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Pregalactic Black Holes: A New Constraint

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Abstract

Pregalactic black holes accrete matter in the early universe and produce copious amounts of x radiation. By using observations of the background radiation in the x and γ wavebands we have been able to impose a strong new constraint upon their possible abundance. If pregalactic black holes are actually present, several outstanding problems of cosmogony can be resolved with typical pregalactic black hole masses of $100M_{\odot}$. Significantly more massive holes cannot constitute an appreciable mass fraction of the universe and are limited by $\Omega_{PGBH}(M) < 10(M_{\odot}/M)\Omega^{-1}$.

Cosmology and astronomy are bedevilled by a rich array of unsolved problems. Both of these fields of study have become increasingly dominated by fundamental developments in gravitation physics which have revealed the probable existence of intrinsically relativistic objects, namely, black holes. The intense gravitational fields associated with such objects may allow us to account for a rich array of high-energy phenomena observed in the universe. Conversely, by utilizing the modern tools of high-energy astrophysics, we may further our understanding of gravitation physics itself. Here we shall focus upon four outstanding phenomenological issues that a single hypothesis concerning the existence of pregalactic black holes (PGBH) can resolve. Of particular significance will be our emphasis that PGBH are observable at x-ray energies. There is now considerable empirical evidence that individual galactic black holes, must notably the candidate source Cygnus X-1, may have already been seen at such high energies. Our contribution extends this result to a logical and exciting implication: if

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a significant mass fraction of galaxies is in the form of PGBH, such objects will presently be detectable by virtue of the high-energy photons radiated by them in the early universe.

The nature of the nonluminous matter that dominates the gravitational potential wells of the great clusters of galaxies remains totally obscure. Gram for gram, such matter must be at least one thousand times less luminous than the sun [1]. Only the dimmest of dwarf stars even approaches such a low intensity, and it is generally considered that conventional stars cannot account for the dark matter. To compound matters, a similar situation appears to arise in the outer regions of spiral galaxies, where considerable quantities of nonluminous material evidently reside [2].

Next, one may consider the question of the origin of the heavy elements. A progressive metal deficiency (relative to the sun) is found in halo stars and globular clusters, culminating with the most metal-deficient stellar systems known having not less than about 1% of the metallicity of the sun [3]. Hence there seems to be an empirical threshold: ordinary star formation could evidently not have proceeded until the protogalaxy was seeded with a minimal level of heavy elements. One has therefore to ascertain where the heavy elements found in the most extreme metal-poor systems could have originated.

A third outstanding problem in cosmology concerns the origin of the galaxies. The existence of galaxies clearly indicates that fluctuations were present in the early universe. However, in the context of the standard big band model, these fluctuations were able to grow only after the decoupling epoch at a red shift of 1000.

One approach to explaining the observed large-scale structure of the universe has been to postulate the existence of small inhomogenities in the matter distribution, but essentially no progress has been made in understanding the origin of such fluctuations [4].

Finally, the relatively uniform cosmic background of diffuse x rays has not hitherto been adequately explained. A noteworthy feature is the energy spectrum of the background radiation, which extends from kilovolt x-ray to megavolt γ-ray photons. Known x-ray sources fail to account for more than a small fraction of the background, and more significantly, they generally peter out toward the higher photon energies [5]. Appeal to a greater number of x-ray sources of conventional type in the past only compounds this difficulty: the cosmological red shift acts to further degrade the photons in energy.

Here then are four of the most challenging problems in modern cosmology, if we accept that its primary goal is to account for the observed properties of the universe in the large. Consider therefore the following radical hypothesis, which, as we shall argue, is capable of satisfactorily resolving the issues we have raised.

Suppose that large matter fluctuations were present at recombination. The possible scale of such fluctuations is constrained by observations of the isotropy of the cosmic microwave background radiation and by the presently observed mass distribution of inhomogeneities. Specifically, one infers [4] from studies of the covariance function of galaxies that the initial fluctuation spectrum varies with mass as $M^{-1/2-n/6}$, where n, the index of the power spectrum of density fluctuations, lies between 0 and -1. The former case corresponds to a white noise initial spectrum. Since mass scales of about 10^{15} solar masses are presently entering the nonlinear regime, one infers (as the density contrast grows approximately in proportion to the increase in the cosmological scale factor) that at a red shift of 1000, large fluctuations were present on scales up to between 10^6 and 10^9 solar masses. Somewhat larger mass scales are inferred in a low-density universe. The requirement of satisfying the isotropy limits on small angular scales of the microwave background radiation imposes similar constraints.

Now we can also specify the minimum scale of large fluctuations that are capable of recollapse immediately after decoupling. This is simply the Jeans mass, equal to about 10^5 solar masses at this epoch, and specifies the minimum scale over which gravitational forces exceed thermal pressure gradients, thereby allowing gravitational instability and the eventual formation of gravitationally bound objects. Thus observational evidence has motivated us to infer the presence of sizable fluctuations on mass scales of between 10^5 and $10^9 M_\odot$ at decoupling. Such a postulate accounts for the subsequent formation of galaxies, although it should be apparent to the astute reader that we have merely managed to explain one problem by introducing another. All viable theories of galaxy formation suffer from a similar degree of arbitrariness. While we will make no attempt here to account for the origin of these fluctuations, we shall now demonstrate that their presence does resolve several other hitherto inexplicable problems.

Consider first the likely fate of large-amplitude inhomogeneities in the early universe. The sudden drop in opacity at decoupling makes the formation of collapsed objects with mass in excess of 10^5 solar masses extremely probable. Recollapse is indeed inevitable, and the most likely outcome is the formation of a single superstar, which would rapidly evolve into a massive black hole. One could only imagine averting this fate by prior fragmentation into stars. In fact, the absence of any appreciable amount of elements heavier than helium guarantees that any newly formed stars will be massive relative to the sun, and therefore short lived [6]. Consequently, such a star cluster is likely to evolve rapidly into a cluster of smaller black holes. PGBH formation is an inevitable consequence of the presence of large matter fluctuations at decoupling.

A substantial mass fraction of the universe in the form of such large inhomogeneities at recombination would, by their rapid evolution and subsequent black hole formation, lead to several direct consequences. The evolution of massive stars (or superstars) would ensure the ejection of appreciable amounts of enriched material at the time of final collapse. The PGBH would constitute an almost invisible mass constituent of the universe. They would also initially be distributed in a similar manner to the luminous material, according to the prescription for the primordial density fluctuations, and then fall into outer parts of galaxies, clustering with galaxies as the universe evolves. Finally, continuing accretion of both intergalactic and galactic gas by the PGBH will result in copious production of hard photons. Since this latter conclusion differs from results reached in several earlier papers on black hole accretion [7], it seems useful to briefly outline our reasoning.

It is generally accepted that a spherical, uniform accretion flow onto a black hole will result in an exceedingly low x-ray luminosity [8]. Radiation losses are dominant far from the black hole, where the radiative efficiency is low and where the gas temperature also remains low during the inflow. Of course, considerable kinetic energy remains in the bulk flow. In the case of a more realistic infall model [9], it seems likely that the kinetic energy reservoir will be tapped, via turbulent dissipation and shock wave generation, until the innermost stable orbits are reached. This results in a prolific source of heat, which suffices to overcome cooling by radiation in large regions. The net effect is that a spherically accreting black hole becomes an efficient radiator of x and γ rays. Only for large black holes, in excess of 10^4 solar masses, does this process become inefficient, the cooling time becoming less than the dynamical heating time scale.[3] Substantial amounts of hard photons are produced even by accretion onto a massive PGBH, the efficiency being reduced in this case by a factor that is inversely proportional to the hole mass.

This accretion model is valid provided that a thin disk does not form. If this happens, relatively soft photons would be produced. However, there is mounting evidence that approximately spherical accretion onto black holes is responsible for hard x-ray emission from several known x-ray sources. Notable among these is the prime candidate for a black hole, Cygnus X-1 [10]. Of importance also are intense sources in the nuclei of two Seyfert galaxies. These x-ray sources are characterized by hard, flat spectra that may extend to γ-ray energies [11]. Here again, massive black hole models are indicated, although other possibilities cannot yet be excluded. Even though no definitive observations of these sources have yet been performed above about 100 keV, theoretical arguments suggest that, if the black hole model is correct, the spectrum should remain relatively

[3]One can express the ratio of local cooling to dynamical time scale as $5 \times 10^{18} T_{10}^{1/2} n^{-1} M_2^{-1}$, where $T_{10} = T/10^{10}$ K and $n = 10^3 (c/V_s)^3 \Omega$. Here V_s is the sound velocity at the accretion radius (where the density n equals the mean cosmological value at decoupling). Ω (in the range $0.1 \lesssim \Omega \lesssim 1$) is the ratio of the mean cosmological density at present to the critical density in a spatially flat Friedmann universe. This ratio yields an estimate of the radiative efficiency of the accretion process.

flat up to photon energies of roughly 0.1 GeV, corresponding to the rest mass energy of a pion.

A reasonable case has been made that PGBH will emit hard x and γ rays be accretion of ambient matter. It is straightforward to demonstrate that the resulting intensity produced per gram of matter in the form of black holes of mass M_2 (equal to $M/10^2$ solar masses at decoupling) is $\sim 10^{16} M_2 \Omega$ erg g^{-1}. The mass accretion rate of a PGBH of mass M (assumed either to be in a state of subsonic motion or to be at rest relative to the cosmological substratum) can be expressed as $\frac{2}{3} G\Omega M^2 V_s^{-3} t^{-2}$. In deriving numerical estimates of the accretion luminosity, we make the conservative assumption that the conversion efficiency for x-ray production is 10^{-3} (cf. footnote (3)). These x and γ rays are red shifted, but will remain in the x-ray band in the energy range between 1 keV and 0.1 MeV. The resulting contribution to the diffuse x-ray background is $10^{13} M_2 \Omega$ erg g^{-1} after allowing for the photon energy loss since production at the decoupling redshift. For comparison, the observed diffuse x-ray background in the energy range 1 keV to 1 MeV amounts to $10^{12}\,\Omega^{-1}$ erg g^{-1}.

Comparison of the predicted x-ray flux to that observed demonstrates the power of our result: *PGBH formed at decoupling would overproduce x rays if their mass fraction (measured relative to the closure density) exceeded* $0.1 M_2^{-1} \cdot \Omega^{-1}$. Since black holes will not form unless their mass exceeds 10 solar masses ($M_2 = 0.1$), *our result provides a significant constraint on PGBH over any mass range. In particular, the possibility of massive PGBH (of mass* $\sim 10^5$ *solar masses) constituting an appreciable mass fraction of the universe can now be eliminated by a wide margin.* What are the loopholes in our argument? Accretion is inhibited if the PGBH acquire a substantial velocity at birth. However, we have only used the mean cosmological density and a conservative estimate of the radiative efficiency in estimating accretion rates: allowance for density inhomogeneities (necessarily present at decoupling if PGBH are to form) will enhance the calculated x-ray emissivity. It is our contention that, at worst, there may be a tradeoff between these effects, and our principal conclusion survives. Quasispherical accretion and shock heating is crucial to the production of hard x rays. Although disks may form, in a realistic accretion flow they are likely to heat up [9], thereby leading to a similar result. The lack of appreciable magnetic fields in the primordial accreting gas guarantees that cyclotron emission (which would result in radiation at optical wavelengths [7]) will not play any role, and relativistic bremsstrahlung at hard x-ray and γ-ray energies is the dominant radiation mechanism.

In summary, pregalactic black holes accrete matter in the early universe and produce copious amounts of x radiation. We have imposed a strong new constraint of their possible abundance. If PGBH are actually present at the allowed level, several outstanding problems of cosmogony can be resolved with typical

PGBH masses of $100M_\odot$. Significantly more massive PGBH cannot constitute an appreciable mass fraction of the universe and are limited by $\Omega_{PGBH}(M) < 10(M_\odot/M)\Omega^{-1}$.

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References

1. Hoessel, J., Melnick, J., and White, S. D. M. (1977). *Mon. Not. R. Astron. Soc.*, **180**, 207.
2. Krumm, N., and Salpeter, E. E. (1977). *Astron. Astrophys.*, **56**, 465.
3. Searle, L. (1977). *The Evolution of Galaxies and Stellar Populations*, eds. B. M. Tinsley and R. B. Larson, p. 219 (Yale University Observatory, New Haven).
4. Gott, J. R. (1977). *Ann. Rev. Astron. Astrophys.*, **15**, 235.
5. Silk, J. (1973). *Ann. Rev. Astron. Astrophys.*, **11**, 269.
6. Silk, J. (1977). *Astrophys. J.*, **211**, 638.
7. Ipser, J. R., and Price, R. M. (1977). *Astrophys. J.*, **216**, 578, and references cited therein.
8. Shapiro, S. L. (1973). *Astrophys. J.*, **180**, 531.
9. Fabian, A. C., Maccagni, D., Rees, M. J., and Stoeger, W. R. (1976). *Nature (London)*, **260**, 683; Mészáros, P., and Silk, J. (1977). *Astron. Astrophys.*, **55**, 289.
10. Thorne, K. S., and Price, R. N. (1975). *Astrophys. J. Lett.*, **195**, L101.
11. Baity, W. A., Jones, T. W., Wheaton, W. A., and Peterson, L. E. (1975). *Astrophys. J. Lett.*, 199, L5; Hall, A. R. D., Meegen, C. A., Walraven, G. D., Djuth, F. T., and Haymes, R. C. (1976). *Astrophys. J.*, **210**, 631.