Contribution of supernova remnants to the cosmic-ray electron AMS-02 data

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Abstract. The Alpha Magnetic Spectrometer (AMS-02) experiment on board of the International Space Station is revolutionizing our understanding of cosmic rays. AMS-02 Collaboration has released the most precise data for several cosmic-ray species ever. Electrons are among the rarest cosmic particles and have been measured between 0.5 and 1000 GeV by AMS-02 with very high precision. This paper explores the possibility that the origin of cosmic-ray electrons is associated with the acceleration of particles from supernova remnants. In this paper we calculate the flux of cosmic electrons from two nearby and radio bright sources in our Galaxies: Vela and Cygnus supernova remnants. We concluded that they contribute at the few percent level at 1 TeV. Finally, we calculate the flux of other bright sources taken from radio catalog of supernova remnants, finding that their cumulative contribution is about 10% at 1 TeV. Further exploration of the AMS-02 data could lead to the conclusion that supernova remnants are among the important accelerators of cosmic-ray electrons in the galaxy.

1. Introduction
Cosmic rays have been discovered in 1911 by Victor Hess by flying with a balloon at tens of km of altitude from the ground. He shared the Nobel prize in 1936 together with Philip Warren Anderson for the discovery of cosmic rays [1]. He used an electrometer to measure the ionization rate and surprisingly, he found that it was constantly increasing with altitude. This was a surprising measurement since at that time particles were thought to be produced only from radioactive material. After other experiments confirmed this result, several physicists proposed that the origin of this ionization rate was due to particles coming from outside the Earth.

Cosmic rays are measured in energy with units of the electron volt (eV), that is defined as the energy gained by an electron by being accelerated under a voltage of 1 V.
Cosmic rays can be produced with energies between MeV and $10^{21}$ eV and they are of Solar, Galactic and extragalactic origin. In particular cosmic rays below 1 GeV comes mostly from the nuclear reactions that take place in the Sun. Cosmic particles with energies between 1 GeV and one million of GeV are of Galactic origin and are primarily accelerated from supernova remnants. Instead, above that threshold particles come primarily from other Galaxies. Cosmic rays are also divided into primary, if they are accelerated from astrophysical sources and injected into the interstellar space, and secondary if they are produced from primaries that collide against atoms of the interstellar medium. Examples of primary cosmic rays are protons and helium while positrons, antiprotons and boron nuclei are mostly of secondary origin.

Galactic cosmic rays are among the most interesting to study since they give us important information on the structure of our Galaxy and on the acceleration mechanism of Supernova Remnants which are among the most efficient accelerators of particles in the Galaxy. These sources accelerate cosmic rays with the so-called Fermi mechanism, that is also labeled as diffuse shock acceleration. In this process the non-relativistic shock wave of the supernova remnant accelerates particles in the shock wave that propagates in the interstellar medium. The particles are trapped inside the shock wave due to the magnetic fields present there until they reach a maximum energy above TeV and they are released in the interstellar medium [12].

Moreover, Galactic cosmic rays could provide important information and the first hints of the interaction of dark matter. This is a mysterious form of matter that constitutes the 80% of the matter in the Universe and that is distributed in Galaxies with huge spherical halos of the size of 100-200 kpc. Dark matter has been detected so far only through the gravitational effects and no signatures of their particles’ interactions have been measured so far (see [2] for a review). Cosmic-ray data are very promising to detect dark matter because these elusive particles could annihilate or decay into particles of the Standard model, as electrons, positrons, protons and so on, and being detected as cosmic particles by our experiments.

The Alpha Magnetic Spectrometer (AMS-02) experiment on board of the International Space Station is revolutionizing our understanding of Galactic cosmic rays. AMS-02 Collaboration have released the most precise data for several cosmic-ray species ever such as protons, helium, nuclei or positrons and electrons [3]. Electrons are among the rarest cosmic particles and have been measured between 0.5 and
1000 GeV by AMS-02 [4]. The origin of cosmic-ray electrons is probably associated to the acceleration of particles from supernova remnants but the exact contribution of individual sources is still not well established.

In this paper, we calculated the flux of cosmic electrons from two nearby and radio bright sources in our Galaxies: Vela and Cygnus supernova remnants. We calculated that they contribute at the few per cent level at 1 TeV. Finally, we calculate the flux of other bright sources finding that they cumulative contribution is at the per cent level too. For this last part, we select sources from the Green catalog of supernova remnant which one of the most updated catalogs of these sources. The contribution of all the supernova remnants considered is about 10% at 1 TeV meaning that supernova remnants are certainly the dominant contributor of electrons in the Galaxy.

2. Model

In order to calculate the flux of electrons, we solve the differential equation for the propagation of cosmic rays [14]:

\[ \frac{d}{dt} N = Q(E, x, t) \]

\[ \partial_t N - \nabla \cdot \{ K(E) \nabla N \} + \partial_E \{ \frac{dE}{dt} N \} = Q(E, x, t) \]  

\( N \) represents the electron number density as a function of energy \( E \), at the location in the Galaxy \( x \) and time \( t \). \( N \) can be written as \( N = N(E, x, t) \equiv \frac{dn}{dE} \).

\( K(E) \), it is the energy-dependent diffusion coefficient, assumed to be isotropic and homogeneous. The term \( dE/dt \) represents the energy losses that describe the loss of energy of cosmic rays while traveling in the Galaxy. Combining these three terms together we get the source term \( Q \) that reflects the property of Galactic source (supernova remnants), specifically is the number of electrons and positrons that are emitted from the source. Therefore, the propagation equation calculates the density of cosmic rays at any given location in the Galaxy, time and energy for particles produced initially by the source with a given flux \( Q(E) \). In our model, the convection and reacceleration are neglected since we only consider high-energy particles.

The process of propagation contains energy losses and diffusion due to magnetic fields in the galaxy. Energy losses are induced by two processes, Synchrotron Radiation and Inverse Compton scattering (ICS). Besides the influence of inverse Compton scattering, there are other factors that cause the losses of energy, including bremsstrahlung, ionization losses and coulomb scattering. Bremsstrahlung also called braking radiation, occurs when an electron or a positron is accelerated by the electric fields associated with interstellar ions or nuclei. Ionization losses are relativistic charged particles moving through a material medium interact with electrons belonging to atoms in that same material. Coulomb scattering represents coulomb collisions in a completely ionized plasma are dominated by scattering off the thermal electrons. However, these additional processes are negligible for high-energy electrons.

Synchrotron radiation produces radio waves emitted by charged particles moving in magnetic fields. While cosmic rays are moving through the galaxy, any charged particle which moves in a curved path or is accelerated in a straight-line path will emit electromagnetic radiation. The energy losses for Synchrotron radiation can be describe with the following equation [14]:

\[ \frac{dE}{dt} = 4 \sigma_T c U_B y^2 \beta^2 \sim 2.53 \times 10^{-18} \left( \frac{B}{\mu G} \right)^2 \left( \frac{E}{GeV} \right)^2 GeV s^{-1}. \]  

In the equation, \( \sigma_T \) represents the Thomson cross section, and \( U_B \) is the total energy density of the electric field proportional to the square of the Galactic magnetic field \( U_B = B^2/(8\pi) \).

The Inverse Compton scattering is the process that takes place when electrons interact with the Interstellar radiation field present in the galaxy. When electron collide with these low-energy photon, X-ray and gamma rays will be produced.
Inverse Compton scattering takes place when highly relativistic electrons and positrons scatter with low energy photon fields. Because of this process leptons lose a part of their energy and photons are up scattered into high-energetic γ rays. We take into account highly energetic electrons which scatter against photons constituted by the Galactic ISRF. The energy-loss rate for an electron with an initial energy $E_0$ and a final energy $E_1$ (after ICS) is expressed in the following way [14]:

$$\frac{dE}{dt} = \int_0^\infty d\epsilon_i \int_{\epsilon_i}^\infty d\epsilon_f (\epsilon_f - \epsilon_i) \times \frac{dN_{colt}}{dtd\epsilon_i d\epsilon_f}.$$  \hspace{1cm} (4)

In the equation, the term $\frac{dN_{colt}}{dtd\epsilon_i d\epsilon_f}$ is the collision rate of electrons and photons. $\epsilon_i$ and $\epsilon_f$ are the initial and final energies of the photon. We show in figure 2 the energy losses for Inverse Compton on the three components of the Interstellar radiation field and for Synchrotron radiation.

![IC/Synchrotron electron energy losses (GC)](image)

**Fig.2**: This figure represents the energy losses for electrons and positron with respect to their energies. The energy losses are reported for Synchrotron emission (brown solid line), inverse Compton scattering on CMB (green dashed line), infrared (red dashed line) and starlight (blue dashed line). The total energy losses for inverse Compton scattering are reported with the black dotted line.

Looking to the figure 2 we see that we can approximate the total energy losses with:

$$\frac{dE}{dt} = 10^{-16} E^2 GeV/s.$$  \hspace{1cm} (5)

By calculating the energy losses, we can calculate the final energy for an electron with initial energy $E_0$ for a source with age $T$ and with energy losses parametrized as $dE/dt = b_0E^{\alpha}$:

$$E_1 = -(b_0T(-\alpha + 1) - E_0^{-\alpha+1})/(-\alpha + 1).$$  \hspace{1cm} (6)

Reversing equation 5 we can calculate the initial energy of a supernova remnant with the final energy detected on earth.

Another propagation process that is important for electrons and positrons is the diffusion. The diffusion takes into account how electrons and positrons travel in the irregularities of the Galactic magnetic field. It can be parametrized as:

$$K(E) \equiv \beta K_0 \left(\frac{R}{1 GeV}\right)^{\delta} \equiv K_0 e^{\delta}.$$  \hspace{1cm} (7)

In the equation, $K_0$ is the normalization of the diffusion coefficient and $\beta$ is the slope. $K_0$ and $\beta$ are found by fitting AMS-02 data for protons, helium and B/C ratio. Below we show the fit to the proton and helium data measured by AMS-02 and to the Boron over carbon ration. These are the data used to find the values of the diffusion coefficient parameters. We use the model in reference [12].
To solve the differential equation of propagation of cosmic rays, we thus define the energy losses and diffusion coefficients using simple power-laws:

\[ b(E) \equiv b_0 e^{\alpha E} = \frac{b_0}{\tau_k} e^{\alpha E} \]  

With \( \epsilon = \frac{E}{E_0} \), \( K_0 \) and \( b_0 \) are the normalization of the diffusion coefficient and the energy-loss rate, respectively, that carry the appropriate dimensions, and \( \tau_k \) is the characteristic energy-loss time.

We use \( \lambda \) to describe the propagational length of electrons due to energy losses and diffusion:

\[ \lambda^2 \equiv 4 \int dE' \frac{K(E')}{b(E')} \]  

The propagation length has the dimension of a length squared \( \lambda^2 \) = \( [E \cdot L^2/T / (E/T)] \). Therefore, by taking the square of \( \lambda^2 \) we have the physical distance traveled by an electron emitted with an initial energy \( E_s \) to reach a final energy \( E \).

By assuming that the diffusion and the energy losses are homogeneous in the Galaxy and that they are parametrized as in Eq. (8), we solve the equation of propagation through the green function [14,15]:

\[ G(x, E \leftarrow x_s, E_s) = \frac{1}{b(E)(\pi \lambda^2)^2} \exp \left\{ -\frac{(x_s-x)^2}{\lambda^2} \right\}. \]  

The green function describes the probability of a particle with initial energy \( E_s \) from position \( x_s \) that could reach earth the locates at \( x \) with a final energy \( E \). The term “\( x_s - x \)” is the distance between the source and earth. Using the Green function formalism, we can write the flux of electrons on Earth as [14,15]:

\[ \Phi(\epsilon, x) = \frac{\rho e}{4\pi} \times \int \int \int dE_x d^3 x G(E_x, x, t) \]  

These three integrals can be calculated analytically by assuming, as we do in this paper that the diffusion and energy losses are homogenous and isotropic in the Galaxy. Moreover, we are assuming the burst-like scenario for which particles are emitted at the time of the supernova explosion. Therefore, the source term is modelled as:

\[ Q(E, x, t) = Q(E) \delta(t) \delta(x). \]  

Where the two delta functions take into account that the source emits particles in a specific location of the Galaxy \( x \) and at a specific time \( t \).

Using these assumptions, the flux of electrons on Earth can be calculated as [14,15]:

Fig.3: Left panel represents the ratio of the flux of boron over carbon as measured by AMS-02 [13] together with the best fit and 1 sigma error for the fit with a cosmic-ray model from reference [12]. Right panel shows the graph fit the same reference to the proton and helium data measured by AMS-02.
\[ \psi(x, E, t) = \frac{b(E)}{b(E_e)} \frac{1}{(2\pi \lambda^2)^{3/2}} \exp \left(-\frac{|x - x_d|^2}{\lambda^2}\right)Q(E_e). \] (13)

In the equation above, \( b(E_s) \) are the energy losses for the initial energy \( E_s \), \( b(E) \) the energy losses for the final energy \( E \), \( \lambda \) is the propagation length. The source term \( Q(E) \) is given by the power-law with an exponential cutoff:

\[ Q(E) = Q_0 \left( \frac{E}{E_0} \right)^{-\gamma} \exp \left(-\frac{E}{E_c}\right). \] (14)

Where \( Q_0 \) is the normalization of the injection spectrum and \( \gamma \) is the injection spectrum of electrons emitted from SNRs. \( E_c \) is the cutoff energy fixed at 10 TeV.

In order to find the normalization of the injection spectrum we calculate the total energy emitted by the SNR as \( W_0 \) as a function of \( E \), \( \eta W_0 = E \text{tot.} \). \( \eta \) is the free parameter associated with the PWN spectrum normalization. \( W_0 \) can be computed starting from the age of the pulsar \( t \), the typical pulsar decay time \( t_0 \) and the spin-down luminosity \( \dot{E} \). The spin-down luminosity \( \dot{E} \), and distance for each pulsar are taken from the ATNF catalog.

The ejection of electrons from supernova remnants can be described by an approximation, that ALL the electrons are generated at a time equal to the age of the source.

\( E_c \) in the equation is the cutoff energy, while \( E_0 \) is 1 GeV. Thus, the total energy emitted in electrons from supernova remnants can be obtain as: (in the unit of GeV)

\[ E_{\text{tot}} = \int_{E_1}^{\infty} dE E Q(E). \] (15)

In order to find the normalization of the injection spectrum, we assume that the radio flux measured from the sources is given by the electrons accelerated by the supernova remnant. Under this hypothesis \( Q_0 \), the injection spectrum normalization, can be described by the following function [14,15]:

\[ Q_{0,\text{SNR}} = 1.2 \times 10^{47} \text{GeV}^{-1} (0.79) \nu \frac{B_{\nu}}{Jy} \left(\frac{d}{\text{kpc}}\right)^2 \left(\frac{\nu}{\text{GHz}}\right)^{-1} \left(\frac{B}{100 \mu G}\right)^{-\frac{\nu + 1}{2}}. \] (16)

Where \( B \) represents the magnetic field in the remnant, and \( B_{\nu} \) is the radio flux density at frequency \( \nu \).

### 3. Results

In this section we use the model for the flux of electrons explained in the previous section to calculate the flux from two nearby supernova remnant: Vela and Cygnus Loop. They have distance and aged of \( d = 0.293 \text{ kpc}/0.54 \text{ kpc} \) and \( T = 11.3 \text{ kyr} / 20 \text{ kyr} \), respectively [5,6,7,8]. These sources are predicted to be among the major contributors of the high energy tail of the AMS-02 electron flux due to their proximity and your age. Moreover, these sources have been detected in radio in a wide range of frequencies: from 85.7 MHz to 2700 MHz for Vela YZ [5] and from 22 MHz to 4940 MHz for Cygnus Loop [10].
Fig. 4: A. de Angelis and M. Pimenta, Introduction to particle and astroparticle physics (Multimessage astronomy and its particle physics foundations), Springer 2018, p577. This figure represents the radio flux for Vela YZ (right panel) and Cygnus Loop (right panel) in the MHz and GHz range from different radio telescopes. Together with the data we report the best fit we find with a power law for the injection spectrum of electrons as reported in Eq.16.

We show in the plots below the radio flux as a function of frequency for the two considered sources.

Fig. 5 This figure shows the main result of our paper: comparison between the flux from the brightest SNRs in the Galaxy with the AMS-02 data for electrons. Each curve is the flux of electrons from a different source while the solid dot-dashed line represents the Total contribution from all the SNRs we have selected.

The magnetic field of Vela YZ is here fixed to B=36 $\mu$G, corresponding to a mean of the values inferred from X-ray data for the Y and Z regions, while for Cygnus Loop we consider the best fit value of B=60 $\mu$G of the hadronic model for the gamma-ray analysis in [11]. Using the equation 16 for the
determination of the normalization of the injection spectrum, we can find that the best fit parameters for the electrons spectral index and total energy are: $\gamma_{\text{Vela}} = 2.47 \pm 0.10$, $E_{\text{tot,Vela}} = (2.28 \pm 0.06) \cdot 10^{47}$ erg, $\gamma_{\text{Cygnus}} = 2.04 \pm 0.04$ and $E_{\text{tot,Cygnus}} = (1.18 \pm 0.16) \cdot 10^{47}$ erg. Assuming that the efficiency for the acceleration of electrons in supernova remnant is usually considered to be $10^{-3}$-$10^{-4}$, the correspondent total supernova energy is about $10^{50}$-$10^{51}$erg. This is consistent with the typical energy related by a supernova explosion.

We calculate the flux of electrons from the Vela and Cygnus supernova remnants by using the model explained in the previous section. We fix the normalization of the injection spectrum by assuming that the radio flux measured from these sources is due to the synchrotron radiation of electrons and positrons accelerated by the supernova remnant. Here we do not assume that there is delay in the injection of particles in the interstellar medium or that the supernova remnants are partially trapped in the remnant.

We chose for Vela and Cygnus the normalization of the injection spectrum and spectral index that fit the observed radio flux. Then we assume the propagation parameters used also in Ref and energy losses given by $b_0=10^{-16}$ GeV/s and $\alpha=2.0$. In the figure 5 we report the flux for these two sources compared with the AMS-02 data for the electrons. We see that the flux shape is peaked at 100-1000 GeV for Vela and at 1000 GeV for Cygnus. The Cygnus source is peaked at higher energies because the spectral index is harder for this source. The cumulative flux from these two sources is at the few % level meaning that these two sources provide a sizeable flux of the electron data.

In order to have a more general idea of the possible contribution of supernova remnants to the AMS-02 data we have also calculated the flux of sources with a bright radio flux. In fact, in our model the radio flux is tightly connected to the flux on Earth of electrons. Therefore, we select the supernova remnants from the Green catalog with a radio flux larger than 100 Jy. The Green catalog is the most updated sample of these sources with all the relevant information for the characteristics of the sources and measurements at different wavelengths. This selection gives us a sample of 12 sources including Vela and Cygnus that has been already taken into account before. For each source we select their distance, age from the literature and the radio fluxes and spectral indexes derived from radio data. In particular we have used the same information reported in in Tab of [5]. We show the result of this analysis in the same figure we put above. Most of the sources in our sample contribute less that the per mile level because of the distance from the Earth that is larger than a few kpc. Since these are young sources, electrons emitted from these are peaked at high energy. TeV electrons lose very quickly energy and so for farther sources the flux is significantly affected by the energy losses. On the other hand, the sources W28, Monoceros, IN 443 and Lupus Loop contribute to the AMS-02 with a similar flux of Cygnus and Vela. The total cumulative flux is at the level of almost 10% at 1 TeV meaning that supernova remnants are certainly among important contributors of high-energy electrons.

4. Conclusions
We have calculated the flux of electrons from SNRs calibrating the injection spectrum with the radio flux measured by telescopes. This method is based on the assumption that the radio flux measured around SNRs is due to Synchrotron radio of electrons accelerated for the diffuse shock acceleration mechanism. We have used for the propagation of electrons in the Galaxy the most advanced diffusion coefficient parameters found by fitting the latest AMS-02 data. First, we have applied our model to Vela YX and Cygnus Loop that are among the brightest and closest SNRs in the Galaxy. These two sources are found to contribute almost 10% of the electrons data at 1 TeV. In order to make our results more general we have also estimated with the same method the flux of electrons from other SNRs that have a bright radio flux. The cumulative flux of these other SNRs is at the 4-5% level. This paper demonstrates the importance of SNRs in the calculation of flux of cosmic rays from these sources and that it is very important to have precise radio data in the MHz-GHz frequencies to have reliable leverage to calibrate their injection spectra. With the precise radio data, future studies in the field would generate more valuable discovering, and I hope that this paper could benefit the further study of SNRs and cosmic rays.
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