Graduate School of Advanced Science and Engineering
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博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Search for Signals of Decaying Dark Matter and Spectral Features in the Flux of Electron and Positron Cosmic-Rays Measured with CALET on the ISS

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Cosmic Rays (CR) are energetic charged particles that impinge on the earth from all directions, which are mostly composed of Proton and Helium. CRs also contain electron and anti-particles such as positrons and anti-protons. The CR energy spectrum from 10^9 eV to 10^{15} eV can be well represented by power law spectrum with spectral index ~ 2.7-2.8. Above this energy region the spectrum gets steeper and this part is called the "knee" region of the spectrum. The spectral index changes again around 10^{18} eV and this part is called the "ankle" of the spectrum. Supernovae are the most commonly accepted CR sources and pulsars are another source of CRs. These primary CR particles propagate in the Interstellar Medium (ISM) and the interaction of these primary particles with the ISM produces secondary particles. The propagation of CRs through the galaxy can be represented by a transport equation which consists of terms for diffusion, diffusive reacceleration, convection and several energy loss processes (Ex. inverse Compton scattering, synchrotron radiation, ionization etc.) and also losses due to radioactive decay and fragmentation which are important for nuclei propagation.

When the CR particles enter the solar system, the magnetic field and the solar wind plasma affects the low energy CRs and the intensity of low energy CRs is significantly reduced. This effect is known as Solar Modulation and the effect of it is parametrized as an average energy loss per charge, called the solar modulation potential. Finally, when CR arrive near the vicinity of earth they can be detected by balloon borne or space-based detectors (Ex. Fermi-LAT, PAMELA, AMS-02, CALET, CREAM, TRACER etc.). While the balloon borne detectors have several limitations due to statistical and systematical error coming mostly from the comparatively shorter exposure time and the atmospheric overburden, the space-based detectors are free from such effects, but costlier than balloon experiments.

CALET (CALorimetric Electron Telescope), a calorimetric telescope, was designed and built in Japan, was funded by the Japanese Space Agency (JAXA) in cooperation with Italian Space Agency (ASI) and NASA, and it was attached to the International Space Station (ISS) in August 2015. It started science operations from October 2015. The primary science goal of CALET is to measure the CR $e^+ + e^-$ spectrum from 1 GeV up to 20 TeV. Due to its thick calorimeter, high proton rejection ratio (1:10^5), and fine energy resolution (2% above 100 GeV), CALET is used to precisely measure and look for fine structures in the $e^+ + e^-$ spectrum. Due to their high energy loss compared to nuclei, TeV energy electrons can be used as a probe for nearby CR sources. CALET will address many longstanding questions in the CR physics, such as - origin and propagation mechanism of CRs, presence of nearby sources and search for Dark Matter (DM) decay and annihilation signals in the CR $e^+ + e^-$ spectrum. In this thesis CR propagation in ISM is studied in detail to find CALET's potential in detecting exotic signals from DM decay or other spectral features in the $e^+ + e^-$ spectrum and distinguishing them from a more generic single pulsar spectrum.

To study and solve the CR propagation equation, GALPROP numerical tool which takes into account the effects of diffusion, reacceleration, convection and energy loss processes is used. In GALPROP, the CR propagation equation is solved by using the Crank-Nicolson method. As the energy loss processes during propagation in the galaxy are much more dominant for electrons compared to protons because of the low mass of the former, it's found that the CR propagation calculation depends on the energy bin size in GALPROP. A method to reduce this effect of the energy binning on the calculated electron spectrum is described in detail with examples including the calculations of propagated background and DM spectrum in GALPROP.

To obtain the DM spectrum at production, PPPC4 (Poor Particle Physicist Cookbook for Dark Matter Indirect Detection) tool is used, and the propagated spectrum is calculated using a version of the GALPROP modified to mitigate the influence of the energy binning. Assuming LKP (Lightest Kaluza-Klein Particle) DM as extra source, 5-years CALET data for the $e^+ + e^-$ spectrum was simulated. It was shown that the deviation of the coarse binning calculation from the unmodified finer binning calculation are exceeding or at least comparable with CALET experiment statistics, while the modified version reduces the deviation to a negligible level.

As mentioned before, because of the fine energy resolution and high proton rejection ratio, CALET can search for spectral features in the $e^+ + e^-$ spectrum which may arise from the DM decay or annihilation. We studied the prospect of CALET to distinguish signals from DM decay from a single generic pulsar source in the thesis in detail. Measuring directly the CR $e^+ + e^-$ spectrum in the TeV region for the first time with CALET will play one important role in indirect DM detection search. Measurements from PAMELA and AMS-02 showed an increase in positron fraction above 10 GeV. Positrons as secondary particles which are produced mostly from collision of protons with the ISM, cannot explain these results, which hint towards an extra source of electron-positron pairs such as emission from pulsars and/or DM decay or annihilation.

Regarding this, we choose 3-body decay of a fermionic DM which can explain the CR positron excess and investigate the prospects of discerning this DM decay signal from a generic single pulsar source spectrum in the CR $e^+ + e^-$ spectrum. In this theoretical model, the Standard Model (SM) is extended by 3 fermionic scalar singlets and two Higgs doublets, where the lightest neutral fermion is the DM candidate. The decay products of the DM are 2 charged leptons and a neutrino which ensures no anti-proton excess. Since the decay is mediated by very heavy scalar, it's assumed in this thesis work, that the lifetime of the mediating scalar is negligible, making a 4-point Fermi interaction a good approximation of the decay process. The probability distribution of the momentum of the outgoing charged particles was calculated and the results are shown in this thesis. From this energy distribution, the e^+, e^- spectrum at production is calculated using PYTHIA event generator. Finally, this spectrum at production is propagated using GALPROP to calculate the e^+ and e^- flux from the 3-particle DM decay.

The propagation parameters used in this process are determined from comparing with the experimental proton and B/C ratio data with GALPROP calculation results. Here it is shown that, assuming same spectral indices at the source for CR electron and proton, the CR electron spectrum calculated with GALPROP would be far too hard to allow room for any extra sources. This problem is also investigated in the thesis. The CR source distribution assumed originally in GALPROP is modeled according to the EGRET γ-ray measurements, and does not properly represent the spiral arm structure of Milky-way galaxy. To mitigate this problem a simple modification in the GALPROP source code is implemented where, the spiral arm structure of the galaxy is modeled as 4 concentric rings with a Gaussian profile. Compared to the original GALPROP source distribution, the modified version causes longer propagation paths for charged particles which ensures more energy loss, which in turn make the CR electron spectrum softer.

Using this modified version of GALPROP, CR proton flux and B/C ratio are calculated, and the propagation parameters are determined by comparing with the experimentally measured data. The same propagation parameters are used for electron/positron propagation coming from DM decay. To discern the DM decay signal from a single pulsar source spectrum a simple parametrization for the propagated e^+ and e^- spectra is assumed.

This parametrization is used to determine the multiple scenarios for DM as extra source explaining positron excess from the minimum χ^2 comparison with the $e^+ + e^-$ and positron flux measured by AMS-02. Since the decay of the DM would cause γ-ray production in the galactic halo, the predicted flux is compared with Fermi-LAT measurements of the diffuse γ-ray flux. While the theoretically predicted 2 TeV model with all possible decay channels was found to be in conflict with this measurement, the arbitrariness of the coupling constants in the chosen theoretical model allows to exclude the ττν channel. The γ-ray flux can be reduced considerably by this, as well as by reducing the mass of the Dark Matter particle, and 1 TeV as well as 1.5 TeV Dark Matter mass models in agreement with the Fermi-LAT measurement were found and studied.

To investigate CALET's capability to distinguish this DM decay signal from a single pulsar source, from the fit of the parametrization to AMS-02 $e^+ + e^-$ flux and positron flux with DM as extra source, 5 years CALET data for the $e^+ + e^-$ spectrum is simulated, and 10000 samples were generated to account for statistical fluctuations. Then the parametrization with single pulsar as extra source is fitted to CALET simulated data and AMS-02 positron flux for the 10000 samples. From the χ^2 distribution plot it's then concluded that using precise measurement of $e^+ + e^-$ spectrum with CALET, the two possible extra source explanations for positron excess can be well discerned with high probability. This discerning capability of CALET increases for the low γ-ray models of the DM which are compatible with Fermi-LAT measurement.

The previous results lead us to study the $e^+ + e^-$ spectrum from 10 GeV to 3 TeV with CALET 1.5 years flight data. To constrain the model by positrons, we combined the CALET measurement with AMS-02 positron flux data, as the $e^+ + e^-$ spectrum measured by CALET and AMS-02 are well in agreement with each-other. We find that a single power-law with single pulsar or DM decay and annihilation as extra source, cannot explain this measurement at 95% CL. We have assumed a broken power-law for electrons and studied the possibility of explaining the full CALET measurement with either DM decay (3-body leptonic decay products) or single pulsar as extra source. It is found that both DM decay and pulsar can explain the combined CALET + AMS-02 measurements, depending upon the background parameters.

We have determined the allowed range of DM masses and single pulsar cut-off energies based upon the background cut-off energy. DM mass as low as 800 GeV was found to be well allowed at 95% CL and due to low DM mass and high branching fraction of electron channel, the γ-ray flux from the DM decay products are well below the flux measured by Fermi-LAT. We have also discussed the possibility of discerning DM signal from the pulsar with this updated results and findings using 5 years CALET simulated data. It is shown that a separation between these two scenarios is possible with 45% probability based on a simple statistical method. Positive χ^2 difference (~20) between DM and pulsar scenario suggests that a better separation is possible with advanced statistical methods.

Finally, we conclude the thesis with a review of the results and implications of the research findings. Also, plans for investigating further CR mysteries in the future using better statistics of CALET experiment are discussed.

早稲田大学　博士（理学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Science), Waseda University)

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