Direct Detection of Intermediate Mass Compact Objects via Submillilensing

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Abstract

A galaxy-sized halo may contain a large number of intermediate mass $10^{2-4} M_\odot$ compact objects (IMCOs), which can be intermediate mass black holes (IMBHs) or the CDM subhalos. We propose to directly detect the IMBHs by observing multiply imaged QSO-galaxy lens systems with a high angular resolution ($\sim 0.03\text{mas}$), which would be achieved by the next-VLBI space missions. The silhouette of the IMBHs would appear as an either monopole-like or dipole-like variation at the scale of the Einstein radius against the QSO jets. As a byproduct, we can also directly detect the $10^{1-5} M_\odot$ CDM subhalos. From a measurement of the local distortion in the surface brightness of the QSO jet, we can make a distinction between a point mass (corresponding to an IMBH) and an extended structure (corresponding to a CDM subhalo). It would be a unique probe of the IMCOs whose nature has been under the veil of mistery.

1 Introduction

Gravitational lensing is a powerful tool for constraining the amount of the dark matter in the form of compact objects. However, there is no stringent constraint on the intermediate mass compact objects (IMCOs) with a mass scale of $10^{2-4} M_\odot$ and on the sub-lunar mass compact objects (SULCOs) with a mass scale of $< 10^{-7} M_\odot$ (Inoue & Tanaka 2003).

In particular, a method of directly detecting the IMCOs has been highly desired because the IMCOs are important baryonic dark matter candidates as well. The IMCO can be an intermediate mass black hole or an intermediate mass cold dark matter (CDM) subhalo. The nature of both types of IMCOs has not been understood well.

In fact, the abundance of these IMCOs can be much larger than expected. Recent observation of the ultra-luminous X-ray sources suggests a presence of IMBHs not only in the neighborhood of galaxy nucleus but also in the star clusters in the galactic halo far from the nucleus (Matsumoto et al 2001, Roberts et al 2004). Furthermore, the early reionization ($z \sim 20$) (Bennett et al. 2003) suggested by the WMAP observation of the temperature-polarization correlation may indicate strong UV radiation from massive first stars at the early period ($z \sim 20$) with a top-heavy IMF (Cen, 2003) or that from a large number of micro-QSOs (Madau, et al. 2004), which imply the existence of a large number of IMCOs. The IMBHs are certainly important building blocks for making the super massive black holes (SMBHs). Unfortunately, their evolution has been under the veil of mistery. Measurements of
the abundance and the spatial distribution of the IMBHs inside the galactic halo would shed a new light on the evolution history of the SMBHs.

Similarly, we do not know anything about the abundance of the intermediate mass $10^{2-5} M_\odot$ CDM subhalos. Although they may suffer the tidal breaking owing to the gradient in the gravitational potential of the galaxy halo, any compact objects whose size is smaller than the tidal radius can survive. Because a calculation of the survival probability during the major merger of galaxies is an intractable problem (see also Taylor & Babul 2005), we need to observationally constrain the abundance of the CDM subhalos.

To do so, we propose to observe radio-loud QSO-galaxy strong lens systems with a submilliarcsecond resolution, which will be achieved by the next space VLBI missions such as the VSOP2 (Hirabayashi et al.). Then the submillilensing effects by IMCO perturbers can be directly measured (Inoue & Chiba 2003).

2 Theory

The Einstein angular radius of a point mass with a mass $M$ is written in terms of the angular diameter distance to the lens $D_L$, to the source $D_S$, between the lens and the source $D_{LS}$ as

$$\theta_E \sim 3 \times 10^{-2} \left( \frac{M}{10^2 M_\odot} \right)^{1/4} \left( \frac{D_L D_S}{D_{LS}} \frac{1}{\text{Gpc}} \right)^{-1/2} \text{mas.} \quad (1)$$

Therefore, the radio interferometer with a resolution of 0.04 mas can resolve the distortion of the image within the Einstein ring for a point mass $M \sim 200 M_\odot$. As is well known, the surface density within the Einstein radius of the macrolens is nearly critical. Therefore, the possibility of gravitational submillilensing by the IMCOs within the Einstein ring of the macrolens (=galaxy halo) is very large. Furthermore, in the high frequency band ($>40$ GHz), any absorption owing to the plasma along the line of sight to the jets is suppressed. Thus, a high-resolution radio mapping of the QSO-galaxy lens systems is an idealistic method for directly detecting the IMCOs.

3 Model

To estimate the observational feasibility, we consider a simple model of a typical QSO-galaxy lensing system B1422+231, which consists of three magnified images A, B, C and a demagnified image D. The redshifts of the source and the lens are $z_S = 3.62$ and $z_L = 0.34$, respectively. To model the macrolensing, we adopt a singular isothermal ellipsoid (SIE) in a constant external shear field in which the isopotential curves in the projected surface perpendicular to the line of sight are ellipses (Kormann et al. 1994). The perturbing IMCOs are modeled as point masses.
4 Simulation

The surface number density of the perturbers near the Einstein ring for the macrolens with a radius \( r_E \sim 3.8 \text{kpc} \) is found to be \( N \sim f \times 2.4 \times 10^4 \left( M/10^3 M_\odot \right)^{-1} \text{mas}^{-2} \) where \( f \) denotes the ratio of the surface mass density of the perturbers to that of the dark halo. If we assume that the area of the magnified image of the QSO jet is \((10 \text{pc})^2\), then we expect one IMBH in the line of sight to the jet of B1422+231 if \( f = 0.003 \). On the one hand, the total mass within the Einstein radius \( r_E \sim 3.8 \text{kpc} \) is \( \sim 10^{11} M_\odot \). On the other hand, the total baryonic mass within the Einstein radius of the macrolens is \( \sim 10^{10} M_\odot \). From the Magorrian relation, the mass of the SMBH at the nucleus is expected to be \( \sim 10^7 - 8 M_\odot \). Thus, we can find an IMBH in the line of sight to the jet if the total mass of the IMBH \( \sim 0.003 \times 10^{11} M_\odot \) is comparable to the mass of the SMBH provided that the IMBHs traces the mass distribution of the dark halo of the macrolens. In the extreme case where the IMBHs constitute the entire macrolens halo, the submillilensing effects owing to the IMBHs are very distinct (figure 1). We would observe a several hundreds of monopole-like or dipole-like distortion patterns in the surface brightness profile of the QSO jet if observed with a submilli-arcsec resolution.

5 Extended-source effect

If the the perturber is spatially extended (e.g. a singular isothermal sphere), then the lensing effect is different from that of a point mass. The density profile of the perturber can be reconstructed from the local mapping between the observed image and the non-perturbed image obtained from the prediction of the macrolens. In fact, the power of the radial density profile of the perturbers can be reconstructed from the perturbed image within the Einstein ring of the perturber (Inoue & Chiba 2005b). Then we can make a distinction between the IMBH and the CDM subhalo. Furthermore, from the distortion outside the Einstein ring of the perturber, the degeneracy between the perturber mass and the distance can be broken provided that the Einstein radius of the perturber is sufficiently smaller than that of the macrolens (Inoue & Chiba 2005a). The precise measurement of the spatial variation in the surface brightness of the QSO jet will provide us a large amount of information about the mass, abundance, and the spatial distribution of IMCOs.

6 Summary

If there are a sufficient number of IMCOs inside the macrolens galactic halo, then we will be able to directly detect the silhouette of the IMCOs using the next space interferometers with a submilli-arcsec resolution in the radio band. By measuring the local distortion of the QSO jet, we will be able to determine the density profile of the IMCOs. The direct detection of the IMBHs or the CDM subhalos will shed a new light on the formation process of the SMBHs and the reionization process which have been under the veil of mistery.
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Figure 1: Simulated zoomed-up multiply lensed images A, B, C, and D in the B1422+231 (center) where the IMBHs constitute the entire macrolens CDM halo $\Omega_{\text{CDM}} = \Omega_{\text{IMBH}}$. The silhouette of the IMBH would appear as a monopole-like or a dipole-like distortion pattern against the radio emission from the QSO. We assumed that the radius of the radio emitting region is $r = 100$ pc and the IMBH mass is set to $M = 10^3 M_\odot$. 