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SEARCH FOR INTERMEDIATE-MASS BLACK HOLES IN AGN DISCS

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1. INTRODUCTION

Intermediate-mass black holes (IMBHs) may grow inside accretion gas discs that surround supermassive black holes (SMBHs) in active galactic nuclei. As they orbit SMBHs, they may open gaps in accretion discs at certain radii. The ratio of masses between the two BHs, $q = M_2/M_1$, is not required to be high for this to happen. Even in situations with $q < 10^{-4}$ gaps may appear (McKernan et al. 2014). The gap, if present, will imprint a broad dip in the spectral energy distribution (SED) of the AGN's accretion disc. This was modeled for SMBH pair mergers by Gültekin & Miller (2012), however the same concept can be used for searching IMBHs.

2. SPECTRAL ENERGY DISTRIBUTION MODELING

A SED of a thermally emitting disc is described by

$$F_\lambda(\lambda) = \int_{R_{in}}^{R_{out}} B_\lambda \left[T(r')\right] g(r') 2\pi r' \mathrm{d}r', \tag{1}$$

where $B_\lambda(T)$ is the Planck function, $T(r')$ is the disc temperature at radius r', R_{in} and R_{out} are AGN disc inner and outer radii, and $g(r')$ is a function that turns emission on and off due to the presence of the gap. The condition for the latter is as following: $g(r') = 1$ where disc material is present, i.e. $R_{in} < r' < r - w$ and $r + w < r' < R_{out}$, where w is gap width and r is the radius where the gap is located in the disc (Gültekin & Miller 2012). Everywhere else, $g(r') = 0$. The outer disk radius can be approximated as per Morgan et al. (2010):

$$\log\left(\frac{R_{out}}{\mathrm{cm}}\right) = 15.78 + 0.8\log\left(\frac{M_{BH}}{10^9 M_\odot}\right), \tag{2}$$

although in order to derive SEDs that match those in the work of Gültekin & Miller (2012), this estimate has to be multiplied by a factor of ~ 100. Gap width depends on the gravitational influence of the orbiting secondary black hole, that is, it's Hill radius, as $w \sim 2R_H$, where:

$$R_H \equiv r\left(\frac{M_2}{3M_1}\right)^{(1/3)} \tag{3}$$

The temperature profile of the SMBH accretion disc can be approximated by (citation needed)

$$T(r') \approx 6.3 \times 10^5 \left(\frac{\dot{M}}{\dot{M}_E}\right)^{1/4} \left(\frac{M}{10^8 M_\odot}\right)^{-1/4} \left(\frac{r'}{R_S}\right)^{3/4} \mathrm{K}, \tag{4}$$

where $\dot{m} = \dot{M}/\dot{M}_E$ is the accretion rate that equals unity for Eddington rate, and $R_S \equiv 2GMc^{-2}$ is the Schwarzschild radius. The inner AGN disc radius is the innermost stable circular orbit (ISCO) (Misner et al. 1973):

$$R_{in} = \frac{6GM}{c^2}. \tag{5}$$

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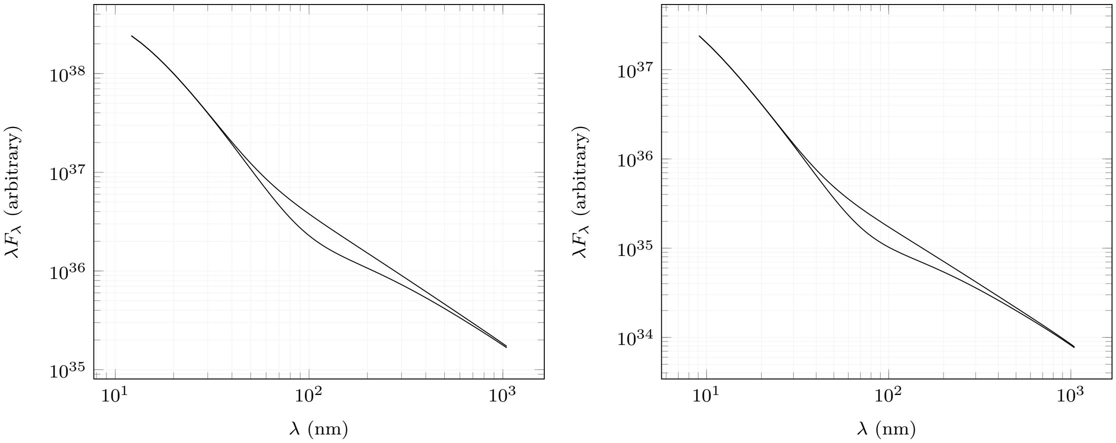

FIG. 1.— Left: SED of a $10^5 M_\odot$ IMBH orbiting a $10^7 M_\odot$ SMBH at $r = 100 R_G$. For comparison, dip-less SED for a single SMBH is provided. λ_b is ~ 55 nm. Right: SED of a $10^4 M_\odot$ IMBH orbiting a $10^6 M_\odot$ SMBH at $r = 200 R_G$. λ_b is ~ 52 nm. Note short wavelength graph is clipped because of the limitations in Excel integration via trapezoidal rule.

I have made an Excel SED calculator available for experimentation by our group at http://109.104.118.160/Gap-opening-IMBHs.xlsx. Using the calculator, we can find that significant dips in SEDs are caused by black hole pairs with $q \gtrsim 0.01$ on close orbits. I.e., larger black holes produce bigger dips. Assuming we target IMBHs of $\sim 10^4$–10^5 $M_\odot$, this limits the upper SMBH mass to $\sim 10^6$–10^7 $M_\odot$, i.e. the search is confined to low-mass AGNs.

The break wavelength in the vicinity of which the dip occurs can be estimated as

$$\lambda_b \sim 140 \eta^{1/4} \left(\frac{r}{R_G}\right)^{3/4} \left(\frac{M_1}{10^8 M_\odot}\right)^{1/4} \left(\frac{\dot{m}}{0.01}\right)^{-1/4} \text{Å}, \tag{6}$$

where η is the accretion efficiency, typically 0.06–0.42 (McKernan et al. 2014), and gravitational radius $R_G = GMc^{-2}$. Figure 1 shows SED models for scenarios with $10^5 M_\odot$ IMBH orbiting a $10^7 M_\odot$ SMBH at $r = 100 R_G$, and $10^4 M_\odot$ IMBH orbiting a $10^6 M_\odot$ SMBH at $r = 200 R_G$. These parameters were found empirically. For both cases and with $\eta = 0.24$, λ_b is $\sim 53 \pm 2$ nm which corresponds to extreme ultraviolet (EUV) radiation.

3. TASKS AND PROBLEMS

There is a number of problems with this approach. First, there is no reason why R_{out} has to be a factor of 100 more than the estimate suggested by Morgan et al. (2010). If the outer disk multiplication factor is not used in the calculator, the dip is not seen. It can be argued that this radius estimate is based on the 2500 Å wavelength, however the disk radius shouldn't vary that much at different wavelengths. Additionally, SEDs from the figure 1 in the work by Gültekin & Miller (2012) cannot be reproduced without multiplication, as gaps at $r \sim 1000 R_G$ used in that work are outside the outer disk radius estimate in the calculator, i.e. $1000 R_G > R_{out}$. This is the most overwhelming evidence that the outer radius estimate used currently is incompatible with that used by Gültekin & Miller (2012). Another problem is confirming whether temperature profile is estimated correctly. The formula used is taken from a presentation, so this either needs to be adjusted or we need a reference.

Assuming the calculator works correctly, we will need to explore the parameter space and find combinations of black hole masses and orbiting radii where breaks are the most frequent in the Universe and which can be observed with existing telescopes. We can find the AGN mass distribution and, using fixed $q = 0.01$ ratio and common IMBH masses, then define a subset of AGNs for observations. We will also need to understand how AGN spectra look like, i.e. is it possible to detect dips predicted by the SEDs or they will be lost in the zoo of AGNs with differences due to external factors?

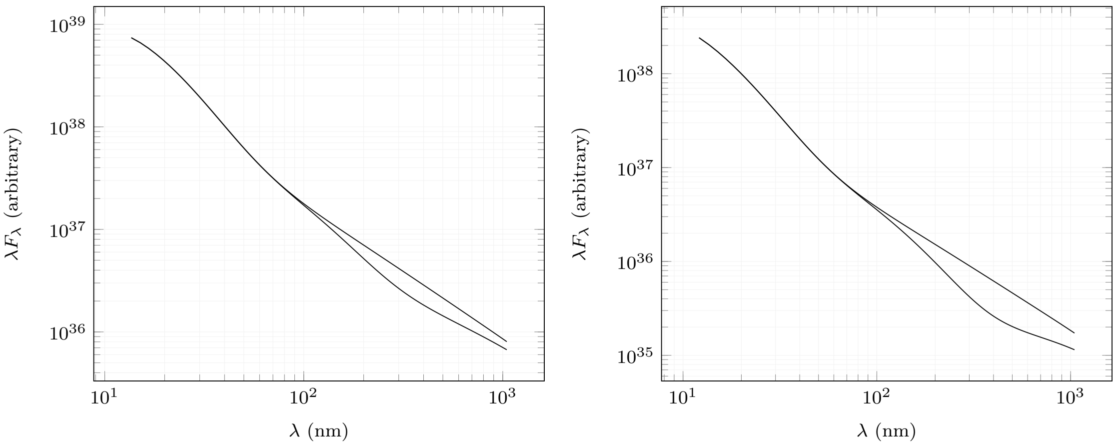

FIG. 2.— Left: SED of a massive $10^6 M_\odot$ IMBH orbiting a $10^{7.5} M_\odot$ SMBH at $r = 400 R_G$. Right: SED of a $10^6 M_\odot$ IMBH orbiting a $10^7 M_\odot$ SMBH at $r = 800 R_G$. λ_b is within *HST/COS* ranges for both cases.

For SMBH-IMBH pair examples mentioned above, we are finding break wavelengths in the EUV range. We will need to find a telescope that can observe broad spectrum in the vicinity of the EUV, perhaps, even extending into X-ray and visible/NIR spectrum if we want to observe the whole gap. I do not think these instruments exist. For the gaps in 1, a range of 10–1000 nm would be required which may not be possible.

Instead of setting a goal to observe the whole gap, we may detect changes in spectra slopes near break wavelengths. Notice that at λ_b the slope changes, and this should be detectable in $\approx$ 30–100 nm range data. However, I am not aware of any UV spectrographs covering this range. Cosmic Origins Spectrograph (COS) on board of the Hubble Space Telescope (*HST*) is the closest at 115–320 nm. The problem, however, is that if the target r is extended further in order to increase targeted λ_b, the dip becomes shallower and may not be detected.

A special and promising case are very massive IMBHs, e.g. a $10^6 M_\odot$ IMBH orbiting a $10^7 M_\odot$ SMBH. At $r \sim 800 R_G$, $\lambda_b \sim 262$ nm, which is well inside the COS range. However, can black hole this massive be considered an IMBH? Some sources say this is within the acceptable range (Ferrara et al. 2014). If we agree to target these massive IMBHs then this program should be applicable to a wider range of instruments. Slope may change may even be detectable with massive SMBHs of $10^{7.5} M_\odot$, and this should extend our AGN sample selection.

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