MOLECULAR CLOUDS TOWARD RCW49 AND WESTERLUND 2: EVIDENCE FOR CLUSTER FORMATION TRIGGERED BY CLOUD–CLOUD COLLISION

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ABSTRACT

We have made CO($J = 2–1$) observations toward the H ii region RCW 49 and its ionizing source, the rich stellar cluster Westerlund 2, with the NANTEN2 submillimeter telescope. These observations have revealed that two molecular clouds in velocity ranges of $-11$ to $+9$ km s$^{-1}$ and $11$ to $21$ km s$^{-1}$, respectively, show remarkably good spatial correlations with the Spitzer IRAC mid-infrared image of RCW 49, as well as a velocity structure indicative of localized expansion around the bright central regions and stellar cluster. This strongly suggests that the two clouds are physically associated with RCW 49. We obtain a new kinematic distance estimate to RCW 49 and Wd2 of $5.4^{+1.4}_{-1}$ kpc, based on the mean velocity and velocity spread of the associated gas. We argue that the acceleration of the gas by stellar winds from Westerlund 2 is insufficient to explain the entire observed velocity dispersion of the molecular gas, and suggest a scenario in which a collision between the two clouds $\sim 4$ Myr ago may have triggered the formation of the stellar cluster.

Key words: H ii regions – ISM: clouds – ISM: individual (RCW 49) – open clusters and associations: individual (Westerlund 2)

1. INTRODUCTION

Massive stars have an enormous impact on the state of the interstellar medium (ISM) and on galactic evolution as a whole. Studies of the ISM around young OB clusters provide valuable information on the nature of the interaction between massive stars and their natal environments. They may also provide vital clues to the mechanisms behind the clustered mode of star formation, in which nearly all massive stars are formed.

Westerlund 2 (hereafter Wd2) is an unusually rich and compact young cluster located close to the tangent of the Carina arm, at $d \sim 284$ kpc. With an age of 2 $\times 10^6$ to 3 $\times 10^6$ yr (Piai et al. 1998), it is one of the youngest known clusters in the Galaxy. Estimates of the total stellar mass range from $\sim 1 \times 10^6$ to $3 \times 10^6 M_\odot$ (Ascenso et al. 2007; Whitney et al. 2004, hereafter W04), with several thousand $M_\odot$ in the form of stars of $1 \leq M \leq 120 M_\odot$ (Ascenso et al. 2007; Rauw et al. 2007). The cluster contains an extraordinary collection of hot and massive stars, including at least a dozen O stars and two remarkable WR stars with strong stellar winds. These stars are ionizing a large, luminous H ii region, RCW 49 (Rodgers et al. 1960).

The distance to Wd2 is uncertain, and values ranging from 2.8 kpc to 8.3 kpc have been estimated by a variety of different methods (e.g., Ascenso et al. 2007; Rauw et al. 2007). Comprehensive discussions are given in Churchwell et al. (2004, hereafter C04) and Aharonian et al. (2007).

Recent observations with the Infrared Array Camera (IRAC) on the Spitzer Space Telescope have produced spectacularly detailed high-resolution mid-infrared images of polycyclic aromatic hydrocarbon (PAH) emission from RCW 49 (C04), as part of the GLIMPSE survey (Benjamin et al. 2003). Analysis of the IR point source population in the region has revealed that star formation is still ongoing in the nebula, with as much as $\sim 4500 M_\odot$ in the form of young stellar objects (W04). This suggests a substantial reservoir of molecular may still remain. In addition, observations with the HESS telescope have revealed a TeV gamma-ray counterpart to Wd2, HESS J1023–575 (Aharonian et al. 2007). Possible emission scenar-
side band at 230 GHz, including the atmosphere toward the zenith. The spectrometer was an acousto-optical spectrometer with 2048 channels, providing a velocity coverage of 390 km s\(^{-1}\) with a velocity resolution of 0.38 km s\(^{-1}\) at 230 GHz. The data were obtained by using an OTF (= on the fly) mapping technique. The final pixel size and velocity channel width of the gridded data are 30 arcsec and 0.95 km s\(^{-1}\), respectively. The effective integration time per pixel is \(\sim 2\) s, and the rms noise per channel is \(\sim 0.9\) K.

3. RESULTS

NANTEN2 CO\((J = 2–1)\) emission over an LSR velocity range of \(-100\) to +100 km s\(^{-1}\) was compared with publicly available GLIMPSE images at 3.6, 4.5, 5.8, and 8.0 \(\mu\)m. We find tight morphological correlations between the IR nebula and molecular gas components peaking at velocities of \(\sim 16\) km s\(^{-1}\) and \(\sim 4\) km s\(^{-1}\), strongly suggesting that these clouds are directly associated with the H II region and stellar cluster. In addition, we find similarly strong evidence of association with a hitherto unnoted velocity components with peak velocities of between \(-9\) and 0 km s\(^{-1}\).

Figure 1 shows the GLIMPSE image overlaid with CO integrated intensity contours. Figure 1(a) shows the CO distribution between 11 and 21 km s\(^{-1}\), corresponding to the \(\sim 16\) km s\(^{-1}\) cloud identified by D07. The cloud is elongated from the northeast to the southwest, extending over the range \((284^\circ 15 \leq l \leq 284^\circ 34)\) and \((-0.63 \leq b \leq -0.20)\). Emission removed from the main body of the cloud to the southeast, at \((l, b) \sim (284^\circ 40, -0.33)\), and southwest, at \((l, b) \sim (284^\circ 19, -0.71)\), represents molecular gas identified by D07 as part of the \(\sim 11\) km s\(^{-1}\) GMC. The southeastern edge of the 16 km s\(^{-1}\) cloud between \((284^\circ 33, -0.28)\) and \((284^\circ 27, -0.40)\) shows a strong correlation with the bright filamentary ridge of mid-infrared emission \(\sim 2\) arcmin southeast of Wd2. This ridge is especially bright in the 4.5 \(\mu\)m band, which is dominated by the hydrogen recombination line Br\(_\alpha\) indicating the presence of highly ionized gas (C04). The CO emission shows signs of localized velocity perturbation coincident with this ridge, with the peak velocity offset to \(-19\) km s\(^{-1}\) (illustrated in Figure 1(b)). This strongly suggests a physical association between the molecular gas and RCW 49. In addition, the 16 km s\(^{-1}\) cloud as a whole shows some sign of depleted emission toward Wd2 itself, consistent with the presence of the evacuated region within \(1^\prime\)–\(2^\prime\) of the cluster.

Figure 1(c) shows the CO distribution between 1 and 9 km s\(^{-1}\), corresponding to the \(\sim 4\) km s\(^{-1}\) cloud identified in D07. Emission at this velocity range is entirely absent within a radius of \(\sim 3^\prime\) of Wd2. At larger distances from the cluster, molecular gas fans out to the north and south, showing an excellent large-scale correlation with extended shape of the IR nebula. We also note the close correspondence between the edge of the CO emission and the curved rim of filamentary IR emission at around \((284^\circ 22, -0.29)\).

Figure 1(d) shows the CO distribution between \(-11\) and 0 km s\(^{-1}\). This emission contains components with peak velocities between \(-9\) and 0 km s\(^{-1}\). The brightest clump in this velocity range is centered on \((l, b) \sim (284^\circ 23, -0.36)\), \(\sim 3^\prime\) southwest of Wd2, at a peak velocity of \(-4\) km s\(^{-1}\), and is coincident with a region of ongoing massive star formation in the nebula (W04). To the northwest, CO emission neatly skirts the edge of the evacuated region around the stellar cluster. Emission in this velocity range is newly identified here as associated with RCW 49 and Wd2; however, it is not distinctly separated from the 4 km s\(^{-1}\) cloud. We hereafter refer to all emission in the range \(-11\) to +9 km s\(^{-1}\) as the 0 km s\(^{-1}\) cloud, based on the intensity-weighted mean velocity of the entire complex.

The velocities of the associated components allow us to obtain kinematic distances. Using the rotation curve of Brand & Blitz (1993), we obtain of distances 6.5, 5.2, and 4.0 kpc, for velocities of 16, 4, and \(-4\) km s\(^{-1}\) respectively. The intensity-weighted mean velocity of all associated emission is 6 km s\(^{-1}\), which corresponds to a distance of 5.4 kpc. In light of the large velocity spread and associated uncertainty, we adopt a conservative distance estimate of 5.4\(^{+1.1}_{-0.9}\) kpc. In the interests of consistency this value is used for all emission components throughout this paper.

The mass of the associated molecular gas is estimated from \(^{13}\)CO\((J = 1–0)\) data from the NANTEN Galactic Plane Survey (Mizuno & Fukui 2004). Although the resolution is lower that the present dataset \((\sim 4')\), the relevant components are readily identified. We adopt a conversion factor \((\text{'X' factor'})\) of \(2.0 \times 10^{20}\) cm\(^{-2}\) K km s\(^{-1}\). This results in molecular hydrogen masses, \(M(\text{H}_2)\), of 9.1\pm 4.1\times 10^4 M_\odot\) and 8.1\pm 3.7\times 10^4 M_\odot\) for the 16 and 0 km s\(^{-1}\) clouds, where the uncertainties propagate through from the distance estimate. The higher resolution CO \((J = 2–1)\) data were also used to derive a virial mass for the 16 km s\(^{-1}\) cloud (see, e.g., Kawamura et al. 1998), which was found to be almost identical to the luminosity-based value. We did not attempt to derive virial masses for the 0 km s\(^{-1}\) cloud, since its velocity distribution is complex and apparently unrelaxed.

D07 argues that the 16 km s\(^{-1}\) cloud lies behind RCW 49 and the 4 km s\(^{-1}\) component in front, based on an analysis of HI absorption spectra seen against the bright continuum background. We concur with his reasoning and note that the absorption spectrum also shows an additional peak at around \(-4\) km s\(^{-1}\), corresponding to the brightest concentration of gas in our most blue-shifted velocity range, placing it too in front of the nebula (see Figure 2 of D07 and the related discussion).

This result is confirmed on inspection of optical data from the ESO Digitized Sky Survey. Good agreement is seen between optical obscuration and the 0 km s\(^{-1}\) cloud, whereas the 16 km s\(^{-1}\) cloud shows no obvious correlation with dark features.

4. DISCUSSION

In the above we have demonstrated the association of Wd2/RCW 49 with a significant mass of molecular gas spanning almost 30 km s\(^{-1}\), consisting of a foreground component at \(-0\) km s\(^{-1}\) and a background component at \(-16\) km s\(^{-1}\). This velocity dispersion is an order of magnitude too large for the clouds to be gravitationally bound. Yet their physical association with RCW 49 implies that their spatial separation must be no more than \(\sim 40\) pc (the linear dimension of the nebula at 5.4 kpc).

An obvious interpretation is that the molecular gas is expanding away from the central cluster, presumably driven by the energy output of the massive stars within it. This is favored by D07, and is consistent with the placement of the various velocity components along the line of sight. However, while it is true that the molecular gas toward the IR nebula does show some signs of localized perturbation due to the cluster’s influence, we are cautious about interpreting the global gas configuration according to this scenario.

Figure 2 shows a CO\((J = 2–1)\) velocity-latitude diagram. The 16 and 0 km s\(^{-1}\) clouds are well separated in \(b\)-\(v\) space.
Gas located directly in the line of sight of the IR nebula shows a velocity signature that is consistent with expansion around the central cluster. This is especially true of the 0 km s\(^{-1}\) cloud, which shows the fastest approaching material located in the direction of the bright central regions, surrounded by gas with less extreme line-of-sight velocities. The top of the 16 km s\(^{-1}\) cloud also shows evidence for interaction, localized to the immediate vicinity of the bright IR ridge, and far less pronounced. However, the majority of the cloud remains at a constant velocity of 16 km s\(^{-1}\), and extends as far as 12\('\) (~20 pc) outside the outer boundary of RCW 49; presumably well outside the range of influence of the cluster. It is therefore difficult to explain the entire 16 km s\(^{-1}\) cloud as a velocity-perturbed clump of the extended 11 km s\(^{-1}\) GMC, as originally suggested by D07.

Furthermore, we may show that any scenario that attempts to explain the entire cloud velocity spread by cluster-driven expansion alone is energetically problematic. Considering the
Figure 2. Velocity vs. galactic latitude diagram for $^{12}$CO$(J = 2–1)$ emission integrated over a longitude range of 284:2–284:4. Emission between $-11$ and $+8$ km s$^{-1}$ and between $+12$ and $+21$ km s$^{-1}$ respectively corresponds to the 0 and 16 km s$^{-1}$ clouds referred to in the text. Solid black circle: velocity signature consistent with expansion around the central cluster and/or bright central regions of RCW 49. The dashed line illustrates the constant velocity of the 16 km s$^{-1}$ cloud outside the region of direct influence of the cluster. Dotted lines mark the latitudes of Wd2 and the bright ridge of IR emission referred to in the text.

The line-of-sight velocity difference of the 0 and 16 km s$^{-1}$ clouds relative to a systemic velocity of 6 km s$^{-1}$, and using the cloud masses estimated above, we obtain an estimated kinetic energy of $\sim 1.2 \pm 0.5 \times 10^{50}$ erg. Significantly changing the underlying assumptions in this simplistic calculation (e.g., varying the systemic velocity, limiting the included mass to gas within the boundary of RCW 49, considering a three-dimensional expansion velocity based on the measured $V_{LSR}$ extremes, etc.) does not greatly affect this value, which remains $\sim 10^{50}$ erg. The $v^2$ dependence of kinetic energy combined with the large velocity spread of the associated material ensures this.

The total mechanical luminosity available from stellar winds in Wd2 is estimated by Rauw et al. (2007) as $3.6 \times 10^{51}$ erg. (The authors note that no supernova should yet have occurred in the cluster’s lifetime.) The required kinetic energy is therefore at least several percent of the total available energy from the cluster. Although in ideal adiabatic wind bubbles 20% of the wind luminosity is transferred to the expanding neutral shell (Weaver et al. 1977), more realistic numerical models suggest that no more than a few percent of the initial wind energy ends up as neutral gas kinetic energy (Arthur 2007). In addition, the small solid angle ($\sim 4\pi$) subtended by the clouds reduces the energy available to them. We therefore conclude that while it is not impossible that stellar wind-driven expansion is responsible for the entire velocity separation of the molecular clouds, the energy requirements are uncomfortably tight.

The implication is that a certain proportion of the cloud velocities are systemic, i.e., unrelated to the dynamical interaction of the complex with Wd2 and RCW 49. We of course only have information on a single velocity component, and the fact that the 0 and 16 km s$^{-1}$ clouds are receding from each other along the line of sight does not necessarily imply that they were once spatially coincident. Nevertheless, rather than postulating a noninteractive close approach between the two clouds, we may consider whether direct interaction between them might have played a role in the formation of a cluster as rich as Wd2. Collisions between molecular clouds can lead to gravitational instability in the dense, shocked gas, resulting in triggered star formation (see Elmegreen 1998, and references therein). Such collisions between molecular clouds are presumably rare. Very roughly, the average time between collisions is $\sim 1/n\sigma v$, where $n$ is the cloud number density, $\sigma$ is the cross sectional area, and $v$ is the cloud–cloud rms velocity dispersion. Assuming that the Milky Way contains $\sim 4000$ GMCs with $\sigma \approx 30^2 \pi$ pc$^2$, $v \approx 5$ km s$^{-1}$, distributed in a 100 parsec-thick ring between $3 < R < 8$ kpc, this value is $\sim 6 \times 10^7$ yr. However, this interval will be considerably smaller in the spiral arms where the cloud density is higher, and nonrandom motions may increase the cloud collision rate. For a relative velocity of $\sim 10$ km s$^{-1}$ the time taken to cover a distance of 40 pc (the assumed separation of the clouds) is $\sim 4$ Myr, which is highly consistent with the estimated age of Wd2 of 2–3 Myr. We therefore conclude that triggered formation of the Wd2 cluster via cloud–cloud collision is a viable—and intriguing—scenario. We also note that the star formation efficiency, defined as the ratio of the cluster mass to the molecular mass of the 16 and 0 km s$^{-1}$ clouds, is $\sim 5\%$, which is consistent with typical Galactic values.

We finally return briefly to the question of whether Wd2/RCW 49 and the molecular clouds presented here may also be associated with the larger 11 km s$^{-1}$ GMC, as suggested by D07. The GMC extends almost a degree to the east and west of Wd2/RCW 49, and with the exception of a small subcomponent at (284:42, $-0.34$), does not fall directly along the line of sight of the nebula. As described above, the 16 and 0 km s$^{-1}$ clouds of this study are not well explained as clumps accelerated from an original systemic velocity of $\sim 11$ km s$^{-1}$. The required energy input is uncomfortably large, and the large offset between much of the 16 km s$^{-1}$ cloud and RCW 49 argues against acceleration of the entire cloud by the cluster. The new identification of associated gas with negative velocities also drags the intensity weighted mean velocity from 11 km s$^{-1}$ to 6 km s$^{-1}$. Finally, we also note that the mass of the directly associated components seems to be sufficient to form such a rich cluster, even without invoking the larger reservoir of gas contained in the 11 km s$^{-1}$ GMC. Nevertheless, we do not completely rule out a loose association with the molecular clouds presented here. We also note that the revised distance estimate of $5.4^{+1.1}_{-1.4}$ kpc presented in this study is consistent with D07’s value of 6.0 kpc.

Finally, we note that presence of the TeV gamma ray source HESS J1023–575 suggests that the present clouds are good candidates for gamma ray production via interaction with cosmic ray protons, and deserve further detailed scrutiny.

5. SUMMARY

1. We have identified molecular gas associated with Wd2 and RCW 49 based on strong correlations between CO$(J = 2–1)$ emission and mid-infrared data from the Spitzer Space Telescope GLIMPSE survey. The molecular gas spans an unusually wide velocity range of $\sim 30$ km s$^{-1}$, with two distinct complexes with mean velocities of 16 and 0 km s$^{-1}$.

2. The intensity weighted mean velocity of the entire mass of associated gas is $\sim 6$ km s$^{-1}$, and this is used to obtain a new kinematic distance estimate to the cluster and H II
3. The molecular gas velocity structure shows evidence for expansion around Wd2 and the central parts of RCW 49. However, consideration of the energetics, and also the extent of the 16 km s$^{-1}$ cloud well outside of the region of influence of RCW 49, argues against the observed velocity dispersion arising entirely as a result of this interaction.

4. We suggest that a collision between the two molecular clouds may have triggered the formation of Wd2 $\sim$ 4 Myr ago.

5. The clouds presented in this study are viable as a target for TeV gamma ray production via interaction with cosmic ray protons.

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