Inhomogeneity in the Supernova Remnant Distribution as the Origin of the PAMELA Anomaly

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ABSTRACT

Recent measurements of the positron/electron ratio in the cosmic ray (CR) flux exhibits an apparent anomaly (Adriani et al. 2009), whereby this ratio increases between 10 and 100 GeV. We show that 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 (∼10 GeV), the source electrons cool via synchrotron and inverse-Compton before reaching Earth. Pairs formed in the local vicinity through the proton/ISM interactions can reach Earth also at high energies, thus increasing the positron/electron ratio. A natural origin of source inhomogeneity is the strong concentration of supernovae in 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 recover the observed positron fraction between 1 and 100 GeV. ATIC’s (Chang et al. 2008) electron excess at ∼600 GeV is explained, in this picture, as the contribution of a few known nearby SNRs. The apparent coincident similarity between the cooling time of electrons at 10 GeV (where the positron/electron ratio up-turn), ∼10 Myr, and the CRs protons cosmogenic age at the same energy is predicted by this model.

PAMELA (Adriani et al. 2009) discovered that the CR positron/electron ratio increases with energy above ∼10 GeV. This ratio should decrease according to the standard scenario, in which CR positrons are secondaries formed by interactions between the primary CR protons and the interstellar medium (ISM) (Moskalenko & Strong 1998). This apparent discrepancy is now commonly known as the “PAMELA anomaly”. It is commonly interpreted as evidence for a new source of primary CR positrons, most likely WIMPs (Bergström, Bringmann & Edsjö 2008; Ibarra & Tran 2008) or pulsars (Harding & Ramaty 1987; Chi, Cheng & Young 1996; Atoyan, Aharonian & Völk 1995; Hooper, Blasi & Dario Serpico 2009; Yuksel, Kistler & Stanev 2008; Profumo 2008). ATIC (Chang et al. 2008) shows an
excess of CR electrons at energies of 300 – 800 GeV. At even higher energies (1 – 4 TeV) HESS measures \cite{HESS_2008} a sharp decay in the electron spectrum. ATIC’s results are usually considered as support for a dark matter interpretation for the PAMELA anomaly, where the observed excess corresponds to the WIMP mass.

In the standard picture, CRs below the knee are thought to originate in SNR shocks. This is indicated by synchrotron \cite{Koyama_1995} and inverse-Compton \cite{Tanimori_1998} emission of high energy electrons in SNRs, and the $\gamma$-ray emission, which is possibly from high energy protons \cite{Aharonian_2004}. Theoretical models for the CR flux describe CR propagation in the Galaxy. CRs diffuse within the disk, and escape once they reach the halo height, $l_H \sim 1$ kpc, above the disk. Most CR diffusion models approximate the diffusion coefficient as $D = D_0 (E/E_0)\beta$ and 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 $\phi^{-}(E) \propto E^{-(\alpha_e+\beta)}$. Positrons are secondary CRs formed from CR protons, and suffer additional propagation loses, implying $\phi^{+}(E) \propto \phi_p(E)E^{-\beta} \propto E^{-(\alpha_p+2\beta)}$, where $\phi^{\pm}$ and $\phi_p$ are the CR positrons, electrons and protons observed fluxes. The predicted flux ratio is $\phi^{+}/(\phi^{-}+\phi^{+}) \approx \phi^{+}/\phi^{-} \propto E^{\alpha_e-\alpha_p-\beta}$, where $\alpha_e$ and $\alpha_p$ are the source power-law indices of electrons and protons respectively. Both electrons and protons are expected \cite{Blandford_1987} to have similar spectral slopes, i.e., $\alpha_e \approx \alpha_p$, which is somewhat larger than 2. This is also supported by synchrotron radiation observed from SNRs, which confirms the slope for the electrons \cite{Duric_1995}. Consequently, $\alpha_p - \alpha_e < \beta \approx 0.3 - 0.6$ and the standard model predicts, in contrast to PAMELA observations, a decreasing $\phi^{+}/\phi^{-}$.

The diffusing electrons and positrons cool via synchrotron and inverse-Compton scattering, with $dE/dt = -bE^2$. This steepens both the electron and positron spectra at an energy where the cooling time equals the typical electron and positron age. However, since both suffer the same loses, this does not affect $\phi^{+}/\phi^{-}$. Additional effects such as spallation and annihilation can be safely ignored at the energies of interest.

This standard model assumes a homogenous, or at least a smoothly varying (on a galactic scale), source distribution \cite{Moskalenko_Strong_1998, Strong_Moskalenko_1998}. However, since in spiral galaxies star formation is concentrated in spiral arms \cite{Lacey_Duric_2001, Shaviv_2003} and SNRs are the canonical sources of CRs, one should consider the effect of inhomogeneities in the CR source distribution on intermediate scales (i.e., scales smaller than the Galactic size but large enough such that discrete sources do not have a strong effect) 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 $\phi^+ / \phi^-$, with similar properties to the one observed by PAMELA.

Motivated by this expectation we construct, first, a simple analytic model for diffusion from an inhomogeneous source. Consider a source at a distance $d$ from Earth. We model the solar neighborhood of the galaxy as a two dimensional slab (see fig. 1). The $x$ coordinate (the Galactic plane) is infinite and the $y$ coordinate (the disk height) is finite, $l_H$. The source is at the origin and Earth is at $(d, 0)$. A CR diffuses within this slab with a constant diffusion coefficient $D(E)$, and it escapes once $|y| > l_H$. The contribution of CR protons that were generated at time $t'$ to the flux at time $t_0$ can be approximated as:

$$\phi_p(d, t') \propto \frac{1}{\sqrt{Dt}} \exp[-(t / \tau_e) - (\tau_d / 2t)],$$  \hspace{1cm} (1)$$

where $t \equiv t_0 - t'$, $\tau_e \approx l_H^2 / D$ is the typical escape time and $\tau_d \approx d^2 / D$ is the typical diffusion time from the source to Earth. Integration over $t$ for a steady source, yields:

$$\phi_p(d) \propto \frac{1}{D} \exp \left[ -\sqrt{2\tau_d / \tau_e} \right],$$ \hspace{1cm} (2)$$

with a similar energy dependence (via $D$) as for uniformly distributed sources. The average age of an observed proton is $a = l_H (l_H + \sqrt{2}d) / 2D \approx \max\{\tau_e, (\tau_e \tau_d)^{1/2}\}$.

We approximate the cooling effect on the electron’s flux as $\phi^- (d, t') \propto \phi_p(d, t') \exp[-t / \tau_c]$, where $\tau_c$ is the typical cooling time. Integration over $t$ reads:

$$\phi^- (d) \propto \frac{\exp \left[ -2\sqrt{\tau_d / \tau_c + \tau_d / \tau_e} \right]}{D \sqrt{1 + \tau_c / \tau_e}}.$$ \hspace{1cm} (3)$$

If $\tau_c < \min\{\tau_d, (\tau_e \tau_d)^{1/2}\}$ the electron flux drops exponentially with decreasing $\tau_c$, while for larger $\tau_c$ the electron flux is proportional to $D^{-1}$ (relative to the source’s spectrum). This is different than the case of uniformly distributed sources, which shows a shallower break at

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1 We assume for simplicity that the diffusion is one dimensional. This results with an exponent once integrated. Two dimensional diffusion (from a linear spiral arm) would give a less transparent Bessel function.
\[ \tau_c \approx \tau_e \text{ from } \phi^-(\tau_c > \tau_e) \propto \tau_e \propto D^{-1} \propto E^{-\beta} \text{ into } \phi^-(\tau_c < \tau_e) \propto \tau_c \propto E^{-1}, \text{ both relative to the source's spectrum.} \]

The positron source function is approximately proportional to \( \phi_p(d) \). As positrons and electrons have the same cooling rate, a source at \( x' \) contributes to the positron flux at \( d \) approximately \( \phi^-(x' - d) \). Therefore:

\[
\phi^+(d) \propto \int_{-\infty}^{\infty} \phi_p(x')\phi^-(x' - d)dx' \propto \frac{\tau_c}{D} \left( \exp \left[ -\sqrt{\frac{2\tau_d}{\tau_c}} \right] - \exp \left[ -\frac{2\tau_d}{\tau_c} + \frac{2\tau_d}{\tau_e} \right] \right). \tag{4}
\]

For \( \tau_c \gg \tau_e \), the energy dependence of \( \phi^+ \) relative to the source spectrum, \( \phi_p^{(s)} \), is \( \phi^+ / \phi_p^{(s)} \propto D^{-2} \propto E^{-2\beta} \) while for \( \tau_c \ll \tau_e \), \( \phi^+ / \phi_p^{(s)} \propto \tau_c / D \propto E^{-\beta-1} \). This behavior is similar to the one from uniformly distributed sources.

Eqs. 3 and 4 show that for a source at a distance \( d \) from Earth, a turnover in \( \phi^+ / \phi^- \) is observed at \( E_b \) which satisfies \( \tau_c(E_b) \approx \min\{\tau_x(E_b), (\tau_e(E_b)\tau_x(E_b))^{1/2}\} \). \( \phi^+ / \phi^- \) for \( E < E_b \) decreases, while it increases for \( E > E_b \). 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 \( D \).

Electrons and positrons in the ISM cool as \( dE/dt = -bE^2 \) where (Kobayashi et al. 2004) \( b \approx 1.8 \times 10^{-16}\text{GeV}^{-1}\text{s}^{-1} \) at 1 GeV (and \( b \approx 1.4 \times 10^{-16}\text{GeV}^{-1}\text{s}^{-1} \) at 1 TeV), implying a cooling time \( \tau_c = 1/(bE) \approx 17 \text{ Myr at } E \approx 10 \text{ GeV} \). Observational constraints on the typical proton CR age are measured at a few 100 MeV. Typical ages obtained are \( 18^{+8}_{-3} \text{ Myr} \) (Wiedenbeck & Greiner 1980), \( 27^{+19}_{-9} \text{ Myr} \) (Lukasiak et al. 1994) or \( 30^{+21}_{-10} \text{ Myr} \) (Simpson & Garcia-Munoz 1988). At 10 GeV, the age should be smaller by a factor of \( \sim 1 - 3 \), depending on the exact energy dependence of the diffusivity. Thus, according to the observations \( a(10\text{GeV}) \approx \tau_c(10\text{GeV}) \approx 10\text{Myr.} \) This apparent coincidence which is explained naturally by our model encourages us to look for a dominant CR source at a distance of \( \sim \text{kpc from earth. Indeed, the nearest spiral arm to Earth is the Sagittarius-Carina arm at a distance of } \approx 1 \text{ kpc, which is just the distance needed to explain PAMELA’s observations.} \]

To demonstrate quantitatively the potential of this model to recover the observed behavior of \( \phi^+ / \phi^- \), we simulated numerically the CR diffusion for a realistic spiral-arm concentrated source distribution (see also Shaviv 2003). 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 $D_0$, $\beta$ 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 of this letter 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.

The geometry of the model is described in fig. 1. We assume a spiral arm/disk SNe ratio of 10. The overall normalization of the sources was fit to give the electron spectrum at 10 GeV. The positron production was normalized to give the positron to electron ratio at the same energy. For the ISM density we took the functional dependence from Strong & Moskalenko (1998). More on the choice of the parameters can be found in Shaviv (2003).

We take a diffusivity of the form $D = D_0(E/1 \text{ GeV})^\beta$ for $E > 4 \text{ GeV}$ and $D = D_0(4 \text{ GeV}/1 \text{ GeV})^\beta$ for $E < 4 \text{ GeV}$. It was realized that such a break is required to explain the observed break in the CR B/C ratio (Strong & Moskalenko 1998) (though it does not play an important role here). We take $\beta = 1/3$ (corresponding to turbulence with a Kolmogorov spectrum) and $\alpha_e = \alpha_p = 2.37$ such that the predicted proton spectrum will be consistent with the observed proton CR slope of 2.7. We also take $D_0 = 6 \times 10^{27} \text{ cm}^2/\text{sec}$, which reproduces the break energy in the electron spectrum and the positron fraction. As predicted by the analytic model the cosmogenic age we obtain in the simulation (14 Myr at 1 GeV per nucleon) is consistent with the observations, without fitting for it. Not surprisingly, the halo size and diffusivity considered here are somewhat different (on the low side) relative to standard values often found in the homogenous model.

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 (Atoyan, Aharonian & Völk 1995; Kobayashi et al. 2004; Profumo 2008). To take this effect into account we truncate the “homogeneous” disk component at $r < 0.5 \text{ kpc}$ and age less than $t < 0.5 \text{ Myr}$, and we add all 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 (Atoyan, Aharonian & Völk 1995) for the diffusion and cooling from an instantaneous point source. For the overall normalization of the point sources, we use the synchrotron observa-
Fig. 1.— The galaxy is modeled as a slab of width $2l_H$, with $l_H = 1$ kpc, inside of which the CR components diffuse. Beyond $y = \pm l_H$, the CRs escape at a negligible time. CR sources are located in both cylinder shaped arms with a Gaussian cross-section of width $\sigma = 300$ pc, and disk sources, with a vertical scale height of 100 pc. The assumption of straight cylinders is permissible given the small spiral arm pitch angle. This also makes the problem effectively two dimensional. We model the Milky Way as having four spiral arms, with a pitch angle of $i \approx 15^\circ$ (Vallee 2008), implying that the arm separation (in the direction perpendicular to the arm axis) is $d \approx (\pi/2)R_\odot \sin i \approx 3$ kpc, while the Sun is at a distance $x \approx 1$ kpc from the nearest spiral arm. Due to the motion of the arms, there is a small drift term carrying the CRs away from them. For a spiral arm periodicity of $P_s \sim 150$ Myr (Shaviv 2003), one obtains a velocity of $v_s \approx (\pi/2)(R_\odot \sin i)/P_s \approx 20$ km/s, which is slower than the two comparable diffusion times $l_H/\tau_e \approx x/\tau_x \approx 100$ km/s. A second component resides in the disk, with an exponential vertical decay. Because nearby sources are considered, the smooth disk distribution is truncated for $r < 0.5$ kpc and $t < 0.5$ Myr.
tions of SN1006, which together with the X-rays constrain the total energy and magnetic field (Yoshida & Yanagita 1997). In particular, electrons with energy \( > 1 \) GeV are found to carry \( \approx 2 \times 10^{48} \text{ erg} \), corresponding to 0.2\% out of the total \( \sim 10^{51} \text{ erg} \) mechanical energy in SNRs. We assume that all nearby sources are similar. Note that due to their very young age, the discrete sources contribute a negligible amount of positrons, nor do they offset the cosmogenic age.

The lower panel of fig. 2 depicts \( \phi^+/\phi^+ + \phi^- \) obtained by the simulation. As expected from the simple analytical model, the fraction decreases up to \( \sim 10 \) GeV and then it starts increasing. This explains the so called PAMELA anomaly. As the CR protons and antiproton spectra are unaffected our results are consistent with PAMELA’s observations of no excess in the anti-proton/proton ratio at the same energy range (Adriani et al. 2009). 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 detected by ATIC.

The upper panel of fig. 2 depicts the electron spectrum and its constituents—primary spiral arm electrons, primary disk electrons (without nearby sources), nearby sources and secondary pairs. There are two bumps in the \( E^3 N_E \) plot. The lower energy bump arises from spiral arm electrons, the higher energy of which cannot reach us due to cooling. The higher energy bump, which corresponds to the ATIC peak, is due to a few nearby SNRs. The three “steps” are due to the cooling cutoffs from Geminga, Loop I and the Monogem SNRs. Note that the high energy behavior is very sensitive to the exact diffusion model parameters and the poorly constrained SNR energy output in electrons. Thus, the ATIC peak is not a prediction of the model but rather one possible outcome.

While the predictions for \( \phi^+/\phi^- \) 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 \( \sim 100 \) GeV the electron spectrum is strongly affected by the sources that produces the ATIC bump (e.g. local SNRs), 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 observed \( \phi^+/\phi^- \).

One of the interesting predictions of the model where the ATIC peak is explained as consequences of propagation effects from local SNRs, is that the electron spectrum around the ATIC peak is dominated by nearby sources. These source produce only primary electrons and
Fig. 2.— *Bottom Panel:* Model results and the measured PAMELA points for the positron fraction. The shaded region is the variability expected from solar modulation effects (Clem et al. 1996). *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 three data sets plotted are of HEAT (DuVernois et al. 2001) (circles), ATIC (Chang et al. 2008) (triangles) and HESS (H. E. S. S. Collaboration 2008) (open squares).
have only negligible contribution to secondary positron flux. As a result ATIC observations force the electron/positron ratio to start decreasing at a few hundred GeV, which is not far 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 the ATIC peak is 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 ATIC peak 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.

Irrespective, this work demonstrates that the intermediate scale inhomogeneities expected in the CR source distribution leave nontrivial imprints on the electron and positron spectra. These should be further investigated before reaching definitive conclusions about the existence of primary positron sources.

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