Inhomogeneity in the Supernova Remnants as a Natural Explanation of the PAMELA/ATIC Observations

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Recent measurements of the positron/electron ratio in the cosmic ray (CR) flux exhibits an apparent anomaly[1], whereby this ratio increases between 10 and 100 GeV. In contrast, this ratio should decrease according to the standard scenario, in which CR positrons are secondaries formed by hadronic interactions between the primary CR protons and the interstellar medium (ISM)[2]. The positron excess is therefore interpreted as evidence for either an annihilation/decay of weakly interacting massive particles, or for a direct astrophysical source of pairs. The common feature of all proposed models is that they invoke new physics or new astrophysical sources. However, this line of argumentation relies implicitly on the assumption of a relatively homogeneous CR source distribution. Inhomogeneity of CR sources on a scale of order a kpc, can naturally explain this anomaly. If the nearest major CR source is about a kpc away, then low energy electrons (~ 1 GeV) can easily reach us. At higher energies ($\gtrsim 10$ GeV), the source electrons cool via synchrotron and inverse-Compton before reaching the solar vicinity. Pairs formed in the local vicinity through the proton/ISM interactions can reach the solar system also at high energies, thus increasing the positron/electron ratio. A natural origin of source inhomogeneity is the strong concentration of supernovae to the galactic spiral arms. Assuming supernova remnants (SNRs) as the sole primary source of CRs, and taking into account their concentration near the galactic spiral arms, we consistently predict the observed positron fraction between 1 and 100 GeV, while abiding to different constraints such as the observed electron spectrum and the CRs cosmogenic age. An ATIC[3] like electron spectrum excess at ~ 600 GeV can be explained, in this picture, as the contribution of a few known nearby SNRs.

PAMELA[1] discovered that the CR positron/electron ratio increases with energy above $\sim$ 7 GeV. The apparent discrepancy between the theoretical standard prediction of a decreasing ratio and these measurements is now commonly known as the "PAMELA anomaly"[4]. It is commonly interpreted as evidence for a new source of primary CR positrons, most likely WIMPs or pulsars. Measurements of the electron spectrum at $0.1-1$ TeV by ATIC[3] show an excess of CR electrons at energies of $300-800$ GeV, and at even higher energies ($1-4$ TeV) HESS measures[5] a sharp decay in the electron spectrum. ATIC's results are usually considered as support of a dark matter origin for the PAMELA anomaly, where the observed spectral bump corresponds to the WIMP mass. Note however that the recent Fermi results[6], exhibit a significantly smaller spectral excess relative to standard CR diffusion models.

In the standard picture[2], the majority of CRs are thought to originate in SNR shocks. SNRs, however, are not expected to be a major source of CR positrons. Instead, as CR protons diffuse through the Galaxy, they collide with interstellar medium (ISM) nuclei, produc-

ing "secondary" positrons and electrons. CRs diffuse within the disk, and escape the Galaxy once they reach the halo height, $l_H \sim 1$ kpc above the disk. The diffusion coefficient can be approximated as $D = D_0(E/E_0)^\beta$. Most CR diffusion models assume that CRs are produced with a power-law spectrum, $N_E \equiv dN/dE \propto E^{-\alpha}$. The observed spectrum is then a convolution of the source spectrum and propagation losses, giving for the primary electrons $N_{E,obs}^{(e)} \propto E^{-(\alpha_e+\beta)}$. Positrons are secondary CRs formed from CR protons, and suffer additional propagation loses, implying $N_{E,obs}^{(s)} \propto N_{E,obs}^{(p)} E^{-\beta} \propto E^{-(\alpha_p+2\beta)}$. The predicted flux ratio is $\phi^+/(\phi^-+\phi^+) \approx \phi^+/\phi^- \propto E^{\alpha_e-\alpha_p-\beta}$, where α_e and α_p are the source power-law indices of electrons and protons respectively. Both electrons and protons are expected to have similar spectral slopes, i.e., $\alpha_e \approx \alpha_p$, which is somewhat larger than 2. Consequently, $\alpha_p - \alpha_e < \beta \approx 0.3 - 0.6$ and the standard model predicts, in contrast to PAMELA observations, a CR positron/electron ratio which decreases with energy.

This standard model assumes a homogenous, source distribution[2,7]. However, as star formation in spiral galaxies is concentrated in spiral arms[8,9] one should consider the effect of inhomogeneities in the CR source distribution on the CR spectrum. This inhomogeneity of sources influences the electrons/positrons spectra via cooling which sets a typical distance scale that an electron/positron with a given energy can diffuse away from its source. For a homogenous distribution cooling affects the spectra of (primary) electrons and (secondary) positrons in the same way and their ratio is unaffected. On the other hand, primary electrons will be strongly affected by an inhomogeneous source distribution at energies for which the diffusion time is longer than the cooling time. Protons are not affected by cooling and are therefore distributed rather smoothly in the galaxy even if their sources are inhomogeneous. The secondary positrons (that are produced by the smoothly distributed protons) are only weakly affected by the inhomogeneity of the sources. This effect would induce an observed signature on ϕ^+/ϕ^-, with similar properties to the one observed by PAMELA.

We [10] considered a simple analytic model for diffusion from a source at a distance d from Earth. We model the galaxy as a two dimensional slab. The Galactic plane is infinite and the disk height is finite, l_H. The source is at a distance d from Earth. A CR diffuses within this slab with a constant diffusion coefficient $D(E)$, and it escapes once $|y| > l_H$. We find that for a a turnover in ϕ^+/ϕ^- is observed at E_b which satisfies $\tau_c(E_b) \approx \min\{\tau_x(E_b), (\tau_e(E_b)\tau_x(E_b))^{1/2}\}$. ϕ^+/ϕ^- for $E < E_b$ decreases, while it increases for $E > E_b$. This is the observed behavior seen by PAMELA, provided that $E_b \approx 10$ GeV, which the case using typical parameters for cooling and diffusion from a source at $d \approx 1$ kpc [10]. The nearest spiral arm to the solar system is the Sagittarius-Carina arm at a distance of ≈ 1 kpc.

At the same time the typical age of CR protons with energy E_b is $a \sim \max\{\tau_e, (\tau_e\tau_d)^{1/2}\}$. Therefore a natural prediction of the model is $a(E_b) \gtrsim \tau_c(E_b)$ and a comparison of the two observables can be used as a consistency test for the model. Moreover, over a wide range of the parameter space for which $d \gtrsim l_H$, the model predicts $a(E_b) \approx \tau_c(E_b)$ regardless of the value of the diffusion coefficient D.

To demonstrate quantitatively the potential of this model to recover the observed behavior of ϕ^+/ϕ^-, we [10] (see also ref. 8) simulated numerically the CR diffusion for a realistic spiral-arm concentrated source distribution. Before presenting these results we stress that all other models explaining PAMELA invoke a new ad hoc source of high energy CR positrons which has a negligible effect on low energy CR components. However, in our model, the PAMELA explanation is intimately related to low and intermediate energy CR propagation in the Galaxy. Namely, by revising the source distribution of CRs, we affect numerous properties of $\sim$ GeV CRs. Given that the interpretation of observations (in particular, isotopic ratios) used to infer model parameters (such as D_0, β or l_H) depend on the complete model, one should proceed while baring in mind that these parameters may differ in our model from present canonical values. In

this sense, the objective is not to carry a comprehensive parameter study, fitting the whole CR data set to an inhomogeneous source distribution model. Instead, our goal is to demonstrate the potential of the model to explain naturally the PAMELA anomaly. To this end we use the simplest possible model, fixing all parameters with the exception of the halo size, l_H, and the normalization of the diffusion coefficient, D_0, that we vary to fit the data.

Small scale inhomogeneities are important at energies larger than a few hundreds GeV, for which the lifetime, and therefore propagation distance, of electrons is so short that the electron spectrum is dominated by a single, or at most a few nearby sources[11,12,13]. To take this effect into account we truncate the "homogeneous" disk component at $r < 0.5$ kpc and age less than $t < 0.5$ Myr, and we add all known SNRs within this 4-volume: Geminga, Monogem, Vela, Loop I and the Cygnus Loop, as discrete instantaneous sources. These sources were described using the analytical solution[11] for the diffusion and cooling from an instantaneous point source.
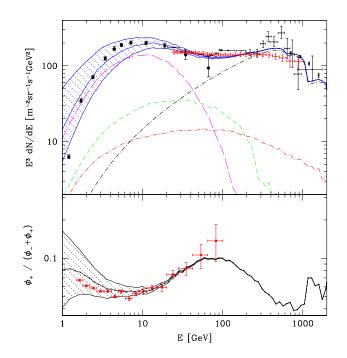

Figure 1: *Bottom Panel*: Model results and the measured PAMELA points for the positron fraction. The shaded region is the variability expected from solar modulation effects[13]. *Top Panel*: The expected electron and positron spectra – Primary arm electrons (long dashed purple), primary disk electrons with nearby sources excluded (short dashed green), nearby SNRs (dot-dashed black), secondary positrons (dot-dashed red), and their sum (blue). The hatched region describes the solar modulation range (from 200 MV to 1200 MV). The four data sets plotted are of HEAT[15] (circles), ATIC[3] (triangles), HESS[5] (open squares) and Fermi[6] (red triangles).

The lower panel of fig. 1 depicts $\phi^+/(\phi^+ + \phi^-)$. As expected from the simple analytical model, the fraction decreases up to ~ 10 GeV and then it starts increasing. At about 100 GeV, the ratio flattens and it decreases above this energy because of the injection of "fresh" CRs from recent nearby SNRs whose high energy primary electrons don't have time to cool. These sources also contribute to higher energy electrons. The cosmogenic age we obtain in this model for 1 GeV per nucleon particles is 14 Myr.

The upper panel of fig. 1 depicts the electronic spectrum and its constituents—primary spiral arm electrons, primary disk electrons (without nearby sources), the spectrum of the nearby sources and the secondary pairs. Evidently, there are two small humps in the $E^3 N_E$ plot. The lower energy hump arises from spiral arm electrons, the higher energy of which cannot reach us due to cooling. At higher energies, the spectrum flattens out because of local SNR contribution. For our nominal CR injection per SNe[10], we obtain a spectrum laying between Fermi[6] and ATIC[3], and which appears like a small hump. The three "steps" in it are due to the cooling cutoffs from Geminga, Loop I and the Monogem SNRs. Note that the average CR flux from these sources is about 3 to 6 times higher than can be expected from the average disk population were it not truncated. This is not surprising given that our local inter-arm region is perturbed by the Orion Spur.

While the predictions for the positron/electron ratio for the spiral arms CR model are very

different than for a homogenous sources distribution, the effect on the electron spectrum is much more subtle. Both models predict a break of the electron spectrum at 10 GeV. The break predicted by spiral arm model is from a power law to an exponential, while in the homogenous model it is a broken power-law. Given that above ~ 100 GeV the electron spectrum is strongly affected by local sources, the energy range between 10 to 100 GeV is too short to distinguish, based on the electron spectrum alone, between the two models. Thus, while both models can adequately reproduce the observed electron spectrum (at least up to 100 GeV), only the inhomogeneous source model can explain the positron/electron ratio.

One of the interesting predictions of this model where both the PAMLEA and the ATIC anomalies are explained as consequences of propagation effects from SNRs, is that the positron fraction should start dropping with energy at ~ 100 GeV, just above the present PAMELA measurement. It should reach a minimum around the "ATIC peak", where it should start rising again. Whether or not it can go up to about 50% at a few TeV depends on whether the CRs from very recent SNe, the Cygnus Loop and Vela, could have reached us or not. This critically depends on the exact diffusion coefficient. Here it is also worth pointing out that above a few TeV the secondaries must be produced within the local bubble, implying that their normalization should be ten times lower than for the lower energy secondaries. These predictions are in contrast to the case where spectral features at higher energies are due to a primary source of pairs, in which case the positron fraction is expected to keep rising also at a few hundreds GeV. With these predictions, it will be straightforward in the future to distinguish between propagation induced "anomalies", and real anomalies arising from primary pairs (in particular, when PAMELA's observations will extend to higher energies). Of course, it is possible that the excess at high energies is due to a source of primary pairs, while the PAMELA anomaly is a result of SNRs in the spiral arms, but then it would force us to abandon the simplicity of the model, that the anomalies are all due to propagation effects from a source distribution borne from the known structure of the Milky Way.

Acknowledgments

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