be compressed into a disk until most of its has turned into stars. Evolution of this kind would, according to Larson, require a strong mechanism for suppressing star formation.

The observational facts we have discussed confirm Larson's conclusion. Furthermore, they enable us in a very natural way to attribute the suppression of star formation to powerful, energetic processes that undoubtedly must have occurred during the eras when the galaxy was being enriched with heavy elements.

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Primordial black holes and the deuterium problem

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An analysis is given of the effect upon cosmological nucleosynthesis of the high-energy particles that would be emitted when primordial black holes of 10^9–10^{12} g mass evaporate. Stringent new limits are placed on the primordial black hole spectrum in this mass range. A new approach toward explaining the origin of cosmological deuterium is outlined.

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In a recent letter, Vainer and Nasel'skii[1] have posed a question of much current interest: How would the evaporation of primordial black holes (PBHs) formed from density peturbations at an early stage in the evolution of the universe affect cosmological nucleosynthesis? These authors have shown that variations are possible in the n/p ratio and in the primordial He^4 abundance due to interaction of high-energy neutrinos and antineutrinos with background nucleons, if the ν, $\bar{\nu}$ are emitted by PBHs having an initial mass $M \approx 10^{10}$-10^{11} g at the epoch $t \approx 1$ sec of neutron hardening.

We shall here examine some other aspects of this question. By considering the baryons and antibaryons emitted by PBHs and the added production of cosmological deuterium (both through breakup of helium and by late neutron capture), one can obtain more stringent estimates for an upper limit on the number of PBHs with a mass in the range $10^9 < M < 10^{12}$ g than the estimates given by Vainer and Nasel'skii[1] and previously by two of us.[2] The PBH hypothesis affords a new opportunity for solving the problem of the origin of cosmological deuterium.

Let us review briefly the history of the PBH problem. The possibility that PBHs might exist was first pointed out by Novikov and one of us,[3] and we also obtained the first upper limits on the density of PBHs. Subsequently Carr and Hawking[4,5] considered PBHs in more detail — in particular, accretion onto these objects.

Hawking[6] has recently shown that black holes will gradually evaporate. By applying this remarkable result to PBHs, one may infer that PBHs of mass $M < 10^{15}$ g should have evaporated by the present epoch. Various restrictions on the density of PBHs with $M < 10^{15}$ g have been obtained, taking evaporation into account.[1,2,7-9] On the basis of the observed radiation spectrum in the γ-ray range, Chapline[7] and Carr[9] have placed restrictions on the spectrum for PBH masses in the range $10^{14} < M < 10^{15}$ g. We have given estimates[2] of the PBH density for masses $M < 10^9$ g according to the entropy of the universe, observed at the present time, and for the mass range $10^{11} < M < 10^{13}$ g by appealing to the absence of distortions in the spectrum of the vestigial background radiation. Vainer and Nasel'skii[1] were the first to consider the influence of evaporating PBHs on the cosmological synthesis of He^4.

In this letter we shall demonstrate that the maximum effect on the change in the neutron concentration at the epoch of hardening is exerted by antinucleons evaporated from PBHs. By interacting with background nucleons, the evaporated antinucleons will strongly influence the nucleosynthesis. However, the sharpest restriction on the spectrum of PBHs with masses $M \approx 10^{10}$-10^{11} g will result from the spallation of He^4 nuclei by ultrarelativistic nucleons and antinucleons emitted by PBHs during a later era in the evolution of the universe, at epochs in the range $10^3 < t < 10^5$ sec.

To complete the picture, let us consider how the evaporation of PBHs influences the nucleosynthesis, beginning at t = 1 sec. In the course of its evaporation, a PBH will emit particles of characteristic energy.

$$E \sim kT_{BH} = \frac{\hbar c^3}{8\pi GM} = \frac{10^{13}}{M\,[g]}\ \mathrm{GeV}$$

(for a Schwarzschild black hole). The evaporation time t_1 depends on the mass M of the PBH, and is given[1)] by the expression $t_1\,[sec] \approx 10^{-27} M^3\,[g]$. Suppose that we have $\varepsilon_{PBH} = \alpha \varepsilon_m$ at $t = t_1$. If the relation $\varepsilon_{PBH} = \beta \varepsilon_m$ holds at the epoch $t_0 \approx GM/c^3$ of formation of a PBH, then $\beta = \alpha (M_{Pl}/M)$ (for $\alpha < 1$), where $M_{Pl} = (\hbar c/G)^{1/2} \approx 2 \cdot 10^{-5}$ g. After the PBHs evaporate, the density of the particles emitted by them will be given by the expression

$$n_i = \alpha \frac{10^{-7} n_m}{t_1^{1/4}} \approx \alpha \frac{20 n_B}{\Omega t_1^{1/4}}, \tag{1}$$

where n_B is the background baryon density at epoch t_1, and $\Omega = \rho/\rho_c$ at the present epoch in the evolution of the

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universe. In Eqs. (1)-(9) of this letter t_1 is expressed in seconds.

The antinucleons emitted by a PBH of mass $M = 10^9$ g ($t_1 = 1$ sec) will annihilate with background nucleons, and can serve to increase the neutron density relative to the proton density without altering the sum $n_n + n_p$. This effect will lead to an enhancement of the proportion of He^4 in primordial matter. The standard model of nucleosynthesis gives at most ≈ 33% He^4 with a ratio $n_n/(n_n + n_p) < 0.17$ at the epoch of He^4 production; here n_n, n_p are the number densities of neutrons and protons.

In order for the abundance of He^4 by mass to be less than 40%, we must have $n_n/(n_n + n_p) < 0.2$. Since the characteristic time of the nucleon annihilation reaction ($N + \bar{N} \to$ hadrons) is $\tau_{N\bar{N}} \approx 1/\sigma n_N v \approx 10^{-8}$ sec if $\sigma \approx 10^{-26}$ cm^2, $n_N \approx 10^{-8} n_\gamma \Omega$, and $v = c$ (if the antinucleons emitted by PBHs have ultrarelativistic energies), we may regard all the antinucleons as capable of reacting with background nucleons. We thereby obtain $n_{\bar{N}}/(n_n + n_p) < 1/20$ and $\alpha \leq 10^{-2}\ \Omega$ for $M \approx 10^9$ g. For masses in the range $10^9 < M < 10^{10}$ g, which corresponds to evaporation times $1 < t_1 < 10^3$ sec, the same process operates, and we obtain the upper limit

$$\alpha \leqslant 10^{-2} t_1^{1/6}\, \Omega. \tag{2}$$

The limits on the PBH spectrum derived from the influence upon cosmological nucleosynthesis of the massless leptons (ν, $\bar{\nu}$) emitted by PBHs are weaker than those given above by a factor of ≈ 10^3 for $\Omega = 0.1$. In arriving at these estimates one should note that the characteristic cross section for scattering of ν, $\bar{\nu}$ with energies E by nucleons at rest in the laboratory system is $\sigma_{\nu n} \approx 3\sigma_{\bar{\nu} p} \approx 10^{-38}$ E [GeV] cm^2 for $E > 1$ GeV.

Now let us consider how PBHs of mass $M > 10^{10}$ g will affect the nucleosynthesis at times $t > 10^3$ sec. The chief process under these conditions will be the spallation of He^4 nuclei by ultrarelativistic nucleons and antinucleons emitted by the PBHs. The neutrons arising through these processes (as well as the ones evaporated originally) will rapidly be captured by protons, forming deuterium nuclei. When $t > 10^3$ sec this deuterium will no longer burn up. Hence estimates in this range of PBH mass may be made by comparing the deuterium density implied by the mechanism just described to the deuterium density in the universe today.

First of all, we estimate the characteristic time of the He^4 spallation process. At the time of evaporation the neutrons and antineutrons will have an energy[2]

$$E_n \sim 3 \cdot 10^4 / t_1^{1/3}\ \text{GeV}. \tag{3}$$

For the characteristic time of He^4 spallation by these particles we obtain the expression

$$\tau_{He^4} = \frac{1}{\sigma_{He^4} n_{He^4} v} = 10^{-8} t_1^{4/3} \Omega^{-1} \text{sec}\ (\sigma_{He^4} = 10^{-25}\,\text{cm}^2\ \ v = c). \tag{4}$$

Equation (4) shows that all the neutrons will be capable of reacting with He^4 and with protons in the times considered.

The next important step will be the formation of deuterium. The neutrons produced through the destruction of He^4 will rapidly be decelerated to thermal velocities. Hence the deuterium production by the reaction $n + p \to D + \gamma$ will proceed at thermal energies. After introducing all the quantities, we obtain for the characteristic time τ_D of deuterium production

$$\tau_D = 5 \cdot 10^{-5}\, t_1^{5/3}\ \Omega^{-1}\,\text{sec}. \tag{5}$$

Under these conditions we must also consider deuterium burning by the reactions $D + D \to T + p$ or $He^3 + n$. For these reactions the characteristic time is

$$\tau_{DD} = 3 \cdot 10^{-4} t_1^{7/6} e^{1.8 t_1^{1/6}} \Omega^{-1}\ \text{sec}. \tag{6}$$

If $t_1 > 3 \cdot 10^3$ sec for $\Omega = 1$ (or $t_1 > 4 \cdot 10^2$ sec for $\Omega = 0.1$), then as Eq. (6) indicates the deuterium produced will not be burned. On the other hand, free neutrons decay in a time $\tau_{\beta^-} \approx 10^3$ sec, and if $\tau_D > 10^3$ sec, corresponding to an evaporation time $t_1 \approx 10^5\, \Omega^{2/3}$ sec, then deuterium will no longer be produced in appreciable quantity.

Using the observed value $\rho_D/\rho_H \approx 5 \cdot 10^{-5}$ for the present deuterium abundance by mass[10] as well as Eq. (4), we obtain the following limit on α in the time interval $10^3 < t_1 < 10^5$ sec (which corresponds to PBH masses in the range $10^{10} < M < 5 \cdot 10^{10}$ g):

$$\alpha \leqslant 10^{-6}\, t_1^{1/6}\ \ \Omega. \tag{7}$$

Then according to the condition (7), if $\Omega = 0.1$ we will have $\alpha < 3 \cdot 10^{-7}$, $\beta < 6 \cdot 10^{-22}$ for $t_1 = 10^3$ sec ($M = 10^{10}$ g) and $\alpha < 5 \cdot 10^{-7}$, $\beta < 5 \cdot 10^{-22}$ for $t_1 = 10^4$ sec ($M = 2 \cdot 10^{10}$ g). The influence of ν, $\bar{\nu}$ on the spallation of He^4 gives estimates lower by four orders of magnitude.

PBHs of mass $M > 5 \cdot 10^{10}$ g will emit a proportion $10^5\, \Omega^{2/3}/t_1$ of their energy during the period $t < 10^5\, \Omega^{2/3}$ sec, which may also serve to increase the deuterium abundance. For such PBHs the expression limiting α has the form

$$\alpha \leqslant 10^{-11} t_1^{7/6}\, \Omega^{1/3}. \tag{8}$$

The best estimate from the distortion of the vestigial radiation is no more than $\alpha \leq 10^{-2}$-10^{-3} (for $t_1 > 10^{12}$ sec). Thus the limit estimated from the chemical composition turns out to be stronger for $t_1 < 10^8$ sec, which corresponds to masses $M < 5 \cdot 10^{11}$ g.

It is of interest to consider the reaction of direct deuterium production through spallation of He^4. Experiment shows that for nucleon energies above 1 GeV the production of deuterium in such a reaction is practically independent of energy and amounts[11] to ≈ 25%. According to Eq. (4), even for $E \approx 1$ GeV the characteristic time for collision with He^4 nuclei is shorter than the expansion time (an energy of 1 GeV corresponds to an evaporation time $t_1 \approx 10^{12}$ sec and a mass $M \approx 10^{13}$ g). We therefore obtain the following limit on α by allowing for direct deuterium production:

$$\alpha < 5 \cdot 10^{-6}\ \ t_1^{1/6}\, \Omega. \tag{9}$$

Then if $\Omega = 0.1$ and $t_1 \approx 10^{12}$ sec we will have $\alpha < 5 \cdot 10^{-5}$, which is no weaker that the limit set by the electromagnetic radiation spectrum, and for $t_1 < 10^{12}$ sec is actually a stronger condition.

A rather different aspect of the matter is also of interest. It is well recognized that the observed deuterium abundance is hard to explain in terms of the customary description of cosmological synthesis if the present mass density ρ in the universe is sufficiently high (if $\Omega = \rho/\rho_c > 0.1$ or $\Omega > 0.5$ for strong, specially selected inhomogeneity). The results obtained above imply that even for $\Omega = 1$ a small number of PBHs ($\beta \approx 10^{-20}-10^{-21}$, $\alpha \approx 10^{-5}-10^{-6}$) with a mass $M \approx 10^{10}-10^{12}$ g might have been adequate to produce the required amount of deuterium, with practically no change in any of the other properties of the Friedmann universe.

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1) We assume that the number of kinds of elementary particles is limited, and that matter has an equation of state of the form $P_m = \frac{1}{3}\varepsilon_m$. For $t \geq 1$, the principal contribution to ε_m and to the total number n_m of particles and (so long as $t \leq 10$ sec) e^-e^+ pairs.

2) At the time of evaporation protons will have the same energy, but in the (e^-e^+) pair production process they will rapidly be decelerated by scattering on the background radiation to energies $E_p \approx t_1^{1/2}$ GeV.

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Distribution of stars in the vicinity of a massive black hole

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The steady-state distribution of stars in the neighborhood of a massive black hole at the center of a star cluster is determined for a finite flux of stars onto the hole. In the zone $r_t < r < r_{\rm crit}$ between the tidal and critical radii, where the diffusion of bound star orbits with respect to angular momentum is important, the star density $n(r)$ in space will vary as $r^{-1/2}$. The solution $n(r) \propto r^{-7/4}$ with a density peak found previously can obtain only in the zone $r_{\rm crit} < r < r_h$, where r_h is the gravitational capture radius of the black hole.

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1. INTRODUCTION

In attempts to solve the problem of whether massive ($M > 10^2\ M_\odot$) black holes exist in the nuclei of normal galaxies and globular clusters, a new approach is afforded by analysis of the interaction of a black hole with the stars surrounding it. In this event it is important to know how these stars are distributed in the neighborhood of the hole.

In the simplest version of the problem one may consider a cluster of identical stars of mass $m \approx M_\odot$, containing at its center a black hole of mass M_h in the range $m \ll M_h \ll Nm$, where N is the total number of stars in the cluster. One would seek the steady-state distribution of stars in the zone $r_t < r < r_h$, where

$$r_t \approx \left(\frac{6}{\pi}\frac{M_h}{\rho}\right)^{1/3} \approx 1.4\cdot 10^{12}\left(\frac{M_h}{10^3 M_\odot}\right)^{1/3}\left(\frac{\rho}{\rho_\odot}\right)^{-1/3} \text{cm} \quad (1)$$

is the tidal radius at which tidal forces become strong enough to disrupt a star of mean density ρ, and

$$r_h = \frac{2GM_h}{\langle v^2\rangle} \approx 2.7\cdot 10^{17}\frac{M_h}{10^3 M_\odot}\left(\frac{\langle v^2\rangle^{1/2}}{10\,\text{km/s}}\right)^{-2}\text{cm} \quad (2)$$

represents the radius of the gravitational influence of the hole on the motion of the stars — the capture radius.

Peebles,[1] the first to discuss this problem, assumed that the distribution function of stars in bound orbits with respect to energy $E = GM_h m/r - mv^2/2$ is a power law of the form

$$f \propto E^p, \quad (3)$$

and from the condition that the flux of stars onto the black hole be independent of E he found $p = 3/4$. This result implies a cusp in the curve for the space density of stars near a black hole: $n(r) \propto r^{-9/4}$.

More rigorous analysis,[2,3] using the one-dimensional Fokker–Planck equation to describe the diffusion of star orbits with respect to energy, has shown that a power-law distribution with $p = 3/4$ is not an admissable solution, because it implies a flux of stars which, although independent of E, is infinitely large. These authors have analytically determined a different value for the exponent, $p = 1/4$, which is obtained from the condition that the flux of stars formally vanish. In this case the star density near the hole will vary according to the law $n(r) \propto r^{-7/4}$. We should like to point out that an analogous solution was obtained some years ago by Gurevich[4] from a study of the distribution of electrons in the neighborhood of a positively

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