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# THE GROWTH OF A PRIMORDIAL BLACK HOLE AT THE CENTER OF A STAR

PARK, SEOK-JAE
Department of Astronomy, University of Texas at Austin
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## ABSTRACT

It has been suggested that there could be a large number of primordial black holes which were formed in the early universe. We analyze the growth of such a primordial black hole following two different accretion rates —— the Eddington accretion rate and the Bondi accretion rate —— at the center of a host star like the sun. We find that a primordial black hole with $M < \sim 10^{17}$ g cannot substantially grow in any case throughout the lifetime of a host star. If $M > \sim 10^{17}$ g, the evolution of a host star depends entirely on the mode of accretion, but it ends as a black hole in either case. Since more stars may have primordial black holes at the center of a galaxy this may result in a cluster of such black holes, and the cluster may eventually collapse to produce a single supermassive black hole.

## I. INTRODUCTION

It has been suggested that there could be a large number of primordial black holes (hereafter, PBHs) which were formed in the early universe (Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974; Lin et al. 1976; Bicknell and Henrikson 1979; Freese et al. 1983). PBHs may be formed at various phase transitions or produced whenever density inhomogenities reach $\delta \rho/\rho \sim 0.1$ over scales smaller than the horizon but larger than the Jeans mass.

Gravitationally collapsing protostars may be able to capture such PBHs due to rapid gravitational potential changing (Rees 1989). Since there is also the possibility that a protostar may form around a PBH (Clayton et al. 1975), we will assume that a star has a PBH at the center and investigate its growth. In §II we will investigate two kinds of mass accretion onto a PBH at the center of a host star, and we will analyze the growth timescales in §III. Finally, we will discuss our conclusions in §IV.

## II. MASS ACCRETION RATES

Hawking (1974, 1975) shows that, because of quantum effects, any black hole of mass $M$

should emit particles like a blackbody with the associate timescale $\tau$

$$\tau \sim 10^{10}\ yr\ \left(\frac{M}{10^{15}\mathrm{g}}\right)^{3}, \tag{1}$$

which corresponds to the rate of mass loss

$$\dot{M} \sim 0.1\mathrm{g}\ s^{-1}\left(\frac{M}{10^{15}\mathrm{g}}\right)^{-2} \tag{2}$$

Equation (1) shows that PBHs of less than mass $\sim 10^{15}$ g would have exploded by now, and the possibility of detecting such events has been discussed (Chapline 1975; Page and Hawking 1976; Carr 1976; Rees 1977; Blandford 1977; MacGibbon and Carr 1989).

The fate of a PBH at the center of a host star, however, must be analyzed in detail by considering the effect of mass accretion. For example, if radiation itself is sucked down into the hole, since the surrounding material is opaque, radiation emission is inefficient at the center of a host star. In this case the lifetime of a PBH would be significantly longer than $\tau$ given by equation (1). In this paper we investigate the consequences of two kinds of mass accretion. In the first case the mass accretion rate $\dot{M}$ is limited by radiation pressure at the Eddington limit,

$$\dot{M} \sim \dot{M}_E = \frac{L_E}{c^2} \sim 0.07\mathrm{g}\ s^{-1}\left(\frac{M}{10^{15}\ \mathrm{g}}\right), \tag{3}$$

where $L_E$ is the Eddington luminosity. Therefore, we have the relation $\dot{M} \propto M$ in this case (see Fig. 1). In the second case radiation emission is inefficient at penetrating infall and $\dot{M}$ is close to the hydrodynamic Bondi accretion rate $\dot{M}_B$ (e.g., see Novikov and Thorne 1973),

$$\dot{M} \sim \dot{M}_B \sim 8 \times 10^{-5}\ \mathrm{g\ s^{-1}}\left(\frac{M}{10^{15}\ \mathrm{g}}\right)^2\left(\frac{\rho_c}{100\ \mathrm{g\ cm^{-3}}}\right)\left(\frac{T_c}{10^7\ \mathrm{K}}\right)^{-3/2}, \tag{4}$$

where $\rho_c$ and $T_c$ are the density and the temperature at the center of the host star, respectively. Therefore, we have the relation $\dot{M} \propto M^2$ in this case (see Fig. 1).

Since we have $\rho_c \sim 160\ \mathrm{g\ cm^{-3}}$ and $T_c \sim 1.5 \times 10^7$ K at the center of the sun, equation (4) becomes

$$\dot{M} \sim \dot{M}_B \sim 7 \times 10^{-5}\ \mathrm{g\ s^{-1}}\left(\frac{M}{10^{15}\ \mathrm{g}}\right)^2 \tag{5}$$

at the center of a host star like the sun. Setting equation (5) equal to equation (3) we get

$$M_{crit} \sim 10^{18}\ \mathrm{g} \sim 5 \times 10^{-16}\ M_{\odot}, \tag{6}$$

which is the mass for the critical case $\dot{M}_E = \dot{M}_B$ at the center of a star (see Fig. 1). Notice that $\dot{M}_B < \dot{M}_E$ if $M < M_{crit}$. The Schwarzshild radius of $M_{crit}$, $r_{crit} \sim 1.5 \times 10^{-10}$ cm in this case, gives an accretion radius of order $r_{crit}(c/c_s)^2$, where $c_s$ is the speed of sound waves. Since we have $c_s \sim$ a

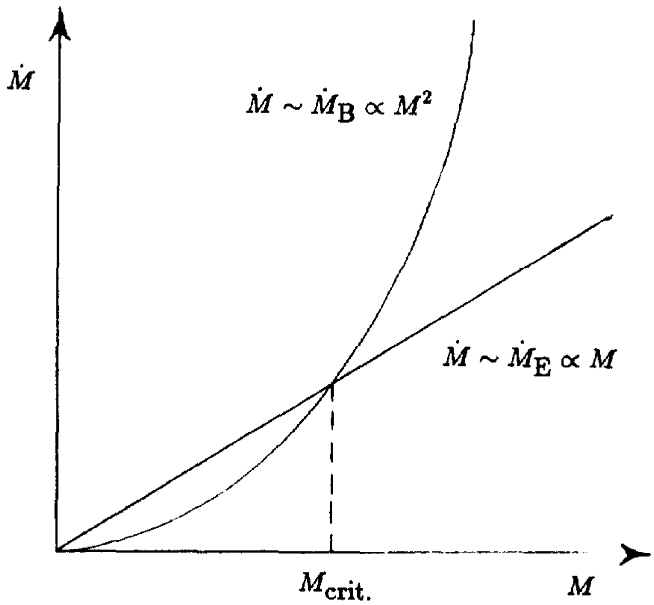


**Fig. 1.** Two accretion rates $\dot{M}_B$ and $\dot{M}_E$

few hundred km $s^{-1}$ at the center of the sun, the accretion radius is of order $\sim 10^{-4}$ cm. This is much greater than the mean free path of particles at the center of the sun, and equation (5) is justified in the vicinity of $M_{crit}$ or in cases of $M > M_{crit}$.

## III. GROWTH TIMESCALES

In this section we analyze the growth of a PBH at the center of a host star like the sun. If the mass of a PBH is smaller than $\sim 10^{14}$ g then $\tau$ given by equation (1) is shorter than $\sim 10^7$ years. Since PBHs in the radiation-dominated universe do not substantially increase their original masses by accretion (Carr and Hawking 1974; Thorne et al. 1986), it is almost impossible to expect a protostar to be formed about a PBH with $M < \sim 10^{14}$g or to expect a star to capture that PBH. If the mass of a PBH is larger than $\sim 1 M_\odot$, it is obvious that the PBH swallows the whole star on a very short timescale (see eqs. [7] and [8]). Therefore, we consider a PBH with $\sim 10^{14}$ g $< M_0 < \sim 1\ M_\odot$, where $M_0$ means the mass of a PBH at the moment when the PBH starts to grow.

**a)** $\sim 10^{14}$ g $< M_0 < \sim 10^{17}$ g Case

Let us consider the case of a PBH with $\sim 10^{14}$ g $< M_0 < \sim 10^{17}$ g at the center of a host star. If a PBH accretes matter according to equation (3), the PBH will grow on a timescale $\tau$

$$\tau \sim 5 \times 10^8 \ yr \ ln \left(\frac{M}{M_0}\right), \tag{7}$$

where $M$ is the final mass of the PBH. Equation (7) shows that PBHs with $\sim 10^{14}$ g $< M_0 < \sim$

$10^{17}$ g cannot grow even as big as an atom ($M \sim 10^{21}$ g) throughout the evolution of a host star.

If a PBH accretes matter according to equation (4), we may use equation (5) for the evolution timescale of a host star because the stellar structure will be affected little by the PBH. Therefore, the PBH will grow on a timescale $\tau$

$$\tau \sim 5\times 10^{11} \text{ yr} \left(\frac{M_0}{10^{15}\text{g}}\right)^{-1}, \tag{8}$$

which is dependent only on $M_0$. Equation (8) also shows that PBHs with $\sim 10^{14}$ g $< M_0 < \sim 10^{17}$ g cannot grow substantially throughout the evolution of a host star. In this case, in spite of equation (1), even a PBH with mass $\sim 10^{14}$ g $< M_0 < \sim 10^{15}$ g may be survived throughout the evolution timescale of a star because the radiation emission is inefficient. The central region of a main sequence star may be such an "incubator" of a PBH with mass $\sim 10^{14}$ g$< M_0 < \sim 10^{15}$ g.

Since $\dot{M}_B < \dot{M}_E$ ($M_0 < M_{crit}$), equation (8) seems to fit better in this case. In either case we can conclude that a PBH with $\sim 10^{14}$ g $< M_0 < \sim 10^{17}$ g cannot substantially grow at the center of a host star.

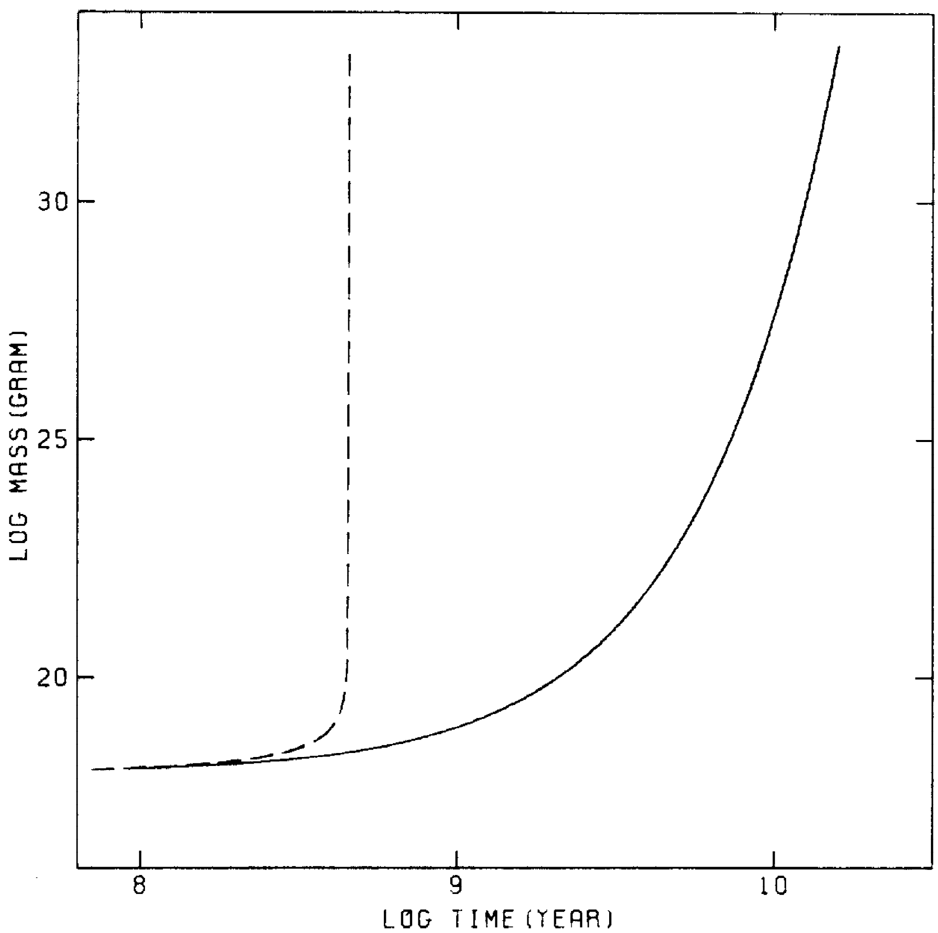


**Fig.2.** Growth of a PBH. The dotted line shows the growth due to $\dot{M}_B$ and the straight line shows that due to $\dot{M}_E$, respectively.

### b) $\sim 10^{17}$g $< M_0 < \sim 1M_{\odot}$ Case

If a PBH with $\sim 10^{17}$ g $< M_0 < \sim 10^{28}$ g begins to grow according to equation (3), the PBH swallows the whole star on a timescale $\tau \sim 10^{10}$ years (see Fig. 2), which is still slightly longer than the evolution timescale of the host star. In this case the host star can possess a PBH with $M > \sim 10^{-7} M_{\odot}$ at its center after a time $\tau < \sim 10^{10}$ years. Therefore, a significant fraction of the luminosity of the host star can be supported by the accretion of the PBH, and the solar neutrino problem may be explained quantitively (Clayton et al. 1975). If a PBH with $\sim 10^{28}$ g $< M_0 < \sim 10^{32}$ g begins to grow, the PBH swallows the whole star on a timescale $\tau \sim 10^9$ years.

If a PBH with $\sim 10^{17}$ g $< M_0 < \sim 1M_{\odot}$ begins to grow according to equation (8), the PBH swallows the whole star on a timescale $\tau < \sim 10^9$ years (see Fig. 2). Especially, if $\sim 10^{27}$ g $< M_0$, the PBH swallows the whole star within a year. In this case the role of the PBH changes dramatically as the evolution of the host star proceeds because $\dot{M}$ is dependent on $\rho_c$ and $T_c$. For example, if the host star has a degenerate core when it becomes a red giant, $\dot{M}$ will increase substantially. If the host star is a $\sim 1M_{\odot}$ neutron star, a $\sim 10^{18}$ g PBH swallows the whole neutron star in $\sim 10^6$ years, which may be the cause of the pulsarquakes as pointed out by Hawking (1971). All the final processes will be violent enough to produce gravitational waves as also pointed out by Hawking (1971).

## IV. CONCLUSIONS

Black holes with stellar masses are normally thought of as being produced by the collapse of the stars, but we have found another possiblity to produce them — a star which captured a PBH or was formed about a PBH may become a black hole when the PBH swallows it. In any case of the two mass accretion rates the fate of a host star ends as a black hole. Since more stars may have primordial black holes at the center of a galaxy this may result in a cluster of such black holes, and the cluster may eventually collapse to produce a single supermassive black hole (e. g., see Shapiro and Teukolsky 1985).

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