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Towards searching for ultra-high-energy photons from galactic PeVatrons

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Recently, several observatories have discovered photons of cosmic origin with maximum energies in the PeV (10^{15} eV) range. Photons at these energies might be produced as by-products from particle acceleration in so-called PeVatrons, which are widely assumed to be the source of a large part of galactic cosmic rays. The first PeVatron to be firmly established was the Crab nebula, a pulsar wind nebula. Another PeVatron may be located in the Galactic Center region. However, the measurement of PeV photons from several other sources indicates the presence of further PeVatrons, which may also be associated with supernova remnants. In this contribution, we present a compilation of recent measurements of PeV photons by LHAASO and HAWC. We extrapolate the measured energy spectra up to the ultra-high-energy (UHE, $E > 10^{17}$ eV) regime to obtain an estimate of the required sensitivity for the measurement of UHE photons from specific source candidates. One goal of this study is to evaluate the potential of present and future cosmic-ray observatories, for example the Pierre Auger Observatory, to detect such photons, which could provide complementary information on the sources of cosmic rays beyond the PeV regime—a key objective of current efforts in multimessenger astronomy.

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1. Introduction

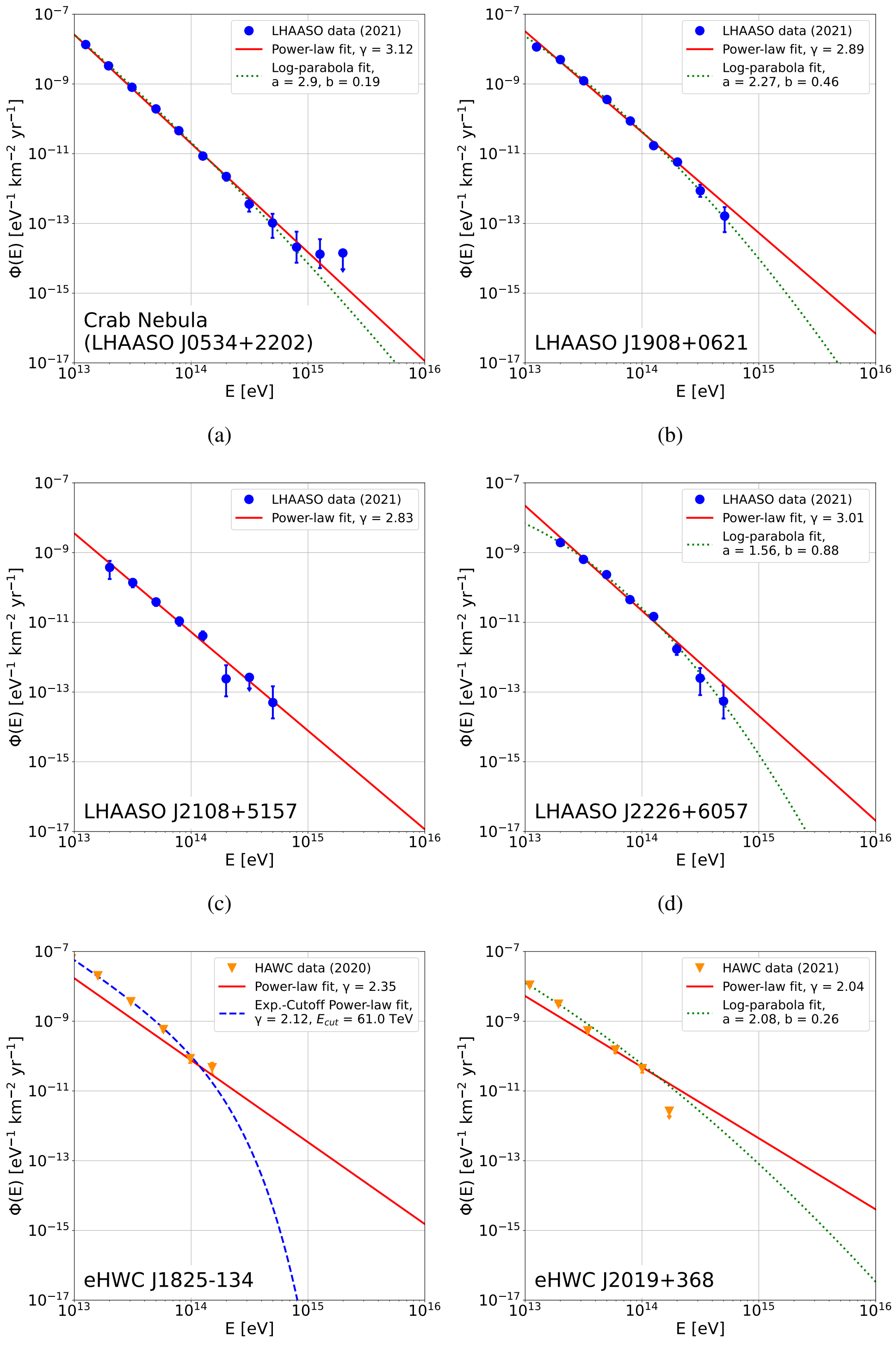
In the past few years, cosmic photons of ever-increasing energy have been observed. Most recently, the LHAASO and HAWC observatories reported the measurement of photons with energies in the PeV (10^{15} eV) range from a number of (galactic) sources [1, 2]. These "photon PeVatrons" are of considerable interest in the context of multimessenger astronomy, in particular for identifying the sources of cosmic rays in the PeV range and above, which is a key objective of current efforts in this rapidly emerging field.

The sites where the acceleration of cosmic rays to PeV energies takes place are commonly termed "PeVatrons". Although the exact mechanisms which are responsible for the acceleration of the initial particles in these PeVatrons are not fully understood yet, it is known that photons are emitted as by-products of the acceleration through different processes, either involving leptons or hadrons (see, e.g., [3–5]). Leptonic processes include Bremsstrahlung and inverse Compton scattering, while hadronic processes include interactions of the initial particles with each other or the surrounding radiation fields, producing neutral pions which then decay into photons. These processes can occur, for example, at supernova remnants, pulsars and pulsar wind nebulae (such as the Crab Nebula), making them possible PeVatrons—in fact, they are widely assumed to be the source of a large part of galactic cosmic rays—but microquasars, superbubbles and young massive starclusters can be seen as PeVatron candidates as well (see, e.g., [3–5]).

The photons produced in the aforementioned processes necessarily have lower energies than the charged particles that are accelerated in such PeVatrons. Hence, photons in the PeV range emitted from photon PeVatrons can be seen as indicative for charged-particle acceleration to energies beyond the PeV scale at these sites. Some of these photon PeVatrons even exhibit energy spectra without a cutoff in the energy range covered by current measurements. A natural question is then how far these spectra extend. Related to this is the question of what the prospects are for observing photons of higher energies from such sources with current instruments. LHAASO and HAWC, however, may not have enough sensitivity to reach photon energies much beyond the PeV range due to their size. On the other hand, large air-shower experiments like the Pierre Auger Observatory [6], mainly targeting ultra-high-energy (UHE, $E > 10^{17}$ eV) cosmic rays, have recently begun to lower the energy threshold for photon searches [7, 8]. In this contribution, we extrapolate the measured power-law spectra of photon PeVatrons measured by LHAASO and HAWC to the UHE regime, with the goal of estimating the prospects of observing UHE photons from such sources with giant air-shower experiments like the Pierre Auger Observatory.

2. Current Measurements in the PeV Range

We focus here on two recent catalogs of galactic sources of photons in the PeV range, published by LHAASO [1] and HAWC [2]. The HAWC catalog contains three sources with significant photon emission above 0.1 PeV, while the LHAASO catalog includes twelve sources of photons with energies above 0.1 PeV and up to 1.4 PeV. These are the highest photon energies ever measured. In Fig. 1, we show exemplarily six of these sources—four from the LHAASO catalog and two from the HAWC catalog—for which the detailed measurement data are available. These sources are the Crab Nebula (LHAASO J0534+2202) [1, 9], LHAASO J1908+0621 [1], LHAASO J2108+5157 [1, 10],



(a) (b) (c) (d) (e) (f)

Figure 1: Measured energy spectra of six exemplary sources from the LHAASO and HAWC catalogs of galactic sources of photons with energies in the PeV range: (a) Crab Nebula (LHAASO J0534+2202) [1, 9], (b) LHAASO J1908+0621 [1], (c) LHAASO J2108+5157 [1, 10], (d) LHAASO J2226+6057 [1], (e) eHWC J1825-134 [2], and (f) eHWC J2019+368 [2, 11]; also shown are power-law fits to the measured data; some spectra are better described by a log-parabola fit or an exponential cutoff power-law fit.

Table 1: Parameters of the power-law fits following Eq. (1) for the Crab Nebula [9] and LHAASO J2108+5157 [10].

Parameter	Crab Nebula	LHAASO J2108+5157
Φ_0 [$\mathrm{eV}^{-1}\,\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$]	2.59×10^{-8}	5.01×10^{-10}
E_0 [eV]	10^{13}	2×10^{13}
γ	3.12	2.83

LHAASO J2226+6057 [1], eHWC J1825-134 [2], and eHWC J2019+368 [2, 11]. We focus here on the high-energy ends of the spectra. Hence, we do not include measurements at lower energies. The measured data have been fitted with a power-law function of the form

$$\Phi_\gamma^{\mathrm{PL}} = \Phi_0 \times \left(\frac{E}{E_0}\right)^{-\gamma}, \tag{1}$$

where Φ_0 denotes the differential photon flux at the pivot energy E_0 and γ is the spectral index. We note that for a number of the sources shown in Fig. 1, a log-parabola fit or an exponential cutoff power-law fit actually provides a better description of the data. However, for two sources—the Crab Nebula, shown in Fig. 1(a), and LHAASO J2108+5157, shown in Fig. 1(c)—no cutoff is visible in the energy range covered by the measurements and the power-law fits provide a good description of the spectra at the high-energy end. The parameters of the power-law fits for the two sources are given in Tab. 1. The maximum energies of the photons observed from these two sources are 1.12 PeV (Crab Nebula) and 0.43 PeV (LHAASO J2108+5157).

3. Extrapolating the Energy Spectra

Since the energy spectra of the Crab Nebula and LHAASO J2108+5157 continue without a cutoff into the PeV range, an extrapolation to higher energies seems feasible. We are interested in the (integral) number of photons N_γ (per unit area and time) reaching Earth from these sources with energies above a given threshold energy E_{thr}. Integrating Eq. (1) yields

$$N_\gamma\left(E > E_{\mathrm{thr}}\right) = \frac{\Phi_0\, E_0}{\gamma - 1} \times \left(\frac{E_{\mathrm{thr}}}{E_0}\right)^{1-\gamma}. \tag{2}$$

It should be noted that propagation effects, such as interactions with cosmic background fields, are not included here. However, the attenuation length of photons in the PeV range for interactions with the cosmic microwave background is at the order of 10 kpc, increasing significantly for higher energies [12]. In a first approximation, such effects can therefore be neglected for galactic sources. In Fig. 2, N_γ is shown as a function of the threshold energy for the two sources, following Eq.(2) with the parameters from Tab. 1. Comparing the extrapolated fluxes for the two sources, one finds that the expected number of photons from the Crab Nebula is larger until about 7 PeV, due to the larger value of Φ_0, but at higher energies, LHAASO J2108+5157 takes over due to the smaller value of γ. At a threshold energy of 3×10^{16} eV, N_γ is at the order of $10^{-3}\,\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$ for both sources.

To estimate the prospects for an observation of UHE photons from these sources—or more general, of any potential source exhibiting a similar energy spectrum—, the background from

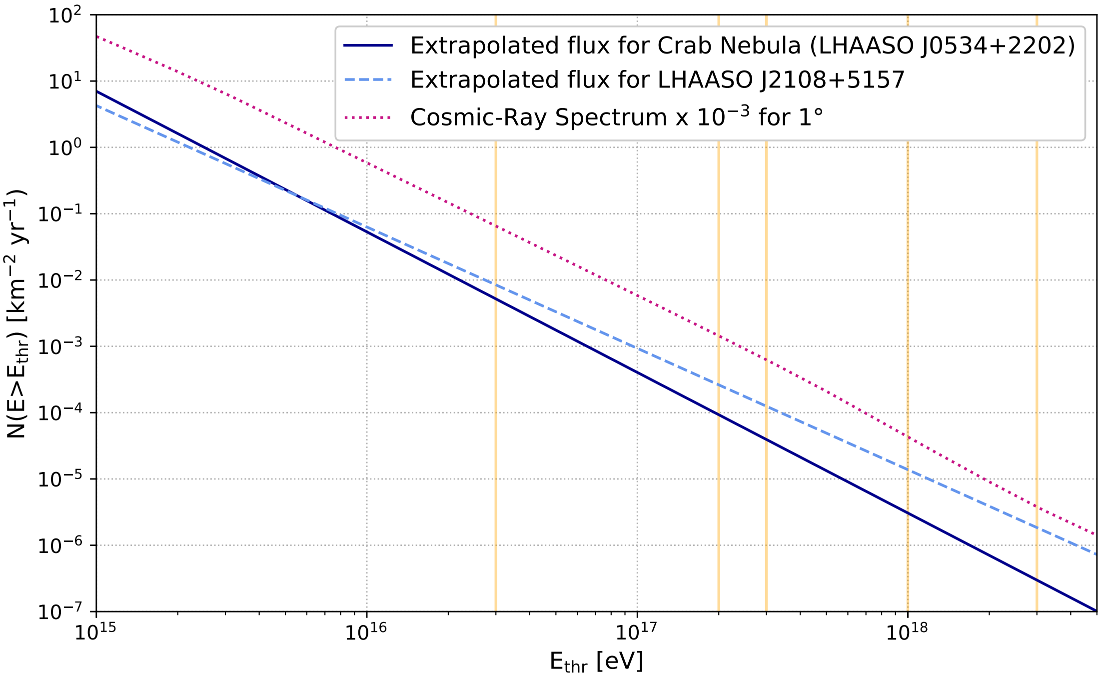


Figure 2: (Integral) number of particles (photons / cosmic rays) N (per unit area and time) reaching Earth with energies above a given threshold energy E_{thr}; N_γ follows Eq. (2) with the parameters for the two sources from Tab. 1; N_{CR} is given for a circle of 1° radius in the sky, it has also been scaled down by a factor of 10^3; the vertical (orange) lines indicate the energy thresholds from Tab. 2.

cosmic rays has to be known. The challenge in searches for photons using air-shower experiments lies in distinguishing air showers initiated by photons from those induced by cosmic-ray particles such as protons and heavier nuclei. In this first approximation, we only compare the sheer numbers of particles arriving at Earth. We therefore only need the cosmic-ray spectrum, which has been measured in the energy region of interest for example by IceCube/IceTop [13] and, towards the highest energies, the Pierre Auger Observatory [14]. The cosmic-ray spectrum is, over a wide energy range, essentially a broken power-law, with three distinct breaking points at $3{\times}10^{15}$ eV (the "knee"), where the spectral index changes from 2.7 to 3.0, at $5{\times}10^{17}$ eV (the "second knee"), where the spectrum further steepens to spectral index of 3.3, and at $4.9{\times}10^{18}$ eV (the "ankle"), where the spectrum gets flatter again with a spectral index of 2.52. Towards the highest energies, beyond the energy region we are interested in here, the flux of cosmic rays is heavily suppressed [14], which we also take into account in the calculations here for completeness. The (integral) number of cosmic-ray particles N_{CR} (per unit area and time) reaching Earth with energies above a given threshold energy E_{thr} is also included in Fig. 2. Since we want to estimate the cosmic-ray background for point sources of photons, N_{CR} is given for a circle of 1° radius in the sky, accounting for typical angular resolutions of air-shower experiments. Hence, N_{CR} does not denote the overall, "full-sky" number of cosmic-ray particles, but rather the background per point source. Comparing N_{CR} to $N\gamma$ for the two sources investigated here, one finds that the number of cosmic-ray particles is several orders of magnitude above the expected number of photons, the impact of which we will briefly discuss in the next section.

4. Prospects for Observations at UHE

In the previous section, we calculated the expected number of photons with energies above the PeV regime from the two sources, per unit area and time. To estimate the potential for an actual observation with air-shower experiments, the parameters of the detector have to be taken into account. For a first estimate, mainly the area covered by the experiment and the energy threshold are relevant, time is essentially a scaling factor. Here, we use the parameters of the Pierre Auger Observatory as a numerical example, as it is currently the largest air-shower experiment in the world. Naturally, the results can be transferred to any current or future air-shower experiment, for example GCOS [16]. We emphasize that the goal is not to estimate the prospects of observing *the* Crab Nebula (or LHAASO J2108+5157) at ultra-high energies with *the* Pierre Auger Observatory, but rather the prospects of measuring photons from *a source like the* Crab Nebula, i.e., one that has a similar energy spectrum, with *a detector like the* Pierre Auger Observatory. The detector could be located anywhere in the world, just as the source could be located anywhere in the sky. For specific sources and detectors, one would have to take into account the visibility of the source from the location of the detector, but we neglect this in a first approximation.

The expected (integral) numbers of photons with energies above the energy threshold for different combinations of detector area and energy threshold, all based on the parameters of detector systems of the Pierre Auger Observatory, are given in Tab. 2 both for a source like the Crab Nebula and a source like LHAASO J2108+5157. The main surface detector array of the Pierre Auger

Table 2: Expected (integral) numbers of photons with energies above the energy threshold for different combinations of detector area and energy threshold, all based on the parameters of detector systems of the Pierre Auger Observatory, for a source like the Crab Nebula and a source like LHAASO J2108+5157 (cf. 2); the numbers are given for a total measurement time of ten years; also given are the expected number of background cosmic-ray particles per point source for the given detector parameters; the two last rows refer to hybrid measurements, for which a reduced duty cycle of 15 % has been taken into account.

Detector parameters		$N_\gamma(E > E_\mathrm{thr}) \times A \times 10\,\mathrm{yr}$ for a source like		$N_\mathrm{CR}(E > E_\mathrm{thr})$ $\times A \times 10\,\mathrm{yr}$
Area A [km^2]	Energy threshold E_thr [eV]	Crab Nebula	LHAASO J2108+5157	per point source
1.95 (cf. Auger SD-433 [15])	$3{\times}10^{16}$	0.101	0.165	1337.4
27.5 (cf. Auger SD-750 [6])	$3{\times}10^{17}$	0.011	0.034	173.1
3000 (cf. Auger SD-1500 [6])	$3{\times}10^{18}$	0.009	0.055	114.6
27.5 (cf. Auger Hybrid, HeCo + SD-750 [7])	$2{\times}10^{17}$	0.004	0.011	61.1
3000 (cf. Auger Hybrid, FD + SD-1500 [7])	$1{\times}10^{18}$	0.014	0.062	194.9

Observator covers 3000 km^2, with an energy threshold of $3{\times}10^{18}$ eV, but there are also smaller sub-arrays, covering 27.5 km^2 (1.95 km^2) with an energy threshold of $3{\times}10^{17}$ eV ($3{\times}10^{16}$ eV). In addition, we give the expected numbers of photons for hybrid measurements employing different surface detector arrays in combination with fluorescence detectors. Hybrid measurements have a lower energy threshold, however, they can only be done in clear, moonless nights, reducing the duty cycle to about 15 %. In all cases, we assume a total measurement time of ten years. For hybrid measurements, this reduced duty cycle has been taken into account in Tab. 2. Overall, the expected numbers of photons are quite small. The largest values are obtained at the lowest energy threshold of $3{\times}10^{16}$ eV—despite the detector area being the smallest here—with 0.165 and 0.101 expected photons in ten years from a source like LHAASO J2108+5157 and a source like the Crab Nebula, respectively.

Also listed in Tab. 2 are the expected numbers of (background) cosmic-ray particles (per point source), calculated from the energy spectrum of cosmic rays (see Sec. 3) for the same combinations of detector area and energy threshold and the same measurement time of ten years. These numbers can be compared to the expected numbers of photons. Assuming similar detection efficiencies for photons and cosmic-ray particles, a background suppression to a level of about 10^{-4} is needed to make a discrimination between photons and cosmic-ray particles feasible. Current photon searches at ultra-high energies (and below) already achieve background suppressions to a level of 10^{-3} and better [7, 18], and further improvements are likely with improved analysis methods.

5. Summary and Outlook

In this contribution, we studied the photon PeVatrons discovered by LHAASO and HAWC in the recent years. Two of these sources, Crab Nebula (LHAASO J0534+2202) and LHAASO J2108+5157 exhibit an energy spectrum that extends to PeV energies without a visible cutoff in the energy range covered by measurements, which makes an extrapolation to even higher energies, up to the UHE range, feasible. An observation of photons with energies beyond the PeV scale from PeVatrons with spectra like the ones studied here is challenging with current air-shower detectors. However, the prospects can be increased: for example, a larger instrumented area would proportionally increase the expected number of photons. Lowering the energy threshold would be even more beneficial. Going, e.g., from $3{\times}10^{16}$ eV to $1{\times}10^{16}$ eV would increase the expected number of photons by about a factor of ten. Finally, we note that it is very likely that there are at least a few photon PeVatrons like the Crab Nebula or LHAASO J2108+5157 in our Galaxy. LHAASO and HAWC have discovered (and continue to discover) a number of sources of PeV photons in the Northern sky. A complementary detector in the Southern hemisphere, like the planned SWGO [17], will likely lead to the discovery of more such sources. Even if their fluxes are too small to detect them individually (yet), they might contribute to a diffuse flux of UHE photons that could be detected.

Acknowledgements

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