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A5 1 Habitable Zones in the Extreme Environments of Active Galactic Nuclei

C. Howitt, D. Booth and A. Friesner

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract

We investigate the plausibility of habitable planets orbiting Active Galactic Nuclei (AGN), powered by accreting supermassive black holes (SMBHs). Using a simplified model, we estimate the location of a habitable zone around a low-mass SMBH of 1.6×10^5 $M_\odot$, where conditions may allow liquid water to exist on a planetary surface. By calculating orbital distances that would result in temperatures conducive to habitability, we demonstrate that under certain optimistic assumptions, planets could maintain life-sustaining conditions in the extreme environment near an AGN.

Introduction

Active galactic nuclei (AGN) are among the most energetic environments in the universe, powered by the accretion of matter onto SMBHs. Their intense luminosities and high-energy radiation are usually considered hostile to life. However, because AGN release energy in a way similar to stars emitting photons, heating nearby material, and exerting gravitational forces. It is worth asking whether habitable planets could exist in their vicinity.

In this paper, we explore whether an Earth-like planet captured by a SMBH during a galactic merger could sustain life under simplified assumptions. By analogy with circumstellar habitable zones (CHZs), we define a "black hole habitable zone" (BHHZ) as the orbital region where stellar-like radiation from the AGN could permit liquid water on a planet's surface. We focus on a relatively low-mass SMBH POX 52 [1] (1.6×10^5 $M_\odot$) and estimate the orbital distances where such conditions might occur.

Our aim is not to provide a comprehensive model, but to demonstrate that, under optimistic conditions, habitable environments near AGN may be theoretically possible, motivating more detailed future work.

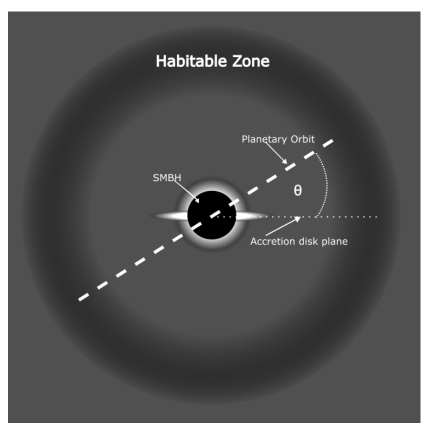

Figure 1: Shows the orbit of a planet in the habitable zone around a SMBH, at the correct inclination Θ relative to the accretion disk

Theory

We will assume a circular orbit around the SMBH to reduce the chance of tidal ripping as the planet approaches the perihelion due to the enormous gravitational force. We also assume the planet has a thick atmosphere that protects the surface from ionising radiation such as high-intensity X-rays from an accreting SMBH, while disregarding greenhouse effects. We define the habitable zone (HZ) in terms of liquid water, the fundamental requirement for life as we know it. Specifically, we consider orbital radii where the equilibrium temperature of the planet lies between 273 K - 373 K. The planetary equilibrium temperature, T_p, is estimated using the Stefan–Boltzmann law: [2]

$$T_p = \left(\frac{L(1-A)}{16\pi\sigma r^2} \right)^{\frac{1}{4}},$$

where L is the luminosity of the central source, A is the Bond albedo (fraction of incident radiation reflected by the planet). r is the orbital radius, and σ is the Stefan–Boltzmann constant. For simplicity, we assume $A = 0$, corresponding to a perfectly absorbing surface. Rearranging for r, we obtain an expression for the HZ radius:

$$r_{\text{hz}} = \left(\frac{L_{\text{Edd}}}{16\pi\sigma T_p^4} \right)^{\frac{1}{2}}, \quad (1)$$

we adopt the Eddington luminosity as an upper limit, which represents the maximum radiative output of an accreting black hole:

$$L_{\text{Edd}} = \frac{4\pi G M m_p c}{\sigma_T}, \quad (2)$$

where G is the gravitational constant, M is the SMBH mass, m_p is the rest mass of a proton, c is the speed of light in vacuum, and σ_T is the Thomson scattering cross-section. For a 1.6×10^5 $M_\odot$ SMBH, L will be 2.01×10^{36}W.

It should be noted that AGN emission is anisotropic: flux is enhanced along relativistic jets and suppressed in the plane of the accretion disk. In this work, we assume that the planetary orbit is inclined in such a way that the received luminosity can be approximated by a uniform value, allowing direct comparison with CSHZs.

Results and discussion

Using Equation 1, we calculate HZ boundaries of 1.13×10^{16}m (75,318 AU) and 6.04×10^{15}m (40,373 AU) for the proposed SMBH at maximum luminosity (Equation 2). At these orbital radii, tidal forces due to the SMBH's strong gravitational field are negligible, giving the planet a higher chance of sustaining life. However, the intense radiation from the SMBH in the form of highly ionising X-rays could easily strip the thick atmosphere in the absence of a mechanism that allows us to maintain the atmosphere's density. We would need our planet to lie in the plane of the accretion disk to minimise these effects and one could extend this work by considering constraints on the inclination of the orbit with respect to the accretion disk.

Conclusion

While our simplified model suggests that planets orbiting the smallest recorded SMBHs could, in theory, maintain conditions conducive to life, the assumptions involved are highly idealised. Despite surface temperatures capable of supporting liquid water at radii that are suitably distant to minimise gravitational effects, the presence of intensely ionising X-ray emission from an accreting SMBH are likely to pose a threat to the atmosphere of our planet. In addition, energetic particles could penetrate a relatively weak magnetosphere. One speculative mechanism to counter this would be the use of tidal forces from the black hole's gravity to generate internal heating, thereby strengthening the planetary dynamo and enhancing magnetic shielding.

A more comprehensive analysis, incorporating factors such as elliptical orbits, varying inclinations, and more realistic models of planetary atmospheres, would provide a clearer understanding of the feasibility of habitability in these extreme environments.

References

[1] Barth,A. J. Barth, L. C. Ho, R. E. Rutledge, and W. L. W. Sargent, “POX 52: A Dwarf Seyfert 1 Galaxy with an Intermediate-Mass Black Hole,” *The Astrophysical Journal*, vol. 607, no. 1, pp. 90–102, 2004

[2] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers with Modern Physics*. New York: W. H. Freeman, 2008.