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Progenitor model of cosmic ray knee

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Abstract The 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 a feature in the spectrum is not satisfactorily solved yet. Here it is proposed that the steepening of the spectrum beyond the knee may be a consequence of the mass distribution of the progenitor of the cosmic ray source. The proposed speculative model can account for all the major observed features of cosmic rays without invoking any fine tuning to match flux or spectra at any energy point. The prediction of the proposed model regarding the primary composition scenario beyond the knee is quite different from most of the prevailing models of the knee, and thereby can be discriminated from precise experimental measurement of the primary composition.

Key words: cosmic rays — acceleration of particles — black hole physics

1 INTRODUCTION

Ever since their discovery more than a hundred years ago, the origin of cosmic rays has been one of the central questions in physics. But despite many efforts, so far there is no consistent and complete model of the origin of cosmic rays.

The energy spectrum of cosmic rays provides important clues about their origin. The most intriguing feature of the energy spectrum is that although it extends over 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 as discovered more than half a century ago by Kulikov and Khristiansen of Moscow State University (Kulikov & Khristiansen 1959). The spectrum also has an ankle at an energy of about 3 EeV where it flattens again to its pre-knee slope. It is relatively 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 the knee is more difficult to explain. The existence of the knee in the spectrum is definitely an important imprint of the true model of the origin of cosmic rays and hence a proper explanation of the knee is expected to shed light on the problem of cosmic ray origins.

Several mechanisms have been proposed so far to explain the knee. Shortly after the discovery of the knee, this spectral feature was interpreted as an effect of the reduced efficiency of the galactic magnetic field to confine cosmic ray particles with energies above the knee within the galaxy (Ginzburg & Syrovatskii 1964; Wdowczyk & Wolfendale 1984; Ptuskin et al. 1993; Candia et al. 2002b; Giacinti et al. 2014). Since the magnetic rigidity of a particle is proportional to its atomic number (Z), cosmic ray protons should start escaping first and hence the observed knee is the proton knee as per this model.

The knee has also been explained based on the acceleration mechanism (Fichtel & Linsley 1986; Jokipii & Morfill 1987; Biermann 1993; Berezhko & Ksenofontov 1999; Stanev et al. 1993; Kobayakawa et al. 2002). For reasons of the power required to maintain the observed cosmic ray energy density, it is widely accepted that cosmic rays up to the ankle energy are of galactic origin whereas those having energies above this energy are extragalactic, though there are also suggestions for lower transitional energies (Blasi 2014; Amato 2014; Aloisio et al. 2012). Among the galactic sources, supernova remnants (SNRs) satisfy the energy budget of cosmic rays. The power law behavior of the energy spectrum on the other hand suggests that cosmic rays are most probably energized by diffusive shock acceleration. The maximum energy that a charged particle can gain by diffusive shock acceleration is proportional to Z. The knee has been assigned in this model as the maximum energy that protons can have under diffusive shock acceleration in SNRs.

A critical analysis of data collected at different experiments worldwide in terms of the energy spectrum suggests that the knee is very sharp, and the spectral slope changes rather abruptly at the knee position (Erlykin & Wolfendale 1997). In contrast, the above mentioned rigidity dependent explanations of the knee predict a smooth change in the spectral slope at the knee because of the sum of the contributions of different atomic nuclei having cut-offs at different energies (depending on Z values). To accommodate the sharp knee feature, a few proposals have been advanced. In the single source model the dominant contribution of the cosmic ray flux at the knee is by a nearby source (Erlykin & Wolfendale 1997; Bhadra 2005; Erlykin et al. 2011; Ter-Antonyan 2014) which is superimposed on a galactic modulated component in which the spectral slope is changing smoothly with energy. In another model the sharp knee is explained in terms of cosmic ray acceleration by a variety of supernovae (SNe) (Sveshnikova 2004, 2003). The later proposal relies on the fact that the explosion energy of all SNe is not the same. The sharp knee also could be due to interaction of cosmic ray particles from a pulsar with radiation from the parent SNR (Hu et al. 2009).

The mass composition of cosmic rays will be heavier beyond the knee if the knee is a proton knee. Several Extensive Air Shower (EAS) measurements (till now the study of cosmic rays above 1 PeV has been of an indirect nature via EAS observations) have been made to determine the mass composition of cosmic rays in the energy region of interest, but the measurements have not yielded mutually consistent results yet due to the weak mass resolution of the measured shower observables (Haungs 2011). Most of the findings (Navarra 1998; Glasmacher et al. 1999; Aartsen et al. 2013; Fomin et al. 1996) based on electron content relative to muon content (or *vice versa*) in EAS suggest that composition becomes heavier with energy beyond the knee, though the Haverah Park experiment and a few other observations (particularly underground muon telescopes) (Blake & Nash 1998, 1995; Danilova et al. 1995; Saha et al. 1998; Aglietta et al. 1990; Ahlen et al. 1992; Kasahara et al. 1997; Longley et al. 1995; Bakatanov et al. 1999) found the opposite trend for mass composition. Mass composition estimated from the measurement of the depth of shower maximum through observation of Cerenkov (Boothby et al. 1997; Swordy & Kieda 2000; Fowler et al. 2001; Chernov et al. 2005; Karle et al. 1995; HEGRA-Collaboration et al. 2000; Dickinson 1999; Efimov & et al. 1991) or fluorescence radiation (Abraham et al. 2010; Abbasi et al. 2008, 2004; Tsunesada 2011; Jui & Telescope Array Collaboration 2012), on the other hand, suggests a lighter mass composition beyond the knee differing from that obtained with muon to electron content ratio (Haungs 2011; Hörandel 2013; Bhadra & Sanyal 2005). The mass composition picture of primary cosmic rays is thus still inconclusive in the PeV and higher energy region.

Considering the possibility that mass composition may become lighter beyond the knee, an alternative explanation of the knee was suggested based on nuclear photo-disintegration at the sources (Hillas 1979; Karakula & Tkaczyk 1993; Candia et al. 2002a). In this scenario, heavier components of cosmic rays, particularly Fe nuclei, undergo nuclear photo-disintegration in interactions with the radiation field of the source so that the flux of heavier nuclei decreases with energy beyond the knee whereas protons lose energy by photo-meson production.

A major problem with the standard scenario of diffusive shock acceleration of cosmic rays in SNRs is that a cosmic ray particle can hardly attain the knee energy under this SNR shock acceleration scenario. Such a problem can be overcome in the Cannonball model (Dar & Plaga 1999; Plaga 2002; Dar 2005; de Rújula 2005) in which masses of baryonic plasma or the so called cannonballs, ejected ultra-relativistically in bipolar SN explosions, are considered to be universal sources of hadronic galactic cosmic rays. In this model, the knee corresponds to the maximum energy gained by nuclei through elastic magnetic scattering of ambient particles from the interstellar medium (ISM) in the cannonball while re-acceleration of cosmic rays by cannonballs from other SN explosions causes the extra steepness above the knee.

There is also a proposal of explaining the knee based on a change in the characteristics of high energy interactions (Nikolsky & Romachin 2000). In this model the knee is not a feature of the primary cosmic ray energy spectrum itself, but is caused by the change in high-energy interaction characteristics, either producing a new type of a heavy particle unseen by air shower experiments, or an abrupt increase in the multiplicity of produced particles. However, this proposal has been ruled out at present as the assumed interaction features have not been observed in the Large Hadron Collider experiment.

None of the prevailing models of the knee are free from problems. If the knee corresponds to a break in the proton spectrum, either because it is the maximum energy to which the proton can be accelerated in a galactic cosmic ray source or due to the start of proton leakage from the galaxy at this energy with or without modifications to the sharp knee, then there should be an Fe knee around 10^{17} eV. Hence a special variety of SNe or some other type of galactic or extragalactic source has to be invoked as a generator of cosmic rays between $\sim 10^{17}$ eV and the ankle or galactic-extragalactic transition should occur around 10^{17} eV. The problem with the latter proposal is that it requires fine-tuning to match both the flux and energy at the point where take over occurs. The Cannonball model also suffers the same fine tuning problem at the knee energy. There are other problems such as lower than expected observed gamma ray fluxes from SNRs. The dilemma of the knee thus still continues.

The viable sources of cosmic rays include SNRs, pulsars, gamma ray bursts (GRBs), active galactic nuclei (AGNs), etc. Whatever may be the sources, there is little doubt that they are products of the stellar evolution process. An interesting fact is that the zero age mass spectrum of stars also exhibits power law behavior (Salpeter 1955; Kroupa 2002; Massey et al. 1995). This immediately suggests that the cosmic ray energy spectrum might have some connection with the mass distribution of the progenitor of their sources. In the present work we explore the idea and propose a model for the cosmic ray origin in which the knee of the primary cosmic ray energy spectrum at ~ 3 PeV is a consequence of mass distribution of the progenitor of cosmic ray sources. The proposed model is free from any fine tuning problem and it also overcomes the issue of maximum attainable energy.

The organization of the article is as follows. The model proposed in this work is presented in the next section. The outcome of the present model is discussed in Section 3. The results of the model are compared with observations in Section 4. Finally the results are concluded in Section 5.

2 THE PROPOSED MODEL

Here we propose a model of the origin of cosmic rays in which there is a single class of major cosmic ray sources in the galaxy.

The basic conjectures of the present model are the following:

(1) Cosmic rays, at least up to the ankle energy, are produced either in gravitational explosions (core collapse) of massive stars that lead to formation of black holes (BHs) rather than neutron stars (NSs), or in accretion onto BHs. No other type of galactic or extragalactic source dominates at least up to the ankle energy. Here we have not identified the source. The probable candidate sources of cosmic rays include hypernovae, AGNs and GRBs.

(2) Particles are accelerated by expanding shock waves up to a maximum energy $E_{\rm max}$. The maximum attainable energy $E_{\rm max}$ is, however, not the same for all the sources (of the same kind) but, depending on energy released in explosion/accretion, it has a range. The minimum $E_{\rm max}$ that is possible for cosmic ray sources is equal to the knee energy. We shall argue in the following section that the correspondence of minimum $E_{\rm max}$ with the knee energy is quite plausible and suggestive.

The observed cosmic ray luminosity demands that the cosmic ray sources must be energetically very powerful and are most likely to be powered by gravitational energy. The gravitational collapse that ultimately leads to the formation of a BH or accretion onto a BH is expected to release the maximum gravitational energy. This is the reason for considering the first conjecture. The maximum energy that a cosmic ray particle can attain in shock acceleration usually depends on the explosion energy. Since a BH has no limiting mass, energy released in BH formation should vary with progenitor mass and hence the maximum attainable energies of cosmic ray particles are expected to vary rather than having a fixed value. Essentially, this is the logic behind the second conjecture.

2.1 The Progenitor Connection

Perhaps the occurrence of relativistic shock and non-relativistic shock depends on whether a BH or an NS is formed in the stellar evolution processes. Through stellar core collapse, progenitor stars with $M < 20\ M_\odot$ are supposed to give rise to an NS or white dwarf whereas stars more massive than 20 to 25 $M_\odot$ form a BH (Fryer 1999; Fryer & Heger 2000; Fryer 2003), though such an end point fate also depends on metallicity (Heger et al. 2003). The formation of an NS is usually associated with an SN explosion. The masses of white dwarfs and NSs have to be within the Chandrasekhar limit and Oppenheimer-Volkoff limit respectively. Consequently, the energy released in all ordinary SN explosions is nearly the same. Since a BH has no such upper mass limit, the energy released in the core collapse of massive stars leading to BHs should depend on the mass of the progenitor star.

The gravitational collapse of massive stars to BHs involves some complex, still poorly understood aspects of stellar physics. In the collapsar mechanism (Woosley 1993), a BH is formed when the collapse of a massive star fails to produce a strong SN explosion, leading to its ultimate collapse into a BH. If the stellar material falling back and accreting onto the BH has sufficient angular momentum, it can hang up, forming a disk. This disk, by neutrino annihilation or magnetic fields, is thought to produce the jets which finally results in AGNs or hypernovae.

In the gravitational collapse of a spherical mass distribution with rest mass M leading to formation of a BH, the maximum energy of extraction out of the collapse will be (Ruffini & Vitagliano 2003; Christodoulou & Ruffini 1971),

$$E_{\rm max}^{\rm collapse} = Mc^2/2\,. \tag{1}$$

During the final stages of stellar evolution, a massive star loses a significant amount of mass. But if a BH is formed, stellar material is likely to fall back and accrete onto the BH (Woosley 1993). The mass of the final produced BH is thus expected to increase linearly with the mass of the progenitor, and hence the distribution of released energy is expected to follow the mass distribution of progenitors.

Instead of a collapse and resulting explosion, a large amount of energy can also be released through the accretion process. The Eddington limit, the maximum steady-state luminosity that can be produced, is given by $L_{\rm ed} = 4\pi G M m_{\rm p} c/\sigma_\tau$ where M is the mass of the BH, $m_{\rm p}$ is the proton mass and σ_τ is the Thomson cross section. The luminosity is thus also proportional to the mass of the BH.

3 OUTCOMES OF THE PROPOSED MODEL

We shall now explore the outcomes of the proposed model regarding the main cosmic ray observables such as luminosity, maximum attainable energy, energy spectrum and nuclear composition.

3.1 The Cosmic Ray Luminosity

The average energy released in BH formation should be around 5×10^{53} erg as per Equation (1), which is more than two orders higher than that released in an SN explosion. Stars more massive than 20 to 25 $M_\odot$ usually form a BH. The rate of stars having $M > 20\ M_\odot$ is $2 \times 10^{-3}\ \mathrm{yr}^{-1}$. However, not all massive stars will end up as BHs. If we denote the probability of BH formation for a star more massive than 20 $M_\odot$ as $\rho_{\rm BH}$, the total energy released in BH production during the cosmic ray confinement period of about 10^6 years in the galaxy is about $\rho_{\rm BH} 10^{57}$ erg. This yields a luminosity of $3\rho_{\rm BH}\zeta \times 10^{43}$ erg s^{-1}, where ζ is the efficiency of conversion of explosion energy into cosmic ray energy. Typically ζ ranges from 0.01 to 0.1 whereas $\rho_{\rm BH}$ may be taken as 0.5 (Clausen et al. 2015).

3.2 The Maximum Attainable Energy

The maximum energy that a particle with charge Ze can attain in a bulk magnetized flow on a scale $R_{\rm s}$, with velocity $c\beta_{\rm s}$ and magnetic field B, is (Hillas 1984)

$$E_{\rm max} = ZeB\Gamma_{\rm s}\beta_{\rm s}R_{\rm s}\,, \quad (2)$$

where $\Gamma_{\rm s}$ is the Lorentz factor of the relativistic shock wave. This value of $E_{\rm max}$ is a factor $\Gamma_{\rm s}$ larger than that obtained from the Hillas condition. In a BH formation scenario, a fraction of all kinetic energy carries debris ejected with the largest Lorentz factor, thereby generating gamma ray emission in the form of a burst, but the bulk of ejecta is less relativistic or even sub-relativistic. Note that if $\sim 10\ M_\odot$ is given $\sim 10^{54}$ erg then the typical velocity of the mass would be 10^{10} cm, i.e. $c/3$. GRBs are likely to occur in BH formation collapse and a hint on typical values of $\Gamma_{\rm s}$ may be found from GRBs. The GRB observations suggest the minimum $\Gamma_{\rm s}$ of the burst is a few tens (Racusin et al. 2011; Lithwick & Sari 2001; Zou et al. 2011). Therefore, the minimum $E_{\rm max}$ for a BH producing an explosion should be a few PeV.

Let us consider a more rigorous description. In the standard scenario the acceleration of cosmic rays occurs at (non-relativistic) shocks of isolated SNRs. The maximum energy that can be attained by a cosmic ray particle in an ordinary SNR when the remnant is passing through a medium of density $N_{\rm H}\ \mathrm{cm}^{-3}$ is (Fichtel & Linsley 1986; Biermann 1993; Berezhko & Ksenofontov 1999)

$$E_{\rm max} \simeq 4 \times 10^5 Z \left(\frac{E_{\rm SN}}{10^{51}\ \mathrm{erg}}\right)^{1/2} \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-1/6} \left(\frac{N_{\rm H}}{3 \times 10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1/3} \left(\frac{B_{\rm o}}{3\mu G}\right)\ \mathrm{GeV}\,, \quad (3)$$

which falls short of the knee by about one order of magnitude. Energy released in BH formation explosions is at least two orders higher than that in SN explosions. Moreover, as stated before, for relativistic shock acceleration $E_{\rm max}$ will be a factor $\Gamma_{\rm s}$ higher. Hence the minimum $E_{\rm max}$ for an explosion that produces a BH should be a few PeV.

An important question for such an explosion that forms a BH in terms of the origin of cosmic rays is whether or not $E_{\rm max}$ could reach the ankle energy. Unlike the almost constant energy released in SN explosions, energy output in such a scenario varies and it may increase at least two orders higher than its minimum value. Such high energy events are expected to occur in a more rarefied medium. Hence it is very likely that the maximum $E_{\rm max}$ will exceed the ankle energy.

Interestingly, the AGN minimum $E_{\rm max}$ is about 3 PeV (Stecker et al. 1991) which is the knee energy and the maximum $E_{\rm max}$ can be many orders higher than that owing to the wide range of luminosities of AGNs.

3.3 Energy Spectrum

In the proposed model, cosmic rays are accelerated in diffusive relativistic shock acceleration. The energy spectrum of accelerated particles in each source is, therefore, given by a power law

$$\frac{dn}{dE} = AE^{-\gamma}\,, \quad (4)$$

with γ around 2.2, and A the normalization constant

$$A \equiv \frac{\epsilon}{(\gamma-2)(E_{\rm min}^{-\gamma+2} - E_{\rm max}^{-\gamma+2})}\,, \quad (5)$$

where $E_{\rm min}$ and $E_{\rm max}$ are respectively the minimum and maximum attainable energies of cosmic ray particles in the source.

The sources do not all have the same $E_{\rm max}$. Above the minimum possible $E_{\rm max}$, which we denote as $E_{\rm max}^{\rm min}$, the spectrum will be modified due to the distribution of $E_{\rm max}$. To get the spectrum beyond $E_{\rm max}^{\rm min}$ we need to obtain the maximum energy distribution of the cosmic ray sources from the mass distribution of their progenitors. The calculation involves a sequence of steps. Using the expression for explosion energy as a function of progenitor mass as obtained in the previous section, we convolve the resulting explosion energy-progenitor mass relation with the initial mass function of the progenitors to obtain the explosion energy distribution. Subsequently using the relation of maximum energy that a cosmic ray particle may attain in the relativistic shock acceleration process with explosion energy, we derive the maximum energy distribution for main cosmic ray sources. Using such a distribution we obtain the energy spectrum of cosmic rays beyond the $E_{\rm max}^{\rm min}$.

The stellar initial mass function, or distribution of masses with which stars are formed, can be represented by a declining power law

$$\frac{dn}{dM} \propto M^{-\alpha}\,, \tag{6}$$

with the universal (Salpeter) value of the exponent $\alpha = -2.35$ over the whole mass range above $3\ M_\odot$ (Salpeter 1955; Kroupa 2002; Massey et al. 1995). Since explosion energy (ϵ) scales linearly with M, the expected explosion energy distribution of massive progenitor stars is also represented by $\frac{dn}{d\epsilon} \propto \epsilon^{-\alpha}$.

The Lorentz factor of a relativistic shock is nearly equal to the initial Lorentz factor of the jet, i.e. $\Gamma_{\rm s} \sim \gamma_o$. The relativistic shock waves must carry a significant fraction of the explosion energy which is subsequently converted to energies of cosmic rays. Hence, $\Gamma_{\rm s}$ should be proportional to explosion energy. On the other hand, $E_{\rm max}$ is also proportional to $\Gamma_{\rm s}$. So for the proposed model, $E_{\rm max} \propto \epsilon$. Thus we have

$$\frac{dn}{dE_{\rm max}} \propto E_{\rm max}^{-\alpha}\,. \tag{7}$$

Therefore, the number of sources having $E_{\rm max} \geq E$ is $j(E_{\rm max} \geq E) \propto E_{\rm max}^{-\alpha+1}$. As the minimum $E_{\rm max}$ of a source is equal to $E_{\rm max}^{\rm min}$, all such sources will contribute to cosmic ray flux when cosmic ray energy is below or equal to $E_{\rm max}^{\rm min}$. However, for energies above $E_{\rm max}^{\rm min}$ ($E > E_{\rm max}^{\rm min}$), only sources having $E_{\rm max} \geq E$ will contribute. The resultant cosmic ray spectrum above $E_{\rm max}^{\rm min}$ will be

$$\frac{dn}{dE} = \int_E \frac{dn}{dE_{\rm max}} A E^{-\gamma} dE_{\rm max} \propto E^{-\gamma-\alpha+2}\,. \tag{8}$$

Therefore, beyond $E_{\rm max}^{\rm min}$ the spectrum should steepen by 0.35 in spectral index as observed. Note that the difference in the exponent of energy by one between the above equation and Equation (3) of Kachelrieß & Semikoz (2006). There the power law distribution of the maximum attainable energy of sources was assumed, due to the fact that our normalization constant A is proportional to the explosion energy (and hence to the maximum attainable energy), unlike the normalization constant that is independent of explosion energy that was adopted in Kachelrieß & Semikoz (2006).

3.4 Mass Composition

According to the proposed model, cosmic rays below and just above $E_{\rm max}^{\rm min}$ are produced in explosions that form a BH comparable to the progenitor's mass. Hence there should not be any abrupt change in mass composition through the $E_{\rm max}^{\rm min}$. In this model, higher energy particles originate from the sources with heavier progenitors. Since a BH is the last stage of evolution for massive stellar objects, the composition is unlikely to change much for BHs from heavier progenitors. Therefore, the resulting composition of accelerated cosmic rays in the proposed model is expected to remain almost unaltered with energy or may become slightly heavier at higher energies.

4 DISCUSSION

We shall now compare the outcomes of the proposed model against the observational features of cosmic rays.

The conventional estimate of cosmic ray luminosity in our galaxy is $\sim 5 \times 10^{40}$ erg s^{-1}. As shown in the previous section, the proposed model yields a cosmic ray luminosity equal to $3\rho_{\rm BH}\zeta \times 10^{43}$ erg s^{-1}. Typically ζ ranges from 0.01 to 0.1 whereas $\rho_{\rm BH}$ is around 0.5 (Clausen et al. 2015). Therefore, the power from explosions that produce BHs in the galaxy satisfies the power requirement for accelerating all galactic cosmic rays. Note that with the rate of occurrence of one per thirty years and the average energy released in each SN explosion of around 10^{51} erg, SNRs satisfy the energy budget for observed cosmic rays (and hence are favored as the main source of cosmic rays) provided the energy conversion efficiency parameter ζ is relatively higher, around 0.1 to 0.2.

The maximum energy that can be attained by a cosmic ray particle in relativistic shock acceleration under the framework of the proposed model varies from source to source (of the same kind). Because of the relativistic effect (through the Lorentz factor) and owing to the much larger explosion energy, the minimum $E_{\rm max}$ for cosmic rays is found to equal a few PeV as shown in the previous section, which can be identified as the knee energy. Interestingly, the minimum $E_{\rm max}$ for an AGN is about 3 PeV (Stecker et al. 1991), whereas the maximum $E_{\rm max}$ is found to exceed even the ankle energy. So, the maximum attainable energy requirement is satisfied in a generic way. In contrast, the maximum energy that can be attained by a cosmic ray particle in an ordinary SNR is 0.3 PeV which falls short of the knee by about one order of magnitude unless the idea of magnetic amplification is invoked. Even with magnetic amplification, it is difficult to exceed 100 PeV and thereby a new source with an unknown nature is required between 100 PeV and the ankle energy.

Since the proposed model relies on standard shock acceleration theory, the overall cosmic ray production spectrum will follow a power law behavior with spectral index equal to –2.2. Due to diffusive propagation of cosmic rays through the ISM, the slope of the spectrum recorded at Earth should steepen to ~ 2.7 till the knee of the spectrum, and the knee should be as sharp as observed. Above the knee, the spectrum will be modified by 0.35 due to the distribution of $E_{\rm max}$ as demonstrated in Section 3.3. Thus the proposed model explains well the observed features of the energy spectrum of primary cosmic rays.

With respect to the mass composition of cosmic rays, particularly above the knee energy, the composition predicted by the model is similar to that of the Cannonball model but different from the prediction of the SN model that has a cosmic ray origin.

Very recent findings by the KASCADE-GRANDE collaboration regarding the existence of an Fe-knee around 80 PeV along with the composition scenario that is dominated by heavier particles (Apel et al. 2013, 2012, 2011), together with earlier results of the KASCADE experiment for a proton knee at 3 PeV (Apel et al. 2009), do not support the composition picture predicted by the proposed model. Importantly in the overlapping energy region around 1 EeV, the composition scenario inferred from the KASCADE-GRANDE or ICETOP findings, with a mixed composition having nearly the same contribution from protons and iron nuclei (Apel et al. 2009), is not in agreement with a proton dominated chemical composition that emerged from observations at the Pierre Auger Observatory (Abraham et al. 2010), HiRes (Abbasi et al. 2008, 2004) and Telescope Array (Tsunesada 2011; Jui & Telescope Array Collaboration 2012). This only shows the difficulty in estimating primary masses from air shower experiments that rest on comparisons of data with EAS simulations where the latter requires hadronic interaction models as input, which are still uncertain to a large extent at present. Moreover, the uniqueness of solutions of primary energy spectra in the knee region from EAS data is also questioned (Ter-Antonyan 2007). It is expected that the mass composition scenario predicted by the present model will motivate newer experiments, exploiting both muon to electron content ratio and optical techniques, to establish unambiguous cosmic ray mass composition in the knee region and in particular to confirm the KASCADE-Grande results including the Fe-knee.

An important question is to identify the sources, or more precisely identifying the gravitational explosions, that lead to formation of BHs. The viable galactic sources resulting in BH formation include Type 1b/1c SNe and hypernovae, whereas GRBs and AGNs seem to be possible extragalactic sources. The observed rate of Type 1b and 1c SNe is around $10^{-3}\ \mathrm{yr}^{-1}$ which is close to the rate of stars having mass greater than $20\ M_{\odot}$. Radio observations suggest that about 5% of Type 1b/1c SNe can be produced in GRBs (Berger et al. 2003). Earlier, Sveshnikova demonstrated that hypernovae can satisfy the power requirement for accelerating all galactic cosmic rays (Sveshnikova 2004) assuming the rate of hypernovae is about 10^{-4} yr^{-1}. The extragalactic origin of cosmic rays is usually considered to be unlikely on energetic grounds. However, such a problem can be circumvented by employing the flux trapping hypothesis as proposed in (Plaga 1998; Burbidge 1962). Hence the possibility of a GRB/AGN as the sole kind of dominant source of cosmic rays cannot be totally ruled out from an energetic consideration.

5 CONCLUSIONS

In summary, the proposed speculative BH based model of the origin of cosmic rays can account for all the major observed features of cosmic rays without any serious contradiction to observational results. The knee of the energy spectrum has been ascribed as a consequence of the mass distribution of the progenitor of the cosmic ray source. Such a philosophy seems applicable to the Cannonball model of cosmic ray origin, replacing the original proposal of second order Fermi acceleration of cosmic rays by Cannonballs of other SN explosions as the cause of spectral steepening above the knee (Dar & Plaga 1999; Plaga 2002; Dar 2005; de Rújula 2005). Precise measurement of the primary mass composition can be used to discriminate the proposed model from most of the standard prevailing models of the cosmic ray knee. No definite cosmic ray sources could be identified at this stage within the framework of the proposed model, which would be an important future task for further development of the proposed model.

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