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Probing the central engine and environment of AGN using ARIES 1.3-m and 3.6-m telescopes

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Abstract: We discuss three long term observational programmes to probe the central engine and environment of active galactic nuclei (AGN) using the recently installed ARIES 1.3-m and 3.6-m telescopes. The first programme is on the photometric reverberation mapping of low luminosity AGN by mainly using the ARIES 1.3-m telescope. The major impact of this programme other than to estimate the black hole mass will be to extend the broad line region (BLR) radius-luminosity (R_{BLR}-L_{AGN}) relation to the unexplored low luminosity regime, and to constrain the AGN broad line region geometry. The second programme is to use long slit spectroscopy on the ARIES 3.6-m telescope to discover new high redshift quasar pairs with angular separation less than $\sim$1-arcmin. Here, the background QSOs sight-line will be used to probe the environment of the foreground QSOs at kpc-Mpc scales. The major impact of this programme will be on the discovery of new pairs which have been missed in the SDSS survey due to fiber collision below 1-arcmin separation, and use them to understand about any excess overdensity around the QSO, any an-isotropic emission of QSOs, and/or any episodic activity of QSOs. The third programme is related to spectral variability studies of the C IV broad absorption line (BAL) QSOs, based on low resolution spectroscopy using the ARIES 3.6-m telescope. Here, those most interesting cases will be monitored, where the BAL flow emerges afresh or disappears completely in the C IV trough of BAL QSOs sample as seen in SDSS multi-epoch observations. Continuous monitoring of such a sample will be important for our understanding of the nature and origin of the flow, along with their stability and dynamical evolution.

1 Introduction

In order to carry out observations in the frontier areas of astronomy, the Aryabhatta Research Institute of observational sciencES (ARIES) has recently set up the 1.3-m Devasthal Fast optical telescope

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(DFOT) and the 3.6-m Devasthal Optical Telescope (DOT) at a site called 'Devasthal' (Longitude : 79° 41′04″E, Latitude :29°21′40″N) at a distance of ∼60-km from ARIES (Nainital). The site has the advantages of having dark skies and excellent observing conditions. The 1.3-m DFOT has been operating since the late 2010, and the 3.6-m DOT since early 2017. For a vigorous and sustained use of these new facilities, it is important to design several long-term observational programmes in frontier areas of astrophysics, with a potential to make a major scientific impact on the national and even international scale. Towards this objective, we propose to initiate long-term extragalactic projects with focus on the following three themes.

2 Project I: Photometric reverberation mapping (PRM) of low luminosity active galactic nuclei

Reverberation mapping (RM) is a technique for studying the structure and kinematics of the broad-line regions (BLRs) of active galactic nuclei (AGN), including their most luminous subset, the quasars (e.g, see Blandford et al. 1982, Peterson et al. 1993). RM is a particularly important tool as the BLRs generally project to angular sizes of only tens of micro-arcseconds or less, too small to be resolved directly by any current or near-future technology. RM experiments are arduous, as they require a large amount of telescope time and coordinated effort. Since the first major reverberation mapping campaigns conducted a quarter of a century ago (e.g see Peterson et al. 1991), RM measurements have been performed for ~ 50 AGN, most often only for the Hβ emission line and almost exclusively for AGN at $z < 0.3$ (see e.g. Bentz et al. 2009, and references therein). These studies have been used to derive the R$_{BLR}$-L$_{AGN}$ relation for AGN, in order to calibrate the single-epoch super massive black hole (SMBH) mass estimation method, used extensively for determining the SMBH mass and the corresponding Eddington ratio of the AGN. However, it should be appreciated that the presently available AGN sample, for which reliable RM measurements have been made, are strongly biased towards very bright (i.e. $L > 10^{43} erg/s$) and highly variable AGNs (see e.g. Fig. 15 of Hass et al. 2011), due to which these existing RM studies do not probe the AGN parameter space with any degree of uniformity. Furthermore, the RM technique has been generally regarded as a 'work in progress'. To remedy this situation, it is imperative to carry out the time-consuming RM programs on relatively modest size telescopes, such as the 1.3-m DFOT, so that one may realistically expect allocation of a large block of observing time to an individual project for deriving continuum and emission-line light-curves.

We plan to achieve this goal by devising a method which would replace the existing spectroscopic element of the RM method (to measure the line flux), with a narrow-band photometry of the emission line(s); this is commonly known as 'photometric-reverberation mapping' (PRM, e.g see Fig. 1 left panel). Using PRM, it will be much easier to obtain the light curves of a chosen emission line, which conventionally was done by spectroscopic studies, hence very time consuming. This we can achieve with the 1.3-m DFOT. The 3.6-m DOT will only be needed for the limited purpose of obtaining the virialised width of emission lines (FWHM), which in conjunction to the PRM based BLR size, $R = c \times \tau_d$, that will be used to estimate the virial black hole mass as: $FHWM^2 = fGM_{bh}/R$, with f being the geometric correction factor (including accretion disc inclination, etc.) and τ_d being the measured time delay between the light curve of Hβ and/or H-α lines in comparison to the continuum light curve. It may be clarified that the virialised velocity width (i.e. the FWHM value) to be used is that from the BLR alone, being close enough to the SMBH to justify the virialisation assumption. In real spectra, the emission line flux is contributed by the BLR as well as the narrow line region (NLR), besides the underlying continuum and also the Fe II blends. For this we have recently developed a novel technique to decompose these individual components by a simultaneous fit of power law continuum, complex profile of the emission line with multiple Gaussians, along with modeling of optical Fe II blends (see e.g. Chand et al. 2010, Joshi & Chand et al. 2012).

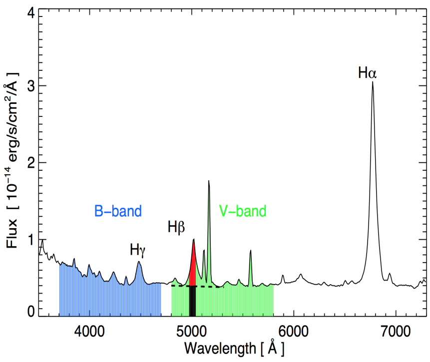
The RM result based estimation of the BLR size R ($\equiv c \times \tau_d$) has also led to a very strong correlation between R_{BLR}-L_{AGN} (see e.g. Fig. 15 of Hass et al. 2011). As a result, a scaling relation has been also derived for the BH-mass estimation where the AGN luminosity has been used as proxy for the BLR-size as:

$$\log M_{\rm BH}({\rm H}\beta) = \log\left[\left(\frac{{\rm FWHM}({\rm H}\beta)}{1000\ {\rm km\ s^{-1}}}\right)^2\right] + (6.91 \pm 0.02) + \log\left(\frac{\lambda L_\lambda(5100\ {\rm \AA})}{10^{44}{\rm erg\ s^{-1}}}\right)^{0.50\pm0.06} \quad (1)$$

However, these scaling relations are particularly derived based on RM experiments of high luminosity AGNs. It is unclear if such a R_{BLR}-L_{AGN} relation would also hold for the lower luminosity regime. Hence it is a matter of considerable importance and urgency to extend the RM experiment to low luminosity AGNs having $L < 10^{43} erg/s$, with a cadence of 1-2 days. The latter is important because such a needed cadence would not be feasible in larger RM surveys like the SDSS targeting high-z AGN for which a cadence of about a week should suffice (e.g. Shen et al. 2015).

2.1 PRM of low luminosity AGNs with the 1.3-m ARIES DFOT

We will use narrow band filter photometry to catch the flux of both the emission line and its underlying continuum (see e.g Fig. 1, left panel). Further to extract the pure emission line light curve from the narrow band light curve, we will subtract the underneath continuum (including the host galaxy) by means of the flux variation gradient method as demonstrated by Hass et al. (2011). Cross correlation of the continuum and emission line light curves will then yield the intensity weighted time lag (τ_d) leading to the BLR size R as $R = c \times \tau_d$. It has been found that imprecise emission-line coverage by the narrow bandwidth has only a small (less then a few percent) effect on R (see e.g. Pozo et al. 2013).



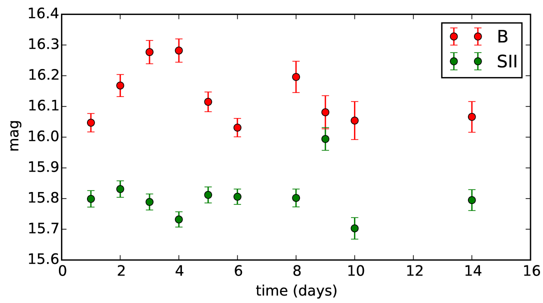


Figure 1: *Left:* Observed spectrum of 3C120 ($z = 0.033$). For illustration, the band passes of the filters used for the photometric monitoring are shaded (blue B-band, green V-band). The narrow band (NB, [O III] 5007 Å) filter catches the redshifted Hβ line. The NB flux is composed of about 50% Hβ line (red shaded) and 50% continuum (black shaded), as found from both the spectrum and the flux calibrated light curves (from Pozo et al. 2012). *Right:* The light curve of the AGN MCG+09-16-013 ($z_{em} = 0.025321$) using the ARIES 1.3-m DFOT. The narrow band S II filter is used to derive the light curve of the H-α emission line as it got redshifted to the S II filter waveband, and the continuum light curve is derived by using the broad B-band filter.

At first we wish to undertake a systematic study using a sample of 80 candidates assembled from the SDSS database with $m_g \sim 18$ and having a Hα luminosity $< 10^{43}$ erg/s. Such low-luminosity

AGNs have a BLR size of just about a few days. Therefore the reverberation time delay of the BLR can be constrained in about 1-2 weeks of monitoring campaign, for nearly a dozen AGN, using the 1.3-m DFOT. Here we propose to get the Hβ and/or H-α luminosity using the narrow-band filter of width about 80-100Å, which is optimal for the strength/width of the AGN emission lines targeted in our sample. Our entire sample at present consists of 210 good candidate AGNs, which will be monitored and later the sample can be expanded by including the potential candidates from DR12.

For feasibility check of our PRM experiment using the ARIES 1.3-m DFOT, we recently carried out a PRM monitoring of an AGN MCG +09-16-013 having $z_{em} = 0.025321$ and $m_v = 16.9$. This source was selected as its redshift is such that its H-α emission line gets redshifted to the waveband of the narrow band S II filter already available at the 1.3-m DFOT site. Hence, we could use observation in the narrow band S II filter to derive the light curve of the H-α emission line and in the broad B-band filter to derive the continuum light curve as shown in the right panel of Fig. 1. As this figure shows, the error-bars on the light curve are very small, and hence the 1.3-m DFOT will be optimal to carry out such a PRM experiment.

Successful completion of this project will be a major observational contribution of the observatory to the world-wide AGN community. This innovative programme of photometric reverberation mapping (with the 1.3-m DFOT), in conjunction with the use of the 3.6-m DOT only for single epoch spectroscopy, will have a major impact on the determination of (i) the BLR geometry, (ii) the SMBH mass vs bulge luminosity relation, (iii) on the estimation of the size of the AGN's dust torus, and (iv) on the physics of the accretion disk, based on the accretion disk reverberation mapping. After completion of this project limited to the RM of low-luminosity AGN using the H-β and/or H-α lines, the entire observational programme can be extended to the RM using the Mg II and C IV lines from AGNs at higher redshifts, in order to study the composition stratification of the BLR in AGNs.

3 Project II: Quasars as probes of distant Quasars - Do QSOs reside in dense gaseous halos?

The analysis of the absorption line systems seen in the spectra of QSOs is found to be one of the most sensitive and powerful tools to determine the physical conditions of the absorbing gas, such as metal abundances, velocity dispersion, temperature, ambient radiation field (or ionisation states), clustering property, etc. However, the atoms and molecules in the absorption systems are found in various ionisation states. This has been attributed to the existence of a ionising UV-background radiation field (J_{21}). It is not always possible to observe absorption lines of any metal in all its ionisation states, therefore to compute the metal abundance one needs to know the nature of the background radiation before applying the ionisation correction.

One independent and traditional way to measure J_{21} is based on the proximity effect. This effect is the measure of the relative enhancement of the ionizing flux due to the local ionizing source (say QSO) compared to the J_{21}. Therefore by knowing the luminosity of the local ionizing source the value of J_{21} can be statistically estimated. Such a standard analysis of the proximity effect assumes that the density field around the QSOs is same as that of the normal IGM. This may not be a reasonable assumption in view of the recent studies showing evidence of excess clustering on few Mpc scale around the QSOs (see e.g. Rollinde et al. 2005; Prochaska et al. 2013).

Recently to probe this in more detail we have selected a sample of 312 QSO pairs (out of a sample of 2,97,000 QSOs in SDSS DR-12), in the redshift range of about 2.5-3.5, having separation less than 1.5-arcminute on the sky. The main principle here is to use the background QSOs sight line (b/g QSO) to probe the effect due to the foreground QSOs (f/g QSOs). This effect will be the combination of ionisation caused by foreground QSOs and the over density, if any, in its environments. We have done the analysis using a controlled sample to compare such proximity regions with what would have been expected in the pure IGM. Our analysis shows that the over-density dominates in less than about 5Mpc regions and over-ionisation dominates in 10-15Mpc regions. More importantly the magnitude of the excess over density seems to be different along the longitudinal and transverse directions as can be seen from Fig. 2, albeit with larger error-bars. This has potentially very important implications for understanding the anisotropy of QSOs emission and/or the episodic activity of QSOs (see e.g. the Poster by Jalan et al.), which we wish to improve by discovering new pairs using the 3.6-m DOT (see below).

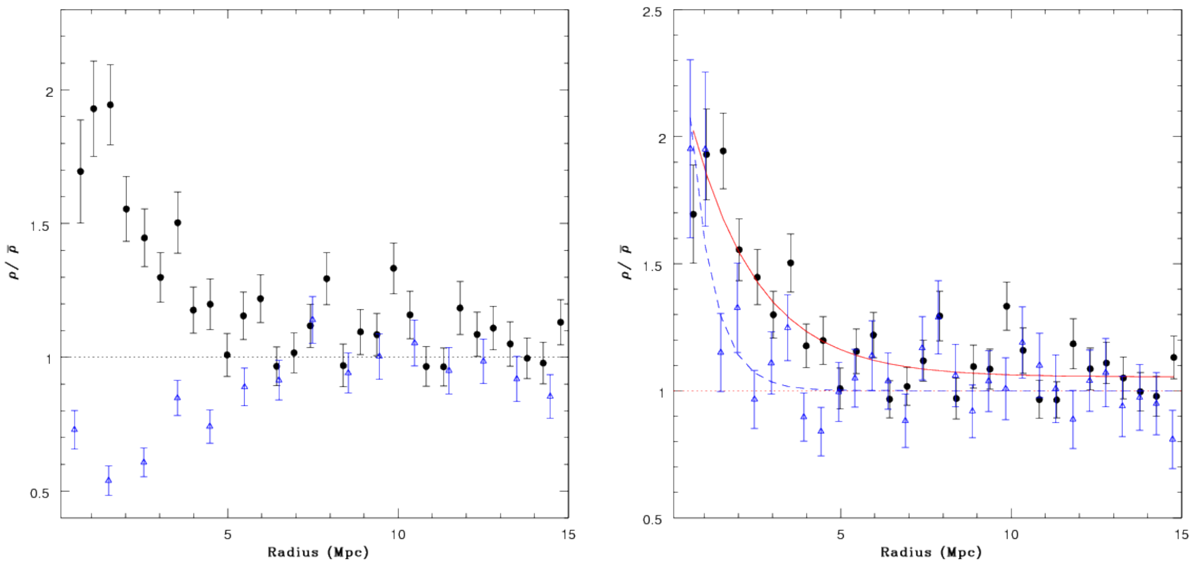


Figure 2: *Left :* The weighted mean of the overdensity ($\rho/\bar{\rho}$) in a radial bin of 1Mpc is plotted for the transverse proximity region (filled circle) and longitudinal proximity region (triangle) using 312 QSOs pairs based on SDSS-DR12. The $\bar{\rho}$ is computed from the controlled sample of absorption in the IGM (i.e free from any proximity effect) matched in redshift and SNR with that of our 312 pairs proximity sample. The plot shows that the excess over density $\rho/\bar{\rho} > 1$ in the transverse direction is more than that along the longitudinal one. *Right:* Same as left but the proximity optical depth is scaled to account for the extra ionisation due to the proximity of QSOs, by taking the best available UV-background radiation measurement from Khaire et al. (2015). The best fit profile for $\rho/\bar{\rho}$ of the form $a \times exp(-r/b) + c$ is also over-plotted both for the transverse (solid line) as well as for the longitudinal (dashed line) direction.

As can be seen from Fig. 2, to conclude firmly on the difference we saw in longitudinal and transverse directions, the error-bar needs to be reduced at least by a factor of a few. This will amount to enhance the sample size by many folds. As we know, it is very difficult to find pairs with a small separation at <1-arcmin, as needed here to probe the QSOs environment on kpc-Mpc scales, where both the proximity effect as well as the overdensity effect will be noticeable. In the SDSS survey, spectroscopy has been carried out in the multiple-fiber based spectroscopy mode, where for separation less than 1-arcmin the SDSS fiber starts colliding. It will be very useful to have a follow-up program to discover such small separation QSO pairs which had been missed out in the SDSS, due to the fiber collision problem in its multi-fiber fed spectroscopy mode, by making long-slit spectroscopic observations with the just commissioned ARIES 3.6-m DOT (e.g. see below).

3.1 New QSO pairs using the ARIES 3.6-m telescope

Based on our preliminary estimate, nearly 83,661 QSOs out of a total 2,97,301 QSOs in SDSS DR12 have emission lines at $z_{emi} > 2.51$, so that their Ly-α forest absorption is redshifted into the optical band. We have searched a field of 1-arcmin radius around each of these 83,661 QSOs, and listed about 4.1 million objects with photometric and color information available. We then used the optical colors in conjunction with the IR color information from the surveys such as WISE and also used the XMM catalog to spot the QSO candidates in these small fields (see e.g. Secrest et al. 2015, and references therein). Finally, limiting ourselves to the QSOs bright enough ($m_r < 20$) for spectroscopy with the ARIES Devasthal Faint Object Spectrograph Camera (ADFOSC) mounted on the 3.6-m DOT, we are left with about 1,000 QSO pair candidates with a separation smaller than 1-arcmin. Our immediate goal post-commissioning of the ADFOSC, is to carry out long-slit spectroscopy of these candidates by orienting the slit suitably to cover both the members of a pair, simultaneously. This approach will overcome the severe problem posed by fiber collision in the SDSS fiber-fed spectroscopy and we shall get the spectra of both members of the pair in a single exposure. This proposed time efficient, long-term project will be a key contribution from the 3.6-m DOT, aimed at discovering new QSO pairs with less than 1-arcmin separation, which is a key requisite for the other proposed DOT project which would use background QSOs to probe the environment of foreground QSOs at kpc-Mpc scales in great detail, allowing us to draw firm conclusions on the anisotropy of the QSOs emission and/or to constrain the QSOs lifetime as hinted in Fig. 2 albeit based on a small sample of just 312 QSO pairs.

4 Project III: Monitoring of the emerging/disappearing trough of C IV BAL QSOs

Accretion disc outflows are an important part of the quasar phenomenon. They are known to be present in at least 50 per cent of optically selected quasars (Ganguly et al. 2008). They can spread chemically-enriched gas through the inter-galactic medium. Moreover, they could inject sufficient mechanical power into the host galaxy, influencing its star formation and evolution, as well as the co-evolution of the galaxies and their central super-massive black holes (SMBH) as implied by the observed correlation between the masses of the SMBH and the galactic bulge. The outflows manifest most conspicuously in the quasar spectra as broad absorption lines (BALs), with typical velocity widths of 5,000-20,000 km/s. Unfortunately, the nature and origin of AGN outflows remain largely unsettled. Most current models favor the equatorial geometry of the BAL outflows, although after the discovery of radio-loud BAL QSOs (Becker et al. 2000) polar outflows have also been considered in some cases. A two-component wind model combining the polar and equatorial components has also been suggested to explain the polar outflows. The exact geometry of the BAL outflows is still under theoretical and observational investigation. As the launching radii of the winds in some models are very close to the QSO central engine, instabilities in the accretion disc may well result in changing outflow properties on year-like time-scales. Thus, BAL variability studies are important for understanding the location, geometry, and physical conditions in the absorbing gas and the cause of these outflows. The time variability of C IV and Si IV absorption has been reported in several BAL QSOs (e.g. Gibson et al. 2008). BAL troughs often vary in equivalent width (EW) and/or line profiles over rest-frame timescales of months to years. Conceivably, such variations could even be driven by changes in the covering factor, velocity structure, or ionization level of the BAL region. Out of these possibilities, the generally favored dominant driver for the BAL variations is the variable covering factor of the outflow which partially blocks the AGN ionizing continuum. Changes in ionization level are generally disfavored as the primary driver, since the BAL troughs are often highly saturated and thus should be only weakly responsive to the ionization-level changes.

Furthermore, BAL trough variations generally do not appear to be correlated with variations of the observed continuum. However, the most interesting cases are the ones where the outflow emerges afresh or shows strong dynamical evolution (i.e. variation in the absorption profile and signatures of acceleration). Because in such case, we shall be observing the outflows making a transition, observations of BAL QSOs with emerging/disappearing BAL components will greatly help in understanding the physical mechanisms driving the outflows (see e.g. Vivek et al. 2016).

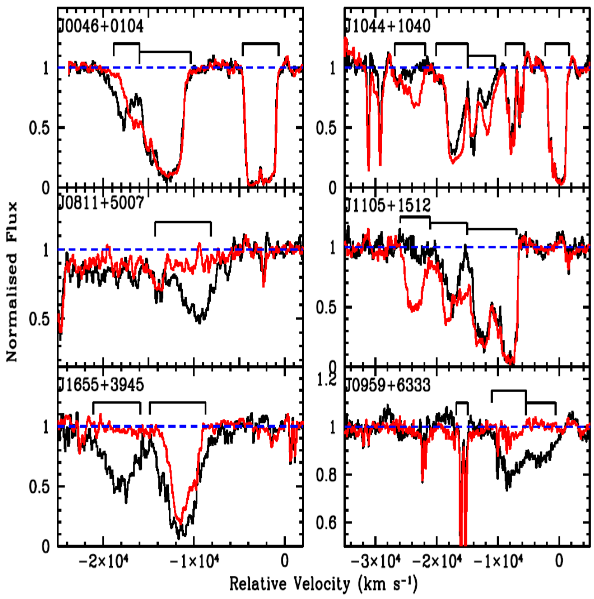


Figure 3: Example of the emergence and/or disappearance of the C IV BAL trough in multi-epoch SDSS observations of BAL QSOs.

4.1 C IV BAL QSOs monitoring with the ARIES 1.3-m and 3.6-m telescope

With the advent of large surveys such as SDSS DR12, a large number of multiple epoch observations are now available which have resulted in many dozen of BAL QSOs with emerging/disappearing BAL components (e.g. see Fig. 3). Systematic monitoring of a well chosen set of these BAL QSOs will be important to understand the nature, origin and the influence of these outflows. As the expected absorption lines are broad, even moderate resolution spectroscopy for studying their variability will suffice for the purpose. However, as the continuum is not well defined due to the presence of broad absorption lines, one needs flux calibrations to get the correct spectral shape. Thus to optimize the telescope time, a spectrograph like ADFOSC mounted on the 3.6m DFOT will be ideally suitable for the spectral variability and broad band based photometric observations with the ARIES 1.3-m DFOT for their continuum variability. The continuous monitoring of these sources will help to put tight constraints on the time-scales for the BAL emergence/disappearance to occur, to study the stability of these outflows and also to probe the connection between the BAL emergence and BAL variability, in general.

5 Summary

To summarise, we discuss here 3 long-term observational programs to probe the central engine and environment of AGN using the recently installed ARIES 1.3-m and 3.6-m telescopes viz: (i) "Photometric reverberation mapping of AGN", to probe the unresolved central engine of AGN: This will be the first systematic monitoring program of its kind, as only spectroscopic monitorings have mostly been done until now, which however require far more telescope time. Any such programs in the past were focused only on success-prone bright AGNs. In contrast, our plan is to carry out a systematic unbiased study covering low-luminosity AGNs ($L < 10^{43} erg/s$) as well, thereby accessing an unexplored portion of the R_{BLR}-L_{AGN} space; (ii) Quasar probing Quasars, "Do QSOs reside in overdense environments?": In this project we shall analyze the spectra of distant quasar pairs with projected separations less than $\sim$1-2 arcmin, so that the excess ionisation by the foreground QSO of its gaseous halo can be studied by analysing the line-of-sight spectrum of the further member of the QSO pair. The candidate quasar pairs will be initially drawn using the optical color data for individual compact objects in the SDSS, in conjunction with the IR/X-ray surveys, with the aim to discover new SDSS QSO pairs at separation less than 1-arcmin, which would have been missed out due to fiber collision in the multi-fiber based spectroscopy mode followed in the SDSS. For this we shall have a dedicated follow-up program of long-slit spectroscopy with the newly installed ARIES 3.6-m telescope, orienting the slit to cover both members of a given QSO pair (even at separations $<$ 1 arcmin), so as to probe the QSO environment on kpc-Mpc scale; (iii) "Monitoring of emerging/disappearing troughs of CIV BAL QSOs": such variability studies can provide important information about the location and physical conditions in the absorbing gas and the physical mechanisms responsible for its outflow. The most interesting cases will be those where the flow shows up newly, or disappears altogether, in the trough of a given C IV BAL QSO. Regular spectroscopic monitoring of such a sample will be valuable for understanding of (a) the nature and cause of the outflow, (b) stability of the outflow, and (c) the dynamical evolution of the outflow and of the broad-line region.

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