Cosmic rays in the surroundings of SNR G35.6−0.4

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ABSTRACT

HESS J1858+020 is a TeV gamma-ray source that was reported to have no clearly catalogued counterpart at any wavelength. However, it has been recently proposed that this source is indirectly associated with the radio source, re-identified as a supernova remnant (SNR), G35.6−0.4. The latter has been found to be middle-aged (~30 kyr) and to have nearby molecular clouds (MCs). HESS J1858+020 was proposed to be the result of the interaction of protons accelerated in the SNR shell with target ions residing in the clouds. The Fermi Large Area Telescope (LAT) First Source Catalog does not list any source coincident with the position of HESS J1858+020, but some lie close. Here, we analyse more than 2 years of data obtained with the Fermi-LAT for the region of interest, and consider whether it is indeed possible that the closest LAT source, 1FGL J1857.1+0212c, is related to HESS J1858+020. We conclude it is not, and we impose upper limits on the GeV emission originating from HESS J1858+020. Using a simplified 3D model for the cosmic ray propagation out from the shell of the SNR, we consider whether the interaction between SNR G35.6−0.4 and the MCs nearby could give rise to the TeV emission of HESS J1858+020 without producing a GeV counterpart. If so, the pair of SNR/TeV source with no GeV detection would be reminiscent of other similarly aged SNRs, such as some of the TeV hotspots near W28, for which cosmic ray diffusion may be used to explain their multifrequency phenomenology. However, for HESS J1858+020, we found that although the phase space in principle allows such a GeV–TeV non-correlation to appear, usual and/or observationally constrained values of the parameters (e.g., diffusion coefficients and cloud–SNR likely distances) would disfavour it.

Key words: ISM: supernova remnants.

1 INTRODUCTION

HESS J1858+020 is a weak gamma-ray source (1.6 per cent Crab Flux) that was reported to have no clearly catalogued counterpart at any wavelength (Aharonian et al. 2008). HESS J1858+020 is a nearly point-like source, with a slight extension of ~5 arcmin along its major axis. Its differential spectral index is 2.2±0.1. The nearby radio source G35.6−0.4 was recently re-identified as a supernova remnant (SNR) (Green 2010). HESS J1858+020 lies towards the southern border of this remnant. Paron & Giacani (2010) have found, using the 13CO (J = 1−0) line from the Galactic Ring Survey and mid-IR data from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE), that there is one or several molecular clouds (MCs) towards the southern border of SNR G35.6−0.4, likely at the same distance of the remnant (10.5 kpc). Paron & Giacani (2010) also provide estimates of the cloud’s total molecular mass and density. They report that the cloud is composed of two molecular clumps, one over the SNR shell and the other is located at the centre of HESS J1858+020 with a molecular mass and a density of ~5 × 10^3 M⊙ and ~500 cm^-3, respectively. They proposed, using a simplified analytical approach described in Torres et al. (2003), that hadronic gamma-ray emission within the clouds, produced by protons diffusing away from the SNR G35.6−0.4, is a possible origin of HESS J1858+020. In a more recent paper, Paron et al. (2011) give more details about the...
molecular material, obtained via observations with the Atacama Submillimeter Telescope Experiment. They discovered a young stellar object (YSO), probably a high-mass protostar, embedded in the molecular clump, but no evidence of any molecular outflows which might in principle reveal the presence of a thermal jet capable of generating the observed gamma-rays. Paron et al. (2011) concluded again that the most probable origin for the TeV gamma-ray emission are hadronic interactions between the molecular gas and the cosmic rays accelerated by the shock front of SNR G35.6–0.4. Here, we focus on a more in-depth analysis of this possibility.

To assess the latter proposal it is important to have an understanding of the GeV emission (if any) of the region. However, the GeV emission at the sky position of HESS J1858+020 has not been studied up to now. A look at the Fermi-LAT First Source Catalog (Abdo et al. 2010a) shows that there is no source at the position of the SNR or the HESS source. The Fermi source Fermi-LAT First Source Catalog (hereafter 1FGL) J1857.1+0212 is the closest one: it is only at 0.3′ from HESS J1858+020, it is unidentified, has an error radius of 0.08′, and its spectral index is 2.31 ± 0.04. In the Fermi-LAT analysis there is no indication that 1FGL J1857.1+0212 is confused. The pulsar PSR B1855+02 lies close (see the map below), but no gamma-ray emission has been detected to be originating from it in the Fermi-LAT data (Abdo et al. 2010b). PSR B1855+02 was suggested as being possibly related to the SNR G35.6–0.4 but the association is unclear (see Green 2009 for details). The proximity of HESS J1858+020 and 1FGL J1857.1+0212, particularly since the point spread function (PSF) of the Fermi-LAT instrument is larger than the separation of the two sky coordinates of interest, requires a careful analysis in order to evaluate the possible relations among these sources.

The case of middle-aged SNRs interacting with MCs, with the subsequent production of gamma-ray sources at GeV and/or TeV energies has also been analysed, for instance, for W51 (Abdo et al. 2009), W28 (Abdo et al. 2010c; Li & Chen 2010; Ohira, Murase & Yamazaki 2011) and IC 443 (e.g. Abdo et al. 2010f; Torres, Rodríguez Marrero & de Cea del Pozo 2010; see also Rodríguez Marrero et al. 2008). However, in these cases there was a GeV detection, except for two of the four TeV hotspots of the SNR W28, namely HESS J1800–230A and HESS J1800–230C for which only upper limits were imposed. These instances of GeV–TeV non-simultaneous detections around SNRs are probably the most interesting ones from a cosmic ray viewpoint (see the discussion in Funk et al. 2008). They allow us to explore a hadronic origin of the highest-energy gamma-ray emission, through cosmic rays accelerated by the SNR shock front, which, diffusing away from it, interact with MCs at a certain distance. Given that only the most energetic protons reach the separate clouds at a given time, these cases allow us to investigate the diffusion environment in which the cosmic ray propagation proceeds.

Section 2 is the observational core of the paper and we present there the analysis of more than 2 years of Fermi-LAT data of this region. We take special care to analyse whether a mislocalization of 1FGL J1857.1+0212c could render it coincident in projection with HESS J1828+020 and prove that this is likely not the case. We then impose upper limits to the GeV radiation at the position of HESS J1858+020. These limits are used in Section 3 to establish possible scenarios where the constraints (detection at TeV, non-detection at GeV) could be satisfied. A discussion of these results and a comparison with the similar case of SNR W28 with nearby MCs is given at the end.

2 GEV ANALYSIS

We searched for gamma-rays emitted by the HESS J1858+020 analysing the publicly available ~28 months of Fermi-LAT data in the energy range 100 MeV–100 GeV, from 2008 August 4 to 2010 November 19. The search is performed by means of the binned likelihood spectral analysis, using the official tool (gtlike) released by the Fermi-LAT collaboration (Fermi Science Tools v9r17p0). All the data, software and diffuse models used for this analysis are available from the Fermi Science Support Center.1 Events from the ‘Pass 6 Diffuse’ class were selected, i.e. the event class with the greatest purity of gamma-rays, having the most stringent background rejection (see details in Atwood et al. 2009). The ‘Pass 6 v3 Diffuse’ instrument response functions (IRFs) were applied in the analysis (Rando 2009). We selected events with energy $E > 100$ MeV in a square aligned with celestial coordinates, inscribed inside a circular region of interest (ROI) of 15′ radius, centred on the HESS source. The good time intervals are defined such that the ROI does not go below the gamma-ray-bright Earth limb (defined at 105′ from the Zenith angle), and that the source is always inside the LAT field of view, namely in a cone angle of 66′. Source detection significance is determined using the test statistic (TS) value, $TS = -2(L_0 - L_1)$, which compares the likelihood ratio of models including an additional source, $L_1$, only with the null hypothesis of the background, $L_0$ (Mattox et al. 1996).

To apply the likelihood analysis, a spectral–spatial model containing diffuse and point-like sources was created. Using the 1FGL Catalog we have 93 sources closer than 20′ and five closer than 3′ from the HESS J1858+020 position. For the Galactic diffuse emission we used the spectral–spatial model ‘gll_iem_v02.fit’, which is the one used by the Fermi-LAT collaboration in order to build the 1FGL (Abdo et al. 2010a). The isotropic diffuse emission was modelled by the spectrum described in the ‘isotropic_iem_v02.txt’ file. The normalization factors of these two models were left free in the fitting procedures. The spectral–spatial model also included all the point-like sources from the 1FGL list closer than 20′ to the HESS source. Each of those point sources was modelled with a simple power law, with the exceptions of those sources that are known to be pulsars, for which a power law with an exponential cut-off was used. The spectral parameters of those sources were set at the 1FGL values or those from the Fermi-LAT First Pulsar Catalog (Abdo et al. 2010b). The flux parameters of all the point-like sources closer than 3′ to HESS 1858+020 were left free in the likelihood fit, except for the closest one, to which we pay special attention below.

Fig. 1 shows the counts map of Fermi-LAT data for $E > 1$ GeV with subtracted Galactic and isotropic diffuse emissions, in a window of 2′ × 2′ centred on HESS J1858+020.

2.1 Testing the hypothesis of an association with the closest Fermi source

HESS J1858+020 is in the Galactic plane at coordinates $l = 35.578$, $b = -0.581$ (RA = 284.584, Dec. = 2.09, J2000) and does not spatially coincide with any source listed in the 1FGL. However, this region is crowded with gamma-ray sources. Indeed, in the spectral–spatial model created for the likelihood analysis we collected 93 Fermi-LAT sources, with 1FGL J1857.1+0212c being the closest source to HESS J1858+020. Even though the HESS...
To investigate the hypothesis of a possible association of 1FGL J1857.1+0212c with HESS J1858+020, we performed two likelihood analyses. In one we set in the spectral-spatial model the coordinates of 1FGL J1857.1+0212c at the HESS position. In the other, we set it at the position of the HESS source. The analyses are performed setting free the flux parameters of all the point-like sources closer than 3° to HESS J1858+020, and modelling 1FGL J1857.1+0212c with a power law with index and flux free. The only difference between the two analyses was the assumed position of 1FGL J1857.1+0212c. This method allows us to test whether the position listed in the 1FGL Catalog is sustained. In the first case we obtained TS = 863, while in the second case, with 1FGL J1857.1+0212c displaced, we obtained TS = 509. A comparison of the two TS values obtained changing the coordinates of 1FGL J1857.1+0212c suggests that the association is significantly unlikely, given that $\Delta$TS > 350.

In order to take into account the systematics due to the uncertainties of the Galactic diffuse model, the analyses were repeated by artificially changing the normalization of the Galactic diffuse model by $\pm$6 per cent (see e.g. Abdo et al. 2010d). Also in these cases, the differences in the TS values (for the putative change in position of 1FGL J1857.1+0212c) was large ($\Delta$TS > 300), which suggests that the association is significantly unlikely. Thus, we believe we can safely entertain the hypothesis that HESS J1858+020 and 1FGL J1857.1+0212c are not associated and proceed to impose upper limits.

2.2 Upper limits

Once the hypothesis of association is rejected, the significance of the plausible gamma-ray emission from HESS J1858+020 was evaluated by means of adding an extra source at its position in the spectral-spatial model for the likelihood analysis. We model it with a power law. When redoing the analysis, we set free the photon index and flux parameters of HESS J1858+020, and the flux parameter of all the point-like sources closer than 3°, with the exception of 1FGL J1857.1+0212c. As discussed above, this is the closest 1FGL source to the position of interest; and for it, we fixed all its parameters. The latter choice can be understood if one takes into account the fact that the Fermi-LAT PSF at 1 GeV (around the peak of the LAT sensitivity) is 0.8. If a new source is supposed to be at a smaller distance from a bright one that is already known in the spectral-spatial model, we expect that the likelihood fitting procedure will not suppress it even if fake, but will simply share the photon counts among them, resulting in a good significance (TS > 25) for both sources. Such a case has been found, for instance, for SGR 1627−41 (Abdo et al. 2010d), where it was found that the high TS derived by the g@[email protected] analysis has been caused by the presence of the rather strong unidentified source (1FGL J1636.4−4737), which lies at 0.12 from the magnetar (although as in this case, it was positionally incompatible with the magnetar).

With these settings, the HESS J1858+020 likelihood analysis always results in a TS < 25, implying no detection. After fitting, we derived 95 per cent flux upper limits for $E > 100$ MeV with the profile method, increasing the flux obtained for HESS J1858+020 until the maximum log-likelihood decreases by 2.71/2. In the same way, the 95 per cent flux upper limits were evaluated in three energy bins (0.1 < $E$ < 100 GeV) fixing the photon index to 2.26 (the result of the likelihood fit is 2.26 $\pm$ 0.13). The uncertainties of the Fermi-LAT effective area, and of the Galactic diffuse emission, are the two main sources of systematics that can affect the results derived with our analysis. We estimated these systematics effects by repeating the upper limits analysis using modified IRFs that bracket the ‘Pass 6 v3 Diffuse’ effective areas, and changing the normalization of the Galactic diffuse model artificially by $\pm$6 per cent. In addition for the evaluation of 95 per cent flux upper limits ($F$95 per cent UL), we derived the energy flux upper limits $[G^{95 \text{ per cent UL}} = \int_{\Delta E} \langle dn/dE \rangle dE]$, and the SED points ($vF$95 per cent UL).

In the same way, we have also evaluated the upper limits on the basis of Helene’s Bayesian method (Helene 1983). The main difference here from the profile method is that in this case the 95 per cent upper limits are found integrating the likelihood profile (function of the source flux $F$) starting from $F = 0$, without any assumption on its distribution. Whereas the results for the upper limits obtained with the two methods were similar, the Bayesian one gave those which are more conservative. The results of this analysis are reported in Table 1.

2.3 Additional checks

We additionally tested that by changing the energy threshold (from 100 to 200 MeV), the Fermi Science tools (from v9r17p0 to v9r18p6), slightly different selection cuts in gtmktime, and different number of sources in the background model (including those
in an ROI with size from $10^0$ to $20^0$) – all the results obtained are stable. Additionally, we repeated the analyses using an updated version of the Fermi-LAT Catalog sources, built using 2 years of data and thus more compatible with the data of the HESS J1858+020 region we focus on. With this catalogue (which is yet internal to the Fermi-LAT collaboration), the number of sources closer than $20^0$ from the HESS J1858+020 source are 107, while those closer than $3^0$ are 10. No significant change in the previous results were found. We have also considered that some of the closest sources could be extended, and also found the results to be stable. We have also recomputed the upper limits with different values of the assumed photon index and found the results to be stable too. For instance, assuming a value of 2.1 for the photon index, which is the mean value of the diffuse emission spectrum, only affects the upper limit in the highest energy bin by about 1 per cent.

### 3 MODELS

In this section we follow the analysis of Aharonian & Atoyan (1996) for a point-like injection, and of Li & Chen (2010) for a non-point-like injection of cosmic rays in order to assess the hadronic production of gamma-rays in the proximity of SNR G35.6–0.4. See these references for notation and further clarifications. In addition of those cosmic rays injected by the SNR, we also consider the contribution of diffuse Galactic protons, as measured in the solar neighbourhood (see, e.g. Dermer 1986). For the gamma-ray spectrum calculations we use the analytic proton emissivity $dN_p/dE_p$ developed by Kelner, Aharonian & Bugayov (2006).

In order to apply the non-point-like approach we consider that the high-resolution radio image of SNR G35.6–0.4 (Green 2010) shows an extent of $15 \times 11$ arcmin$^2$ and thus we approximate the average radius as $R_{SNR} \sim 20$ pc using the distance of 10.5 kpc based on the proximity of the remnant with the H II region G35.5–0.0 (Paron & Giacani 2010). The remnant radius and age at the transition from the Sedov phase to the radiative phase are given by (Lozinskaaya 1991)

$$R_{cool} = 20E_{51}^{0.295}n_0^{-0.409} \text{ pc},$$

$$t_{cool} = 2.7 \times 10^4 E_{51}^{0.2}n_0^{-0.52} \text{ yr},$$

respectively. If we assume the SNR explosion energy $E_{SNR} = 10^{51}$ erg and the ambient gas density $n_0$ of the order of 1 cm$^{-3}$, G35.6–0.4 seems to be near the transition time, of age $\sim 27$ kyr. Thus we use the Sedov (1959) law for the previous evolution of G35.6–0.4:

$$R_{SNR} = 0.34 \left( \frac{E_{51}}{\mu n_0} \right)^{0.2} \left( \frac{t}{\text{yr}} \right)^{0.4} \text{ pc}.$$  

We shall adopt different values for the diffusion coefficient, considering that the slow diffusion corrections around SNRs are possible (e.g. Fujita et al. 2009; Torres et al. 2010) and an efficiency $\eta = 0.1$ (e.g. Blandford & Eichler 1987), i.e. a total injection in cosmic rays of $10^{50}$ erg (10 per cent of the explosion power) along the SNR lifetime. In any case, the transition from the Sedov phase to the radiative phase is not sharp; and as usual, key parameters (such as distance, accurate radius, ambient density and explosion energy) are uncertain. Because of this, we also explore possible fits with the simple point-like injection approach, more appropriate for larger time-scales.

#### 3.1 Point-like injection

We first adopt the point-like injection approximation and analyse as to which are the possible combinations of parameters, if any, that would show the GeV–TeV phenomenology seen before. Fig. 2 shows some examples of these cases. In the first place, we show the resulting SED in the gamma-ray domain for a point-like impulsive cosmic ray injection, of $10^{50}$ erg. The accelerator is placed at the centre of the SNR G35.6–0.4, and the SED is the result of the interaction of the diffusing cosmic rays with the molecular material, assumed to be located in a cloud at a separate position. Table 2 and the top panels of Fig. 2 summarize the results. The diffusion coefficient is assumed to be in the form of a power law in energy (see e.g. Aharonian & Atoyan 1996) $D(E) = 10^{28} \chi(E/10 \text{ GeV})^\delta$ cm$^2$ s$^{-1}$, where $\chi$ is the correction factor for slow diffusion around the SNR (e.g. Fujita et al. 2009) and $\delta \approx 0.3$–0.7 (e.g. Berezinskii et al. 1990). The value $10^{28} \chi$ cm$^2$ s$^{-1}$ is referred to as $D_0$ hereafter. To simplify, we adopted a fiducial value for the slope of the injected cosmic ray spectrum $p = 2$, and $\delta = 0.5$, since other values within the corresponding typical phase space of these parameters do not change our conclusions. Instead, we show results for different values of $D_0$, from $10^{26}$ to $10^{27}$ cm$^2$ s$^{-1}$. We see that the higher the value of $D_0$, the more important becomes the contribution of the cosmic ray sea with respect to that of the accelerator. This happens because in order to have a reasonably good fit to the GeV–TeV data, we need larger values of SNR–MC separation and MC masses. The latter cannot attain any needed value, of course, but it is constrained to be less than the measured one in the region, which is of the order of $10^5 M_\odot$ (Paron & Giacani 2010). In addition, the separation cannot be arbitrarily large, since, unless the clouds are significantly in the foreground or background of the accelerator (which admittedly may well be the case), the projected distance would be larger than measured. The projected distance of the MC to the SNR centre is $\sim 30$ pc. These constraints exclude most models with an impulsive injector and $D_0 > 10^{26}$ cm$^2$ s$^{-1}$. A value of $D_0 = 10^{27}$ cm$^2$ s$^{-1}$ with an impulsive injection from the SNR is untenable, for instance, since it would require 2 orders of magnitude more molecular material than available. For the largest $D$ (top panel, right), even considering unrealistic masses and distance, the model fits for large separations are above the upper limits and seem inadequate. Reasonably good fits, i.e. resulting in separation and MC masses in agreement with measurements, and within the assumptions made, would require a very low value of the diffusion coefficient. Such values of $D_0$, representing a very slow diffusion, have been used, for instance, by

| Energy (GeV) | $F^{95\%\text{UL}}$ (10$^{-9}$ photons cm$^{-2}$ s$^{-1}$) | $G^{95\%\text{UL}}$ (10$^{-11}$ x erg s$^{-1}$ cm$^{-2}$) | $\nu F^{95\%\text{UL}}$ (10$^{-11}$ x erg s$^{-1}$ cm$^{-2}$) |
|-------------|---------------------------------|-----------------|-----------------|
| 0.10–1.00   | 50                              | 1.85            | 0.72            |
| 1.00–10.00  | 6.93                            | 2.56            | 1.00            |
| 10.00–100.00| 0.21                            | 0.76            | 0.30            |
| >0.10       | 113                             | 7.33            | –               |

Table 1. Fermi-LAT upper limits at the position of HESS J1858+020.

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Figure 2. Point-like injection model for the gamma-ray spectrum of HESS J1858+020, compared with HESS observations (Aharonian et al. 2008) and Fermi-LAT upper limits (this work). The parameters we have used in this figure are in correspondence with those given in Table 2. The top panels show cases with impulsive injection. The bottom panels show cases with continuous injection. In both panels, from left to right, we show results with increasing value of $\chi$, from 0.001 to 0.1. In each panel, solid, dashed, dotted, and dash–dotted curves stand for results with increasing values of separation between the accelerator and the cloud, according to Table 2.

| Kind      | $R_c$ (pc) | $p$ | $\delta$ | $M_{cl}$ ($10^4 M_\odot$) | $\chi$ |
|-----------|------------|-----|-----------|----------------------------|--------|
| Impulsive | 27         | 2   | 0.5       | 0.08                       | 0.001  |
| Impulsive | 29         | 2   | 0.5       | 0.16                       | 0.001  |
| Impulsive | 31         | 2   | 0.5       | 0.28                       | 0.001  |
| Impulsive | 33         | 2   | 0.5       | 0.39                       | 0.001  |
| Impulsive | 40         | 2   | 0.5       | 3.36                       | 0.01   |
| Impulsive | 50         | 2   | 0.5       | 6.05                       | 0.01   |
| Impulsive | 60         | 2   | 0.5       | 8.40                       | 0.01   |
| Impulsive | 70         | 2   | 0.5       | 12.61                      | 0.01   |
| Impulsive | 120        | 2   | 0.5       | 168                        | 0.1    |
| Impulsive | 130        | 2   | 0.5       | 220                        | 0.1    |
| Impulsive | 140        | 2   | 0.5       | 280                        | 0.1    |
| Impulsive | 150        | 2   | 0.5       | 388                        | 0.1    |
| Continuous| 25.5       | 2   | 0.5       | 0.04                       | 0.001  |
| Continuous| 26.5       | 2   | 0.5       | 0.06                       | 0.001  |
| Continuous| 27.5       | 2   | 0.5       | 0.07                       | 0.001  |
| Continuous| 28.5       | 2   | 0.5       | 1.00                       | 0.001  |
| Continuous| 35         | 2   | 0.5       | 1.7                        | 0.01   |
| Continuous| 40         | 2   | 0.5       | 2.2                        | 0.01   |
| Continuous| 50         | 2   | 0.5       | 2.8                        | 0.01   |
| Continuous| 55         | 2   | 0.5       | 3.9                        | 0.01   |
| Continuous| 60         | 2   | 0.5       | 12                         | 0.1    |
| Continuous| 50         | 2   | 0.5       | 20                         | 0.1    |
| Continuous| 60         | 2   | 0.5       | 30                         | 0.1    |
| Continuous| 70         | 2   | 0.5       | 40                         | 0.1    |

Gabici, Aharonian & Blasi (2007), but it is likely that they require a much denser cloud to be feasible.

In Fig. 2 and Table 2, we also show several examples of the resulting SED for a continuous injection of $1.17 \times 10^{38} \text{erg} \cdot \text{s}^{-1}$ (totalizing $10^{50} \text{erg}$ in the lifetime of the SNR) with the accelerator also located at the SNR centre. Again, reasonably good fits can only be obtained with low values of $D_{10}$, up to $\sim 10^{26} \text{cm}^2 \cdot \text{s}^{-1}$. Values of the needed molecular mass in interaction with the cosmic ray population increases with $D_{10}$, but in this case, values up to $D_{10} = 10^{26} \text{cm}^2 \cdot \text{s}^{-1}$ are able to produce a good fit, whereas higher ones would require masses beyond those measured.

In Fig. 3 we show the cosmic ray spectrum at the position of HESS J1858+020 resulting from the point-like models of Fig. 1, as compared with the cosmic ray sea. From left to right, we plot the cases with $\chi = 0.001$, 0.01 and 0.1, using the same colour coding and parameters as those presented in Fig. 1 and Table 2. The only solutions that may be in agreement with the total molecular mass measured in this environment correspond to the leftmost top panel, and the two leftmost bottom panels in this figure. The particles injected by the accelerator dominate the cosmic ray sea for energies above $\sim 10 \text{ GeV}$ in these cases, and quickly overcome it by several orders of magnitude for higher energies.

We note, however, that the caveat of this analysis might be in its point-like assumption. The size of the SNR shell, and position of the cloud with respect to the centre of the SNR, are comparable, and it is thus an approximation to consider this set-up. In order to explore this environment further, especially for the continuous injection, we apply the cumulative diffusion model to exploring the range of parameters for which the source HESS J1858+020 could be associated with the newly identified SNR G35.6$-$0.4, resulting in the non-detection at GeV energies when the SNR is no longer assumed to be point-like.
3.2 Non-point-like injection

The way in which the cosmic ray spectrum is constructed in the cumulative model is different from the more direct point-like approach. In the cumulative model, we are adding contributions coming from different distances, and thus diffusing differently. This is especially important when the MC is indeed close to the SNR shell. In this case the cosmic rays entering the cloud arrive from distances that span from a few to tens of pc (for those coming from the other side of the shell).

With these SNR parameters, the GeV–TeV data of HESS J1858+020 are fitted (as plotted in Fig. 4) and the resulting parameters are listed in Table 3. To compare with the former case, we adopted an initial spectral index of escaping protons, $p = 2$, predicted by the classic Fermi-type acceleration process, and $\delta = 0.5$. We also explored steeper values of $p$ to fit the gamma-ray spectrum of this source so as to study the parameter dependence. For $p$-values equal to 2.1 or 2.2, the needed $\delta$ would decrease a little in the range 0.3–0.5 to better fit the spectral data, while the lower limit of $R_c$ would still be at $\sim 40–60$ pc. Higher values of $p$, e.g. 2.4 and beyond, would produce $\delta < 0.3$, which is unreasonable for the cosmic ray diffusion process.

The fitting results for $\chi = 0.001$, 0.01 and 0.1 are shown in Fig. 3. As expected, among the fitted parameters, the MC mass ($M_{cl}$) and the distance from the SNR centre to the MC ($R_{cl}$) decrease when the $\chi$ value is reduced. At the higher end for the diffusion coefficient ($\chi = 0.1$), the fitted $R_{cl}$ value should be in the range of 50–80 pc. But also for the 3D model it can be noted that the MC mass required for $\chi = 0.1$ is of the order of $10^6 M_{\odot}$, which significantly conflicts with the observed value. In the more realistic 3D model, also the case with $D_{10} = 10^{26}$ cm$^2$ s$^{-1}$ requires a mass beyond the one measured, by a factor of $\sim 6$ or more if the clouds are more distant. On the other hand, at the lower end of $D_{10}$ ($\chi = 0.001$), the distance from the SNR centre to the MC is quite similar to the SNR radius itself ($\sim 20$ pc), implying that the MC is essentially at the end of the shock front, which actually could be argued from the projected maps of Paron & Giacani (2010). Thus we find that in order for a hadronic origin of the gamma-ray emission seen to be possible, the diffusion
Table 3. Parameters of the non-point-like (3D) diffusion model applied to HESS J1858+020, for an impulsive and a continuous injection of $10^{50}$ erg along the SNR lifetime.

| Kind | $R_c$ (pc) | $p$ | $\delta$ | $M_d$ $(10^4 M_\odot)$ | $\chi$ |
|------|-----------|-----|--------|----------------------|------|
| 3D   | 22        | 2   | 0.5    | 1.1                  | 0.001|
| 3D   | 23        | 2   | 0.5    | 1.1                  | 0.001|
| 3D   | 24        | 2   | 0.5    | 1.2                  | 0.001|
| 3D   | 25        | 2   | 0.5    | 1.6                  | 0.001|
| 3D   | 30        | 2   | 0.5    | 6.7                  | 0.01 |
| 3D   | 35        | 2   | 0.5    | 8.2                  | 0.01 |
| 3D   | 40        | 2   | 0.5    | 12                   | 0.01 |
| 3D   | 45        | 2   | 0.5    | 19                   | 0.01 |
| 3D   | 50        | 2   | 0.5    | 70                   | 0.1  |
| 3D   | 60        | 2   | 0.5    | 80                   | 0.1  |
| 3D   | 70        | 2   | 0.5    | 100                  | 0.1  |
| 3D   | 80        | 2   | 0.5    | 120                  | 0.1  |

3.2.1 An energy-independent diffusion?

We checked whether the case of an energy-independent diffusion, i.e. $\delta = 0$, can provide a good fit. To do that we used the same parameters (except for $\delta$) as those shown in Table 3 to explore their matching to the multiwavelength data. As an example, results for $\chi = 0.001$ and 0.01 are shown in Fig. 6. Additionally, we also set other parameters free (apart from fixing $\delta = 0$) to fit the HESS data and the Fermi-LAT upper limits: for instance, in order to fit the HESS data with gamma-ray index $\sim 2.2$, the proton spectrum index $p$ should also be 2.2 if $\delta = 0$. The right-hand panel of Fig. 6 shows the case for $R = 30$ pc, $p = 2.17$, $\delta = 0$, $M_d = 2 \times 10^7 M_\odot$, and $\chi = 0.01$, which matches the HESS data, at the price of unavoidably violating the Fermi-LAT upper limits. The required MC mass would be much larger than the one measured in the region, and the model is already ruled out by this. A spectral break between GeV and TeV is needed to fit the spectral data, which can be naturally produced by an energy-dependent diffusion model.

4 DISCUSSION

The GeV counterparts of some unidentified very high energy sources have been found by Fermi-LAT and some of them show spectral breaks between the GeV and TeV bands (e.g. HESS J1834−087/HESS J1804−216), which may imply that the spectra cannot be treated as a single emission component (Tam et al. 2010). These scenarios have been studied earlier by Funk et al. (2008) using EGRET data. The very faint X-ray emission from these unidentified sources indicates that, unless they are evolved pulsar wind nebulae, these sources are likely not gamma-ray emitters themselves, and cosmic ray diffusion origins such as the one explored in this paper could be a possible alternative.
The cumulative diffusion model predicts concave gamma-ray spectra, in which two peaks are present. The one at the lowest energies is attributed to the diffuse Galactic protons, while the one at the highest energies, and putatively responsible for the emission detected from HESS J1858+020, is attributed to the accelerated protons that escaped from the nearby SNR G35.6−0.4. It can be seen that the high-energy emission peak shifts to higher energies when the distance between the SNR and the cloud increases. Therefore, accelerator-illuminated gamma-ray sources, which have the property of being TeV bright but GeV faint, can be explained by diffusion effects. Such a scenario was applied, for example by Li & Chen (2010), to explain the gamma-rays of the four sources in the SNR W28 field. In W28, four gamma-ray sources with various GeV and TeV brightesses are accounted for by assuming different distances from the SNR centre. HESS J1858+020/SNR G35.6−0.4 might in principle be another case of such generic phenomenology.

In this paper we have studied HESS J1858+020 at GeV energies, while considering its possible association with the radio source, recently re-identified as an SNR G35.6−0.4. The latter has been found to be middle-aged (30 kyr) and to have nearby MCs (Paron & Giacani 2010). The 1FGL did not list any source coincident with the position of HESS J1858+020, but the closest Fermi-LAT source, 1FGL J1857.1+0212, could have in principle been associated with it. A detailed analysis of 2 years of Fermi-LAT data disfavours this association, and we have imposed upper limits to the GeV emission from the ROI. Using both a point-like model and a 3D model for the cosmic ray injection into, and propagation out from, the shell of the SNR, we considered whether the interaction between SNR G35.6−0.4 and the MCs nearby could give rise to the TeV emission of HESS J1858+020 without producing a GeV counterpart. We have found that although the phase space in principle allows for such a situation to appear, usual and/or observationally constrained values of the parameters (e.g. diffusion coefficients and cloud-SNR shell distance) would disfavour it. Specifically, for the currently assumed distance of SNR G35.6−04 and the MC complex, the diffusion coefficient near this SNR should be greatly suppressed with respect to the average Galactic value, by more than 1 order of magnitude, in order for the gamma-ray phenomenology detected to be a viable outcome of the three hadronic models considered here. This may be possible, and such cases have earlier been considered in the literature to be possible, but the size and density of this particular cloud are possibly too low to generate such a slow diffusion timescale.

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