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Origin of the Knee in the Cosmic Ray Energy Spectrum

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Primary energy spectrum of cosmic rays exhibits a knee at about 3 PeV where a change in the spectral index occurs. Despite many efforts the origin of such feature of the spectrum remains unresolved. Here it is proposed that the steepening of the spectrum beyond the knee may be a consequence of mass distribution of progenitor of cosmic ray source.

1. Introduction

The energy spectrum of cosmic rays is the main source of information about their origin. The most important feature of the energy spectrum is that though it extends a wide range of energies, from sub GeV to at least 3×10^{20} eV (the highest energy observed so far), it can be well represented by a steeply falling power law for energies above the solar modulated one. However, the spectrum has a knee around 3 PeV where it steepens sharply and it also has an ankle at an energy about 3 EeV where it flattens again. It is easier to interpret the flattening of the spectrum above the ankle as the eventual superseding of a harder cosmic ray component which is sub-dominant at lower energies. In contrast the feature of knee is more difficult to digest.

It is generally believed that the cosmic rays below the ankle are of galactic origin whereas those having energies above the ankle are extragalactic though there are also claims for lower transitional energies. Among the galactic sources the remnants of supernova explosions are considered as the most potential candidate [1], at least below the knee energy. Gamma Ray Bursts (GRBs) /Cannonballs [2] are also recently evolved as possible sources of cosmic rays of all energies. Whatever may be the sources, there is little doubt that they are products of stellar evolution process. And an interesting fact is that the ZAMS mass spectrum of stars also exhibits power law behavior. This immediately suggests that the cosmic ray energy spectrum could have some connection with the mass distribution of progenitor of their sources. In the present work we explore the idea and propose a model of origin of cosmic rays in which the steepening of the spectrum beyond the knee is a consequence of mass distribution of progenitor of cosmic ray sources.

2. The proposed model

Though a number of arguments favor the model of supernova (SN) origin of cosmic rays but it also suffers from some persistent problems [2, 3]. In particular, it seems that the maximum energy that a cosmic ray particle may achieve in diffusive shock acceleration process can hardly reach the ankle energy for an ordinary supernova remnant (SNR). Hence a special variety of SNe or some other type of source has to be invoked as generator of cosmic rays between the knee and the ankle. The problem with such a proposal is that it requires fine tuning to match both the flux and the energy at the point of taking over.

During the last few years a new class of SNe has been discovered which have distinctly large explosion energies compared to previously known SNe and are often called as hypernovae (HNe). The observations suggest that the kinetic energy released from HN explosion could be as much as order of two higher than that of an ordinary SN. In a recent model of origin of cosmic rays by Sveshnikova [4], HNe are considered as the dominant cosmic ray sources below the knee energy whereas type II SNe are assumed as major sources beyond the knee. Here we propose a model of origin of cosmic rays in which HNe are the sole class of major cosmic ray sources in the galaxy. The basic features of the present model are:

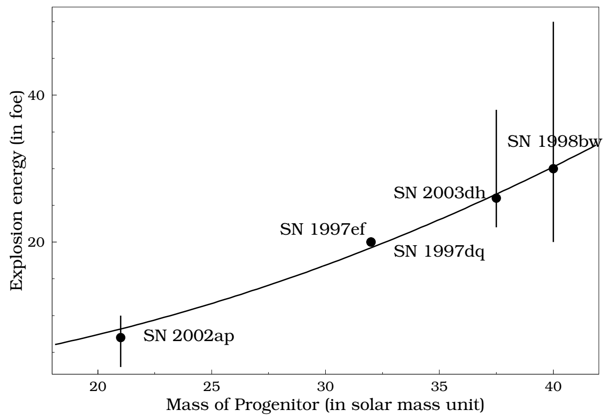

Figure 1. Explosion energy versus progenitor's mass for hypernovae

1) Hypernovae are the main sources of galactic cosmic rays. No other variety of SNe or any other type of galactic source dominates at any energy range.
2) Particles are accelerated by expanding shock waves from hypernovae up to a maximum energy E_{max}. The minimum E_{max} that is possible for HNe corresponds to the knee energy.

3. The Progenitor connection

Perhaps one distinction between a HN and an ordinary SN is whether a black hole (BH) or a neutron star (NS) is formed in the stellar evolution processes. It is generally believed that stars with $M < 20M_{\odot}$ give rise to a NS whereas stars more massive than 20 to $25M_{\odot}$ form a BH. However, it is unlikely that all BH formation events lead to a HN because this would overproduce HNe by a large factor. Probably only stars with rotating BH give rise to HNe.
The estimation of mass of the HNe progenitor, obtained from fitting of the optical light curve and spectra, indicates that they are very massive. Moreover explosion energy is found larger for larger progenitor's mass. The variation of the explosion energy with the progenitor's mass has been studied from the estimated data. So far six HNe have been discovered, SN 1997ef [5], SN 1998bw [6], SN 1999as, SN 1997dq [7], SN 2002ap [8] and SN 2003dh [9], out of which the spectral coverage of SN 1999as is not extensive. As a result the properties of this HN is not accurately known. Hence it is not included in the analysis. The parameters of HNe as estimated in different works are, however, not unique. But the general trend is that the explosion energy increases rapidly with the progenitor's mass. The variation can be described by a power law $\epsilon_{HN} \sim M^{\zeta}$ with ζ is around 2.0 (Figure 1). The mass of the ejected material also found to increase in similar manner [10].

Whether there is any upper mass cutoff of the stars is not conclusively known yet. A recent study on mass distribution in a massive and apparently young cluster Arches near the galactic centre indicate that the maximum mass that a star can possess in the Galaxy is around 150 solar mass [12]. This corresponds to a explosion energy of around 5×10^{53} erg which is larger by an order than the observed maximum kinetic energy in a HN explosion and thus may appear questionable. However, it needs to keep in mind that though HNe explosions generate enormous amount of kinetic energies, they are discovered only recently.
The stellar initial mass function, or distribution of masses with which stars are formed can be approximated by a declining power law [13, 14]. The exact slope of the mass function, however, has been subject of intense

discussion. For higher mass range (mass greater than 10 solar mass) the distribution is found steeper than the Salpeter slope of $\Gamma = -1.35$ and is better represented by $\Gamma = -1.7$ [15]. The expected explosion energy distribution of HNe, thus, can be represented by

$$N(>\epsilon_{HN}) \sim \epsilon_{HN}^{-\alpha} \quad (1)$$

where α is expected to be around ~ 0.85.

4. The Cosmic Ray Spectrum

In the present model cosmic rays are accelerated in sub-relativistic or in mildly relativistic shocks produced in HN explosions. Hence the energy spectrum of accelerated particles is given by $\frac{dn}{dE} \sim E^{-\gamma}$ where γ is around 2 to 2.1. Due to diffusive propagation of cosmic rays through the interstellar medium slope of the resulting spectrum would be steepen to ~ 2.7.
However, all HNe do not have the same E_{max}. Contribution of a single hypernova is given by

$$\frac{dn}{dE} \simeq \frac{\xi\epsilon_{HN}}{log(E_{max}/m_A)} \quad (2)$$

As explosion energy increases the generation of accelerated particles by a hypernova also increases. However, the frequency of the hypernovae of larger energies is small and is governed by the mass distribution of progenotor. The maximum energy roughly goes as $E_{max} \propto \epsilon_{HN}^{1/2}/M_{ej}^{1/6}$. So the distribution of E_{max} follows from that of distribution of progenitor's mass as $N(>E_{max}) \sim E_{max}^{-\beta}$ where β is around 2.4. Consequently the slope of the energy spectrum would be steeper by ~ 0.4 after the knee.

5. Discussion

As shown by Sveshnikova [4], hypernovae can satisfy the power requirement for accelerating all galactic cosmic rays. In doing so the rate of hypernovae is assumed as $2 \times 10^{-4}\ yr^{-1}$ which seems larger than the observed rate of $\sim 10^{-5}\ yr^{-1}$ [16]. However, HNe are detected only recently, during last few years and it appears from the detection rate that HNe explosions are more frequent than that obtained from the present data. Moreover, the observed rate of Type 1b and 1c SNe is around $10^{-3}\ yr^{-1}$. The rate of stars having $M > 20M_{\odot}$ is $2 \times 10^{-3}\ yr^{-1}$. Hence an event rate of at least $10^{-4}\ yr^{-1}$ for the hypernovae seems very likely.
The main problem is, however, the maximum energy attainable in the acceleration process. In the standard scenario of cosmic ray origin, the acceleration occurs at the shocks of isolated SNRs. The maximum energy that can be attained by a cosmic ray nuclei in the process when the remnant is passing through a medium of density $N_H\ cm^{-3}$ is [17]

$$E_{max} \simeq 4 \times 10^5 Z \left(\frac{E_{SN}}{10^{51}\ erg}\right)^{1/2} \left(\frac{M_{ej}}{10M_{\odot}}\right)^{-1/6} \left(\frac{N_H}{3 \times 10^{-3}\ cm^{-3}}\right)^{-1/3} \left(\frac{B_o}{3\mu G}\right)\ GeV \quad (3)$$

The above expression is valid for HNe also as they belong to a class (SN type 1c) of SNe. An explosion energy of around 10^{51} erg can give E_{max} equal to knee energy for realistic values of the other relevant parameters. The main question is whether or not E_{max} could reach the ankle energy. The E_{max} increases very slowly with mass and it is difficult to reach the ankle energy. However, as the explosion energy increases the shock velocity becomes relativistic and hence the above expression for maximum energy does not valid in such situation. So more analysis is required before any final conclusion.

According to the present model, cosmic rays below and just above the knee region are produced in HNRs of comparable progenitor's mass. Hence there should not be any abrupt change in mass composition through the knee. The observations appear to support such a scenario [18]. The higher energy particles originated from the source of heavier progenitor, thus resulting composition is expected to become heavier as observed. The other features of cosmic ray composition scenario also favors for massive progenitor of cosmic ray sources as adopted in the present model.

6. Conclusion

Recent observations clearly indicate that HNe are associated with GRBs. Hence there is a possibility that energy released in GRBs are also related with the progenitor's mass and the present explanation of steepening of the spectrum beyond the knee may also be applicable for the model of GRB origin of cosmic rays.

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