Correlating Cosmic-Ray Electrons and Positrons in Search of Spectral Features from Pulsars

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Introduction

Cosmic rays are charged particles which travel through the galaxy, spiraling around magnetic field lines. Because the magnetic field lines can bend and because particles with high energies can have a very large radius to their spiral, these particles end up having random orientations at large scales. Specifically, the cosmic rays we look at here are the electron and the positron. The positron is what we call an antiparticle to the electron. If an electron and a positron come close enough, they will annihilate into gamma-rays; however, otherwise positrons are stable particles. This is why it is important to study them in space: the positrons can survive long enough for them to tell us something about their origin and how they propagate to us. We ask this of both the positrons and electrons because, as antiparticles, they are often produced in pairs together during pair production. This is a process in reverse of the annihilation, where two photons create an electron-positron pair, which happens regularly in the Milky Way. Looking at these particles together, they might inform us about their origins.

The fluxes of these particles have been well documented by the Alpha Magnetic Spectrometer (AMS-02) [1,2,3,4,5] in recent years. This is a detector roughly the size of a refrigerator, that is aboard the International Space Station, collects information about the fluxes of various types of cosmic rays. For the groundwork of this study, we use the publicly available AMS-02 electron and positron flux data, and later we test the findings against simulations of potential sources of electrons and positrons performed in [6].

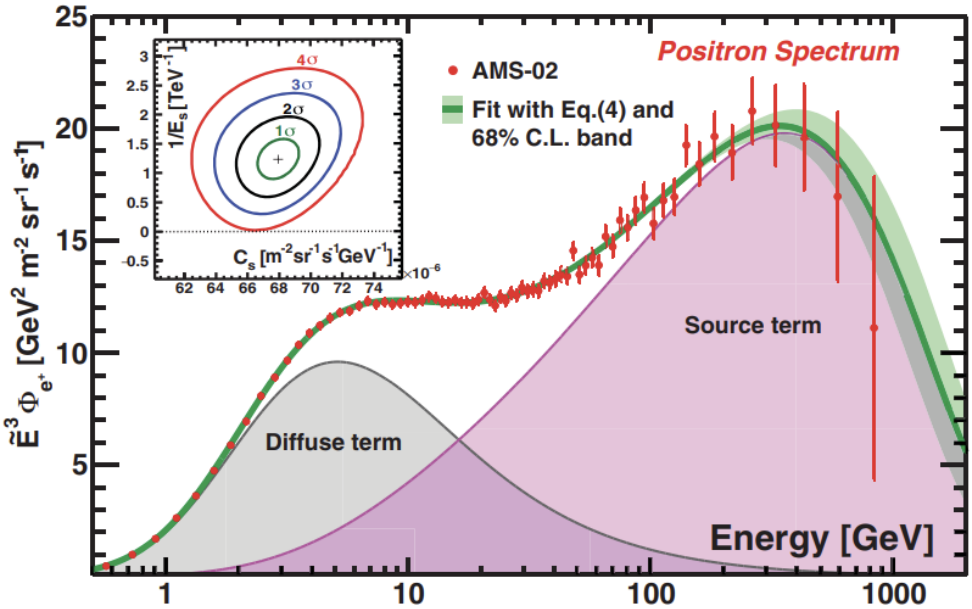

Figure 1. This is figure 4 from [4]. It shows the measured flux of cosmic-ray positrons versus energy, with the error bars in red. Each is multiplied by the energy cubed. The fit they created is in green. The bumps in the figure represent the power laws that the fit follows, showing that the data follows two distinct terms.

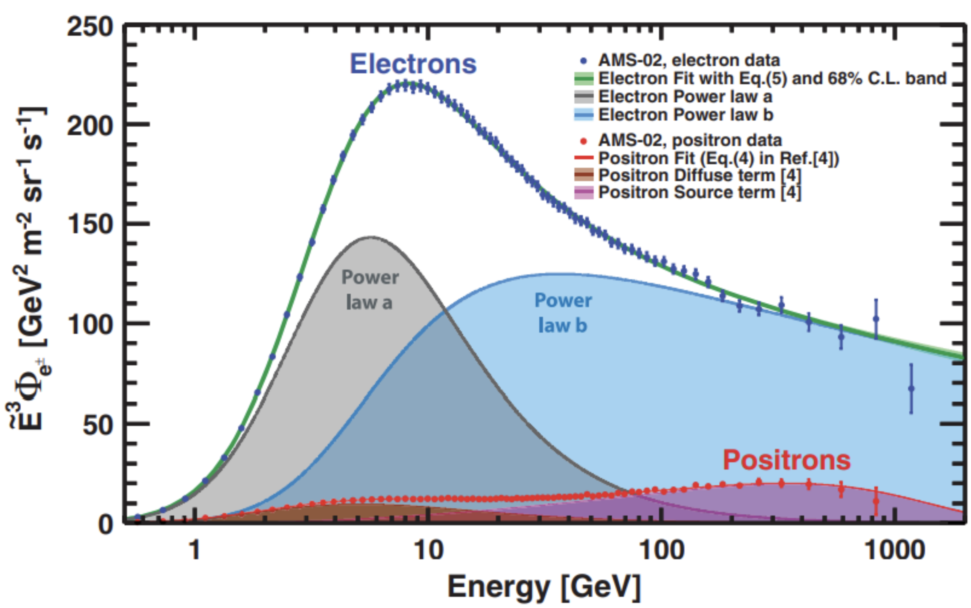

Figure 2. This is figure 4 from [2]. The cosmic-ray electron flux and error bars, multiplied by energy cubed, are shown in blue. The AMS collaboration's fit is shown by the green line, with its uncertainty given by the thickness of the surrounding green area. This figure shows that the electron flux follows a combination of two power laws, represented by the change in the spectral shape. The positron data, fit, and power laws are added for comparison.

From the AMS-02 data, there are prominent features in the positron spectrum (figure 1) [4]. By eye, there are also tiny features present in the electron spectrum as well (figure 2) [2]. Our goal is to use a cross correlation analysis [7] to test if these features are related to each other. If the features are related, we might be able to see the signature of where and when they were created. One candidate type of source is pulsars. Pulsars are compact objects, specifically neutron stars with strong magnetic fields, which eject high energy photons along their magnetic pole in a beam. Electrons, and other charged particles, on the surface of the pulsar also get ripped away from the surface and carried off by this beam. Furthermore, some of the photons in this beam produce electrons and positrons by a process called pair production.

The magnetic pole is not perfectly aligned with the axis of rotation, so the beam sweeps out a cone shape rather than a straight line. This means that we only see the beam when it faces us, similar to how a lighthouse rotates and you only see the flashes of light when it faces you [8]. Each pulsar produces electrons and positrons with a spectrum of energies, and the flux from a given pulsar peaks at a specific energy, as shown in figure 3 [6]. At higher positron energies, fewer sources can contribute to the positron flux, thus spectral features are not drowned out by the number of overlapping signals and can appear. What we want to know is if the features we observe in the AMS-02 data for both the positrons and electrons follow these spectral peaks.

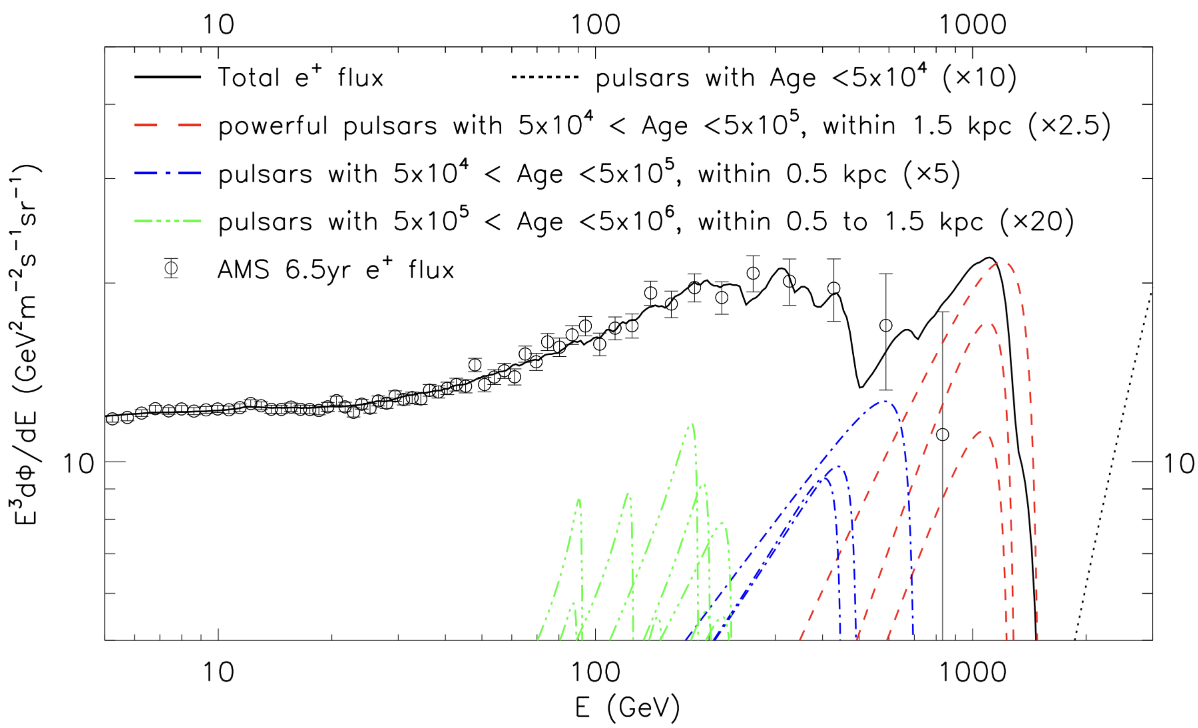

Figure 3. This is figure 1 from [6]. The black data points are the positron flux multiplied by energy cubed. The dashed lines of various colors are the contributions of individual simulated pulsars with the defined ages and distances, and scaled for legibility, all as specified in the legend. This figure highlights the possible contribution of pulsars to the flux of positrons measured by AMS-02.

If these spectra are unrelated, however, then it would not make sense for these features to come from pulsars. This is because the pulsars create both particles together, meaning their spectra would also peak at the same energy. Thus, we expect a strong cross-correlation signal that we will describe in later. In the case they are unrelated, we would need a different source to explain the production of these particles at these energies. One alternative candidate for their production is dark matter. Under the assumption that dark matter is responsible for the production of these particles, we would expect uncorrelated features.

Motivation

We want to know what makes up the Universe and in what quantities. AMS-02 has provided, with newfound accuracy, the amounts of various cosmic rays that reach our location. By testing the amounts and trends of these measurements, along with the knowledge of physics that we already hold, we can find possible sources for their production. Furthermore, If we can determine the source for a particle, then we can also learn more about that source in turn. We can also learn more about the nature of the various particles, objects, processes, and physics of everything involved the more we work to understand them.

Recent data analyses of the positron and electron fluxes from the AMS-02 have drastically improved the quality of the measured cosmic-ray positron and electron spectra. AMS-02 has been gathering data on cosmic rays since May 19, 2011 and released its measurements only recently in November 12, 2017, thereby providing better measured quantities in wider ranges of energies than ever before. Specifically, it opened a new energy range for inquiry, 200 GeV to 1 TeV [1], which may include new physical phenomena for cosmic-ray electrons and positrons. [4] specified the positron spectrum into four distinct regions, each with its own dominating term. These sections are the low energy portion, the portion of the graph (figure4) where the spectrum flattens, then the portion where the spectrum begins to rise again, and finally a portion where the spectrum falls dramatically. This rise and fall of the positron fraction at high energies indicates that there is something other than the normal production found at the lower energy levels happening. The dominating terms, with all necessary constants, were combined into a function which fits the spectrum very well, as shown in figure 1 [4]. The rising portion of the spectrum, where the high energy positrons are, is dominated by the source term; the cause of this source term is yet to be determined. The current endeavor is to try to find a physical source which fits the necessary conditions set by the source term.

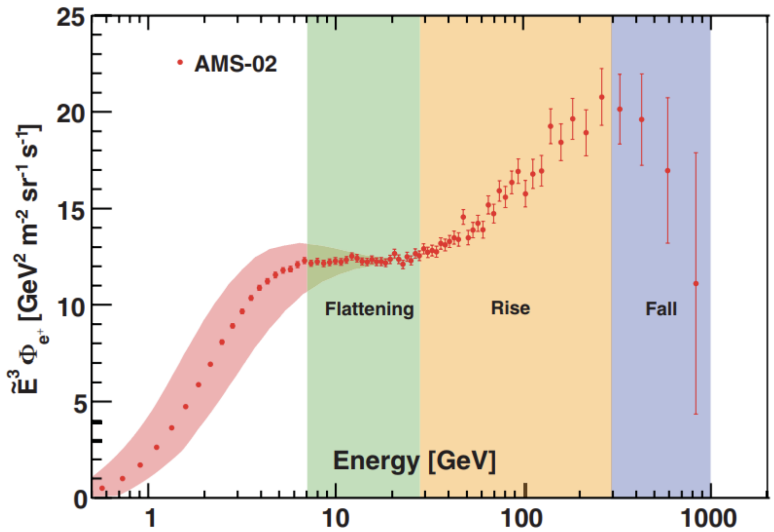

Figure 4. This is figure 1 from [4]. In red are the positron flux, with error bars, multiplied by cosmic-ray energy cubed. In the lower regions a red band is added instead of error bars because of the “time variation of the flux at low energies due to solar modulation.” [4] The colored vertical sections display the curious sections where the positron flux changes its behavior.

By the same methods applied for positrons, [2] narrowed the precision of the electron spectrum as well. The data for the flux of electrons is consistent with predictions with or without a shared high energy source between the cosmic-ray electrons and positrons. Unlike the positrons, the high energy electrons do not seem to experience any cut off energy. There are some sources, such as energetic pulsars or annihilating dark matter, which give fluxes which are significant for electrons and suppressed for positrons at energies such as 1 TeV. Furthermore, during the supernova explosion, the surrounding regular electrons that have no positron counterparts can be accelerated to cosmic-ray energies. This would give higher values in the electron fluxes than in the positron fluxes. The contribution in production of electrons and positrons by some other source, such as pulsars or dark matter, would become prominent above a certain energy. That certain energy depends on the underlying assumptions of how these sources would produce the particles and the rates of their production.

Figure 5 [9] graphically shows the AMS-02 positron fraction measurements compared to a few different models, including a simulated pulsar population, plotted vs energy. For the case of pulsars these are small, yet observable wiggles in the positron fraction data. These wiggles would correlate to specific pulsars within the general pulsar population. Very recently, a feature has also been discovered in the electron flux data, which [10] attributes to Geminga's pulsar.

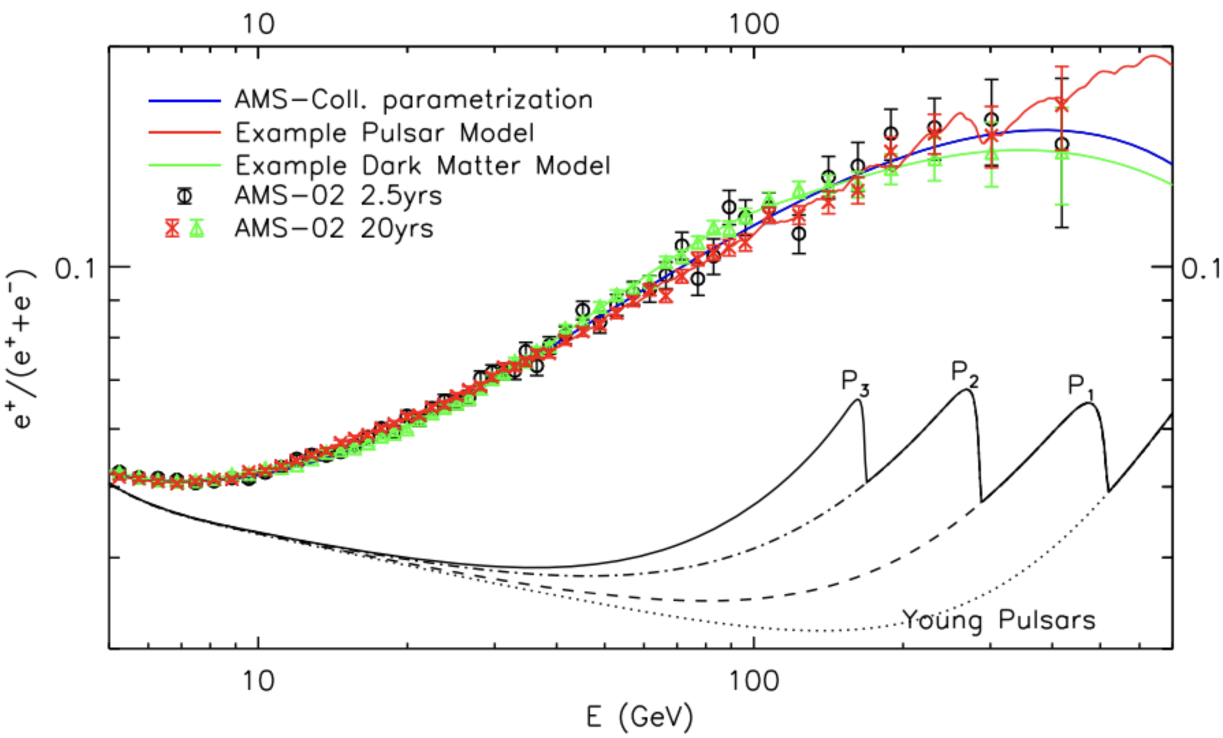

Figure 5. This is figure 1 from [9]. In blue is the model from the AMS collaboration, red is a Milky Way pulsar population model, and green is a dark matter model. An important thing to note is that the pulsar model has features and the dark matter model is smooth. The black curves toward the bottom are sample pulsar sources with specific characteristics.

This work will be building from that point. Carrying out a cross correlation analysis on the positron and electron flux data, the goal is to find whether there is a positive correlation between the two at high energies and at small energy-scales: looking for sharp spectral features at the high energies. The correlation of the fluxes is a prediction of the hypothesis that nearby pulsars can significantly contribute, as a single source for both, to the flux of high energy cosmic ray electrons and positrons as shown in figure 6. If, instead, there is no correlation between these spectra, this is an indication that the origin of the high energy positrons and electrons could be dark matter.

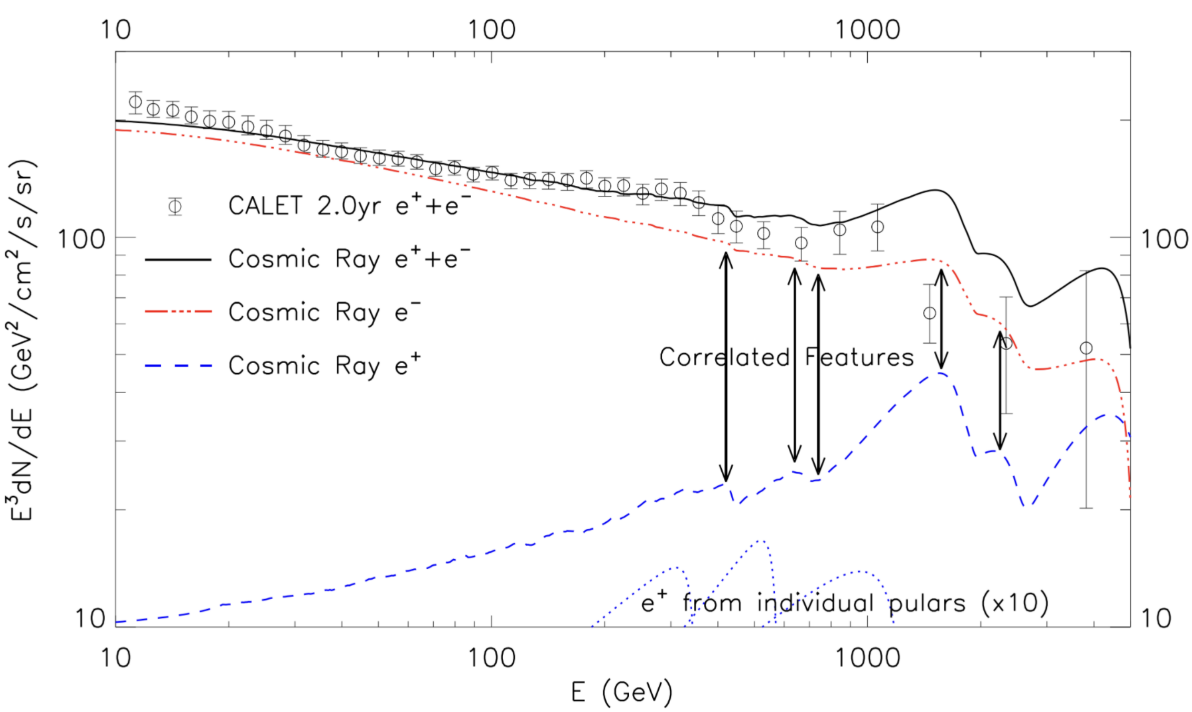

Figure 6. A comparison of cosmic-ray electron and positron spectra with possible pulsar sources creating features in both. This figure displays how the bumps in each of the spectral align with the possible pulsar sources. It also shows that the contribution to the positron flux is more noticeable in the features than it is in the electron flux, as we see in the data from AMS-02.

Physics of pulsars

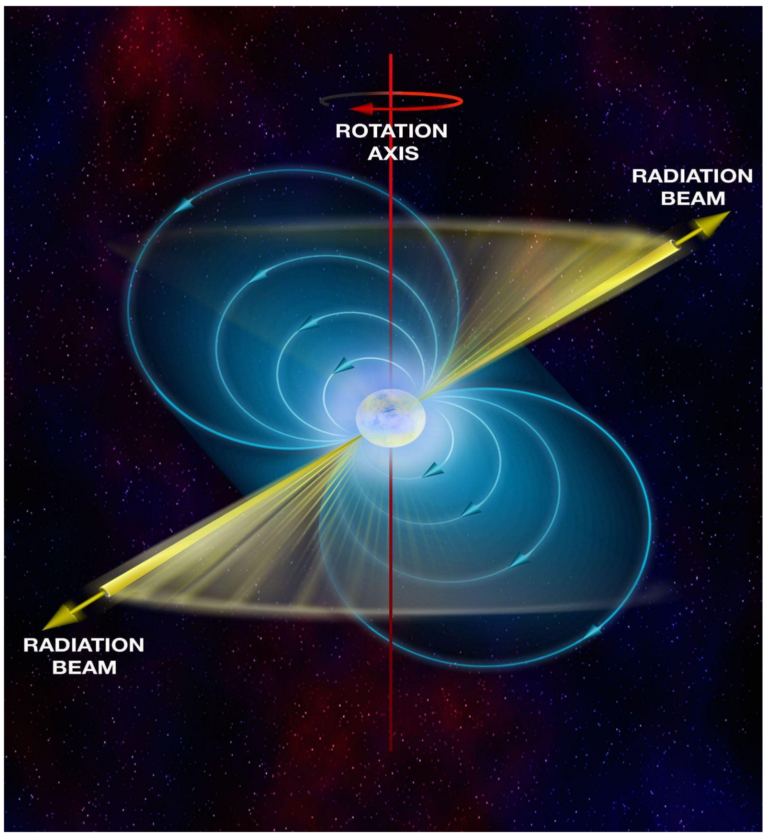

Figure 7. Parts of a Pulsar, credit: [11]. This is an artist's illustration of the major components of a pulsar. The radiation beam is the signal often detected in the radio wavelengths; it aligns with the magnetic pole of the pulsar. The blue lines represent the magnetic field lines which encircle the pulsar.

A pulsar forms when a massive star's core collapses in on itself. The matter in the core becomes so dense that the following matter, which is still trying to fall into the gravitational center, hits the already collapsed part like a wall and bounces off. This effect causes the supernova explosion. In this process, the pulsar becomes very tightly compact and its size decreases tremendously. When the size decreases, so does the surface area. Due to Gauss' law, because the magnetic flux of the pulsar is conserved, when the surface area decreases, the magnetic field will increase, and this change creates the magnetic field shown by the blue lines in figure 7 [11]. Due to conservation of angular momentum, when the matter that makes up the star collapses into the center, the radius decreases, and the angular velocity increases around the rotational axis. All of these changes occur in the extreme so each of the effects become very large.

The magnetic pole does not align to the rotational axis, so the magnetic fields of the pulsar circle around the axis of rotation, meaning they change with time. Because the magnetic field changes with time, an electric field is induced; and because the magnetic field is very strong, and rotating very quickly, the subsequent electric field is also extremely strong. This electric field propels the charged particles away from the surface of the star. The positive particles are repelled from near the equator, whereas the negatively charged particles are repelled at the magnetic poles [12]. This produces a highly energetic electron beam coming from the magnetic pole and circles with the rotation of the pulsar.

The strong magnetic field discussed earlier creates a barrier for the electrons, thereby keeping them close to the pulsar for a time. During this time the electrons are spiraling around the pulsar's magnetic field lines. As a charged particle experiencing an acceleration, the electron emits energy. This process is called synchrotron radiation, whereby an electron emits a photon when it interacts with a magnetic field.

The photons can then undergo pair production. In this process, two high energy photons collide and produce an electron and a positron. Alternatively, some lower energy photons which do not undergo pair production might instead collide with electrons in a process called inverse Compton scattering. This would transfer energy from an electron to a photon, possibly giving those photons enough energy to undergo more pair production. These electrons and positrons that have been created eventually travel to the outskirts of the pulsar wind nebula (PWN), where the pressure of the radiation from the pulsar is equal to the pressure from the interstellar medium (ISM). The electrons and positrons accumulate in this region and therefore can emit even more radiation in that region.

Finally the moment comes when the pulsar creates a shock wave, accelerating the particles in the PWN and sending them outward into space. As they propagate through the ISM, eventually some can reach us. The particles released by the shock wave have a flux with a nonthermal distribution with respect to their energy. For each pulsar, this flux peaks at a particular energy. We believe that the features that we see in figure 3 [6] may correspond to the peaks of nearby pulsars.

The electrons and positrons ejected by the shock wave are randomly diffused. Because they carry a charge, they still want to circle around any magnetic field lines of the ISM that they find. The strength of the magnetic field in the ISM, together with the initial velocity of the particles as they leave the PWN, gives their Larmor radius. This is the distance from the magnetic field line that the electron orbits as it spirals. Higher energy electrons will have a higher velocity, and thereby a larger Larmor radius. The larger this radius is, the less discernible the magnetic field line it follows becomes. When the electron has a larger radius, the segments of the arc it follows appear less curved. These effects result in the path appearing random when the electrons propagate out to a distance where they can reach us. These same effects apply to the positrons, except that they will orbit in the reverse direction to the electrons. The electrons and positrons ejected from the PWN should have a high enough energy that they diffuse through space in an effectively randomized manner, without a preferential direction. This randomness in the diffusion is why we cannot immediately know from where and from what these particles come to us. The flux of these particles detected by AMS-02 should not therefore be preferential to a direction, and should follow a three-dimensional population of pulsar sources, as constrained by the measurements from AMS-02 and other previous experiments and simulated in [6].

There are far more electrons detected by AMS-02 than positrons. Electrons have more methods of production than positrons do. For example, as outlined earlier, before the electron-positron pair is produced by the photon-photon pair production, those photons are first produced as radiation from electrons. Other methods of production aside, from this alone we would expect more electrons to be detected.

Alternatively, dark matter sources would not create distinct spectral peaks. Assuming dark matter has a particle nature, it should produce these electron-positron pairs at a stable rate without giving spectral features. This becomes important later when we focus on obtaining residuals. When subtracting the smooth models from their respective measured fluxes, in the case of the dark matter production route, we would not be left with meaningful features. The residuals which would be left behind in this case would appear as random fluctuations around a fit line. We aim to see if these fluctuations are indeed random or whether they follow a trend.

There is hope that the detected particles could be a signal from dark matter, and thereby, we can analyze that signal to learn more about its nature. This is why determining whether or not pulsars are responsible for the signal is important in the search for dark matter explanations and detections.

The data we work with is the publicly available AMS-02 measurements [3,5]. This detector is onboard the International Space station and has been collecting measurements of cosmic ray fluxes since May 19, 2011. It uses a combination of magnetic fields, detectors, and trackers to measure the charge, momentum, and energy, in order to classify the particles crossing through it.

Methodology

Coinciding spectral features would support the prediction of high energy pulsars being a significant class of sources for these particles. By employing a cross correlation analysis on their residual fluxes, any existing correlation will be determined. If the correlation is positive, it would follow the prediction that nearby pulsars significantly contribute as a source of high energy electrons and positrons. If there is no correlation, this is an indication that the source in question cannot be a set of individual sources, such as pulsars, making dark matter a more likely candidate.

The electron's flux measurement data covered the energy ranges of 0.50 GeV to 1400.0 GeV [3], and the positron's flux measurement data covered 0.50 GeV to 1000.0 GeV [5]. We want to have the same energy bins for both sets, so the last energy bin of the electron flux, from 1000.0 GeV to 1400.0 GeV, was ignored for the rest of the project. At this point, there were 74 energy bins for each, along with their respective information. Most importantly, these give their energies, fluxes, statistical errors and systematic errors.

The last question for preparing the datasets is what to use for the respective errors. Both sets have a statistical and systematic error for each energy bin. As discussed in a later section, we use the form of the cross-correlation function which incorporates different errors for each datapoint. The errors to be considered are the statistical errors, the systematic errors, or the sum of these in quadrature. For the following discussion on the cross-correlation, the errors referred to are the statistical errors.

We focus on the statistical errors because the systematic errors should be the same for the electrons and positrons, as they have all the same physical characteristics, just opposite charges. As an example, if a systematic error causes the electrons to increase by 5%, then the same systematic error could increase the positrons by 5%. And this would give long features over many energy bins. We care only about small features in the fluxes. We focus on the statistical errors because the systematic errors span larger ranges of energy bins than the features cover. This is why the simulations become important to the discussion: they don't hold systematic errors.

The positron and electron fluxes are not suitable for comparison as they are. We are concerned with looking for comparisons between the features of the fluxes, so we must analyze the residual spectra for coinciding features. To isolate the features, we analyze the residuals, rather than the functions themselves. For this reason, the models are crucial to the analysis as a whole.

To determine the residual on which we will perform the cross-correlation, we subtract the model of the flux from the value of the flux at each energy bin. In order for these residuals to be useful, the models cannot systematically underpredict or overpredict the data points. For this reason, our next step is to find reasonable models for the positron and electron fluxes. AMS provided a mathematical model, equations 1 and 2, in each of the particles' respective papers [2,4], so we start there. Figure 8 shows the models, fluxes, and residuals as given by the AMS papers, recreated by me, discarding the energies we do not care about and ignoring information superfluous to this project provided in figures 1 and 2.

$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}\left[1 + \left(\frac{\hat{E}}{E_t}\right)^{\Delta\gamma_t}\right]^{-1}\left[C_a\left(\frac{\hat{E}}{E_a}\right)^{\gamma_a} + C_b\left(\frac{\hat{E}}{E_b}\right)^{\gamma_b}\right]$$

Equation 1. This is the parameterized AMS collaboration's model of the electron flux, equation 5 in [2]. $\hat{E}$ is the sum of the energy (E) and a parameter φ. φ, E_t, E_a, E_b, C_a, C_b, $\Delta\gamma_t$, γ_a, and γ_b are all free parameters which are marginalized to fit the electron spectrum.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d\left(\frac{\hat{E}}{E_1}\right)^{\gamma_d} + C_s\left(\frac{\hat{E}}{E_2}\right)^{\gamma_s}\exp\left(-\frac{\hat{E}}{E_s}\right)\right]$$

Equation 2. This is the parameterized AMS collaboration's model of the positron flux, equation 4 in [4]. Again, $\hat{E}$ is the sum of the energy (E) and a parameter φ. φ, E_1, E_2, E_s, C_d, C_s, γ_d, and γ_s are all free parameters, with no connection to the electron data parameters, which are marginalized to fit the positron flux spectrum.

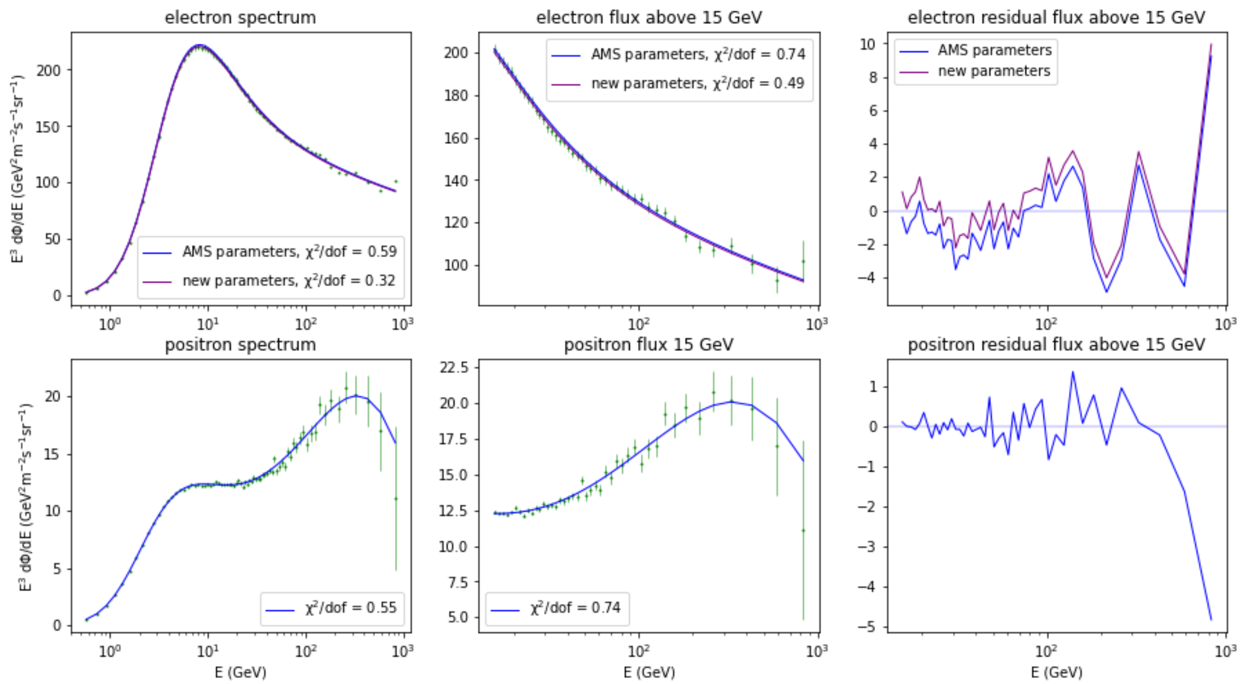

Figure 8. The top row is for the electrons and the bottom is for the positrons. The data is in green with its error bars. The model given by equation 2 with AMS parameters and new parameters are shown in blue and purple, respectively. The left column has the data and models for the entire energy range, and the middle column is for energies between 15 GeV and 1000 GeV. And the right column is the residuals under each parameterization.

If the models do not follow the data closely enough, then we cannot extract proper residuals. Therefore, the functions developed must be sensitive, without over or underpredicting the data for large energy ranges. The positron function does well in this, as shown by the residuals oscillating around zero. The electron's (in blue) however display a clear overprediction, leading to negative residuals for a large portion of the middle energy ranges.

$$\Phi_{e^-}(E) = C_s\left(\frac{E}{41.61\ GeV}\right)^{\gamma_s}\exp\left(-\frac{E}{E_s}\right)$$

Equation 3. This is a power law function used to represent the electron fluxes as a function of energy. γ_s is the spectral index, E_s is a cutoff energy, and C_s is a scaling constant. 41.61 GeV is the lower bound of the energy range that this parameterization is set up for.

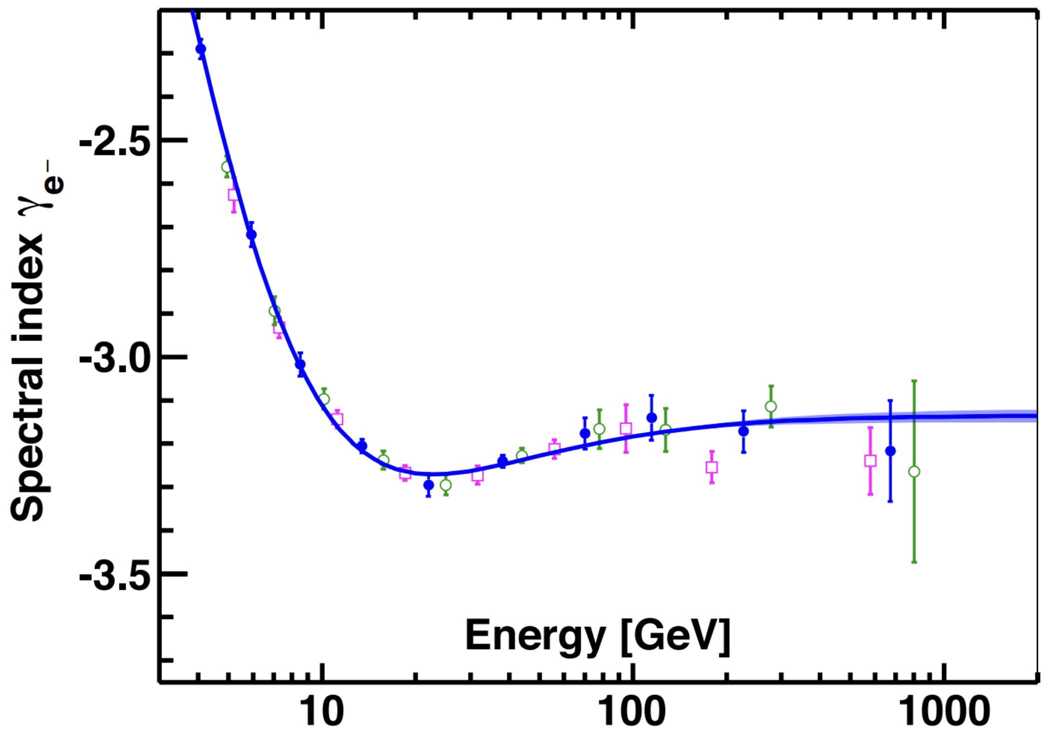

Figure 9. This is figure 8 from [3]. It shows the spectral index values versus energy. This is where the spectral index-cutoff energy pairs were found.

The first method used to correct for this is to create a piecewise power law function based on equation 3. New cutoff energies were attached to the corresponding changes in the spectral index, as found by using figure 9 [3]. From this I created a piecewise function from equation 3 [2], with each new spectral index-cutoff energy pair defining the transition in the domain of the function. 41.61 GeV was substituted in each range with the lower bound of energy for that range. The constants were created such that the piecewise function would remain smooth when the transitions occurred. This method of modeling couldn't predict the function, and we were left to try something new.

In [2], we are told that the cutoff energies (E_a, and E_b) are chosen, while all other parameters are fitted. To decrease the χ^2 per degree of freedom measurement, we try a different fitting method. Because equation 2 is non-linear, we cannot use the sequential least squares programming (SLSQP) algorithm; instead, we use dual annealing. This is a stochastic global optimization algorithm for nonlinear functions. This method was chosen because it can fit several parameters at once and the function need not be linear. Because it is stochastic, each time it runs, we receive slightly different values for its parameters, and it takes a longer runtime than other more straightforward methods would. The results are the purple curve in figure 8. The best resulting curve was produced under the parameter combination below.

Parameter	Units	AMS-02 Value	New Value
φ_{e^-}	GeV	0.87	0.87
E_t	GeV	3.94	3.94
γ_t		-2.14	-2.15
C_a	$[m^2\ sr\ s\ GeV]^{-1}$	0.0113	0.0112
E_a	GeV	20	20
γ_a		-4.31	-4.31
C_b	$[m^2\ sr\ s\ GeV]^{-1}$	$3.96 * 10^{-6}$	$3.93\ x\ 10^{-6}$
E_b	GeV	300	300
γ_b		-3.14	-3.14

Table 1. A parameter combination comparison. The parameters optimized and their units are provided, along with the AMS-02 collaboration's fitted values and the new fitted values from this project.

Under this parameterization, the residuals become the upper right graph in figure 8. Importantly, the residuals in the lower to middle energy ranges are oscillating around zero rather than staying negative for the entire range. Under this parameterization, we can isolate the features to be used in the next steps of the project.

The goal is to see if the features in two datasets are related, so we employ a cross correlation analysis [7]. This is a mathematical operation which takes sets of discrete numbers, and creates a function which describes the relatedness of each point, as a function of a shift variable. It takes each given point of one set and multiplies it by the corresponding point in another set after the second set is shifted. The sum of all the products in the set is then divided by the errors of each set and the total number of terms in the summation. This returns the value of the cross-correlation function at the point of the shift value. The number of terms in the summation is crucial for consideration, because each time you shift by one, you lose one term. By dividing by the total number of terms, you constrict the function so it can't blow up around zero shift by purely adding more terms in the summation.

$$r_{xy}(m) = \frac{1}{L\sigma_x\sigma_y}\sum_{n=0}^{L-1} x(n)y(n+m)$$

Equation 4. The cross-correlation function. This function provides the level of sameness of two datasets as a function of the shift factor m.

Each of our data points comes with its own unique error, and these errors tell us something important about each individual energy region. This differs from the original form of the cross-correlation function, where each point has the same error measurement. For these reasons, we alter the equation so that the value of the flux at each energy is divided by its own respective error when it appears for multiplication and thereafter addition.

While the autocorrelation has been used on cosmic-ray fluxes in the past [13], the cross-correlation is still a new approach to analyzing cosmic ray spectral data, meaning furthermore that this project is developing a new technique of analysis which can be applied in studying future cosmic-ray species as well.

In equation 4, the x set is the positron dataset, and the y set (the shifting one) is the electron dataset. The cross-correlation code first imports the data from the residuals found and saved prior to its use. It creates a set of the shifting parameters, m, of integers spanning the length of the electron set in the positive and negative directions. The result is a function of m, that gives the level of correlation between the two sets at that given shift value. Due to the noisiness of the measurements, amplified by the loss of terms with increasing magnitude of m, the set of shifting values was decreased to span only -25 to +25.

Results

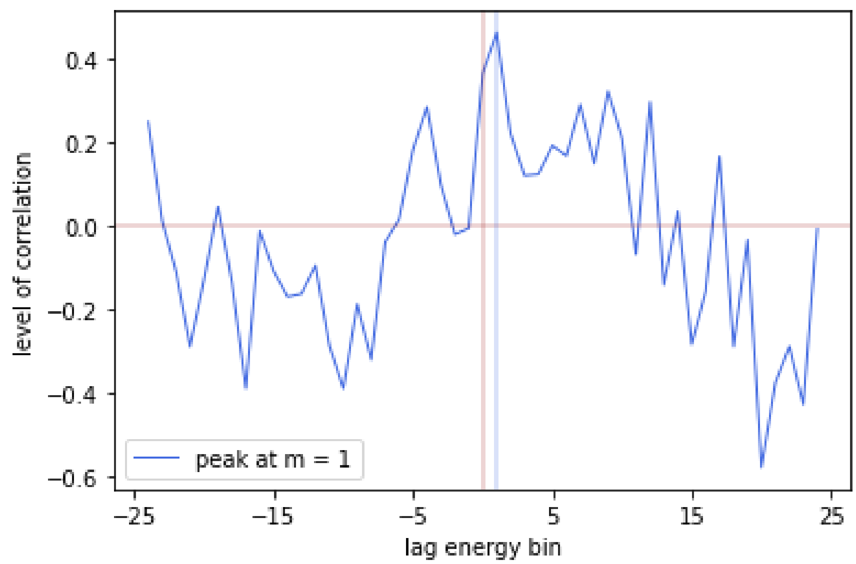

Figure 10. The cross-correlation function between the electron and positron residual fluxes. The red, horizontal guide line is at $y = 0$ to show positive or negative correlation. The vertical, red guide line is at $x = m = 0$, and the vertical, blue line is at $m =+ 1$, showing a peak in the analysis. This peak corresponds to the electron fluxes being shifted by $+ 1$ energy bin.

The largest positive peak is at $m =+ 1$, which in part matches what we hoped for. It is possible that, because the electrons exist in much higher numbers than the positrons, and by taking the shape of their original spectral curve into account, that the peaks of the electrons might be bunched up in a way, giving a shift of +1 rather than the exact 0 originally expected.

Because of the noise in the measurement and the systematic errors involved, this alone is not enough to seal the result of pulsars as a source. Next steps are necessary.

To the future

The next steps are to take this analysis and test it over many simulations for the potential sources of cosmic-ray electrons and positrons. We want to know if the signature discovered in Figure 10 matches the signature from these simulations. As mentioned above, using dual annealing to find parameter values is time consuming, so we are continuing to find more efficient methods to fit the data. A promising method to fit the data is to convolve an interpolated rendition of the dataset with a gaussian function. This should give a smooth curve that closely follows the data with far less runtime necessary.

The processes described for the AMS-02 data will be repeated over a set of pulsar simulations [6] that have been selected for their closeness to what AMS-02, CALET (Calorimetric Electron Telescope), and DAMPE (Dark Matter Particle Explorer) have measured. This will be done to check whether our findings are consistent with a diverse range of pulsar sources. If our conclusion is reproducible under many pulsar source simulations, then it holds stronger than if it was only relevant to a single simulation. There are ~1,000 Milky Way pulsar simulated fluxes for each of the positrons and electrons fluxes, 10 noisy simulations of how each of those pulsar simulations would be read by the detector within 2σ of the AMS-02 positron data, and 10 noisy simulations of how they would be read between 2σ to 3σ of the AMS-02 positron data [6].

After this convolution code is created, it will find smooth functions for each of the pulsar simulations. This smooth function will be used as our smooth function has been used so far in this project, to find residuals for each of the noisy datasets. Once these residuals have been found, we will run the cross-correlation analysis within each of the 2σ and 2σ-3σ noisy electron-positron dataset pairs. This will show the predicted signal of the cross-correlation function over a range of assumptions for their origins (as given by each of the original pulsar simulation variations).

By the end of the project, we will have run our analysis on over 10,000 combinations of datasets with various assumptions on the pulsar sources involved. Together with the AMS-02 findings, these should give a picture of whether pulsar sources can give the signal we see.

References (In Astrophysics style)

[1] M. Aguilar et al. (AMS), "First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV," Phys. Rev. Lett. **110**, 141102 (2013)

[2] M. Aguilar et al. (AMS), "Towards Understanding the Origin of Cosmic-Ray Electrons," Phys. Rev. Lett. **122**,101101 (2019).

[3] AMS Collaboration, "Towards Understanding the Origin of Cosmic-Ray Electrons: Supplemental Material," Phys. Rev. Lett. **122**,101101 (2019).

[4] M. Aguilar et al. (AMS), "Towards Understanding the Origin of Cosmic-Ray Positrons," Phys. Rev. Lett. **122**, 041102 (2019).

[5] AMS Collaboration, "Towards Understanding the Origin of Cosmic-Ray Positrons: Supplemental Material," Phys. Rev. Lett. **122**, 041102 (2019).

[6] I. Cholis and I. Krommydas, Phys. Rev. D **105**, 023015 (2022).

[7] K. Kido, (2015), Correlation. Digital Fourier analysis: Advanced techniques (pp. 23-52), Springer, New York, NY. https://doi.org/10.1007/978-1-4939-1127-1_2.

[8] B. Carroll and D. Ostilie (2007), "An Introduction to Modern Astrophysics," Pearson Education, Inc..

[9] I. Cholis, T. Karwal, and M. Kamionkowski, "Features in the Spectrum of Cosmic-Ray Positrons from Pulsars," Phys. Rev. D **97**, 123011 (2018).

[10] P.-P. Zhang, B.-Q. Qiao, W. Liu, S.-W. Cui, Q. Yuan, and Y.-Q. Guo, "Possible Bump Structure of Cosmic Ray Electrons Unveiled by AMS-02 Data," J. Cosmol. Astropart. Phys. 05 (2021) 012.

[11] B. Saxton, Parts of a Pulsar, National Radio Astronomy Observatory, accessed 3 March 2022, <https://public.nrao.edu/gallery/parts-of-a-pulsar/>.

[12] D. Kuzur, R. Bhattacharyya, and R. Mallick, "Acceleration of Charged Particles in Rotating Magnetized Star," J. Phys. G: Nucl. Part. Phys. 47 105203 (2020).

[13] I. Cholis, T. Karwal, and M. Kamionkowski, "Studying the Milky Way Pulsar Population with Cosmic-Ray Leptons," Phys. Rev. D **98**, 063008 (2018).

[14] Z.-Q. Huang, R.-Y. Liu, J. C. Joshi, and X.-Y. Wang, "Examining the Secondary Product Origin of Cosmic-Ray Positrons with the Latest AMS-02 Data," Astrophys. J. **895**, 53 (2020).

[15] W. Becker (2009), "Neutron Stars and Pulsars," Springer-Verlag Berlin Heidelberg.