Discovery of GeV Gamma-Ray Emission from Pulsar Wind Nebula Kes 75 and PSR J1846–0258

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Abstract

We report the detection of gamma-ray emission from pulsar wind nebula (PWN) Kes 75 and PSR J1846–0258. Through modeling the spectral energy distribution incorporating the new Fermi-LAT data, we find that the observed gamma-ray emission is likely a combination of both the PWN and pulsar magnetosphere. The spectral shape of this magnetospheric emission is similar to the γ-ray spectrum of rotation-powered pulsars detected by Fermi-LAT, and the results from our best-fit model suggest that the pulsar’s magnetospheric emission accounts for 1% of the current spin-down luminosity. Prior works attempted to characterize the properties of this system and found a low supernova (SN) explosion energy and low SN ejecta mass. We reanalyze the broadband emission incorporating the new Fermi emission and compare the implications of our results to prior reports. The best-fit gamma-ray emission model suggests a second very hot photon field possibly generated by the stellar wind of a Wolf–Rayet star embedded within the nebula, which supports the low ejecta mass found for the progenitor in prior reports and here in the scenario of binary mass transfer.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Pulsar wind nebulae (2215); Neutron stars (1108); Rotation powered pulsars (1408); Magnetars (992); Gamma-ray sources (633); Gamma-ray astronomy (628)

1. Introduction

Neutron stars (NSs) are formed in core-collapse supernovae (SNe) and have a wide range of observational manifestations, such as rotation-powered pulsars (RPPs), central compact objects (CCOs), and magnetars. The relationship between these manifestations is unknown, and they could be separate objects or different phases of evolution (see, e.g., Harding 2013; Kaspi 2018, for a review). The vast majority of the over 3000 known NSs are observed as RPPs, where the associated emission comes from the radiating relativistic particles and is powered by the loss of the NS’s rotational energy. A less common class of NSs are magnetars, for whom in nearly all cases the bursting activity requires an energy source larger than their available rotational energy. In these sources, the energy released by the decay of extremely strong (∼ 1014 G) surface magnetic field is believed to be the dominant contributor to their observed emission (Kaspi & Beloborodov 2017). Unlike RPPs, magnetars produce outbursts in X-rays and gamma-rays and are generally not observed to show radio pulsations. In the past decade, the distinct border between RPPs and magnetars has started to fade, with some RPPs having a similarly strong spin-down-inferred dipolar surface magnetic field and the discovery of magnetar-like outbursts in a couple of young pulsars. This fading distinction is also present in the P-Plot diagram for pulsars, challenging the source class distinction between magnetars and RPPs. Among the previously assumed “regular” RPPs displaying magnetar-like behavior is the X-ray pulsar PSR J1846–0258, powering the pulsar wind nebula (PWN) Kes 75 (Gavriil et al. 2008). With a surface dipolar magnetic field of $B = 5 \times 10^{13}$ G, a spin-down luminosity of $\dot{E} = 8.1 \times 10^{36}$ erg s$^{-1}$, and a characteristic age of $\tau_c = 723$ yr (Gotthelf et al. 2000; Livingstone et al. 2011), this pulsar was believed to be an RPP with a high surface magnetic field.

In 2006 this pulsar was detected to emit magnetar-like bursts (Gavriil et al. 2008), and its spectrum was observed to change with time (Kumar & Safi-Harb 2008; Ng et al. 2008). After the observed variability, the pulsar returned to its previous (quiescent) state, with the exception of its braking index, which was now measured to be $n = 2.16 \pm 0.13$ (Livingstone et al. 2011) rather than the $n = 2.65$ it was before the outburst. In recent years, PSR J1846–0258 showed another period of magnetar-like bursts (Krimm et al. 2020; Blumer et al. 2021), before returning to “normal” X-ray luminosities.

The behavior of PSR J1846–0258 indicates that perhaps young pulsars can evolve into either RPPs or the magnetar class by an emerging surface magnetic field (e.g., Gullon et al. 2015). In order to understand why some pulsars show magnetar-like behavior, it is crucial to understand the circumstances that lead to the formation of the NS. Hence, determining the properties of the NS at birth, as well as its progenitor, is key.

If the rotational power output is strong enough from the pulsar, a PWN can form. A PWN is a highly relativistic plasma consisting of electrons and positrons that were injected by the central pulsar. The interaction between the colder pulsar wind and the relativistic plasma generates a shock wave called the “termination” shock. The particles are injected by the central pulsar and accelerated at the termination shock as they enter the nebula. Their evolution strongly depends on the SN and NS.
characteristics (Gaensler & Slane 2006). By studying the spectral and dynamical evolution of a PWN, combined with the observed properties of the pulsar, one can then obtain information on the surroundings of the supernova remnant (SNR) and the NS birth properties, such as its initial spin period and spin-down energy (see, e.g., Gelfand et al. 2009). Applying this type of study to PSR J1846–0258 and PWN Kes 75 allows valuable constraints in understanding why this source exhibits both RPP-like and magnetar properties. From this we can understand whether this is an evolutionary phase of young and energetic NSs or a separate class.

PWN Kes 75 has been the focus of multiple studies from radio to infrared, X-ray, and TeV (see, e.g., Salter et al. 1989; H.E.S.S. Collaboration et al. 2018; Reynolds et al. 2018; Temim et al. 2019; Gotthelf et al. 2021). Kes 75 radiates via synchrotron emission at lower energies and via inverse Compton scattering (ICS) at TeV gamma-ray energies. However, for precise characterization of the IC spectrum and thus local photon field characterization, MeV–GeV measurements are imperative.

The properties of the photon fields, such as the temperature and energy density, enable a more complete picture of the local environment for Kes 75, which in turn constrains the magnetic field of the PWN. Previous attempts in the search for gamma-ray emission coincident with Kes 75 have been unsuccessful. However, a 4σ Fermi Large Area Telescope (Fermi-LAT) detection of the pulsar’s pulsed γ-ray emission up to 100 MeV has been reported by Kuiper et al. (2018). This work, however, is focused on energies above 100 MeV, where the pulsed emission is thus expected to not be significant.

In this paper, we report the likely detection of the PWN to the Kes 75 complex with Fermi-LAT. We analyze the contributions from both the pulsar and the nebula to characterize the observed MeV–GeV emission. We first discuss the data analysis and the results in Section 2. We use these results in modeling of the PWN in Section 3.2 and discuss our findings and their implications in Section 4, before concluding in Section 5.

2. Fermi-LAT Analysis and Results

Fermi-LAT is a pair-conversion telescope detecting γ-ray photons from 20 MeV to more than 1 TeV. Since beginning operation in 2008 August, the telescope has performed all-sky surveys every 3 hr. The recently improved sensitivity and spatial resolution of the instrument are enabled by the Pass 8 update (Atwood et al. 2013). The Pass 8 update, in its current version P8R3 (Bruel et al. 2018), offers a higher acceptance of detected photons and a narrower point-spread function (PSF) at higher energies, allowing for better analysis of point sources at higher energies. A main addition to the update was the inclusion of PSF quartiles. The Fermi-LAT-detected photons are divided into four quartiles, categorized based on their reconstruction accuracy, where PSF 0 has the lowest quality and PSF 3 has the highest quality. This enables the observer to specify the PSF quality of the photons, to optimize between spatial resolution and sensitivity.

2.1. Data Selection

We have analyzed 11.5 yr (2008 August 4 to 2020 February 26) of data toward PWN Kes 75, selecting data in a 20° radius centered on the X-ray coordinates of PWN Kes 75, RA = 18°46′25.0″ and decl. = −02°59′13′″. We constrained our data selection to the 100 MeV–500 GeV energy range. We allowed a maximum zenith angle of 100° to reduce Earth limb contamination. The data were selected to only include photons in the upper three-quartile selection of PSFs (PSFs 3, 2, 1) and binned to 0.1° pixel−1 to accommodate the resolution at higher energies, with 8 bins per decade in energy. We consider sources up to a 10° radius in the global source model. To model the Galactic diffuse background, we use template gll_iem_v07.fits, and for the isotropic diffuse backgrounds we use the iso_P8R3_SOURCE_V3_v1.txt template. As the analysis is performed using more than 10 yr of data, we used the 4FGL-DR3 catalog (Abdollahi et al. 2022), version gll_psc_v27.fit, to build our source model. The analysis is performed using fermi tools v.2.2.0, with fermipy v.1.1.6 (Wood et al. 2017).

2.2. Data Analysis

To investigate whether there is a detection of PWN Kes 75 and PSR J1846–0258, we consider nearby unassociated7 sources to be a possible counterpart. The nearest source within this region, at 0°230, was 4FGL J1846.9–0247c, described as a point source with a log-parabola spectrum. Its location and energy range make it a good candidate to actually describe emission from PWN Kes 75, and hence we exclude this source from the model. In the new catalog, 4FGL-DR3 (Abdollahi et al. 2022), a new source is reported near the location of PWN Kes 75, 4FGL J1845.8–0236c, at 0°54, significantly farther away. We do not consider this source to be the counterpart. Indeed, we achieve the best-fit model where J1846.9–0247c is replaced by a point source at the position of PWN Kes 75 and includes the nearby, unassociated source J1845.8–0236c, which is modeling excess diffuse emission unrelated to PWN Kes 75. We then fit for a point source at the location of PWN Kes 75 and compute a test statistic (TS) map with the abovementioned source excluded. The TS is defined to be the natural logarithm of the difference in the likelihood of one hypothesis (e.g., presence of one additional source) and the likelihood for the null hypothesis (e.g., absence of source):

$$\text{TS} = 2 \times \frac{\log L_i}{\log L_0}$$

The TS quantifies how significantly a source is detected with a given set of location and spectral parameters, and the significance of such a detection can be estimated by taking the square root of the TS. For a significant detection, the Fermi-LAT detection threshold is TS = 25 for 4 degrees of freedom. As shown in Figure 1, there is significant residual TS (TSmax ∼ 70, Npred = 2112) from a point source coincident with Kes 75 for energies from 100 MeV to 500 GeV, fitted with a power-law spectrum with index = 2.0. Allowing the point source to vary in location did not improve the fit. A previous examination of this region using the 4FGL-DR2 model in which the newly reported source 4FGL J1845.8–0236c was not included showed an excess in that region. After inclusion of this source in 4FGL-DR3, no such excess is observed in the analysis presented in this work. Given its proximity to

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7 Sources not associated with any astronomical counterpart.
PWN Kes 75, we tried to optimize the location for both PWN Kes 75 and the new source by running a localization analysis on both sources in fermipy. No better location was found within 0°.5 of each source. Even though PWN Kes 75 is much smaller than the PSF of the Fermi-LAT instruments (∼0°.15 for E > 10 GeV), we have tested the source for extension using the extension templates RadialDisk and RadialGaussian. Using the radial disk template, we find a best-fit extension of 0°.283 ± 0°.033 and a 95% upper limit of 0°.32 with TS_{ext} = 12.5. For the radial Gaussian template, we find a size of 0°.247 ± 0°.048 and a 95% upper limit of 0°.34 with TS_{ext} = 15.0. Both these extensions are insignificant, and we conclude that there is no evidence for source extension. We additionally tested the extension results by changing the Galactic diffuse model flux by ±5% (as we do for the measured flux; see below) and find significant changes in the extension results. Because PWN Kes 75 lies in a complex region of diffuse emission, we therefore interpret the extension results as not significant and favor instead the point-source model.

To investigate the systematic uncertainties in the Galactic diffuse background and effective area, we analyzed the data using the following configurations:

1. the 4FGL catalog instead of 4FGL-DR3;
2. the previous version of the Pass 8 instrument response function (IRF) newly released isotropic diffuse background version P8R3_SOURCE_V2;
3. by reducing the maximum zenith angle to 90°, further decreasing any Earth limb contamination; and
4. by altering the normalization of the diffuse background by ±5%.

The obtained spectra as a result of using different configurations in the data analysis are shown in Figure 2 and show good agreement with each other. When applying the 4FGL catalog, we included the newly reported source 4FGL J1845.8−0236c to remain consistent with the other source models. For the remainder of this report we adopt the maximum and minimum bounds (including upper limits) from the tested configurations to represent the systematic error (see Table 1).

The obtained spectrum describes the entire PWN complex, which is both the PWN and the pulsar. In Section 3.2 we find the energies where the pulsar dominates (100 MeV < E < 5 GeV) and where the PWN dominates (5 GeV < E < 500 GeV). We therefore also test spectral models best describing both components in the Fermi-LAT source model. The spectrum in energies 100 MeV < E < 5 GeV is best described using a PLEC2 model (power law with superexponential cutoff), and we find an improvement of the fit compared to fitting a simple power law. The TS for PWN Kes 75 in this energy range also increases from 73 to 89. Its best-fit parameters have index1 = 1.46 ± 0.44, index2 = 0.67, exponent factor =

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**Figure 1.** TS maps centered at the location of PWN Kes 75. These maps show the TS of an additional point source at any pixel on the map. The left panel shows the TS map for energies between 100 MeV and 500 GeV, and the right panel shows the TS map for energies between 1 GeV and 500 GeV. The inner contour in the right panel is drawn at TS = 40.

**Figure 2.** Fluxes of a point source at the location of PWN Kes 75, using six different configuration files to assess the influence on the systematic errors. See Section 2.2 for the different configurations.

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8 https://fermi.gsfc.nasa.gov/science/instruments/table1-1.html
9 https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html#PLSuperExpCutoff2
Table 1

Observed Properties of PWN Kes 75 Used in the Modeling of This Source

| Property                  | Observed  | Model       | Citation                     |
|---------------------------|-----------|-------------|------------------------------|
| PSR J1846–0258            | $8.10 \times 10^{36}$ | Fixed       | Livingstone et al. (2011)    |
| $E_{\text{50 keV}}$       | 2.65 ± 0.01 | Fixed       |                              |
| $P_{\text{ns}}$           | 326.57    | ...         | Livingstone et al. (2011)    |
| Pulsar Wind Nebula        |           |             |                              |
| Angular radius $\theta_{\text{pwn}}$ | $30^\circ \pm 1.7^\circ$ | $30^\circ 3$ | Reynolds et al. (2018)       |
| Angular expansion rate $\dot{\theta}_{\text{pwn}}$ | $(0.249 \pm 0.023) \text{ yr}^{-1}$ | $0.253 \text{ yr}^{-1}$ |                               |
| $\delta_{14}$ (mly)       | 348 ± 52  | 341         | Salter et al. (1989)         |
| $\delta_{27}$ (mly)       | 247 ± 37  | 254         | Salter et al. (1989)         |
| $\delta_{15}$ (mly)       | 172 ± 26  | 168         | Salter et al. (1989)         |
| $\delta_{90}$ (mly)       | 80 ± 12   | 86          | Bock & Gaensler (2005)       |
| $f_{\text{2–10 keV}}$    | $2.031 \pm 0.025 \times 10^{-12}$ | $2.130 \times 10^{-12}$ | Gotthelf et al. (2021)       |
| $f_{\text{2–55 keV}}$    | 2.13 ± 0.022 | 2.04       |                              |
| $F_{\text{0.176 GeV}}$   | $<8.49 \times 10^{-12}$ | $4.78 \times 10^{-12}$ | This work                    |
| $F_{\text{0.549 GeV}}$   | $<0.189–19.91 \times 10^{-12}$ | $7.50 \times 10^{-12}$ | This work                    |
| $F_{\text{1.71 GeV}}$    | $2.38–7.86 \times 10^{-12}$ | $5.61 \times 10^{-12}$ | This work                    |
| $F_{\text{5.32 GeV}}$    | $0.554–1.34 \times 10^{-12}$ | $1.21 \times 10^{-12}$ | This work                    |
| $F_{\text{16.6 GeV}}$    | $0.968–1.0 \times 10^{-12}$ | $1.35 \times 10^{-12}$ | This work                    |
| $F_{\text{51.6 GeV}}$    | $1.07–1.18 \times 10^{-12}$ | $1.65 \times 10^{-12}$ | This work                    |
| $F_{\text{160 GeV}}$     | $<2.03 \times 10^{-12}$ (3σ) | $1.71 \times 10^{-12}$ | This work                    |
| $F_{\text{0.332 TeV}}$   | $8.38 \times 10^{-12}$ | $7.72 \times 10^{-12}$ | HESS Collaboration et al. (2018) |
| $F_{\text{0.787 TeV}}$   | $1.30 \times 10^{-12}$ | $1.20 \times 10^{-12}$ | HESS Collaboration et al. (2018) |
| $F_{\text{1.96 TeV}}$    | $1.34 \times 10^{-13}$ | $1.41 \times 10^{-13}$ | HESS Collaboration et al. (2018) |
| $F_{\text{4.87 TeV}}$    | $1.48 \times 10^{-14}$ | $1.30 \times 10^{-14}$ | HESS Collaboration et al. (2018) |
| Supernova Remnant         |             |             |                              |
| Angular radius $\theta_{\text{snr}}$ | $1.50 \pm 0.15$ | $1/44$ | Verbiest et al. (2012)       |
| Distance $d'$             | $(5.8^{+0.5}_{-0.4}) \text{ kpc}$ | $5.82 \text{ kpc}$ |                              |

Note.

- Unabsorbed flux given in units of erg s$^{-1}$ cm$^{-2}$.

(0.009 ± 2.6) × 10$^{-6}$, and a prefactor of (7.5 ± 4.5) × 10$^{-12}$.

The data above 5 GeV are best described by a power law with index $= 2.49 \pm 0.38$ and prefactor $= (2.32 \pm 2.25) \times 10^{-12}$, with a TS of 16.5. Further in this work we model the full spectrum of the PWN complex, using the obtained fluxes given in Table 1.

We note that the obtained spectrum of PWN Kes 75 is very similar to the unassociated source 4FGL J1846.9–0247c located at 01:230 from the X-ray coordinates of PWN Kes 75. Given the obtained source spectrum (see Section 3.1), the detection of PWN Kes 75 at energies of 0.332 TeV and above in the HESS Galactic plane survey (HESS Collaboration et al. 2018) makes us conclude that the unassociated source 4FGL J1846.9–0247c describes emission from PWN Kes 75.

3. PWN Modeling

3.1. Spectral Analysis

The fluxes obtained above and given in Table 1 are for fitting a γ-ray point source at the X-ray coordinates of PWN Kes 75. Furthermore, since the PWN complex is unresolved by Fermi-LAT, this source contains emission from the PWN and the pulsar. Due to the lack of nonthermal X-ray emission observed from the SNR shell (Gotthelf et al. 2021), it does not seem likely to contribute significantly. Given the previous nondetection of pulsed gamma-ray emission in the energy band analyzed in this work (Kuiper et al. 2018), we assume magnetospheric pulsar emission typical of other gamma-ray pulsars, which does not necessarily arise from the same emission mechanism responsible for the detection at lower energies (<100 MeV). The γ-ray emission from typical gamma-ray pulsars is primarily observed below ≤1–10 GeV and well described by a power law or power law with an exponential cutoff (Abdo et al. 2013). As described below, we model the observed γ-ray emission of this source with a power law with an exponential cutoff typical of a pulsar and the γ-ray emission from the PWN as predicted by our model described below.

3.2. PWN Model

As the evolution of a PWN inside an SNR depends heavily on the properties of the progenitor star, the SN explosion, and the NS at birth, modeling the PWN allows for obtaining information on the aforementioned. Following both the dynamical and spectral evolution of the PWN is currently best done using one-zone models. We use the evolutionary model as described by Gelfand et al. (2009) to obtain values for the properties given in Table 2. The procedure used to fit the observed properties of a PWN with the values predicted by this model for a particular combination of input parameters is described in detail by Hattori et al. (2020), and we refer the reader to those papers for an extended description of the model and its applications. We do note that this model and its fitting procedures have successfully reproduced the properties of several PWNe, all with different sets of measured properties.
4. Discussion

As discussed in Section 3.2, our modeling of the observed dynamical and spectral properties of PWN Kes 75 allows us to estimate the properties of the associated pulsar—its birth properties, the γ-ray efficiency, and the spectrum of its magnetospheric emission. We derived the properties of the pulsar wind powered by the loss of rotational energy of the pulsar, the progenitor SN explosion, and its environment. In Section 4.1, we discuss the very high energy (VHE) emission of the pulsar and compare the observed properties of the magnetospheric γ-ray emission of this pulsar with those observed from other RPPs. In Section 4.2, we discuss the implication of the derived properties for the SN explosion. Lastly, in Section 4.3, we discuss the physical significance concerning our measurements regarding the environment of this source.

4.1. VHE Pulsar Emission

In our analysis of the PWN+PSR complex, at energies above 100 MeV, we assume a power law with exponential cutoff for the pulsar. We find a good agreement with the observed flux in the range from 100 MeV to ∼2 GeV range and conclude it likely that the flux in this energy range is emitted by the pulsar magnetosphere. In the following sections this magnetospheric emission is compared with its detected MeV emission and with gamma-ray pulsars reported in the second Fermi pulsar catalog (Abdo et al. 2013).

4.1.1. Comparison to Its MeV Pulsed Emission

Since the discovery of PSR J1846-0258 in X-ray by Gotthelf et al. (2000), there have been numerous studies related...
to its high-energy ($\gtrsim 2\,\text{keV}$) pulsed emission. Kuiper & Hermsen (2009) reported a measurement of the high-energy pulsed spectrum of the pulsar in the $\sim 2-300\,\text{keV}$ band and revealed a major spin-up glitch at the onset of the magnetar-like bursts and enhancement in X-ray flux in 2006 (Gavriil et al. 2008; Kumar & Safi-Harb 2008). A first attempt to detect the pulsar at higher energies, in the MeV–GeV band of Fermi-LAT, was conducted by Parent et al. (2011) using the first $\sim 20$ months of data, who reported a nondetection of PSR J1846–0258 for energies above 100 MeV. A follow-up study by Kuiper et al. (2018), who used 8 yr (2007 August 28–2016 September 4) of Fermi data and a multi-instrument timing solution of the pulsar derived from X-ray observations covering these dates, reported a $4.2\sigma$ detection of pulsed emission from PSR J1846–0258 in the 30–100 MeV band, with no pulsed emission detected at photon energies larger than 100 MeV and a pulsed spectrum well described by a log-parabola that peaks at a photon energy of $3.5 \pm 1.1\,\text{MeV}$. Our detection at energies above 100 MeV does not have sufficient photons to allow for a pulsation analysis.

Figure 4 shows our SED model with the pulsar pulsed flux model derived in Kuiper et al. (2018) overlaid. The flux point in our lowest energy range (centered at 0.176 GeV; see Table 1) detected in our analysis of the Fermi data is consistent with this model. However, the flux measured at higher photon energies is not consistent with an extrapolation of the MeV pulsed emission reported by Kuiper et al. (2018), suggesting that the higher-energy emission ($>100\,\text{MeV}$) does not arise from the same emission mechanism. A similar discrepancy is observed in the SED of the pulsed emission from the Crab pulsar in this energy (see Figure 8 of Kuiper et al. 2018), which also cannot be described by a single parabola. The here-reported GeV component is similar to the one predicted for PSR J1846–0258 by Harding & Kalapotharakos (2017). In their modeling of the VHE pulsar emission of J1846–0258, they predict an emission component in the $\sim\text{GeV}$ range caused by curvature radiation, whose predicted shape is qualitatively similar to what is observed here (Figure 3; Harding & Kalapotharakos 2017).

4.1.2. Comparison to 2PC

To determine whether the magnetospheric $\gamma$-ray emission of J1846–0258 is comparable to that of RPPs not associated with magnetar-like activities, we compare the pulsar properties obtained from our modeling to that of other young, energetic RPPs as compiled in the second Fermi pulsar catalog (2PC; Abdo et al. 2013). The properties we obtain for the pulsar and compare to the pulsars in Abdo et al. (2013) are given in Table 2. In Abdo et al. (2013), Figures 7–10 describe pulsar properties from the detected sample to which we can compare our obtained properties. The magnetic field at the light cylinder is taken from the ATNF catalog ($B_{\text{LC}} = 1.31 \times 10^4\,\text{G}$; Manchester et al. 2005), and the gamma-ray luminosity in the 0.1–100 GeV range derived in this work is given in Table 2.

The gamma-ray efficiency $\eta_\gamma$ of 0.97% is typical for gamma-ray pulsars with similar spin-down energy. Its gamma-ray luminosity ($L_\gamma \sim 7.86 \times 10^{35}\,\text{erg}\,\text{s}^{-1}$) seems to be on the lower end and more in line with $L_\gamma \propto E_\gamma^2$ than a linear relation, consistent with the findings in 2PC on gamma-ray pulsars. The obtained photon index of $\Gamma \sim 1.29$ seems to be harder than most other pulsars of similar spin-down energy, but within the range of values observed in this sample. The cutoff energy of the spectrum of $\sim 1\,\text{GeV}$ compared to its magnetic field at the light cylinder is observed to be similar to other pulsars in the $B_{\text{LC}} \sim 10^4\,\text{G}$ region.

The obtained pulsar properties agree well with what is obtained for the larger sample of gamma-ray-emitting pulsars, supporting the assumption that this additional component originates in the pulsar’s magnetosphere, and suggesting that the underlying physical emission mechanism is similar to that observed from RPPs.

4.2. PWN Model

In Gotthelf et al. (2021) we modeled PWN Kes 75 after adding new X-ray measurements as observed in that work. From our modeling we obtain that the dynamical and spectral properties of PWN Kes 75 can best be described to be formed in a low-energy SN explosion with low ejecta mass (see

\footnotesize{[10] Given the detection approach of 2PC, the catalog is biased toward radio-emitting pulsars.
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Table 2: \( E_{\text{inj}} = 1.1 \times 10^{50} \text{ erg}, M_2 = 0.37 M_\odot \). This is very similar to, albeit a bit lower than, what is derived in Gotthelf et al. (2021). Other works also seem to favor a low explosion energy and ejecta mass (Leahy & Tian 2008). We further compare our results to the modeling results presented in Gotthelf et al. (2021), providing a one-on-one comparison to the influence of the Fermi-LAT measurements on the SED and the evolution of the PWN. From Table 2 it is shown that the addition of the GeV emission shows the need of an additional high-temperature IC photon field. Next to the additional photon field, this work reports a higher wind magnetization \( \eta_2 \gtrsim 0.04 \) than previous studies (see Table 2). This is the result of the increased IC emission required by our Fermi-LAT detection of this source. The additional IC radiative losses associated with this emission decrease the particle energy inside the PWN, and therefore a more strongly magnetized wind is needed to produce the same synchrotron luminosity. The increased wind magnetization also affects the low-energy particle index, which is found to be lower in this work. Furthermore, the slightly longer pulsar spin-down timescale leads to a longer initial spin period.

4.3. Implications of the Additional IC Field

The energy range observed by Fermi-LAT provides an excellent view of the ICS part of the spectrum of PWN Kes 75 that was not probed by previous observations performed by the H.E.S.S. Galactic Plane Survey (H.E.S.S. Collaboration et al. 2018). With the addition of the flux points in the 100 MeV–500 GeV energy range, we need a second background photon field to properly reproduce the IC part of the spectrum in our modeling.

As was the case for Gotthelf et al. (2021), one photon field has a temperature of \( \sim 32 \text{ K} \), which agrees well with the temperature of the surrounding dust (Temim et al. 2019). However, our Fermi-LAT result requires an additional, high-temperature photon field, with \( T_{\text{lc,2}} \sim 1.5 \times 10^5 \text{ K} \) and an energy density

\[
\begin{align*}
  u_{\text{lc,2}} &= K_{\text{lc,2}} T_{\text{lc,2}}^4 \\
  &\approx 5.4 \times 10^{-9} \text{ erg cm}^{-3} = 3.4 \text{ keV cm}^{-3},
\end{align*}
\]

(3)

where \( a \) is the radiation constant, which is orders of magnitude larger than the energy density of the local interstellar radiation field at the ultraviolet (UV) energies where this emission should peak (e.g., Habing 1968).

To identify the possible source of such an intense background photon field, we first calculate the total energy of photons \( E_{\text{lc,2}} \) inside the PWN, assuming that it is a sphere of radius \( R_{\text{pwn}} = \theta_{\text{pwn}} d \approx 0.85 \text{ pc} \) for the values given in Table 1, such that \( E_{\text{lc,2}} \sim 4 \times 10^{47} \text{ erg} \). Assuming that these photons cross the PWN in a time \( \tau_{\text{cross}} \approx \tau_{\text{lc,2}} \approx 2 \times 10^9 \text{ s} \), the rate at which such photons are injected into the PWN \( L_{\text{lc,2}} \) is

\[
L_{\text{lc,2}} \sim \frac{E_{\text{lc,2}}}{\tau_{\text{cross}}} \approx 2.3 \times 10^{39} \text{ erg s}^{-1} = 6 \times 10^2 L_{\odot}.
\]

(5)

Assuming that the energy injection rate \( L_{\text{lc,2}} \) and temperature \( T_{\text{lc,2}} \) of this additional background photon field correspond to the luminosity and (effective) temperature of its source, both values are comparable to those observed from Wolf–Rayet stars (e.g., Abbott 2004; Tramper et al. 2015; Aadland et al. 2022a, 2022b)—suggesting the presence of such a star inside the PWN. If present, this star would have an absolute magnitude \( M_V \lesssim -6 \) (e.g., Aadland et al. 2022b). Using the derived relationship between X-ray absorption and optical extinction (e.g., Foiht et al. 2016), the interstellar hydrogen column density toward Kes 75 (\( N_H \approx 4 \times 10^{22} \text{ cm}^{-2} \); e.g., Gotthelf et al. 2021) implies an extinction \( A_V \gtrsim 14 \text{ mag} \). For a distance of \( d = 5.8 \text{ kpc} \) (Table 1), the apparent magnitude of a Wolf–Rayet star inside Kes 75 would be \( m_V \approx 22 \) fainter than current surveys of this field (e.g., Pan-STARRS; Magnier et al. 2020). If present, such a star was likely the binary companion on the stellar progenitor and would provide important information on its properties and evolution before exploding.

5. Conclusions

In this report we analyze the emission associated with the unknown source 4FGL J1846.9–0247c, coincident with the location of PWN Kes 75. Performing a detailed analysis of the source points to a PWN+PSR origin from PWN Kes 75. From our modeling of the obtained spectrum, we derive both the physical properties of the PWN and the gamma-ray properties of the pulsar. The pulsar’s gamma-ray parameters are found to be consistent with those observed in pulsed emission from known gamma-ray pulsars. The magnetospheric component we observe can be explained by a curvature radiation component around these energies as predicted for this source by Harding & Kalapotharakos (2017).

We find that the Fermi-LAT flux measurements provide valuable constraints to the local photon fields and, when combined with the derived progenitor characteristics, support a scenario where the progenitor was in a binary system before going SN. The high-temperature IC photon field suggests the presence of a Wolf–Rayet star embedded within the PWN. This Wolf–Rayet star was then likely the binary companion of the progenitor to PWN Kes 75.

Furthermore, the addition of the Fermi-LAT flux measurements gives rise to the need for a higher wind magnetization than previously reported in Gotthelf et al. (2021), underlining the importance of Fermi-LAT in the study of PWNe.

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Facility: Fermi.

Software: Fermipy (Wood et al. 2017), ATNF pulsar catalog (Manchester et al. 2005).

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