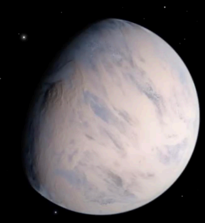
The Scientific Accuracy of the Water Exoplanet“Miller’s Planet” in the Movie Interstellar

Suin Matsui (The University of Tokyo)

1.Introduction: What is the Movie Interstellar?

The movie Interstellar, directed by Christopher Nolan, is a sci-fi film about humanity's mission to find a new home by passing through a wormhole near Saturn. It features three exoplanets: Miller’s Planet, Mann’s Planet, and Edmunds’ Planet. This poster focuses on Miller’s Planet, a water-covered planet orbiting the supermassive black hole (SMBH) "Gargantua." Due to the black hole's gravity, extreme time dilation occurs—one hour on the planet equals seven years on Earth. The planet also experiences massive tidal waves caused by the black hole's tidal forces, making it uninhabitable.
As my research focuses on SMBHs, I became curious about the scientific accuracy of an exoplanet orbiting so close to an SMBH and whether a water-covered planet could exist under such conditions.



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2.The accuracy of the SMBH properties: Gargantua

Table1

Abbreviation	Name	Mass Range	Formation Process	Features/Role
SMBH	Supermassive Black Hole	$10^6 - 10^9 M_\odot$	Growth after star formation, direct collapse	Found at galaxy centers, influences galaxy evolution
IMBH	Intermediate-Mass Black Hole	$10^2 - 10^5 M_\odot$	Stellar mergers, collapse of dense star clusters	Rare; bridge between stellar BHs and SMBHs
Stellar BH	Stellar-Mass Black Hole	$3 - 100 M_\odot$	Core-collapse supernova of massive stars	Common; remnants of massive stars, part of binary systems
VMBH	Very Massive Black Hole	$10^9 - 10^{11} M_\odot$	Growth of SMBHs, intergalactic gas collapse, SMBH mergers	Possibly formed only in special environments

Table2

Type	Mass Range	Features	Role/Properties
Kerr Black Hole	Any (Stellar BH to VMBH)	Rotating black hole	Frame-dragging effects, jet formation, presence of ergosphere
Schwarzschild Black Hole	Any (Stellar BH to VMBH)	Static, non-rotating black hole	Simplest black hole model, used as a foundational theoretical framework

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Gargantua has a mass of 10^8 M_{sun}. In the context of current galaxy evolution, black holes are typically classified into four types: VMBHs, SMBHs , IMBHs and stellar BHs (Table 1). Based on this classification, Gargantua would be considered an SMBH, likely located at the center of a galaxy.

Black holes are categorized by rotation: Schwarzschild for non-rotating and Kerr for rotating (Table 2). The mention that one hour on Miller’s Planet equals seven years on Earth suggests significant frame-dragging, indicating Gargantua is a nearly maximally spinning Kerr black hole (a/M ~ 0.999). Designed under Nobel laureate Kip Thorne’s supervision, Gargantua is likely theoretically accurate.

However, according to the official website of the Event Horizon Telescope (EHT), the Doppler effect was turned off in the movie for aesthetic reasons. In reality, the approaching side of an SMBH's rotating accretion disk would appear brighter and hotter (bluish-white), while the receding side would appear dimmer and redder. Additionally, Gargantua is depicted with an extremely thin accretion disk, whereas astronomical observations of Sgr A* and the M87 black hole show their accretion disks to be much thicker and more torus-like in appearance (Figure 1).

3. The accuracy of a water exoplanet orbiting a SMBH

In Section 2, the supermassive black hole (SMBH) Gargantua was deemed theoretically plausible. However, can a planet realistically orbit such a dangerous SMBH like Gargantua? The size of the black hole's event horizon (Schwarzschild radius) can be calculated using Eq. (1).

$$r_s = \frac{2GM_{\rm BH}}{c^2} \quad (1)$$

Gargantua has a mass of MBH = 10^8 [M_{sun}], giving it a Schwarzschild radius of approximately r_s ~ 2.95 x 10^8 [km]. Meanwhile, in the movie, it is mentioned that 1 hour on the water planet is equivalent to 7 years on Earth. Using eq(2), the orbital radius can be roughly estimated.

$$\Delta t_{\rm distant} = \Delta t_{\rm local}\sqrt{1-\frac{2GM}{rc^2}} \quad (2)$$

Calculating the orbital radius gives r_p = 2.95 x 10^8 [km], which is almost the same as the Schwarzschild radius. This means that the water planet is orbiting very close to Gargantua's event horizon. Additionally, planets orbiting a black hole experience strong tidal forces. The tidal radius rt, at which the planet would be disrupted by the black hole, can be determined using eq(3).

$$r_t \sim 7\times10^{12}\,{\rm cm}\left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{1/3}\left(\frac{M_*}{M_\odot}\right)^{-1/3}\left(\frac{r_*}{R_\odot}\right) \quad (3)$$

Calculations show that r_t = 2.05 x 10^8 [km], which is almost the same as the orbital radius. If Gargantua were a non-rotating Schwarzschild black hole, the water planet would be destroyed by tidal forces. Fortunately, Gargantua is an ultra-fast spinning Kerr black hole, which generates a frame-dragging effect. This effect causes the black hole's rotation to drag the surrounding spacetime. As a result, the ISCO (Innermost Stable Circular Orbit), where a planet can stably orbit the black hole, can exist even within the event horizon's vicinity (as shown in Figure 2). This enables the water planet to avoid tidal disruption.

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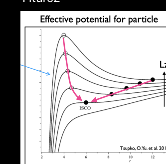

Ishibashi 2024 fig.2

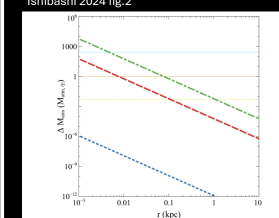

Figure 2. Atmospheric mass-loss induced by the SMBH based on observational constraints of the past activity of Sgr A*. Variations in central luminosity and episode duration: an X-ray flare with $L = 10^{41}$ erg/s and $\Delta t = 1$ yr (blue dotted), a Seyfert-like episode with $L = 5\times10^{43}$ erg/s and $\Delta t = 10^5$ yr (red dashed), a quasar-like event with $L = 5\times10^{44}$ erg/s and $\Delta t = 10^6$ yr (green dash-dot). The three horizontal lines are the same as in Fig. 1.

Even if a planet avoids tidal disruption, the environment near a black hole remains extremely harsh. If the black hole has an accretion disk, gas and dust falling into the black hole emit intense X-rays and gamma rays during the accretion process. When this radiation strikes the planet, its surface temperature can rise significantly, threatening not only the possibility of life but also the planet's structural stability itself. Furthermore, as noted in Ishibashi (2024), accreting black holes emit high-energy radiation (extreme ultraviolet and X-rays), which can lead to XUV photoevaporation of planetary atmospheres.
In Ishibashi (2024), the authors evaluated atmospheric mass loss using both theoretical estimates of black hole radiation output and observational constraints on the past activity of Sgr A*. By analyzing mass loss caused by black hole irradiation as a function of distance from the galactic center, it was found that Sgr A* could have a significant impact on exoplanets located in the inner regions of the galaxy, such as the galactic bulge. A considerable fraction of atmospheric mass can be stripped away by black hole irradiation, and in extreme cases, the initial atmosphere can be completely removed. Such mass loss could have profound effects on atmospheric chemistry and the potential evolution of life.

Sgr A* has a mass of 4.28 x 10^6 [M_{sun}] and a very low mass accretion rate of 10^{-6} [M_{sun}/yr], making it a nearly dormant black hole. Yet, it significantly affects planetary atmospheres. The 2022 EHT image of Sgr A* suggested it might be a rotating Kerr black hole based on the surrounding accretion disk and radiation distribution. Gargantua, in contrast, is about 100 times more massive than Sgr A*. Based on the film's visuals, Gargantua appears to have an accretion disk and emits high-energy radiation comparable to Sgr A*. The water planet orbits Gargantua at r_p = 2.95 x 10^8 [km] = 9.56 x 10^{-6} [pc], an extremely close distance, suggesting its atmosphere should be significantly stripped by high-energy radiation. However, in the movie, the water planet still has an atmosphere, which creates a scientific inconsistency.

Picture1 (©Medium.com)

Choosing a planet near a black hole for the Lazarus Project seems unnatural. Black holes can be inferred from the motion of orbiting objects, and current technology like the EHT can image them. With the advanced science in the movie, this should have been known, suggesting it was done for dramatic effect.

4. Reference

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