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Star formation in QSO host galaxies ☆

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Abstract

Many of the conditions that are necessary for starbursts appear to be important in the triggering of QSOs. However, it is still debatable whether starbursts are ubiquitously present in galaxies harboring QSOs. In this paper we review our current knowledge from observations of the role of starbursts in different types of QSOs. Post-starburst stellar populations are potentially present in a majority of QSO hosts. QSOs with far-infrared colors similar to those of ultraluminous infrared galaxies invariably reside in merging galaxies that have interaction-induced starbursts of a few hundred Myr or less. Similar, but dramatically more luminous post-starburst populations are found in the recently discovered class of QSOs known as post-starburst QSOs, or Q + A's. Both of these classes, however, comprise only a small fraction (10–15%) of the total QSO population. The so-called ''red'' QSOs generally suffer from strong extinction at optical wavelengths, making them ideal candidates for the study of hosts. Their stellar populations typically show a post-starburst component as well, though with a larger range of ages. Finally, optical ''classical'' QSO hosts show traces of major star formation episodes (typically involving >10% of the mass of the stellar component) in the more distant past (1–2 Gyr). These starbursts appear to be linked to past merger events. It remains to be determined whether these mergers were also responsible for triggering the QSO activity that we observe today.

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Contents

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1. Introduction

The relationship between mergers, starbursts, and active galactic nuclei (AGN) has long since been the subject of vigorous research. It is clear that at least some of the ingredients necessary to trigger starbursts are also necessary to trigger AGN: both phenomena require fuel, and both require that this fuel be somehow displaced from one point to another, whether to replenish the material in the accretion disk, or to compress it resulting in enhanced star formation. There is also evidence that mergers are important to both phenomena, although the precise role that they play is still debatable. The high incidence of mergers in starburst galaxies (Sanders and Mirabel, 1996, and references therein) might indicate that mergers are indeed necessary to trigger massive starbursts, but they are not sufficient, since mergers often result in only moderately enhanced star formation (e.g., Bergvall et al., 2003). Mergers have, on the other hand, only been shown to be required to trigger nuclear activity in far-infrared (FIR) loud QSOs (Canalizo and Stockton, 2001), and are certainly not sufficient, as can be seen from the relatively low incidence of AGN in any catalog of interacting galaxies.

What are the additional ingredients necessary to trigger starbursts and AGN? Are these ingredients common to both phenomena? We already know that starbursts can exist in the absence of AGN, as has been found in the case of many ultraluminous infrared galaxies (at least at the lower luminosity end; e.g., Sanders and Mirabel, 1996). In these proceedings, we address the question of whether the converse is true, i.e., whether it is possible to trigger a high luminosity AGN (specifically a QSO) without triggering also a starburst. In the following sections, we review our current knowledge of star formation in different kinds of QSOs. For the purposes of this discussion, we have grouped QSOs into four classes according to some of their observational characteristics rather than their intrinsic properties.

2. Starbursts in QSO hosts

2.1. Color-selected FIR QSOs

One hypothesis that clearly ties in merger-induced star formation with QSO activity is that of Sanders et al. (1998), who suggest that ultraluminous infrared galaxies (ULIRGs) play a dominant role in the formation of all QSOs. According to this hypothesis, ULIRGs are the result of strong interactions or mergers which funnel gaseous material into the central regions of galaxies, thus fueling intense star formation and the QSO activity. ULIRGs are then dust-enshrouded QSOs which, after blowing away the dust, become classical QSOs.

We have tested this hypothesis through a systematic imaging and spectroscopic study of host galaxies of low-redshift QSOs found in a region of the far-infrared (FIR) two-color diagram between the region where most QSOs lie and the region occupied by ULIRGs (Canalizo and Stockton, 2001, and references therein). These objects are presumably in some transition stage between the ULIRG and "normal" QSO phases. Spectra were obtained of the host galaxies and/or strongly interacting companions for all QSOs in the sample with the Keck low-resolution imaging spectrometer (LRIS). We obtained ages for the starburst or post-starburst component in different regions of each host galaxy using the procedure illustrated by Fig. 1. Using these data along with *HST* and ground-based images, we constructed detailed star-formation and interaction histories for each of the objects in the sample.

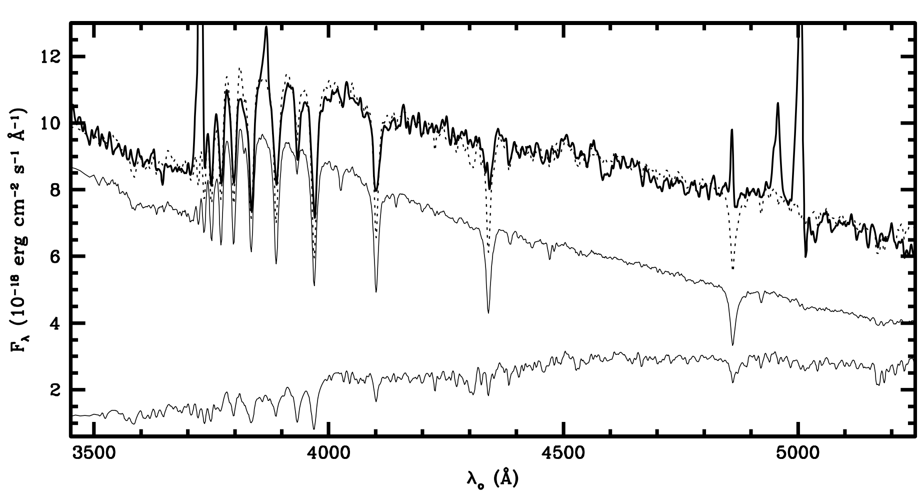

Fig. 1. Spectrum of the FIR QSO 3C 48 host galaxy in a region ~2″ E of the quasar (heavy solid line). This spectrum has been fitted with a Bruzual-Charlot model (dotted line) comprising a starburst component of weighted average age 5 Myr (upper light solid line) and an older component with exponentially decreasing star formation (e-folding time 5 Gyr; lower light solid line). The lower Balmer absorption lines are contaminated with emission and are not used in the fitting procedure; these and other emission lines are due, not to H II regions, but rather to extended emission photoionized by the quasar. The exposure totaled 3600 s with LRIS on Keck II through a 1″ slit. (From Canalizo and Stockton, 2000).

We found that every "transition" QSO is undergoing a strong tidal interaction, and most are major mergers where at least one of the parent galaxies was a disk galaxy. The spectra are characteristic of E + A galaxies, and are successfully modeled by an underlying old population (the stellar component present in the parent galaxies prior to interaction) plus a superposed instantaneous burst population (presumably resulting from the interaction). All of the hosts have very young starburst ages, ranging from ongoing star formation to ~300 Myr. By modeling spectra from many discrete regions across the hosts, we created velocity fields and age maps from the stellar populations. By comparing the starburst ages of the central stellar components with those of the more extended emission, we determined the relative ages between stellar populations in various regions of the host galaxies. These estimates, along with dynamical ages, place constraints on the timescale for concentrating material in the nucleus. The concentration of material is likely to have triggered the central strong starbursts and the QSO activity roughly simultaneously. The age of the peak starburst is, therefore, representative of the age of the QSO activity. To summarize, our study showed that the QSO and ULIRG phenomena are physically related in these transition objects, and firmly established that at least some QSOs can be traced back to a merger and a starburst phase.

Star formation in these QSOs is then, not only prominent, but clearly linked to the triggering of the QSO activity. However, these FIR QSOs may not be telling the story of the QSO population as a whole. By comparing the distribution of the ratio L_{IR}/L_{UV} for PG QSOs (Sanders et al., 1989) and for "transition" QSOs, we estimate that the transition sample is representative of ~7.5% of the optically selected PG QSO sample. While there are many uncertainties in this estimate (especially since the ratio may be more indicative of reddening than of intrinsic characteristics in the objects), it clearly shows that these objects are not representative of the majority of (at least optical) QSOs, but rather form a relatively small fraction of the population.

2.2. Post-starburst QSOs

The rare class of post-starburst quasars shows simultaneously an AGN and a massive luminous starburst of a few ×100 Myr old. Because of their composite spectra displaying broad emission lines as well as the Balmer jump and strong Balmer absorption lines characteristic of type-A stars, these QSOs are sometimes called "Q + A" objects. A striking case is UN J1025-0040 (Brotherton et al., 1999). The strong starburst component has an age of ~400 Myr, and a bolometric luminosity of $10^{11.6}$ $L_\odot$, equal to that of the quasar. A younger UN J1025-0040 (tens of Myr after the starburst) would have a more luminous stellar population and would likely be dust enshrouded, placing it in the ULIRG class. UN J1025-0040 has a nearby companion galaxy also in a post-starburst phase (Canalizo et al., 2000). The companion appears to be interacting with the quasar host galaxy, and this interaction may have triggered both the starburst and the quasar activity in UN J1025-0040. *HST* WFPC2 imaging (Brotherton et al., 2002) shows that the starburst is nuclear, the host resembles a merger remnant, and a less massive young starburst is also present.

The new large QSO surveys 2dF and SDSS are revealing post-starburst QSOs in significant numbers for the first time. We have spectroscopically selected post-starburst quasars in the SDSS data release 2 (DR2) using an automated algorithm based on one that Zabludoff et al. (1996) used to select post-starburst galaxies. We have found ~250 post-starburst quasars – roughly 5% of $z < 0.75$ QSOs – that show clear evidence for post-starburst stellar populations of significant luminosity/mass (Brotherton et al., in preparation). SDSS images show that about 40% of our objects appear to be close interacting doubles or have companions within 10″. Even most single sources show some extended fuzz from the host galaxy, and often features like tidal tails indicating merger activity. An *HST* Advanced Camera for Surveys (ACS) snapshot survey of these objects is currently underway and is already revealing a much higher rate of tidal interaction than can be inferred from the SDSS images. In Figs. 2 and 3 we show, respectively, the image and spectra of one of the SDSS QSOs with its companion, which appears to have a similar, though much less luminous, post-starburst population to that of the host.

Post-starburst QSOs represent the most dramatic cases of star formation in QSO host galaxies. However, they are only a small fraction of the total QSO population, and their relationship to other QSOs as well as to ULIRGs and E + A galaxies is currently unknown. We are conduct-

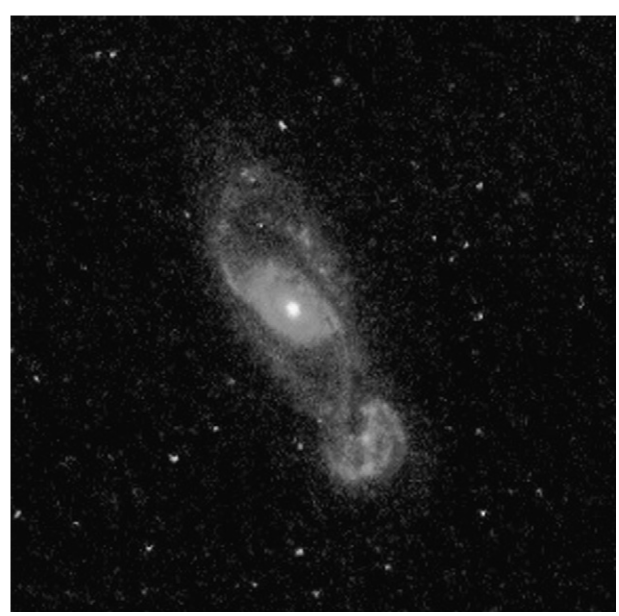

Fig. 2. *HST* ACS snapshot of the post-starburst QSO SDSS 231055-090107 and its interacting companion galaxy.

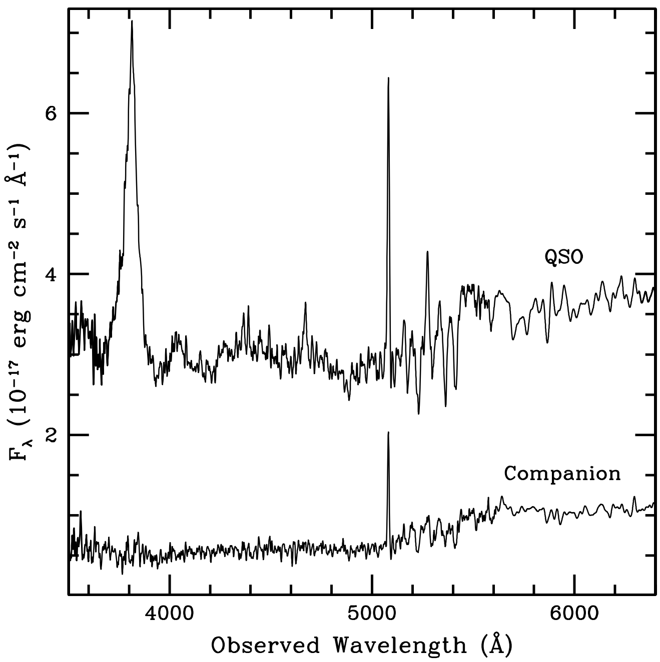

Fig. 3. Keck LRIS spectra of the post-starburst QSO SDSS 231055-090107 an its companion, showing that both have undergone dramatic episodes of star formation.

ing a comprehensive study including *HST* ACS (Fig. 2), Keck LRIS (Fig. 3), and Spitzer IRS observations that will help us determine the nature of this relationship.

2.3. Red QSOs

Another class of QSOs that is being uncovered with the advent of large area surveys at longer wavelengths, such as 2MASS and FIRST, is that of the so-called "red" QSOs. In general, these objects have some of the same characteristics as blue QSOs, such as (at least some of the) strong broad emission lines and high bolometric luminosities, but with much redder continua. At present, there is not a clear definition for red QSOs, so that the different objects that are catalogued as red QSOs do not form a homogeneous class. For example, in the sample of red QSOs drawn from the Parkes Half-Jansky Flat-radio-spectrum Sample (PHFS; Francis et al., 2001), the reddening is most likely due to red synchrotron emission. The majority of red QSOs discovered to date, however, appear to be reddened by dust, and thus they are considered the dust-obscured equivalent of the blue QSO population (e.g., Cutri et al., 2002; Marble et al., 2003; Hall et al., 2002; Glikman et al., 2004; White et al., 2003). Even then, there are cases where the dust is intervening rather than intrinsic to the QSO (e.g., Gregg et al., 2002). Here we focus on those objects where the dust is presumably near the nucleus.

The nature of red QSOs remains uncertain. There are two popular theories to explain why some quasars appear reddened by dust. The first uses an analogy with the Seyfert galaxy and radio galaxy/quasar orientation-based unified schemes in which whether the observer sees a type-1 (Seyfert-1, normal quasar) object or a type-2 (Seyfert-2, quasar-2) object depends on the angle at which the observer views the AGN. In this model, dust-reddened quasars are predicted to be objects viewed close to the transition angle between type-1 and type-2 which just scrapes the surface of a torus of gas and dust surrounding the AGN. The radio-loud red quasar 3C68.1 is thought to be at an angle to the line of sight between those of normal radio-loud lobe-dominated quasars and their fully obscured counterparts, radio galaxies (Brotherton et al., 1998). The second theory is that the dust which reddens the QSO is produced in young objects as a result of the starburst which follows the merger of two galaxies and which also triggers the QSO, once again as in the scenario of Sanders et al. (1998). Thus a red QSO phase might be expected at some point early in the life of most quasars.

In either case, the heavy extinction of the QSO nuclei at optical wavelengths makes red QSOs excellent candidates to study stellar populations in their host galaxies, yet this fact has remained largely unexploited. We have obtained Keck ESI spectra of 15 red QSOs from Marble et al. (2003) 2MASS sample; spectra of two of these objects are shown in Fig. 4. The spectra, which clearly show stellar absorption lines, have not been corrected for scattered QSO light, demonstrating that they suffer little contamination from the nucleus at wavelengths shorter than Hα.

Roughly half of the sample show strong post-starburst populations similar to those of post-starbursts QSOs. Of the remaining objects, most, if not all, show evidence for

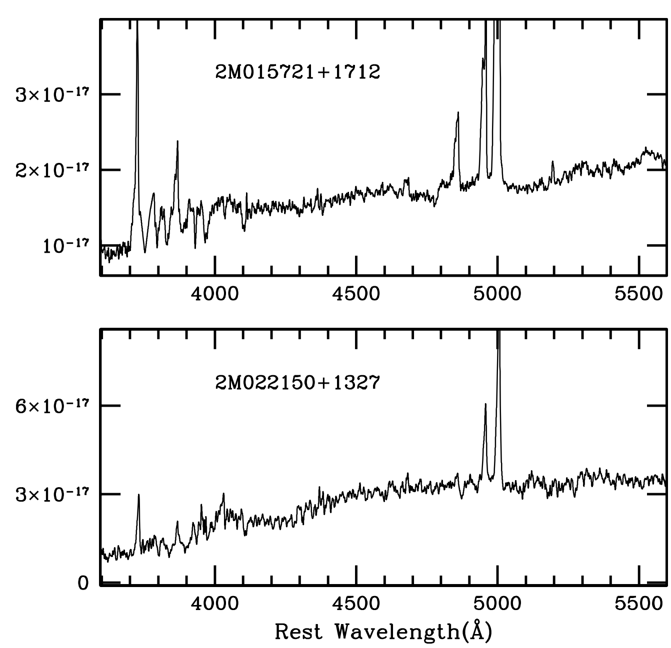

Fig. 4. Keck ESI spectra of red 2MASS QSOs. Although these objects show broad Hα emission characteristic of QSOs, the spectra of the host galaxies suffer little contamination from the QSO at shorter wavelengths. The spectra shown here have not been corrected for scattered QSO light to illustrate this point. The spectrum of 2M015721 + 1712 shows a post-starburst spectrum characteristic of post-starburst QSOs while that of 2M022150 + 1327 shows a somewhat older population.

relatively recent star formation. Thus it appears that starbursts also play an important role in these objects.

How common are red QSOs? Glikman et al. (2004) estimated that heavily dust-reddened QSOs comprise 20% of the total QSO population for $K < \sim 15.5$. Lacy et al. (2002) and White et al. (2003), among others, suggest that so far we have only detected the "tip of the red quasar iceberg", which could comprise up to several times the blue QSO population. As more surveys are published and selection methods are refined, estimates for the fraction of red QSOs are likely to become more accurate. This will have important consequences in areas ranging from galaxy evolution to cosmology and, for the current discussion, it will allow us to have better statistics on the number of QSO hosts that show young post-starburst populations.

2.4. Classical QSOs

We use the term "classical" here to describe any luminous optical QSO not covered by the first three classes of QSOs discussed above. Recent imaging studies have shown that the majority of low-redshift classical QSOs, whether radio-loud or radio-quiet, reside in the centers of galaxies that have relaxed light distributions like those of elliptical galaxies (e.g., Disney et al., 1995; Bahcall et al., 1997; Dunlop et al., 2003; Floyd et al., 2004).

Unlike the case of red QSOs, the study of stellar populations in classical QSO hosts is hampered by the difficulty of observing absorption line spectra in galaxies that tend to be overpowered by their bright nuclei. For this reason, there have been few spectroscopic studies that deal with star formation in these objects.

Dunlop et al. (2003, and references therein) carried out imaging and spectroscopy of a statistically-matched sample of radio galaxies, quasars, and radio-quiet QSOs at $z \sim 0.2$. They find that essentially all of the host galaxies having nuclei in the quasar luminosity range are bulges that have properties "indistinguishable from those of quiescent, evolved, low-redshift ellipticals of comparable mass." In particular, they suggest that these galaxies have truly old stellar populations with no episodes of massive star formation in the recent past.

Several other surveys of AGN host galaxies (e.g., Jahnke et al., 2004; Sanchez et al., 2004; Kauffmann et al., 2003) also indicate that galaxies hosting the most luminous AGN are most often bulge-dominated. However, all of these surveys find that the host colors are significantly bluer than those of inactive elliptical galaxies and they are consistent with the presence of intermediate age starbursts. Based on their position in the $D_n(4000)/\mathrm{H}\delta_A$ plane, Kauffmann et al. (2003) suggest that these AGN hosts have had significant bursts of star formation in the past 1–2 Gyr.

The objects studied in these surveys are on average $\sim$1 magnitude fainter than those in the Dunlop et al. sample. However, it is possible that the same signs of intermediate age starbursts may be present in the hosts of higher luminosity objects, but that they are simply more elusive due to the technical difficulties mentioned above. To investigate this possibility, we have obtained and modeled very deep ($\sim$2 h exposures) Keck LRIS spectra of 14 $z \sim 0.2$ classical QSO host galaxies in the Dunlop et al. sample that are dominated by spheroids. The surprising results are that we have found a starburst component in all but one of the host galaxies, and in the majority of objects we find traces of major starburst episodes involving >10% of the mass of the stellar component, with ages ranging from 0.6 Gyr to 2.2 Gyr (see Fig. 5). While there are uncertainties in the precise starburst age estimates due to metallicity, initial mass function, and the models themselves, the high signal-to-noise ratio of the spectra clearly show, in addition to an underlying very old component, a younger stellar component that is significantly older than a few $\times 10^8$ yr. This component cannot be mimicked either by a small amount of constant star formation or by one less dramatic and substantially younger starburst phase. In any case, our results show conclusively that the host galaxies of classical QSOs are *not* made up almost purely of ancient stellar populations.

Are these major starbursts episodes connected to a merger event? Elliptical hosts formed through mergers would be expected to show fine structure indicative of past tidal interactions. This tell-tale structure, which includes shells, ripples, and boxy isophotes, is commonly seen in nearby ellipticals and indicates that these early type galaxies were either formed or structurally modified by mergers in the not so distant past. Fine structure tends to persist even after the more overt signs of interaction have faded, and it is thought to be sensitive to the dynamical age of the merger (e.g., Schweizer et al., 1990; Sansom et al., 2000). These studies indicate that fine structure can in general be detected even a few Gyr after the last major merger event.

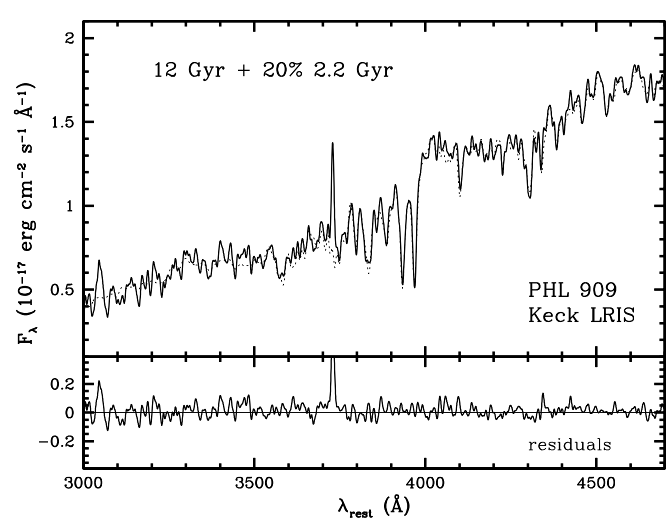

Fig. 5. Keck LRIS spectrum of the host galaxy of the classical QSO PHL 909 in rest frame (heavy line) and a χ^2 fit of a two-component model to the data (dotted line). The model is the sum of a 12 Gyr old population and a 2.2 Gyr instantaneous starburst model which comprises 20% of the mass of the total population. The bottom panel shows residuals of the fit.

We are obtaining very deep *HST* images of five of the host galaxies for which we have Keck spectra, using ACS with the F606W broad-V filter. The subsample was chosen to include those objects for which we have the most robust age determinations and that do not show emission lines in the host galaxy to avoid confusion in the interpretation of the imaging when using a broad filter. Three objects have been observed so far, and all three show signs of tidal interactions: one appears to be in a system of three or four interacting galaxies, while the other two show traces of past merger events. Fig. 6 shows a dramatic example of shell structure in one of the QSO hosts.

The results from both our Keck spectroscopic and *HST* imaging observations point toward the same conclusion: classical QSOs reside in host galaxies that have had a major tidal interaction and starburst episode within the last two or so billion years. But the question remains: Is there a connection between this catastrophic event in the past and the current nuclear activity? An oversimplistic interpretation assuming that the Gyr old merger triggered the QSO activity at that time implies a QSO duty cycle of more than a billion years, a result in stark contrast to current theoretical estimates (e.g., $(3–13) \times 10^7$ yr by Yu and Tremaine, 2002). The scenario may be more complicated, however. QSO activity may require, for example, a two-step process: first, collection of gas by a major merger, and then, triggering of the nuclear activity by other mechanisms such as a minor merger.

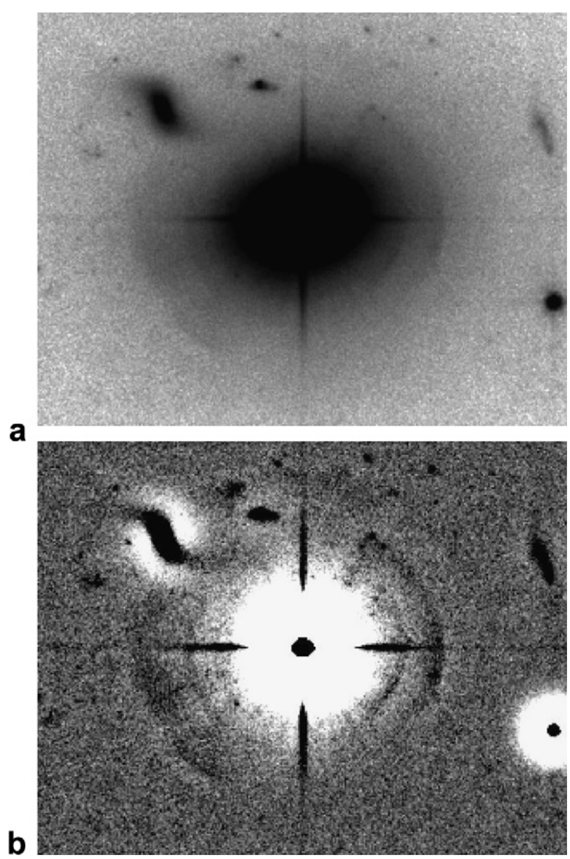

Fig. 6. *HST* ACS image of the $z \sim 0.2$ classical QSO MC2 1635 + 119 showing spectacular shell structure. The second panel shows unsharp-like masking to highlight the sharp features that make up the shells.

However, before we worry about these complex possibilities, a more fundamental question needs to be considered: are the host galaxies of classical QSOs truly distinct from typical inactive elliptical galaxies? In other words, if we were to study a sample of inactive ellipticals at $z \sim 0.2$ in the same depth, might we find similar shell structure and traces to major starburst episodes? A matching study of a control sample of elliptical galaxies in environments similar to those of QSOs and with similar effective radii is clearly necessary in order to answer these questions. Such a study would allow us to interpret our results in the proper context and determine once and for all whether classical QSOs reside in normal elliptical galaxies or not.

3. Summary

Although we are not yet able to answer the question of whether the triggering of a QSO is necessarily accompanied by the triggering of a starburst, we have strong hints that this may well be the case. Star formation plays a prominent role in three of the QSO classes we have discussed: FIR QSOs, Q + A's, and red QSOs. Most of these objects, as well as a small fraction of classical QSO hosts, show relatively young post-starburst populations of a few $\times 10^8$ yr. However, it is still unclear what fraction of all QSOs is represented by these objects. A conservative estimate would indicate that they form at least one-fourth of the total QSO population if we add 7.5% for FIR QSOs, 5% for Q + A's, and 20% for red QSOs, and allow for some overlap between these classifications. However, the fraction could be as high as 80% or more if the population of red QSOs proves to be as numerous as currently suspected (White et al., 2003). The rest of the QSO hosts appear to have traces of massive starbursts with ages $(1–2) \times 10^9$ yr. Whether these starburst episodes are linked to the event that triggered the nuclear activity remains to be established.

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