Cosmic ray electrons and positrons from supernova explosions of massive stars

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We attribute the recently discovered cosmic ray electron and cosmic ray positron excess components and their cutoffs to the acceleration in the supernova shock in the polar cap of exploding Wolf Rayet and Red Super Giant stars. Considering a spherical surface at some radius around such a star, the magnetic field is radial in the polar cap as opposed to most of $4\pi$ (the full solid angle), where the magnetic field is nearly tangential. This difference yields a flatter spectrum, and also an enhanced positron injection for the cosmic rays accelerated in the polar cap. This reasoning naturally explains the observations. Precise spectral measurements will be the test, as this predicts a simple $E^{-2}$ spectrum for the new components in the source, steepened to $E^{-3}$ in observations with an $E^{-4}$ cutoff.

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Recently an excess of both cosmic ray (CR) positrons and cosmic ray electrons has been detected by three instruments, PAMELA [1], ATIC [2], and H.E.S.S. [3]. The ATIC and H.E.S.S. results on cosmic ray electrons are consistent with a discovery of an excess, compared to the normal measured spectrum of $E^{-3.26\pm0.06}$ [4]; we emphasize that also the H.E.S.S. result is above such an extrapolation. Both excesses take the form of a flatter component emerging from below a steeper, perhaps normal, component; this has been interpreted in many ways, such as, e.g., the decay of a new particle representing dark matter [5], or as evidence of a nearby special source [6]. Here we wish to point out that such spectral components are expected from particle acceleration in the explosion of stars with magnetic winds [7]: There is a small polar cap component, where the acceleration in a supernova (SN) shock proceeds with the magnetic field parallel to the shock normal, yielding an $E^{-2}$ spectrum [8]. At the same time, over most of $4\pi$ the magnetic field is best approximated by an Archimedean spiral [9], implying a near-perpendicular configuration for acceleration [10]. In such a situation the curvature becomes important, and the acceleration gives a slightly steeper spectrum and is faster - once injection has been effected. This was discussed again recently by Meli & Biermann [11]. The spectrum predicted is $E^{-7/3-0.02\pm0.02}$ [12, 13, 14]. The normal observed cosmic ray electron spectrum for $E > 10$ GeV provides a test, since it gives $E^{-2.26\pm0.06}$ after correcting for losses [4, 15].

Our approach here is to adopt the following point of view [12, 16]:

a) Most of the interactions of cosmic rays happen near the sources, and the escape from the Galaxy is governed by a simple Kolmogorov description [17].

b) The bend in the spectrum, the knee at $10^{15}$ eV is due to spatial limitations given by a shocked shell racing through a Parker-type magnetic wind [12, 14].

c) We do invoke the physics of the stars that explode [18], and distinguish three zero age mass ranges of massive stars which explode: The stars between about 8 and 15 solar masses, which explode into the interstellar medium; the stars between 15 and about 25 solar masses which explode as Red Super Giant (RSG) stars, and the stars above about 25 solar masses, which explode as Blue Super Giant, or Wolf Rayet (WR) stars. Both RSG stars...
and WR stars explode into their stellar wind \[13\, 19\], which is magnetic, and enriched from exposing the deeper layers of the star through mass ejections \[20\].

It was shown in Ref. \[21\] that such a combination of two components, a dominant \(E^{-7/3}\) spectrum, with an additional \(E^{-2}\), injected at the level of a few percent, yields a good fit to the cosmic ray air shower data. Protons and heavier nuclei spectra are well described right through the knee of the cosmic ray spectrum (near \(10^{15}\) eV) after accounting for transport that steepens the spectrum by \(E^{-1/3}\). At this energy the polar cap component increases the overall flux by about a factor of 2, before cutting off due to spatial constraints \[12\, 22\]. The theoretical assumptions about acceleration in highly oblique shocks \[10\, 11\] used in Ref. \[12\] were justified by the good agreement with data \[23\]: prediction \(E^{-8/3}\), data \(E^{-2.68\pm0.02}\). This earlier success encouraged us to apply precisely the same concept here. Additional enhancements of magnetic fields may occur also in such a situation \[24\].

We find, that using just the parameters of earlier papers it is possible to explain both the cosmic ray electron spectrum and the cosmic ray positron excess.

At GeV energies most of the cosmic ray (CR) electrons are accelerated in supernova (SN) shocks, running through the interstellar medium (ISM), the ISM-SN CRs. This predicts a spectrum of \(E^{-2.42\pm0.04}\) \[23\], in agreement with radio data of other galaxies, for which the leakage energy dependence modifies the predicted spectrum to \(E^{-2.75\pm0.04}\) \[24\]. Already the data beyond about 10 GeV suggest that the wind-supernovae cosmic rays may have taken over also for cosmic ray electrons \[4\].

Helium, Carbon and heavier nuclei give an indication \[21\] of what fraction of \(4 \pi\) the polar cap component may have. This component reaches the same flux by itself as the rest of \(4 \pi\) at \(3 \times 10^{6}\) GeV/nucleus for CNO, yielding a surface fraction of about 2 percent. Since this fraction does not depend on distance from the star (see below) we assume that it defines the energy when the polar cap spectrum exceeds the \(E^{-7/3}\) component.

Electrons, however, are injected at about 30 MeV, the lowest energy at which they see the shock \[27\]. This number derives from the injection condition for electrons, that they must “see” the waves excited by the ions freshly injected by shocks in the assumption, that the plasma is dominated by ionized Hydrogen, and that the shock velocity is about \(10,000\) km/s. In a Wolf-Rayet star wind the main element is, however, not Hydrogen, but heavier nuclei, and already before the star explodes as a supernova, there are accelerated electrons: The velocity of the shocks caused by instabilities in the radiation driving is of order \(1000\) km/s \[28\], and so the electron energy at injection then is at about \(6\) MeV.

This immediately implies that the polar cap component of cosmic ray electrons rises at a flux equal of the rest at \(\geq 400\) GeV, matching the uncertain observed energy of about \(300 - 500\) GeV. So at this energy the sum of the two components is twice the base spectral component. We interpret the ATIC data here as a \(E^{-3}\) component, rising above the base spectral component of \(E^{-10/3}\) around \(30\) to \(100\) GeV.

Cosmic ray positrons derive from collisions of nuclei, and formation of nuclei to the left of the valley of stability which decay in \(\beta^-\)-emission, and also from pion production and decay. However, here we have to remember, that acceleration is faster for perpendicular shocks, by a factor up to \(c/(3V_{sh})\), probably more like 2 - 3 \[11\]. This implies that the polar cap component is more efficient in producing positrons because of its slower acceleration and higher interaction probability. Since the hadronic interaction cross section is almost energy independent and does not introduce a break in the spectrum, the polar cap component becomes dominant at an energy between \(2^3\) to \(10^3\) lower than for electrons, i.e. between \(0.5\) to \(60\) GeV.

30 GeV seems to be compatible with the data, suggesting that the enhancement given by perpendicular shock acceleration is about a factor of 2 - 3. However, as there is a second source of positrons at lower energy, resulting from interaction in the immediate environment of massive exploding stars and in the interstellar space \[29\, 30\], the cross-over may be at lower energy, suggesting a possibly higher efficiency enhancement. In a CR-positron to CR-(electron+positron) ratio this results in a rise with \(E^{-1/3}\).

From all these interaction sites here should be a corresponding neutrino-emission with a spectrum of \(E^{-2}\). On the other hand, as the cosmic ray electrons approach a spectrum of \(E^{-3}\) themselves, in the ratio positrons to electrons we approach a constant from somewhere in the range \(30 - 100\) GeV, when both electron and positron components are dominated by the polar cap.

Here we discuss the second positron component at low energy, introduced above, which distorts the positron spectrum:

The wave-field in the magnetic field excited by the cosmic rays of spectrum \(E^{-7/3}\) \[13\] in the predecessor stellar wind naturally yields a specific spectrum of turbulence, in energy per volume and wave number \(I(k) \sim k^{-13/9}\), where \(k = 2\pi/r_g\), and \(r_g = pc/(ZeB)\), the Larmor radius (here \(p\) is the momentum of the particle, \(Z\) its charge, \(c\) the speed of light, \(\epsilon\) the elementary charge, and \(B\) the ambient magnetic field component perpendicular to the motion of the particle). This spectrum of magnetic irregularities then governs the transport of cosmic rays and the cosmic ray interaction as a function of energy. This in turn gives rise to a secondary to primary ratio going as \(E^{-5/9}\) \[20\]. This prediction was confirmed in Ref. \[31\] which showed that the best fit of the secondary to primary ratio had an energy dependence of \(E^{-0.54}\). However, there is also another spectral component of turbulence induced by instabilities leading to many weak shock waves \(I(k) \sim k^{-2}\), which is steeper. The total summed spectrum of turbulence has then a cross-over towards lower wave-numbers, corresponding to higher particle energies; this spectrum \(I(k) \sim k^{-2}\) induces no energy dependence of the production of secondaries. For
the most massive stars, exploding as WR stars, we estimate the cross-over to correspond to somewhere near 10 GeV in electron energy. For somewhat lower mass stars, those exploding as red super giant stars, we argue that there the cross-over between the two spectral regimes of turbulence is at lower energies, or higher wavenumbers, since the winds are less powerful. The cosmic ray induced turbulence is driven by the mass flow through the supernova shock, and so a wind of lesser density produces a weaker cosmic ray induced wave field. This results in secondaries having the same spectrum as the primaries, for WR stars above about 10 GeV, and for RSG stars at much lower energy, disregarding for a moment the polar cap component.

This helps understand the diffuse gamma-ray emission of the disk of our Galaxy as interaction near the RSG stars, more abundant than the WR stars. This model interprets all the secondary to primary ratios at low energy.

This may then explain the low energy cosmic ray positrons, seen with PAMELA, as argued earlier.

The acceleration time for cosmic ray particles in strong shocks is \( \tau_{acc} = 5 \kappa / V_{sh} \). Comparison of \( \tau_{acc} \) to the synchrotron loss time \( \tau_{syn} = 6 \pi m_e c / \sigma_T \gamma e B^2 \) gives a limit on the maximal energy of the electrons or positrons.

In the polar cap \( B \sim r^{-2} \), while over most of \( 4 \pi B \sim r^{-1} \). In the polar cap we assume maximal turbulence and Bohm diffusion \( \kappa = (1/3) r I_c \). In the rest of the surface we adopt the approximation \( \tau_{acc} \approx \kappa / r I_{sh} \). The leads to maximum \( \gamma_{e,max} = 1.5 \cdot 10^6 B_{sh,14}^{-1/2} V_{sh,9} (r / r_0) \) for the polar cap case, where \( B_{sh,14} \) is the magnetic field at radius \( 10^{14} \) cm in units of 3 Gauss, and \( V_{sh,9} \) is the SN shock velocity in units of \( 10^9 \) cm/s. For most of \( 4 \pi \) the maximum is \( \gamma_{e,max} = 4.5 \cdot 10^6 B_{sh,14}^{-1/2} V_{sh,9} (r / r_0) \). Using the adopted values of the magnetic field and shock velocity, at \( 10^{16} \) cm radial distance covered by the SN-shock in the wind the maximal energy of the CR electrons from the polar cap will dominate. Since the expressions used for \( \kappa \) for both segments of the star’s surface are simplified both energies are likely to be smaller. But \( \gamma_{e,max} \) from the polar cap increases as \( r \) while for most of \( 4 \pi \) it increases as \( \sqrt{r} \). This implies that the polar cap component will quickly pass the other component in maximal energy.

Last, we check whether the angular fraction is really distance independent, as required by such a model. Combining the results derived in Refs. 10, 11, 12, 13, 19 we match the acceleration time scale in the polar cap with the acceleration time over most of \( 4 \pi r \). In the limit of a small angular extent \( \theta \) of the polar cap this gives: \( \theta = 3 (B_{sh,p/c} / B_{sh,4}) (V_{sh,c} / c) \) suggesting for \( V_{sh,c} / c \approx 0.03 \) a ratio of surface magnetic fields of \( B_{sh,p} / B_{sh,c} \approx 0.6 \), very close to unity and independent of radius. It is an interesting question if for some stars this ratio might be different. Accelerated electrons have energy loss given by the synchrotron loss time \( \tau_{syn} \) and they can also escape the Galaxy with \( \tau_{eak} \sim \gamma_{e}^{-1/3} \). Then we have \( N(E) \sim E^{-7/3-1} \) spectrum in the limit \( \tau_{syn} < \tau_{eak} \) and \( N(E) \sim E^{-7/3-1/3} \), in the opposite limit. We can estimate from observations, radio measurements as well as direct data, that the switch-over is near 10 - 20 GeV.

CR electrons reach us in a random walk, in which the distance actually travelled is given by \( r \approx \Delta r \sqrt{N} \), where \( \Delta r(E) \) is the diffusion scattering mean free path, the step, and \( N \) is the number of uncorrelated steps. The time this takes is given by \( t \approx (\Delta r/c) N \), while \( \Delta r \sim E^{1/3} \) and hence \( t \sim 1/E \). Therefore \( r \sim E^{-1/3} \). The region from which we obtain CR electrons is the volume for which this time is less than the synchrotron time \( \tau_{syn} \). The source volume is proportional to \( r^3 \sim E^{-1} \). Adopting the viewpoint that at high energies the polar cap component of the CR contribution of the the wind-SNe dominates implies then a combined spectrum of \( \sim E^{-3-1} \). So the CR electron spectrum is predicted in this approximation to be \( E^{-10/3} \) then \( E^{-3} \), and thereafter \( E^{-4} \) which is consistent with the H.E.S.S. data. Nearby massive stars exist and the associated supernovae may have provided a large fraction of the cosmic rays we observe. A test for our predictions would be a measurement of the exact spectrum of both cosmic ray electrons as well as cosmic ray positrons. This model simply predicts that their spectrum is a simple additional \( E^{-2} \) component at source.

The positron fraction should reach a plateau, the exact number depending on the dominant path to produce positrons, decay from isotopes pushed by photo-dissociation and spallation off the valley of stability in a \( N, Z \) plot, or just simply pion decay.

Ion collisions produce very few if any anti-protons and contributions from WR star explosions will be negligible. The RSG explosions will produce anti-protons, and their polar cap contribution should come up at some higher energy, perhaps above 30 - 100 GeV.

Obviously, both cosmic ray electrons as well cosmic ray positrons are in their respective loss limit at such energies, above about 10 - 20 GeV, where losses overpower diffusion and steepen the spectrum by unity; the limited spatial reach gives a further steepening by \( E^{-1} \). Therefore there must be some yet higher energy where the losses from the nearest most recent source cut everything completely off; the ATIC and H.E.S.S. data suggest that this happens beyond energies of several TeV. It would be very interesting to measure the positron component to this energy.

We have proposed a simple explanation for the cosmic ray electron and cosmic ray positron components, in terms of the magnetic field topology in a magnetic wind, and SN-induced shock acceleration in such a topology. The new component is just that population of energetic particles accelerated in the polar cap of massive magnetic stars with winds, when they explode. We attempted to explain a) the low energy PAMELA data, b) the higher energy PAMELA data, c) the ATIC data, and d) the H.E.S.S. data, all in the context of a basic picture proposed and worked out earlier.
and consistent with other measurements.

In the cosmic rays produced by a shock running through such a wind there is always a polar cap component, of a few percent strength at injection, but with a flatter spectrum.

The explosions of Wolf Rayet stars and their cousins, the Red Super Giant stars, into their respective magnetic wind, may play a key role in allowing us to understand the physics of cosmic rays.

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