Positron Excess from Cosmic Ray Interactions in Galactic Molecular Clouds

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Abstract. The recent data on cosmic ray positron flux measured near the Earth by the Alpha Magnetic Spectrometer (AMS-02) experiment extends to TeV energy. The positron flux measured in GeV$^2$ m$^{-2}$ sec$^{-1}$ sr$^{-1}$ rises with energy and shows a peak near a few hundred GeV. This rising positron flux cannot be explained by interactions of cosmic rays with interstellar hydrogen gas. Due to the progress in multi-wavelength astronomy, many new Galactic Molecular Clouds (GMCs) have been discovered in our Galaxy recently. We use the updated list of GMCs, which are distributed in the Galactic plane, to find the secondary positrons produced in them in interactions of cosmic rays with molecular hydrogen. Moreover, by analysing the Fermi LAT data, new GMCs have been discovered away from the Galactic plane. We also include some of these GMCs closest to the Earth where cosmic ray interactions are producing secondaries. After including these GMCs we show that the positron excess can be mostly well explained, with a small contribution from unknown extra component near the peak.

Keywords: cosmic ray theory, cosmic ray experiments
1 Introduction

Galactic cosmic rays (CRs) are generally considered to be accelerated in shocks near the supernova remnants (SNRs) [1–5] and propagate throughout the Galaxy. During their propagation, they are deflected by the Galactic magnetic field (GMF), also interact with interstellar hydrogen gas. The secondary CRs, produced in subsequent interactions of primary CRs with interstellar hydrogen gas [6], are important probes of CR acceleration, distribution of interstellar matter and diffusion of CRs in the Galaxy which depends on the magnetic field structure. Even after more than a hundred years of discovery of CRs, new observational data brings in new challenges for theoretical interpretations [7], due to this reason, this field has remained an active area of research.

Electrons are injected by CR sources, also they are produced in interactions of CR protons and nuclei with interstellar matter during their propagation in the Galaxy. While CR protons and nuclei can propagate long distances without losing energy significantly, electrons lose energy within a much shorter distance due to radiative losses. Positrons and antiprotons are secondary particles produced in interactions of CR protons and nuclei with interstellar matter. Being antiparticles, they are useful probes of new physics.

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) is a satellite-borne apparatus for recording charged CRs. The positron fraction measured by PAMELA between 1.5 and 100 GeV was the first result showing deviation from the conventional secondary production model [8, 9]. The more recent results of PAMELA confirm that additional sources, either astrophysical or exotic, may be required to explain the CR positron spectra [10].

Fermi-LAT collaboration reported the CR electron and positron spectrum separately and also the positron fraction in the energy range of 20-200 GeV [11]. They confirmed that the positron fraction rises with the energy in 20-100 GeV energy range, and the three spectral points in that spectrum between 100 and 200 GeV are also consistent with the same feature.

The Alpha Magnetic Spectrometer (AMS) on the International Space Station has measured CR fluxes with high precision over a wide energy range. The AMS collaboration published their results on high precision measurements of fluxes of CR protons (p) [12], helium (He)[13], Boron (B) to Carbon (C) flux ratio [14], and also antiprotons (p) [15]. Their first results on precise measurements of positron fraction in primary CRs in the energy range of
0.5-350 GeV showed that the positron fraction steadily increases in the energy range of 10 to 250 GeV, however beyond 20 GeV, the slope decreases by an order of magnitude [16]. Their subsequent results gave better statistics over an extended energy range [17–19]. Their recent results of CR electron [20] and positron spectra [21] provide high quality measurements of fluxes up to TeV energy. The positron flux plotted in GeV$^2$ m$^{-2}$ sec$^{-1}$ sr$^{-1}$ shows significant excess starting from 25.2$^{±1.8}$ GeV and a sharp decrease above 284$^{±91}_{−64}$ GeV. The flux has a cutoff at 810$^{±310}_{−180}$ GeV. The data shows that at high energy the positrons may be originated either from dark matter (DM) annihilation or from other astrophysical sources.

The DM origin of positron excess was studied in many earlier papers [22–27]. Both DM and pulsar scenarios could be the possible origin of the positron excess. Along with anisotropy could be another useful probe to discriminate these two scenarios [28]. Geminga pulsar has long been identified as a nearby gamma ray source. The possibility of explaining the GeV positron excess with the TeV gamma ray source Geminga was explored by Yüksel et al. [29]. Hooper et al. [30] suggested that a significant contribution to the positron flux between 10 to 100 GeV might be originated from mature pulsars such as Geminga and B0656+14. The Advanced Thin Ionization Calorimeter (ATIC) reported a “bump” in the high energy flux of electrons and positrons [31]. Several candidate pulsars were listed in [32] that could individually or coherently contribute to explain the PAMELA and ATIC data. After more precise observation by AMS-02, the role of nearby pulsars was further explored and they were identified as possible origin of the positron excess [33–35].

Previously, very high energy gamma ray data from High Altitude Water Cherenkov (HAWC) [36] detector also indicated that significant high energy positron flux from nearby pulsars such as Monogem and Geminga can explain the positron excess at 10-100 GeV energy range [37]. However, the recent measurement of surface brightness profile of TeV nebulae surrounding Geminga and PSR B0656+14 by HAWC [38] suggests inefficient diffusion of particles from the sources. When the HAWC and Fermi-LAT data are combined, Geminga and PSR B0656+14 are disfavoured as major sources of positron excess in the energy range of 50-500 GeV [39] for Kolmogorov type diffusion. In a more recent work, the pulsar PSR B1055-52 is found to be a promising source for explaining positron excess [40]. In future, gamma ray astronomy can shed more light on the origin of positron excess.

Micro-quasars were also considered to be viable sources for explaining the positron excess. It was shown that photo-hadronic interactions in the jets of micro-quasars can produce the excess positron flux which can explain the rise above 10 GeV [41].

In this work, we consider Galactic SNRs as the primary sources of CRs. During their random movement in the interstellar medium (ISM), CRs interact with ambient gas and also in Galactic Molecular Clouds (GMCs). We will show that the secondary positrons produced from interactions of CRs in nearby GMCs can explain the rise of positron flux above 10 GeV. Our self-consistent model of CR propagation also fits the data of CR electrons, positron fraction, protons, antiprotons and B/C ratio as measured by AMS-02 and PAMELA. In this paper, we will represent our analysis by dividing it into three parts namely CASE 1, CASE 2 and CASE 3. CASE 1 considers interactions of primary CRs with interstellar hydrogen gas, CASE 2, then, takes into account the interactions inside GMCs residing on the Galactic plane and listed by Rice et al. [42]. We find that the total flux of positrons from CASE 1 and CASE 2 is not sufficient to explain the positron excess above 10 GeV. Subsequently, we incorporate the contributions of secondary CRs from three nearby GMCs of the Gould Belt Complex, which is our CASE 3. We show that the total flux from CASE 1, CASE 2 and CASE 3 can mostly explain the positron excess along with a small contribution from an unknown extra
component near the peak.

The outline of this paper is as follows. In section 2 we discuss the model set up for CR propagation to obtain the results from CASE 1 and CASE 2. In the next section, we obtain the secondary flux contributions from CR interactions in nearby GMCs. The spectral fits of CR proton, antiproton and B/C data remain unaffected even after we incorporate the CR interactions in nearby GMCs. In section 4, we discuss our results. All the data used in plots are obtained from AMS-02 and PAMELA. We summarize our findings in section 5.

2 Modeling of cosmic ray propagation

2.1 Model setup

The propagation of CRs can be studied, for a given source distribution, density distribution of interstellar medium (ISM), GMF and injection spectrum of primary cosmic rays from their sources, by solving the CR transport equation \[4, 5\]. In the present work, we study high energy CR propagation in our Galaxy, by solving the transport equation numerically, using publicly available code DRAGON (Diffusion of cosmic RAys in Galaxy modelization) \[44–46\]. DRAGON incorporates various physical processes such as propagation and scattering of CRs in regular and turbulent magnetic fields, CRs interacting with ISM and GMCs, energy losses due to radioactive decay of the nuclei, ionisation loss, Coulomb loss, Bremsstrahlung loss, synchrotron and IC loss, re-acceleration and convection in the Galactic medium, to obtain the solution of the transport equation for the CR propagation in the Galaxy. In this subsection, we give an overview of the source distribution model, GMF model, ISM gas density distribution and diffusion coefficient, that we have chosen for our work.

DRAGON solves the transport equation in 3D geometry, where the Galaxy is assumed to be cylindrical in shape. The outermost radial boundary is denoted as \(R_{\text{max}}\), vertical boundary as \(L\), and halo height as \(z_t\), where \(L = 3z_t\) \[47\]. The location of the observer is specified at Sun’s position with respect to the Galactic center (GC), with \(x = 8.3\) kpc, \(y = 0\), \(z = 0\). We are propagating CR particles with atomic number ranging from \(Z=1\) to \(Z=14\), considering propagation of particles with higher mass numbers does not affect our results. The model setup used in this work was also used in our earlier work \[48\]. Primary CRs in our work, are assumed to be produced from SNRs in our Galaxy. Assuming SNRs as the major sources of CRs with an universal injection spectrum, the source term is used from the paper by Ferriere \[49\].

Interstellar gas plays an important role in the process of CR interactions and secondary production. During propagation, CR particles interact with different gas components of the ISM. The gaseous components are mainly atomic hydrogen (HI), ionized hydrogen (HII) and molecular hydrogen (\(H_2\)). As discussed earlier, we divide the contribution from the interaction of primary CRs with these components into two cases, CASE 1 for contribution from ISM gas density distribution, and CASE 2 contribution from interactions in GMCs listed in Rice et al. \[42\].

**HI density distribution:** Neutral or atomic hydrogen cannot be detected in optical wavelengths. Generally, HI can be detected by the observation of Lyman \(\alpha\) \[50, 51\] and 21-cm line \[52, 53\]. Previously, many models have been given to describe HI gas distribution \[54–56\]. In our calculation, the radial dependence of HI number density in the Galactic plane

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1 All data are taken from the database \[43\] unless otherwise specified.
2 The 3D version of the DRAGON code is available at https://github.com/cosmicrays/DRAGON for download.
is defined by a table in ref. [57], which is renormalized to make it consistent with the data of ref. [52]. The z-dependence is calculated using the approximation by [52] for \( R < 8 \) kpc, by [53] for \( R > 10 \) kpc, and interpolated in between.

**HII density distribution:** Radio signals from pulsars and other Galactic and extragalactic compact objects give us the information about the ionized component of hydrogen gas. Some of the models for the distribution of ionized hydrogen component are [55, 58, 59]. Cordes et al. [60] provided the space averaged free electron density depending on dispersion, distance and scattering measurements of pulsars. The distribution of ionized component HII is calculated using the cylindrically symmetrical model for space averaged free electron density [60].

**H\(_2\) density distribution:** Molecular hydrogen (H\(_2\)) is the most abundant molecule in our Galaxy. Second most abundant molecule is CO. Study of H\(_2\) cannot be done reliably from UV and optical observations, because UV and optical observations suffer from interstellar extinction. H\(_2\) is studied indirectly by radio observation of CO molecules as CO molecule has \((J = 1 \rightarrow 0)\) rotational transition at radio wavelength of 2.6 mm [49]. Such transition of CO acts as a tracer of H\(_2\), where CO-to-H\(_2\) conversion factor, \( X_{CO} \) is used to obtain information of H\(_2\) distribution in Galaxy [55, 56, 61–63]. Most of the H\(_2\) contribution in our Galaxy comes from large, discrete clumps of H\(_2\) distributed throughout the Galaxy, known as GMCs. These clumps of H\(_2\) reside mainly in the Galactic plane. The radial distribution of molecular clouds is discussed in subsection 2.2.

Galactic magnetic field (GMF) plays a crucial role in CR propagation. CR leptons lose energy by synchrotron emission in GMF. There are several methods to constrain the intensity and the orientation of GMF: Zeeman splitting observations [64], infrared, synchrotron and starlight polarisation studies [65–67], and Faraday rotation measures of the Galactic and extragalactic sources [68, 69]. The Galactic magnetic field \( \vec{B} \) is usually described as a sum of two components: a large scale regular, and a small scale turbulent, both having a strength of the order of \( \mu \)G in the Galaxy [70].

In this work, we use the GMF model as given by [69]. The GMF has three components, namely disc, halo and turbulent. The normalizations of the three components are denoted as \( B_0^{\text{disc}} \), \( B_0^{\text{halo}} \) and \( B_0^{\text{turbulent}} \) respectively. \( B_0^{\text{disc}} \) and \( B_0^{\text{halo}} \) lie in the range of 2-11 \( \mu \)G but their role in CR propagation is insignificant [47]. Among these components, the turbulent component of the GMF plays an important role in CR propagation. Obervationally, the most relevant information of the turbulent component of GMF comes from Faraday Rotation measurements. A functional relation between magnitude of the turbulent magnetic field and halo height \((z_t)\) is given in [47] by theoretical modeling of the propagation of the Galactic CR electrons and positrons to fit their observed fluxes, their synchrotron emission and its angular distribution. This expression from [47],

\[
\left( \frac{B_0^{\text{turbulent}}}{1 \mu G} \right)^2 = 148.06 \left( \frac{1 \text{kpc}}{z_t} \right) + 19.12
\]

has been used to calculate the intensity of random magnetic field. The shape of the vertical profile is poorly constrained. We have used exponential profile of the random component of the magnetic field, which is compatible with presently available data.

In the present work, we have used the following form of diffusion coefficient to study the CR propagation in the Milky Way Galaxy.
\[ D(\rho, z) = \beta^\eta D_0 \left( \frac{\rho}{\rho_0} \right)^\delta \exp \left( \frac{z}{z_t} \right), \quad (2.2) \]

where, \( \rho \) being the rigidity, \( z \) is the vertical height above the Galactic plane and \( \delta \) denotes the power law index. \( z_t \) and \( \beta \) are Galactic halo height and dimensionless particle velocity respectively. The power \( \eta \) of \( \beta \) accounts for the uncertainties that arise due to propagation of CRs at low energies [71]. \( D_0 \) denotes the normalisation of diffusion coefficient and \( \rho_0 \) is the reference rigidity. Also note that, to avoid the boundary effects, we set \( L = 3z_t \) in our work [47]. The z-component of diffusion coefficient and the turbulent magnetic field are related by

\[ D(z)^{-1} \propto B_{\text{turbulent}}(z) \propto \exp(-z/z_t). \quad (2.3) \]

In our study, we have used injection spectra of protons and heavy nuclei in the following form [72]:

\[ \frac{dN^k}{d\rho} \propto \begin{cases} \left( \rho/\rho_{br,1}^k \right)^{-\alpha_1^k} & \rho \leq \rho_{br,1}^k \\ \left( \rho/\rho_{br,2}^k \right)^{-\alpha_2^k} & \rho_{br,1}^k < \rho < \rho_{br,2}^k \\ \left( \rho/\rho_{br,2}^k \right)^{-\alpha_3^k} \left( \rho_{br,1}^k/\rho_{br,2}^k \right)^{-\alpha_2^k} & \rho_{br,2}^k \leq \rho \end{cases} \quad (2.4) \]

In DRAGON, \( \alpha_1^k, \alpha_2^k, \alpha_3^k, \rho_{br,1}^k, \rho_{br,2}^k \) are free parameters, which have been tuned to fit the observed CR spectra. In the above relation, \( k \) denotes protons and heavy nuclei \((k = 1, 2, ..., 14)\), whose spectra, we assumed to be similar in our case. Similarly, for electron injection spectra, we use a similar form:

\[ \frac{dN^e}{d\rho} \propto \begin{cases} \left( \rho/\rho_{br,1}^e \right)^{-\alpha_1^e} & \rho \leq \rho_{br,1}^e \\ \left( \rho/\rho_{br,2}^e \right)^{-\alpha_2^e} & \rho_{br,1}^e < \rho < \rho_{br,2}^e \\ \left( \rho/\rho_{br,2}^e \right)^{-\alpha_3^e} \left( \rho_{br,1}^e/\rho_{br,2}^e \right)^{-\alpha_2^e} & \rho_{br,2}^e \leq \rho \end{cases} \quad (2.5) \]

We also need to take into account the solar modulation effect which is dominant below 10 GeV. In accordance with the force-field approximation, we have modelled the solar modulation with a potential \( \phi \) such that the observed spectrum can be modified by a factor [73],

\[ \epsilon(E_k, Z, A, m_Z) = \frac{(E_k + m_Z)^2 - m_Z^2}{(E_k + m_Z + \frac{Zq}{A} \phi)^2 - m_Z^2} \quad (2.6) \]

where \( q \) is the electronic charge unit, \( m_Z \) is the mass of the nucleus having atomic number \( Z \) and mass number \( A \), and \( E_k \) is the kinetic energy of the nucleus. Similarly, for electron and positron, the factor will take the form,

\[ \epsilon(E_e, m_e) = \frac{(E_e + m_e)^2 - m_e^2}{(E_e + m_e + \phi)^2 - m_e^2} \quad (2.7) \]

where \( E_e \) is the energy of the electron-positron, \( m_e \) is the mass of the electron or positron and \( \phi \) is the solar modulation potential.
2.2 Distribution of Galactic Molecular Clouds

We use the catalog of GMCs from Rice et al. [42], where they presented a list of 1064 clouds, by using a dendogram-based decomposition of a previous most uniform, large-scale all-Galaxy CO survey [74]. The objects are distributed in the Galactic disk between $180^\circ > l > 13^\circ$ and $348^\circ > l > 180^\circ$ within $-5^\circ < b < 5^\circ$, widely spread in the Galaxy covering distances from the GC from $\sim 1$ to $\sim 16$ kpc. Using the information of the Galactic latitude ($b$) and longitude ($l$) from the catalog, we can calculate the positions of the clouds in the Galaxy in galactocentric coordinate system. We use the equations from [42, 75, 76], taking into account that the Sun is at $z_0 \sim 25$ pc above the Galactic plane. The equations are

\begin{align*}
    x_{\text{gal}} &= R_0 \cos \theta - d_\odot (\cos l \cos b \cos \theta + \sin b \sin \theta), \\
    y_{\text{gal}} &= -d_\odot \sin l \cos b, \\
    z_{\text{gal}} &= R_0 \sin \theta - d_\odot (\cos l \cos b \sin \theta - \sin b \cos \theta),
\end{align*}

where, $\theta = \sin^{-1} \frac{z_0}{R_0}$, $R_0 = 8.34$ kpc is the distance of the Sun from the GC, $d_\odot$ is the kinematic distance of the individual clouds from the Sun. Positional distribution of these clouds are given in figure 1.

Generally, by tracing the CO emission in the Galaxy and multiplying the CO emissivity with the CO-to-$\text{H}_2$ conversion factor, the gas density of molecular hydrogen is modeled [55, 56, 61–63]. It can be seen that the molecular clouds taken from the catalog, predominantly resides in the Galactic plane. We consider only radial distribution of the GMCs. We assume concentric circles of constant bin size of 100 pc, centered at the GC, and build histograms for the number of GMCs residing in each bin in the Galactic plane, covering the radial distance from the GC to the outermost edge of the Galaxy. The region adjacent to the GC (within $12^\circ$) is excluded in the catalog in use [42], hence there is a large wedge shaped gap between the first and fourth quadrant. The histograms give us the variation of the number of GMCs with radial distance. Then we have fitted the distribution of histograms with two Gaussian distribution functions, the inner region with radius extending from 1 kpc to 8 kpc, and the outer region with radius from 8 kpc to 16 kpc are shown by shaded regions in Figure 2.

We have taken the concentric circular regions starting from 1 kpc, because the region near the GC has been excluded in the catalog we are using. The Gaussian radial distribution function has the general form $N(r) = \frac{a}{\sigma \sqrt{2\pi}} e^{-\frac{(r-\mu)^2}{2\sigma^2}}$, where $\sigma$ is the variance, $\mu$ is the mean, ‘a’ is the normalisation factor. Integrating $N(r)$ radially one gets the total number GMCs within the inner and outer regions. The fit parameters, for 100 pc bin size, are given in the following Table 1. Although, the two Gaussian distributions overlap in Figure 2, the GMCs in the overlapping region are not double counted in our calculations as we have used different ranges in the values of the radial distance, $1 < r \leq 8$ kpc for the GMCs used from the first Gaussian distribution and $8 < r \leq 16$ kpc from the second Gaussian distribution.

In order to obtain the radial, average $n_{\text{H}_2}$ gas density profile in our Galaxy, we have used the following expression,

\begin{equation}
    n_{\text{H}_2}(r) = \langle n_{\text{H}_2} \rangle \times \left( \frac{N(r)}{N_{\text{total}}} \right),
\end{equation}

where $N_{\text{total}}$ is the total number of GMCs in the Galaxy.
Figure 1. Upper panel: All sky map of the GMCs taken for this work from Rice et al. catalog [42]. Lower panel: Positional distribution of the GMCs in a 2D X-Y plane.
best fit for 1 to 8 kpc range
best fit for 8 to 16 kpc range
number histogram with bin size = 100 pc

Figure 2. Radial number profile of GMCs in Galaxy. The red shaded region, bounded by red solid Gaussian distribution fit depicts the radial number profile for the region 1 to 8 kpc, and the blue shaded region, bounded by blue dotted Gaussian distribution fit depicts the radial number profile for the region between 8 to 16 kpc.

where \( N(r) \) represents the Gaussian distribution fits for the number of GMCs in the inner and outer circular regions, \( N_{\text{total}} \) is total number GMCs considered in the catalog, and \( <n_{\text{H}_2}> \) is the average number density. The number density generally considered for GMCs is \( \sim 100 \, \text{cm}^{-3} \) [77]. Since we have essentially smoothed out each discrete clumps of GMCs into a radially, continuous distribution of molecular hydrogen, ranging from \( \sim 1 \, \text{kpc} \) to \( \sim 16 \, \text{kpc} \), the average density of the distribution is taken as \( <n_{\text{H}_2}> \sim 10 \, \text{cm}^{-3} \).

The inclusion of vertical distribution of GMCs does not affect the density distribution used in our study, since all the GMCs considered in this work reside near the Galactic plane as previously stated. The secondary particle production in these GMCs during propagation of CRs is considered in our CASE 2.

3 Contributions from neaby, sub-Kpc GMCs

After combining CASE 1 and CASE 2 we find that the total positron flux is insufficient to fit the observed data. Hence, in order to fit the observed flux, we consider the contributions of nearby GMCs (\( d < 500 \, \text{pc} \)), which is defined as CASE 3 previously. GMCs are dense reservoirs of cold protons in the ISM. When primary CR protons injected from the SNRs propagate through these clumps of cold protons, gamma rays and leptons are produced by hadronic interactions (\( pp \)). Also, antiprotons are expected to be produced in interactions of CR protons and nuclei with cold protons.

We include three nearest GMCs Taurus, Lupus and Orion A, which act as local sources of secondary CRs, and contribute to the total fluxes of leptons, antiprotons and gamma rays.
Table 2. GMC parameters: Galactic coordinates (l, b), masses M, distances from the Earth (d), Galactocentric distance ($R_{GC}$) and the B parameter from [78] and references therein.

| Cloud   | l (deg) | b (deg) | Mass ($10^5 M_\odot$) | d (kpc)       | $R_{GC}$ (kpc) | B     |
|---------|---------|---------|------------------------|--------------|----------------|-------|
| Taurus  | 171.6   | -15.8   | 0.11                   | 0.141±0.007  | 8.4            | 5.6   |
| Lupus   | 338.9   | 16.5    | 0.04                   | 0.189±0.009  | 8.2            | 1.0   |
| Orion A | 209.1   | -19.9   | 0.55                   | 0.43±0.02    | 8.4            | 3.0   |

Table 3. The spectral indices and CR proton densities at 10 GeV derived from the gamma ray and CO data at the location of the clouds [78], errors on the normalisation result from the sum in quadrature of the statistical error deriving from the fit and the 30% uncertainty on the B parameter (see Table III of [78]).

| Cloud   | $\rho_{0,CR}$ $10^{-12}$ GeV$^{-1}$ cm$^{-3}$ | $\alpha$ |
|---------|---------------------------------------------|----------|
| Taurus  | 1.43 ± 0.5                                  | 2.89 ± 0.05 |
| Lupus   | 1.09 ± 0.4                                  | 2.74 ± 0.1  |
| Orion A | 1.55 ± 0.5                                  | 2.83 ± 0.05 |

We note that these clouds are not included in the catalog of Rice et al. [42]. These three clouds represent the Gould Belt complex, and being our nearest GMCs, they contribute significantly to the positron and electron flux. The gamma ray analysis of these clouds was done in detail in [78]. Previously, Taurus and Orion A were studied in [79, 80], while Lupus was studied for the first time in [78]. Following the definition given in [78] $B \equiv M_5 \frac{d}{d_{kpc}}$, where $M_5 = \frac{M}{10^5 M_\odot}$ and $d_{kpc} = \frac{d}{1kpc}$, M is the mass of the clouds, d is the distance of these three clouds from the Earth and $M_\odot$ is the solar mass, these three clouds from the Gould Belt complex have ‘B’ parameter sufficiently higher than 1, which makes them detectable by Fermi-LAT. The position coordinates, masses, distances from the Earth and GC, values of the parameter ‘B’ of these three clouds are given in Table 2.

The gamma ray fluxes produced in these GMCs in pp interactions through the production of neutral pions and their subsequent decay have been calculated in [78] and fitted to Fermi LAT data. They have calculated the parent CR proton density spectrum $J_p(E_p)$ for each of these clouds by fitting the observed gamma ray spectrum,

$$J_p(E_p) = \rho_{0,CR} \left(\frac{E_p}{E_0}\right)^{-\alpha}$$

where $\rho_{0,CR}$ is the normalisation constant, $E_0 = 10$ GeV is the reference energy, and $\alpha$ is the spectral index. The values for CR proton density $\rho_{0,CR}$ at 10 GeV and spectral index $\alpha$, for the three GMCs used in our work are given in Table 3.

In pp interactions charged pions are produced along with neutral pions, which subsequently decay to charged muons. Electrons and positrons are produced from decay of these charged muons. We have calculated the electron and positron fluxes produced in these three GMCs from pp interactions following the formalism given in [81] and using the proton density spectrum given in [78]. We note that if we include more GMCs which are further away from the Earth and away from the Galactic plane our result does not change significantly, as the effect of the nearest GMCs is most dominant on the electron and positron fluxes.
The magnetic field inside the GMCs is higher compared to the mean interstellar magnetic field [82]. The secondary electrons and positrons produced in nearby GMCs are expected to lose energy before they are injected into the ISM. The radiative loss of higher energy leptons is more than the lower energy ones, as a result we expect an exponential cut-off in their spectrum at high energy.

The injection spectra is expressed as a power law in Lorentz factor of the injected electrons and positrons $\gamma_e = E_e/m_e c^2$,

$$Q(\gamma_e, d) = Q_0 \gamma_e^{-\beta_e} \exp \left( -\frac{\gamma_e}{\gamma_{e,c}} \right) \delta(d)$$

where the cut-off Lorentz factor $\gamma_{e,c} = E_{e,c}/m_e c^2$, unit of $Q_0$ is $GeV^{-1} s^{-1}$, $d$ is the distance of each cloud from the observer and the Dirac delta function in this case signifies that we are considering point sources. During propagation in the ISM for time scales ($t$) less than $10^7$ years, the dominant radiative loss processes of relativistic electrons and positrons are synchrotron and inverse Compton (IC) scattering. The formalism for including the propagation effects by solving the transport equation including radiative losses and diffusion has been discussed in [83]. The expression for IC and synchrotron energy loss term $p_2$ has been used from [83],

$$p_2 = 5.2 \times 10^{-20} \frac{w_0}{c^2} s^{-1}$$

where $w_0 = w_B + w_{MBR} + w_{opt}$, $w_B$ is the energy density of the magnetic field, $w_{MBR}$ is microwave background radiation energy density, $w_{opt}$ is energy density of optical-IR radiation in interstellar space. For our study, we assume $w_0 \approx 1 eV cm^{-3}$.

The diffusion term has been included following [83],

$$D(\gamma_e) = D_0 \left( 1 + \left( \frac{\gamma_e}{\gamma_{e,*}} \right) \right)$$

Thus $D$ is constant for $\gamma_e << \gamma_{e,*}$, and energy dependent for $\gamma_e \geq \gamma_{e,*}$, where $\gamma_{e,*} = E_{e,*}/m_e c^2$.

For point sources emitting continuously with a constant rate during the time $0 \leq t' \leq t$, we get the following energy spectrum,

$$f_{st}(d, t, \gamma_e) = \frac{Q_0 \gamma_e^{-\beta_e}}{4 \pi D(\gamma_e) d} \frac{d}{2 \sqrt{D(\gamma_e) t_{\gamma_e}}} \exp \left( \frac{-\gamma_e}{\gamma_{e,c}} \right)$$

where $t_{\gamma_e} = \min(t, \frac{a}{p_2 \gamma_e})$ and $a = 0.75$ [83], in our case $t >> \frac{a}{p_2 \gamma_e}$.

The electron and positron flux from nearby GMCs after including solar modulation effect is,

$$J_{e, \text{obs}}(\gamma_e) = \epsilon(E_e, m_e) \left( \frac{c}{4 \pi} \right) f_{st}(d, t, \gamma_{e, sm})$$

where $\gamma_{e, sm} = (E_e + \phi)/m_e c^2$, is the modified Lorentz factor. The values of the relevant parameters used to calculate the secondary electron and positron fluxes from these three nearby GMCs are listed in Table 6. Using equation (3.6), we calculate the total $e^\pm$ fluxes from the three nearby GMCs, which is our CASE 3. The antiproton fluxes produced in these GMCs are calculated using the formalism discussed in [84]. Finally, we add the CR fluxes from CASE1, CASE 2 and CASE 3 to fit the observational data.
4 Results and Discussions

We have used the plain diffusion (PD) model to study CR propagation with the DRAGON code assuming the sources follow SNR distribution [49]. This model includes diffusion and interactions of CRs without any effect of reacceleration or convection. In our analysis, we have fitted the observed CR data in the following way.

We have fixed $z_t$ to a favourable value [47], and then subsequently set $B_{turbulent}^0$ using equation (2.1). We have fixed the value of the reference rigidity ($\rho_0$) and adjusted the normalisation ($D_0$), $\delta$ and $\eta$ to get a good fit to the observed data of B/C ratio. Then the spectral indices and breaks of the injected CR spectra are adjusted to get a good fit to the observed proton data given by AMS-02 and PAMELA. We also get a fit for the CR antiprotons (\bar{p}) using the same parameters.

Then we adjust the injection spectrum of primary electrons given by broken power-law to get a good fit to the data. The CR protons and heavy nuclei interact with neutral and ionised hydrogen gas in ISM (CASE 1) and molecular hydrogen in GMCs in the Galactic plane (CASE 2), producing secondary electrons and positrons.

We have used the catalog of GMCs near the Galactic plane from [42], which consists of 1064 GMCs. We have taken bin size of 100 pc in radial distance to build histograms for the number of GMCs in each bin. We have considered two ranges in the radial distance from the GC. The histograms in the range of 1 kpc to 8 kpc are fitted with one Gaussian distribution, and the other histograms in the range of 8 kpc to 16 kpc are fitted with another Gaussian distribution. These distributions are used with average number density of hydrogen molecules $<n_{H_2}> \sim 10 \text{ cm}^{-3}$. Instead of discrete clumps of GMCs we have assumed continuous distribution of matter along the Galactic plane, due to this reason the number density of hydrogen molecules is lower than typical density of hydrogen molecules in GMCs [77].

Electron spectrum is dominated by primary CR electrons, they are included in our CASE 1. We add up the contributions from CASE 1 and CASE 2 to obtain a good fit to the electron and positron spectra. CR positrons require more nearby sources to explain the observed data. We consider the contribution of CR interactions in GMCs close to the Earth (CASE 3), which are not included in [42]. We have considered three GMCs, Taurus, Lupus and Orion A, which are closest to the Earth. If we include more GMCs which are further away, our result does not change significantly. We also have to add an extra component, which traces Ferriere SNR distribution [49], to get a better fit at higher energies for both electron and positron fluxes. The values of the parameters used for the extra components are shown in Table 5. The CR electrons and positrons may originate from different sources as electrons are mostly primary particles and positrons are secondaries produced in interactions of CR protons and nuclei. Due to this reason the extra components may not be the same for electrons and positrons.

We have plotted the proton flux and B/C ratio of fluxes, along with with observational data from AMS-02 and PAMELA, in figure 3. The blue solid (dashed) line corresponds to solar modulated (unmodulated) fluxes. All the values of the parameters used in CR propagation are displayed in Table 4. Our Table 6 shows the values of the parameters used to calculate the secondary electron and positron fluxes from the nearby GMCs, Taurus, Lupus and Orion A.

In figure 4 the electron and positron fluxes calculated in this work are plotted with their observed data from AMS-02 and PAMELA. The black line shows the total flux after adding CASE 1, CASE 2 and CASE 3. The red line shows the contribution from GMCs,
| Model/Parameter | Option/Value |
|-----------------|--------------|
| $R_{\text{max}}$ | 16.0 kpc     |
| $z_t$           | 4.0 kpc      |
| $L$             | 12.0 kpc     |
| HI gas density type | [52, 53, 57] |
| HII gas density type | [60] |
| $H_2$ gas density type | Equation (2.9) |
| Source distribution | Ferriere |
| Diffusion type | Exponential (see equation (2.2)) |
| $D_0$          | $1.1 \times 10^{29}$ cm$^2$/s |
| $\rho_0$       | 4.0 GV       |
| $\delta$       | 0.5          |
| $\eta$         | -0.40        |
| $v_A$          | 0            |
| $v_w$          | 0            |
| $\frac{dv_w}{dz}$ | 0          |
| Magnetic field type | Pshirkov |
| $B_{\text{disk}}^0$ | $2 \times 10^{-6}$ Gauss |
| $B_{\text{halo}}^0$ | $4 \times 10^{-6}$ Gauss |
| $B_{\text{turbulent}}^0$ | $7.5 \times 10^{-6}$ Gauss (see equation (2.1)) |
| $\alpha_k^1/\alpha_k^2/\alpha_k^3$ | 1.7/2.3/2.35 |
| $\rho_{br,1}^k/\rho_{br,2}^k$ | 5/140 GV |
| $\alpha_s^1/\alpha_s^2/\alpha_s^3$ | 1.9/2.77/2.4 |
| $\rho_{br,1}^s/\rho_{br,2}^s$ | 8/65 GV |
| $\rho_{c}^s$ | 10 TeV       |
| $\phi$         | 0.564 GV     |

Table 4. Models and parameter values selected in PD model to fit the observed CR spectra, using DRAGON, are listed in this table. The parameters used here have been discussed before. $D_0$ in this case is the diffusion coefficient normalisation constant used for (CASE 1 + CASE 2). $v_A$ is the Alfven velocity, $v_w$ is the wind or convection velocity, $\frac{dv_w}{dz}$ is vertical gradient of convection velocity.

which includes CASE 2 and CASE 3. Blue line solid (dashed) corresponds to modulated (unmodulated) fluxes from CASE 1 and CASE 2, note that for electrons this also includes the primary electrons. In the right panel of figure 4 the positron flux is shown. The contribution from GMCs when added to the flux from CASE 1, the total flux does not require any extra component (yellow line) to fit the observed data except near the peak. Near the peak also the contribution of GMCs is more than the extra component.

In figure 5, positron fraction based on our model is plotted against the observational data given by AMS-02 and PAMELA. In the right panel, the antiprotons flux has been plotted along with data from AMS-02 and PAMELA. The scenario presented in this work explains the CR data quite well. Moreover, anisotropy in lepton flux is insignificant in our model even at very high energy as there are multiple sources in different locations.
Table 5. Table for values of the parameters for the modelling of the extra components in our study. The extra electron component injected is assumed to follow a simple power-law with spectral index $\alpha_{1}^{\text{extra},e}$. The extra positron component injected is assumed to be a broken power-law with spectral indices $\alpha_{1}^{\text{extra},e^{+}}$ and $\alpha_{2}^{\text{extra},e^{+}}$ below and above the break in rigidity at $\rho_{br,1}^{\text{extra},e^{+}}$.

| Parameter          | Value     |
|--------------------|-----------|
| $\alpha_{1}^{\text{extra},e}$ | 2.1       |
| $\alpha_{1}^{\text{extra},e^{+}}/\alpha_{2}^{\text{extra},e^{+}}$ | 0.5/2.6   |
| $\rho_{br,1}^{\text{extra},e^{+}}$ | 400 GV    |

Table 6. Table for the parameters used to calculate total $e^{\pm}$ flux observed on Earth from three selected clouds. Parameters: $Q_{0}$ is injection normalisation constant, $\beta_{c}$ is the spectral index for $e^{\pm}$ injection from the GMCs, $D_{0}$ is the diffusion coefficient normalisation constant, $\delta$ is the diffusion index, $E_{e^{\ast}}$ is reference energy for diffusion coefficient, $E_{e,c}$ is the cutoff energy, $\phi$ is the solar modulation potential. $D_{0}$ in this case, is the diffusion coefficient normalisation constant used for CASE 3.

| Cloud    | $Q_{0}$ [GeV$^{-1}$s$^{-1}$] | $\beta_{c}$ | $D_{0}$ [cm$^{2}$/s] | $E_{e^{\ast}}$ [GeV] | $\delta$ | $E_{e,c}$ [GeV] | $\phi$ [GV] |
|----------|-------------------------------|-------------|---------------------|----------------------|----------|----------------|-----------|
| Taurus   | $1.5 \times 10^{44}$          | 2.83        | $3.7 \times 10^{29}$ | $5 \times 10^{8}$    | 0.5      | $5 \times 10^{3}$ | 0.564     |
| Lupus    | $2 \times 10^{43}$            | 2.72        | $3.7 \times 10^{29}$ | $5 \times 10^{3}$    | 0.5      | $5 \times 10^{3}$ | 0.564     |
| Orion A  | $7 \times 10^{44}$            | 2.81        | $4.5 \times 10^{29}$ | $5 \times 10^{3}$    | 0.5      | $5 \times 10^{3}$ | 0.564     |

Figure 3. Left panel: Proton flux calculated using DRAGON code, and plotted with the observational data given by AMS-02 [12] and PAMELA [85]. Right panel: B/C ratio plotted against the observational data reported by AMS-02 [14] and PAMELA [86]. Solid (dashed) line is for solar modulated (unmodulated) flux.

5 Summary and Conclusion

The CR positron flux measured in GeV$^{2}$ m$^{-2}$ sec$^{-1}$ sr$^{-1}$ rises with energy and peaks near 200 to 300 GeV. CR positrons are secondary particles produced in interactions of CR protons and heavy nuclei with hydrogen gas in ISM, and also in GMCs. It is difficult to explain the rise in CR positron flux unless there are sources close to the Earth. Earlier, pulsars and DM have been suggested as the origin of the rising positron flux or excess. In this work we discuss a self-consistent scenario of CR propagation, where CR positrons are produced in nearby...
Figure 4. Left panel: Electron flux calculated using DRAGON code, and plotted with the observational data given by AMS-02 [20] and PAMELA [87]. Solid (dashed) blue line is the solar modulated (unmodulated) total flux for (CASE 1 + CASE 2), yellow line is flux due to extra component considered. Red line shows the total flux for (CASE 2 + CASE 3). Black line corresponds to the total flux for CASE 1 + CASE 2 + CASE 3. Right panel: Positron flux plotted against the observational data reported by AMS-02 [21] and PAMELA [88]. Line styles used are same as in Left panel.

Figure 5. Left panel: Positron fraction calculated using DRAGON code, and plotted with the observational data given by AMS-02 [21] and PAMELA [88]. Right panel: Antiproton flux plotted against the observational data reported by AMS-02 [15] and PAMELA [89, 90]. Pink, green and brown lines show the antiproton fluxes from Orion A, Taurus and Lupus respectively without the effect of solar modulation. Black line is the total Antiproton flux.

GMCs in CR interactions and contribute significantly to the observed positron excess. In this scenario the CR interactions in ISM, in GMCs in Galactic plane and also nearby GMCs together explain the positron excess with a small contribution from extra component near the peak. CR proton and antiproton fluxes, B/C ratio, electron, positron fluxes and positron fraction calculated using our model fit well to the observed data from AMS02 and PAMELA experiments. Thus we conclude that nearby GMCs may play an important role in explaining the positron excess.

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