X-shooter Spectroscopy of Massive Stars in the Local Group and Beyond

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Combined with the collecting power of the Very Large Telescope, X-shooter is the most sensitive medium-resolution spectrograph currently in operation, allowing us to perform quantitative spectroscopy of objects that, up to now, were deemed too faint. In addition, with its unique wavelength coverage, X-shooter provides access to an unprecedentedly large number of diagnostic lines. We review our recent work on massive stars in Local Group dwarf galaxies and in NGC 55, an irregular galaxy in the foreground of the Sculptor Group. The observations were obtained as part of the ESO Science Verification Programme and the NOVA–Dutch Guaranteed Time Observation Programme. The aim is to investigate the evolutionary status of high-mass stars in various environments and to test the theory of radiation-driven stellar winds at metallicities below that of the Small Magellanic Cloud.

Massive stars are linked to a wide variety of astrophysical processes and phenomena. Their intense radiation fields, strong stellar winds and violent supernova explosions stir the ambient interstellar medium, which is typically a site of star formation. Their explosions produce the neutron stars and black holes that are used to test extreme physics and general relativity. Massive stars affect the dynamical evolution of the star clusters in which they reside and are thought to play a crucial role in the formation and evolution of galaxies. They are also the candidate first stars, anticipated to have reionised the Universe some few hundred million years after the Big Bang. Given their importance for various fields of astrophysics, a clear understanding of the formation and evolution of massive stars is essential.

At optical and near-infrared wavelengths massive stars emerge from their natal clouds typically within the first million years after formation, such that a census of their masses, rotation rates and multiplicity characteristics may provide important insight into the end product of the star formation process. A detailed understanding of their evolution further requires the identification and analysis of stars in various evolutionary phases up to the pre-supernova stage, thus deriving evolutionary connections between these phases. Comparisons between observations and stellar evolution models must be done for stars in different chemical environments as the ratios of stars in different phases (e.g., that of O to Wolf–Rayet stars), as well as the ratio of Type Ib/c to Type II supernovae, are found to be metallicity dependent. With most long-duration gamma-ray bursts occurring at low metallicity and the anticipated role played by massive stars in the early Universe, including its re-ionisation and galaxy formation, it is particularly interesting to study massive stars in low metallicity environments.

These considerations have motivated the study of massive stars in the Large and Small Magellanic Clouds (LMC and SMC respectively). Massive OB, Luminous Blue Variable (LBV) and Wolf–Rayet (WR) stars in the Magellanic Clouds have been studied intensively in the past decade (e.g., Mokiem et al., 2007; Evans et al., 2008). One important result that has emerged from these studies is that the rate of gas outflow driven by radiation pressure on spectral lines is both predicted and found to be metallicity, Z, dependent in a range from $Z_\odot$ to 0.2 $Z_\odot$. This mass-loss rate *versus* metallicity dependence is expected to play an important role in explaining the observed frequencies of different evolutionary phases and of supernova types.

With the latest generation of 8–10-metre-class telescopes, massive stars in more distant galaxies can now be individually resolved, allowing us to probe a wider span in environmental properties, albeit so far mostly at low spectral resolution ($R \sim 2000$) and within the Local Group (e.g., Bresolin et al., 2007). Although quite a number of exciting objects have been identified, detailed quantitative spectroscopic analyses of the most massive stars have remained cumbersome for obvious reasons: low signal-to-noise ratio and/or modest spectral resolution complicate (or prevent) the removal of nebular emission, among other corrections. Besides enabling a better nebular subtraction, the higher spectral resolution offered by X-shooter allows a more accurate surface temperature, gravity and mass-loss determination. It also allows for the analysis of weak metallic lines, crucial to derive abundances and accurate projected rotational velocities. These quantities are the key to establish and characterise the evolutionary stages of massive stars and their feedback. Here we report on the first analyses of massive star mass loss at sub-SMC metallicity, which appears to contradict our expectations.

Mass loss at low metallicity

The gas outflow of hot massive stars is driven by radiation pressure on metallic ions in the star's atmosphere, and consequently its strength is predicted to scale with metallicity ($\dot{M} \propto Z^{0.69 \pm 0.10}$; Vink et al., 2001). This prediction has been verified for massive stars in the Galaxy and in the Magellanic Clouds observed in the VLT–Flames Survey of Massive Stars (Evans et al., 2008), where the empirical relation $\dot{M} \propto Z^{0.78 \pm 0.17}$ was found (Mokiem et al., 2007). The theory has, however, never been tested at sub-SMC metallicity. Because the evolution of massive stars is greatly influenced by the amount of mass and angular momentum lost through their strong stellar winds, determining the wind strength was one of the main goals of our quantitative spectroscopic analysis.

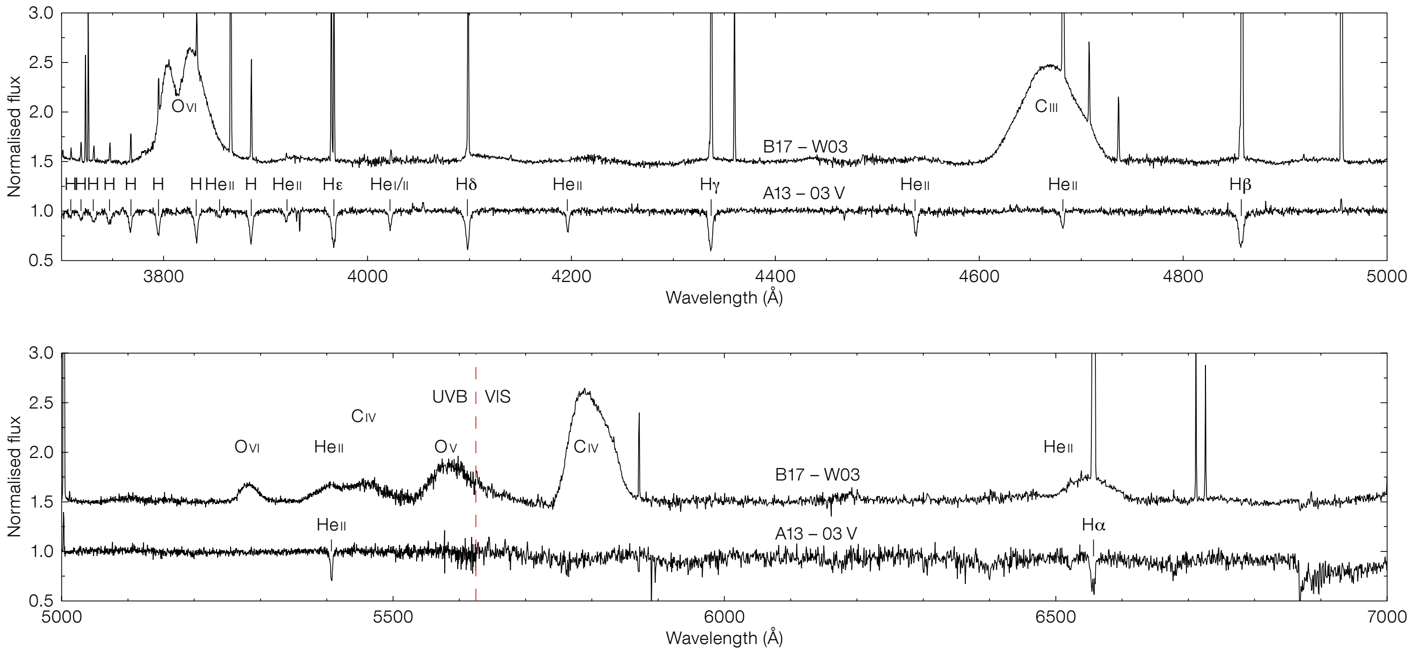
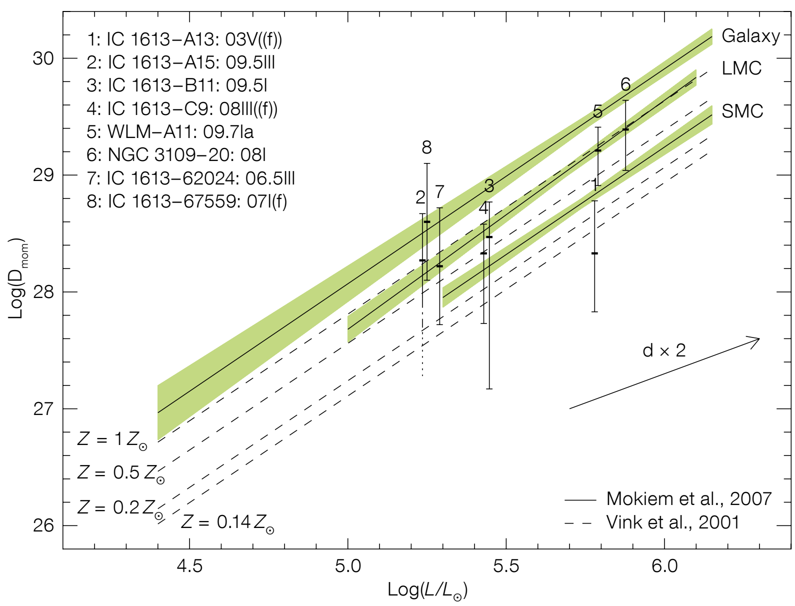


Figure 1 (above). Part of the X-shooter normalised spectra of two sources in IC 1613 are shown: A13 (O3V, lower spectrum in the two panels) and B17 (WO3, upper spectrum in the two panels). The WO spectrum has been reduced in flux by a factor of five and shifted to fit the panel. The main spectral lines are labelled. The vertical dashed line marks the transition between the UVB and VIS arms of X-shooter.

The Local Group dwarf galaxies IC 1613, the Wolf–Lundmark–Melotte (WLM) galaxy and NGC 3109 are ideally suited to probe the properties of massive stars in low-metallicity environments. These galaxies all have a metallicity of approximately $Z_{\odot}/7$ (i.e. lower than that of the SMC), a very low foreground reddening, and a young stellar population. Their distances are such that one can still resolve and individually study the brightest objects. We have thus obtained X-shooter spectra of several massive stars in these galaxies (four in IC 1613, and one each in WLM and NGC 3109). The targets were chosen to probe the whole range of O-type stars, with spectral types ranging from O3 V to O9.5 I. An example spectrum is displayed in Figure 1.

We find that the stars in our sample appear to exhibit surprisingly strong winds, with a mass-loss rate expected for LMC metallicity (objects 2–6 in Figure 2; Tramper et al., 2011). In a similar study, Herrero et al. (2011) also report stronger than predicted mass-loss rates for another two massive stars in IC 1613 (objects 7 and 8 in Figure 2). Although more stars need to be observed and analysed to draw firm conclusions, these unexpected results may have interesting implications. For example, the single-star channel to produce long-duration gamma-ray bursts depends on a star retaining a rapidly spinning core at the end of its life, and the star therefore cannot lose too much angular momentum through its wind. This result would thus

Figure 2 (below). The wind momentum–luminosity diagram is shown. Dashed lines indicate theoretical predictions from Vink et al. (2001) for different metallicities. Solid lines and shaded areas indicate the observed wind momentum–luminosity relations for the Galaxy, LMC and SMC samples (Mokiem et al., 2007). The shift between the predictions and the empirical measurements can be explained by wind inhomogeneities, which are not included in the analysis. Our observations in metal-poor galaxies are overplotted, objects 1–6 are from Tramper et al. (2011). Objects 7 and 8 are from Herrero et al. (2012) and Herrero et al. (2011), respectively. Although the error bars are large, the positions of objects 5, 6 and 8 are incompatible with theoretical predictions. Figure adapted from Tramper et al. (2011).



imply that fewer progenitors are produced through this channel. Also the single-star population at low metallicity would produce more Wolf–Rayet stars than currently thought, as a consequence of the higher mass-loss rate. This would lead to an increase of the number of Ib and, potentially, Ic supernovae.

Herrero et al. (2012) recently re-analysed object 7 in Figure 2 and concluded that the object position in the wind momentum-luminosity diagram can be reconciled with a sub-SMC line-driven wind model, assuming that the object is a fast rotator seen pole-on with an unusually rapid acceleration law for its stellar wind; it is this solution that is presented in Figure 2. Whether such a scenario can explain the other three problematic objects in Figure 2 remains to be investigated. From a purely statistical point of view, it seems unlikely that four high-inclination fast rotators have been picked out in a sample of only eight objects. Clearly, a larger observational sample is needed to understand the origin of this apparent discrepancy between the observations and the line-driven wind theory at sub-SMC metallicity.

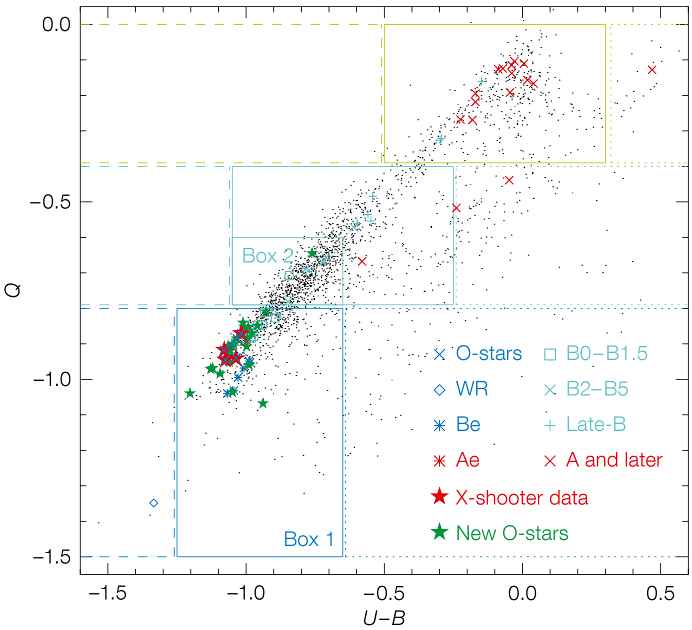


Figure 3. The *Q vs. U–B* diagram of IC 1613 is shown with the locus of O and B stars. Black dots represent good quality photometric data for IC 1613 stars. For each *Q*-horizontal band, the central box corresponds to unreddened or moderately reddened objects. Large symbols mark the position of stars with known spectral type (from Bresolin et al., 2007). X-shooter observations from Tramper et al. (2011) are marked with red stars. Green stars mark the position of newly confirmed O-type stars from low-resolution VLT-VIMOS or GTC-OSIRIS spectroscopy and illustrate that O-type stars concentrate in Box 1. Figure adapted from Garcia et al. (2009).

Searching for new massive stars in IC 1613

As currently only a small number of massive stars are known in galaxies beyond the Magellanic Clouds, a large effort to identify new O-type stars has been initiated at the Instituto de Astrofísica de Canarias (IAC) in Tenerife. This identification proceeds in two steps: a photometric pre-selection of the most promising massive star candidates, followed by a spectroscopic confirmation using low-resolution multi-object spectroscopy.

The photometric pre-selection is based on the reddening-free parameter *Q*. Calculated from broadband Johnson photometric colours, $Q = (U–B) – 0.72(B–V)$ increases monotonically from spectral type O to A. Because of its definition the Q-parameter depends on the adopted reddening law and is subject to larger photometric errors than for individual filters. OB stars occupy a well-defined locus in the *U–B vs. Q* diagram (see Figure 3). While *Q* is an indicator of spectral type, *U–B* holds the information about whether the star is reddened or not. Known O stars and B supergiants in nearby resolved galaxies are mostly found in a progressing sequence in the *U–B vs. Q* diagram (marked with boxes 1 and 2 in Figure 3), and usually have $Q \leq -0.4$.

The target selection method thus proceeds as follows. Starting from a catalogue with small photometric errors (< 0.05 mag) to minimise the uncertainty on *Q*, "blue-*Q*" stars with $Q < -0.8$ are first selected; this provides a list of OB star candidates. In order to separate the O- and B-type stars, additional information is needed (see Garcia et al., 2009). The final list of O-star candidates is made of "blue-*Q*" objects with evolutionary masses over 30 $M_{\odot}$ as derived from colour–magnitude diagrams (Garcia et al., 2010) and a detection in far ultraviolet images from the GALEX satellite (GALEX-FUV).

The method has been tested in IC 1613 using low-resolution ($R \sim 2000$) spectra taken with the VLT-VIMOS and GTC-OSIRIS instruments. The success rate of this pre-selection method is impressive. For VIMOS, the pre-selection was based only on the *Q*-parameter. Fourteen O stars were newly identified out of a sample of 24 candidates, thus a success rate of 60 %. The success rate of the GTC-OSIRIS list, that also uses evolutionary masses and GALEX detection, reaches 70 %: 9 out of 13 candidates are O stars, while the other objects are early-B stars.

To summarise, the VLT-VIMOS and GTC-OSIRIS observations have provided us with a list of 23 newly identified O stars (see Figure 4) to be followed up with X-shooter. This multiplies the sample of known O stars in IC 1613 by a factor of four and will allow for a much larger-scale study of the winds of early-type stars at very low metallicity.

Beyond the Local Group

To test even further the capabilities of X-shooter in this field of research, we set out to perform quantitative spectroscopy of some of the most massive early-type stars beyond the Local Group. The NGC 55 galaxy lies in front of the Sculptor group, at a distance of about 2 Mpc and is similar in shape and metallicity to the LMC. The population of massive blue stars in this galaxy has been identified in the context of the Araucaria project (Gieren et al., 2005). Classified as an early-O supergiant from published low-resolution FORS2 spectra (Castro et al., 2008), we selected source C1_31 as a candidate very massive star in this galaxy

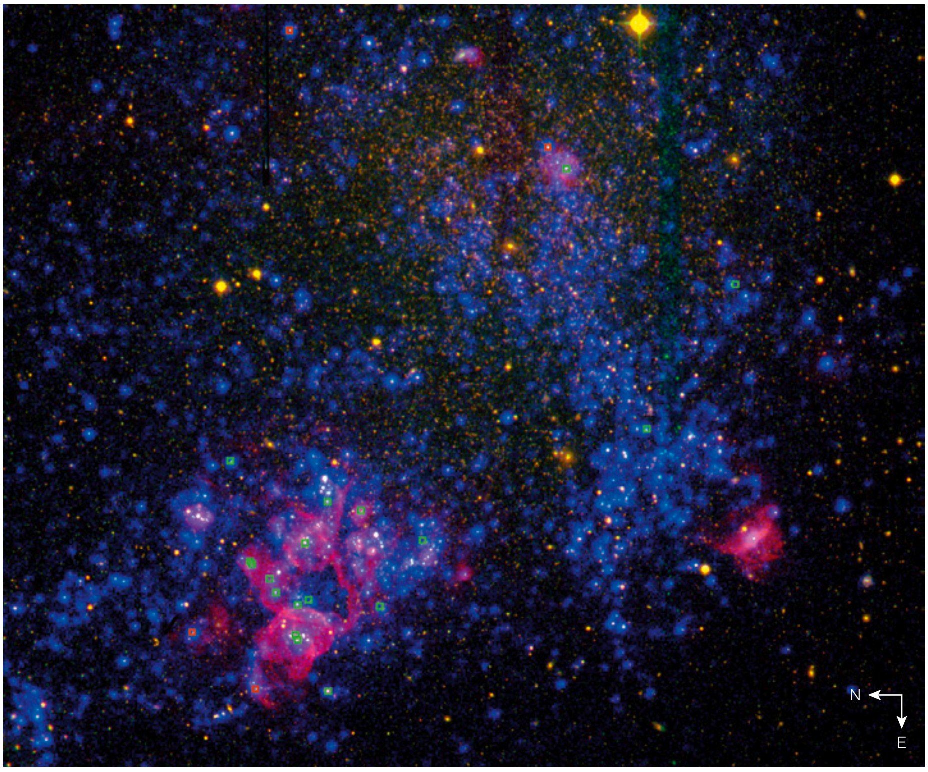


Figure 4. IC 1613 three-colour composite image made with INT-WFC images taken with the Hα- (red) and *V*-band (green) filters plus GALEX's FUV-channel (blue). Red squares mark the objects with X-shooter spectra (see Figure 3 and Tramper et al., 2011) while green squares show the location of newly identified O-type stars from low-resolution VLT-VIMOS or OSIRIS-GTC spectroscopy.

(Figure 5), and observed it with X-shooter during Science Verification.

The spectrum that we obtained has been a riddle (Hartoog et al., 2012). Most of the Balmer lines and the He I lines were strongly affected by nebular contamination, in stark contrast with previous low-resolution data. Yet, the resolving power of X-shooter was sufficient to separate the wings of the stellar photospheric lines from the nebular emission affecting the line cores (see Figure 5). The absence of the He II 4200,4541 Å lines in the spectrum was, given our signal-to-noise ratio, setting a firm upper limit to the effective temperature of about 35 000 K, in contradiction with the proposed early-O supergiant classification. The properties of the superposed nebular spectrum, however, suggested a very hot ionising source, with a temperature of about 50 000 K.

We compared the observed spectrum with synthetic spectra from a grid of FASTWIND stellar atmosphere models, which allowed us to investigate the nature of the source and its stellar parameters. A model resembling a late O star could reproduce all the hydrogen and helium line profiles, except for He II 4686 Å and Hα. These lines, present in emission in our X-shooter spectrum, have a full width at half maximum of about ~3000 km/s, and are reminiscent of the lines found in WR star spectra. However, peaking at about 20 % of the continuum level, these lines are not very strong, and definitely too weak for typical WR stars.

The large spectral coverage of X-shooter allowed us to estimate the extinction directly from our data by a comparison of the (relative) flux-calibrated spectrum with the spectral energy distribution of a standard hot star model. Given its extinction-corrected flux, we estimated the source to be about a factor ten more luminous than typical early-O supergiants.

In order to synthesise these different elements into a consistent picture, we considered C1_31 to be a small stellar cluster rather than a single source. Indeed the projected size of our entrance slit corresponds to a physical distance of just below 10 pc, i.e. large enough to contain a small open cluster such as Trumpler 14 or NGC 6231. Pursuing this solution, we can reproduce all observed spectral features, the properties of the surrounding ionised region and the visual brightness of the target by combining about ten late-O/early-B (bright) giants, and one or two WN stars, a class of WR stars that can be very hot, but do not show very strong carbon lines (which would have been prominent in the target spectrum).

This work illustrates an inherent difficulty in extragalactic stellar spectroscopy, i.e., the risk of observing a cluster (or an unresolved multiple object) instead of a single star. Thanks to the unique combination of high resolution and large wavelength coverage, allowing many different diagnostic lines to be observed, X-shooter can play a critical role in unveiling the composite character of such objects. Obviously the cluster composition that we proposed for NGC 55 C1_31 may not be the unique solution, but the conclusion that NGC 55 C1_31 is not a single star but a cluster that contains at least one very hot WR star, is robust. Higher angular resolution is a must to further disentangle such a group of stars and to study the evolutionary stage of the identified population.

Future prospects

With the advent of the European Extremely Large Telescope (E-ELT) it will become possible to resolve stellar populations in a representative sample of galaxies of different morphologies in and beyond the Local Group, such as the spiral-dominated Sculptor and M83 groups and starburst galaxies such as M82. The high contrast and sensitivity of wide-field (up to 10 arcminutes) adaptive optics, routinely providing a spatial resolution a factor of ten better than seeing-limited observations at the VLT, will provide the opportunity to simultaneously obtain spectra of several hundreds of individual (massive) stars within a targeted galaxy. Several concepts of the required E-ELT multi-object spectrograph (OPTIMOS and EAGLE) have been explored (Hammer et al., 2010; Le Fèvre et al., 2010; Morris et al., 2010). For the study of massive stars, wavelength coverage as far to the blue as possible would be required, but also the near-infrared provides valuable spectral diagnostics. For the first time we will be able to explore the properties of massive stars over the full range of environments, from the lowest metallicities up to the sites of violent star formation in starburst galaxies.

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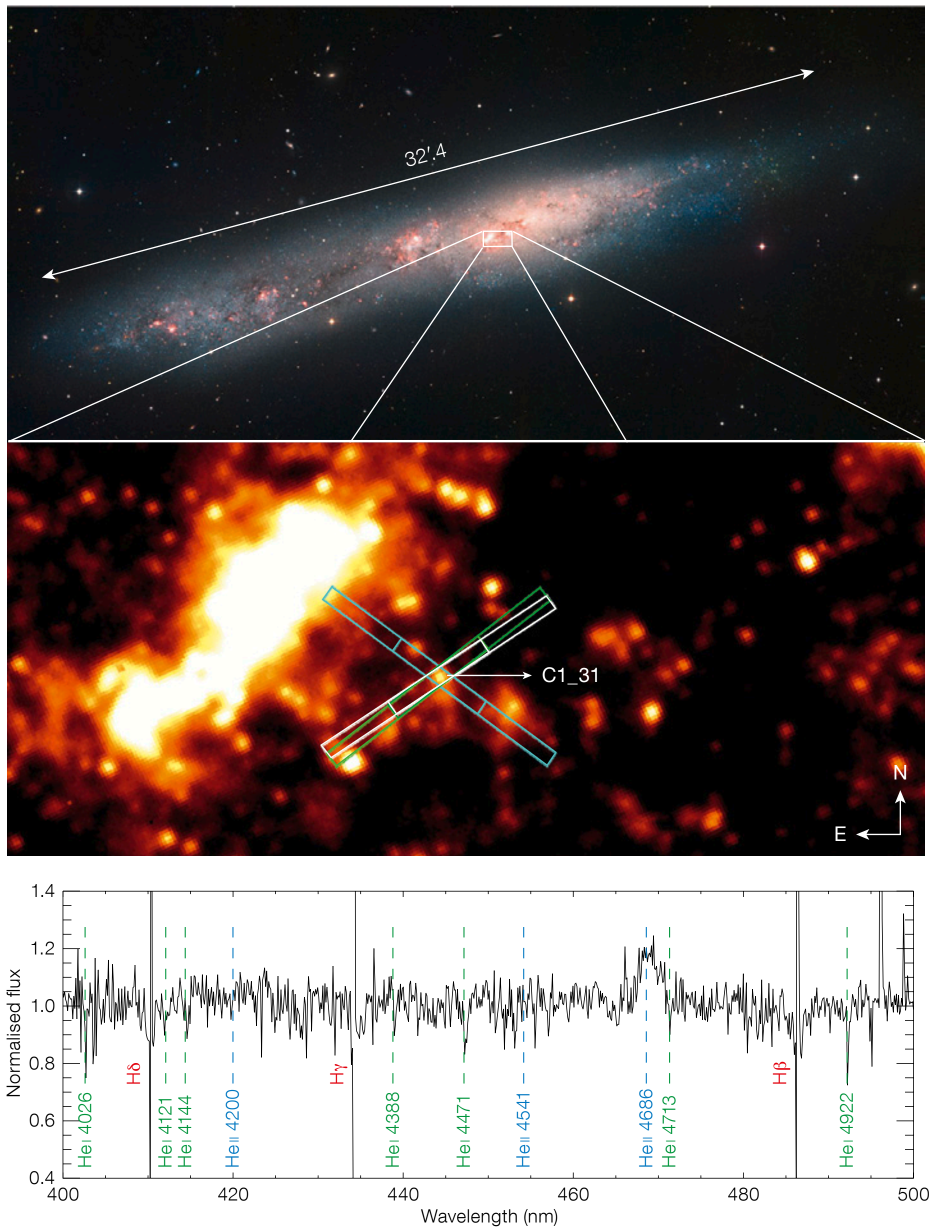

Figure 5. Top panel: MPG/ESO 2.2-metre WFI colour-coded image (*B*, *V*, Hα) of NGC 55 is shown. Middle panel: zoomed-in FORS2 Hα image around the position of C1_31; the rectangles indicate the projections of the X-shooter entrance slit during our three different observations. Bottom panel: Co-added C1_31 spectrum with the main spectral features identified. Figure adapted from Hartoog et al. (2012).

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NGC 4945, shown here, is an SB barred spiral galaxy in the nearby Centaurus A group of galaxies. The colour image was formed from exposures taken with the 1.5-metre Danish telescope at the La Silla Observatory in *B*-, *V*- and *R*-bands. NGC 4945 has a heavily obscured Seyfert 2 active galactic nucleus which has been extensively studied. See Picture of the Week 1007 for more details.