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Origin of High Energy Cosmic Rays: A Short Review

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Abstract

I provide here a short review of some recent observational findings in the field of cosmic rays and of selected theoretical advancements in our understanding of acceleration and propagation of cosmic rays, from below the knee to the highest energies observed so far.

Key words:

1 Introduction

In the recent few years several new observational and theoretical findings have considerably contributed to improve our understanding of the origin and propagation of cosmic rays.

Direct measurements of cosmic ray fluxes have been extended to reach closer to the knee region. These measurements are now available for all nuclei from H to Fe, and accurate measurements of the abundancies of nuclei heavier than Fe are being carried out. Some of these elements, such as Ge and Ga, can provide useful information on the characteristics of the environment where cosmic ray acceleration takes place. These direct measurements provide the best determination of the spectrum of nuclear species below the knee and seem to lead to approximately power law spectra for all the species with approximately the same slope, ~ 2.7. The spectrum of He, as provided by ATIC-2 and CREAM-I (see Blasi (2007) for a review of the most recent results as presented at the 30th ICRC), seems to be slightly flatter than the proton spectrum, but a better statistics in the highest energy bins is needed to confirm this finding.

At energies around and above the knee, the KASCADE (and now the KASCADE-Grande) data and the data from the Tibet Array are basically the only ones that can shed light on the origin of the knee. Unfortunately there is no definite agreement between the data of KASCADE and Tibet Array (only preliminary data on the all-particle spectrum are available from KASCADE-Grande). The proton spectrum as measured by KASCADE shows a pronounced and well defined knee at $\sim 10^{15}$ eV. The proton spectrum above the knee is rather steep and might even represent a cutoff in the spectrum. The He spectrum also shows a similar behaviour. The proton spectrum as measured by Tibet Array is somewhat steeper than the KASCADE spectrum and does not show a clear evidence for a knee. The He spectra measured by the two experiments are clearly different in shape and in relative normalizations.

The view that would arise from a simple extrapolation of the proton spectrum as measured by KASCADE is however impressively interesting. If the knees in the single chemical components are induced by a rigidity effect, possibly associated with the acceleration process, then the knee in the all-particle spectrum is likely to be interpreted as a superposition of the spectra of the different chemical elements. The most effective way to prove or disprove this picture would be to extend the direct measurements as close as possible to the knee or even across it, possibly using ultra-long duration balloon flights.

Both experiments, KASCADE and the Tibet array, agree however on the presence of protons in the spectrum up to energies of $\sim 10^{15} - 10^{16}$ eV. This implies that the maximum energy of cosmic rays accelerated at the sources must be at least that high. If the KASCADE data are adopted, then the proton spectrum has a steepening or a cutoff at energies $\sim 3 \times 10^{15}$ eV, which might be the first detection of the end of the Galactic cosmic ray proton spectrum as it is generated at the sources, possibly supernova remnants.

Another crucial implication of adopting the KASCADE results is that the Galactic spectrum should end at energies of order $E_{end} \approx Z_{Fe} \times E^p_{knee}$, where $Z_{Fe} = 26$ is the charge of fully ionized Fe nuclei and $E^p_{knee} \approx 3 \times 10^{15}$ is the position of the knee in the proton spectrum. This leads to $E_{end} \sim 10^{17}$ eV, which clearly conflicts with the standard picture of the transition from Galactic to extragalactic cosmic rays, as provided by the traditional ankle model (see the review paper by Hillas (2005) and references therein), where the Galactic cosmic ray spectrum need to extend above $\sim 10^{19}$ eV.

All these new data are contributing in a fundamental way to establishing an exciting new scenario for the origin of cosmic rays, partly based on some new theoretical insights and partly fueled by recent observations of supernova remnants at different wavelengths.

The review is organized as follows: in §2 I will summarize these new obser-

vations and the theoretical scenario that is emerging. In §3 I will discuss the implications of this scenario for the description of the transition from Galactic to extragalactic cosmic rays. Some recent results on ultra-high energy cosmic rays (UHECRs) are discussed in §4. I summarize in §5.

2 A new supernova paradigm for the origin of cosmic rays

The supernova paradigm for the origin of cosmic rays is mainly based on an energetic argument: supernova remnants (SNRs) eject enough energy in the form of kinetic energy of the expanding ejecta that if a fraction $\sim 10-20\%$ of it is converted to cosmic rays, the observed flux of cosmic rays can be accounted for. Clearly there are many more ingredients that add to this paradigm (the spatial distribution of SNRs, the chemical composition of accelerated material and many others) but the basic picture remained unchanged.

The motion of the ejecta is supersonic and leads to the formation of a strong shock wave. Particle acceleration is expected to occur at this shock through the first order Fermi process. Since this scenario was first discussed (Krymsky (1977); Bell (1978); Blandford & Ostriker (1978)), a problem was immediately recognized (Lagage & Cesarsky (1983a,b)): particle acceleration at energies comparable with that of the knee is possible only if substantial magnetic field amplification takes place at the shock location and particle scattering across the shock takes place at roughly the Bohm rate. Both these requirements have been for long time two assumptions of the problem.

A few years ago, high resolution X-ray observations of some SNRs led to the measurement of the thickness of the X-ray bright regions at the shock location (Warren et al. (2005); Völk et al. (2005)). Most X-rays are non-thermal and are the result of synchrotron emission of high energy electrons. The thickness of the emission regions is related to the loss length of such electrons as due to synchrotron losses, so that it is possible to infer the strength of the magnetic field from measurements of the geometric thickness of the rims. In virtually all cases that have been investigated, the measured magnetic fields are of order $100-500\mu G$ (Völk et al. (2005)), a factor ~ 100 larger than the typical interstellar medium (ISM) magnetic fields. This is the first convincing evidence of magnetic field amplification at SNR shocks.

The amplification is naturally achieved due to streaming instability (Bell (1978, 2004)). The super-alfvenic motion of the accelerated particles upstream of the shock leads to the development of an instability which results in amplification of perturbations in the magnetic field strength upstream of the shock. The amplified field is further enhanced by compression at the shock surface (this amplified and compressed downstream field is the one which is observed

in the form of bright X-ray rims in SNRs).

Since the first order Fermi process is a stochastic diffusive mechanism, the acceleration time for particles of given momentum is the sum of the diffusive propagation times in the upstream and downstream sections. It is therefore important that the magnetic field is high in both regions, in order to make the acceleration time short and lead to efficient acceleration to high energies. Such a requirement is certainly satisfied by streaming instability. The modes which are unstable depend on the shock velocity and on the efficiency of particle acceleration. When particle acceleration occurs efficiently and the shock speed is high (the two things are not independent) non-resonant modes appear (Bell (2004)) which grow faster than the resonant modes (Bell (1978)). This suggests that at different stages during the evolution of a SNR, different modes will be dominant and the maximum energy of the accelerated particles may be a non-trivial function of time (Marcowith et al. (2006); Blasi & Amato (2007)).

If particle acceleration occurs efficiently, as requested for the SNR paradigm to hold up, the dynamical reaction of the accelerated particles on the shock is not negligible and leads to a variety of very interesting effects: 1) a precursor is formed upstream, consisting of a region in which the upstream fluid, as seen in the shock frame, slows down. This implies that the effective compression factor felt by particles may exceed the limit for a standard fluid shock, namely $r = 4$. Moreover the velocity profile in the precursor makes the compression factor a function of the momentum of the particles, so that the expected spectrum of accelerated particles is not a power law, as would be expected in test particle theory. The predicted spectra are concave, being steeper than E^{-2} below $1 - 10$ GeV and flatter at higher energies. 2) The effective acceleration process makes less energy available for gas heating, so that the temperature of the downstream plasma is expected to be lower than that predicted for a standard fluid shock.

Both the dynamical reaction of the accelerated particles on the shock and the magnetic field amplification due to streaming instability are aspects of what is now known as the *non linear theory of particle acceleration at shock waves* (see the review paper by Malkov & Drury (2001)), which is an important step forward with respect to the simple test particle theory, and even more important, it is required to explain observations. A recent discussion of all these effects in the context of the so-called kinetic approaches to non linear particle acceleration can be found in the paper by Amato et al. (2007).

The scenario outlined above is completed by the recent gamma ray observations of SNRs by Cherenkov imaging gamma ray telescopes, such as HESS, MAGIC and VERITAS. Especially the HESS observations of SNR RXJ17.13 (Aharonian et al. (2007a)) and Vela Junior (Aharonian et al. (2007b)) have provided plausible evidence of the hadronic origin of the gamma ray emission,

though not yet solid enough to be called a *proof*. The presence of strong magnetic fields in the shock region is a pivotal point to reach such a conclusion, since it makes inverse compton models of the gamma ray emission less tenable (Berezhko et al. (2007a,b)). The spectrum of gamma rays as observed in RXJ17.13 has a cutoff at ∼??? TeV, which corresponds to a maximum energy of protons about one order of magnitude larger. This does not need to be correspond to the position of the knee in the proton spectrum since such high energies are reached only at the beginning of the Sedov phase.

3 From galactic to extragalactic cosmic rays

Both the standard model for the origin of galactic cosmic rays, based on the supernova paradigm, and some observational data (see the discussion above) hint to the fact that cosmic rays should have extragalactic origin at energies exceeding $\sim 3 \times 10^{17} - 10^{18}$ eV, clearly at odds with the ankle scenario, where the spectrum of galactic cosmic ray iron nuclei should extend to energies around 10^{19} eV. The dip scenario (Berezinsky et al. (2006, 2005)) and the mixed composition model (Allard et al. (2005a)) predict an end of the Galactic spectrum roughly in the correct energy region, though for very different physical reasons.

The dip is a feature in the diffuse spectrum of ultra-high energy (UHE) extragalactic protons in the energy range $10^{18} - 4 \times 10^{19}$ eV, which is caused by electron-positron pair production on the cosmic microwave background (CMB) radiation. For an injection spectrum $Q(E) \propto E^{-\gamma_g}$ with $\gamma_g \approx 2.7$ one can fit the data of AGASA, HiRes, Fly's Eye and Yakutsk with an excellent χ^2. The fit to Auger data is also satisfactory but with a worse χ^2. In the dip scenario, extragalactic cosmic rays are strongly proton dominated (a contamination of at most 15% helium can be allowed for). At energies below 10^{18} eV the spectrum becomes flatter, so that the transition from Galactic to extragalactic cosmic rays is characterized by the crossing of a steep Galactic spectrum with a flatter extragalactic spectrum, as it happens in the ankle model. A detailed discussion of the dip model and its implications can be found in the paper by Aloisio et al. (2007).

The observed all-particle spectrum can also be fit well by assuming a mixed composition of cosmic rays at the source (Allard et al. (2005a,b)). The propagation of the different chemical elements from the sources (with an injection spectrum $\propto E^{-\gamma_g}$ with $\gamma_g \sim 2 - 2.3$) to Earth leads to a substantial modification of the spectra and conversion of heavier nuclei into lighter ones. A good fit to the data can be achieved, provided the relative abundances of the different chemicals at the sources are chosen properly.

The main discriminant between these two scenarios is in the chemical composition predicted in the transition region, between 10^{17} eV and 10^{19} eV. In the dip scenario, a sharp transition from the iron dominated Galactic component to a proton dominated extragalactic component is expected (Aloisio et al. (2007)). The composition is dominated by protons at 10^{18} eV. The strong dominance of the proton component is confirmed by HiRes, HiRes-Mia and Yakutsk datarXiv:0705.3723a, while Akeno and Fly's data favor a mixed composition. The data of the Pierre Auger Observatory favor a mixed composition at all energies (Unger et al. (2007)), including at the highest energies, as based on the measurement of the mean value of the depth of shower maximum $< X_{max} >$.

The mixed composition scenario predicts a much smoother transition from Galactic iron to pure protons in terms of $< X_{max} >$ (Allard et al. (2007)). The model fits well the Auger data on $< X_{max} >$ with the exception of the last few data points which seem to suggest a continuous trend towards heavier elements above 10^{19} eV.

In addition to $< X_{max} >$, the distribution of values of penetration depths around the mean also provides important clues to the chemical composition, the spread being larger for protons than it is for iron nuclei. An investigation of the implications of the dip and ankle models on the width of the distribution of values of X_{max} in different energy bins has been recently presented by Aloisio et al. (2007), but the comparison with the results of different experiments leads to ambiguous conclusions: the comparison of the expected distributions for the dip and ankle scenarios in the lowest energy bin in the Fly's Eye data ($(1-3) \times 10^{17}$ eV) shows that while the peak of the distribution in the two cases is essentially at the same position, $\sim 600\,\mathrm{g\ cm^{-2}}$, as expected for iron-dominated showers, the tail of the distribution cannot be explained unless a substantial amount of protons is present, as expected in the dip model. This part of the distribution cannot be fit by the ankle scenario. The dip model also provides a good fit to the Fly's Eye data in the higher energy bins. The ankle and dip models provide basically the same distribution of X_{max} only at energies in excess of 10^{19} eV, where the composition becomes proton-dominated in both scenarios.

It is interesting to notice that in the two Fly's Eye data bins that contain the transition through the dip ($(3-10) \times 10^{17}$ eV and $(1-3) \times 10^{18}$ eV), the predicted distributions of values of X_{max} show a slight excess of the light component in the tail. This might suggest that a somewhat heavier component might be needed to improve the fit.

The comparison with HiRes data on the distribution of X_{max} in the three energy bins $(3-6) \times 10^{17}$ eV (from HiRes-MIA), $E_0 \simeq 10^{18}$ eV (from HiRes mono) and $E_0 > 10^{18}$ eV (from HiRes stereo) shows a very good agreement

with the dip model.

A comparison of the predictions of the mixed composition scenario with the observed distributions of values of X_{max} has so far not yet been carried out.

A reliable measurement of the distribution of penetration depths in the energy range $E > 10^{17}$ eV remains a crucial goal to understand the origin of cosmic rays, but it appears that our ability to extract from these data the physically relevant information on chemical composition remains hindered by the uncertainties in the description of shower developments (see talk by T. Stanev, these proceedings, for further discussion).

4 Origin of ultra high energy cosmic rays

The results recently reported by the Pierre Auger Observatory have shed light on some crucial aspects of the problem of the origin of UHECRs and at the same time opened several new questions.

The spectrum observed by Auger (Yamamoto et al. (2007)) shows a flux reduction that is consistent with the GZK suppression predicted by Greisen (1966); Zatsepin & Kuzmin (1966). The GZK feature is caused by a sharp increase in the loss length for photopion production of particles at energies around $(5 - 10) \times 10^{19}$ eV. This implies that at sufficiently high energies, particles can reach us only from the nearby universe, while at lower energies, where photopion production is not effective, the loss length is comparable with the size of the universe. The number of sources contributing a flux in the two energy regimes is therefore very different.

This is especially important in terms of the expected anisotropy of the directions of arrival of cosmic rays. The local universe is far from being spatially homogeneous. Therefore cosmic rays contributed by nearby sources are not necessarily expected to have an isotropic flux. The Pierre Auger Observatory has recently presented evidence for a correlation of the arrival directions of cosmic rays with energy $> 10^{19.7}$ eV with the local distribution of matter (Pierre Auger Collaboration (2007)) [1].

The correlation appears when cross-correlating the arrival directions with the position of active galactic nuclei in the Veron-Cetty Catalog (Veron-Cetty & Veron (2006)). The location of the sources and of the UHECRs arrival directions are within ~ 3 degrees of each other, hinting to a negligible role of

[1] These results were presented in November 2007, after the RICAP 2007 Conference. A short description is introduced here because of their relevance

magnetic fields, intervening between the sources and the Earth. The correlation on such small angular scales also suggests that the primary particles are protons: slightly heavier nuclei would be deflected by more than ~ 3 degrees in the Galactic magnetic field.

The Pierre Auger Collaboration has also presented results on chemical composition, as discused above, but I will arXiv:0705.3723not develop further on this topic here, for lack of space. The only point that it is worth stressing is that the need for protons at the highest energies, as required by the correlations with AGN, appears at odds with the results on the elongation rate, which suggest a rather heavier composition at high energies, and especially in the last two energy bins.

From the theoretical point of view, the possibility that UHECRs are actually accelerated in AGN, as suggested by the latest Auger results, is extremely interesting and needs to be further investigated, especially in the perspective of having multifrequency observations of AGN from radio to gamma rays.

5 Summary

I provided a short review of some recent observational and theoretical results in cosmic ray acceleration and transport. As far as Galactic cosmic rays are concerned, the discovery of strong magnetic field amplification in several supernova remnants has represented a breakthrough in our ability to understand acceleration up to the knee region. The standard model of cosmic ray origin in SNRs includes now magnetic field amplification, due to streaming instability induced by cosmic rays themselves. Such standard model leads to the conclusion that protons should be accelerated up to $\sim 10^{15} - 10^{16}$ eV, while nuclei with charge Z would have a maximum energy higher by a factor Z. This implies that the Galactic cosmic ray spectrum should therefore end at energies $\leq 3 \times 10^{17}$ eV. This makes the standard ankle scenario for the transition from galactic to extragalactic cosmic rays hardly tenable.

The dip model and the mixed composition model both require an end of the galactic cosmic ray spectrum in the energy region between 10^{17} and 10^{18} eV. The main observational difference between the two scenarios is in the chemical composition in such transition region. The sharp transition from iron dominated to proton dominated in the dip model should result in a sharp rise in the value of $< X_{max} >$ as a function of energy. The rise is much smoother for the mixed composition model. Additional insights can be gathered based on the distribution of values of X_{max} around the mean.

In the region of the highest energy cosmic rays, the most important news

consists of the detection of anisotropies, in the form of a correlation of the directions of arrival of UHECRs with sources in the nearby universe. Aside from the obvious implications for the identification of the sources of UHECRs, this discovery can be viewed as the first confirmation that UHECRs have extragalactic origin and that the flux reduction observed by Auger is in fact the GZK feature. But even more important, the Auger result confirms the possibility of carrying out cosmic ray astronomy. The identification of the sources and the direct measurement of the spectrum from single sources will require an even larger detector, as Auger North is expected to be.

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