

The Glowing Abyss: Quasars, Accretion, and the Early Universe



Artist's rendering of quasar P172+18, Credit:ESO/M. Kornmesser

In the unfathomable depths of the cosmos, far beyond the reach of ordinary telescopes and the boundaries of familiar time, lie some of the most mysterious and powerful objects ever discovered: quasars. They are cosmic contradictions; they emit dazzling light, yet their brilliance stems from the darkest objects in space, supermassive black holes at the hearts of galaxies. When quasars were first discovered in the early 1960s, they looked like stars at first glance, concealing their true nature. In reality, gas is caught in the black hole's great gravitational grip, whirling around and rubbing against other gas to attain tremendous temperatures, lighting up intensely before plunging into the abyss. These celestial titans are not stars, but rather incandescent signals from the youth of the universe, brilliant lighthouses that outshine entire galaxies and serve as windows into the deepest puzzles of existence.

THE ENGINES OF THE EARLY COSMOS



Image of Quasar 3C 273, Credit: ESA/Hubble & NASA

Quasars- a portmanteau for "quasi-stellar radio sources" are the incredibly luminous cores of distant active galaxies. Because the central engine of a quasar is minuscule on a cosmic scale, it appears as a mere point of light, or "star-like",

through optical telescopes. However, this point source is deceiving. The nearest quasar, 3C 273, boasts a luminosity of 2.5×10^{40} watts, shining roughly 25 trillion times brighter than our Sun. Astronomers quantify the immense distances of these objects using cosmological redshift (z), defined mathematically as:

$$z = \frac{(\lambda_{\text{obs}} - \lambda_{\text{rest}})}{\lambda_{\text{rest}}}$$

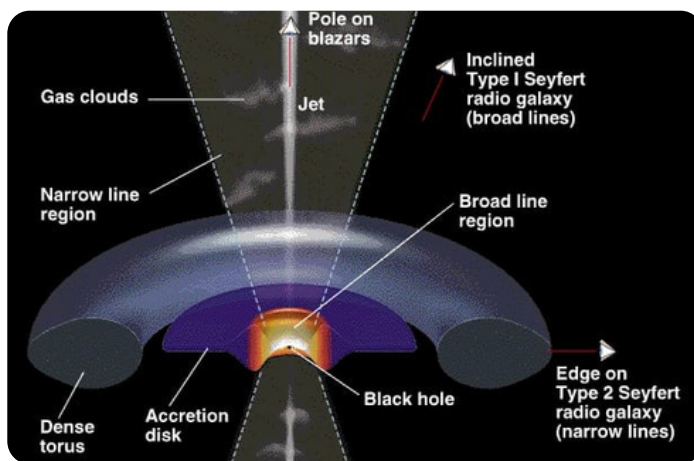
where λ_{obs} is the observed wavelength and λ_{rest} is the emitted wavelength. When astronomer Maarten Schmidt analyzed 3C 273 in 1963, he discovered a redshift of $z=0.158$, proving the object was abnormally distant and luminous, fundamentally shifting our understanding of the universe's scale.

THE MECHANICS OF A GLOWING ABYSS

To truly comprehend a quasar, one must look at the gravitational monster powering it: a supermassive black hole boasting a mass millions to tens of billions of times that of our Sun. A quasar is simply the spectacular manifestation of this black hole actively feeding. As illustrated in the accompanying diagram, this extreme engine consists of several interconnected structures:

- **The Accretion Disk:** As giant clouds of molecular gas fall toward the black hole, they queue up, forming a flattened, spiraling accretion disk.
- **Thermal Radiation:** The inner parts of this gas cloud orbit the black hole at velocities ranging from 10% to over 80% the speed of light. Friction heats the gas to millions of degrees, causing it to emit dazzling amounts of light.
- **Relativistic Jets:** Powerful magnetic fields entwine with the spinning black hole to funnel a portion of the material away, creating highly luminous, magnetically collimated jets.

To understand the physical limits of this energy output and growth, astrophysicists rely on the Eddington limit. This limit represents the point at which the radiation pressure pushing outward from the infalling material balances the gravitational



A diagram of a Quasar: Wadsworth Publishing force pulling it inward. In simpler terms, it is the fastest rate at which a black hole can eat without blowing away its own food supply. This mathematical boundary is defined as

$$L_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_p c}{\sigma_T}$$

where M_{BH} is the mass of the black hole, m_p is the mass of the proton, σ_T is the Thomson scattering cross-section, π , G , and c are the usual constants.

At this limit, black holes can grow steadily, but not quickly. Sustaining this cosmic object is not a simple process, because as infalling matter is converted into radiation, the resulting photons exert pressure that can impede additional gas from falling into the black hole.

AWAKENING THE GIANTS: COSMIC ORIGINS



Artist's rendering of ULAS J1120+0641, $z=7.085$: ESO
The genesis of quasars poses one of modern cosmology's greatest paradoxes. When observing quasars at extreme redshifts ($z > 6$), we are seeing the universe as it was less than a billion years after the Big Bang. Yet, these early quasars already contained black holes weighing billions of solar masses.

Finding such massive objects so early in cosmic

history completely defies standard expectations.

According to standard accretion models bound by the Eddington limit, growing a stellar seed to a billion solar masses requires nearly a billion years, the entire age of the universe at those redshifts. Regarding the 1.6-billion-solar-mass black hole found in quasar J0313-1806, astronomer Feige Wang emphasizes the gravity of the paradox: "This discovery basically puts a very extreme constraint on the black hole growing scenario. That's why it's special."

Astrophysicists now theorize these giants may have bypassed standard limits through "super-Eddington" accretion, or perhaps they were born massive, collapsing directly from pristine gas clouds in the early universe.

SHAPING GALACTIC EVOLUTION

Quasars are active sculptors of their host galaxies. The tremendous radiation pouring out of an active quasar generates a phenomenon known as 'feedback.'

This feedback drives powerful outflows of ionized gas via intense radiation winds. These winds have contradictory effects: as they expand, they can compress molecular gas clouds together, triggering gigantic bursts of rapid star formation. Conversely, the immense thermal energy can heat the interstellar medium so much that it becomes too energetic to collapse or expel the gas entirely, starving the galaxy of star-forming fuel for hundreds of millions of years.



Artist's Concept of a quasar's Radiation Winds
Credits: NASA, ESA and J. Olmsted (STScI)

THE MYSTERIES AND THE WAY AHEAD

Compounding the rapid growth paradox are recent spectral analyses of quasar proximity zones, regions where the quasar's ultraviolet radiation has ionized the intergalactic hydrogen fog. Observations of ultra-distant quasars reveal shockingly small proximity zones, implying active lifetimes of $t_Q < 10^6$ years and sometimes mere thousands of years. Measurements using extended Lyman-alpha ($\text{Ly}\alpha$) nebular emission confirm these incredibly short lifespans, proving these supermassive black holes just "woke up." The agonizing question remains: how can a celestial engine that has only been active for a cosmological blink of an eye already host a black hole weighing a billion suns?

Since their perplexing discovery in the late 1950s as radio anomalies, quasars have continually redefined our cosmic boundaries and forced us to confront these exact types of impossibilities.

The sheer power of these objects was initially almost impossible for the scientific community to accept; upon realizing the true nature of what they were seeing in 1960, radio astronomer John Bolton wrote in a letter to a colleague:

"I thought we had a star. It is not a star.. The absolute photographic magnitude is -24, which is two magnitudes greater than anything known."

From the nearest quasar (3C 273) to the most distant (J0313-1806, seen as it was 13.13 billion years ago), these engines push the absolute limits of observational astrophysics. As instruments like the James Webb Space Telescope and the Extremely Large Telescope look deeper into the dark dawn of the universe, these ancient lighthouses will undoubtedly illuminate the fundamental physical laws of creation itself.

"The night I discovered the quasar redshift, it was a fantastic prospect. We could now easily get to very large redshifts, because these darn things are so bright."

~Maarten Schmidt, discoverer of the first quasar redshift

-Written by Arnav Jain