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Optical spectroscopy of host-galaxies of intermediate mass black holes: evolution of central black holes

V. Goradzhanov[1,3], I. Chilingarian[2], M. Demianenko[4], I. Katkov[5,6], K. Grishin[1,7], V. Toptun[8], E. Rubtsov[1], D. Gasymov[1], and I. Kuzmin[1,3]

[1] Sternberg Astronomical Institute, M.V.Lomonosov Moscow State University, Moscow, 119992 Russia
[2] Center for Astrophysics — Harvard and Smithsonian, Cambridge, MA 02138 United States
[3] Department of Physics, M.V. Lomonosov Moscow State University, Moscow, 119234 Russia
[4] Max-Planck-Institut für Astronomie, Heidelberg, 69117 Germany
[5] New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[6] Center for Astro, Particle, and Planetary Physics, NYU AD, Abu Dhabi, United Arab Emirates
[7] Université Paris Cité, CNRS(IN2P3), Astroparticule et Cosmologie, Paris, 75013 France
[8] European Southern Observatory, Garching bei München, 85748 Germany

Abstract. Intermediate-mass black holes (IMBHs) with masses below ($2 \times 10^5 M_\odot$) are key to understanding the origin and growth mechanisms of supermassive black holes (SMBHs) in galactic nuclei. This study focuses on the search for and detailed analysis of central lightweight black holes in various galaxies. An extended sample of IMBH candidates was selected from the RCSED optical spectral catalog, followed by refined spectral observations using large telescopes, including the Magellan, SALT, Keck, and CMO telescopes. Analysis of more than 70 spectra has obtained accurate virial masses, stellar population parameters, and kinematics. One significant result includes the detection of a binary black hole system with masses of ($1.7 \times 10^5 M_\odot$) and ($1.4 \times 10^6 M_\odot$). Our results indicate that IMBHs and their low-mass SMBH counterparts do not necessarily co-evolve with their host galaxies, suggesting that super-Eddington accretion is the dominant growth mechanism. This research improves the precision of virial mass estimates and provides new insights into the $M_{\rm BH} - \sigma_{\rm bulge}$ relation, with potential implications for future high-redshift SMBH observations using next-generation facilities.

Keywords: cosmology: observations; early universe; galaxies: active, nuclei, Seyfert; quasars: supermassive black holes

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1 Introduction

About a hundred so-called intermediate-mass black holes (IMBH, $M_{\rm BH} < 2*10^5 M_\odot$) have already been discovered. In the coming decades, even more IMBHs will be discovered by the Laser Interferometer Space Antenna (LISA) (Amaro-Seoane et al. 2023) and the Multi-AO Imaging Camera for Deep Observations (MICADO) (Davies et al. 2016; Demianenko et al. 2024b) at the Extremely Large Telescope (ELT). Currently, the origin and evolutionary mechanisms of these objects are not well understood. Understanding the origin and evolution of IMBHs is extremely important in modern astrophysics, as it will provide a key to understanding an even more global problem — the mystery of the origin and growth mechanisms of supermassive black holes (SMBHs) in the nuclei of galaxies. This work is dedicated to the search and study of central light-weight black holes in galaxies of different types.

The discovery of quasars in the early Universe (z > 6.3, only 750–900 Myr after the beginning of the expansion of the Universe) containing SMBHs with masses of the order of $10^{10} M_\odot$ (Mortlock et al. 2011) cannot be explained only by accretion of gas onto stellar-mass black holes alone. Even if black holes were formed shortly after the beginning of the expansion of the Universe, by the collapse of the nuclei of population III stars, it would take more than 1 billion years for the SMBH to grow, unless the accretion rate significantly exceeds the Eddington limit for a long time.

At the same time, IMBHs are too massive to be formed by the gravitational collapse of a single star, but too light to be considered supermassive. However, there are currently hypotheses about the formation of IMBHs as a result of the collapse of supermassive stars of population III (Schneider et al. 2002).

SMBHs are thought to co-evolve with the spheroids of their host galaxies (hereafter host galaxies) (Kormendy & Ho 2013). Thus, there is a so-called "scaling relation" between the black hole mass and the velocity dispersion of the host galaxy.

In recent years we have expanded the known sample of IMBH candidates and confirmed several times more IMBHs (Chilingarian et al. 2018, 2023; Goradzhanov et al. 2022; Toptun et al. 2022); by optical variability Demianenko et al. (2022, 2024a)). The basis of our galaxy sample is the RCSED optical spectral catalog of galaxies (Chilingarian et al. 2017), in which in turn we have analyzed the SDSS spectra (Abazajian et al. 2009). The resolution of the SDSS spectra (R 2000) is not suitable for obtaining accurate virial masses, but allows us to make an initial selection of galaxies with low-mass black holes at the center. After selecting IMBH candidates and so-called 'light-weight' SMBHs (LWSMBH, $< 10^6 M_\odot$), we followed them up with spectral observations in the optical range on large telescopes (6.5-m Magellan Telescope, 10-m Southern African Large Telescope, 10-m Keck Telescope, 2.5-m Caucasus Mountain Observatory Telescope).

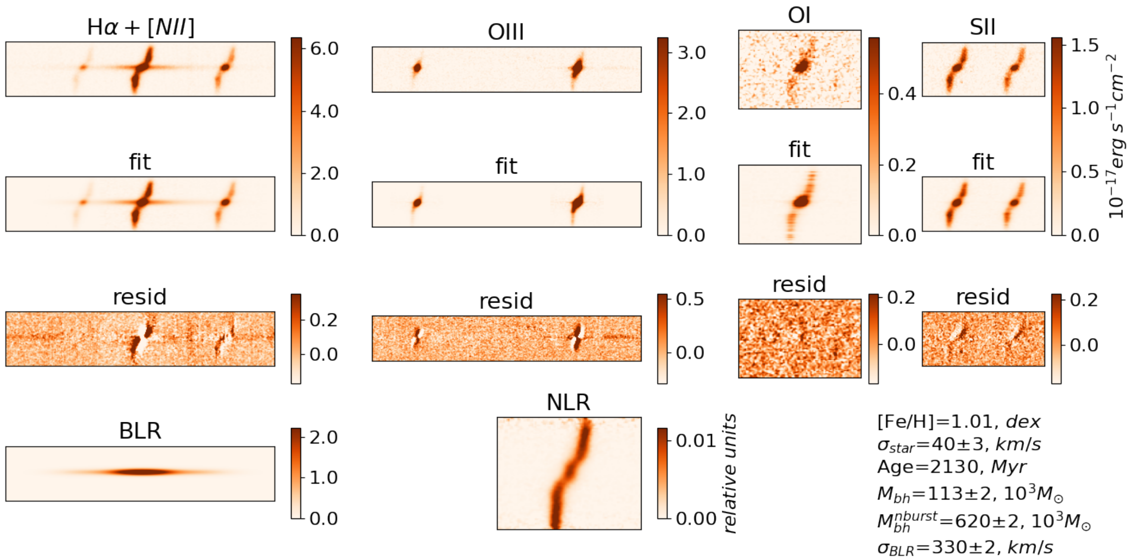

Fig. 1. The result of the 2d nonparametric reconstruction of the NLR-component profile. The top line is the emission spectrum of one of the sample galaxies in the selected spectral regions, the second line is the line fit, and the third line is the fit residuals. The fourth line shows the profiles of the parametric BLR component and the nonparametric NLR-component. Also shown in the bottom right are the parameters of the BLR component, the parameters of the stellar population model — metallicity and age of the stars, black hole mass from the NBURSTs decomposition, and from the nonparametric analysis are displayed.

2 Follow-up observations and their analysis

Spectra of more than 70 galaxies have now been obtained from the MagE (Magellan, echelle), ESI (Keck, echelle), RSS (SALT, long-slit), and TDS (CMO, long-slit) instruments. First, a standardized reduction of our observations was performed by the pipeline we wrote. Flux calibration of the spectra was carried out to obtain accurate virial masses of the black holes. The primary analysis of the spectra consisted in finding the parameters of the stellar population (metallicity, age, kinematics) with our NBURSTs method (Chilingarian et al. 2007).

Then the stellar continuum is subtracted from the original spectra and only the emission spectrum is analyzed. A nonparametric decomposition of the H_α line profile into BLR and NLR components is performed. The NLR profile reconstruction method approximates all strong emission lines simultaneously: H_β, [OIII], [OI], H_α, [NII], [SII] by a linear combination of a narrow line component with a nonparametric shape and a broad Gaussian component in the Balmer lines. The BLR parameters: the velocity dispersion ($\sigma_{\rm BLR}$), the radial velocity of the center of the BLR component, and the parameters h3 and h4 are fit in a nonlinear minimization loop. The parameters psf and the BLR center on the slit are also fit in this loop, since we are dealing with the two-dimensional case, Fig.1. The broad Hα flux and width are then used to estimate the virial $M_{\rm BH}$ using the calibration from Reines et al. (2013): $M_{\rm BH} = 3.72 \cdot 10^6 ({\rm FWHM}_{\rm H\alpha}/10^3 {\rm km/s})^{2.06} \cdot (L_{\rm H\alpha}/10^{42} {\rm erg/s})^{0.47}$. The calculated masses have been corrected for the slit light losses.

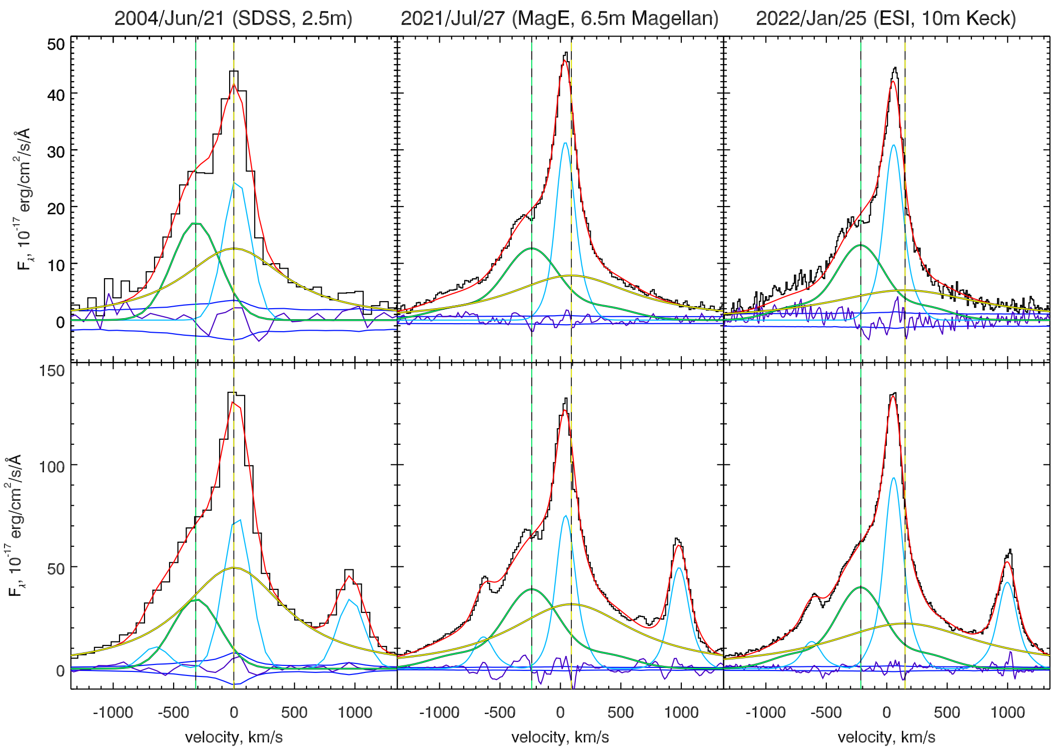

Fig. 2. The picture shows spectra of the host galaxy of a binary black hole at different instruments with subtracted stellar continuum. Top panel — spectra (from right to left SDSS, MagE, ESI) of the binary black hole near the H_β line, bottom panel — near the H_α.

3 Evolution of central black holes

As a result of the analysis of one of the spectra obtained at MagE, a binary black hole has been detected in one of the galaxies, based on the presence of a double broad

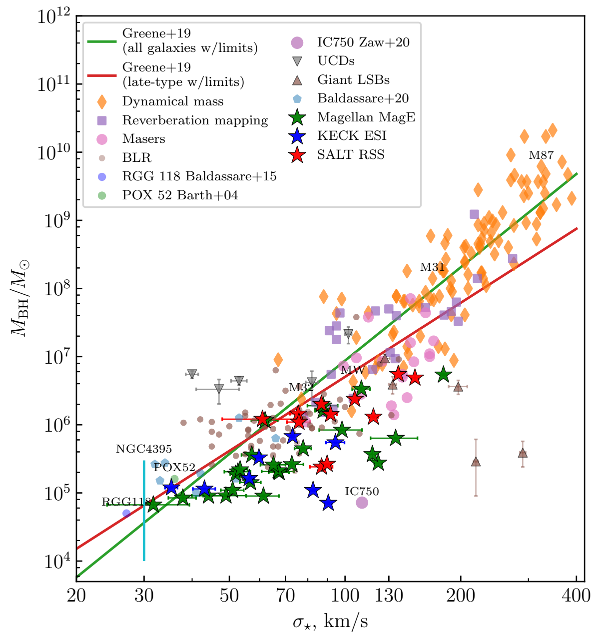

Fig. 3. The $M_{\rm BH} - \sigma_*$ relation featuring IMBHs and light-weight SMBHs. Only one IMBH has a mass estimate based on masers (Zaw et al. 2020); the rest of the data points are virial estimates from Hα. New data from MagE, ESI, and SALT are shown by green, blue, and stars, respectively.

component in the Balmer line series, Fig.2. The black hole masses are $1.7 \cdot 10^5 M_\odot$ and $1.4 \cdot 10^6 M_\odot$ respectively. The two BLR components are separated by 150 km/s. After the discovery of this object on MagE, we made observations of this galaxy on other telescopes: Keck and CMO. This object is currently under multi-wavelength study.

As a result of our analysis, the masses of more than 70 IMBH candidates have been refined. The optical spectra (with good spectral resolution) of the currently largest sample of IMBH and LWSMBH have been analyzed: the parameters of the stellar populations, the kinematics of stars and gas have been obtained, and the virial masses of the central black holes have been measured. The values of the virial masses of the black holes are more accurate than those obtained from the SDSS. The higher spectral resolution has allowed the AGN outflow to be separated from the BLR component of the Balmer lines.

The dependence $M_{\rm BH} - \sigma_{\rm bulge}$ is constructed from the obtained dispersions of the bulge velocities and the virial masses of the black holes, Fig.3. From the results obtained for low-mass black holes based on the $M_{\rm BH} - \sigma_{\rm bulge}$ relation, we can conclude that IMBHs in the nearby Universe do not appear to evolve with their host galaxies: they grow by accretion, while their hosts grow secularly (although gas sources may be associated). The scaling relations are preserved, but the dependence of the black hole mass on the velocity dispersion is different. If the same happens at high redshifts, then (super) Eddington accretion is the dominant mechanism for the growth of supermassive black holes at low masses, and we expect to see supermassive black holes with large z in X-rays with the next-generation facilities Athena or Lynx. However, there may be another explanation for the position of IMBHs on the $M_{\rm BH} - \sigma_{\rm bulge}$ relation: the Reines et al. (2013) scaling relation for black hole mass estimation is not valid for small black hole masses. To test the reliability of the $M_{\rm BH} - {\rm FWHM}_{\rm H\alpha}$ relation, we started a BLR reverberation campaign with narrow Hα filters (Demianenko et al. in prep.) at the CMO of the Sternberg Astronomical Institute of Moscow State University (SAI MSU).

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