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ON THE POSSIBILITY THAT THE HALO MACHO EVENTS AND
SHORT GAMMA-RAY BURSTS ARE DUE TO PRIMORDIAL BLACK HOLES*

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ABSTRACT

The possibility that the Universe contains significant amounts of primordial black holes (PBHs) with a fraction of a solar mass ($\sim 10^{32}$ g or less) is not excluded at present. Although there are limits on the number of low-mass PBHs ($m \sim 10^{15}$ g), there is some evidence for their existence. We show that the recently observed MACHO events could be the result of PBHs, but they are unlikely to be due to either white dwarfs or low-mass stars (red dwarfs). The abundance of PBHs is not inconsistent with the fluctuation density in the early Universe, especially near the time of the quark-gluon phase transition. The observed mass spectrum would be $M_{\text{PBH}}^{-2/3}$, which is inconsistent with inflationary fluctuations. The galactic halo could contain large numbers of PBHs with masses from $10^{15} - 10^{32}$ g that could be sites for gamma-ray bursts (GRBs).

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1. INTRODUCTION

The existence of massive black holes ($m \geq 3 M_{\odot}$) is now generally accepted. Currently it is believed that our galaxy may have as many as 10^9 such objects (Timmes et al. 1996). These are presumed to be produced as the aftermath of a Type-II supernova explosion of a massive star. There is no known stellar mechanism to produce lower mass black holes (e.g., $M_{\text{PBH}} \sim 1/2 M_{\odot}$) or microscopic black holes with $M_{\text{PBH}} = 10^{15}$ g. If black holes of this mass exist in our galaxy, they would presumably be due to primordial production in the early Universe, and they indeed would give new information about the early Universe (Crawford & Schramm 1982; Carr, Gilbert, & Lidsey 1994; Fuller & Schramm 1996).

There are several mechanisms leading to density fluctuations that could have produced PBHs in the early Universe:

1. Inflationary horizon-scale fluctuations (Carr et al. 1994),
2. Density fluctuations at phase transitions (e.g., quark-gluon) and bubble formation and collapse (Crawford & Schramm 1982),
3. Baryon isocurvature fluctuations on small scales (Dolgov & Silk 1993).

To our knowledge, none of these mechanisms can be proven to exist in significant enough importance to ensure PBH formation and, therefore, the major question is whether present constraints from the observed parameters of the Universe, galaxies, and stellar objects rule out the existence of PBHs. There are numerous constraints on the density of low-mass black holes in the Universe that are nicely summarized in MacGibbon & Carr (1991). Additional constraints that come from microlensing techniques using quasi-stellar objects are summarized in Dalcanton et al. (1994). At present, in the mass range of $10^{15} - 10^{32}$ g, the existing constraints give $\Omega_{\text{PBH}} < 0.2$! In the mass

range of black holes ($10^{14} - 10^{15}$ g), there are constraints arising from the diffuse γ -ray background at $E_\gamma \sim 100$ MeV, which gives $\Omega_{\text{PBH}} (\sim 10^{15} \text{ g}) \leq 10^{-8}$ (MacGibbon & Carr 1991).

2. POSSIBLE EVIDENCE FOR PBHs

Recently three groups have developed the microlensing technique proposed by B. Paczynski (1986) and have detected signals from unknown objects in the halo or disk of the Galaxy. Even more recently, the MACHO collaboration (Alcock et al. 1996) has reported eight halo MACHO events that we focus on in this letter.

The new MACHO data were presented at a 1996 UCLA symposium (Bennet et al. 1996). These data are best fit by a MACHO mass of between $1/4$ to $1/2 M_\odot$ (Bennet et al. 1996) and represent an appreciable fraction of the halo mass. In this letter, we assume this to be a correct interpretation of the events and explore the consequences. There is strong evidence against a sizable population of red or white dwarfs in the Galaxy (Flynn, Gould, & Bahcall 1996; Reid 1996) that give more than 1% of the halo mass. If this is true, the MACHO events are best explained as PBHs. We assume, consistent with the data, that a population of this type in the Universe gives $\Omega_{\text{PBH}} \sim 0.1$ for the PBHs of mass $\sim 1/4 M_\odot$. Figure 1 shows the resulting density of high- and low-mass PBHs (Cline 1995; Cline & Hong 1996). We note that the mass spectrum varies like $M_{\text{PBH}}^{-2/3}$. If this is confirmed, this power spectrum could give a clue to the origin of these black holes in the early Universe.

Ever since the discussion of microscopic PHBs began, there have been suggestions for the experimental detection of such objects (Page & Hawking 1976; Hawking 1974, 1975). Low-mass ($\leq 10^{15}$ g) black holes could produce adequate radiation to be detected either individually or collectively. However, the real-time detection depends on the final state evolution of the PBH (i.e.,

Figure 1. Possible density of PBHs in the Universe as discussed in the text. This mass spectrum follows $M_{\text{PBH}}^{-2/3}$ approximately.

as the temperature of the PBH rises, it sheds mass into the region of hadronic interactions and final states). The most extreme model that was used to simulate this final state was the Hagedorn model, which predicted an explosion lasting $\sim 10^{-7}$ s, whereas other QCD-inspired calculations suggested a final-state collapse time of the order of seconds (Carter et al. 1976; MacGibbon & Weber 1990). We questioned the validity of the QCD-inspired calculations and pointed out that the final state interactions and non-perturbation effects could increase the low-energy particle luminosity and even the collapse time due to the quark-gluon phase transition, both of which must make detection easier (Cline & Hong 1992). We note that there are clear indications of at least two classes of GRBs (Kouveliotou et al. 1993). The approach taken here is to determine if there are GRBs that could be consistent with PBH evaporation. There are two recent developments:

1. New estimates of the amount of PBHs that may have originated at the time of the early Universe (Carr et al. 1994), and

2. A suggestion by Cline & Hong (1994) that some of the BATSE GRB events could have the characteristics that are expected from PBH evaporation within a specific model of the hadronic interaction (Cline & Hong 1994, 1996; Cline 1995; Cline, Sanders, & Hong 1995).

Beginning in 1990, we have studied many of the experimental papers on GRBs and noticed that there is a class of short GRBs (few 100 ms) that, in many cases, seems to have a hard gamma spectrum. Recently, the BATSE group has recorded such a GRB, and it is very interesting; this short GRB also has characteristics that are consistent with PBHs as given in our model (Cline & Hong 1996).

Since very short-burst γ rays from the PBH fireball are expected to be seen at a distance of, at most, a few parsec around the earth, we expect to find that short bursts selected from among the BATSE data are an homogeneous and isotropic distribution of sources in a static Euclidean (HISE) space.

To make any reasonable assessment about the spatial distribution of the short GRBs, we need to study the $\log N(C_p)$ vs $\log (C_p/C_{lim})$ or $\log (C_p)$, where C_p and C_{lim} refer to the peak and background limited counts for an event. This distribution may contain a bias resulting from the variable-threshold burst durations, as suggested by Petrosian et al. (1993, 1994). By following their suggestions, we corrected for the bias due to variability of C_{lim} . (The Petrosian analysis is justified, because of the expected loss of short, weak bursts.) The corrected distribution is consistent with a slope of $-3/2$, as expected for HISE (of course the statistical limitation is evident). We note as well that the short bursts observed by PHEBUS also give $V/V_{max} \sim 1/2$ (Cline 1995). They have a remarkable simplicity, as would be expected for a simple source such as PBH evaporation near the solar system. Recently we have studied the latest BATSE data and have reached a similar conclusion concerning the interpretation of short GRBs as candidates for PBH evaporation (Cline et al. 1995).

3. SUMMARY

The search for signals for PBHs has been going on since 1975. The traditional, very short GRB signature ($\Delta\tau \sim 10^{-7}$ s) is likely incorrect by current physics theory. However, short GRBs can occur from PBHs under the following conditions:

1. $M_{\text{PBH}} \sim 10^9$ g, QCD burst,
2. $M_{\text{PBH}} \sim 10^{14}$ g, quark–gluon phase transition.

While no candidates for the former exist, there are several GRB events that have characteristics expected for the latter. If these events are due to PBHs, the density in the galaxy could be $10^8 - 10^{10}$ pc^{-3} .

Another argument for the possible existence of $\sim 10^{15}$ g PBHs comes from the observation that the spectrum and rate of galactic cosmic $\bar{p}$, e^+ , and diffuse photons can be explained by PBH evaporation (MacGibbon & Carr 1991). The density of PBHs in the Universe implied by the short GRBs and the cosmic ray arguments are the same within these considerable model-dependent uncertainties.

Promordial black holes produced in a radiation-dominated early Universe should have a mass spectrum of the form (Carr et al. 1994)

$$\frac{dn}{dM_{\text{PBH}}} \propto \frac{1}{M_{\text{PBH}}^\alpha} ; \quad \alpha = 5/2 .$$

In this case, the density level implied by identifying the MACHO events with PBHs would lead to a vast number of low mass PBHs giving

$$\Omega_{\text{PBH}} \gg 1 ,$$

which would overclose the Universe. This would also lead to a very large level of diffuse γ -ray

background, which would be inconsistent with observations (MacGibbon & Carr 1991). On the other hand, if the PBHs are produced by fluctuations at a phase transition, the mass spectra could be quite different. To the best of our knowledge, however, there are no specific predictions at present.

If we assume that the level of PBH density is set by the short GRB–PBH and MACHO events, we obtain the PBH mass spectrum shown in Figure 1, which gives

$$\alpha \approx 0.7 \quad .$$

We note that this leads to the density of PBHs in the Universe that goes from $\Omega_{\text{PBH}} \sim 10^{-8}$ for $M_{\text{PBH}} \sim 10^{15}$ g to $\Omega_{\text{PBH}} \sim 10^{-1}$ for $M_{\text{PBH}} \sim 10^{32} - 10^{33}$ g, which is a wide range of variation.

It has been shown that fluctuations due to inflation can not produce the spectrum of PBH mass shown in Figure 1 (Carr et al. 1994). Perhaps the most promising way that such a spectrum of PBHs could form would be as a result of a cosmological phase transition, or perhaps the quark–gluon phase transition, at $t \sim 10^{-5}$ s in the early Universe (Crawford & Schramm 1982; Fuller & Schramm 1996). In our model, the PBH “explodes” at the quark–gluon phase transition temperature, which we assume to be a first order transition, and makes the GRB detachable from earth (Cline & Hong 1992). It is remarkable that the same quark–gluon phase transition in the early Universe may have helped to create the PBHs (Crawford & Schramm 1982).

In this letter, we have pointed out that there is some circumstantial evidence for primordial black holes in the mass range of $10^{15} - 10^{32}$ g. If taken as evidence, this would require an M_{PBH} spectrum varying as $M_{\text{PBH}}^{-2/3}$, which would likely be inconsistent with production by inflationary generated fluctuations. However, fluctuations at a cosmological phase transition or the quark–gluon phase transition may be a viable candidate for this effect.

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REFERENCES

- Alcock, G., et al. 1996, *ApJ*, 461, 84
- Bennet, D. P., et al. 1996, in *Proceedings, Sources and Detection of Dark Matter in the Universe*, ed. D. B. Cline (North Holland: Elsevier), in preparation.
- Carr, B. J., Gilbert, J. H., & Lidsey, J. E. 1994, *Phys. Rev. D* 50, 4853
- Carter, B., et al. 1976, *A&A*, 52, 427
- Cline, D. B. 1995, *AP&SS*, 231, 393
- Cline, D. B. & Hong, W. P. 1992, *ApJ*, 401, L57
- _____ 1994, *AIP Conf. Proc.* 307: *Gamma-Ray Bursts, 2nd Workshop*, ed. G. L. Fishman et al. (New York: AIP), 577
- _____ 1996, "Very Short Gamma-Ray Bursts and primordial black hole evaporation," *Astropart. Phys.*, in press
- Cline, D. B., Sanders, D. A., & Hong, W. P., "Further evidence for gamma ray bursts consistent with primordial black hole evaporation," 1995, *ApJ*, submitted.
- Crawford, M. & Schramm, D.N. 1982, *Nature*, 298, 538
- Dalcanton, J., et al. 1994, *ApJ*, 424 550
- Dolgov, A. & Silk, J. 1993, *Phys. Rev. D* 47, 4244

Flynn, C., Gould, A., & Bahcall, J. "Hubble deep field constraint on baryonic dark matter," 1996, *Astrophys. J.*, in press.

Fuller, G. & Schramm, D. N. 1996, private communication and to be published.

Hawking, S. W. 1974, *Nature* 248, 30

_____ 1975, *Commun. Math. Phys.* 43, 199

Kouveliotou, C., et al. 1993, *ApJ*, 413, L101

MacGibbon, J. H. & Carr, B. J. 1991, *ApJ*, 371, 447

MacGibbon, J. H. & Weber, B. R., 1990, *Phys. Rev. D* 41, 3052

Page, D. N., & Hawking, S. W. 1976, *ApJ*, 206, 1

Paczynski, G. 1986, *ApJ*, 304, 1

Petrosian, V. et al. 1993, *ApJ*, 402, L33

_____ 1994, *AIP Conf. Proc.* 307: *Gamma-Ray Bursts, 2nd Workshop*, ed. G. L. Fishman et al. (New York: AIP), 93

Reid, N. April 1994, seminar at UCLA on using the Keck telescope to search for red and white dwarfs in the halo; also private communication

Timmes, F. X., et al. 1996, *ApJ*, 457, 834