PRODUCTION AND ACCELERATION OF ULTRA HIGH ENERGY PARTICLES BY BLACK HOLES AND STRINGS

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ABSTRACT Some possible new mechanisms based on physical processes associated with objects such as black holes and strings are outlines to account for the production of extremely energetic cosmic ray particles (> 10^{20} eV) such as the 300 EeV event

Keywords UHE particles, decaying cosmic superstrings, evaporating black holes

Conventional supernova remnant models cannot accelerate cosmic ray particles to much above energies $\sim 10^{14} eV$ As is well known, this is essentially bceause the interstellar magnetic field is only $\sim 5 \mu G$ However, the cosmic ray spectrum is observed to continue through the 'knee' to much higher energies Pulsars are possible sources or sites for acceleration to higher energies Even here there are limits ($\sim 10^{18} eV$) or at most $\sim 10^{19} eV$ for iron nuclei

Moreover acceleration near neutron stars is difficult because of the high energy loss rates of charged particles in intense magnetic fields Consequently in some models the acceleration sites are located further into the relativistic wind region In short none of these processes can account for particles of $\sim$ 300 EeV energy A proton with such energy will pass straight through the galaxy The Larmor radius of a 300 EeV proton in the galactic magnetic field is $\sim$ 100 Kpc and the estimated maximum propagation length is $\sim$ 30 Mpc

As acceleration in pulsar magnetic and electric fields is clearly inadequate by a large factor to produce such energetic particles one can consider more compact objects than neutron stars, i e black holes As an illustration of the potential (in a literal sense!) of such objects to produce ultra high energy (UHE) particles we next discuss the acceleration of charged particles by electrically charged black holes Such black holes are predicted to exist and for a black hole of mass M and charge Q, the radius of the event horizon[1] is given by

$$r = GM/c^2 \pm [\frac{G^2M^2}{c^4} + \frac{GQ^2}{c^4}]^{1/2} \qquad (1)$$

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(G is the gravitational constant and c the velocity of light) The maximal electric charge that a black hole of mass M can have is given by

$$Q = G^{1/2} M \tag{2}$$

This implies that a particle with charge e, approaching such a black hole would have at the horizon, i e. on reaching $r_s = GM/c^2$, an energy given by (i e maximum possible energy)

$$E_{max} \simeq \frac{G^{1/2} Me}{GM/c^2} = \frac{c^2 e}{G^{1/2}} \simeq 10^{25}\ eV \tag{3}$$

This is a number independent of the black hole mass This is potentially the maximal energy (allowed by general relativity) to which a proton can be accelerated to by a charged black hole In general the equation of motion is. (for particle of mass m)

$$\ddot{x} = \frac{G^{1/2} Me}{mx^2} - \frac{e^2}{3c^3}\dddot{x} + \textit{higher order terms} \tag{4}$$

where x is the position co-ordinate

Electrons would lose energy at a far more rapid rate, as loss rate is proportional to $(\ddot{x})^2$ which in turn is proportional to $1/m^2$ So electrons as usual will not be accelerated to very high energies

Solution[2] of eq (4) shows that a proton deflected at $r \simeq 3r_s$, can leave the hyperbolic trajectory with a maximal energy $\sim 10^{23} eV$ Below $r < 3r_s$, as is well known, orbits are unstable

It is also well known[3] that charged black holes can have a magnetic dipole moment (indeed for a rotating charged black hole, the gyromagnetic ratio is 2, the same as for a Dirac particle) Such a black hole can thus also interact with a particle having a magnetic moment The interaction energy in this case is given by

$$E_{int} \simeq \frac{{}^{\mu}BH\,{}^{\mu}P}{r^3} \times \textit{curved space factors} \tag{5}$$

Here ${}^{\mu}$BH and ${}^{\mu}$P are the magnetic dipole moments of the black hole and the particle respectively

For ${}^{\mu}P \approx {}^{\mu}B$ (the Bohr magneton) and for a maximally charged hole (cf eq (2)) this gives a maximal energy (at $r = r_s$) of

$$E_{max} \simeq \frac{{}^{\mu}Bc^4}{MG^{3/2}} \tag{6}$$

For a 10^{17} gm primordial Hawking black hole (to be discussed later) this gives (note E α 1/M)

$$E_{max} \simeq 10^{23} eV$$

The equations of motion can also be written down for this case as in the earlier example (cf eg (4)) If the black hole is embedded in a magnetic field such high energy particles accelerated by the hole can also emit ultra high frequency gamma radiation (suppressed by $1/m^4$) However, this turns out not to be significant

We next consider the acceleration of particles by cosmic strings and fundamental superstrings Superstrings are produced near the Planck scale (energy E_{pl} or $M_{pl} \sim 10^{19}$ GeV) They are characterized by a tension $T_{pl} \sim c^2/G$ (mass per unit length) $T_{pl} \sim 10^{28} gcm^{-1}$ strings produced by symmetry breaking at any other energy (mass scale) $\sim M$ have a tension given by

$$T_s \simeq \frac{c^2}{G}(\frac{M}{M_{pl}})^2 \tag{7}$$

In addition one can have conducting cosmic strings which are essentially topological line defects

There are some nice analogies between vortex lines in a Type II superconductor (carrying a quantized flux $\hbar c/2e$) and conducting cosmic strings For instance, the field vanishes everywhere in a superconductor (Meissner effect), i e $F_{ab} = 0$, everywhere except along Abrikosov vortex lines carrying a confined quantized flux $\hbar c/2e$ Inside a superconductor we have the Landau equations

$$\Delta^2 \bar{B} + \lambda^2 \bar{B} = \bar{J} \tag{8}$$

The vanishing of the field inside a superconductor is an effect of the Landau-Ginzburg theory where we have the Maxwell field coupled to a scalar field as

$$D_\mu D^\mu \phi = a\phi(\mid \phi \mid^2 - \lambda^2) \tag{9}$$

$\mid \phi \mid \simeq \lambda$ near the broken symmetric state
Far from the flux tube

$$D_\mu \phi = (\delta_\mu + ieA_\mu)\phi = 0$$

and

$$[D_\mu, D_\nu]\phi = ieF_{\mu\nu}\phi = 0$$

So either ϕ or $F_{\mu\nu}$ must vanish This has the solution

$$A_\mu = -(1/e)\delta_\mu \phi, \phi = \lambda e^{i\theta}$$

The Higgs field responsible for these defects is described by a relativistic version of the Landan-Ginzburg model and consequently it can be shown that conducting strings also carry a flux[5,6]

$$\phi = n\hbar c/e \tag{10}$$

The flux can be shown to give rise to an electric field[5] given by

$$V \simeq cT_s GM_{pl}^2/e\hbar$$

$$\simeq \frac{Gc}{e\hbar} T_s M_{pl}^2 \tag{11}$$

Thus charged particles can be accelerated to a maximal energy given by (corresponding to a critical current[6])

$$E \simeq ecT_s^{1/2} \ G^{1/2} M_{pl} \tag{12}$$

For a string tension, corresponding to a GUT scale $M \simeq 10^{15} GeV$, (the corresponding tension being given by eq (7))

$$E \simeq 10^{21} eV \tag{13}$$

A higher string tension T_s gives rise to a higher value of E For a GUTs scale $M \sim 10^{16} GeV$, $E \approx 10^{22}$ eV

So far we have considered production of UHE particles by acceleration by black holes and cosmic strings However, it must be noted that UHE particles can be spontaneously generated by Evaporating black holes (EBH)

An important consequence of attempts to link gravity with quantum physics is the prediction[7] that black holes must spontaneously emit radiation and decay This effect is however significant only for primordially formed black holes with masses $<< M_\odot$ The lifetime for decay is

$$t_H \approx \frac{G^2 M^3}{\hbar c^4} \tag{14}$$

The occurrence of $\hbar$ shows that this is a quantum effect As $\hbar \rightarrow 0$, $t_H \rightarrow \infty$, i e a classical black hole stay for ever For t_H comparable to the Hubble time scale $\sim 1/H(\sim 10^{10} yrs)$, we have a horizon size $GM/c^2 \approx 10^{-13}$ cms (1 fermi) which is a typical elementary particle Compton length. If the horizon size is comparable to Compton wavelength $\hbar/mc$ of particles of mass m, then the quantum uncertainty principle implies that virtual pairs of this particle would be produced near the horizon

The rate of energy emission[8] by spontaneous creation of these virtual pairs is

$$dE/dt \ \simeq \ \frac{mc^2}{\hbar/mc^2} \ \simeq \ \frac{m^2c^4}{\hbar},$$

and as $\frac{GM}{c^2} \simeq \frac{\hbar}{mc}$,

$$\frac{dE}{dt} \simeq \frac{\hbar c^6}{(GM)^2} \tag{15}$$

The rate of energy emission maximal for the heaviest elementary particles one can conceive The energy of the particles spontaneously emitted by the EBH is given by

$$E \simeq \frac{\hbar c^3}{GM}$$

$$\simeq 10^{20} eV [\frac{1kg}{M}] \qquad (16)$$

Equations (15) and (16) imply that when the evaporating black hole reaches one kilogram mass, it can emit $\sim 10^{16}$ particles of $\sim 10^{20} eV$ energy each in a time scale (i e burst) of $\sim 10^{-20} s$. With a density of primordial black holes in a given mass range, one can get the background flux of such spontaneously emitted UHE particles by integrating over all red shifts[9] From known upper limits on the flux of such UHE particles (i e with energies $> 10^{3} EeV$), one can estimate that the background density of such priomordial evaporating black holes is $< 10^{9}/Kpc^{3}$ (assuming they cluster, eg in Virgo) The Hawking-Page bound from the diffuse gamma ray background is interestingly of same order. Such holes emit TeV $\gamma - rays$, when their mass becomes $\sim 10^{8} kg \sim 10^{2}$ Tons At lower masses they emit, pairs of particles, so that antiparticles of the same energy (blackhole decay is expected not to violate (CPT invariance) are also emitted

Strings produced at GUTs phase transition, i e at energies around 10^{15} or 10^{16} GeV, also decay spontaneously into high energy particles with energies ranging from 10^{21} to 10^{25} eV, with a rate depending on the string tension T, The spectrum of high energy particles produced by the string is of the form

$$N(m) \approx Am^{-n} exp[m/KT_{Hag}] \qquad (17)$$

T_{Hag} is the Hagedorn temperature, which is related to the string tension and for superstrings is $\sim 10^{27} eV$ n $\simeq 3$ for the heterotic string (a favourite candidate for ToE) For m$<<$ T_{Hag} which is the case for UHE particle energies m between 10^{20} to 10^{25} eV,

$N(E) \sim AE^{-3}$, not inconsistent with FLY's EYE results Black holes emitting UHE particles in their terminal stages have a similar E^{-3} spectrum

Thus in conclusion both evaporating black holes in their terminal stages and decaying strings, both produced in the early universe, are capable of producing UHE particles of energies $> 10^{20}$ eV with an approximate E^{-3} spectrum

However, there are some very definite signatures of such processes which are testable in future experiments

Some of these are

1 One expects also equal numbers of antiparticles, (i.e for eg antiprotons) at such high energies Thus one predicts $\bar{P}/P \rightarrow$ one, at $> 10^{21} eV$

2. One does not expect, any heavier elements i e nothing other than protons If one sees oxygen or Fe nuclei at energies $> 10^{21} eV$, then clearly these are not the mechanisms to produce such particles.

3 In the case of decaying strings, one expects a cut off around 10^{25} eV or less (these are based on constraints from inflation theories which fix the scale M$<<$ M_{pl}) However for evaporating black holes the spectrum can continue till 10^{28} eV, the Planck scale! What about the possibility that we have some neutrinos with UHE $> 10^{21}$ eV? Such UHE neutrinos can interact with the thermal cosmic background neutrinos which are expected to have a temperature around $2^{\circ} K$, through processes like $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$ etc In principle this can cause a cut off in the UHE ν flux However, the cross sections are low[10] There is a sharp enhancement of the C S at the Z° resonance which is $\approx 10^{-32}$cr corresponding to a cut-off energy around $\sim 10^{8}$ Such UHE

neutrinos interacting with the galactic neutrino halo (assuming all the DM in the halo is due to neutrinos with mass of a few electron volts) have a mean free path ~ halo radius Thus if the DM density is distributed as $\rho \sim \rho_o/(1 + a^2/r^2)$, then $\rho_o \sim 10^{-25} gcm^{-3}$ gives a background number density $n_\nu \sim 10^9 cm^{-3}$, which with a C S ~ $10^{-32} cm^2$, implies a $mfp \sim 10^{23} cm$ ~ few Kpc

In principle future experiments should be able to discern such dips in the UHE neutrino cosmic rays[10]

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