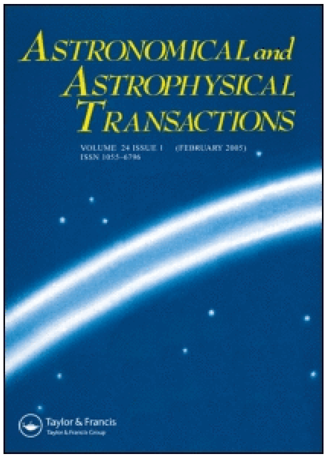

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QUARK JETS FROM EVAPORATING BLACK HOLES

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(2 February, 1993)

It is a great pleasure for me to speak at this meeting. I was privileged to meet Zeldovich on several occasions and—like so many other cosmologists—my work has been very influenced by him. It is particularly appropriate for me to speak about primordial black holes since it was he who first drew attention to their importance some 25 years ago and, since then, Russian cosmologists have always played a prominent role in studying them. The topic is also of great personal interest since my first papers—written as a research student under Stephen Hawking—were on primordial black holes. In fact, I was fortunate enough to meet Zeldovich in the very first year of my research at an IAU meeting in Poland in 1973. Zeldovich's energy, enthusiasm and insights at that meeting made an indelible impression on me and he was just as inspiring when I met him for the last time at an IAU meeting in Hungary in 1987.

KEY WORDS Primordial black holes, Hawking radiation, cosmic rays.

1. HISTORICAL REVIEW

It was first pointed out by Zeldovich & Novikov (1967) and then by Hawking (1971) that black holes could have formed in the early Universe as a result of density inhomogeneities. Indeed this is the only time when black holes smaller than a solar mass could form since a region of mass M must collapse to a density $\rho_{\rm BH} \simeq 10^{18}(M/M_\odot)^{-2}\,{\rm g/cm^3}$ in order to fall within its Schwarzschild radius and only in the first moments of the Big Bang could the huge compression required arise naturally. In order to collapse against the background pressure, overdense regions would need to have a size comparable to the particle horizon size at maximum expansion. On the other hand, they could not be much bigger than that else they would be a separate closed universe rather than part of our universe, so primordial black holes (PBHs) forming at time t would need to have of order the horizon mass $M_H \simeq c^3G^{-1}t \simeq 10^5(t/s)M_\odot$. This conclusion was confirmed by detailed numerical calculations of Nadejin *et al.* (1978). Thus PBHs could span an enormous mass range: those forming at the Planck time (10^{-43} s) would have the Planck mass (10^{-5} g), whereas those forming at 1 s would be as large as the holes thought to residue in galactic nuclei.

For a while the existence of PBHs seemed unlikely since Zeldovich and Novikov (1967) had pointed out that they might be expected to grow catastrophically. This is because a simple Newtonian argument suggests that, in a radiation-dominated universe, the mass of a black hole should evolve according to

$$M(t) = M_H(t)\left[1 + \frac{t}{t_0}\left(\frac{M_H(t_0)}{M_0} - 1\right)\right]^{-1} \simeq \begin{cases} M_0 \text{ for } M_0 \ll M_H(t_0) \\ M(t) \text{ for } M_0 \sim M_H(t_0) \end{cases} \qquad (1)$$

where M_0 is the mass of the hole at some initial time t_0. This implies that holes much smaller than the horizon cannot grow much at all, whereas those of size comparable to the horizon could continue to grow at the same rate as the horizon ($M \propto t$) throughout the radiation era. Since we have seen that a PBH *must* be of order the horizon size at formation, this suggests that all PBHs could grow to have a mass of order $10^{15} M_\odot$ (the horizon mass at the end of the radiation era). There are strong observational limits on how many such giant black holes could exist in the Universe, so the implication seemed to be that very few PBHs ever formed.

The Zeldovich–Novikov argument was questionable since it neglected the cosmological expansion and this would presumably hinder the black hole growth. Indeed the notion that PBHs could grow at the same rate as the horizon was disproved by myself and Hawking: we demonstrated that there is no spherically symmetric similarity solution which contains a black hole attached to a Friedmann background via a pressure wave (Carr and Hawking, 1974). Since a PBH must therefore soon become much smaller than the horizon, at which stage cosmological effects become unimportant and Eq. (1) *does* pertain, one concludes that a PBH cannot grow very much at all. I announced this result at the IAU meeting where I first met Zeldovich in 1973. I remember being rather nervous at disagreeing with such a great man but he was very nice about it!

The realization that small PBHs could exist after all prompted Hawking to consider their quantum properties. I believe he was very influenced in this by the earlier work of Zeldovich and Starobinsky on the superradiance effects associated with rotating black holes. This led to his famous discovery that black holes should radiate thermally with a temperature $T \simeq 10^{-7}(M/M_\odot)^{-1}$ K and evaporate completely in a time $\tau \simeq 10^{10}(M/10^{15}\,\mathrm{g})^3 y$ (Hawking, 1975). I am not certain whether Zeldovich immediately accepted this result but he certainly came to do so very quickly. There is a famous—and probably apocryphal—story in this context. The story goes that when Roger Penrose visited Moscow in 1974, he had to stay up all night rewriting his lecture because he had heard that Zeldovich did not believe in Hawking radiation, only to learn the next morning that Zeldovich had changed his mind!

Despite the conceptual importance of Hawking's result (it illustrates that it is sometimes useful to study something even if it does not exist!), it was rather bad news for PBH enthusiasts. For since PBHs with mass of 10^{15} g would have a temperature of order 100 MeV and radiate mainly at the present epoch, the observational limit on the gamma-ray background density at 100 MeV immediately implied that the density of such holes could be at most 10^{-8} in units of the critical density (Chapline, 1975; Page and Hawking, 1976). Not only did this exclude PBHs as solutions of the dark matter problem, but it also implied that there was little chance of detecting black hole explosions at the present epoch (Porter and Weekes, 1979).

Despite this negative conclusion, it was realized that PBH evaporations could still have interesting cosmological consequences and the next five years saw a spate of papers focussing on these. In particular, people were interested in whether PBH evaporations could generate the microwave background (Zeldovich and Starobinsky, 1976) or modify the standard cosmological nucleosynthesis scenario (Novikov *et al.*, 1979; Lindley, 1980) or account for the cosmic baryon asymmetry (Barrow, 1980). On the observational front, people were interested in whether PBH evaporations could account for the unexpectedly high fraction of antiprotons in cosmic rays (Kiraly *et al.*, 1981; Turner, 1982) or the interstellar electron and positron spectrum (Carr, 1976) or the annihilation line radiation coming from the Galactic centre (Okeke and Rees, 1980). Renewed efforts were also made to look for black hole explosions after the realization that—due to the interstellar magnetic field—these might appear as radio rather than gamma-ray bursts (Rees, 1977).

In the 1980s attention switched to several new formation mechanisms for PBHs. Originally it was assumed that they would need to form from primordial density fluctuations but it was soon realized that PBHs might also form very naturally if the equation of state of the Universe was ever soft (Khlopov and Polnarev, 1980) or if there was a cosmological phase transition leading to bubble collisions (Kodama *et al.*, 1979; Hawking *et al.*, 1982; Hsu, 1990). In particular, the formation of PBHs during an inflationary era (Naselsky and Polnarev, 1985) or at the quark-hadron era (Crawford and Schramm, 1985) received a lot of attention. More recently, people have considered the production of PBHs through the collapse of cosmic strings (Polnarev and Zembovicz, 1988; Hawking, 1989) and the issue of forming Planck mass black holes through thermal fluctuations has also been of interest (Gross *et al.*, 1982; Kapusta, 1984; Hayward and Pavon, 1989). All these scenarios are constrained by the quantum effects of the resulting black holes.

Recently work on the cosmological consequences of PBH evaporations has been revitalized as a result of calculations by my former PhD student Jane MacGibbon. Previous approaches to this problem (including my own) had been rather simplistic, merely assuming that the relevant particles are emitted with a black-body spectrum as soon as the black hole temperature exceeds their rest mass. However, if one adopts the conventional view that all particles are composed of a small number of fundamental point-like constituents (quarks and leptons), it would seem natural to assume that it is these fundamental particles rather than the composite ones which are emitted directly once the temperatures go above the QCD confinement scale of 140 MeV. MacGibbon therefore envisages a black hole as emitting relativistic quark and gluon jets which subsequently fragment into the stable leptons and hadrons (i.e. photons, neutrinos, gravitons, electrons, positrons, protons and antiprotons). On the basis of both experimental data and Monte Carlo simulations, one now has a fairly good understanding of how the jets fragment. It is therefore straightforward in principle to convolve the thermal emission spectrum of the quarks and gluons with the jet fragmentation function to obtain the final particle spectra (MacGibbon and Webber, 1990; MacGibbon, 1991; MacGibbon and Carr, 1991). As discussed here, the results of such a calculation are very different from the simple direct emission calculation, essentially because each jet generates a Bremmstrahlung tail of decay products, with energy extending all the way down to the decay product's rest mass.

Lately attention has turned to the issue of Planck mass relicts. Most early work assumed that PBHs evaporate completely. However, this is by no means certain and several people have argued that evaporation could discontinue when the black hole gets down to the Planck mass (Bowick *et al.*, 1988; Coleman, *et al.*, 1991). In this case, one could end up with stable Planck mass objects. MacGibbon (1987) pointed out that such relicts would naturally have around the critical density if 10^{15} g PBHs have the density required to explain the gamma-ray background and Barrow *et al.* (1992) have considered the constraints associated with such relicts in more general circumstances.

2. THE FORMATION OF PRIMORDIAL BLACK HOLES

(1) *Inhomogeneities with Hard Equation of State*

If the PBHs form directly from primordial density perturbations, then the fraction of the Universe undergoing collapse at any epoch is just determined by the root-mean-square amplitude of the horizon-scale fluctuations at that epoch ε and the equation of state $p = \gamma\rho$ $(0 < \gamma < 1)$. In this section, we assume that γ is not zero, so that we have a hard rather than soft equation of state. We have seen that an overdense region must be larger than the Jeans length at maximum expansion and this is just $\sqrt{\gamma}$ times the horizon size. This requires the density fluctuation to exceed γ at the horizon epoch, so one can infer that the fraction of regions of mass M which form a PBH is (Carr, 1975)

$$\beta(M) \sim \varepsilon(M) \exp(-\gamma^2/2\varepsilon(M)^2) \tag{2}$$

where $\varepsilon(M)$ is the value of ε when the horizon mass is M. This assumes that the fluctuations have a Gaussian distribution and are spherically symmetric. The PBHs can have an extended mass spectrum only if the fluctuations are scale-invariant (i.e. with ε independent of M) and, in this case, the number density of PBHs is given by (Carr, 1975)

$$dn/dM = (\alpha - 2)(M/M_*)^{-\alpha} M_*^{-2} \Omega_{\mathrm{PBH}} \rho_{\mathrm{crit}} \tag{3}$$

where $M_* \simeq 10^{15}$ g is the current lower cut-off in the mass spectrum due to evaporations, Ω_{PBH} is the total density of the PBHs in units of the critical density ρ_{crit} (which itself depends on β), and the exponent α is uniquely determined by the equation of state:

$$\alpha = (1 + 3\gamma)/(1 + \gamma) + 1. \tag{4}$$

If one has a radiation equation of state $(\gamma = 1/3)$, as is consistent with the Elementary Particle picture, then $\alpha = 5/2$. This means that the integrated PBH mass spectrum falls off as $M^{-1/2}$, so most of the PBH density is contained in the smallest ones. If $\varepsilon(M)$ decreases with M, then the spectrum falls off exponentially with M and PBHs can form only around the Planck time $(t_{\mathrm{Pl}} \sim 10^{-43}\,\mathrm{s})$ if at all; if $\varepsilon(M)$ increases with M, the spectrum rises exponentially with M and PBHs would form very prolifically at sufficiently large scales but the microwave anisotropies would then be larger than observed. Fortunately, many scenarios for the cosmological density fluctuations do predict that ε is scale-invariant, so Eq. (3) represents the most likely mass spectrum.

(2) *Inhomogeneities with Soft Equation of State*

The pressure may be reduced for a while $(\gamma \ll 1)$ if the Universe's mass is ever channelled into particles which are massive enough to be non-relativistic (Kholopov and Polnarev, 1980). In this case, the effect of pressure in stopping collapse is unimportant and the probability of PBH formation depends upon the fraction of regions which are sufficiently spherical to undergo collapse; this can be shown to be (Polnarev and Khlopov, 1981)

$$\beta = 0.02\varepsilon^{13/2} \tag{5}$$

The holes should have a mass which is smaller than the horizon mass at formation by a factor $\varepsilon^{3/2}$, so the period for which the equation of state is soft directly specifies their mass range. In this case, the value of β and hence Ω_{PBH} is not as sensitive to ε as in case (1).

(3) *Inflationary Period*

In the standard inflationary scenario, the amplitude of the density fluctuations increases logarithmically with mass and the normalization required to explain galaxy formation would then preclude the fluctuations being large enough to give PBHs on a smaller scale. One way around this would be to invoke a "double inflation" scenario, in which there is a second period of inflation associated with a larger value of the self-coupling constant λ (Naselsky and Polnarev, 1984). Since the amplitude of the resulting fluctuations scales as $\lambda^{1/2}$, one needs fine-tuning of λ to get an interesting value of Ω_{PBH}. Note that λ also determines the duration of the inflationary period since this should go as λ^{-1} (Polnarev and Khlopov, 1981). Thus, if ε is to be as high as 0.05 (as required for $\Omega_{PBH} \sim 1$), inflation can persist for at most a factor of 10^3 in time and this implies that the PBH spectrum can only extend over three decades. Another possibility is to invoke a non-standard inflationary scenario in which the fluctuations have a more complicated dependence on mass-scale. In fact, if PBH formation is to occur at all, one needs the fluctuations to decrease with increasing mass and—in the chaotic inflation scenario—it turns out that this is only possible if the scalar field is accelerating sufficiently fast. This means that one must violate the usual slow-roll-over friction-dominated assumptions (Carr and Lidsey, 1993). For example, one can generate fluctuations which decrease as a power of mass ($\varepsilon \propto M^{-\alpha}$) if the potential $V(\phi)$ has terms which depend on $\sec\phi$. The COBE quadrupole anisotropy measurement (which specifices ε on a scale of $10^{22} M_\odot$) implies that one needs $\alpha \simeq 0.08$ if PBH formation at 10^{15} g is to be interesting. COBE itself requires $0.1 < \alpha < -0.07$ on scales above 10°, which just about allows this. In any case, the important point is that an analysis of PBH formation places very interesting constraints on inflationary scenarios since COBE and PBHs together limit the fluctuations over 45 decades of mass.

(4) *Bubble Collisions*

Even if the Universe starts off perfectly smooth, bubbles of broken symmetry might arise at a spontaneously broken symmetry epoch and it has been suggested that black holes could form as a result of bubble collisions (Kodama *et al.*, 1982; Hawking *et al.*, 1982; La and Steinhardt, 1989). In fact, this happens only if the bubble formation rate is finely tuned: if it is too large, the entire Universe undergoes the phase transition immediately; if it is too small, the bubbles never collide. In consequence, the holes should again have a mass of order the horizon mass at the phase transition. For example, PBHs forming at the Grand Unification epoch (10^{-35} s) would have a mass of order 10^3 g. Only a phase transition before 10^{-23} s would be relevant in the context of evaporating PBHs.

(5) *Collapse of Cosmic Loops*

A typical cosmic loop will be larger than its Schwarzschild radius by the inverse of the factor $G\mu$ which represents the mass per unit length. In the favoured scenario, $G\mu$ is of order 10^{-6}. However, Hawking (1989) and Polnarev and Zemboricz (1988) have shown that there is still a small probability that a cosmic loop will get into a configuration in which every dimension lies within its Schwarzschild radius. Hawking estimates this to be

$$\beta \sim (G\mu)^{-1}(G\mu x)^{2x-2} \tag{6}$$

where x is the ratio of the loop length to the correlation scale. If one takes x to be 3, Ω_{PBH} exceeds 1 for $G\mu > 10^{-7}$, so he argues that one overproduces PBHs. However, Ω_{PBH} is very sensitive to x and a slight reduction would give a rather interesting value. Note that spectrum (3) still applies since the holes are forming at every epoch. A more recent analysis by Polnarev (1993) comes to rather different conclusions, as described in the talk which follows this.

In all these scenarios, the value of Ω_{PBH} associated with PBHs which form at a redshift z or time t is related to β by

$$\Omega_{\mathrm{PBH}} = \beta\Omega_R(1+z) = 10^6\beta(t/s)^{-1/2} \tag{7}$$

where $\Omega_R \sim 10^{-4}$ is the density of the microwave background. Since t is very small, the constraint $\Omega_{\mathrm{PBH}} < 1$ implies that β must be tiny over all mass ranges. This is because the radiation density falls off as $(1+z)^4$, whereas the PBH density falls off as $(1+z)^3$. If the PBHs form at a phase transition, as in cases (2) to (4), then they have a very narrow mass spectrum and t is just the time of the transition. If they have a continuous mass spectrum, as in cases (1) and (5), then the dominant contribution to Ω_{PBH} comes from the holes with mass $M \sim 10^{15}$ g evaporating at the present epoch. These form at $t \sim 10^{-23}$ s and so eqn (7) implies $\beta \sim 10^{-17}\,\Omega_{\mathrm{PBH}}$.

3. PRIMORDIAL BLACK HOLE EVAPORATIONS

A black hole of mass M will emit particles in the energy range $(Q, Q+dQ)$ at a rate (Hawking, 1975)

$$d\dot{N} = \frac{\Gamma\, dQ}{2\pi\hbar}\left\{\exp\left(\frac{Q}{kT}\right) \pm 1\right\}^{-1} \tag{8}$$

where T is the black hole temperature, Γ is the absorption probability and the + and − signs refer to fermions and bosons respectively. This assumes that the hole has no charge or angular momentum. This is a reasonable assumption since charge and angular momentum will also be lost through quantum emission but on a shorter timescale that the mass (Page, 1977). Γ goes roughly like Q^2T^{-2}, though it also depends on the spin of the particle and decreases with increasing spin.

Thus a black hole radiates roughly like a black-body with temperature

$$T = \frac{\hbar c^3}{8\pi GkM} = 10^{26}\left(\frac{M}{g}\right)^{-1} K = \left(\frac{M}{10^{13}\,g}\right)^{-1} \text{GeV} \tag{9}$$

This means that it loses mass at a rate

$$\dot{M} = -5 \times 10^{25} M^{-2} f(M)\,\mathrm{g\,s^{-1}} \tag{10}$$

where the factor $f(M)$ depends on the number of particle species which are light enough to be emitted by a hole of mass M, so the lifetime is

$$\tau(M) = 6 \times 10^{-27} f(M)^{-1} M^3\,\mathrm{s} \tag{11}$$

The factor f is normalized to be 1 for holes larger than 10^{17} g and such holes are only able to emit "massless" particles like photons, neutrinos and gravitons. Holes in the mass range $10^{15}\,\mathrm{g} < M < 10^{17}\,\mathrm{g}$ are also able to emit electrons, while those in the range $10^{14} < M < 10^{15}$ g emit muons which subsequently decay into electrons and neutrinos. The latter range includes, in particular, the critical mass for which τ equals the age of the Universe. This can be shown to be (MacGibbon and Webber, 1990)

$$M_* = 4.4 \times 10^{14} h^{-0.3}\,\mathrm{g} \tag{12}$$

where h is the Hubble parameter in units of 100 km/s/Mpc and we have assumed that the total density parameter is $\Omega = 1$.

Once M falls below 10^{14} g, the hole can also begin to emit hadrons. However, hadrons are composite particles made up of quarks held together by gluons. For temperatures exceeding the QCD confinement scale of $\Lambda_{\mathrm{QCD}} \simeq 250$–$300$ GeV, one would therefore expect these fundamental particles to be emitted rather than composite particles. Only pions would be light enough to be emitted below Λ_{QCD}. Since there are 12 quark degrees of freedom per flavour and 16 gluon degrees of freedom, one would also expect the emission rate (i.e. the value of f) to increase dramatically once the QCD temperature is reached.

The physics of quark and gluon emission from black holes is simplified by a number of factors. Firstly, since the spectrum peaks at an energy of about $5\,kT$, Eq. (9) implies that most of the emitted particles have a wavelength $\lambda \simeq 2.5M$ (in units with $G = c = 1$), so the particles have a size comparable to the hole. Secondly, one can show that the time between emissions is $\Delta\tau \simeq 20\lambda$, which means that short range interactions between successively emitted particles can be neglected. Thirdly, the condition $T > \Lambda_{\mathrm{QCD}}$ implies that $\Delta\tau$ is much less than $\Lambda_{\mathrm{QCD}}^{-1} \simeq 10^{-13}$ cm (the characteristic strong interaction range) and this means that the particles are also unaffected by gluon interactions. The implication of these conditions is that one can regard the black hole as emitting quark and gluon jets of the kind produced in collider events. The jets will decay into hadrons over a distance T/m^2 and, since this is much larger than M for $T \gg m$, gravitational effects can be neglected. The hadrons will themselves decay into protons, antiprotons, electrons, positrons and photons on a somewhat longer timescale.

To find the final spectrum of stable particles emitted instantaneously from a black hole one must convolve the Hawking emission spectrum given by Eq. (8) with the jet fragmentation function. This gives

$$\frac{d\dot{N}_x}{dE} = \sum_j \int_{Q=0}^{Q=\infty} \frac{\Gamma_j(Q,T)}{2\pi\hbar}\left(\exp\frac{Q}{T} \pm 1\right)^{-1} \frac{dg_{jx}(Q,E)}{dE}\,dQ \tag{13}$$

Here x and j label the final particle and the directly emitted particle, respectively, and the last factor specifies the number of final particles with energy in the range $(E, E+dE)$ generated by a jet of energy Q. For hadrons this can be represented by

$$\frac{dg_{jh}}{dE} = \frac{1}{E}\left(1 - \frac{E}{Q}\right)^{2m-1} \theta(E - km_h c^2) \tag{14}$$

where m_h is the hadron mass, k is a constant of order 1, and m is 1 for mesons and 2 for baryons. The fragmentation function therefore has an upper cut-off at Q, a lower cut-off around m_h and an E^{-1} Bremmstrahlung tail in between. It also peaks around m_h. By examining the dominant contribution to the Q-integral one obtains

$$\frac{d\dot{N}}{dE} \sim \begin{cases} E^2 e^{-E/T} & \text{for} \quad E \gg T \qquad (Q \sim E) \\ E^{-1} & \text{for} \quad T \sim E \gg m_h \quad (Q \sim T) \\ dg/dE & \text{for} \quad E \sim m_h \ll T \quad (Q \sim m_h) \end{cases} \tag{15}$$

where the terms in parentheses indicate the value of Q which dominates. This equation enables one to understand qualitatively the form of the instantaneous emission spectrum shown in Figure 1 for a $T = 1\,\text{GeV}$ black hole (MacGibbon and Webber, 1990). The direct emission just corresponds to the small bumps on the right. All the particle spectra show a peak at 100 MeV due to pion decays; the electrons and neutrinos also have peaks at 1 MeV due to neutron decays.

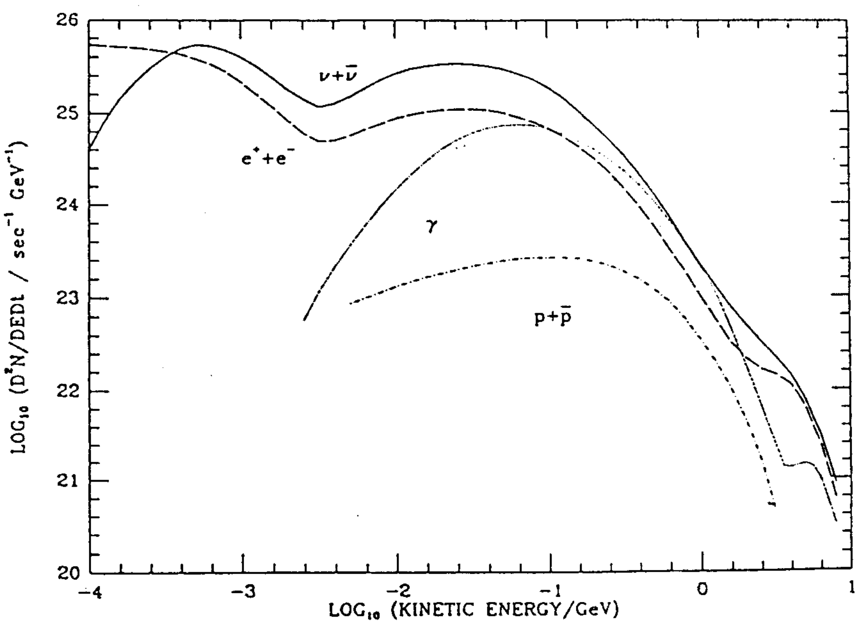

Figure 1 This shows the instantaneous emission from a black hole with a temperature of 1 GeV, taken from MacGibbon and Webber (1990). The neutrino emission is summed over all neutrino species.

4. COSMIC RAYS FROM PRIMORDIAL BLACK HOLES

In order to determine the present day background spectrum of particles generated from PBH evaporations, we must integrate first over the lifetime of each hole of mass M and then over the PBH mass spectrum (MacGibbon, 1991). In doing this, we must allow for the fact that smaller holes will evaporate at an earlier cosmological epoch, so that the particles they generate will be redshifted in energy by the present epoch. If the holes are uniformly distributed throughout the Universe, the background spectra should have the form indicated in Figure 2. All the spectra have rather similar shapes: an E^{-3} fall-off for $E > 100$ MeV due to the final phases of evaporations at the present epoch and an E^{-1} tail at $E < 100$ MeV due to the fragmentation of jets produced at the present and earlier epochs. Note that the E^{-1} effect masks any effect associated with the PBH mass spectrum: in the absence of jets, the spectra would rise like $E^{2-\alpha}$ as one goes to lower energies (Carr, 1976) but this is shallower than E^{-1} for $\alpha < 3$, so the E^{-1} tail dominates the integral.

The situation is more complicated if the PBHs evaporating at the present epoch are clustered inside our own Galactic halo (as is most likely). In this case, any charged particles emitted after the epoch of galaxy formation will have their flux enhanced relative to the photon spectra by a factor ζ which depends upon the halo concentration factor and the time for which the particles are trapped inside the halo by the Galactic magnetic field. Assuming the particles are uniformly

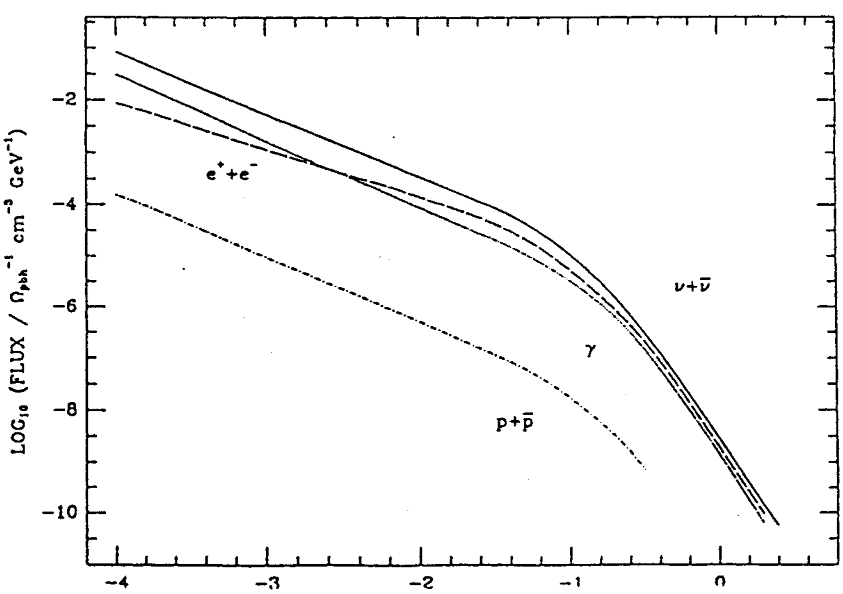

Figure 2 This shows the background produced by a distribution of PBHs holes emitting over the lifetime of the Universe. We assume $\Omega = 1$ and $h = 0.5$. All interactions are neglected apart from redshift effects.

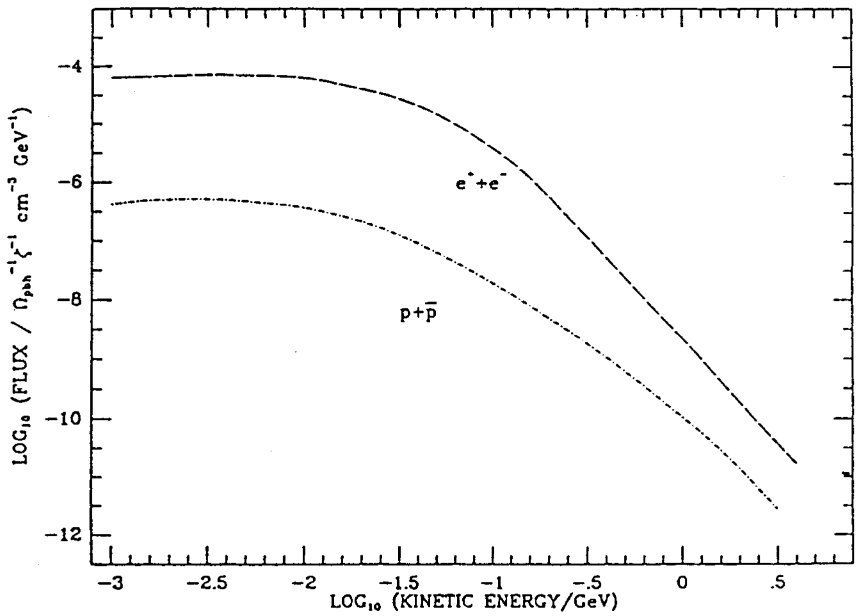

Figure 3 This shows the postgalactic $e^+ + e^-$ and $p + \bar{p}$ emission from PBHs clustered in the Galactic halo. We assume $\Omega = 1$, $h = 0.5$ and $\tau_{gal} = 1.2 \times 10^{10}$ y. The enhancement factor ζ is in the range 10^3–10^4.

distributed throughout a halo of radius R_h, one finds

$$\zeta = \left(\frac{\tau_{\rm leak}}{\tau_{\rm gal}}\right)\left(\frac{\rho_{\rm halo}}{\Omega\rho_{\rm crit}}\right) = 10^6 h^{-2}\left(\frac{\tau_{\rm leak}}{\tau_{\rm gal}}\right)\left(\frac{R_h}{10kpc}\right)^{-2} \tag{16}$$

The ratio of the leakage time to the age of the Galaxy is rather uncertain and also energy dependent. At 100 MeV we take $\tau_{\rm leak}$ to be about 10^7 y for electrons or positrons ($\zeta \sim 10^3$) and 10^8 y for protons or antiprotons ($\zeta \sim 10^4$). The total background of charged particles should therefore consist of the superposition of two components: one produced before galaxy formation and the other after it. The latter contribution, shown in Figure 3, corresponds to just a narrow range of masses below M_* (a factor of 2 if galaxies form at a redshift ~ 10).

For comparison with the observed cosmic ray spectra, one needs to determine the amplitude of the spectra at 100 MeV. This is because the observed fluxes all have slopes between E^{-2} and E^{-3}, so the strongest constraint comes from measurements at 100 MeV. The amplitudes all scale with the density parameter of the holes $\Omega_{\rm PBH}$ and are found to be

$$\frac{dF}{dE} = \begin{cases} 1.5 \times 10^{-5} h^2 \Omega_{\rm PBH}\,{\rm GeV}^{-1}\,{\rm cm}^{-3} & \text{(photons)} \\ 9.5 \times 10^{-3} h^2 \Omega_{\rm PBH}(\zeta/10^3)\,{\rm GeV}^{-1}\,{\rm cm}^{-3} & (e^+, e^-) \\ 4.5 \times 10^{-4} h^2 \Omega_{\rm PBH}(\zeta/10^4)\,{\rm GeV}^{-1}\,{\rm cm}^{-3} & (p, \bar{p}) \end{cases} \tag{17}$$

We now apply this result to examining whether PBH evaporations could contribute appreciably to the observed spectra of these particles.

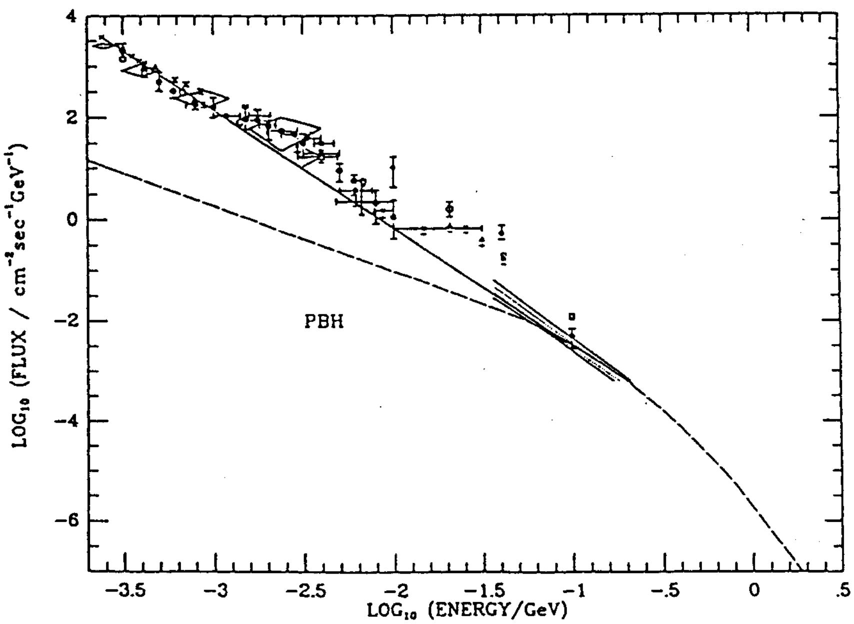

Figure 4 This compares the gamma-ray background observations with the maximum PBH background (broken line) which is permitted by the Fichtel *et al.* data (dotted line).

(1) *Photons*

Since the observed γ-ray background spectrum (Fichtel *et al.*, 1975) goes like $E^{-2.4}$ at around $E \sim 100\,\text{MeV}$, which is much steeper than the Bremmstrahlung tail from the jets, the dominant constraint on Ω_{PBH} comes from measurements of the background at 100 MeV itself. This gives an upper limit (MacGibbon and Carr, 1991)

$$\Omega_{PBH} \leq 7.6(\pm 2.6) \times 10^{-9} h^{-2} \tag{18}$$

as illustrated in Figure 4. In principle, PBH emission could be the dominant contribution to the photon flux above 50 MeV, in which case one has a clear prediction for the spectrum. The only observations above 600 MeV come from the EGRET experiment but there is the problem of separating the Galactic and extragalactic components. Note that Eq. (18) corresponds to a limit of $\beta(M_*) < 10^{-26}$. If PBHs form from initial inhomogeneities, Eq. (2) implies that the corresponding limit on their amplitude is $\varepsilon < 0.03$. It should be stressed that photons emitted prior to a redshift $z_{free} \simeq 400$ will be degraded due to pair-production off background nuclei but this will only affect the present-day spectrum at energies below 1 MeV. This contrasts to the situation which would pertain if one only had direct emission of photons because, in this case, the spectrum would be modified up to 10 MeV (Page and Hawking, 1976). Eq. (18) implies that the frequency of black hole explosions at the present epoch could be at most $0.1\,\text{pc}^{-3}\,\text{y}^{-1}$, even if they are clustered inside the Galactic halo, and there is then little chance of their being detected (Halzen *et al.*, 1991).

(2) *Electrons and Positrons*

If the PBHs are not clustered within galaxies, the electrons and positrons they generate should have the spectrum indicated by Figure 2. However, all the ones generated pregalactically would have been degraded through inverse scattering off the microwave background photons, so one could only observe the ones produced recently and the flux would then be uninteresting. However, we have seen that the flux would be enhanced if the PBHs were currently clustered inside the Galactic halo. In this case, electrons and positrons with $E < 10\,\mathrm{MeV}$ would be degraded by ionization losses, while those above 10 GeV would be degraded by inverse Compton losses. Thus the PBH spectrum should be dominated by 10 MeV to 10 GeV particles produced within the last $\tau_{\mathrm{leak}} \sim 10^7$ y. An interesting feature of the observations is that the electrons and positrons have comparable fluxes at 100 MeV, even though the electrons are much more numerous at higher energies. This feature is unexplained in most cosmic ray models but it is a natural consequence of the PBH scenario since electrons and positrons are emitted in equal numbers. It is also interesting that the positron spectrum falls off like E^{-3} above a few GeV, as expected in the PBH model. It is difficult to estimate the value of Ω_{PBH} required to generate *all* the observed positrons accurately but comparison with the interstellar positron flux at 300 MeV (Ramaty and Westergaard, 1976) indicates that it should be about

$$\Omega_{\mathrm{PBH}} \simeq 2 \times 10^{-8}\,(\tau_{\mathrm{leak}}/10^7\,\mathrm{y})^{-1}(R_h/10kpc)^{-2} \tag{19}$$

(MacGibbon and Carr, 1991). This is comparable to the γ-ray limit given by Eq. (18) for reasonable values of τ_{leak} and R_h.

(3) *Annihilation Line Radiation*

If PBHs are clustered inside the Galactic halo, their density should be even more enhanced towards the Galactic centre. One would therefore expect an especially strong emission of positrons from that direction. Some of these positrons should annihilate, producing a 0.511 MeV line, so it is relevant that such a line has indeed been detected from the Galactic centre (Leventhal *et al.*, 1989). The intensity of the line corresponds to $3\text{–}10 \times 10^{42}$ annihilations s^{-1}. Okeke and Rees (1980) discussed whether these annihilations could be generated by PBH positrons. For relativistic particles, the optical depth of the Galaxy to annihilation is only about 0.1. However, the annihilation cross-section scales as the inverse speed of the particle, so annihilations can still be important if the antiprotons are slowed down by ionization losses. Assuming one has mainly molecular hydrogen at the Galactic centre, then positrons will be slowed sufficiently to annihilate providing their energy is less than $E_{\mathrm{slow}} \simeq 13\,\mathrm{MeV}$. In order to produce the observed line, one would then require (MacGibbon and Carr, 1991)

$$\Omega_{\mathrm{PBH}} \simeq 0.5 - 17 \times 10^{-6} h^{-2}(R_c/kpc)^2(\theta/20^0)^{-3} \tag{20}$$

where R_c is the halo core radius and θ is the angle subtended by the region generating the 0.511 MeV line. This is well above the γ-ray limit, so we conclude that PBHs are not a plausible explanation.

(4) *Antiprotons*

The protons and antiprotons generated in the final explosive phase of PBH evaporations should contribute to the cosmic ray background. However, since the observed $\bar{p}:p$ ratio is less than 10^{-3}–10^{-4} over the energy range 0.1–10 GeV, whereas PBHs should produce the particles in equal numbers, PBHs could only contribute appreciably to the antiprotons. It is usually assumed that antiproton cosmic rays are secondary particles, produced by the spallation of the interstellar medium by primary cosmic rays. However, Buffington *et al.* (1981) claimed that the observed $\bar{p}$ flux at 130–320 MeV exceeds the predicted secondary flux by a factor of 100 and this prompted Kiraly *et al.* (1981) and Turner (1982) to examine whether PBH evaporations could explain the antiproton cosmic rays. In fact, more recent observations (Streitmatter *et al.*, 1990) around 100 MeV give an upper limit which is a factor of 10 below Buffington's claim but it still exceeds the expected secondary flux by an order of magnitude and it includes two possible detections. It is therefore interesting to redetermine the expected antiproton spectrum on the basis of the jet calculations. If the PBHs are uniformly distributed throughout the Universe, the antiproton flux is too small to be interesting. However, if the PBHs are clustered in halos, the spectrum would be dominated by the antiprotons produced within our halo in the last $\tau_{\rm leak} \sim 10^8$ y. In order to compare with observations, one must allow for the effects of ionization (which are important below 50 MeV) but, if the $\bar{p}:p$ ratio has the value $\sim 10^{-5}$ indicated by Streitmatter *et al.*, one gets a rough fit with the interstellar proton flux at 1 GeV (MacGibbon and Carr, 1991) for

$$\Omega_{\rm PBH} \simeq 0.6-4\times 10^{-9}\,{\rm h}^{-2}(\tau_{\rm leak}/10^8\,{\rm y})^{-1}(R_h/10kpc)^{-2} \tag{21}$$

This is somewhat less than the value of $\Omega_{\rm PBH}$ required to explain the positron and γ-ray observations but within an order of magnitude of it.

5. CONCLUSIONS

The jet calculations described above suggest that PBH evaporations could contribute appreciably to photons, positrons and antiprotons in the energy range above 100 MeV. Indeed it is rather remarkable that the value of $\Omega_{\rm PBH}$ is of order 10^{-8} in all three cases. However, PBH evaporations could not contribute appreciably to the 0.5 MeV line from the Galactic centre and it will be hard to detect black hole explosions. If cosmic ray positrons and antiprotons really do derive from PBHs, then their spectra could yield vital information about particle physics. However, it should be stressed that one would expect the same signature for any other process which produces jets [eg. the annihilation of supersymmetric particles (Rudaz and Stecker, 1988)].

If $\Omega_{\rm PBH} \sim 10^{-8}$, then the fraction of the Universe going into PBHs is $\beta \sim 10^{-26}$ at their formation epoch. If the holes form from initial inhomogeneities, this requires fine-tuning: the horizon-scale fluctuations need to have an amplitude of about 3%. If they form from the collapse of cosmic loops, then the string parameter μ must be finely tuned, although the precise value required is uncertain. Note that if PBHs leave Planck mass relicts and if the PBH spectrum is given by Eq. (3), then one expects the Planck relicts to have a density which is $(M_*/M_{\rm Pl})^{1/2} \sim 10^9$ times higher than $\Omega_{\rm PBH}$. As MacGibbon (1987) has pointed out, this is intriguingly close to the critical density if M_* holes have the density required to explain the cosmic ray observations.

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