Red Supergiants as Cosmic Abundance Probes

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By studying a galaxy's present-day chemical abundances, we are effectively looking at its star-forming history. Cosmological simulations of galaxy evolution make predictions about the relative metal contents of galaxies as a function of their stellar mass, a trend known as the mass–metallicity relation. These predictions can be tested with observations of nearby galaxies. However, providing reliable, accurate abundance measurements at extragalactic distances is extremely challenging. In this project, we have developed a technique to extract abundance information from individual red supergiant stars at megaparsec distances. We are currently exploiting this technique using the unique capabilities of KMOS on the VLT.

A well-known correlation exists between the mass of a galaxy and its metal content, whereby more massive galaxies tend to be more metal-rich (Lequeux et al., 1979). This is understood qualitatively as being due to progressive enrichment by stellar and supernova nucleosynthesis, moderated by the infall of pristine gas and outflow of enriched material via winds. This enriched gas escapes more easily from lower-mass galaxies due to the shallower potential well, preventing them from reaching high metallicities, and gives rise to the functional form of the mass–metallicity [*Z*] relation we see today. State-of-the-art cosmological simulations (e.g., Shaye et al., 2015) make specific predictions about the quantitative nature of the mass–metallicity relation, which makes it possible to test the current theories of galaxy evolution under the dark energy, cold dark matter framework.

Such tests, however, require reliable and robust measurements of a galaxy's chemical abundances. Historically this has been done using emission lines from extragalactic H II regions. The "direct" method requires measurements of auroral lines, such as [O III] 436.3 nm, which allows the observer to uniquely determine the gas temperature and, crucially, the abundance of the element. Unfortunately, these auroral lines are often very weak, especially at high metallicity. This means that one must attempt to derive abundances based on only the strong emission lines (e.g., [O III] 500.7 nm), which contain no temperature information on their own, by calibrating against either results from the direct method or from photoionisation models. The limitation of these strong-line methods is that they have well-known systematic offsets from one another, particularly at high metallicity, where two different calibrations may give results ~ 0.8 dex apart (Kewley & Ellison, 2008).

In order to solve this problem, our team has been pioneering new ways to obtain the metallicities of external galaxies by studying their constituent stars individually. The stars chosen as targets must be: (a) young, so that their abundances reflect those of H II regions; and (b) luminous, so that they can be observed at megaparsec distances. This means that the obvious targets of choice are supergiants — massive, post main-sequence stars, which can outshine entire globular clusters and dwarf galaxies. Substantial recent progress has been made using optical spectroscopy of blue supergiants (BSGs; see Kudritzki et al. [2014] and references therein). However, to really take advantage of the next generation of telescopes such as the European Extremely Large Telescope (E-ELT), it is crucial to reduce our dependence on optical techniques and move to the near-infrared (NIR). At these wavelengths, the gain from adaptive optics will be the most profound, as the increase in sensitivity scales with the fourth power of the mirror diameter.

Red supergiants: A novel, NIR-based technique for extragalactic metallicity studies

To this end, in recent years we have been developing a technique to obtain extragalactic abundances using NIR spectroscopy of red supergiants (RSGs). These stars are extremely bright (> $10^5\ L_\odot$), young (< 30 Myr), and have the advantage that their fluxes peak at NIR wavelengths. A challenge for abundance work using these stars is that they are cool, with effective temperatures around 4000 K, and so their spectra are dominated by absorption from thousands of molecular lines. Historically this has meant that high spectral resolving powers were needed to study individual lines, making these stars unsuitable for extragalactic work due to the large integration times required.

In order to adapt these techniques to be useful at extragalactic distances, in Davies, Kudritzki & Figer (2010) we identified a spectral region around 1.2 μm that is relatively free of molecular lines, the dominant features being those of neutral metallic atoms. We then demonstrated that metallicities relative to Solar (defined as [*Z*]) may be determined from moderate spectral resolutions of only R ~ 3000, making this technique viable at large distances, and well-suited to the latest multi-object spectrographs (MOSs), such as the *K*-band Multi-Object Spectrograph (KMOS) on the Very Large Telescope (VLT). Using instrument simulators, we then demonstrated the potential with the E-ELT, showing that we could measure [*Z*] at distances of 75 Mpc (Evans et al., 2011).

Building the tools for the job

Spurred on by the potential of this technique, we set about developing the necessary analysis tools. The initial task in this project was to build a suite of model spectra from which we can derive high-precision abundances. We generated a grid of MARCS (Model Atmospheres in Radiative and Convective Scheme) model atmospheres (Gustafsson et al., 2008), computed under the assumptions of spherical symmetry and local thermodynamic equilibrium (LTE), which span the parameter ranges in effective temperature, surface gravity, microturbulence and metal abundances appropriate for RSGs. We use these models to compute synthetic spectra with full non-LTE radiation transport for the diagnostic chemical elements Fe, Si, Mg and Ti (Bergemann et al., 2012; 2013; 2015). Fitting the models to the data is done by a χ^2-minimisation process of matching the observed strengths of the diagnostic metal lines, described in detail in Davies et al. (2015).

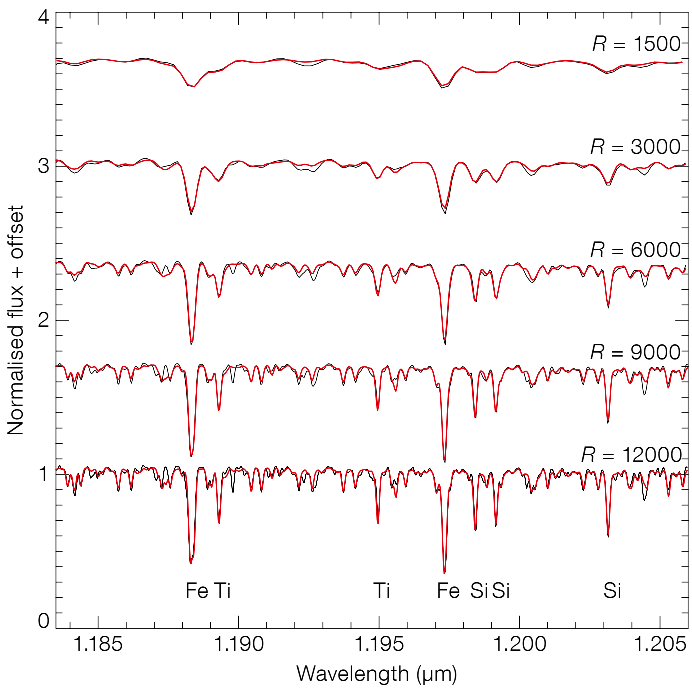

Figure 1. A spectrum of an RSG in Per OB1 observed with Subaru and IRCS in black, and the best-fitting model (red), at bottom. The other spectra are the same data but degraded to lower resolution and re-fit, showing that the diagnostic lines are still identifiable down to resolutions of R = 3000. Taken from Gazak et al. (2014a).

Road-testing in the Milky Way

The next phase of our project was to demonstrate that our technique works at high precision in the Solar Neighbourhood. For our target we chose the nearby Perseus OB1 association, which contains several RSGs, and which we can safely assume all have the same metallicity. Using high-resolution spectroscopy from the Infrared Camera and Spectrograph (IRCS) on the Subaru Telescope, we obtained a metallicity averaged over all RSGs in the region consistent with Solar, $[Z] = -0.02 \pm 0.08$, as would be expected (Gazak et al., 2014a). Further, by degrading the spectral resolution of the data and repeating the analysis, we showed conclusively that this technique is stable down to resolutions of $R < 3000$, typical of MOS instruments (see Figure 1).

Extragalactic baby steps: The Magellanic Clouds

With the technique now proven at Solar metallicities, the first sub-Solar metallicity systems to be studied were the Large and Small Magellanic Clouds (LMC and SMC). The data here were provided by X-shooter on the VLT (Davies et al., 2015). From analysis of ten and nine stars in the LMC and SMC respectively, we measured average metallicities of $[Z]_{LMC} = -0.37 \pm 0.14$ and $[Z]_{SMC} = -0.53 \pm 0.16$, consistent with contemporary results from observations of hot supergiants (see Davies et al. [2015] and references therein).

The added value of the X-shooter data was that, in addition to the coverage of our spectral window at 1.2 µm, we obtained spectra covering the whole of the optical and near-infrared, from 0.3–2.5 µm. This allowed us to verify that the temperatures we obtain from our narrow window in the *J*-band were consistent with those from fits to the spectral energy distributions. The agreement for the SMC stars was excellent, while the LMC stars were also similar to within the errors, aside from the two stars in our sample with the highest temperatures.

Beyond the Local Group with KMOS: A study of NGC 300

Our first target beyond the Local Group was chosen to be the Sculptor Group member NGC 300. This galaxy is a relatively nearby (2 Mpc) face-on spiral with a strong abundance gradient, as measured from H II regions with the direct method, and with BSGs (Bresolin et al., 2009; Kudritzki et al., 2008). It is therefore an excellent testbed to provide one more validation of our technique.

For these observations, we employed the new VLT NIR multi-object spectrograph KMOS. Since our project requires high-precision absorption-line spectroscopy of the highest possible quality, it is therefore essential that we take the greatest care in removing sky emission and telluric features from our data. After extracting the calibrated datacubes using the KMOS data reduction pipeline, we found that variations in spectral resolution and wavelength calibration were introducing noise into the final spectra. In Figure 2, we demonstrate these variations across the field of view of one integral field unit (IFU), as measured from the sky emission lines. We corrected for this effect in a process we call KMOGENIZATION, whereby we smooth the spectra at each spaxel down to a level which is common to all spaxels to be extracted. This is usually defined to be R = 3000–3200. The spatially varying wavelength calibration effects are minimised by only extracting spectra within a 1 spaxel radius of the flux peak. Although this discards a small amount of flux, this is more than compensated for by the reduction in artefacts that can be introduced when removing sky and telluric features. Repeated observations of the same target, for which the wavelength calibration may vary throughout the night, were co-added onto a master wavelength scale without resampling, so as to minimise systematic noise.

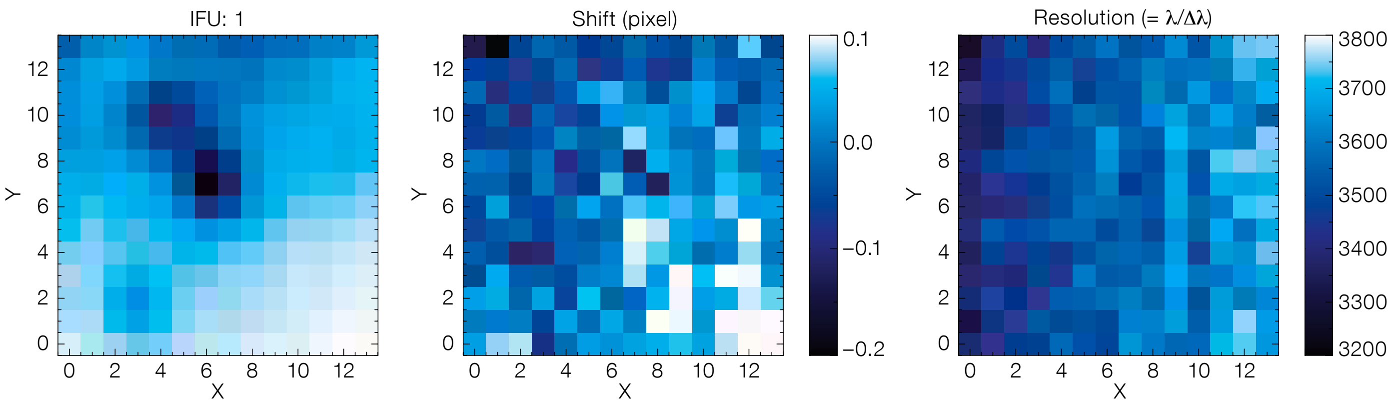

Figure 2. Output from our KMOGENIZATION software. The left panel shows the wavelength-collapsed image of one KMOS IFU, in this case IFU#1, which has been positioned on a star cluster in NGC 4038. The centre and right panels show the spatial variations in wavelength calibration and spectral resolution respectively. We correct for these variations to minimise systematic noise in our extracted spectra.

After the spectra were extracted and analysed, the RSG-based metallicity gradient was constructed (Gazak et al., 2015), and is shown in Figure 3. The agreement between the RSG gradient and that from observations of BSGs is remarkable — the gradients are identical to within the errors, and with a systematic offset of only 0.05 dex. The agreement between the RSG/BSG gradients and that of the direct H II region measurements is equally striking, see Bresolin et al. (2009).

A survey of the mass–metallicity relation in the local Universe with KMOS

With all the validation and road-testing phases complete, we are now beginning to construct a mass–metallicity relation for galaxies in the nearby Universe based only on observations of RSGs. The weapon of choice for this project is KMOS, with its multiplexing, spectral range and resolving power being ideally suited to our technique.

We began with a recently published study of NGC 6822, which found a mean abundance of [*Z*] = −0.52 ± 0.21 (Patrick et al., 2015). This will continue with a study of Sextans A (data taken April 2015), and a recently approved KMOS programme to observe NGC 55, WLM and IC1613 in Period 96.

One step beyond: RSG-dominated star clusters

When observing stars at very large distances, the issues of crowding and source blending must always be considered. For this project, RSGs are so much brighter than any other class of star in the near-infrared that the only blending sources to worry about are other RSGs. It is well known that massive star clusters with ages between 7–50 Myr may contain dozens of RSGs. If such a cluster was at a distance so great that it was totally unresolved and appeared as a point source, and we mistook it for a single abnormally bright RSG, what would we see?

Our hunch was that an unresolved star cluster dominated by RSGs would have the spectral appearance in the *J*-band of a single RSG. Firstly, since the RSGs in the cluster are effectively coeval, and the RSG lifetime (< 1 Myr) is short compared to the age of the cluster, all the RSGs should have roughly the same mass and hence gravity. Secondly, since the stars formed from the same molecular cloud, they should have the same metallicity. Finally, we know from our previous studies that RSGs span only a narrow range in temperature and microturbulence. Our prediction was therefore that the spectrum of an unresolved cluster of 100 RSGs would be indistinguishable from that of one of its constituent stars, but be 100 times brighter. This then means we could use our technique on massive star clusters at distances ten times further than for individual stars.

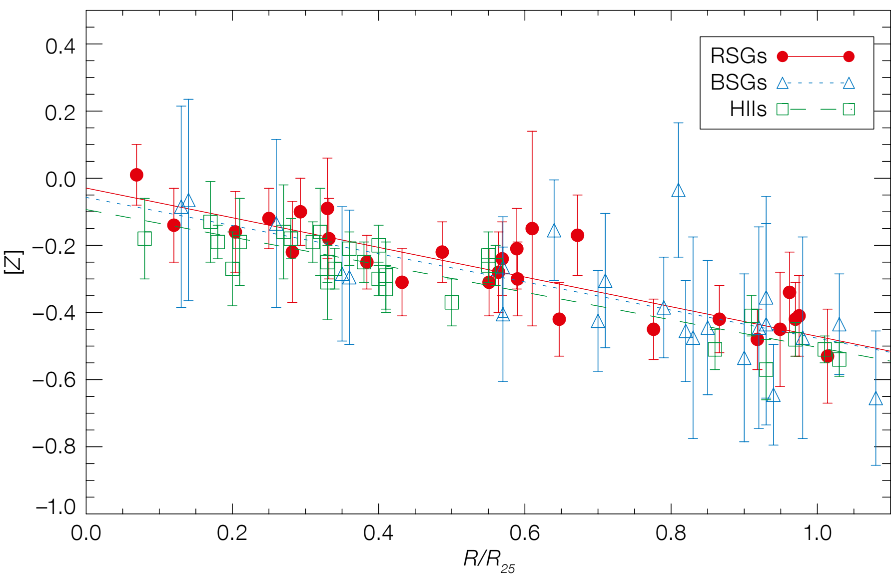

Figure 3. Radial metallicity gradient in NGC 300, as measured from RSGs (red points), BSGs (blue points), and direct method (auroral line) H II region observations, illustrating the stunning agreement between the different methods.

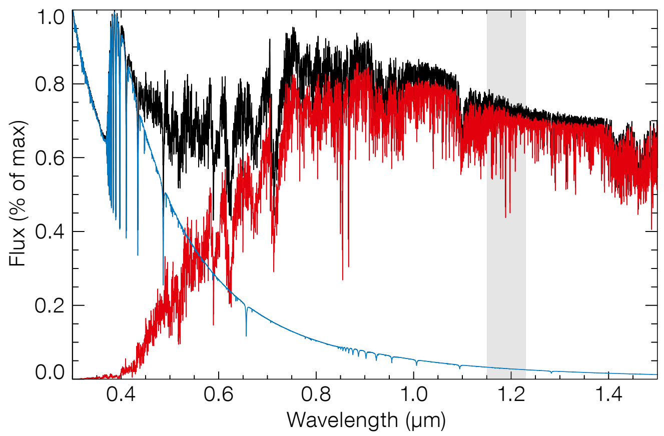

Figure 4. The relative contributions to the overall flux of a 15 Myr old star cluster by the RSGs (red) and the rest of the stars (blue). Our *J*-band spectral window for deriving metallicities is shown in grey. The figure shows that 95 % of the flux at *J* comes from the RSGs, which are only 0.1 % of the stars. From Gazak et al. (2014b).

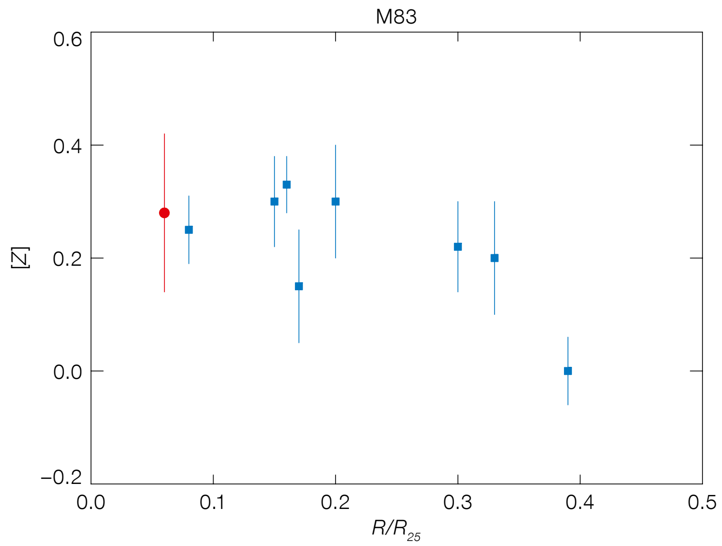

Figure 5. The metallicity of an RSG-dominated star cluster close to the centre of M83 (red), as measured in Gazak et al. (2014b), plotted against galactic radius. The blue points show a recent study of the same galaxy using BSGs (Bresolin, Kudritzki & Gieren, in prep). The agreement between the two methods is excellent, providing further evidence that the RSG-cluster method can determine accurate metallicities.

This is a prediction that was confirmed in Gazak et al. (2014a; 2014b), where the spectra of the individual RSGs in Per OB1 were combined to make a mock star cluster spectrum. This spectrum was then analysed in the same way as that of a single star, with an almost identical metallicity retrieved. We also performed population synthesis experiments to show that the RSGs account for > 95 % of the flux in the *J*-band (Figure 4), and that neither the age of the cluster nor the contribution to the *J*-band flux by the other stars has a significant effect on the inferred metallicity.

This RSG cluster based technique was first utilised on bright objects in M83 and

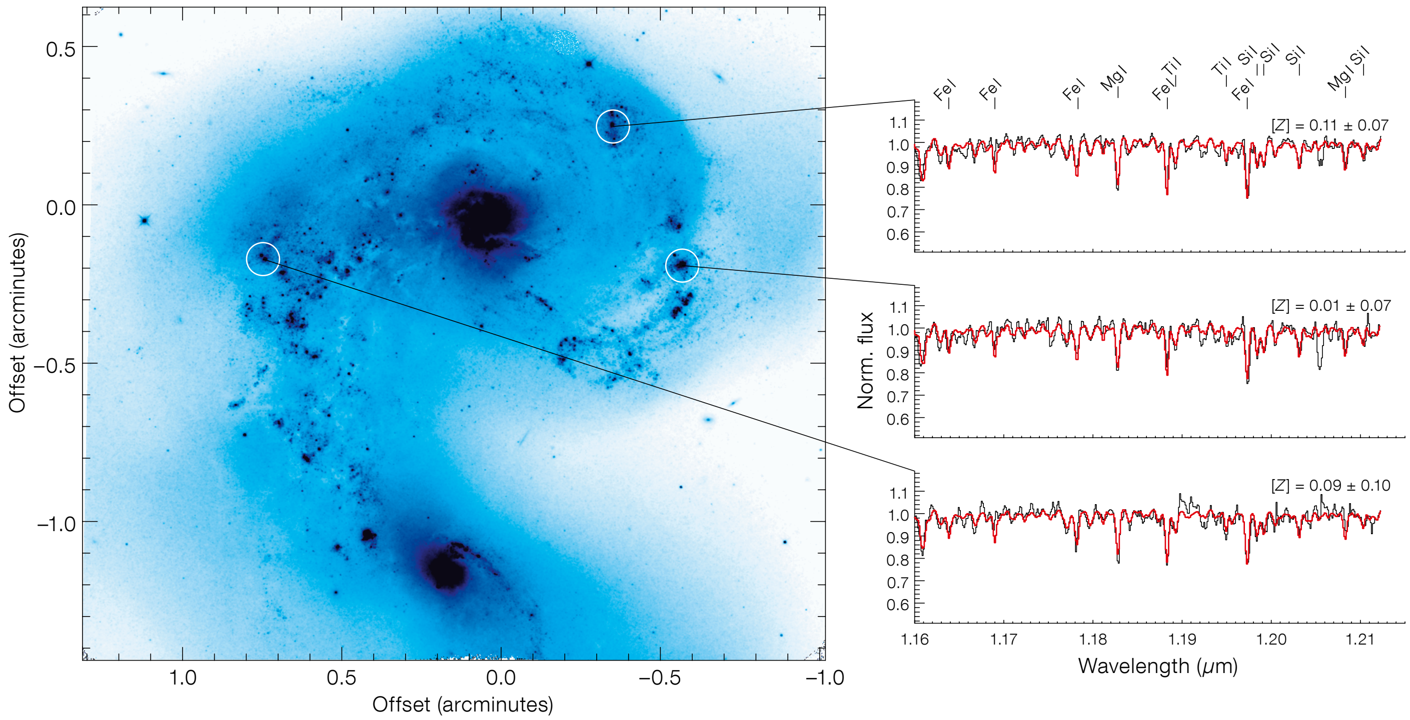

Figure 6. Hubble Space Telescope Wide Field Camera 3 *J*-band image of the Antennae Galaxies, illustrating the locations of the observed star clusters that contain dozens of RSGs. Their KMOS spectra are shown on the right (black), along with their best-fitting models (red) and abundances.

NGC 6946 in Gazak et al. (2014b), using the Infrared Spectrometer And Array Camera (ISAAC) on the VLT and the SpeX medium resolution spectrograph on the NASA Infra-Red Telescope Facility (IRTF) respectively. Our result of a super-Solar metallicity in the centre of M83 is in excellent agreement with recent observations of BSGs in the same galaxy (Bresolin, Kudritzki & Gieren, in prep.; see Figure 5).

Our first study of a sample of massive young clusters across a galaxy is to be submitted shortly. We obtained KMOS observations of three clusters in the interacting galaxy NGC 4038 (one half of the Antennae system), showing that the galaxy has a flat abundance gradient — consistent with theoretical predictions for merging galaxies (Lardo et al., in prep; see Figure 6).

Prospects

We have shown in this article that RSGs are extremely powerful cosmic abundance probes, and in combination with instruments like KMOS can provide high-precision metallicities at distances of several megaparsecs. The next stage of our project is to provide an RSG-based mass–metallicity relation that will have the power to directly test cosmological simulations of galaxy formation. The first set of KMOS observations required to complete this are scheduled for the coming semester.

References

Bergemann, M. et al. 2012, ApJ, 751, 156
Bergemann, M. et al. 2013, ApJ, 764, 115
Bergemann, M. et al. 2015, ApJ, 804, 113
Bresolin, F. et al. 2009, ApJ, 700, 309
Davies, B., Kudritzki, R.-P. & Figer, D. F. 2010, MNRAS, 407, 1203
Davies, B. et al. 2015, ApJ, 806, 21
Evans, C. et al. 2011, A&A, 527, A50
Gazak, J. Z. et al. 2014a, ApJ, 788, 58
Gazak, J. Z. et al. 2014b, ApJ, 787, 142
Gazak, J. Z. et al. 2015, ApJ, 805, 2
Gustafsson, B. et al. 2008, A&A, 486, 951
Kewley, L. J. & Ellison, S. L. 2008, ApJ, 681, 1183
Kudritzki, R.-P. et al. 2014, ApJ, 788, 58
Kudritzki, R.-P. et al. 2008, ApJ, 681, 269
Lequeux, J. et al. 1979, A&A, 80, 155
Patrick, L. R. et al. 2015, ApJ, 803, 14
Schaye, J. et al. 2015, MNRAS, 446, 521

The nearby dwarf irregular galaxy NGC 6822 (Barnard's Galaxy) is shown in an MPG/ESO 2.2-metre telescope image taken with the Wide Field Imager (WFI) with *B*, *V* and *R* broad band filters and a narrow Hα filter. Young shell H II regions with prominent Hα emission are visible in the outer regions of the galaxy. See Release eso0938 for more details.