

The Host Galaxies of the Brightest Quasars: Gas-Rich Galaxies, Mergers, and Young Stars

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Because they are faint and hidden in the glare of a much brighter unresolved source, quasar host galaxies still challenge the most powerful telescopes, instrumentation and processing techniques. Determining their basic morphological parameters and their integrated colours is feasible, but difficult, from imaging alone. However, detailed information on their stellar and gas contents and on their dynamics is achievable with deep spectroscopy. We have completed such a deep spectroscopic study, with the VLT and FORS1 in MOS, for the host galaxies of 20 bright qua-

sars ($M_V < -23.5$). A new observational approach is implemented, based on spatial deconvolution and decomposition of the spectra. Our clean, deep, spectra of quasar host galaxies show that the brightest quasars reside in all types of galaxies, that their stellar populations are compatible with those of young discs, even when the host galaxy is an elliptical one. Most of the host galaxies show prominent gas emission lines, whose metallicity suggests a rather inefficient star formation. The source of ionisation of the gas is the quasar in 50 % of the objects. All these objects are undergoing interactions, suggesting that interactions play a major role in the ignition and fuelling of the brightest quasars.

Quasars are among the most luminous objects in the Universe. Powered by the accretion of matter falling onto a 10^7 – $10^{10} M_\odot$ supermassive black hole, they radiate at almost every wavelength of the electromagnetic spectrum, from γ -rays and X-rays to the radio domain. Although, at the time of their discovery, quasars were found to be point sources, it was soon realised that they were in fact located in the centre of much larger, but also much fainter, envelopes. The envelopes of the most nearby quasars extend over a few arcseconds, making it possible to obtain spectra of their external parts, even in moderate seeing conditions. Boroson et al. (1984) obtained the very first spectra of a small sample

of 'quasar envelopes', and demonstrated that they were made of gas and stars, and that they were at the same redshift as the quasars. These pioneering observations unambiguously established the connection between quasars and galaxies.

The huge quantities of luminous energy escaping from quasars immediately leads to questions about the properties of their host galaxies. Are quasar host galaxies normal galaxies? Are they more massive? Where does the matter fuelling the central black hole come from? What are the physical processes responsible for the ignition of a quasar and what is its life-time, if any typical value exists at all? The answers to these questions rely not only on accurate observations of quasars themselves, but also on the characterisation of their host galaxies. Most quasar host studies carried out over the last two decades concentrate on imaging and have led to the global picture that the most luminous quasars reside in large elliptical galaxies. The VLT spectroscopic observations described in this article support a different picture, where galaxies of all types can harbour bright quasars and where gravitational interactions between galaxies or even mergers, play a major role in the ignition and fuelling of quasars. This was suggested already by the discovery of binary quasars (e.g., Djorgovski et al. 1987, Meylan et al. 1990) but has never been investigated in detail for single quasars.

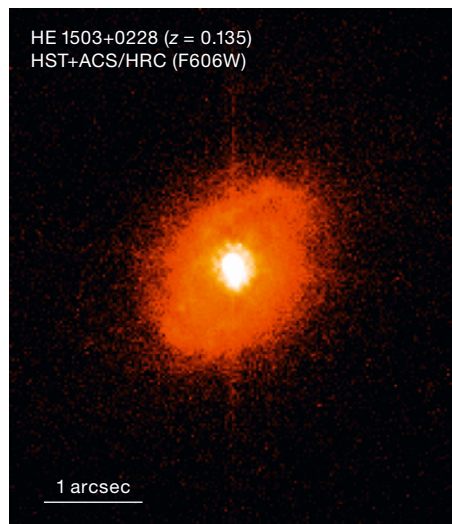


Figure 1: Example of an HST/ACS observation of a low-redshift quasar with its spiral host galaxy, HE 1503+0228, at $z = 0.135$. Even with the excellent resolution of the High-Resolution Channel of the ACS, the bright central quasar makes it difficult to see the internal parts of the galaxy. The image on the right has been spatially deconvolved and the quasar has been subtracted using the MCS deconvolution algorithm. The spiral arms are now obvious even in the centre of the galaxy, as well as the bulge of the galaxy (Letawe et al. 2006b).

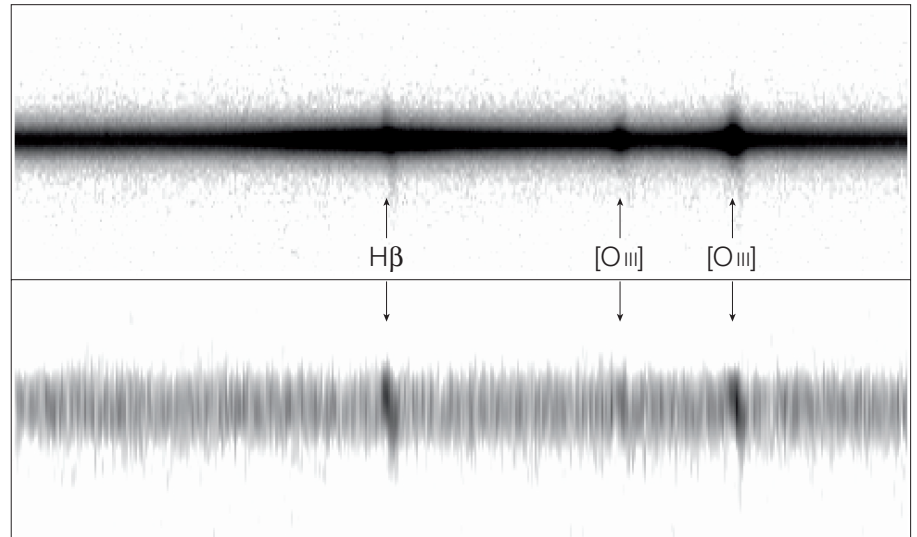
A VLT/FORS1 MOS study of quasar host galaxies

The high contrast between the central quasar and its host, and the small angular size of the host are the main limitations to a spectroscopic study. Quasar host galaxies are typically 2–3 magnitudes fainter than their central quasar. Their angular size is only a few arcseconds at low redshift ($z \sim 0.1$ – 0.3). Figure 1 gives an example of a spiral galaxy hosting a quasar. Even with excellent seeing or HST data, the observations remain challenging, because the wings of the observed PSF, even a few arcseconds away from the quasar, still strongly contaminate the data. Two observational strategies are then possible to minimise the mutual contamination of the quasar and host spectra: (1) to carry out ‘off-axis spectroscopy’, by placing the slit of the spectrograph a few arcseconds away from the quasar in the hope that less quasar light will contaminate the host galaxy, (2) to develop reliable decomposition techniques in order to separate the individual spectrum of the quasar from that of its host galaxy. We make the latter choice for our study, which considers ‘on-axis spectra’ of 20 bright quasars with the VLT and FORS1.

We adopt the Multi-Object-Spectroscopy mode (MOS) of FORS1 and devise a new observational strategy in which one of the 19-arcsecond-long slitlets is used to observe the quasar while the other slitlets are used to simultaneously observe field stars used as PSFs. The simultaneous observation of the object of scientific interest and of several PSF stars allows us to use the spectroscopic version of the ‘MCS deconvolution algorithm’ (Magain et al. 1998, Courbin et al. 2000), which takes advantage of the *spatial information* contained in the spectrum of PSF stars in order to carry out a *spatial deconvolution and decomposition of the spectra*. This strategy was already proposed by Courbin et al. (1999, 2002). It has now been used to decompose numerous VLT spectra of quasar hosts and of galaxies lensing distant quasars (e.g., Eigenbrod et al. 2006). Figures 2–3 give an example of our spectra decomposition, applied to a FORS1 spectrum of the $z = 0.23$ quasar HE 2345-2906. Both figures indicate no residual contamination of

Figure 2: Example of spectra decomposition for the $z = 0.23$ quasar HE 2345-2906, using the MCS deconvolution algorithm (Magain et al. 1998, Courbin et al. 2000). The top panel shows a portion of the original VLT/FORS1 spectrum, after reduction and sky subtraction. The bottom panel shows the spectrum of the host galaxy alone, after removal of

the quasar spectrum. The continuum and emission lines of the host can be followed even ‘underneath’ the quasar PSF. The height of the spectrum is 19 arcseconds. The seeing during the observations was 0.7 arcsecond and the spatial resolution after deconvolution is 0.2 arcsecond (Letawe et al. 2006a).



the host spectrum by that of the quasar. With a mean signal-to-noise of 10–20 per spectral resolution element, this spectrum allows us to measure several of the important Lick indices describing the stellar content of the galaxy. The prominent emission lines are used to infer the ISM gas metallicity as well as the ionisation source (stars versus central AGN) responsible for the measured emission line ratios. Curved emission lines are seen in the 2-D spectra of the host galaxy (Figure 2), making it possible to measure its velocity field.

The variety in quasar and quasar-host properties is such that many objects in our sample require slight modifications of the general techniques used to analyse the sample as a whole. While a few quasar hosts are in isolated spiral galaxies (e.g. HE 1503+0228; Courbin et al. 2002),

about 50% are undergoing interactions to the point that it is hard to even infer a morphological type. While the fraction of quasar hosts with gravitational interactions is about the same as for normal galaxies, we show with our data (see below) that the most powerful quasars are systematically in hosts with signs of interactions. In one extreme case, the host galaxy may have been even completely disrupted in a strong collision with a galaxy (HE 0450-2958; Magain et al. 2005; see also ESO Press release 23/05).

Aside from the extreme cases, our spectroscopic sample allows us to infer general characteristics of quasar hosts, as compared with their quiescent, non-AGN, counterpart. While the full analysis and interpretation are described in Letawe et al. (2006a), we summarise here the main conclusions.

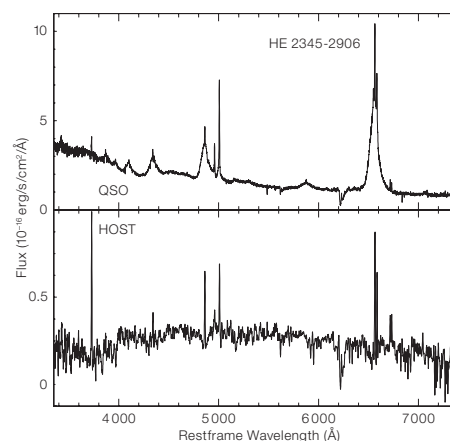


Figure 3: Integrated spectrum of HE 2345-2906. The top and bottom panels display respectively the spatially deconvolved quasar and host spectra, integrated in the spatial direction. Each spectrum is obtained by using the three FORS1 grisms G600B,R,I, ($R \sim 400$) in order to cover the full optical range. The spectra are displayed in the rest frame. Note the quasar broad emission lines, that are seen narrow in the host galaxy. The $H\alpha + NII$ (6565 Å) emission line is even resolved in the spectrum of the host, because of the lower circular velocity than in the quasar (Letawe et al. 2006a).

Stellar populations

Studies based on imaging only conclude that almost all of the most luminous quasars reside in massive elliptical galaxies (e.g., Floyd et al. 2004, based on HST imaging). We measure in our spectra the Mg2, H β and G4300 Lick indices, indicative of the stellar content of the galaxies. The results are plotted in Figure 4 along with the same measurements for two control samples of non-AGN galaxies. Most objects have stellar populations that compare well with late-type rather than early-type galaxies. Only two objects have stellar populations consistent with their early-type morphology. Quasar host galaxies show on average bluer colours than those of non-AGN galaxies, indicative of an additional underlying young stellar population (e.g., Jahnke et al. 2004) that might be explained by recent gravitational interactions. The majority of the objects we study here shows stellar populations inconsistent with normal inactive early-type galaxies or massive bulges, but rather shows spectral features more typical for young discs.

Gas ionisation and metallicity

Emission-line ratios are well-known indicators of the source of ionisation of the Interstellar Medium (ISM). We measure in Figure 5 the [O III]/H β ratio as a function of the [N II]/H α ratio for 14 quasar host galaxies that have significant narrow emission lines. These two ratios compare high and low ionisation lines, hence allowing us to discriminate between high-energy ionisation sources and sources of lower energy. Galaxies where the ISM is ionised by star formation are therefore located, in such a diagram, at a different place than the galaxies where the ISM is ionised by the central quasar. The result is striking: half of the galaxies show the signature of an ISM ionised by the quasar itself. All these are undergoing interactions. In addition, the line ratios in these objects indicate that even the gas located several kpc away from the centre of the quasar is ionised by the hard radiation field of the quasar. The objects are also the brightest of the sample, making it clear that interactions play a major role in the ignition and fuelling of

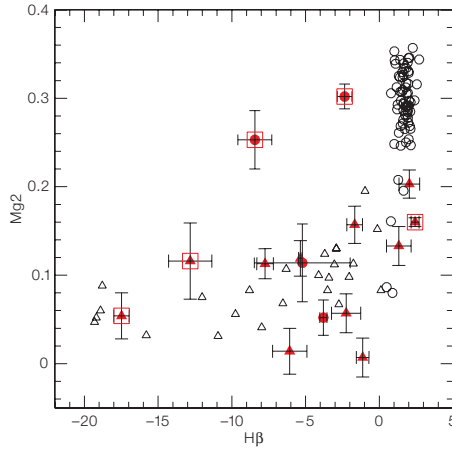


Figure 4: Lick Mg2 and H β indices for 14 of the quasar host galaxies (red symbols), compared with the non-active galaxies of Trager et al. (1998) and Kennicutt (1992). Circles stand for elliptical galaxies, while triangles indicate later-type galaxies. Red open squares indicate the objects that contain gas ionised by the central AGN itself. Our values of the Lick indices match well those measured for late-type galaxies. The only two objects that have metallicities compatible with elliptical galaxies are undergoing interactions (Letawe et al. 2006a).

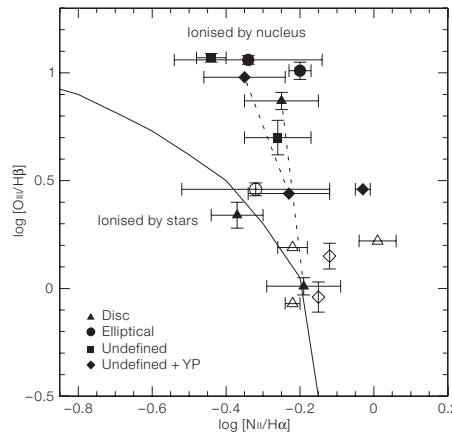


Figure 5: Emission-line ratios for 14 of the quasar host galaxies. The solid line indicates the limit between objects with an ISM ionised by star formation and the objects with an ISM ionised by the central quasar. Filled symbols represent objects with obvious signs of interactions, while open symbols are isolated objects. All objects with ionisation by the quasar are undergoing interactions. They also correspond to the brightest quasars. Measurements connected by a dashed line are for the same object but correspond to measurements in the central or external parts of the galaxy, where the ionisation is found to be respectively by stars or by the AGN (Letawe et al. 2006a).

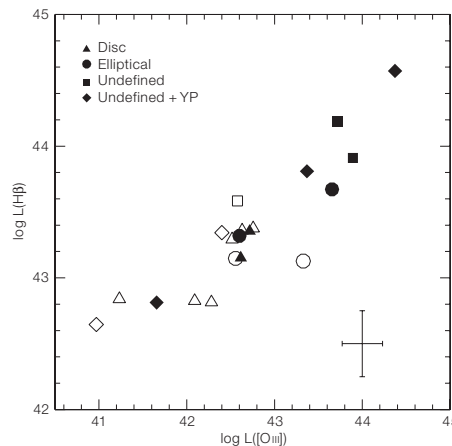


Figure 6: Luminosity of the quasar in the H β emission line (erg s^{-1}) as a function of its [O III] (5007 Å) luminosity. The typical 1- σ error bar is given in the lower right corner. The characteristics of the host galaxies are as stated in the legend, where open symbols represent isolated galaxies, and filled symbols are for galaxies that display signs of interactions. It is immediately seen that the quasars with the brightest emission lines tend to reside in interacting systems (Letawe et al. 2006a).

the brightest quasars. Figure 6 adds more support to this picture, by establishing a clear correlation between the luminosity of the central quasar in the emission lines, and the fact that the quasar resides in an interacting system. In Figure 6, all the bright quasars are undergoing interactions, while the faintest ones rather reside in disc-dominated galaxies. Isolated elliptical galaxies host only moderate-luminosity quasars.

When the source of ionisation of the ISM is stellar, it is possible to estimate the Star-Formation Rate (SFR) using the [OII] equivalent width. Although more objects would be needed to draw a definite conclusion, we note that three hosts out of four with confirmed elliptical morphology have significant [OII] emission, in contrast with non-AGN elliptical galaxies. In all the cases where it can be measured, the SFR is comparable to what is generally found in young discs.

The metallicity of the gas traces how galaxies have evolved. The hosts of our sample have a mean $\log(O/H)+12$ of about 8.4, i.e., in the low part of the metallicity distribution of spiral galaxies (see Figure 7). Only two galaxies have a gas metallicity well compatible with the mean value of 8.8, typical for spirals. This suggests that star formation has been rather inefficient, and that the ignition of the quasar activity might therefore be related to an early stage of evolution of their host. Note, however, that a statistically more significant sample is necessary to confirm this trend, as we have selected the objects where we are sure that the gas is ionised by star formation, i.e., a subsample dominated by a young stellar population.

Dynamics

The spectral resolution of the data is sufficient to derive rough velocity information on the host galaxies, as can be noticed already from Figure 2. This information is valuable, not only in estimating the total mass of the galaxies when unperturbed rotation is seen, but also to unveil signs of interactions. Indeed, all objects that show irregular or even distorted shapes on the VLT acquisition images, also have disturbed velocity curves, hence confirm-

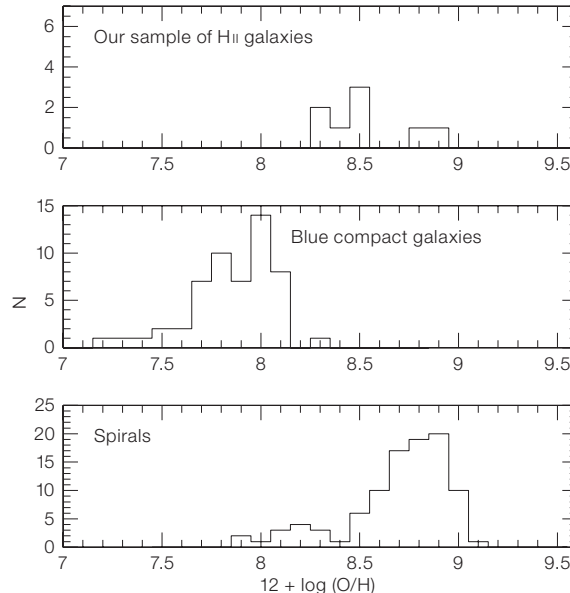


Figure 7: Gas metallicities of the quasar host galaxies (top), and of two samples of metal-poor blue compact galaxies (middle panel), and metal-rich galaxies (bottom). Although our sample is dominated by discs/spirals, their metallicity remains low compared with normal spirals, suggestive of a low efficiency of star formation (Letawe et al. 2006a).

ing the presence of interactions. When the host is a spiral galaxy, we fit a three-component velocity model including a central point mass, a rotating disc, and a dark matter halo. The masses we compute in that way are in the range $10^{11} - 3 \cdot 10^{12} M_{\odot}$, integrated over a 10-kpc aperture, i.e., in good agreement with the masses of normal, non-AGN galaxies.

Not all symmetrical velocity curves can be adequately fitted by three-component models, and other structures in the quasar host galaxies are found to mimic rotating discs when observed at such small angular sizes. The case of HE 1434-1600 is a good example, where highly ionised gas displaying a velocity field that can be mistakenly interpreted as circular motion, is in fact distributed in shell-like structures along the slit. However, accurate fit of the velocity curve allows us to rule out circular rotation (Letawe et al. 2004), as confirmed by HST imaging that unveils the details of the gas distribution in the host. Figure 8 shows an HST/ACS image that we have obtained for HE 1434-1600. The host galaxy of this quasar is classified as an elliptical galaxy using ground-based imaging. The HST image immediately confirms shell structures. By combining these data with 3D spectra, as can be obtained with ARGUS (Figure 9), it will be possible to decide whether the shells are expanding away from the central quasar or whether they are residual material left in the host's ISM after an encounter

with a neighbour. Indeed, the companion galaxy seen in the HST image is at the same redshift as the quasar. It is however already apparent from the FORS1 spectra and from the HST images that interactions are or have been present during the history of this elliptical galaxy.

On the role of interactions in quasar formation

Accurate image-processing techniques combined with deep slit spectroscopy yields a wealth of information that makes it possible to unveil connections between the physical properties of quasars and of their host galaxies.

We find that bright quasars do not exclusively reside in large elliptical galaxies. Half of the galaxies in our sample show stellar populations typical of young discs.

A second striking result is that most of the host galaxies, including the ellipticals, contain large amounts of gas. This gas has probably been brought into the ISM through gravitational interactions. Indeed, the brightest quasars are *systematically* in interacting systems, independent of their morphological type, when a morphological type can be determined at all.

In all galaxies with interactions, the gas is ionised by the central AGN rather than by star formation, even several kpc away

from the quasar. This remains true for quasars that have large reddening values, hence ruling out the possibility that bright quasars are seen brighter because the dust in their host has been destroyed during mergers or encounters.

Finally, we find that quasars that reside in non-interacting galaxies appear to be in metal-poor but gas-rich spiral galaxies. These galaxies harbour the less luminous quasars.

The general picture drawn from our study is that the brightest quasars are clearly related to gravitational interactions or even mergers between several galaxies. Aside from the clear case of the brightest quasars, the fainter quasars might form in the early stage of formation of their host galaxy, which are all metal-poor, i.e., galaxies where star formation has been rather inefficient so far. While we find very large amounts of gas in the latter galaxies, it is not clear what mechanism brings the gas to their central AGN. The mechanisms involved are probably more 'local' than global mergers or interacting systems, e.g., the explosion of supernovae, gravitational instabilities or bar-driven fuelling. It will be interesting in the future to investigate the correlation between quasar luminosity and the presence of bars in the host galaxy.

On the technical side, our study shows that clean, deep, multi-slit spectroscopy is a powerful way to characterise high-contrast objects such as quasar host galaxies. While integral-field spectroscopy is useful in order to map the ionisation state of the gas across the galaxy and to measure the velocity field of the gas, obtaining deep continuum spectra remains only accessible to slit spectra in MOS. In addition to be much more sensitive, slit spectrographs and their MOS capability provide easy access to the PSF information mandatory to the removal of the central quasar. There is therefore a strong complementarity between 3D and slit spectroscopy as far as quasar host galaxies are concerned. The general trends unveiled by the present 20-object sample call for a more systematic study including, e.g., all known bright low-redshift quasars and Seyfert galaxies.

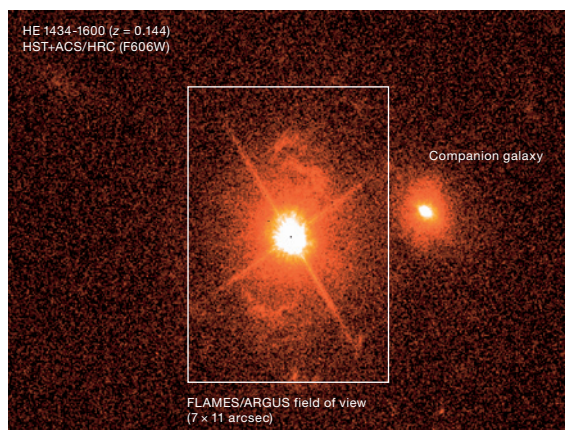


Figure 8: HST image of the $z = 0.144$ quasar HE 1434-1600. The image has been taken through the F606W filter, using the High-Resolution Channel of the Advanced Camera for Surveys onboard the HST. The slit of our FORS1 spectrum is about vertical in this image. The FLAMES/ARGUS field of view is also indicated. Note the obvious shell-like structures that may expand away from the quasar. The companion galaxy to HE 1434-1600 is at the same redshift and is in gravitational interaction with the quasar and its host galaxy (Letawe et al. 2004).

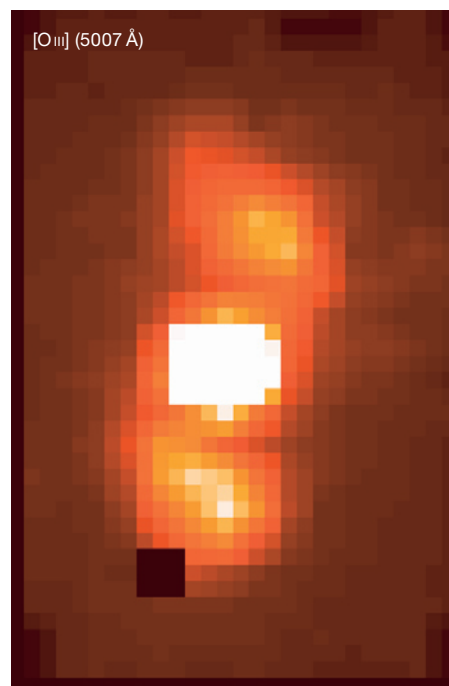
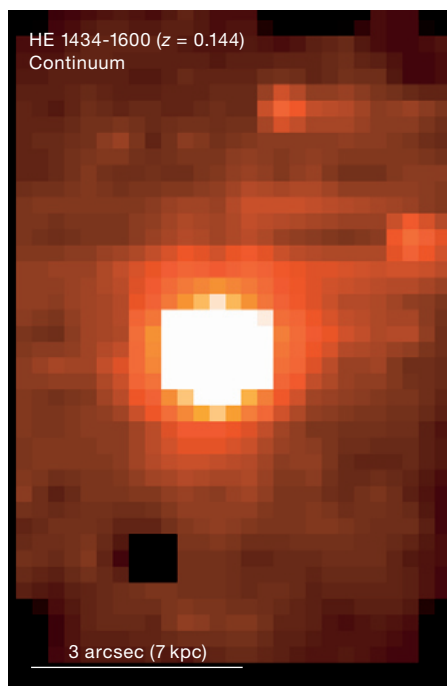


Figure 9: ARGUS quasi-monochromatic images of the $z = 0.144$ quasar HE 1434-1600. The fibre size in this image is 0.25 arcsecond, after subsampling of the original data (which have 0.5 arcsecond fibres). The seeing was 0.6 arcsecond during the observations. The images display the two spectral regions centred on the [O III] (5007 Å) emission line (right) and on a continuum region (left) with the same wavelength coverage. These data allow us to trace the gas across the galaxy and to determine its ionisation state from the central kpc to the outer parts. However, the stellar continuum remains only accessible to slit spectra, hence pointing to the complementarity between the two techniques.

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