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A study of super-luminous stars with the *Fermi* Large Area Telescope

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The γ-ray emission from stars is generated by the interaction of cosmic rays with stellar atmospheres and photon fields. This emission is expected to come in two components: a stellar disk emission, where γ-rays are mainly produced in atmospheric showers generated by hadronic cosmic rays or in stellar flares, and an extended halo emission, where the high density of thermal photons in the surroundings of stars serve as targets for cosmic-ray electrons, which upscatter them to the γ-ray domain. Besides the Sun, no other disk or halo from single stars has ever been detected in γ-rays. However, by assuming a cosmic-ray spectrum similar to that observed on Earth, the predicted γ-ray emission of super-luminous stars, like e.g. Betelgeuse and Rigel, could be high enough to be detected by the *Fermi* Large Area Telescope (LAT) after its first decade of operations. In this work, we use 12 years of *Fermi*-LAT observations along with inverse Compton models to study 9 super-luminous nearby stars, both individually and via stacking analysis. Our results show no significant γ-ray emission, but allow us to restrict the stellar γ-ray fluxes to be on average $< 3.3 \times 10^{-11}$ ph cm^{-2} s^{-1} at a 3σ confidence level, which translates to an average local density of electrons in the surroundings of our targets to be less than twice of that observed for the Solar System. The detailed results of this work can be found at [8].

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1. Introduction

There are three main channels trough which γ-rays are generated in stars. The first channel is the stellar disk emission, where γ-rays are produced in atmospheric cascades induced by hadronic cosmic rays. There is no precise theoretical description of this phenomenon so far, even for the Sun, however there are several insightful works in this topic [see 1–3, to name a few]. The second channel is the stellar extended photon halo, where cosmic-ray electrons upscatter the soft thermal photons from the stars to the high-energy domain [4]. This emission is well understood and, in the case of the Sun, is in good agreement with the theoretical predictions [5]. The last channel is via stellar flares, where explosive events caused by the recombination of stellar magnetic fields can lead to the production of high energy photons, with a γ-ray spectral distribution typically represented by a soft photon index, i.e., $\Gamma \gtrsim 2.5$ [6].

The γ-ray emission from these components has never been observed in other isolated stars than the Sun, although the collective emission from a complex of $\sim$ 1700 O and B stars in the Cygnus OB2 region has been successfully described [7] by the upscattering of soft stellar photons by freshly accelerated cosmic rays (i.e., the second channel discussed above). In this contribution we present the first systematic study of nearby super-luminous stars with the *Fermi* Large Area Telescope (LAT), but we refer the reader to [8] for a complete description of our sample and methods.

2. Sample: why nearby super-luminous stars?

In the neighborhood of super-luminous stars, the density of thermal photons is so high that the expected γ-ray emission from the inverse Compton scattering on the stellar extended photon halo is expected to outshine the other two γ-ray components (i.e., disk + flares), as discussed in detail by [8]. Supported by this, we selected 9 super-luminous stars from [4] considered to be the best candidates for detection with the *Fermi*-LAT. Namely, they are κ Ori, ζ Pup, ζ Ori, Betelgeuse, δ Ori, Rigel, ζ Per, λ Ori, and ϵ CMa. All these stars are closer than 600 pc from the Sun and their predicted γ-ray flux for energies above 100 MeV and integrated over 5° elongation angle is above 10^{-10} ph cm^{-2} s^{-1}, making them suitable targets for *Fermi*-LAT.

3. Results and discussion

For each star in our sample, we select γ-ray data within a $16° \times 16°$ region-of-interest (ROI) centered on the optical position of the stars. The period of observations ranges from August 4, 2008 to August 10, 2020, and the chosen energy range is 100 MeV – 100 GeV for the standard analysis and 500 MeV – 100 GeV for the stacking analysis.

For simplification purposes, in this contribution we consider the stars as point-like γ-ray sources, but a full analysis including the angular extension of the stellar photon halos is discussed in detail in [8]. We start our analysis by recomputing the predicted γ-ray flux of these stars with `StellarICS` [9], where we assume that the distribution of cosmic-ray electrons in the neighborhood of the stars is similar to the distribution observed in the Solar System and consider updated values for the interstellar cosmic-ray electron spectrum measured with the Alpha Magnetic Spectrometer [10] on the International Space Station. These predictions and the results of the *Fermi*-LAT γ-ray

Name	Pred. flux (10^{-10} cm^{-2} s^{-1})	UL (10^{-10} cm^{-2} s^{-1})
κ Ori	1.6	5.4
Betelgeuse	2.3	4.1
δ Ori	0.6	2.7
ϵ CMa	0.7	2.4
λ Ori	0.4	4.2
Rigel	1.6	3.3
ζ Ori	0.9	0.9
ζ Per	1.1	4.4
ζ Pup	3.1	3.0

Table 1: Predicted IC γ-ray fluxes considering the stars as point-like sources, and 95% confidence level upper limits (UL) for energies > 100 MeV and photon index $\Gamma = 2$. ζ Pup is the only star for which the upper limit is not consistent with the theoretical prediction. The significance, in σ, is nearly zero for each target.

observations are shown in Table 1. The flux upper limits for all stars are consistent with the updated theoretical predictions, except for ζ Pup.

As we are not able to detect these super-luminous stars individually, we try to detect their collective emission via a γ-ray stacking analysis. The stacking is done by summing up the log-likelihood values of each individual ROI, under the assumption that the stellar population can be well represented by the same photon index, Γ. This is a powerful method when dealing with faint γ-ray sources, but has to be used with caution. If sources in the sample have very different characteristics from each other, the small contribution from each source will not sum up properly and the final result will be meaningless.

The stacked test statistics (TS) map can be seen in Figure 1, where the contribution from each super-luminous star is summed up assuming that all of them have a photon index $\Gamma = 2$. If there was significant collective emission from our sample, we should see and excess of TS within the green circle in the center of the map. The observed hotspots, far away from the center of the figure, are caused by the sum of residual diffuse γ-ray emission that could not be perfectly taken into account by the ROI models and do not have a physical meaning.

In Figure 2, the blue line represents the stacked TS for the adopted sample in terms of the photon index Γ. We see that, independently of the value of Γ, the stacked TS is always consistent with the stacked background (represented by the black line). In summary, we did not find significant emission of the IC emission from stellar halos around super-luminous stars. We are able, however, to derive a γ-ray flux upper limit for the stacked population. If we consider that these super-luminous stars have roughly the same brightness in γ-rays, they must emit on average $< 3.3 \times 10^{-11}$ ph cm^{-2} s^{-1} for energies > 500 MeV, otherwise we would detect them as a population at the 3σ confidence level. This result enable us to constrain the density of cosmic-ray electrons in the surroundings of these stars to be less than twice the value measured in the Solar System.

This contribution is going to be updated soon. For more details, we refer the reader to [8].

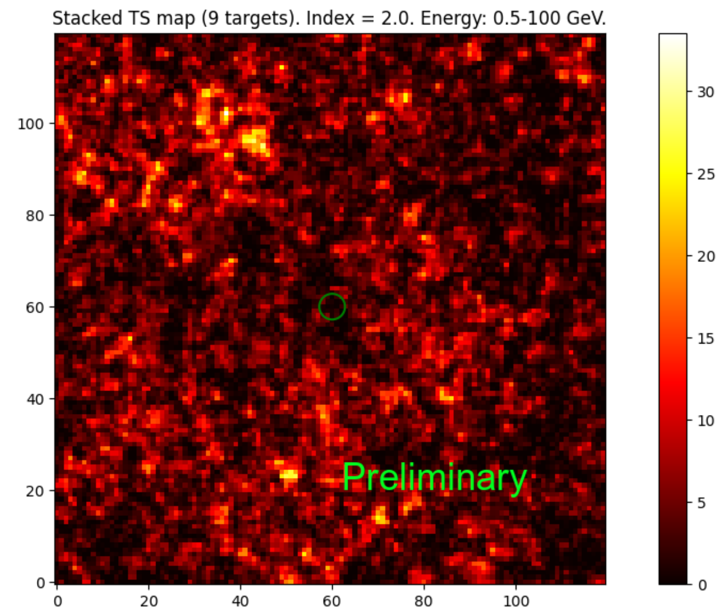

Figure 1: Stacked TS map for the 9 super-luminous stars. There is no hint for collective γ-ray emission from this sample in the *Fermi*-LAT data. The x and y axes are in pixels (the stacked map has no physical coordinates). The color bar represents the TS value.

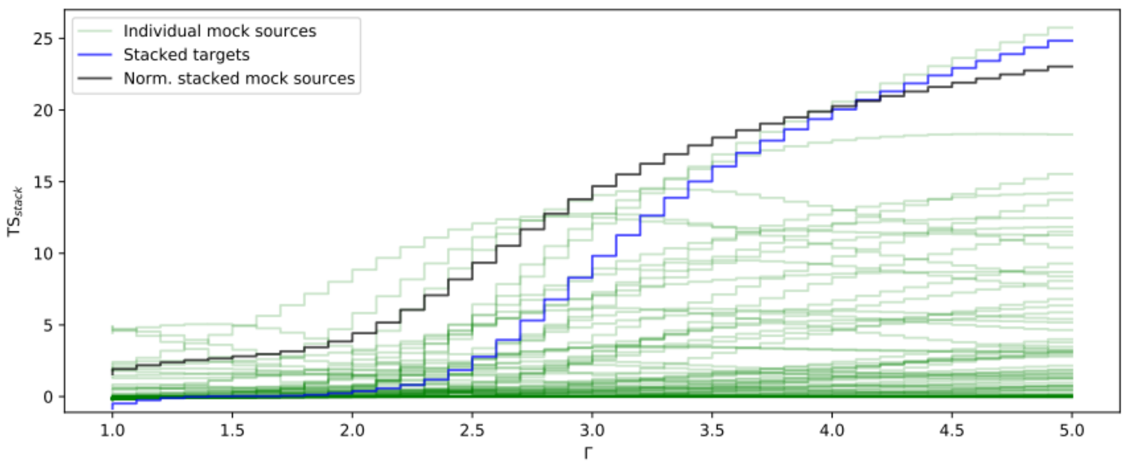

Figure 2: Distribution of TS_{stack} in terms of the photon index Γ. The blue line represents the stacked TS for our targets, while the black line represents the normalized stacked background, built with the stacking of 108 mock sources (green lines). Our results are consistent with random background fluctuations. The complete description of this analysis can be found at [8].

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