Investigating Quasar Quenching of Star Formation via AGN-Driven Outflows

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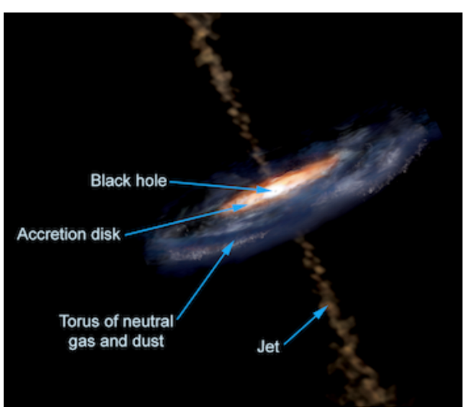
Black holes have long fascinated astrophysicists due to their gravitational light-trapping capabilities. Yet, quasars, a captivating counterpart to black holes, have emerged as a recent focus. These complex celestial entities represent actively growing black holes, characterized by their emission of powerful material and energy outflows spanning immense distances. By using the IRAM PdBI radio telescope, researchers discovered exceptional outflow in the host galaxy of the quasar J1148+5251 at $z = 6.4189$. They observed the [C II] (158 µm) emission line with broad wings, tracing a quasar-driven massive outflow. A congruent study looked into the "Observational evidence of quasar feedback quenching star Formation" where the outflow and presence of the quasar 2QZJ002830.4-281706 was concluded to have a negative impact on star formation. The dual implication of these studies has a profound influence of outflow and velocity dispersion supporting the process of quenching, which halts star formation by depleting galactic gases of energy, velocity, and heat. The AGN (Active Galactic Nucleus) feedback mechanism associated with these quasars is suggested to be responsible for cleansing the gas in the host galaxies, leading to the quenching of star formation within a remarkably short timeframe.

Relationship between quasars and stellar formations



Quasars are characterized by broad spectral lines due to the rapid motion of gas clouds orbiting the center. They manifest their dynamic nature through vigorous outflows powered by the accretion of material and energy.[1]

Figure 1: This illustration above shows the different features of an active galactic nucleus (AGN). The extreme luminosity of an AGN is powered by accretion onto a supermassive black hole. Some

[1] https://www.youtube.com/watch?v=V4Z8EdiJxgk&t=100s

AGN have jets, while others don't possess this feature (Credit: Aurore Simonnet, Sontoma State University)[2]

Recent advancements in observational tools, propelled by the James Webb Space Telescope (JWST), have opened new avenues for quasar analysis, facilitating exploration into their pivotal role in the evolution of galaxies.

Recently, Xuheng Ding (2023)and his international team delved into the dynamics of two specific quasars, HSC J2236+0032 and HSC J2255+0251, using the JWST to detect their emissions. The two quasars were originally discovered by the Subaru Telescope's wide-field camera, but now "The Subaru HSC survey has been quite successful in finding more than 160 quasars in the early universe"[3] according to Dr. Masafusa Onoue, a key member of the research team. The powerful combination of the Subaru Telescope and JWST, viewing quasars at redshifts of 6.40 and 6.34, has offered a unique glimpse into the early universe, a mere 860 million years post-Big Bang. Currently, in this discovery of quasars at further distances, much is inquired about whether host galaxies control the growth of their black holes or whether the black holes dictate the growth of the host galaxies[4]. This idea inquires on the relationships between star formation and a quasar's presence. To resolve these questions, Dr. Rebecca J. Smethurst (2020) in her video titled "Galaxies can die?!", discusses how these relationships between star formation and AGN feedback have resulted in a two-dimensional graph where the process of quenching can exist externally or internally and either quickly or slowly .

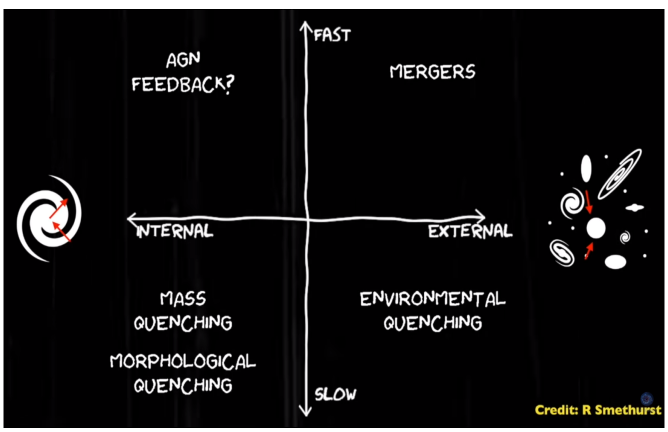


Figure 2: AGN feedback, as an internal effect, results in the fast acting quenching of stars (above). [5]

[2] https://sites.google.com/view/sources-quasars/

[3] https://subarutelescope.org/en/news/topics/2023/06/28/3281.html#:~:text=%22The%20Subaru%20HSC%20survey%20has,area%20and%20the%20deep%20imaging.

[4] https://subarutelescope.org/en/news/topics/2023/06/28/3281.html#:~:text=Last%20updated%3A%20August%201%2C%202023,years%20after%20the%20Big%20Bang.

[5] https://www.youtube.com/watch?v=pD6D3u7g_cA&ab_channel=Dr.Becky

Quasar influence and AGN feedback

The consequential phenomenon, the quenching of star formation, results from the AGN driven outflows. Dr.Rebecca, addresses this phenomenon by reporting how since the black hole isn't an “endless hoover.. that eats as much material as it wants to”, when the accretion disk becomes overloaded, it triggers an outflow of material, releasing a significant amount of energy. This energy can either heat up the surrounding environment or expel the gas necessary for star formation. Consequently, this process leads to a reduction in energy, velocity, and thermal characteristics within the galactic gas. The intricate interplay of these processes, driven by AGN feedback, underscores the rapid attenuation of star formation, deepening the concept of galactic cleansing.

The implications of this concept offers a valuable lens through which the intricate interrelationships between quasars, massive black holes, and their host galaxies can be studied. On the topic of AGN feedback, recent studies conducted by Maiolino(2012) and his colleagues have proposed a similar significant insight into the phenomenon of AGN feedback. In their work titled "Evidence of strong quasar feedback in the early Universe", the researchers propose that the outflow generated by these quasars effectively cleanses the gas in the host galaxy, leading to the rapid cessation of star formation within a relatively short period. These observations provide concrete evidence supporting the hypothesis that quasars possess a substantial role in shaping the evolutionary trajectory of galaxies, specifically by curbing star formation.

Telescope and Instrument Choice

Delving into observations for AGN feedback, in his study titled "Observational evidence of quasar feedback quenching star formation at high redshift," Cano-Díaz (2012) undertakes an in-depth analysis of quasar outflow by employing the Chilean ground based telescope, VLT-SINFONI, at near-IR integral field spectra of the quasar 2QZJ002830.4-281706. This quasar, located at a redshift of $z = 2.401$, was selected from the sample of robust [OIII]λ5007 emitters discovered by Shemmer et al. (2004). The selection of the VLT-SINFONI instrument stemmed from its remarkable sensitivity and unparalleled resolution prowess, elevating it as an indispensable choice for conducting optical and infrared observations. Additionally, with the near infrared integral field spectrograph SPIFFI (SPectrograph for Infrared Faint Field

Imaging),[6] SINFONI covers the near-infrared wavelength range of approximately 1.0 to 2.45 micrometers (μm). The telescope offers different spectral resolution modes of 2000, 3000, 4000, and 1500 in J, H, K, and H+K respectively. Based on these qualities, it specializes in studying high-redshift objects by resolving combined H and K near-infrared bands, enabling the capture of faint and distant sources. The SINFONI field of view on the sky is sliced into 32 slitlets, leading to a field of views on the sky of 8" 8" , 3" 3" and 0.8" 0.8" respectively. Each one of the 32 slitlets is imaged onto 64 pixels of the detector. Thus, the telescope obtains 3264 = 2048 spectra of the imaged region of the sky. In regard to the sensitivity of SINFONI, limiting magnitudes[7] are characterized at around a 17 - 18 mag in J, H, and K.[8]

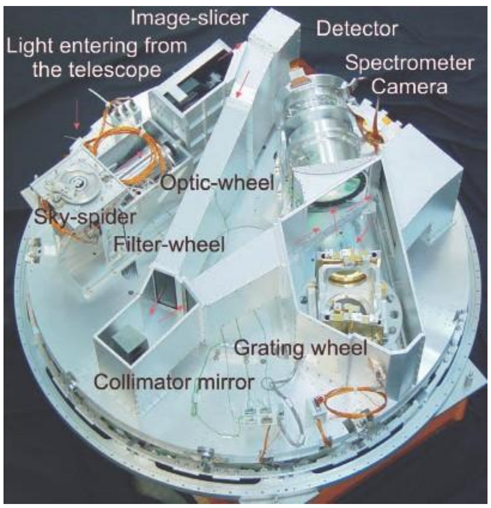


Figure 3[9]: An inside view of SPIFFI tailored to support the SINFONI (SINgle Faint Object Near-IR Investigation) facility. Light enters from the top, and passes the sky-spider. The diameter of the instrument is 1.3 m and the image slicer rearranges the two dimensional field into a pseudo-long slit, which allows three diamond turned mirrors to collimate the light on one of the four gratings.

Figure 3 shows the opto-mechanical components of SPIFFI, which are also cooled in a bath cryostat to the temperature of liquid nitrogen[10]. The choice of using VLT-SINFONI was also influenced by its ability to precisely detect the [OIII]λ5007 emission line, vital for understanding the gas kinematics in the quasar's surroundings. The instrument's integral field spectroscopy feature allowed scientists to obtain spatially resolved spectra revealing important insights into the interaction between the outflow and the galactic disk. By analyzing the kinematics of [OIII]λ5007, the Cano-Díaz study reveals a suppression of Hα emission within the region characterized by the strongest outflow, a phenomenon likely to hinder star formation. Researchers additionally estimated that the outflow rate of ionized gas is about 200 M yr −1, which is, however, a lower limit of the total gas outflow

[6] https://arxiv.org/pdf/astro-ph/0306191
[7] Limiting magnitudes and not a signal-to-noise ratio (SNR) was utilized.
[8] http://www.eso.org/sci/facilities/paranal/instruments/sinfoni/doc/VLT-MAN-ESO-14700-3517_v101.1.pdf
[9] https://www.eso.org/sci/publications/messenger/archive/no.113-sep03/messenger-no113-2-9.pdf
[10] https://www.eso.org/sci/publications/messenger/archive/no.113-sep03/messenger-no113-2-9.pdf

rate. Both the high outflow velocity (>1000 km s−1) and the fact that the wind is mostly traced by the [OIII] line strongly suggest that the outflow is mostly driven by the quasar. This paper will expound further on the logical chain of inference developed to comprehend outflow velocities influencing stellar birth.

Logical Chain of Inference: Application of outflow velocity and emission lines

To get the logical chain of inference in deciphering how energetic outflows from quasars influence star formation, a step by step process must be formulated to investigate AGN feedback.

As a starting point in our solar system, when observing the Sun, astrophysicists can identify specific emission lines in the solar spectrum where by scrutinizing these lines, scientists gain insights into the Sun's composition, temperature, and dynamic processes occurring on its surface. These lines result from the interaction of sunlight with various elements in the Sun's outer layers, such as hydrogen and helium, allowing for the study of phenomena like solar winds.

Bridging this understanding to the broader astronomical perspective of the milky way, astronomers employ spectroscopy, a technique that splits the light from the stars into its component colors or spectra, in spectrometer devices that are often attached to telescopes to capture the spectra of distant celestial objects.

Venturing far beyond our own galaxy, Pupil-Tracking systems have been integrated into the SINFONI telescope, enhancing its suitability for pinpointing faint quasars. This is achieved by employing Spectral Angular Differential Imaging (S-ADI) [11], allowing for simultaneous imaging and spectroscopy of faint companion sources. In the analysis of quasars, these techniques are coupled with the essential step of cross-referencing observed lines with databases containing known atomic and molecular transitions. This process aids in the identification of the specific chemical elements or molecules contributing to the emission.

Astronomers recognize quasars as exceptionally brilliant objects that emit and absorb light at distinct wavelengths corresponding to transitions of elements within their surrounding gas. Due to the notable brightness and the substantial energy generated through the quasar's accretion process, it becomes feasible to capture its spectrum—a procedure that entails dispersing the object's light into its constituent colors. The accretion generated energy manifests in diverse forms, encompassing a spectrum of wavelengths, X-rays, and even particle jets.

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[11] http://www.eso.org/sci/facilities/paranal/instruments/sinfoni/doc/VLT-MAN-ESO-14700-3517_v101.1.pdf

Driven by this energetic force, the collective impact of radiation pressure within the gas near the quasar's core leads to a notable outflow of gas from this region[12]. This departing gas is propelled to high velocities due to the force exerted by radiation pressure.

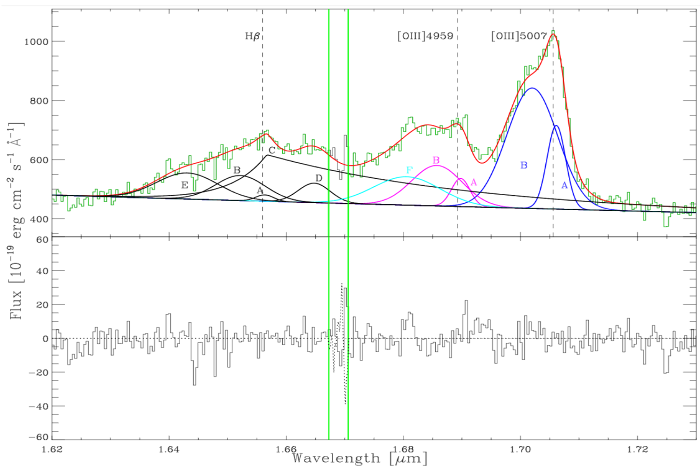

Figure 4: To the left is an image showing the observation of 2QZ0028-28 in the H and K bands, where the hydrogen lines are redshifted, suggesting high velocity dispersion of the quasar. The integrated emission of the narrow Hα yields star formation that is heavily suppressed in the SE region, which is characterized by the excess of outflow with high-velocity dispersion. (credit: Cano-Díaz, M. *et al.* (2012))

Based on figure 4, spectroscopic observations of the quasar's spectrum reveal that these lines are shifted from their expected positions due to the Doppler effect caused by the motion of the gas. High-velocity outflows result in blue-shifted absorption lines and red-shifted emission lines in the spectrum. The blue shift indicates that the gas is moving towards us, and the red shift indicates that it's moving away from us.

Logical chain of inference: Quasar feedback based on velocity dispersion and outflows

Emphasizing the significance of the strong outflow, particular attention is directed towards the south east region exhibiting the highest velocity dispersion, as illustrated in Figure 5 (below (right)). (The region in the figure is positioned to be where the potent outflow interacts with the host galaxy disk.)

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[12] Refer back to end of **Relationship between quasars and stellar formations** for the mechanics of triggered outflow

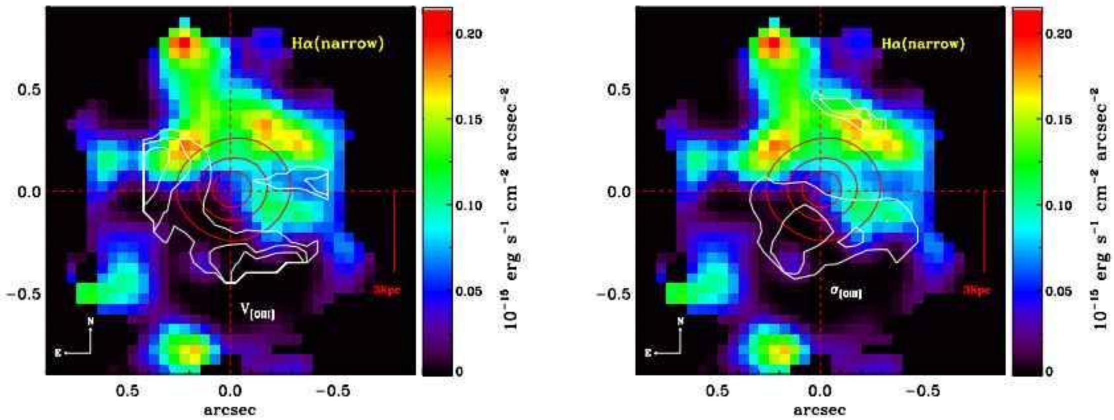

Figure 5: The narrow component of Hα depicts velocity shift (left panel) and velocity dispersion (right panel). From this representation, star formation, traced by Hα, is heavily suppressed in the SE region where the strongest outflow is traced by [OIII]. (Credit: Cano-Díaz, M. *et al.* (2012))

The pronounced suppression of star formation observed in the region with the strongest quasar-driven outflow provides compelling evidence for the presence of quasar feedback mechanisms at play. The investigation by Cano-Díaz (2012) sheds light on the intricate interplay between quasar activity, outflows, and their impact on the star-forming properties of the host galaxy.

In continuation of the logical chain of inference, the high velocities associated with these outflows are far beyond what is typically observed in normal galaxies or non-active regions of galaxies. (Figure 5) The integrated emission of the narrow Hα yields a total star formation rate in the host galaxy of about 100 M yr^-1 (by using the conversion factor given in Kennicutt 1998), which is not unusual in high-z quasars (e.g. Lutz et al. 2008). However, as previously mentioned, the most interesting result is that the star formation is heavily suppressed in the SE region.

Line	Component	Fitting function	λ_{obs} (μm)	*FWHM* (km s^{-1})	Flux (10^{-16} erg cm^{-2} s^{-1})	Velocity[1] (km s^{-1})
[OIII]5007	A	Gaussian	1.7061	652	10.9 ± 0.56	92
	B	Gaussian	1.7020	1797	43.6 ± 2.3	–663
Hβ	A	Gaussian	1.6564	652	0.79 ± 0.66	92
	B	Gaussian	1.6522	1797	8.8 ± 3.6	–663
	C	Broken Power Law	1.6567	5508	57.9 ± 4.6	156
	D	Gaussian	1.6648	1150	4.4 ± 2.9	1622
	E	Gaussian	1.6431	2243	11.3 ± 0.26	–2306.6
No ID	F	Gaussian	1.6806	2378	13.18 ± 2.3	–
Hα	A*	Gaussian	2.2361	616	1.9 ± 0.3	20
	B	Gaussian	2.2310	1797	9.3 ± 3.5	–663
	G	Gaussian	2.2391	3386	73.7 ± 5.5	422
	H	Gaussian	2.2478	9717	220.8 ± 10.4	1588
[NII]6584	A*	Gaussian	2.2433[1]	616[1]	<0.4	7[2]
	B	Gaussian	2.2382	1797	1.7 ± 1.5	–663

Figure 6: The names of the components correspond to those shown in Figure 4. The velocities of the components are obtained by assuming the peak of [OIII]λ5007 as a rest frame reference. For this [NII] line, the width and velocity were forced to estimate the upper limit to the values found for the corresponding A* component in Hα.

Utilizing figure 6 as an aid to calculate the outflow velocities, it is clear that the observations with the theoretical predictions of quasar behavior further confirms the computation of the outflow velocities. Furthermore, the previous emission lines can be fitted with multiple Gaussians and, in the case of the broad lines, power-law profiles. In figure 6, The initial spectral fit is performed on a spectrum, showing the Hα profile (dominated by the broad component, tracing the BLR (Broad line region)) being clearly different from the Hβ profile, which is a property that is common to many AGNs that ascribe to complex radiative transfer within the dense gas of the BLR. Because the velocity dispersion map is very noisy (Figure 5), Astrophysicists used the best-fit velocity and FWHM of component A* of Hα, which are similar to component A of [OIII]. This further suggests that the latter component of [OIII] is partly contributed by the ionized gas in the star-forming regions traced by the narrow Hα. Because values of Hα are different from [OIII]5007, the inferred FA*Hα/FA[OIII]~ 0.17, at the verge of the range typically observed in star-forming galaxies, indicates that the flux of component A of [OIII] is not incompatible with being partly originated by star formation but probably a contribution by the AGN NLR (Narrow-Line Region),[13] thus complementing the idea of AGN driven outflows imparting on star formation in some positive or negative regard.

Future Implications and current limitations

The analysis and figures of the observational data unequivocally demonstrate the presence of narrow Hα emission, leading to a significant suppression of star formation within the Southeast (SE) region where the strongest outflow is detected. This crucial observational finding provides substantial support to future theoretical models that invoke quasar feedback as a

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13 https://web.kamihq.com/web/viewer.html?source=extension_pdfhandler&extension_handler=webrequest_1_autoload_true_user_20780415&file=https%3A%2F%2Fwww.aanda.org%2Farticles%2Faa%2Fpdf%2F2012%2F01%2Faa18358-11.pdf&referer=https%3A%2F%2Fwww.aanda.org%2Farticles%2Faa%2Ffull_html%2F2012%2F01%2Faa18358-11%2Faa18358-11.html

predominant mechanism, eventually reinforcing the role of quasar feedback as a regulator of galaxy evolution in the early universe.

High outflow velocity, often exceeding 1000 km/s, is associated with the [OIII] emission line and is indicative of activity within the Narrow-Line Region (NLR). This provides compelling evidence that these outflows are predominantly driven by the quasar's energetic processes. These ideas are revolutionary but given the limited information available, astronomers can not fully elaborate on sophisticated models determining outflow velocities. To determine the high outflow velocities, the Cano-Díaz (2011) study assumed a simple scenario in their calculations where the outflow is assumed by a simplified conical (or biconical) dispersion distributed out to a radius R_{kpc} (in units of kpc).

$$\dot{M}_{\rm ion}^{\rm out} = 164 \frac{L_{44}([\rm OIII])\, v_3}{n_{e3}\, 10^{[\rm O/H]}\, R_{\rm kpc}}\, M_\odot\ {\rm yr}^{-1}$$

Figure 7. Size of the outflow rate based on geometry given above where v is the outflow velocity.

[14]Hopefully, these equations are yet to be remodeled, but because outflows produce intriguing asymmetry in regions of the quasar's nucleus, there should also be further investigation into the underlying mechanisms that fuel this directional preference in the future .

Direct observational evidence that quasar driven outflows quench star formation in their host galaxies is still lacking but as the trajectory of future research unfolds, detection of this phenomena will be possible based on upgrades from telescopes like JWST or SINFONI operating at higher redshifts. With direct detection being absent, the angular resolution of our data also does not allow us to map the kinematics of the outflow.[15] Nevertheless, new higher angular resolution observations will allow astronomers to better constrain the kinematics. For example, based on the Frank Eisenhauer (2000) proposal, the SPIFFI optical system will be configured to accommodate gratings with a resolution of up to 10,000, which could potentially be improved and be incorporated into future enhancements of SPIFFI. In the J, H, and K bands, the spectrometer will offer greater spectral resolution of approximately 4,000, ensuring in-depth kinematic investigations and more accurate astronomical observations in the future while simultaneously providing effective suppression of atmospheric emission lines associated with OH molecules.

[14] https://academic.oup.com/mnrasl/article/425/1/L66/1015004
[15] https://academic.oup.com/mnrasl/article/425/1/L66/1015004

Currently, theoretical physicists are convinced that we need AGN feedback in simulations to match the observational studies of outflow quenching star formation[16], but only indirect observations that were not statistically significant have been measured. Delving into future implications, AGN feedback will hopefully be studied across millions of galaxies, solidifying the specific mechanisms responsible for energetic large-scale outflows and potentially digging deeper into the positive aspects of AGN feedback based on the compression of gas in the outer regions of a galactic system.

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