Study of the molecular clump associated with the high-energy source HESS J1858+020

S. Paron1,2, E. Giacani1,2, M. Rubio3, and G. Dubner1

1 Instituto de Astronomía y Física del Espacio (CONICET-UBA), CC 67, Suc. 28, 1428 Buenos Aires, Argentina
e-mail: sparon@iafe.uba.ar
2 FADU – Universidad de Buenos Aires, Argentina
3 Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

Received 22 December 2010 / Accepted 20 March 2011

ABSTRACT

Aims. HESS J1858+020 is a weak γ-ray source lying near the southern border of the SNR G35.6-0.4. A molecular cloud, composed of two clumps, shows signs of interaction with both the SNR and a nearby extended HII region. In particular, the southernmost clump coincides with the center of the H.E.S.S. source. We study this clump in detail to help us identify the nature of the very-high energy emission.

Methods. We observed the aforementioned molecular clump using the Atacama Submillimeter Telescope Experiment (ASTE) in the 12CO J = 3–2, 13CO J = 3–2, HCO+ J = 4–3, and CS J = 7–6 lines with an angular resolution of 22″. To complement these observations, we analyzed IR and submillimeter continuum archival data.

Results. From the 12CO and 13CO γ-rays. We conclude that the most probable origin of the TeV γ-ray emission is a hadronic interaction between the molecular gas and the cosmic rays accelerated by the shock front of the SNR G35.6-0.4.

Key words. ISM: clouds – ISM: supernova remnants – gamma rays: ISM – ISM: individual objects: HESS J1858+020

1. Introduction

HESS J1858+020 is a weak γ-ray source that has been detected with the Cherenkov telescope High Energy Stereoscopic System (H.E.S.S.). Though nearly a point-like source, its morphology is slightly extended by ~5″ along its major axis. The source was detected at a significance level of 7σ with a differential spectral index of 2.2 ± 0.1 (Aharonian et al. 2008). The radio source G35.6-0.4, which was identified as a supernova remnant (SNR) by Green (2009), is seen in projection over the northern border of HESS J1858+020. The system was free of emission.

2. Observations

The molecular observations were performed on July 14 and 15, 2010 with the 10 m Atacama Submillimeter Telescope Experiment (ASTE; Ezawa et al. 2004). We used the CATS345 GHz band receiver, which is a two-single band SIS receiver remotely tunable in the LO frequency range of 324–372 GHz. We simultaneously observed 12CO J = 3–2 at 345.796 GHz and HCO+ J = 4–3 at 356.734 GHz, mapping a region of 90″ × 90″ centered at l = 35°57′, b = −0°57′ (RA = 18°58′19.5″, Dec = +02°05′23.9″, J2000). We also observed 13CO J = 3–2 at 330.588 GHz and CS J = 7–6 at 342.883 GHz towards the same center mapping a region of 40″ × 50″. The mapping grid spacing was 10″ and the integration time was 60 sec per pointing in both cases. All the observations were performed in position switching mode. We verified that the off position (l = 35°47′, b = −0°540′) was free of emission.

We used the XF digital spectrometer with a bandwidth and spectral resolution set to 128 MHz and 125 kHz, respectively. The velocity resolution was 0.11 km s−1 and the half-power beamwidth (HPBW) was 22″ at 345 GHz. The system temperature varied from Tsys = 150 to 200 K. The main beam efficiency was ηmb ~ 0.65. The spectra were Hanning smoothed to improve the signal-to-noise ratio and only linear or/and some third order polynomials were used for baseline fitting. The data were reduced with NEWSTAR and the spectra processed using the XSpec software package.

To complement the new molecular data, we used the mosaicked images from GLIMPSE and MIPSGAL surveys from the Spitzer-IRAC (3.6, 4.5, 5.8, and 8 μm) and Spitzer-MIPS.
Fig. 1. Left: region of about $30' \times 30'$ towards SNR G35.6-0.4 presenting the emission at $8 \mu m$ with contours of the radio continuum emission at 20 cm. The contours levels are 17, 22, and 30 K. The first contour is slightly above the data $3\sigma_{\text{rms}}$. The circle shows the position and the extension of HESS J1858+020. We note that the SNR is possibly partially superimposed on an HII region. Right: smaller portion of the region displaying the $8 \mu m$ emission and showing the area mapped with the molecular observations (yellow box).

(24 and 70 $\mu m$), respectively, IRAC has an angular resolution of between $1''5$ and $1''9$ and MIPS $6''$ at $24 \mu m$. In addition, we analyzed the continuum emission at 1.1 mm obtained from the Bolocam Galactic Plane Survey (BGPS), which has a FWHM effective resolution of $30''$.

3. The studied region

In Fig. 1 (left), we present a region of about $30' \times 30'$ towards the SNR G35.6-0.4. The image displays the $8 \mu m$ emission from Spitzer-IRAC with contours of the radio continuum emission at 20 cm. The circle shows the position and the extension of $\sim 5'$ of the source HESS J1858+020 (Aharonian et al. 2008). On the basis of the $8 \mu m$ emission tracing polycyclic aromatic hydrocarbons (PAHs), that partially borders the radio continuum emission extending to the south, we suggest that the SNR G35.6-0.4 partially overlaps an extended HII region, which is likely part of the same complex. This probably explains the confusion about the nature of G35.6-0.4 in the past years (see Green 2009, and references therein). Towards the center of HESS J1858+020, there is an emission peak of $8 \mu m$, which, as studied by Paron & Giacani (2010), coincides with a molecular clump detected in the $^{13}$CO $J = 1$–$0$ line. Paron & Giacani (2010) detected evidence of star forming activity that coincides with this clump. This region is catalogued in the IRAS Catalogue of Point Sources (Version 2.0; Helou & Walker 1988) as IRAS 18558+0201.

Figure 1 (right) shows an enlargement of the area of interest indicated by a yellow box the region where the new molecular observations were carried out.

4. Results and discussion

Figure 2 (up) shows the $^{12}$CO $J = 3$–$2$ spectra obtained towards the observed region. Across the whole area, the main component at $\sim 53$ km s$^{-1}$, already detected in the $^{13}$CO $J = 1$–$0$ clump studied by Paron & Giacani (2010), is present. A second, less intense, component is observed mainly towards positive RA and negative Dec offsets (bottom left in the image) with a velocity of $\sim 64$ km s$^{-1}$. Owing to a lack of observing time, three positions were not observed (top right of the image). Figure 2 (bottom) displays the $^{13}$CO $J = 3$–$2$ spectra observed towards the central $\sim 20$ square arcseconds. In the observed area, this line has a unique component centered at $\sim 53$ km s$^{-1}$. In both cases,
the horizontal axis of each spectra is velocity and ranges from 30 to 80 km s\(^{-1}\), while the vertical axis is brightness temperature and goes from -1 to 7 K. The \(^{12}\)CO \(J = 3-2\) component at -64 km s\(^{-1}\) has no correspondence neither in the \(^{13}\)CO \(J = 3-2\) emission presented in this work, nor in the \(^{13}\)CO \(J = 1-0\) emission analyzed in Paron & Giacani (2010). We suggest that this velocity component can be unrelated molecular gas seen along the line of sight. In what follows, we focus our analysis on the -55 km s\(^{-1}\) molecular component. Table 1 summarizes the derived parameters of the \(^{12}\)CO and \(^{13}\)CO \(J = 3-2\) lines obtained from a Gaussian fitting. \(T_{\text{mb}}\) is the main beam peak brightness temperature, \(V_{\text{LSR}}\) is the central velocity referred to the local standard of rest and \(\Delta v\) is the line width (FWHM). The Gaussian fitting was performed on the averaged spectrum of each line, which was obtained from the pointings within the area mapped by the \(^{13}\)CO emission, at the center of the region. The quoted uncertainties are formal 1\(\sigma\) value for the model of the Gaussian shape.

An inspection of the \(^{12}\)CO \(J = 3-2\) spectra indicates that there are neither spectral wings nor intensity gradients along symmetric directions in the plane of the sky, which allows us to conclude that, at the present data resolution, there is no evidence of outflow activity neither in the plane of the sky nor along the line of sight. The detected molecular clump peaks approximately at the (10, 0) offset (see Fig. 2), corresponding to the sky position \(l = 35\degree57, b = -0\degree58\). Figure 3 displays a two color image with the 8 \(\mu\)m and 24 \(\mu\)m emissions shown in red and green, respectively, with contours of the \(^{12}\)CO \(J = 3-2\) emission integrated between 48 and 57 km s\(^{-1}\). The circle represents the source HESS J1858+020. From this image, it can be appreciated that the molecular clump mapped in \(^{12}\)CO \(J = 3-2\) coincides with the condensation of PAHs seen at 8 \(\mu\)m. This image reveals that this clump also emits at 24 \(\mu\)m, indicating warm dust. This clump, lying exactly at the geometric center of the HESS source, suggests that its study may help us to elucidate the nature of the high energy emission. We note that we did not detect any emission from the HCO\(^+\) \(J = 4-3\) and CS \(J = 7-6\) lines at sensitivity levels of about 0.13 and 0.2 K, respectively, in the direction of this molecular concentration.

To estimate the physical parameters of the molecular clump, we assume LTE conditions and a beam filling factor of 1, which may not be completely true but allows us to make a first approach to the problem. From the peak temperature ratio of the CO isotopes (\(^{12}\)CO/\(^{13}\)CO)\(^{3}\), it is possible to estimate the optical depths from (e.g. Curtis et al. 2010)

\[
\frac{^{12}T_{\text{mb}}}{^{13}T_{\text{mb}}} = \left(\frac{v_{12}}{v_{13}}\right) \left(\frac{[^{12}\text{CO}]}{[^{13}\text{CO}]}\right) \left(1 - \exp(-\tau_{12})\right),
\]

where \(v_{12} = 345.796\) GHz and \(v_{13} = 330.558\) GHz are the transition frequencies of \(^{12}\)CO and \(^{13}\)CO \(J = 3-2\) lines, respectively, \(\tau_{12}\) is the optical depth of the \(^{12}\)CO gas, and \([^{12}\text{CO}]/[^{13}\text{CO}]\) is the isotopic abundance ratio. Assuming that 8 kpc is the distance to the Galactic center and using \([^{12}\text{CO}]/[^{13}\text{CO}]\) = (6.21 ± 1.00)\(\Delta\)GC + (18.71 ± 7.37) (Milam et al. 2005) where \(\Delta\)GC = 6.73 kpc is the distance between the source and the Galactic center, we obtain \([^{12}\text{CO}]/[^{13}\text{CO}]\) = 56.7 ± 13.5. Thus, the \(^{12}\)CO \(J = 3-2\) optical depth is \(\tau_{12} = 32 ± 11\). Using the typical LTE equations and taking into account that the \(^{12}\)CO \(J = 3-2\) line is optically thick as shown above, from its emission we estimate an excitation temperature of \(T_{\text{ex}} = 17 ± 1\) K. Using this factor and the \(^{13}\)CO \(J = 3-2\) emission, we derive an optical depth for the \(^{13}\)CO of \(\tau_{13} = 0.70 ± 0.12\) and a \(^{13}\)CO column density of \(N(^{13}\text{CO}) = (8.2 ± 1.2) \times 10^{15}\) cm\(^{-2}\). Adapting the isotopic abundance ratio \([^{12}\text{CO}]/[^{13}\text{CO}]\) used above and the relationship of \(N(\text{H}_2)/N(^{12}\text{CO}) \sim 10^4\) (see Black & Willner 1984, and reference therein), we obtain an \(\text{H}_2\) column density of \(N(\text{H}_2) = (5.0 ± 1.8) \times 10^{23}\) cm\(^{-2}\). Finally, assuming spherical geometry for the clump, which is compatible with what is seen in Fig. 3, with a radius of -30\(\rho^2\) (-1.5 pc at the distance of 10.5 kpc), we estimate a mass and a volume density of \((1.5 ± 0.5) \times 10^{3} \times 10^{15}\) \(M_\odot\) and \((2.1 ± 0.7) \times 10^{9} \times 10^{15}\) \(M_\odot\) \(\text{pc}^3\), respectively for this structure, where \(d\) is the distance. The quoted errors, of the order of 30\%, do not include the error in the distance, which is a major unknown and depends on Galaxy models. We thus present the estimated values as a function of the distance.

Using the \(^{13}\)CO line width of \(\Delta v = 2\) km s\(^{-1}\) and a radius of \(R = 1.5\) pc, we also calculate the virial mass from \(M_{\text{vir}} = B \times R \times \Delta v^2\), where \(B\) is a constant that depends on the density profile. If one assumes a uniform density profile, that is \(\rho(r) = \text{const.}, B = 210\), while if a density profile \(\rho(r) \sim 1/r\) is assumed, \(B = 190\) (MacLaren et al. 1988). Both cases produce the same virial mass within the errors, \(M_{\text{vir}} = (1.1 ± 0.1) \times 10^3 \times 10^{15}\) \(M_\odot\). The ratio of the virial and the LTE mass is \(M_{\text{vir}}/M_{\text{LTE}} = (0.8 ± 0.3) \times 10^{15}\) \(M_\odot\). Kawamura et al. (1998) performed a large-scale survey of molecular clouds towards the Gemini and Aurora regions and shows that star-forming \(^{13}\)CO clouds have low \(M_{\text{vir}}/M_{\text{LTE}}\), while all the clouds with high \(M_{\text{vir}}/M_{\text{LTE}}\) have no sign of star formation. On the other hand, several molecular cores studied in the active star forming complex in Taurus have on average, \(M_{\text{vir}}/M_{\text{LTE}} \sim 0.6\) (Onishi et al. 1996), which is quite similar to the value of 0.8 derived here.

Another way to estimate the volume density of the molecular feature is by investigating of the dust content. Figure 4 displays

\[\text{Figure 3. Two-color image with the 8 \(\mu\)m and 24 \(\mu\)m emissions presented in red and green, respectively. The contours correspond to the \(^{12}\)CO \(J = 3-2\) emission integrated between 48 and 57 km s\(^{-1}\), at the levels of 22, 26, and 30 K km s\(^{-1}\). The rms noise is about 4 K km s\(^{-1}\). The circle represents the extension of the source HESS J1858+020.}\]
Table 2. Near- and mid-IR fluxes of IRS1 and IRS2.

<table>
<thead>
<tr>
<th>Source</th>
<th>$J$ (mag)</th>
<th>$H$ (mag)</th>
<th>$K_s$ (mag)</th>
<th>3.6 $\mu$m (mag)</th>
<th>4.5 $\mu$m (mag)</th>
<th>5.8 $\mu$m (mag)</th>
<th>8.0 $\mu$m (mag)</th>
<th>24 $\mu$m (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRS2</td>
<td>15.318</td>
<td>13.344</td>
<td>12.342</td>
<td>10.731</td>
<td>10.137</td>
<td>9.625</td>
<td>9.053</td>
<td>0.150</td>
</tr>
</tbody>
</table>

Assuming a typical dust temperature of $T_d = 20$ K and a distance of 10.5 kpc, we obtain a total mass for the core BGPS G035.578-00.584 of $M = (535 \pm 15) \times \left(\frac{d}{10\text{kpc}}\right)^2 M_\odot$. Finally, using this mass and assuming an angular radius of 14″ ($R \sim 0.7$ pc), from $n_H = 3M/(4\pi R^2 \mu m_H)$, where $m_H$ is the hydrogen atom mass and $\mu = 2.37$ the mean particle mass, we obtain a particle density of $n_H = (6.6 \pm 0.2) \times 10^3 \times \left(\frac{10.5\text{kpc}}{d}\right)^{-2}$ cm$^{-3}$. The adopted angular radius is based on the angular size of this object reported in the catalog. As can be appreciated, the minor axis size is smaller than the rms size of the BGPS beam, thus it is not possible to calculate the deconvolved angular radius following Rosolowsky et al. (2010).

In summary, from two different methods we obtain a density of a few $10^3$ cm$^{-3}$ for the studied clump. Taking into account the lack of emission of the CS $J = 7-6$ and HCO$^+$ $J = 4-3$ lines, tracers of higher densities, we conclude that $10^3-10^4$ cm$^{-3}$ is a plausible range for the density in the clump.

4.1. Young stellar objects in the molecular clump

Paron & Giacani (2010) conducted a search for young stellar objects (YSOs) probably embedded in the molecular cloud mapped in the $^{12}$CO $J = 1-0$ line. Using the color criteria of Allen et al. (2004) for GLIMPSE sources, the authors found six YSO candidate sources. In this work, we search for YSOs probably embedded in the discovered $^{12}$CO $J = 3-2$ clump using criteria based on the intrinsic reddening of the sources and studying the physical parameters extracted from the YSOs spectral energy distributions (SEDs). These criteria assume that YSOs always display an intrinsic infrared excess that cannot be attributed to scattering and/or absorption of the ISM along the line of sight.

We therefore used the GLIMPSE Point-Source Catalog to search for this kind of sources within the molecular clump. Robitaille et al. (2008) defined a color criterion to identify intrinsically red sources using data from the Spitzer-IRAC bands. Intrinsically red sources satisfy the condition $m_{4.5} - m_{8.0} \geq 1$, where $m_{4.5}$ and $m_{8.0}$ are the magnitudes in the 4.5 and 8.0 $\mu$m bands, respectively. To consider the errors in the magnitudes, we use the following color criterion to select intrinsically red sources $m_{4.5} - m_{8.0} + \varepsilon \geq 1$, where $\varepsilon = \sqrt{(\Delta m_{4.5})^2 + (\Delta m_{8.0})^2}$ and $\Delta m_{4.5}$ and $\Delta m_{8.0}$ are the errors in the 4.5 and 8.0 $\mu$m bands, respectively. By inspecting a circular region of about 30° in radius centered at $l = 35^\circ.758$, we find 27 GLIMPSE sources, and by applying the abovementioned color criterion, we find only two intrinsically red sources that appear to be related to the molecular clump, called SSTGLMC G035.5768-00.5862 and SSTGLMC G035.5765-00.5909, hereafter IRS1 and IRS2, respectively. These sources were classified as class I and II, respectively in Paron & Giacani (2010) following the Allen et al. (2004) classification. In view of our more complete study, we now suggest that IRS1 is very likely to be embedded in the analyzed molecular clump, while for IRS2, lying on the border of the observed region, the connection with the studied molecular feature is less compelling (see Fig. 5 left).

In Table 2, we present the catalogued near- and mid-IR fluxes of these sources extracted from the 2MASS and GLIMPSE point...
In Table 3, it has a massive envelope that must still be accreting mass. The evolutionary stage of IRS1 derived from its SED and the lack of evidence of molecular outflows in the clump where it is embedded, suggest that IRS1 is an evolved YSO probably in the last stages of formation. Moreover, the presence of a condensation of PAH around this source suggests that IRS1 could be a high-mass protostellar object (HMPO) that has not yet reached the ultracompact HII region stage.

4.2. The scenario

On the basis of the results presented above, we discuss the possible origin of the very high-energy emission.

As mentioned in Sect. 3, we propose that the SNR G35.6-0.4 partially overlaps an extended HII region, whose eastern border is delineated by PAHs revealed by the 8 μm emission. A molecular cloud composed of at least two clumps lies over this border, and one of them is located at the center of HESS J1858+02. We have shown that there is at least one YSO embedded in this clump (that we called IRS1), which can, in principle, create a population of relativistic particles inside the host molecular cloud via a thermal jet. These particles, in a high density ambient environment matter can produce γ-ray emission by means of inverse Compton and relativistic bremsstrahlung losses (Araudo et al. 2007). However, for IRS1, at the present data resolution, no evidence of molecular outflows has been found in either the plane of the sky or along the line of sight, therefore weakening the probability of a physical link between IRS1 and HESS J1858+02. Since we have demonstrated that a YSO in the molecular clump is unlikely to play a decisive role in producing the observed γ-rays, and because of the lack of any other candidate in the region at any distance, we conclude that the only possible Galactic counterpart to the HESS source is the SNR G35.6-0.4 with its molecular enviroment. In this case, the supernova shock is a source of accelerated cosmic rays and the dense molecular clump provides the nuclei responsible for the production of neutral pions (by means of inelastic pp collisions), which will decay yielding the observed γ-rays.

5. Summary

Using molecular observations obtained with the Atacama Submillimeter Telescope Experiment (ASTE) and IR and submillimeter continuum archival data, we have studied a molecular clump associated with the IR source IRAS 18558+0201 that lies at the center of the very-high energy source HESS J1858+020. Our main results can be summarized as follows:

(a) From the 12CO and 13CO J = 3−2 lines and the 1.1 mm continuum emission for this clump we have measured a density between 10^3 and 10^4 cm^{-3}. This clump is part of a larger molecular cloud that is being disturbed by the SNR G35.6-0.4 and a nearby extended HII region.

(b) From the analysis of the mid-IR data and a photometric study, we have discovered a YSO very likely embedded in the aforementioned molecular clump. Analyzing its spectral energy distribution, we suggest that this source could be a high-mass protostellar object that has not yet reached the ultracompact HII region stage.

(c) We did not find any evidence of molecular outflows from the discovered YSO that would reveal the presence of a thermal jet capable by itself of generating the very-high energy emission.
We conclude that a clumpy molecular cloud, similar to the one investigated in this work, is the most plausible explanation of the very-high energy emission. The molecular gas may be acting as a target for the cosmic rays accelerated by the shock front of the SNR G35.6-0.4 generating the $\gamma$-ray emission by means of hadronic processes.

Acknowledgements. S.P., E.G. and G.D. are members of the Carrera del Investigador Científico of CONICET, Argentina. This work was partially supported by Argentina grants awarded by Universidad de Buenos Aires, CONICET and ANPCYT. M.R. wishes to acknowledge support from FONDECYT (CHILE) grant No. 108033. She is supported by the Chilean Center for Astrophysics FONDAP No. 15010003. S.P. and M.R. are grateful to Dr. Shinya Komugi for the support received during the observations. We wish to thank the anonymous referee whose comments and suggestions have helped to improve the paper.

References

Helou, G., & Walker, D. W. 1988, Infrared astronomical satellite (IRAS) catalogs and atlases, The small scale structure catalog, 7