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How quasars and galaxies get to know each other

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Before the last years of the past Millennium there was no clear evidence of a possible connection between the formation of galaxies and quasars (objects whose luminosity is powered by gravitational accretion onto a super-massive black hole). The paper by Silk and Rees in 1998 put forward for the first time the idea that the evolutionary tracks of these two types of cosmic objects were not independent and that actually quasars and their host galaxies mutually influence each other through a series of so-called feedback (or *self-regulation*) processes. This proposal was certainly stimulated by puzzling observations, described below, that were hard to understand without the premises introduced by the paper. The study is a textbook example of how the complexity of a natural phenomenon recorded in experimental data can be interpreted and clarified by the astonishingly simple and yet profound beauty of a one-line formula, i.e. Eq. (1) of the paper. This formula essentially expresses the relationship between the mass of the super-massive black hole and that of the galactic spheroid hosting it. This is one of the most important formulas in modern cosmology, and the physical idea behind it will be discussed later on. The work was first presented at the 13th IAP Astrophysics Colloquium in Paris in July 1997. While listening to Prof. Silk describe the paper's results, I got the clear perception that this apparently simple idea would change the field forever, and indeed it did so.

Sparse evidence of a possible connection between quasars and galaxies was already present before 1998. For example, it was already clear that, rather than being permanent but rare phenomena, quasars are short-lived phenomena occurring in a large fraction of galaxies (if not all of them). If so, the most promising sites to search for quasar remnants are the high-density central regions of giant galaxies where the high concentrations of matter would make formation of super-massive black holes more probable. Hints in that direction came from the work of Faber's group in October 1996 (Faber et al. 1997). They showed that luminous, "hot" (a proxy for spiral bulges) galaxies have a core whose origin was most likely explained by the action of a central black hole erasing the central density cusp. It was also tentatively argued that the BH mass per spheroid was a fixed fraction of the stellar mass of the core, thus providing the first link between the galaxy and the central black-hole mass.

The year 1997, blessed by landmark IAU Symposia in Kyoto where the results were first presented, witnessed the final burgeoning of experimental data, with two (and perhaps more) independent groups coming to similar, albeit different, conclusions (Magorrian et al. 1998; Ford et al. 1998). In short, the main idea behind these experiments, made possible by the aberration-corrected *Hubble Space Telescope*, was to measure the motions of stars and gas with great precision within the influence region (50–100 pc) of the central black hole, thereby determining the rise of the gravitational potential associated with the compact object. The sub-arcsecond resolution required by the experiment was previously not achievable from the ground and had to wait for space telescopes like HST. Although these observations made clear that most galaxies indeed host a (dormant) black hole in their centers, a vigorous debate was concentrated on the quantity to which the black-hole mass, $M_\bullet$, was correlated. While one group found no clear evidence of a correlation with the spheroid luminosity, the other one showed that indeed $M_\bullet$ was correlating with the spheroid mass according to the linear scaling $M_\bullet = 0.002\, M_{\rm sph}$. However, few ideas were available to explain this evidence prior to the paper by Silk and Rees.

In addition, an associated problem needed to be addressed in the same context. During those years quasars powered by super-massive ($M_\bullet > 10^8\, M_\odot$) black holes beyond redshift $z = 4$ were already known (the record-holding quasar today having $z = 6.4$, Fan et al. 2003). This evidence posed the problem of the rapid build-up of these objects from available seeds. Such black holes could have formed from the merging of smaller black holes left over by the death of massive Pop III stars (Madau & Rees 2001); alternatively, their seed could have formed via the homologous collapse of giant, pristine gas clouds (Loeb & Rasio 1994). Both mechanisms have their own weaknesses. The first must postulate the presence of massive stars and might require too long a dynamical timescale to coagulate small black holes into a super-massive one in galactic mergings. The latter requires a UV background-induced suppression of molecular hydrogen that could lead to a fragmentation of the cloud before it reaches substantial densities leading to runaway collapse into a compact object. Like today, this question has not yet received a final answer, although a large set of scientific papers has been produced on the subject, most likely stimulated by the importance of the question that is central to the Silk and Rees scenario. The authors favored this second channel for black-hole formation in the center of galaxies and started from there to explore the growth of the black hole seed fed by material brought in by galaxy mergings and regulated by a wind driven by quasar luminosity.

Once the above hypothesis is made, the physical understanding of the observed relation between black-hole and spheroid mass in galaxies becomes crystal clear. The basic physics of the idea is the following. Suppose that a black hole is present at the center of a spheroid whose stellar velocity dispersion is equal to σ. The *self-regulation* idea proposed in their paper states that the upper limit to the black-hole mass growth is determined by its ability to accelerate the mass accreted on a dynamical timescale to the galactic escape velocity (approximately equal to σ^2) by momentum transfer from its own radiation, emitted at some fraction of the Eddington luminosity, L_E. Stated mathematically, this is equivalent to requiring that $(\mathrm{d}M/\mathrm{d}t)|_{\rm acc}\sigma^2 = L_E \propto M_\bullet$. A larger black hole would have enough luminosity to expel the entire gas content from the host galaxy thus suppressing its own fuel delivery. The natural mass accretion rate for such an object is equal to the Jeans mass divided by the free-fall time, which can be shown to be $(\mathrm{d}M/\mathrm{d}t)|_{\rm acc} \propto \sigma^3$, and it follows that $M_\bullet \propto \sigma^5$. This fundamental relation is detailed in Eq. (1) of the paper and it represents the backbone of the scientific idea.

The above finding has profound implications for the evolution of quasars and galaxies. After the Silk and Rees paper such objects could no longer be studied separately, but a new term, *quasar-galaxy co-evolution*, has been coined to signal that galaxy mergings provide fuel to the quasar, which feeds back by possibly "quenching" the star formation activity, thus regulating the properties of the host galaxy. This amazing implication of the one-line formula in Eq. (1) helps for solving the following serious difficulty faced by the standard hierarchical LCDM models. It is well known that more massive galaxies tend to be predominantly spheroid-dominated, with red colors, old stellar populations, low gas fractions, and little recent star formation, while low-mass galaxies tend to be disk-dominated and gas-rich, with blue colors and ongoing star formation. Also, the transition from star-forming disks to "dead" spheroids occurs rather sharply at a characteristic stellar mass of about $3\times10^{10}\,M_\odot$. If – as suggested by Silk and Rees – the most massive galaxies, where quenching is observed to be the most efficient, host the largest black holes, then the puzzle can be solved. Additional implications of this scenario currently being investigated concern the interpretation of the fundamental plane of elliptical galaxies, the origin of the quasar luminosity function, and its evolution over cosmic history; finally, quasar winds represent an alternative mechanism to disperse the nucleosynthetic products of stellar evolution in the intergalactic medium.

Of course, a full and detailed comprehension of such quasar feedback is yet to come, due to the very complex and difficult physics of accretion and radiation hydro-dynamics involved. This has by no means prevented theorists from including this effect at least in a phenomenological manner in their cosmological galaxy formation models and numerical simulations. Many works have explored different flavors of the idea, showing the profound intellectual influence exerted by that simple one-line formula hiding a whole new vision of the way in which the Universe has grown to the diversity we observe today.

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