Abstract

Active galactic nuclei (AGNs) are among the most luminous sources observed in the Universe - their overall luminosity can be over 12-15 orders of magnitude more luminous than our Sun's. They harbour supermassive black holes at their centres that are estimated to have masses up to 10 billion solar masses and possess immense gravitational potential. When matter falls towards a black hole due to this potential, it gets heated up and shines. This is the only way to observe AGNs and their immediate environment. Quasars can be observed from cosmological distances and they can be excellent, not yet appreciated, indicators of the universe's expansion rate. The analysis of several, mutually related issues regarding quasars is presented in this dissertation which will later facilitate the use of quasars in cosmology and tie them with the evolution of galaxies across cosmic time.

Matter in-falling under the action of the gravity of the central supermassive black hole loses angular momentum while being accreted onto the black hole. This manifests in the form of an accretion disk around the black hole which in turn makes these systems non-spherically symmetric. The accreted matter gets heated up and radiates. The photon energy of the dissipated radiation spans from the near-infrared to the ultraviolet/X-rays and the radiation then illuminates the material surrounding the accretion disk. This phenomenon leads to the formation and emission of strong and broad emission lines. The size of this region, named broad line region (BLR) extends within few tens to a few thousand gravitational radii. These broad emission lines allow measuring the mass of the central supermassive black hole and underlie the use of quasars for cosmological applications, in addition to their vital role in estimating the driving parameters of the central engine and statistical studies that help address the diversity in AGN. Some of these emission lines are produced from the disk outflows which are highly ionized and are known as High-Ionization Lines (HILs, ionization potential (IP) $\gtrsim$ 50 eV). On the other hand, emission lines from other ionic species are low ionized (IP $\lesssim$ 20 eV) and are produced in a less ionized medium. These are called the Low-Ionization Lines (LILs). In this thesis, I concentrate on these Low-Ionization emission lines which are more reliable for black hole mass measurements.

The emission line shapes, their intensity ratios and broadband spectral indices lead to the classifications of quasars. Principal Component Analysis (PCA) - a dimensionality reduction technique, allowed to extract meaningful information from large datasets containing diverse quasar populations. A clear pattern originates from the analysis of the optical plane, i.e. the anti-correlation between the strength of the Fe IIλ4570 (also known as $R_{\rm FeII}$) and the full width at half maximum (FWHM) of Hβ, and is known as the Quasar Main Sequence. The main sequence of quasars is an analogous scheme to the Hertzsprung-Rusell diagram. The stellar main sequence in the Hertzsprung-Rusell diagram is easy to understand since stars are characterized solely by their mass. Unlike stars, quasars are more complex. Their appearance is defined by the mass of the black hole, the accretion rate, spin and their inclination angle to the observer.

The first issue is an attempt to have a deeper understanding of why such complex objects form an almost one-parameter family in the optical plane. Therefore, I introduce a physically motivated model which can explain these emission lines' statistics. This model takes into account the underlying ge-

ometry of the active nucleus, including black hole mass, radiation from the accretion disk surrounding the black hole, with the presence of hot corona, and the BLR gas cloud at the right distance from the centre. This ionized BLR gas cloud absorbs the radiation and re-emits in the form of the emission lines that are then observed in a spectrum. The radiative transfer in these media is solved to obtain the emission line ratios and line kinematic widths reflecting the motion of the line emitting clouds. The results from these model predictions are compared with available measurements of the emission line properties in ∼1 million quasars from the publicly available quasar catalogues. The model successfully reproduces the Main Sequence trend. In particular, iron emission calculations in the optical range require taking into account the iron atom model containing 371 levels with 68,535 transitions. The program shows that the model reproduces the behaviour of the quasar well if one also considers the complex relationship between the chemical composition and the density of the BLR clouds with the accretion rate. The higher the accretion rate, the more elements such as iron must be produced. This issue is addressed for the first time (Panda et al., 2018) by systematic theoretical modelling of the spectra of active galaxies.

The results published in the first work required further clarification. Subsequently, I also include an additional spectral component - a warm corona (an inner warm comptonizing region to produce the soft X-ray excess) in the model (Panda et al., 2019a), and then incorporate the role of the viewing angle at which we observe the AGN (Panda et al., 2020a; Panda et al., 2019c). Treating the aspect of viewing angle and the distribution of the BLR clouds appropriately, I confirm the dependence of the Main Sequence on the Eddington ratio and the related observational trends - as a function of the shape of the ionizing continuum, cloud density, and composition, verified from prior observations. This allows me to affirm that quasars with different properties populate different parts of the Quasar Main Sequence. The results show that quasars that have very strong iron emission, accrete close to the Eddington limit and are seen under relatively small angles. These sources can serve as "standardizable" luminosity candles to probe the expansion of the Universe.

The Fe II emission is observed from the ultraviolet to the near-infrared and acts as one of the main coolants of the BLR. However, the complex electronic structure of Fe II owing to varied excitation mechanisms makes it difficult to model the atom. In the concluding chapter of the thesis, the physical properties and location of the low ionization lines using the NIR Ca II triplet emission as a reliable proxy to the Fe II is explored. In the first part of the series (Panda et al., 2020b), the observational correlation between the strengths of the two species is updated and various photoionization models are tested taking into account (a) the ionization parameter, (b) the cloud density, (c) the metallicity, and (d) the column density, and, recover a linear, almost one-to-one relationship between the strengths of the two species. In the second part (Panda, 2020), synthetic equivalent widths (EWs) are derived accounting for reasonable covering fractions for these low-ionization species and a significant overlap in the emitting regions of the two species is recovered. This work also highlights the role of metallicity and cloud sizes in the study of accreting quasars and in addition the effect of inclusion of microturbulence allows to limit the metal content in the BLR for the adequate Fe II emission.

The collection of works in this thesis have shown that (i) the broad-line regions of active galaxies have an almost universal local density, (ii) there exists a coupling between the Eddington ratio and the metal content in these ionized media which validates the co-evolution of the host galaxy and the

AGN, and (iii) the quasars can be used as reliable cosmological probes to investigate the expansion of our Universe.