On the detectability of primordial black holes in the Galaxy

Julia K. Becker*, Marek A. Abramowicz*† and Peter L. Biermann‡ § ¶ ∥ **

*Insitutionen för Fysik, Göteborgs Universitet, 41296 Göteborg, Sweden
†N. Copernicus Astronomical Centre, Polish Academy of Sciences, Bartycka 18, 00-716 Warszawa, Poland
‡ MPI for Radioastronomy, Bonn, Germany
§ Bonn University, Germany
¶ Dept. of Phys. & Astr., Univ. of Alabama, Tuscaloosa, AL, USA
∥ Dept. of Phys., Univ. of Alabama at Huntsville, AL, USA
** FZ Karlsruhe, and Phys. Dept., Univ. Karlsruhe, Germany

Abstract. **In the mass range of 10^{15} g up to 10^{26} g, primordial black holes (PBHs) as a possible contribution to the dark matter are still unexplored. In this contribution, we investigate the possibility of an electromagnetic signal from PBH interactions with astrophysical objects in the Galaxy. We find that a signal from passages cannot be observed, since, depending on the mass, either the interaction probability or the energy loss is too small. Further, we discuss possible effects from high-mass PBHs at masses $> 10^{26}$ g, where PBHs can still contribute to the dark matter at the order of $\sim 10\%$. Here, we find that a significant fraction of PBHs can be captured in the Hubble time. These captures could therefore lead to detectable effects.**

***Keywords*: primordial black holes, dark matter, PBH capture**

I. Introduction

Although the existence of dark matter was already established by Zwicky in 1933 [6], its origin and nature is still unknown. Several models were proposed to explain the missing matter, among others weakly interacting massive particles (WIMPs), sterile neutrinos, regular neutrinos, massive astrophysical compact halo objects (MACHOS) and also primordial black holes (PBHs). MACHOs and regular neutrinos have been shown to have a negligible effect on dark matter. Primordial black holes, on the other hand, can contribute up to 100% in the mass range 10^{15} g $< m_{pbh} < 10^{26}$ g. Here, m_{pbh} is the mass of the primordial black hole. Below and above this mass range, the contribution of PBHs to the dark matter is constrained, with current limits shown in Fig. 1: PBHs with masses at $5 \cdot 10^{14}$ g are expected to evaporate in the local universe, with a unique signature of high-energy photon emission with energies above 20 MeV. Measurements by the EGRET experiment do not show any evidence of PBH evaporation signatures and the contribution of PBHs to dark matter is strongly constrained to a fraction of less than $3 \cdot 10^{-9}$ [5], [2]. New data from the Fermi experiment will provide further improvement to this limit. The region above 10^{26} g is constrained to a level of less than $\sim 10\%$ of the dark matter and for PBHs of the order of solar masses and above, constraints are much more stringent, up to 10^{-8}, see e.g. [3] and references therein.

In this paper, we investigate if it is possible to detect PBHs, or alternatively to constrain their contribution to the dark matter, by their interactions with stellar objects in the Galaxy. In order to do this, we discuss the following questions: In Section II, we discuss how often interactions between PBHs and stellar objects happen. We answer the question of the energy loss in a single passage in Section III. In Section IV, we investigate at what point is the PBH captured by stellar objects and possible consequences. Section V discusses the results. All our results are based on simple estimates, without considering exact distributions of the PBH masses, velocities or the spatial distribution of dark matter. Effects of including these effects are either negligible or would decrease the sensitivity to the observation of PBH interactions (see [1] for a detailed discussion). The aim of this paper is to give an upper limit on possible effects.

II. Interaction probability

In the following calculation, we consider the interaction of PBHs with four classes of objects: main sequence stars (MS$\star$), red giant cores (RGC), white dwarfs (WD) and neutron stars (N$\star$) The rate of PBH interactions with a class of stellar objects is given by

$$\dot{n} \approx N_\star \cdot j_{pbh} \cdot \sigma_{pbh,\star} \,. \qquad (1)$$

Here, $N_\star$ is the number of stellar objects in the considered class. The flux of primordial black holes, j_{pbh}, is given by the product of the PBHs' number density n_{pbh} with their velocity v_0:

$$j_{pbh} = n_{pbh} \cdot v_0 \,. \qquad (2)$$

We use the measured rotational velocity of matter in the Galaxy as the relative velocity between PBHs and stellar objects, $v_0 \approx 2.2 \cdot 10^7$ cm s^{-1}. The number density of primordial black holes can be determined by assuming that PBHs represent a fraction η of the DM in the Galactic halo, $M_{DM} \approx 9 \cdot 10^{11}\, M_\odot$. The spherical halo has an approximate radius of $r_{halo} \sim 50$ kpc. We further assume that all PBHs are produced at the same

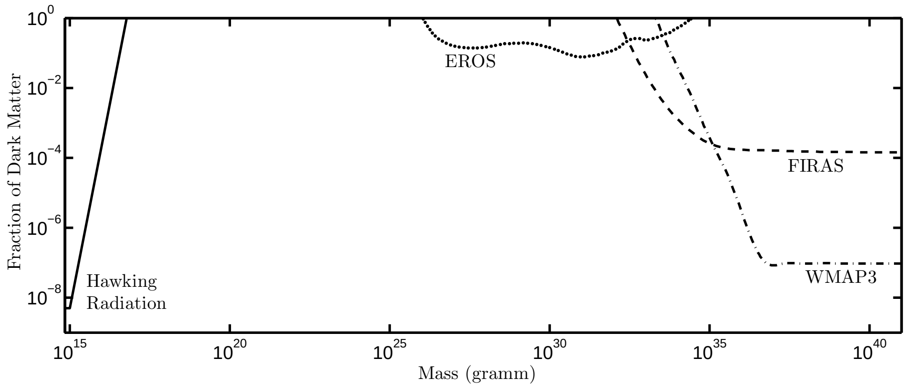

Fig. 1. Constraints on the contribution of PBHs to the dark matter

mass value m_{pbh}, with m_{pbh} as a free parameter. Thus, the number density of PBHs is

$$n_{pbh} = \frac{\eta \cdot M_{DM}}{4/3\,\pi\, r_{halo}^3} \cdot \frac{1}{m_{pbh}} \tag{3}$$

and the event rate can be written as

$$\dot{n} \approx N_\star \cdot \frac{\eta \cdot M_{DM}}{4/3\,\pi\, r_{halo}^3} \cdot \frac{v_0}{m_{pbh}} \cdot \sigma_{pbh,\star}\,. \tag{4}$$

The cross section of a PBH interacting with a star is given as

$$\sigma_{pbh\,\star} = \pi\, R_0^2\,. \tag{5}$$

Here, we use the conservation of angular momentum in order to estimate the impact parameter R_0, which guarantees the collision with the star. Angular momentum conservation gives the relation

$$v_0\, R_0 \approx v_\star \cdot R_\star \tag{6}$$

with the PBH's velocity $v_\star$ when it reaches the surface of the star. The final velocity is determined using energy conservation:

$$\frac{1}{2} v_0^2 - \frac{G\, M_\star}{R_{dist}} = \frac{1}{2} v_\star^2 - \frac{G\, M_\star}{R_\star} \tag{7}$$

with $M_\star$ as the mass of the stellar object. The characteristic distance of the PBH entering the gravitational field of the star can be approximated as the typical distance between objects in the galaxy, R_{dist}, assuming that each star-like objects deflects the PBH at least marginally. We assume this typical distance to be $R_{dist} \sim 1$ pc. The gravitational energy is negligible in the initial state[1] and the final velocity can be expressed as

$$v_\star \approx \sqrt{v_0^2 + \frac{2\, G\, M_\star}{R_\star}} = \sqrt{v_0^2 + v_{esc}^2}\,. \tag{8}$$

Using Equ. (8) in Equ. (6) results in the correlation

$$R_0 = R_\star \cdot \frac{v_*}{v_0} = R_\star \cdot \frac{\sqrt{v_0^2 + v_{esc}^2}}{v_0}\,. \tag{9}$$

[1]For $R_{dist} = 1$ pc, we get $G\, M_\star / R_{dist} \approx 7000$ cm s^{-1}

Replacing the impact parameter R_0 in Equ. (4) by using Equ. (9) yields

$$\dot{n} \approx N_\star \cdot \frac{\eta \cdot M_{DM}}{4/3\,\pi\, r_{halo}^3} \cdot \frac{v_0}{m_{pbh}} \cdot \left(\frac{v_\star}{v_0}\right)^2 \cdot R_\star^2 \tag{10}$$

$$= 2 \cdot 10^{-3} \mathrm{yr}^{-1} \cdot N_{\star,9} \cdot \eta_1 \cdot v_{\star,0}^2 \cdot R_{\star,9}^2 \cdot m_{pbh,20}^{-1}\,. \tag{11}$$

We use fixed numbers for the dark matter mass in the Galaxy, $M_{DM} = 9 \cdot 10^{11}\, M_\odot$ and for the halo radius, $r_{halo} = 50$ kpc. Other variables are $N_{\star,9} := N_\star/10^9$, $\eta_1 := \eta/1$, $v_{\star,0} := v_\star/v_0$, $R_{\star,9} := R_\star/(10^9 \mathrm{cm})$ and $m_{pbh,20}/(10^{20}\,\mathrm{g})$.

Apart from the PBH mass, which we leave as a variable, the remaining parameters depend on the property of the astrophysical objects considered. The basic properties of the source classes are listed in table I. The resulting event rate scales as $m_{pbh,20}^{-1}$ and the values for $\dot{n}(m_{pbh,20} = 1)$ are given in table II.

TABLE I
PROPERTIES OF SOURCE CLASSES IN THE GALAXY, CONSIDERED AS CANDIDATES FOR INTERACTIONS WITH PBHS.

parameter	MS⋆	RGC	WD	N⋆
$N_\star$	10^{11}	10^9	10^9	10^9
$M_\star/M_\odot$	1	1	1	1
$R_\star$ [cm]	10^{11}	10^{10}	10^9	10^6
$\rho_\star$ [g cm^{-3}]	10^2	10^4	10^5	10^{13}

III. ENERGY LOSS IN A SINGLE PASSAGE

In this estimate, we follow the calculations of Ruderman & Spiegel [4], originally done for a galaxy moving through the interstellar medium. This logic can directly be transferred to the problem of a PBH moving through a stellar object. Here, it is assumed that the kinetic energy which is transferred from the black hole to the star is radiated. In this first estimate, we assume a uniform and frictionless medium and we disregard the fact that the gas is self-gravitating. For more details, see [1].

In first order approximation, we consider the motion of the black hole to be at constant speed. In addition, we assume the velocity to be supersonic, so that the drag force, and hence for the energy loss, reduces to the one presented in [4]. The bow shock is negligible compared to the tail shock's energy loss. Consequently, the energy loss per time is constrained to

$$\frac{dE_{\rm loss}}{dt} = \frac{4\pi G^2 m_{pbh}^2 \rho_\star}{v_\star} \ln \frac{r_{\rm max}}{r_{\rm min}} , \qquad (12)$$

where $r_{\rm max}$ is the maximal linear dimension of the star (i.e. its diameter), $r_{\rm min}$ is the linear dimension of the accretor, lying between the black hole horizon and the Bondi-Hoyle radius of the black hole. Here, we use $\ln(r_{\rm max}/r_{\rm min}) = 10$ as an estimate of the logarithmic ratio. The total energy loss is then determined to

$$E_{\rm loss} = \frac{dE_{\rm loss}}{dt} \cdot dt = \frac{8\pi G^2 m_{pbh}^2 R_\star \rho_\star}{v_\star^2} \ln \frac{r_{\rm max}}{r_{\rm min}} , \quad (13)$$

at a passage time of $dt \approx 2 \cdot R_\star / v_\star$. Then, Equ. (13) can be expressed as

$$E_{\rm loss} = 2 \cdot 10^{27} \, {\rm erg} \cdot m_{pbh,20}^2 \cdot R_{\star,9} \cdot v_{\star,0}^{-2} \cdot \rho_{\star,5} \quad (14)$$

with $\rho_{\star,5} := \rho_\star / (10^5 \, {\rm g\, cm^{-3}})$. The energy loss with the four different object types discussed here are listed in table II.

IV. PBH CAPTURES

A capture of a PBH in a star can by itself lead to much more significant effects than a single passage. It provides the possibility of continuous radiation or it can even cause the collapse of the star. The PBH is captured by a stellar object, if the following conditions are met:

1) The energy loss must be larger than the initial energy,

$$E_{\rm loss} > E_{\rm ini} = \frac{1}{2} m_{pbh} \, v_0^2 , \qquad (15)$$

2) The point of return R of the PBH must be smaller than half the distance to the next star, $R < 1/2 \cdot R_{dist}$ - otherwise, the PBH would randomly pass through a number of different stars. While this would also result in a diffuse, but relatively weak signal, we investigate the case of an actual capture. Here, we assume an average distance of $R_{dist} \approx 1$ pc between stars.

Using energy conservation between the point when the PBH exits the star and its point of return to the star

$$\frac{1}{2}, m_{pbh} \, v_0^2 - E_{\rm loss} = -G \frac{m_{pbh} \, M_\star}{R} > -G \frac{m_{pbh} \, M_\star}{\frac{1}{2} R_{dist}} . \qquad (16)$$

The inequality corresponds to condition (2), $R < 1/2 \, R_{dist}$. We can now insert Equ. (11) and (14) in Equ. (16):

$$\begin{aligned} \frac{1}{2}, m_{pbh} \, v_0^2 \quad &- \quad 2 \cdot 10^{27} \, {\rm erg} \cdot m_{pbh,20}^2 \cdot R_{\star,9} \cdot v_{\star,0}^{-2} \cdot \rho_{\star,5} \\ &> \quad -G \frac{m_{pbh} \, M_\star}{\frac{1}{2} R_{dist}} . \end{aligned} \qquad (17)$$

It can now be solved to give a lower limit to the PBH mass that can be captured,

$$\begin{aligned} m_{pbh} \quad &> \quad m_{pbh}^{capture} = 1.2 \cdot 10^{27} \, {\rm g} \cdot \\ &\cdot \quad (R_{\star,9} \cdot \rho_{\star,5})^{-1} \cdot \left(\frac{v_\star}{2.2 \cdot 10^7 \, {\rm cm/s}} \right)^2 \end{aligned} \quad (18)$$

Here, we denote the lowest possible mass to be captured as $m_{pbh}^{capture}$. We list the actual values for the minimum capture masses in table II. Our result implies that PBHs in the unexplored mass range, 10^{15} g $< m_{pbh} < 10^{26}$ g, are typically not captured by stars. The mass range of 10^{28} g $< m_{pbh} < 10^{32}$ g, on the other hand, can potentially be explored with PBH captures, since limits in this mass range still allow for a PBH contribution of the order of 10% to the dark matter.

V. RESULTS AND CONCLUSIONS

We considered two processes for a possible emission from PBH interactions with stellar objects: a large number of single passages or a smaller number of captures. In this final section, we investigate if it is feasible to detect such signatures.

A. Detectability of a single passage

In Section II, we showed that the event rate of PBH interactions with stellar object scales as $\dot{n} \propto m_{pbh}^{-1}$, implying that PBH passages are very frequent at low masses and decrease towards high masses. On the other hand, the total energy loss scales as m_{pbh}^2, as shown in Section III. This means that the most powerful events happen for large mass PBHs. We can combine the two properties into a total luminosity arising from PBH interactions with stellar objects in the Galaxy:

$$L = \dot{n} \cdot E_{\rm loss} . \qquad (19)$$

For the different object classes, we get numerical values of

$$L = m_{pbh,20} \cdot \left\{ \begin{array}{ll} 2 \cdot 10^{22} \, {\rm erg/s} & {\rm MS}\star \\ 1 \cdot 10^{19} \, {\rm erg/s} & {\rm RGC} \\ 2 \cdot 10^{17} \, {\rm erg/s} & {\rm WD} \\ 1 \cdot 10^{16} \, {\rm erg/s} & {\rm N}\star \end{array} \right. . \qquad (20)$$

This calculation is based on the assumption that PBHs can be the dominant source of the dark matter. This implies that it can only be valid in the unexplored region between 10^{15} g $< m_{pbh} < 10^{26}$ g. Figure 2 shows the total luminosity versus PBH mass in the interesting mass range. The maximum luminosity comes from PBHs with a mass of 10^{26} g, interacting with main sequence stars. Even for this optimal case, the luminosity is less than $2 \cdot 10^{28}$ erg/s, i.e. far below solar luminosities. Thus, single passages of PBHs through stellar objects cannot be observed by any detector, since the luminosity lies far below what is observed from classical radiation processes in the Galaxy.

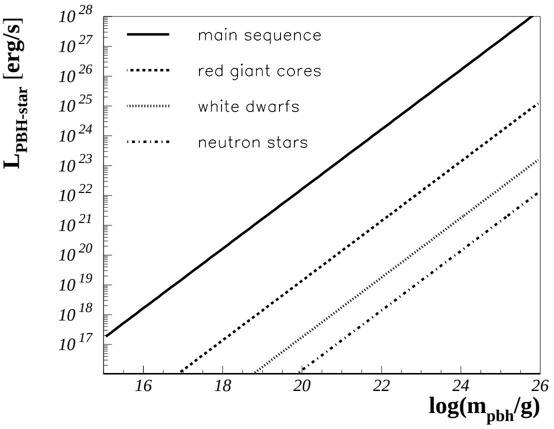

Fig. 2. Total luminosity from PBH interactions with stellar objects. Solid line: MS⋆; dashed line: RGC; dotted line: WD; dashed line: N⋆.

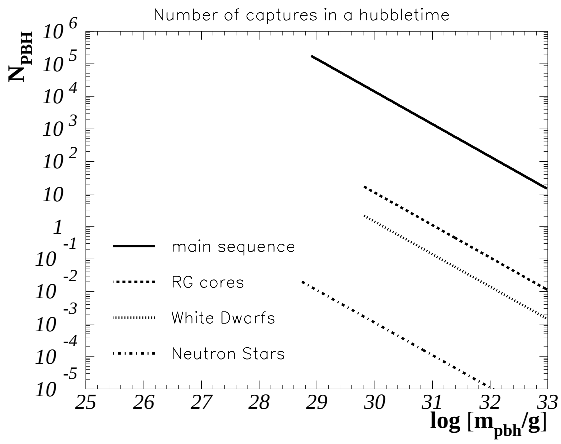

Fig. 3. Number of captures in a Hubble time, $t_H = 10^{10}$ yr, for different source classes. Solid line: MS⋆; dashed line: RGC; dotted line: WD; dashed line: N⋆.

B. Probability of PBH captures

In Section IV, it was shown that captures of PBHs are possible for masses above $\sim 10^{28}$ g. The question is again, if these events are frequent enough to lead to detectable effects. Here, we discuss the mass region 10^{28} g $< m_{pbh} < 10^{32}$ g, as PBHs can still contribute with 10% to the dark matter. Thus, we use $\eta = 0.1$ in the following calculations. Using Equ. (11), we determine the number of interactions between PBHs and stellar objects in a Hubble time, $t_H = 10^{10}$ yr,

$$N_{pbh} = \dot{n}(\eta = 0.1) \cdot t_H \quad (21)$$
$$= 10^6 \cdot N_{\star,9} \cdot v_{\star,0} \cdot R^2_{\star,9} \cdot m^{-1}_{pbh,20} \cdot \quad (22)$$

The best capture rate is at the lowest mass to be captured, $m_{pbh}^{capture}$. The results for the different source classes are listed in table II. Figure 3 shows the number of captures versus the PBH mass. The number of captured objects in red giant cores, white dwarfs and neutron stars are of the order of 1 in a Hubble time or smaller. Clearly, this is a negligible effect. Main sequence stars, on the other hand, can capture up to $2 \cdot 10^4$ PBHs in a Hubble time, which can lead to significant effects like enhanced high-energy radiation from those stars or even the collapse of a star due to the influence of the PBH. Calculations on the energy loss and further influence of the PBH on the stars are in preparation. As we have used the most optimistic assumptions for our calculations so far, a more detailed investigation of the number of captured PBHs is necessary as well. With a detailed description of the energy loss and the event rate, captures of PBHs in main sequence stars may lead to limits of their contribution to the dark matter, or even to the detection of their existence. Apart from using our own Galaxy, dwarf elliptical galaxies are a good target for observation, as they are nearby, well-defined observation targets with a low background rate.

TABLE II

RESULTS FOR THE ENERGY LOSS AND EVENT RATE IN A STELLAR OBJECT FOR A PBH WITH A MASS OF 10^{20} G. THE ENERGY LOSS SCALES AS $E_{\rm loss} \propto m^2_{pbh,20}$, WHILE THE EVENT RATE BEHAVES AS $\dot{n} \propto m^{-1}_{pbh,20}$. THE LUMINOSITY L IS THE PRODUCT OF THE TWO. WE FURTHER GIVE THE LOWER LIMIT FOR MASSES OF PBHS TO BE CAPTURED AND THE EXPECTED NUMBER OF CAPTURES.

	MS⋆	RGC	WD	N⋆
$\dot{n}$[yr^{-1}] ($m_{pbh} = 10^{20}$ g)	$1.3 \cdot 10^4$	11	1.4	$1.1 \cdot 10^{-3}$
$E_{\rm loss}$ [erg] ($m_{pbh} = 10^{20}$ g)	$4 \cdot 10^{25}$	$4 \cdot 10^{25}$	$4 \cdot 10^{24}$	$4 \cdot 10^{26}$
L [erg/s] ($m_{pbh} = 10^{20}$ g)	$2 \cdot 10^{22}$	$1 \cdot 10^{19}$	$2 \cdot 10^{18}$	$1 \cdot 10^{16}$
$m_{pbh}^{capture}$ [g]	$8 \cdot 10^{28}$	$6 \cdot 10^{28}$	$6 \cdot 10^{29}$	$6 \cdot 10^{27}$
N_{pbh} ($m_{pbh} = m_{pbh}^{capture}$)	$2 \cdot 10^4$	2	0.2	$2 \cdot 10^{-3}$

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