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Explosions of massive stars with magnetic winds:

cosmic ray acceleration

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Abstract. We follow the consequences of cosmic ray acceleration in supernova remnants from the explosions of massive stars in the pre-supernova stellar winds. The theory for such acceleration predicts that in small fraction of the remnants - its polar caps - cosmic rays will be accelerated on a flat spectrum and will dominate the highest energies. This has been observed in the spectra of different cosmic ray nuclei. The same theory predicts cosmic ray electron spectra having E^{-3} slope up to 1,000 GeV and higher positron to electron ratio above 10 GeV. These relatively flat electron spectra may explain the WMAP haze in the vicinity of the galactic center.

Key words. Cosmic ray acceleration; Explosions of massive stars; Cosmic ray energy spectra and composition; Cosmic rays electrons and positrons

1. Introduction

The cosmic rays energy spectrum extends from a GeV (10^9 eV) to more than 10^{11} GeV as a smooth power law $E^{-\alpha}$. Apart from some recently discussed features the spectral index α changes twice: first at energy of about $3{\times}10^6$ GeV it changes from about 2.7 to 3.1; it flattens again to about 2.7 at energy above $3{\times}10^9$ GeV. The first feature is called the cosmic ray *knee* and the second is the cosmic ray *ankle*. The current assumption is that the particles up to about 10^9 GeV are accelerated in the Galaxy and higher energy particles have extragalactic contribution. The propagation in extragalactic space and the energy loss in interactions in the microwave background cause the end of the cosmic ray spectrum - the GZK effect We know the shape and magnitude of the spectrum quite well but its understanding took a lot of time.

The first ideas of cosmic ray acceleration were published by E. Fermi (Fermi 1949). The idea was that cosmic rays are accelerated in magnetized molecular clouds. Transferring cosmic rays to the cloud and back Fermi demonstrated that cosmic rays could be accelerated, and the the acceleration was proportional to the cloud velocity β^2, where $\beta = v/c$. The next step was done by Ginzburg & Syrovatskii (1969) who suggested that cosmic rays are accelerated at supernova remnants (SNR) when their expansion velocity decreases since they have dragged large amount of matter from interstellar space. This suggestion is based simply on energetics. If there are three supernovae per century in the Galaxy and only 5-10% of their kinetic energy is converted to cosmic rays it will be enough to supply all galactic cosmic rays.

The acceleration process at the shock front of the expanding supernova remnant was suggested in the late 1970s (Krymsky 1977; Axford, Lear & Skadron 1977; Bell 1978). The acceleration at the shock would be proportional to β and the velocity of the expanding remnant is much higher than that of the cloud. The question then is how this acceleration process can explain the observed cosmic ray spectrum and composition. The composition is important since the maximum acceleration energy is proportional to the particle charge Z. Since in the case of shock acceleration particles gain energy at every crossing of the shock (independently of the direction) the maximum energy depends on the number of crossings. Lagage & Cesarsky (1983) estimated the maximum energy E_{max} to 3×10^4 GeV for a shock velocity of 5×10^8 cm/s. This is certainly not enough to explain the cosmic ray knee since even iron nuclei cannot reach the knee. Newer calculations using higher β predicted higher E_{max} but still not high enough to explain all galactic cosmic rays.

2. Acceleration in SNR from heavy stars with massive winds

Völk and Biermann (1988) published a paper discussing the differences between acceleration in SNR that expand in the average interstellar medium and those who expand in the winds of massive stars. Their investigation was probably connected to the explosion of SNR1987A since they use some estimates from its predecessor star. They estimate the cosmic ray acceleration and adiabatic losses as a function of the stellar mass loss and its magnetic field and reach two important conclusions: the maximum energy in red giant wind shocks is more like $Z\ 3\times10^6$ GeV and it may be achieved one year after the explosion; since the stellar wind is highly ionized one expects the composition of the accelerated cosmic rays to follow the composition of the stellar wind, not the average composition of the interstellar medium. If the stellar magnetic field is even higher one can think of energies ten times higher. Protons thus can be accelerated to the energy of the knee while heavier nuclei may achieve much higher energy. This is close to an explanation of the knee although this is not emphasized in the paper.

Further developments of these ideas followed during the next several years ending in predictions in Biermann (1993) and Stanev, Biermann & Gaisser (1993). At that time the acceleration of of cosmic rays was described in a mass sequence of the progenitor stars: stars with less than 10 $M_\odot$ exploding in the regular interstellar medium, red giants exploding in red giant winds, and Wolf-Rayet stars exploding in W-R winds. The cosmic rays accelerated in these explosions are expected to have different chemical compositions depending on the composition of the predecessor star winds. Red giant supernovae will most likely accelerate Helium nuclei and Wolf-Rayet supernovae would accelerate Oxygen nuclei. There is, however, a new element. Following Parker (1958) the asymptotic magnetic wind topology is assumed to have *caps* around the rotational axis where the magnetic field is strictly radial and has r^{-2} dependence and tangential (with $1/r$ behavior) over the most of the 4π phase space.

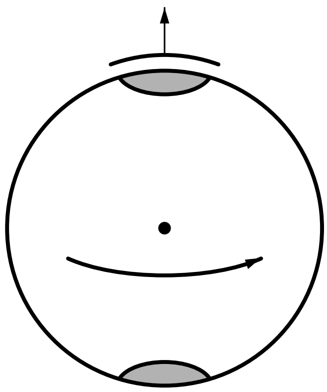

Fig. 1. Magnetic field geometry at the shock

This suggests that different acceleration mechanisms co-exist in supernova remnants. In the polar caps the shock normal is parallel to the magnetic field and in the rest of the phase space it is perpendicular (see Fig. 1). In parallel shocks the acceleration is slower but the spectral shape is flatter E^{-2}. According to Biermann (1993) the acceleration perpendicular shocks is faster but the spectral index is steeper - 7/3. If only a small fraction of the phase space (order of a few %) supports parallel shocks in the approach of E_{max} the flat spectrum will dominate. If this were true one expects to see features in the cosmic ray spectrum: flattening in all components of the cosmic ray composition which may or may not be visible.

3. Recent measurements of the cosmic ray spectrum and chemical composition

During the last several years there were first rumors, and then papers, describing new results from the biggest balloon experiments ATIC (Panov et al. 2009) and CREAM (Ahn et al. 2009; Ahn et al. 2010) and the satellite experiment Pamela (Adriani et al. 2009). The Hydrogen and Helium results from these experiment are shown in Fig. 2. The original published figures are in different units (energy/nucleus or energy/nucleon) and are multiplied by different powers of the energy. We plot the fluxes in energy per nucleus and multiplied by $E^{2.6}$ so that one can visually compare the different measurements.

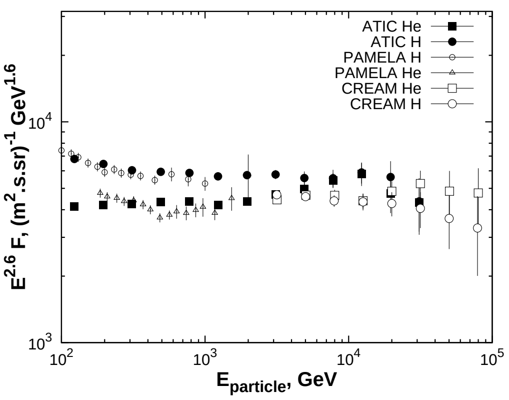

Fig. 2. Hydrogen and Helium fluxes measured by CREAM, ATIC, and Pamela. All fluxes are per nucleus and are multiplied by $E^{2.6}$

In spite of the small difference between the Hydrogen fluxes measured by CREAM and ATIC in the approach to 10^4 GeV all three experiments show the same feature: at the highest energies these experiments could measure the He component exceeds the Hydrogen component that dominates the cosmic ray flux in the GeV region. It is also amazing that the He component have an $E^{-2.6}$ or flatter spectrum between 10^4 and 10^5 GeV. The absolute values of the fluxes of these two components are in a very good agreement with the measurements of Pamela at lower energy.

If one concentrates on the He spectrum it is indeed very flat as predicted in Biermann (1993) and Stanev et al (1993). An additional flattening appears at the approach to 10^5 GeV. The Hydrogen spectrum, on the other hand, seems to approach its highest acceleration energy E_{max} and decline. It is interesting to compare these results with the conclusions of the Kascade air shower array (Antoni et al. 2005) which extracted a He spectrum exceeding the Hydrogen one by a factor of 2 at 10^6 GeV. It all seems to be fully consistent.

In Fig. 3 we present the fluxes of Helium, Oxygen, and Iron measured by ATIC (Panov et al. 2009) again multiplied by $E^{2.6}$. Both Oxygen and Iron fluxes seem to be as flat as the He spectrum. The fluxes of Oxygen and Iron seem to be equally abundant at the measured energy range. There is no signature of approaching the maximum acceleration energy of either component. According to the Kascade air shower analysis (Antoni et al. 2005) (which has higher error bars than the direct measurements) the main cosmic ray components follow the Z dependence of E_{max} as expected.

The open circles in Fig. 3 show the all particle cosmic ray flux measured by ATIC. It appears to have an $E^{-2.6}$ energy spectrum (or slightly flatter) over the whole energy range. There is an obvious flattening in the five highest energy points that is not visible in the spectra of the individual components shown here. It must be due to the other components (C, Ne, Mg, Si) measured by ATIC and not shown here.

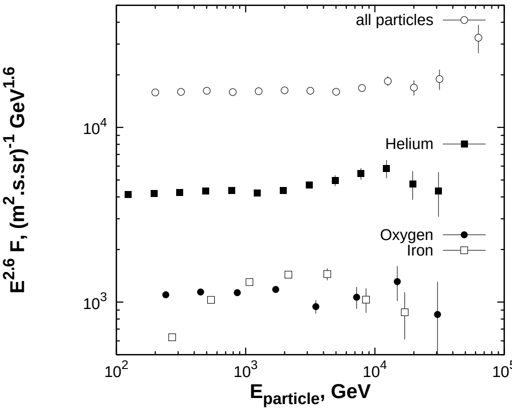

Fig. 3. Fluxes of Helium, Oxygen and Iron nuclei measured by the ATIC experiment. Open circles show the all particle spectrum. All spectra are multiplied by $E^{2.6}$.

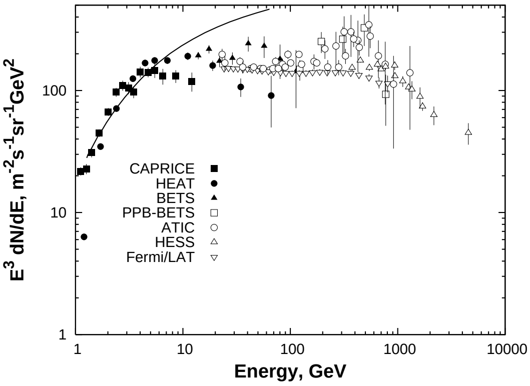

Fig. 4. Results of the most recent measurements of the cosmic ray electrons plus positrons energy spectrum. The smooth line shows the cosmic ray proton spectrum divided by 100. All measurements are multiplied by E^3.

4. Other measurements that can be related to the acceleration at SNR of massive stars with magnetized winds

The classical thinking about the electron spectra in the Galaxy is that at GeV energies the electron spectrum is similar to the proton one, but is about 100 times lower. At energy between 5 and 10 GeV the electron energy spectrum should become steeper by E^{-1} because of the strong synchrotron energy loss in the galactic magnetic fields. This is why when the ATIC experiment (Chang et al. 2008) published its energy spectrum this led to a big excitement and to lots of new measurements. The most recent measurements of the electron spectrum extending up to 1,000 GeV are shown in Fig. 4.

The ATIC data, as well as the data of PPB-BETS experiment show a *bump* in the spectrum at about 400 GeV. The first interpretation of the bump was related to dark matter decay or annihilation. There were also interpretations in terms of nearby sources of cosmic ray interpretation. Further measurements by the HESS TeV γ-ray telescope (Aharonian et al. 2008) and the Fermi/LAT γ-ray satellite experiment (Abdo et al. 2009) did not confirm the bump but confirmed that the cosmic ray electron spectrum is not steeper than E^{-3} up to 1,000 GeV.

We will not discuss the dark matter or nearby electron source interpretations and will proceed with the fact that this flat electron spectrum is fully consistent with the acceleration in SNR of heavy magnetized stars. At GeV energies most of the cosmic ray electrons are accelerated in supernova shocks, running through the interstellar medium (ISM). This predicts a spectrum of $E^{-2.42\pm0.04}$ (Biermann & Strom 1993), in agreement with radio data of other galaxies, for which the leakage energy dependence modifies the predicted spectrum to $E^{-2.75\pm0.04}$ (Biermann 1997).

Electrons, however, are injected at about 30 MeV, the lowest energy at which they see the shock (Protheroe & Biermann 1996). 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 $c/3$. In a Wolf-Rayet star wind the main elements are ionized 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 and so the electron energy at injection then is about 6 MeV.

This immediately implies that the polar cap component of cosmic ray electrons should rise to a flux equal of the rest at about 400 GeV, matching the bump observed at energy of about 300 - 500 GeV. So at this energy the sum of the two components is twice the base spectral component. The ATIC data are thus interpreted as a E^{-3} component, rising above the base spectral component of $E^{-10/3}$ around 30 to 100 GeV. After reaching E_{max} of approximately 1,000 GeV the electron spectrum steepens as the highest HESS points show. The other new measurement that immediately invited dark matter interpretations was that of the positron to electron ratio measured by Pamela (Adriani et al. 2008) shown in Fig. 5. There are

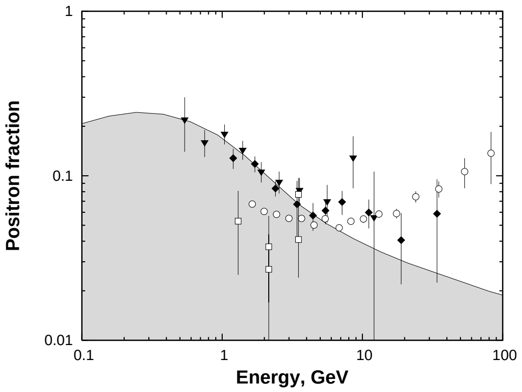

Fig. 5. The positron to electron ratio measured by Pamela is shown with open circles. The black symbols are for different measurements that agree with the predictions of Moskalenko & Strong (1998). This prediction is shown with the shaded area.

two surprising features in this result. The first one is the increase of the e^+/e^- ratio above 10 GeV. The other one is the low ratio in the GeV energy range. This second effect was already qualitatively explained by Clem & Evenson (2004) who measured the ratio in 2002. Their data is shown with empty squares. The decrease of the ratio, Clem & Evenson stated, is dues to the A^- polarity of the Sun during which positrons lose more energy while they propagate in the solar system. The increase of the ratio, however, was not explained.

Cosmic ray positrons derive from collisions of nuclei, and formation of nuclei to the left of the valley of stability which decay in β^+-emission, and also from pion production and decay. The classical picture is that of cosmic ray interactions while they propagate in the Galaxy (Protheroe 1982; Moskalenko & Strong 1998). There may be also a second component that is due to cosmic ray interactions in the vicinity of the acceleration site. Such contribution would be stronger around SNR expanding in the dense Wolfe-Rayet wind nebulae. While discussing this possibility one has to remember that acceleration is faster for perpendicular shocks, by a factor up to $c/(3V_{sh})$, probably more like 2 - 3. 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 to 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, the cross-over may be at lower energy, suggesting a possibly higher efficiency enhancement. In a positron to (electron+positron) ratio this results in a rise with $E^{1/3}$.

5. Related effects outside cosmic ray measurements

After the first results of the WMAP satellite it was established (Finkbeiner 2004) that a region around the galactic center exhibits radio emission that cannot be related to the typical cosmic ray electrons spectrum, The WMAP measurement covered the region of 20 to 100 GHz where the observed spectral index is very flat. We have already seen why at the approach of the maximum acceleration energy the cosmic ray electron spectrum will flatten, especially if the acceleration happens at SNR of massive stars that expand in the pre-supernova winds. And one expects to have many more massive stars around the galactic center.

The important point in this discussion (Biermann et al 2010) is the that electrons up to 20 GeV have mostly diffusive losses and at higher energy they have energy losses because of synchrotron radiation in the galactic magnetic fields and inverse Compton interactions. The magnetic fields in the vicinity of the galactic center are higher, closer to 10 μG than in the vicinity of Earth. The question then is, will the diffusion loss dominate at lower energy. Biermann et al (2010) argue the opposite. They estimate that diffusion in Kolmogorov type of very high turbulence close to the galactic center is faster than in the vicinity of the Earth and depends inversely to the turbulence strength (Becker et al. 2009)

In such a case the diffusive losses will dominate to higher electron energies and the flat spectrum coming from the SNR caps will be able to diffuse away and cause the flat radio spectrum at 20 to 100 GHz around the galactic center. The spectrum at lower frequencies will correspond to the electron spectrum generated in the most of the phase space of the SNR.

One wonders if the same arguments could be used to explain the Fermi bubbles (Su, Slatyer & Finkbeiner 2010) - the two almost spherical regions extending North and South of the galactic center with flat γ-ray flux which roughly coincide with the extension of the WMAP haze. Such an explanation has not been attempted yet and it is not obvious it will work. Having in mind how extensive the consequences of the cosmic ray acceleration at SNR from massive stars have been, I will not be surprised if it does.

6. Discussion

JIM BEALL: What is the source for the seed particles for the cosmic rays?

TODOR STANEV: It is the composition of the shock environment¿ So in ISM it is mostly H and He. In the shocks after explosion of massive stars it is mostly heavier nuclei from the stellar mass loss.

WOLFGANG KUNDT: By what mechanism you hope to accelerate cosmic rays with magnetic winds to VHE energies? In my talks in Vulcano I always concluded - using the modified Hillas argument - that only neutron stars can do that.

TODOR STANEV: To start width - we are not talking acceleration to 10^{20} eV. The magnetic fields at the shock are higher because of the magnetic winds. This increases E_{max} by roughly a factor of 10, as in Völk & Biermann. The existence of ionized iron nuclei in the wind gives you another factor of 26, as E_{max} is proportional to tha charge Z. So if explosions in the ISR accelerate protons to 10^{15} one can reach close to 10^{18} eV in such supernova remnants.

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