microquasar Workshop, ed. Ph. Durouchoux, Y. Fuchs, & J. Rodriguez (Kolkata: Center for Space Physics) astro-ph/0208432
Fukui, Y. 1989, in Proc. ESO Workshop on Low Mass Star Formation and Pre–Main Sequence Objects, ed. B. Reipurth (Garching: ESO), 95
Fukui, Y., Onishi, T., Abe, R., Kawamura, A., Tachihara, K., Yamaguchi, R., Mizuno, A., & Ogawa, H. 1999, PASJ, 51, 751
Fukui, Y., et al. 2006, Science, 314, 106
Gallo, E., Fender, R., Kaiser, C., Russell, D., Morganti, R., Oosterloo, T., & Heinz, S. 2005, Nature, 436, 819
van Gorkom, J. H., Goss, W. M., & Shaver, P. A. 1980, A&A, 82, L1
Hartman, R. C., et al. 1999, ApJS, 123, 79
Hjellming, R. M., & Johnston, K. J. 1981, ApJ, 246, L141
Huang, Y.-L., Dame, T. M., & Thaddeus, P. 1983, ApJ, 272, 609
Jackson, J. M., et al. 2006, ApJS, 158, 178
Kassim, N. E., Baum, S. A., & Weiler, K. W. 1991, ApJ, 374, 212
Kato, Y., Hayashi, M. R., & Matsumoto, R. 2004, ApJ, 600, 338
Kotani, T. 1998, Doctoral Thesis of University of Tokyo
Kray, H., & Inutsuka, S. 2002, ApJ, 564, L97
Krause, M., Fendt, C., & Neininger, N. 2007, A&A, 467, 1037
Lada, C. J. 1985, ARA&A, 23, 267
Lebrun, F., et al. 1983, ApJ, 274, 231
Lockman, F. J., Blundell, K. M., & Goss, W. M. 2007, MNRAS, 381, 881
Margon, B. 1984, ARA&A, 22, 507
Margon, B., & Anderson, S. F. 1989, ApJ, 347, 448
Margon, B., Ford, H. C., Grandi, S. A., & Stone, R. P. S. 1979, ApJ, 233, L63
Marshall, H. L., Canizares, C. R., & Schulz, N. S. 2002, ApJ, 564, 941
Matsunaga, K., Mizuno, N., Morimochi, Y., Onishi, T., Mizuno, A., & Fukui, Y. 2001, PASJ, 53, 1003
McClure-Griffiths, N. M., Dickey, J. M., Gaensler, B. M., Green, A. J., Havernorn, N., & Strasser, S. 2005, ApJS, 158, 178
Mirabel, I. F., & Rodríguez, L. F. 1994, Nature, 371, 46
Mirabel, I. F., & Rodríguez, L. F. 1999, ARA&A, 37, 409
Mirabel, I. F., Rodríguez, L. F., Cordier, B., Paul, J., & Lebrun, F. 1992, Nature, 358, 215
Mizuno, A., & Fukui, Y. 2004, ASP Conf. Ser., 317, 59
Mizuno, A., Yamaguchi, R., Tachihara, K., Toyoda, S., Aoyama, H., Yamamoto, H., Onishi, T., & Fukui, Y. 2001, PASJ, 53, 1071
Moldovan, A., Safi-Harb, S., Fuchs, Y., & Dubner, G. 2005, Adv. Space Res., 35, 1062
Ogawa, H., Mizuno, A., Hoko, H., Ishikawa, H., & Fukui, Y. 1990, Int. J. Infrared Millimeter Waves, 11, 717
Onishi, T., Yoshikawa, N., Yamamoto, H., Kawamura, A., Mizuno, A., & Fukui, Y. 2001, PASJ, 53, 1017
Oosterloo, T. A., & Morganti, R. 2005, A&A, 429, 469
Pavlov, G. G., Teter, M. A., Kargaltsev, O., & Sanwal, D. 2003, ApJ, 591, 1157
Reynoso, E. M., & Mangum, J. G. 2000, ApJ, 545, 874
Rodríguez, L. F., Mirabel, I. F., & Martí, J. 1992, ApJ, 401, L15
Safi-Harb, S., & Ogelman, H. 1997, ApJ, 483, 868
Safi-Harb, S., & Petre, R. 1999, ApJ, 512, 784
Shibata, K., & Uchida, Y. 1990, PASJ, 42, 39
Tachihara, K., Toyoda, S., Onishi, T., Mizuno, A., Fukui, Y., & Neuhiusser, R. 2001, PASJ, 53, 1081
Tamura, K., Kawai, N., Yoshida, A., & Brinkmann, W. 1996, PASJ, 48, L33
Uzdensky, D. A., & MacFadyen, A. I. 2006, ApJ, 647, 1192
Vermeulen, R. C., McAdam, W. B., Trushkin, S. A., Fendel, S. R., Fiedler, R. L., Hjellming, R. M., Johnston, K. J., & Corbin, J. 1993, A&A, 270, 189
Voges, W., et al. 1999, A&A, 349, 389
Wang, Z.-R., McCray, R., Chen, Y., & Qu, Q.-Y. 1990, A&A, 240, 98
Weisskopf, M. C., et al. 2000, ApJ, 536, L81
Yamaguchi, N., Mizuno, N., Moriguchi, Y., Yonekura, Y., Mizuno, A., & Fukui, Y. 2000, PASJ, 53, 1017
Yamamoto, H., Kawamura, A., Tachihara, K., Mizuno, N., Onishi, T., & Fukui, Y. 2006, ApJ, 642, 307
Yamamoto, H., Onishi, T., Mizuno, A., & Fukui, Y. 2003, ApJ, 592, 217
Zealey, W. J., Dopita, M. A., & Malin, D. F. 1980, MNRAS