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MASSIVE STAR FORMATION TRIGGERED BY COLLISION BETWEEN GALACTIC AND ACCRETED INTERGALACTIC CLOUDS

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ABSTRACT

We present mapping observations of molecular lines ^{12}CO (2–1), ^{12}CO (3–2), ^{13}CO (2–1), and ^{13}CO (3–2) toward the massive star-forming region IRAS 04000+5052 that suggest kinematics consistent with cloud-cloud collision and a possible unusual abundance ratio of carbon isotopes. Together with the previous spectroscopic study that shows an extreme deficiency in heavy elements in the surrounding nebulosity—suggestive of primordial nature—we propose that the cloud material is of intergalactic origin and that the young star cluster in IRAS 04000+5052 is the consequence of triggered star formation due to the collision of a Galactic cloud with accreted intergalactic material.

Subject headings: intergalactic medium — ISM: abundances — ISM: clouds — stars: formation

Online material: color figures

1. INTRODUCTION

Collision between molecular clouds is considered an efficient mechanism to trigger cloud collapse to form stars. Various observations show that the process is taking place within the Milky Way (Loren 1976; Scoville et al. 1986a; Lattanzio et al. 1985; Vallee 1995; Sato et al. 2000). On the other hand, it is known that our Galaxy is accreting intergalactic material (Wakker et al. 1999; Lubowich et al. 2000; Brook et al. 2003; Stephens 2001). Such intergalactic clouds conceivably might be colliding with Galactic molecular clouds, leading to active formation of stars. Observational diagnosis of such a process includes kinematics consistent with cloud-cloud collision, existence of recently formed stars, and chemical heterogeneity of primordial intergalactic material in a Galactic environment.

The elusive source IRAS 04000+5052 was first thought to be an external galaxy, as listed in the SIMBAD database before 2002. Wouterloot & Brand (1989) made a ^{12}CO survey of a few hundred *IRAS* sources and found CO emission in IRAS 04000+5052. Wang et al. (1993), based on near-infrared photometry and optical CCD images, proposed that it might be associated with a Galactic H II region. Takata et al. (1994) made redshift measurements of a number of bright *IRAS* galaxies behind the northern Milky Way and concluded that IRAS 04000+5052 should be a Galactic object.

Recent studies show that IRAS 04000+5052, located at a distance of 4.27 kpc, twice as far as the Perseus arm, hence near the edge of the Galactic disk, is a compact H II region associated with a small, isolated young stellar cluster (Wang et al. 2002). The optical spectrum indicates that the nebulosity is exceedingly deficient in metallicity, with [N II]/$H_\alpha \sim 1/16.3$, much lower than ever found in any Galactic H II region (Wang et al. 2002). The origin of the chemical peculiarity is not known. In this Letter, we present data on cloud kinematics and a possibly unusual carbon isotopic ratio, which, together with the previous spectroscopic results, suggest a scenario of accretion of intergalactic material that collides with a Galactic molecular cloud to form the young star cluster found in IRAS 04000+5052.

2. OBSERVATIONS

The mapping observations of molecular lines ^{12}CO (2–1), ^{12}CO (3–2),^{13}CO (2–1), and ^{13}CO (3–2) were made at the Köln Observatory for Submillimeter Astronomy (KOSMA) millimeter/submillimeter telescope between 2002 September and 2003 April. A dual-channel SIS receiver tunable between 210 and 270 GHz and 330 and 360 GHz was used, with receiver noise temperatures of 130 and 100 K, respectively. The beam size is 120″ for both ^{12}CO (2–1) and ^{13}CO (2–1) and 80″ for both ^{12}CO (3–2) and ^{13}CO (3–2). For the maps, we used on-the-fly (OTF) observing mode. The number of mapping points is 121 (11 × 11) for each frequency, with spacing of 1′ in both the right ascension and declination directions. The total integration time for each spectrum was 1.6 minutes for ^{13}CO (2–1), 1.3 minutes for ^{13}CO (3–2), and 1.0 minute for ^{12}CO (2–1) and (3–2), respectively. The observing methods we used were both total power position (TP) switching and dual beam switching, with very flat baselines of a total of 39 minute integration, giving a 3 σ sensitivity limit of 39 mK. The emission-free reference position at R.A. = $03^h8^m48^s$ (B1950.0), decl. = 49°50′52″ (B1950.0) was used for TP and OTF.

Figure 1 shows the spectra of ^{12}CO (2–1), ^{12}CO (3–2), ^{13}CO (2–1), and ^{13}CO (3–2) lines at the central position of the region (0, 0) of the mapping observations. It is clear that three distinct emission features are associated with ^{12}CO, but somewhat unusually, only one emission feature is seen in the ^{13}CO spectra.

3. DATA ANALYSIS AND DISCUSSION

3.1. *The Molecular Line Spectra*

The ^{12}CO data (Fig. 1) show a double-peaked main line at $v_{\rm LSR} = -30.52$ and -34.41 km s^{-1}, respectively, and a satellite line at $v_{\rm LSR} = -4.08$ km s^{-1}. The ^{13}CO data, in contrast, display only a single-peaked main line at $v_{\rm LSR} = -30.52$ km s^{-1}, with no trace of any satellite components. No ^{13}CO emission, despite the sufficient signal-to-noise ratio of the data, is detected at the position of the ^{12}CO satellite line down to the sensitivity limit of our observations. We argue below that the data can be accounted for by kinematics of a cloud-cloud collision.

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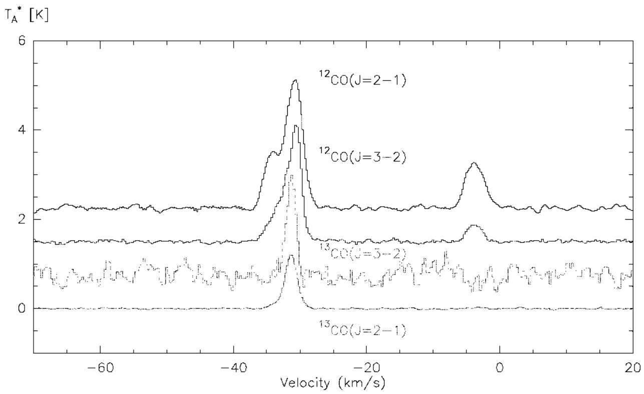

FIG. 1.—Spectra of molecular lines ^{12}CO (2–1), ^{12}CO (3–2), ^{13}CO (2–1), and ^{13}CO (3–2) at the central position of the region (0, 0) of the mapping observations. [*See the electronic edition of the Journal for a color version of this figure.*]

Two possible explanations can be put forth to explain a double-peaked feature of a molecular line, namely, two velocity components associated with different clouds or self-absorption in a collapse or infall configuration (Zhou et al. 1993; Wu & Evans 2003).

In a collapse or infall motion, the line is characterized by a "blue profile" for an optically thick line with a self-absorption dip between a brighter blue peak and a fainter red peak, whereas an optically thinner line would peak near the dip of the optically thicker line (Zhou et al. 1993; Myers et al. 1996). In IRAS 04000+5052, the optically thick line (^{12}CO) is double-peaked but the red peak is brighter than the blue peak, in contradiction to the infall model. Furthermore, the optically thinner line (^{13}CO) peaks not at the absorption part of the ^{12}CO double line but instead clearly at the same position of the red peak of the ^{12}CO double line. In addition, the velocity range of the two main components is too large for a collapsing case, because the infalling velocities in a collapsing cloud in general are quite small, on the order of 10^{-1} km s^{-1} (Zhou et al. 1993). The double-peaked ^{12}CO main line of IRAS 04000+5052 must therefore result from two separate clouds.

On the position-velocity diagrams of the spectra (Fig. 2), one sees three distinct velocity components in the ^{12}CO line and one in the ^{13}CO line. The coincidence of size, position, and orientation among all the components—the adjacent two to the left associated with the main line and the third one to the right—bears remarkable resemblance to the configuration of cloud-cloud collision, especially with the velocity continuity of the left two in the double-peaked ^{12}CO main line. The only *IRAS* source in the region also happens to be at the center of the cloud (Wang et al. 2002). We note that our data satisfy all characteristics for a cloud-cloud collision: (1) clouds adjacent in space and in velocity, (2) gas/dust intensity peaking at the impact site, and (3) a double line seen in spectra near the impact site (Vallee 1995). In Figure 3, the molecular line emission is superposed with the near-infrared image of an embedded stellar cluster of more than a dozen stellar objects. It shows clearly that the three cloud components have nearly identical sizes and central positions. We propose that the formation of the star cluster was the consequence of the cloud-cloud collision process.

3.2. *Abundance Ratio of* ^{12}CO/^{13}CO

3.2.1. *Analysis of the High* ^{12}CO/^{13}CO *Line Ratio*

The abundance ratio ^{12}CO/^{13}CO in Galactic molecular clouds is typically between 40 and 100 (89 for solar and terrestrial environments), giving a line intensity ratio of 2–5. In IRAS 04000+5052, the line ratio is 2.9 for the cloud with detection of ^{13}CO, consistent with that of typical Galactic clouds. However, for the two clouds with no detection of ^{13}CO at the sensitivity limit, the ^{12}CO to ^{13}CO line intensity ratio is at least 25–30. There are three possible explanations to this unusual line intensity ratio, namely, optically thin ^{12}CO clouds, the presence of a far-ultraviolet radiation field, or an abnormal abundance of ^{13}CO in the clouds.

To check whether the ^{12}CO line could have been optically thin, hence its higher abundance making it more easily detected than the ^{13}CO line, we made a radiative transfer calculation based on the KOSMA mapping data, from which the size and column density of each cloud could be estimated. Under the assumption of optically thin ^{12}CO, and an excitation temperature of 30 K, derived by using the line ratio method (Lada 1985; Scoville et al. 1986b), an upper limit was obtained on the volume density of molecular hydrogen, which ranges from 3 to 20 cm^{-3}, far lower than the critical density of 1.17×10^4 cm^{-3} required to produce ^{12}CO (2–1) emission under the same excitation temperature. Even ^{12}CO (1–0) would need a critical volume density of 1.22×10^3 cm^{-3}. We therefore conclude that ^{12}CO in IRAS 04000+5052 cannot be optically thin.

Optically thick ^{12}CO molecules may be able to shield themselves from the UV photons from massive stars, whereas the optically thinner ^{13}CO molecules are less protected and more readily destroyed. The ^{12}CO to ^{13}CO line ratio could then be higher than normal as long as the cloud is not too dense ($A_v \sim 1$) so that ^{13}CO molecules also become shielded. In the case of the isolated star-forming region IRAS 04000+5052, for which such a selective photodissociation process operates within the molecular cloud owing to the central forming young star cluster—as opposed to that of external illumination (Lequeux et al. 1994)—the increase in the ^{12}CO/^{13}CO line ratio is expected to be moderate (Kaufman et al. 1999). Photodissociation therefore cannot fully account for the large line ratio observed in IRAS 04000+5052.

On the other hand, such a photodissociation process under intense far-UV flux in theory could produce a high ^{12}CO/^{13}CO line ratio, even though the ^{12}C/^{13}C abundance ratio is normal. However, in fact, we seldom observed such a high ^{12}CO/^{13}CO line ratio in Galactic clouds although many of them are also forming star clusters or massive stars. It could mean that in the Galactic environment such a high ^{12}CO/^{13}CO line ratio is simply unusual. In contrast, in some metal-poor galaxies such as the SMC, large ^{12}CO/^{13}CO line ratios are indeed detected (Lequeux et al. 1994).

The remaining alternative of a high ^{12}CO/^{13}CO line ratio is an abundance abnormality intrinsic to the carbon isotopes. Since ^{13}C is produced in stars as a result of hydrogen to helium nucleosynthesis, the lack of ^{13}CO supports what has already been evinced in optical spectroscopic observations: that the material has not been much nucleochemically enriched by stars, as in normal Galactic environments. That the null detection of the ^{13}CO line arises from an isotopic anomaly may be regarded as circumstantial as the other two aforementioned possibilities, namely, an optically thin ^{12}CO line or excessive far-UV radiation. But if considered collectively with the cloud geometry, kinematics, and optical spectroscopic data, the low ^{13}C abundance explanation is what we advocate; i.e., the high ^{12}CO/^{13}CO line ratio detected in IRAS 04000+5052 is mainly attributed to the abundance abnormality of carbon isotopes, but we do not rule out the possibility that far-UV radiation also contributes to it in some proportion.

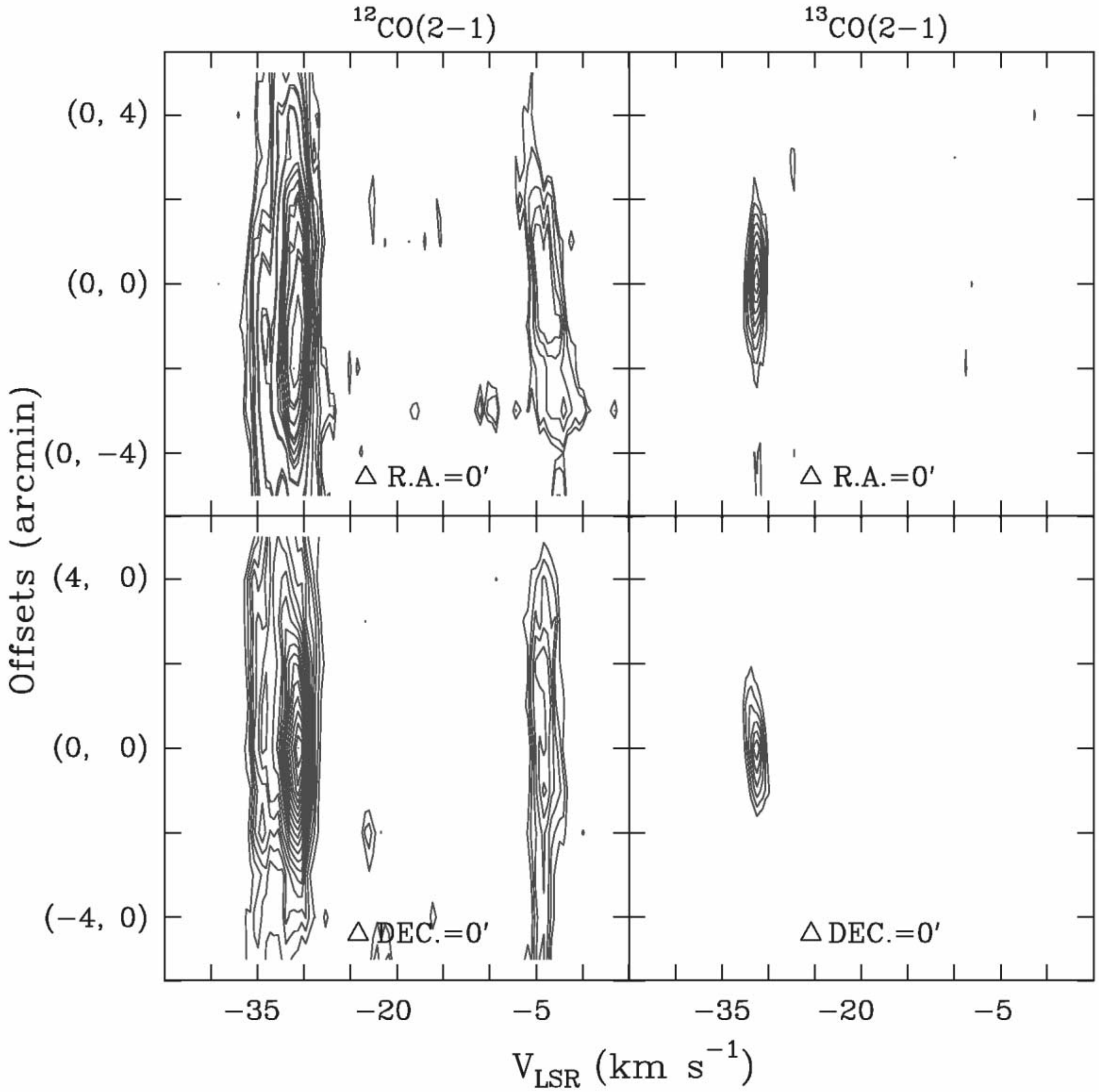

FIG. 2.—Position-velocity diagrams of the molecular lines. There are three velocity components in the ^{12}CO line along both the directions of right ascension and declination. The three components appear to have nearly the same sizes and share a common center. It is therefore highly unlikely that the configuration is due to the projection of clouds at different distances. In comparison, the ^{13}CO line shows only one velocity component. [*See the electronic edition of the Journal for a color version of this figure.*]

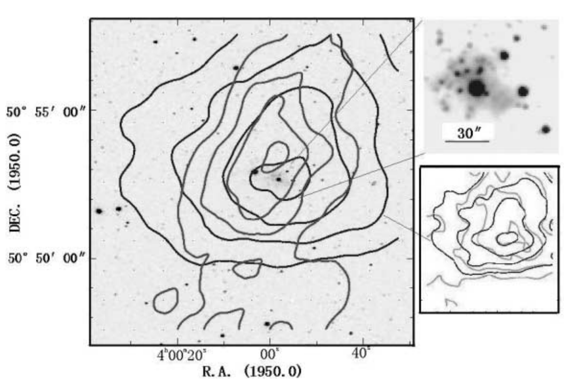

FIG. 3.—Near-infrared 2 μm (2MASS K_s band) image superposed with the ^{12}CO (2–1) line maps in IRAS 04000+5052. The contours represent the integrated line intensity of the main line (*dark*) and the satellite line (*light*), respectively, each with contour levels at 35%, 55%, 75%, and 95% of the maximum intensity. The lower right panel depicts the contours of the two main line components (see text), for which the sizes and the centers are almost the same as the dark contour in the left panel. The upper right panel shows the enlarged image of the infrared star cluster at the center of the clouds. [*See the electronic edition of the Journal for a color version of this figure.*]

3.2.2. *Origin of the Abnormal Abundance Clouds*

Given its Galactic peripheral location, the nearly primordial material in IRAS 04000+5052 could be either local at the outer reach of the Milky Way or from accretion of intergalactic clouds. We prefer the intergalactic origin because with a low concentration of molecular clouds at the outer Galactic disk—and they tend to corotate around the Galactic center—the chance of cloud collision would be slim. In comparison, intergalactic clouds, likely distributed isotropically, would be incident and collide with Galactic clouds with high speeds, thereby triggering star formation and leaving behind heterogeneous clouds, as in the case of the stellar exogamy we are witnessing in IRAS 04000+5052.

The low abundance of ^{13}C, or heavy elements in general, in intergalactic material may be made analogous to the early universe when the first-generation stars were formed out of metal-poor or even metal-free clouds. Formation of low-mass stars was hindered owing to the lack of an effective cooling mechanism by metals. Massive stars, on the other hand, according to theoretical nucleosynthesis calculations, would produce abnormally low $^{13}C/^{12}C$ ratios. The ejected material from the "first-generation intergalactic supernovae" would mix with the pristine matter, which would have low metallicity and a low abundance of ^{13}C but still allow molecules to form. The intergalactic molecular clouds could be accreted by the Galaxy and collide with the clouds densely concentrated in the Galactic disk.

There has been mounting kinematic and chemical evidence of ongoing accretion by the Milky Way of low-metallicity or nearly primordial matter, either stripped off from Local Group dwarf galaxies (Wakker et al. 1999) or a surplus from galaxy formation (Wakker et al. 1999; Lubowich et al. 2000). This may account for the origin at least partially of some high-velocity clouds interacting with Galactic matter (Mirabel & Morras 1990). The intergalactic medium has been normally detected by H I observations. Only recently did a few observations demonstrate the existence of molecules, e.g., ^{12}CO in the Magellanic bridge (Muller et al. 2004) and in a few very small intergalactic H II regions (Oosterloo et al. 2004; Ryan-Weber et al. 2004), that symbolize intergalactic massive star formation. So far, no detection of ^{13}CO emission has been reported toward these intergalactic clouds, implying a possibly genuine deficiency of ^{13}CO in such environments. Star formation triggered by collision between Galactic and intergalactic clouds, such as observed in IRAS 04000+5052, hence may not be an isolated case and may well be ubiquitous, especially on the outer edge of the Galactic disk.

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