Characterization of the gamma-ray emission from the Kepler supernova remnant with Fermi-LAT

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ABSTRACT

The Kepler supernova remnant (SNR) had been the only historic SNR that lacked a detection at GeV and TeV energies, which probe particle acceleration. A recent analysis of Fermi-LAT data reported a likely GeV γ-ray candidate in the direction of the SNR. Using approximately the same data set but with an optimized analysis configuration, we confirm the γ-ray candidate to a solid > 3σ detection and report a spectral index of 2.14 ± 0.12stat ± 0.15syst for an energy flux above 100 MeV of (3.1 ± 0.6stat ± 0.3syst) × 10^{-12} erg cm^{-2} s^{-1}. The γ-ray excess is not significantly extended and is fully compatible with the radio, infrared, and X-ray spatial distribution of the SNR. We successfully characterized this multiwavelength emission with a model in which accelerated particles interact with the dense circumstellar material in the northwest portion of the SNR and radiate GeV γ rays through π0 decay. The X-ray synchrotron and inverse-Compton emission mostly stem from the fast shocks in the southern regions with a magnetic field B ∼ 100 μG or higher. Depending on the exact magnetic field amplitude, the TeV γ-ray emission could arise from either the south region (inverse-Compton dominated) or the interaction region (π0 decay dominated).

Key words. supernovae: individual : Kepler – ISM: supernova remnants – ISM: cosmic rays – Gamma rays: general – Astroparticle physics –Shock waves

1. Introduction

The last Galactic supernova to be observed from Earth occurred on October 9, 1604, and a detailed report was produced by Johannes Kepler, whose name is now attached to the supernova and its remnant. The Kepler supernova remnant (SNR) is most certainly the remnant of a Type Ia explosion, but the large-scale asymmetry, with brighter emission toward the north from radio to X-rays (DeLaney et al. 2002; Cassam-Chenaï et al. 2004; Blair et al. 2007; Reynolds et al. 2007), has caused some confusion to X-rays (DeLaney et al. 2002; Cassam-Chenaï et al. 2004; Blair et al. 2007). Proper motion studies of these filaments was later revealed by Chandra observations (Bamba et al. 2005; Reynolds et al. 2007). Nonthermal emission from thin synchrotron-dominated filaments was later revealed by Chandra observations (Bamba et al. 2005; Reynolds et al. 2007). Proper motion studies of these synchrotron rims (Vink 2008; Katsuda et al. 2008) show fast shocks, with velocities ranging from 2000 km s^{-1} in the northern region to ∼5000 km s^{-1} in the south.

The slower velocities in the north are related to the higher CSM density in this direction. Measurement of the thickness of these filaments suggests a high magnetic field of 150-300 μG if the width is energy loss limited (Bamba et al. 2005; Parizot et al. 2006).

Despite being one of the youngest SNRs in our Galaxy with high velocity shocks and signs of dense material and interaction, Kepler had been the only historic SNR without detected γ-ray emission. This has changed with the recent report by Xiang & Jiang (2021) of a ∼ 3.8σ detection with the Fermi-LAT telescope in the direction of the Kepler SNR. In addition, the recent detection of TeV γ rays after a deep exposure with the H.E.S.S. telescopes (152 hours; Prokhorov et al. 2021) opens the window for a detailed γ-ray study of this young and historic SNR.

In this work we aim to transform the status of the Fermi-LAT discovery from likely candidate to solid detection by using a more sophisticated analysis with approximately the same data set (see Sect. [2]). In addition to the modest significance, Xiang & Jiang (2021) find a slightly offset best-fit position from the SNR. We thus analyze in detail if this offset is statistically compatible with SNR morphology as realized by multiwavelength spatial templates. We conclude in Sect. [3] by modeling Kepler’s....
multiwavelength emission under the assumption that γ rays are emitted from the northern interacting region and synchrotron and inverse-Compton emission arises mostly from the fast shocks in the southern region.

2. Analysis

2.1. LAT data reduction and preparation

The Fermi-LAT is a γ-ray telescope that detects photons via conversion into electron-positron pairs from 20 MeV to higher than 500 GeV (Atwood et al. 2009). The following analysis was performed using 12 years of Fermi-LAT data (2008 August 04 to 2020 August 03). A maximum zenith angle of 90° below 1 GeV and 105° above 1 GeV was applied to reduce the contamination from the Earth limb, and the time intervals during which the satellite passed through the South Atlantic Anomaly were excluded. Our data were also filtered, with time intervals around solar flares and bright γ-ray bursts removed. The data reduction and exposure calculations were performed using the LAT ferrmitools version 1.2.23 and fermipy (Wood et al. 2017) version 0.19.0. We performed a binned likelihood analysis and accounted for the effect of energy dispersion (when the reconstructed energy differs from the true energy) by using edisp_bins = 3. This means that the energy dispersion correction operates on the spectra with three extra bins below and above the threshold of the analysis. Our binned analysis was performed with ten energy bins per decade, spatial bins of 0.02° for the morphological analysis and 0.05° for the spectral analysis over a region of 15° × 15°. We included all sources from the LAT 10-year Source Catalog (4FGL-DR2) up to a distance of 15° from Kepler. Sources with a predicted number of counts below 1 and a significance of zero were removed from the model.

The summed likelihood method was used to simultaneously fit events with different angular reconstruction quality (PSF0 to PSF3 event types). The Galactic diffuse emission was modeled by the standard file gll_iem_v07.fits, and the residual background and extragalactic radiation were described by a single isotropic component with the spectral shape in the tabulated model iso_p8r3 SOURCE_V3_v1.txt. The models are available from the Fermi Science Support Center.

Since the point spread function (PSF) of the Fermi-LAT is energy dependent and broad at low energy, we started the morphological analysis at 1 GeV. The spectral analysis was made from 100 MeV up to 1 TeV.

2.2. Morphological analysis

The spectral parameters of the sources in the model were first fit simultaneously with the Galactic and isotropic diffuse emissions from 1 GeV to 1 TeV. During this procedure, a point source fixed at the position (RA(J2000) = 262.62°, −21.49°) reported by Xiang & Jiang (2021) was used to reproduce the γ-ray emission of the Kepler SNR. To search for additional sources in the region of interest (ROI), we computed a test statistic (TS) map that tests at each pixel the significance of a source with a generic $E^{-2}$ spectrum against the null hypothesis $S = 2\ln(L_1 - L_0)$, where $L_0$ and $L_1$ are the likelihoods of the background (null hypothesis) and the hypothesis being tested (source plus background). We iteratively added four point sources in the model where the TS exceeded 25. We localized the four additional sources (RA(J2000) = 255.56°, −22.47°; 260.13°, −26.95°; 263.04°, −27.97°; and 264.78°, −16.30°), and we fit their power-law spectral parameters. We then localized the source associated with Kepler and obtained our best point source model at RA(J2000) = 262.618° ± 0.023°, Dec(J2000) = −21.488° ± 0.026°. The radii at 68% confidence and 95% confidence provided by fermipy are 0.036° and 0.058°. During this fit, we left free the normalization of sources located closer than 4° from the ROI center as well as the Galactic and isotropic diffuse emissions. Figure 1 (left panel) presents our best localization and confidence radii superimposed on the TS map above 1 GeV. We tested its extension by localizing a 2D symmetric Gaussian. The significance of the extension is calculated through $\text{TS}_{\text{ext}} = 2(\ln L_{\text{ext}} - \ln L_{\text{0s}})$, where $L_{\text{ext}}$ and $L_{\text{0s}}$ are the likelihood obtained with the extended and point source model, respectively. For Kepler, we found $\text{TS}_{\text{ext}} = 0.3$, which indicates that the emis-

\footnotesize

1 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_edisp_usage.html
2 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_catalog
3 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html
4 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html
5 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html
6 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
tion is not significantly extended; this is compatible with the result from Xiang & Jiang (2021). The 95% confidence level upper limit on the extension is 0.09 (for comparison, the radius of the SNR is 0.03°).

Finally, we also examined the correlation of the γ-ray emission from Kepler with multiwavelength templates derived from the VLA at 1.4 GHz (DeLaney et al. 2002), Spitzer in the infrared at 24 μm (Blair et al. 2007), and Chandra in the 0.5-4 keV energy band (Reynolds et al. 2007). We cannot use the likelihood ratio test to compare the hypothesis of a point source model to that of a multiwavelength template, because the two models are not nested. However, we can use the Akaike information criterion (AIC; Akaike 1974), which takes the number of independently adjusted parameters in a given model, k, into account. The standard AIC formula is \( AIC = 2k - 2\ln L \). Here we estimate a \( \Delta AIC = 2k - TS \), comparing the AIC of the null source hypothesis and the AIC of the source being tested. The lowest \( \Delta AIC \) value, reported in Table 1, is obtained for the infrared template from Spitzer. While a lower \( \Delta AIC \) indicates statistical preference for a model, the similar \( \Delta AIC \) values indicate that each of these models provides an equally good representation of the γ-ray signal detected by the LAT. This result is consistent with our expectations from the Fermi-LAT PSF (\( \sim 1° \) at 1 GeV) and the 0.03° SNR radius: all templates have a similar structure when convolved with the relatively broad PSF. Hence, in our analysis below, we adopt the infrared template but emphasize that any of these templates would yield similar residual TS maps or inferred spectral properties.

2.3. Spectral analysis

Using the best-fit infrared spatial template, we performed the spectral analysis from 100 MeV to 1 TeV. We first verified whether any additional sources were needed in the model by examining the TS maps above 100 MeV. Two additional sources were detected at RA_J2000 = 264.19°, −20.01°; 263.72°, −21.36° (not detected in the 1 GeV – 1 TeV range used in Sect. 2.2). The TS map obtained with all the sources considered in the model (see Fig. 1 middle panel) shows no significant residual emission, indicating that the ROI is adequately modeled. We then tested different spectral shapes for Kepler. During this procedure, the spectral parameters of sources located up to 4° from the ROI center were left free during the fit, like those of the Galactic and isotropic diffuse emissions. We tested a simple power-law model, a logarithmic parabola, and a smooth broken power-law model. Again, the improvement between the power-law model and the two other models was tested using the likelihood ratio test. In our case, \( \Delta TS \) is 2.4 for the logarithmic parabola model and 3.1 for the smooth broken power-law representation, indicating that no significant curvature is detected.

Assuming a power-law representation, the best-fit model for the photon distribution yields a TS of 38.3 above 100 MeV, a spectral index of 2.14 ± 0.12stat ± 0.15syst, and a normalization of (2.71 ± 0.57stat ± 0.26syst) \( \times 10^{-14} \) MeV\(^{-1} \) cm\(^{-2} \) s\(^{-1} \) at the pivot energy of 2947 MeV. This implies an energy flux above 100 MeV of (3.1 ± 0.6stat ± 0.3syst) \( \times 10^{-12} \) erg cm\(^{-2} \) s\(^{-1} \) and a corresponding γ-ray luminosity of (0.93 ± 0.18 ± 0.09) \( \times 10^{36} \) erg s\(^{-1} \) at a distance of 5 kpc.

The systematic errors on the spectral analysis depend on our uncertainties on the Galactic diffuse emission model, on the effective area, and on the spatial shape of the source. The first is calculated using eight alternative diffuse emission models following the same procedure as in the first Fermi-LAT SNR catalog (Acero et al. 2016) and the second is obtained by applying two scaling functions on the effective area. We also considered the impact on the spectral parameters when changing the spatial model from the infrared template to the best point source hypothesis. These three sources of systematic uncertainties were added in quadrature.

The Fermi-LAT spectral points shown in Fig. 1 (right panel) were obtained by dividing the 100 MeV – 1 TeV energy range into five logarithmically spaced energy bins and performing a maximum likelihood spectral analysis to estimate the photon flux in each interval, assuming a power-law shape with fixed photon index Γ = 2 for the source. The normalizations of the diffuse Galactic and isotropic emission were left free in each energy bin, as were those of the sources within 4°. A 95% confidence level upper limit was computed when the TS value was lower than 1. Spectral data points are given in Table 3.

We examined the reason for the significant improvement of the derived TS value (of 38.3) with respect to the TS value of 22.9 above 700 MeV reported by Xiang & Jiang (2021). To do so, we reanalyzed the source above the same threshold, 700 MeV, using a point source localized at the position reported by Xiang & Jiang (2021). Their setup corresponds to configuration 4 in Table 2 and we find a TS value very similar to theirs (22.9). We tested several analyses with different spatial bin sizes, region sizes, and with or without the summed likelihood, and the improvement is shown step by step in Table 2. The higher TS value that we find in our analysis is most likely due to the summed likelihood analysis and the finer spatial binning of 0.05° (configuration 1). These improvements together with our lower energy threshold of 100 MeV boost our detection to the TS value of 38.3.

3. Discussion

We next modeled the γ-ray emission in a multiwavelength context. As Kepler is a well-studied SNR, we aimed to build a co-

Table 1. Results of the fit of the LAT data between 1 GeV and 1 TeV using different spatial models. The second column reports the TS values obtained for each spatial model, while Col. 3 indicates the number of degrees of freedom, k, adjusted in the model. The delta Akaike criterion is reported in the fourth column. See Sect. 2.2 for more details.

<table>
<thead>
<tr>
<th>Spatial model</th>
<th>Summed Bin size</th>
<th>Region size</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray template</td>
<td>0.05</td>
<td>15</td>
<td>33.9</td>
</tr>
<tr>
<td>Radio template</td>
<td>0.05</td>
<td>15</td>
<td>30.6</td>
</tr>
<tr>
<td>Infrared template</td>
<td>0.1</td>
<td>15</td>
<td>23.2</td>
</tr>
<tr>
<td>Best point source</td>
<td>0.1</td>
<td>20</td>
<td>21.4</td>
</tr>
</tbody>
</table>

Table 2. Impact on the source significance of different analysis setups above a 700 MeV energy threshold. For comparison, our setup corresponds to configuration 1 and that of Xiang & Jiang (2021) to configuration 4.

<table>
<thead>
<tr>
<th>Configuration number</th>
<th>Summed Bin size</th>
<th>Region size</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>0.05</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>0.05</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>0.1</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>0.1</td>
<td>20</td>
</tr>
</tbody>
</table>

https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
Table 3. Fermi-LAT flux data points using the infrared template. The flux parameter with an asterisk denotes an upper limit. The first and second flux errors represent statistical and systematic errors, respectively.

<table>
<thead>
<tr>
<th>Energy band GeV</th>
<th>$E^2 dN/dE$ 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 (0.10-0.63)</td>
<td>7.39 (2.77,-2.77) (2.19,-2.32)</td>
<td>7.22</td>
</tr>
<tr>
<td>1.58 (0.63-3.98)</td>
<td>3.70 (1.23,-1.30) (0.97,-1.03)</td>
<td>9.72</td>
</tr>
<tr>
<td>10.00 (3.98-25.1)</td>
<td>3.17 (0.96,-1.11) (0.59,-0.68)</td>
<td>16.85</td>
</tr>
<tr>
<td>63.10 (25.1-158)</td>
<td>1.87 (1.27,-1.75) (0.48,-0.65)</td>
<td>4.44</td>
</tr>
<tr>
<td>398.11 (158-1000)</td>
<td>6.41*</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Our assumption is that, on the one hand, the observed GeV γ-ray emission is mostly of hadronic nature ($\pi^0$ decay) and is beaming radiated from the northwest hemisphere, where the shock is in interaction with the dense CSM as traced by infrared and optical maps. On the other hand, the leptonic components (synchrotron and inverse-Compton) arise from high velocity regions mostly observed in the south, with shock speed\(^9\) ranging from 4000-7000 km s\(^{-1}\) (regions 4-12). X-ray synchrotron emission requires high-speed shock regions, but radio emission is produced by slower shocks. However, for simplicity, we modeled the electron population with a single radio to X-ray population. Consequently, we expect our model will underpredict the radio data points.

We used the measured and inferred properties of the SNR to fix various parameters of our model. First, we fixed the fast shocks (leptonic components) at 5000 km s\(^{-1}\) and the slower shocks in the interacting region at 1700 km s\(^{-1}\) for a target density of 8 cm\(^{-3}\) as reported in [Sankrit et al. 2016]. Secondly we derived the electron spectral distribution assuming that the electron maximal energy is limited by synchrotron losses and that proton maximal energy is limited by the age of the remnant.

3.1. Model motivation

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3.2. Theoretical context

Following the prescription of [Parizot et al. 2006], the acceleration timescale for the particles to reach an energy $E$ at the forward shock can be written as

$$\tau_{acc} \approx (30.6 \text{ yr}) \frac{3r^2}{16(r-1)} k_0(E) \times E_{\text{TeV}} B_{\text{100}}^{-1} V_{\text{sh},3}^{-2},$$

(1)

where $r$ is the compression ratio assumed at the shock, $B_{\text{100}}$ the downstream magnetic field in units of 100 $\mu$G, and $V_{\text{sh},3}$ the shock speed in units of 1000 km s\(^{-1}\). The deviation to Bohm diffusion is parametrized by $k_0 \geq 1$, defined as $D(E) = k_0 D_{\text{Bohm}}(E)$, where $D_{\text{Bohm}}$ is the Bohm diffusion coefficient. At a value of one, the acceleration at the shock is the most efficient, and the maximal reachable energy decreases for higher values of $k_0$.

In the loss-limited regime, the electron maximal energy can be obtained by equating the acceleration timescale, $\tau_{acc}$, to the synchrotron loss time at the shock, giving

$$E_{e,max} \approx (8.3 \text{ TeV}) \times \frac{f(r)}{f_0} \times \frac{r_0^{1/2}}{r^{1/2}} \times B_{\text{100}}^{1/2} \times V_{\text{sh},3}^3,$$

(2)

where $f(r) \equiv f(r)/f(4)$, with $f(r) = \sqrt{r-1}/r$. The maximal proton energy is obtained by equating $\tau_{acc}$ to the age of the remnant of 400 years, giving

$$E_{p,max} \approx (13.1 \text{ TeV}) \times T_{400} \times f(r)^2 \times k_0^{-1} \times B_{\text{100}} V_{\text{sh},3}^3.$$

(3)

where $T_{400}$ is the age of the remnant in units of 400 yrs. For the magnetic fields considered in this modeling ($B \sim 100 \mu$G), the synchrotron cooling is non-negligible and is modeled with a broken power law, with $E_{\text{break}}$ obtained by equating the age of the remnant and the synchrotron loss time downstream of the shock, giving

$$E_{\text{break}} \approx (3.1 \text{ TeV}) \times T_{400}^{1/2} B_{\text{100}}^2.$$

(4)

Because of the cooling and the cut at the maximum energy, the electron population is modeled as an exponentially cutoff broken power law, with a change in slope at $E_{\text{break}}$ to $\Gamma_2 = \Gamma_1 + 1$.

Assuming that the synchrotron emission is limited by cooling, the acceleration efficiency parameter, $k_0$, can be indirectly estimated by comparing the shock speed and the cutoff energy of the X-ray synchrotron spectrum using Eq. 34 of [Zirakashvili & Aharonian 2007]. Such a study was carried out by [Tsujii et al. 2021] on a population of SNRs, including Kepler. For Kepler’s southeastern regions, where fast shocks are observed (Tsujii et al. 2021; reg 4-8 in Table 2), $k_0$ (their $\eta$) ranges from 2.0 to 3.2, which is equivalent to 3.1 to 5.0\(^9\) when rescaled to a distance of 5 kpc instead of 4 kpc. Given the measured values mentioned above, we decided to fix $k_0 = 3.4$ (the median value of the distribution) for our modeling for both the electron and proton populations (radiative model shown in Fig [2]).

The radiative models from the naima packages [Zabalza 2015] were used with the Pythia8 parametrization of [Kafexhiu et al. 2014] for the $\pi^0$ decay. For the inverse Compton, a far-infrared field ($T=30 \text{ K}$, $U_{\gamma0} = 1 \text{ eV cm}^{-3}$) was used in addition to the cosmic microwave background [Porter et al. 2006].

3.3. Multiwavelength data and spectral energy distribution

For the multiwavelength data presented in Fig [2] we used the updated compilation of radio fluxes from [Castelletti et al. 2021], the X-ray data from the Suzaku XIS + HXD instruments (covering the 3-10 keV and 15-30 keV band), [Nagayoshi et al. 2021], and the H.E.S.S. flux points from [Prokhorov et al. 2021]; [H. E. S. S. Collaboration et al. 2022]. The newly derived Fermi-LAT flux points using the infrared spatial template are presented (same as Fig [1]).

The resulting adjusted models, shown in Fig [2], were obtained with only four free parameters, namely the downstream magnetic field, a unique spectral index for electrons and protons, and the associated energy budgets (see Table [4]). The electron population spectral index and the amplitude of the magnetic field are correlated in the spectral energy distribution (SED) fitting. Motivated by theoretical expectations from recent kinetic hybrid simulations [Diesing & Caprioli 2021] predicting spectral indices steeper than 2, we present two different scenarios for spectral indices of 2.3 and 2.2, corresponding to an intermediate (90 $\mu$G) and high magnetic field value (170 $\mu$G), respectively. A viable scenario, not shown in Fig [2] can also be obtained for $B=250 \mu$G if the spectral index is changed to 2.15. Such a magnetic field value is compatible with the estimated values at

\(^9\) Velocity is derived from proper motion, which depends linearly on the distance, and $\eta$ has a square dependence on shock speed (see Eq. 3 from Tsujii et al. 2021).
The intermediate and high magnetic field scenarios reproduce equally well the GeV to TeV flux points and cannot be disentangled from the SED analysis alone. However, we note that the inverse-Compton emission dominates above 300 GeV in an intermediate magnetic field case, while the hadronic emission dominates the entire γ-ray band for a high magnetic field scenario. Therefore, if the inverse-Compton emission arises from the fast moving shocks in the southern regions, the precise location of the TeV γ-ray emission might be able to constrain the hadronic or leptonic nature of the emission and, indirectly, the average magnetic field in the SNR. The distance between the dense interacting region in the northwest and the southern rim is on the order of 0.05°. While this is at the limit of the H.E.S.S. telescopes source localization precision for a faint source, a comparison of the GeV and TeV best-fit positions could shed light on the nature of TeV γ-ray emission. With an increased sensitivity and spatial resolution, the next-generation Cherenkov Telescope Array (Cherenkov Telescope Array Consortium et al. 2019) will probe Kepler’s γ-ray emission spatial distribution with greater accuracy and bring additional constraints on its nature.

### 3.4. Kepler SNR γ-ray emission in context

The detection of the Kepler SNR at GeV and TeV energies completes our high-energy view of historical SNRs. In this section we compare the global spectral properties of the young and likely hadronic-dominated SNRs Kepler, Tycho, and Cassiopeia A to those of the older middle-aged SNRs W 44, IC 443, and Cygnus Loop. We note that other young SNRs, such as SN 1006, RX J1713.7−3946, and RCW 86, which show a spectral slope Γ ~ 1.5 at GeV energies (see, e.g., Acero et al. 2015), are likely dominated by leptonic emission and are not considered in our sample. The distances to the sources are fixed to 3.3 ± 0.1 kpc for Cassiopeia A (Alarie et al. 2014), 4 ± 1 kpc for Tycho (Hayato et al. 2010), 5.1 ± 0.5 kpc for Kepler (Sankrit et al. 2016), 735 ± 25 pc for Cygnus Loop (Fesen et al. 2018), 3.0 ± 0.3 kpc for W 44 (Ranasinghe & Leahy 2018), and 1.7 ± 0.1 kpc for IC 443 (Wu et al. 2019).

Figure 3 compares the SED in terms of luminosity of the aforementioned SNRs. As a proxy to discuss spectral curvature, we estimated the hardness ratio $HR = F_{\text{GeV}} / F_{\text{TeV}}$. Tycho, Kepler, and Cassiopeia A exhibit a nearly flat spectrum (HR=0.2-0.4), while the curvature is stronger for IC 443 (HR=0.015) and W 44 (< 2 × 10⁻³). Such a contrast is due to differences in the acceleration and emission mechanisms. In the young SNR sample, high shock speeds (3000-6000 km s⁻¹) that produce highly energetic cosmic rays are observed; the cosmic rays interact with circumstellar material. The second sample exhibits lower shock speeds (few 100 km s⁻¹) with the presence of radiative shocks, where the compression and reacceleration of preexisting cosmic rays takes place, producing a spectral break at lower energies than for the young SNR sample. We note that the separation in terms of luminosity in our sample is not as clear. While W 44 is 50-100 times more luminous at 1 GeV than Kepler and Tycho, it is also 100 times more luminous than Cygnus Loop at 1 GeV.

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Table 4. List of parameters obtained from the modeling of the SED in different scenarios. Parameters in brackets are fixed from observables or theory (see Sect. 3.4 and Sect. 3.5, while other parameters are adjusted to the data. The energy budget values are integrated above 1 GeV.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$B$ $\mu$G</th>
<th>$n_0$ cm⁻³</th>
<th>$V_{sh,e}$ km s⁻¹</th>
<th>$V_{sh,p}$ km s⁻¹</th>
<th>$\Gamma_{e,1}/\Gamma_{e,2}$</th>
<th>$E_{\text{break, e}}$ TeV</th>
<th>$E_{\text{max, e}}$ TeV</th>
<th>$W_p$ TeV</th>
<th>$W_p$ erg</th>
</tr>
</thead>
<tbody>
<tr>
<td>High magnetic field</td>
<td>170 [8]</td>
<td>[5000]</td>
<td>[1700]</td>
<td>[1700]</td>
<td>2.2 [3.2]</td>
<td>[1.1]</td>
<td>[18.4]</td>
<td>2.2</td>
<td>[21.2]</td>
</tr>
<tr>
<td>Intermediate magnetic field</td>
<td>90 [8]</td>
<td>[5000]</td>
<td>[1700]</td>
<td>[1700]</td>
<td>2.3 [3.3]</td>
<td>[3.9]</td>
<td>[25.3]</td>
<td>2.3</td>
<td>[11.2]</td>
</tr>
</tbody>
</table>

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Fig. 2. Spectral energy modeling in an intermediate and high magnetic field scenario. The leptonic emission is assumed to arise from the fast shocks in the southern regions and the hadronic emission from the northwest interaction region. For the Fermi-LAT flux points, both the statistical errors and summed errors ($\sqrt{\text{stat}^2 + \text{sys}^2}$) are shown. Modeling parameters are listed in Table 4. The shock given the thin X-ray synchrotron filament size (Bamba et al. 2005; Rettig & Pohl 2012). When changing $k_0$ to 1 for the protons (i.e., maximal acceleration efficiency), $E_{\text{p, max}}$ increases and slightly improves the model agreement with the H.E.S.S. flux points in the hadronic-dominated case.

Assuming that the hadronic emission arises from a small angular region in the SNR could explain the modest energy budget required (5.6 × 10⁸⁸ erg). On the Spitzer infrared 24 μm images and the Hubble Hα images from Sankrit et al. (2016), the northwest interacting region has an opening angle of ~45°. Assuming a similar angle in the third dimension, this spherical cap represents ~15% of the SNR surface. The local proton energy budget is therefore equivalent to about 4% of the local kinetic energy, assuming an energy explosion of 10⁵⁴ erg.
The SED is modeled in a scenario with only four free parameters ($B$, $\Gamma$, $W_0$, and $W_p$), the rest being fixed using literature values and on theoretical grounds. The GeV $\gamma$-ray emission is interpreted as $\pi^0$ decay from the northwest interaction region. The TeV emission could be inverse-Compton dominated ($B < 100 \mu G$; expected peak location in the south) or $\pi^0$ decay dominated ($B > 100 \mu G$; expected peak location in the northwest).

Assuming a particle density of $8 \text{ cm}^{-3}$, derived from infrared observations, and that the interaction region represents 15% of the SNR surface, the local fraction of kinetic energy transferred to accelerated particles is on the order of 4%.

While this is at the limit of current generation instruments, a comparison of the Fermi-LAT and H.E.S.S. best-fit positions and errors could help to understand the dominant emission process at TeV energies. In addition, future observations with the Cherenkov Telescope Array will enable a detailed morphological analysis of the $\gamma$-ray emission and probe the high end of the $\gamma$-ray spectrum to test the maximal energies that this young particle accelerator can reach.

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Software: This research made use of astropy, a community-developed Python package for Astronomy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018), of fermipy a Python package for the Fermi-LAT analysis (Wood et al. 2017), and of gammappy, a community-developed Python package for TeV gamma-ray astronomy (Deil et al. 2017). The naima package was used for the modeling (Zabalza 2015).

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