Tracing the massive inflows feeding super-massive black holes in quasars

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Received: December 21, 2022; Accepted: January 2, 2023; Published Online: January 2, 2023; https://doi.org/10.1016/j.xinn.2023.100376

Citation: Jiang P., Shi X., and Zhou H. (2023). Tracing the massive inflows feeding super-massive black holes in quasars. The Innovation **4(1)**, 100376.

ACCRETION OF SMBHs IN QUASARS

Strong observational evidence accumulated since the end of the last century indicates that the vast majority of galaxies host at their centers a black hole with a mass range of $M_{SMBH} \sim 10^6 - 10^{10}\ M_{\odot}$ (solar mass). Going back in time, these super-massive black holes (SMBHs) should grow from seed black holes possibly with $M_{seed} \sim 10^2 - 10^5\ M_{\odot}$, "activated" mainly by accretion of the interstellar medium in their host galaxies. During their fast growing phase, such SMBHs manifest themselves as quasars, producing as much as 10^4 times the luminosity of a typical galaxy, such as the Milky Way. Most of the observed energy is emitted by a hot accretion disk around the SMBH, with a radius of several light days, where the gravitational energy of the inspiralling gas is converted into thermal energy. Considering the energy budget, an enormous amount of the fueling gas, at up to several tens $M_{\odot}$/year, is expected to be transported into the accretion disk and be consumed, at last, from the galactic environment at a scale of 10^5 light years or more from the center.

DIFFICULTY IN OBSERVING DISK-FEEDING INFLOWS

Although astronomers have learned much about quasars since their first discovery 70 years ago, some of the most basic questions have not yet been dealt with, including the mechanics triggering, maintaining, and terminating the quasar activity and the duty cycle of the quasar phase in the evolution of galaxies. Basal difficulty on these problems, as noted by Julian Henry Krolik,[1] is that no photons have been reliably identified as coming from the wide radii of several orders of magnitude outside the accretion disks, and thus there is little we can say about it. Specifically, no massive inflows feeding the accretion disk of SMBHs as the fuel of quasars has hitherto been detected firmly. This dilemma, to some extent, is analog to the Buridan donkey effect, where a donkey placed precisely midway between two identical piles of hay was unable to choose between the two and eventually starved to death. The problem is not the lack of photons from the infalling gas feeding the accretion disk of SMBHs but that it is hard to identify the corresponding signals from the energetic radiation of quasar as a whole.

HYDROGEN AND HELIUM ABSORPTION LINES

Substantial gas lying along the line of sight (LOS) would imprint atomic/ionic absorption lines on the spectra of quasars. Analysis of the abundances and profiles of these lines can reveal the physical conditions and dynamics of the absorbing gas. The advantage of the absorption-line technique is that it naturally provides extremely high spatial resolutions, making the direct detection of massive inflows feeding SMBHs possible, if our LOS toward the central continuum radiation source occasionally penetrates them (see Figure 1). In ~ 15%

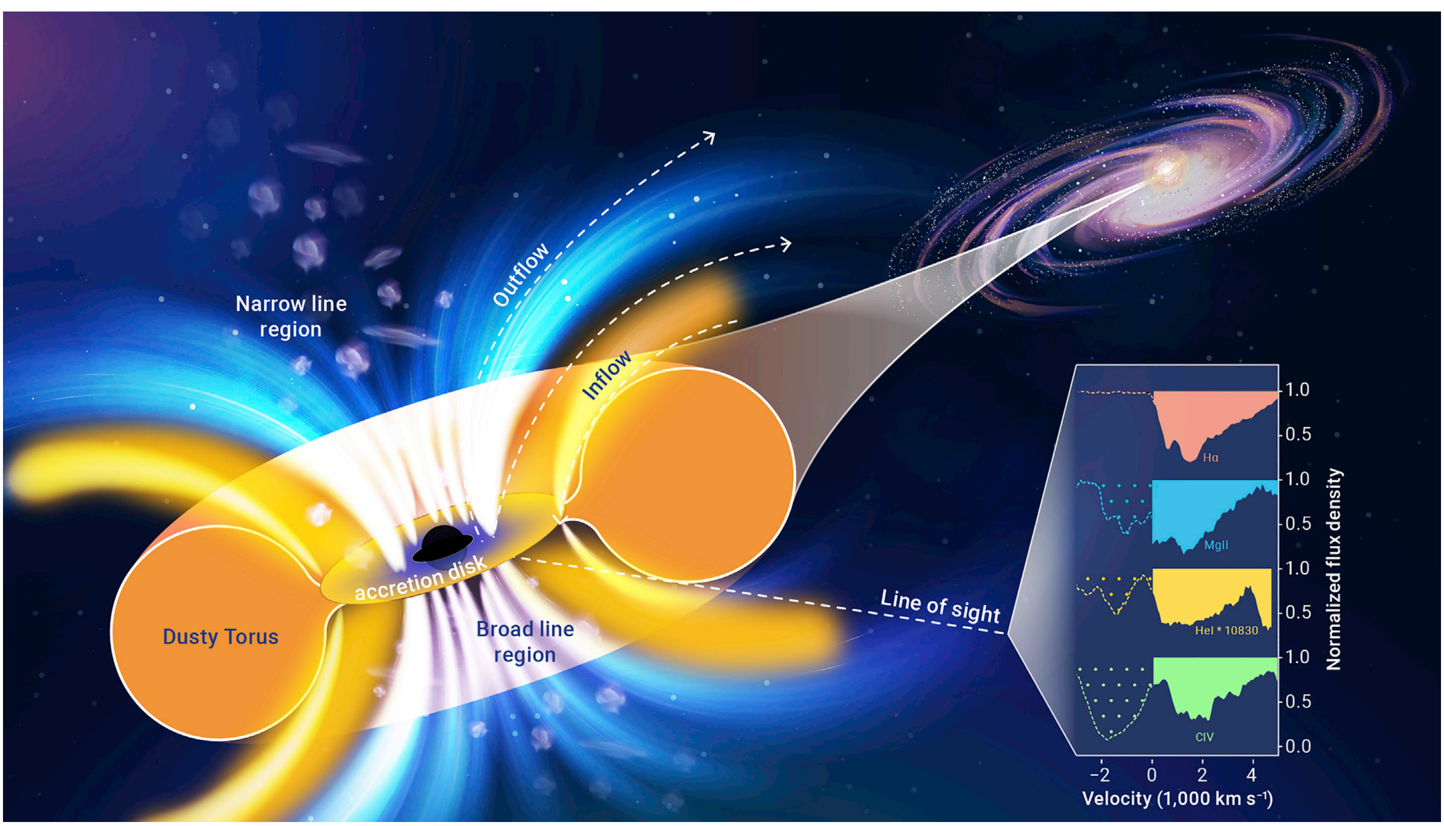

Figure 1. Schematic diagram of the quasar nucleus In the unification model of quasars, the accretion disk around an super-massive black hole, the broad line region, the narrow line region, and the dusty torus are well-known components. The outflows are commonly observed with their blueshifted BALs. However, unambiguous observations of the long-sought inflows, which feed the accretion disk as fuels, have been elusive. In a small sample of quasars, a large amount of cold, dense, and high-column-density infalling gas is revealed by the redshifted H I and He I* BALs. The spectrum observed in the quasar J1035 + 2422 is illustrated for an example. The wide Doppler velocity structure essentially represents the gravitational acceleration by the super-massive black hole. Analysis of photo-ionization locates the gas in a few thousand gravitational radii, close to the outer edge of the accretion disk. The redshifted H I and He I* BALs provide compelling evidence for the massive inflows directly feeding the accretion disk in quasars.

quasars, blueshifted broad absorption lines (BALs) with velocity dispersions greater than 2000 km s^{-1} are commonly observed in their optical-ultraviolet spectra, mainly produced by resonant transitions of alkaline-like ions, eg, O VI, N V, C IV, Si IV, Al III, and Mg II. However, these lines are usually subject to serious saturation and line-blending problems. The shortcomings of the resonant lines are especially serious for studying the disk-feeding inflows, which are thought to be cold dense gas with high column densities. The problems have been gradually solved with the increasing detections of two series of atomic BALs in the large sample of quasar spectra collected by the Sloan Digital Sky Survey. The hydrogen Balmer lines are produced by electron transitions from a quantum number of two or higher, which are mainly populated by collisional excitation in the neutral zone of gaseous clouds with a high electron density of $n_e > 10^6$ cm^{-3}. The meta-stable neutral helium multiplets are produced by electron transitions from the highly meta-stable 2^3S level to higher levels, which are mostly populated via recombination of He^+ ions.[2] The relatively low abundances of excited hydrogen atoms and meta-stable helium atoms help some of the weak member lines in the series from getting saturated even for extremely thick absorbing gas. Moreover, the wavelength separations of these lines are moderately wide, and thus the line-blending contamination is not severe even for very large velocity dispersions. Physical analysis on photo-ionization models suggests that the strength of H I Balmer lines depends on both the electron density and the ionization parameter, while the He I meta-stable lines almost solely depend on the ionization parameter.[3] Joint analysis of these hydrogen and helium lines can well determine the electron density and the ionization parameter and the resulting distances of the absorber to the central ionizing source.

Recently, a systematic searching experiment discovered such redshifted H I and He I* BALs in a small sample of eight quasars.[4] The quasar J1035 + 2422, ie, the archetype of the sample, shows an extremely wide Doppler velocity structure in the absorption troughs spreading from v $\sim$ 0 up to a maximum velocity of v $\sim$ 5000 km s^{-1} continuously. The pure Doppler redshift indicates the radially inward motion of the absorbing gas toward the accretion disk around the central SMBH. Simply assuming that the maximum radial velocity v $\sim$ 5000 km s^{-1} equals to the free-falling speed due to the gravity of the SMBH, a distance of the innermost gas to SMBH can be derived as R $\sim$ 7000 gravitational radii. The result here should be treated as an upper limit since the kinematics of the inflowing gas might not be pure radial free-fall motion. Inevitably, the inflows with such high radial velocities must be in the innermost region of the quasar and should be overwhelmingly influenced by the strong gravitational field of the SMBH. The observed large velocity gradient echoes with the large gravitational acceleration of the inflowing streams across a wide radial distance. Photo-ionization modeling confirms this result derived from the simplified dynamical analysis and further constrains the distance of inflows to the SMBH as R $\sim$ 1000 gravitational radii, close to the outer edge of the accretion disk in the quasar. The inflow gas probably has no other destiny than being dumped into the accretion disk pulled by the strong gravity force of the SMBH.

Given the superb spatial-resolving power of the absorption line technique and the sensitivity to diagnose astrophysical properties of the cold and dense gas with high column densities via excited hydrogen atoms and meta-stable helium atoms, the redshifted H I and He I* BALs provide compelling evidence for the long-sought massive inflows directly feeding the accretion disk of SMBHs and consequently keeping quasars luminous.

INFLOWS IN UNIFICATION MODEL OF QUASARS

In the unification model of quasars,[5] a dusty torus with a certain height lies on a plane and blocks the vast majority of the edge-on view of the LOS. If the quasar inflow is also mostly along the edge-on view, as expected from our commonly accepted picture of how gas gets accreted, the inflows would be heavily obscured by the torus and essentially undetectable. Only a small fraction of them may be observed in the LOS occasionally passing through gaps between clumpy clouds in the torus or at a grazing angle up to the surface of the torus. Therefore, the deficiency of disk-feeding inflows of confirmed detection in quasars may be due to serious observational bias. Although they are hidden by the dusty torus in most of quasars, massive disk-feeding inflows are an indispensable component for the paradigm of quasar black hole accretion since quasars would be extinct without enough fuels. Doppler redshifted hydrogen Paschen emission lines in infrared, if detected by penetrating the dusty torus, might reveal the global properties of the disk-feeding inflows.

MULTIBAND OBSERVATIONS OF INFLOWS

Direct detections of disk-feeding inflows shed new light on the most fundamental questions on quasars. For the redshifted H I and He I* BAL quasars, when backtracking along the accretion flow, it is expected to detect redshifted molecular absorption lines in radio and infrared, such as these from the CO, OH, and HCN. These lines may arise from the headstream of the disk-feeding inflows, where the temperature and ionization of the absorbing gas is lower. Such observations can help to address the question of how the host galaxies determine the activity of central SMBHs in the coevolution of galaxies and black holes. On the other end at the downstream of the disk-feeding inflow, where the temperature and ionization would be much higher, it is expected to detect high-ionization BALs in UV and X-ray, such as those from the C IV, N V, O VI, and H- and He-like O and Fe ions. The absorption lines are expected to have extremely large redshifts, probably up to a fraction of the speed of light. Such observations are important to explore the geometry, dynamics, and physical conditions of the accretion flows in the immediate vicinity of the SMBHs and possibly are also applicable to test the general relativity in the extremely strong gravitational fields.

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ACKNOWLEDGMENTS

This work was supported by the Natural Science Foundation of Shanghai (grant nos. 20ZR1463400, 20ZR1473600, and 22ZR1481200).

DECLARATION OF INTERESTS

The authors declare no competing interests.