The environment around the young massive star cluster RSGC 1 and HESS J1837−069

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Abstract

We report on Mopra observations of the young massive star cluster RSGC 1, adjoined to and possibly associated with the gamma-ray source HESS J1837−069. We measure the CO ($J = 1–0$) distribution around the cluster and gamma-ray source, and find that the cluster is slightly higher than the velocity ranges associated with the Crux–Scutum arm. We reveal that the cluster is associated with much less molecular gas compared with other young massive clusters in the Galaxy, Westerlund 1 (Wd 1) and 2 (Wd 2), which also radiate gamma-rays. We find no other structures that would otherwise indicate the action of supernova remnants, and due to the lack of material which may form gamma-rays by hadronic interaction, we conclude that the gamma-rays detected from HESS J1837−069 are not created through proton–proton interactions, and may more plausibly originate from the pulsar that was recently found near RSGC 1.

Key words: ISM: clouds — ISM: individual objects (HESS J1837–069) — open clusters and associations: individual (RSGC 1).

1 Introduction

Studies of red supergiants (RSGs) have been hampered by their small numbers, in spite of their importance of investigating the stellar evolution at stages immediately preceding supernova explosions. The star cluster RSGC 1 is one of the rare clusters in the Galaxy containing a significant number ($> 10$) of RSGs (Figer et al. 2006; Davies et al. 2008). RSGC 1 is fairly young and very massive, with an initial mass estimated to be (2–4) $\times 10^4 M_{\odot}$, and an age of $\sim 10$ Myr (Figer et al. 2006; Davies et al. 2008).

It has been shown that RSGC 1 may host high-energy objects; the HESS telescope array found the diffuse, $\sim 20$ pc gamma-ray source HESS J1837−069 near RSGC 1 (Aharonian et al. 2005), implying that cosmic rays (CRs) are accelerated around the cluster. CR acceleration in massive young clusters is thought to arise from either of the two processes: the CRs are accelerated by pulsars in the clusters; the CRs are accelerated by shock waves formed by collisions of stellar winds or by supernova explosions in the clusters. In the former, electrons are mainly accelerated, while in the latter both electrons and protons can be...
accelerated. In the case of RSGC 1, the former has often been supported. In fact, INTEGRAL found a hard X-ray source AX J1838.0−0655 (Molkov et al. 2004; Bird et al. 2004; Malizia et al. 2005), approximately collocated with RSGC 1, where later observations with the Rossi X-Ray Timing Explorer (RXTE: Gotthelf & Halpern 2008) led to the discovery of 70.5 ms pulsations (see also Ananda et al. 2009). The pulsar PSR J1838−0655 is a rotation-powered pulsar with spin-down luminosity $\dot{E} = 5.5 \times 10^{36} \text{erg s}^{-1}$ and characteristic age $\tau = 2.3 \times 10^4 \text{yr}$; the properties of the pulsar and the pulsar wind nebula (PWN) have also been theoretically studied by Mattana et al. (2009) and Lin et al. (2009). The hydrogen column density toward the pulsar is almost the same as those for stars in RSGC 1, which may imply that the pulsar is associated with the cluster (Gotthelf & Halpern 2008). The discovery of the pulsar supports the scenario where the observed gamma-rays are formed by inverse Compton scattering of the CR electrons in the PWN (leptonic process: Atoyan & Aharonian 1996; Tanaka & Takahara 2010).

RSGC 1 is not the only young massive cluster in the Galaxy that radiates gamma-rays, other canonical examples being Westerlund 1 (Wd 1) and 2 (Wd 2). Gamma-rays are observed from a wide ($\sim 160 \text{pc}$) region around Wd 1 (Abramowski et al. 2012), although the source of the CRs that emit the gamma-rays has not been identified. In contrast to RSGC 1, the extremely large spatial scale would hinder CR electrons from prevailing in the gamma-ray emission region before they are affected by cooling (Abramowski et al. 2012). Thus, in the case of Wd 1, CR protons may be responsible for generating the observed gamma-rays, through their interaction with gas protons and the pion-decay process (hadronic process), and, in fact, Wd 1 has sufficient gas mass to enable this process (Abramowski et al. 2012). In the case of Wd 2, the spatial size of the gamma-ray emission region is $\sim 6–31 \text{pc}$ (depending on the radial distance: Aharonian et al. 2007; Abramowski et al. 2011). Since pulsars have been detected in the gamma-ray emission region (Abdo et al. 2009), PWNe are likely responsible for generating the observed gamma-rays. However, as CR protons can certainly be accelerated in stellar winds or at the shock waves of supernova remnants (SNRs), gamma-ray formation through the hadronic process cannot be ruled out (Fujita et al. 2009; Abramowski et al. 2011). Near the young cluster, the Arches cluster, at the Galactic center, is another gamma-ray source, 3EG J1746−2851, which may radiate via inverse Compton scattering of the radiation field of the cluster (Yusef-Zadeh et al. 2003). However, since the Galactic center is well populated with a wide variety of such putative objects and is somewhat dynamic and confused, it may be premature to definitively conclude that this is the precise mechanism operating in this case (Pohl 2005; Tatischeff et al. 2012).

In this paper, we present the results of our observations of molecular material toward RSGC 1, traced by $^{12}\text{CO}(1−0)$ at 115.271 GHz. This study is motivated by the discovery of the pulsar near the cluster, which implies that the gamma-rays need not necessarily have a leptonic origin: The existence of the pulsar is important in suggesting that CR protons could have been accelerated at the SNR associated with the pulsar. If sufficient gas exists around the cluster, the protons contained in the gas may collide with the CR protons, generating and radiating gamma-rays. The study of the gas distribution around the cluster may also give us clues to the evolution of massive clusters, bearing in mind that the age of RSGC 1 is 10–14 Myr (Davies et al. 2008), and those of Wd 1 and 2 are $\sim 5 \text{Myr}$ and $\sim 2 \text{Myr}$, respectively (Lim et al. 2013; Carraro et al. 2013), and a difference in their ages necessarily implies that the gas distributions around those clusters will be at different evolutionary stages, and therefore, will be dispersed differently.

CR acceleration in massive young clusters is also important in the context of high-energy CR protons and their role in the “knee” in the CR energy spectrum ($\sim 10^{15} \text{eV}$). As usually thought to be accelerated in the shock waves of isolated SNRs, the observed energy of CRs around such SNRs is generally much smaller than $10^{15} \text{eV}$ (Butt 2009). In a massive cluster, however, overlapping SNRs would develop into super bubbles with shocks whose larger size and longer lifetime may accelerate CRs up to the knee, thereby generating TeV gamma-ray emissions (Butt 2009). If this is the case, and if the gas density around the cluster is high, then strong and widespread gamma-rays of hadronic origin would be observed from the cluster.

The radial velocity of RSGC 1 is well constrained through the observations of stars in the cluster. In this study, we assume that the radial velocity is $V_{\text{LSR}} = 123 \pm 4 \text{ km s}^{-1}$ and the distance to the cluster is $d = 6.60 \pm 0.89 \text{ kpc}$ (Davies et al. 2008). Thus, 1° corresponds to 1.9 pc. The position of the field center corresponds to the cluster center at RA = 18$^h$37$^m$58$^s$ and Dec = −6°52′53″ (J2000.0), as shown in Figer et al. (2006).

2 Observations

Observations of the $J = 1−0$ transition of $^{12}\text{CO}$ were made with the Mopra 22 m single-dish radio telescope\(^1\) in Australia, in 2012 September. The half-power beam width of the telescope was 33″ [at the $^{12}\text{CO}(1−0)$ transition

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Fig. 1. Integrated intensity map of the $^{12}$CO emission for $116 \mathrm{ km \ s}^{-1} \leq V_{\mathrm{LSR}} \leq 130 \mathrm{ km \ s}^{-1}$ with contour levels of 3, 6, 9, and 12 K km s$^{-1}$. The origin of the coordinates is RA = 18$^h$37$^m$58$^s$ and Dec = $-6^\circ$52'53" (J2000.0). The dashed circle is the approximate extent of the massive star cluster RSGC 1 (Figer et al. 2006). The square shows the position of AX J1838.0$-$0655. The dotted ellipse represents the observed excess of the TeV emission identified as HESS J1837$-$069 (Aharonian et al. 2006).

The gamma-ray emission region appears to cover a large portion of the field (Aharonian et al. 2006), and the X-ray source AX J1838.0$-$0655 is shown, located to the southeast of RSGC 1. Significantly, we do not find any obvious unusually high column densities of CO at this velocity range corresponding to RSGC 1.

Figure 2a shows the CO ($J = 1$–0) velocity–latitude diagram integrated over a RA offset range of $-400''$ to $-50''$ (see figure 1), where the velocity channels are binned over 20 channels. This RA range contains the gamma-ray radiating region (dotted line in figure 1). While the gas is deficient for

3 Results

An integrated intensity map of the observed $15' \times 15'$ region centered on RSGC 1 is shown in figure 1. These data are integrated across the velocity range corresponding to that of RSGC 1: $116 \mathrm{ km \ s}^{-1} \leq V_{\mathrm{LSR}} \leq 130 \mathrm{ km \ s}^{-1}$. The gamma-ray emission region appears to cover a large portion of the field (Aharonian et al. 2006), and the X-ray frequency of 115 GHz, sampled with a spectrometer over 4096 channels. The resulting velocity resolution is $0.087 \mathrm{ km \ s}^{-1}$; pixel size is $15''$ and the rms noise per channel is $\sim 0.4 \mathrm{ K}$ (efficiency not corrected). We compute the main-beam temperatures by using an efficiency of 0.55, as recommended for extended structures by Ladd et al. (2005). This efficiency value was confirmed to be consistent by our concurrent observations of M 17SW, which yielded peak antenna temperatures of $25 \pm 1 \mathrm{ K}$, and is generally consistent with archived SEST results where the extended beam efficiency is assumed to be 20% higher than the cited compact (as it is for Mopra) of 0.45. The data were reduced with the Australia Telescope National Facility analysis programs, LIVEDATA and GRIDZILLA, and they were analyzed using the AIPS software package.

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1 (http://www.apex-telescope.org/sest/html/telescope-calibration/calib-sources/m17sw.html).
2 (http://www.atnf.csiro.au/computing/software/livedata/).
3 (http://www.aips.nrao.edu/index.shtml).

V_{LSR} \gtrsim 120 \text{ km s}^{-1}, it is abundant for V_{LSR} \lesssim 120 \text{ km s}^{-1}. The gas-rich region at V_{LSR} \lesssim 120 \text{ km s}^{-1} apparently corresponds to the Crux–Scutum arm that is located at V_{LSR} \sim 95 \text{ km s}^{-1} (see also figure 3). RSGC 1 has a velocity slightly higher than the Crux–Scutum arm. There seems to be no structure associated with the gamma-ray radiating region (from −400′′ to 0 in the Dec offset; see figure 1). Figure 2b is the same as figure 2a but is integrated over a RA offset range of −100′′ to 100′′ (see figure 1) in order to study the region including RSGC 1 and AX J1838.0−0655. We assume in the figure that the velocity of AX J1838.0−0655 is the same as that of RSGC 1. CO emission around RSGC 1 and AX J1838.0−0655 is rather small. If we adopt a conversion factor of $1.8 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Dame et al. 2001), the column density in the region for 116 km s$^{-1} \leq V_{LSR} \lesssim 130 \text{ km s}^{-1}$ is $N_{\text{H}_2} \lesssim 1 \times 10^{21} \text{ cm}^{-2}$. However, it is not clear whether the lack of emission is physically associated with RSGC 1 and AX J1838.0−0655.

4 Discussion

Figure 2 does not reveal any notable or peculiar structure in the distribution of the molecular component around the velocity of RSGC 1 ($V_{LSR} \sim 123 \text{ km s}^{-1}$). We may constrain the mass of molecular gas associated with RSGC 1 by estimating the mass in a velocity range of 116 km s$^{-1} \lesssim V_{LSR} \lesssim 130 \text{ km s}^{-1}$. We chose this velocity range because the range is not greatly affected by the Crux–Scutum arm. Note that since RSGC 1 is located on the peak of the Galactic rotation curve in that direction (figure 4 in Davies et al. 2008), molecular gas with $V_{LSR} \gtrsim 123 \text{ km s}^{-1}$ does not rotate with the Galactic disk. For a conversion factor of $1.8 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Dame et al. 2001), the molecular hydrogen mass in the entire $15' \times 15'$ field for the velocity range is $M_g = 1.2 \times 10^4 M_\odot$. The mass of the gas that is gravitationally associated with the cluster could be even smaller, because the apparent size of the cluster is smaller than the $15' \times 15'$ field (figure 1). We also derive the gas mass in the gamma-ray radiating field inside the dotted line in figure 1 for 116 km s$^{-1} \leq V_{LSR} \leq 130 \text{ km s}^{-1}$. We found that it is only $M_{g\gamma} = 2.5 \times 10^3 M_\odot$.

The rarity of the gas around RSGC 1 is notable after comparing its gas mass with those of other young massive star clusters such as Wd 1 and 2. Abramowski et al. (2012) estimated that the hydrogen molecular density within a radius of 1:1 from Wd 1 is $\sim 12 \text{ cm}^{-3}$ (see also Dame et al. 2001; Yamamoto et al. 2003). If the hydrogen is spherically distributed, the total mass would be $1.4 \times 10^6 M_\odot$. In the case of Wd 2, two molecular clouds are associated with the cluster and their total mass is $1.7 \times 10^7 M_\odot$ (Furukawa et al. 2009). Here we can note that a difference in their gas masses may be due to that of cluster ages; evolved massive stars and/or supernovae in RSGC 1 may have injected sufficient energy to disperse or even photodissociate the molecular gas during the cluster lifetime.

We examine the foreground (i.e., the lower-velocity regime) of RSGC 1. Figure 3 shows that molecular material is concentrated at $V_{LSR} \sim 55$ and 95 km s$^{-1}$. In the direction of RSGC 1 ($l = 25.3$ and $b = -0.2$), these concentrations are the Carina–Sagittarius arm and the Crux–Scutum arm, respectively (figure 3 in Momany et al. 2006). In the direction of the gamma-ray radiating region (from −400′′ to 0′′ in the Dec offset; see figure 1), we find no obvious structures that may indicate the existence of SNRs around...
the velocities of the arms where SNRs are often found. Thus, we consider it unlikely that the gamma-rays observed in the direction of RSGC 1 are emitted by foreground SNRs.

If the gamma-rays observed around RSGC 1 have a hadronic origin, they should be created through interactions between CR protons and the protons in the gas around the cluster. However, the deficiency of the gas around the cluster strongly suggests that there is a lack of target protons for the interactions, without which the observed gamma-ray emission would require an extremely large flux of CR protons to produce a given gamma-ray luminosity. Based on the model by Fujita et al. (2009), we estimate the total energy of the CR protons required to produce the observed gamma-ray luminosity for the measured molecular gas mass ($M_{\text{gas}} = 2.5 \times 10^4 \, M_\odot$) to be $E_{\text{CR}} \sim 10^{52}$ erg. This energy is unreasonably large, and corresponds to the energy of CRs accelerated by $\sim 100$ supernovae (assuming an acceleration efficiency of $\sim 10\%$). Even if $\sim 100$ supernovae have exploded, CRs contained in older SNRs must have been expelled by newer SNRs. That is, if the total gas and CR energy of $10^{53}$ erg is confined in the gamma-ray emitting volume ($\sim 10^4$ pc$^3$), the pressure there should be $\sim 3 \times 10^{-7}$ dyn cm$^{-2}$. This is much larger than the typical pressure in the Galactic disk ($\sim 10^{-12}$ dyn cm$^{-2}$), and the gas and CRs in that volume cannot be physically confined. Therefore, we can confidently reject the hadronic scenario for gamma-ray production toward RSGC 1, in contrast with Wd 1 and 2. Although our field does not include the whole gamma-ray radiating region (figure 1), it contains most of it, and thus the conclusion is solid. A lack of spatial correlation between the gamma-ray radiating field and the CO emission in the lower-right corner in figure 1 also supports the conclusion. The recent discovery of the pulsar PSR J1838−0655 at the position of AX J1838.0−0655 suggests that the PWN associated with it is the gamma-ray source (Gotthelf & Halpern 2008), and further supports our findings here.

5 Conclusions

We observed the distribution of $^{12}$CO ($J = 1-0$) emission toward and around the massive young star cluster RSGC 1 with the Mopra 22 m radio telescope. The cluster is located just outside the Crux–Scutum arm, and we find that the gas mass around the cluster is much smaller than those of other massive young clusters in the Galaxy, such as Wd 1 and 2. The gas distribution of the foreground region is rather smooth and there seems to be no evidence of active activities that might imply additional energetic processes. The low gas mass around the cluster indicates that the gamma-ray emission around the cluster (HESS J1837−069) is insufficient to provide enough mass to support the hadronic scenario for gamma-ray production, and we suggest that the CR emission appears to be coming from the pulsar found near the cluster.

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