# EXTRAPLANAR STAR FORMATION IN NGC 55

*We present the first VLT spectra of two compact Hα-emitting objects, located in the halo of the edge-on spiral galaxy NGC 55. The detection of stellar continuum and the observed emission-line characteristics indicate that these objects are extraplanar HII-regions. CLOUDY model simulations establish photoionisation by single OB-type stars as ionisation mechanism and finally confirm the HII-region character. Hydrodynamical considerations unambiguously restrict the origin of these regions to the halo. Their creation was most likely triggered by star formation activity in the disc below. In this picture the gas clouds, out of which the OB stars formed, could cool and collapse only between two successive bursts of star formation.*

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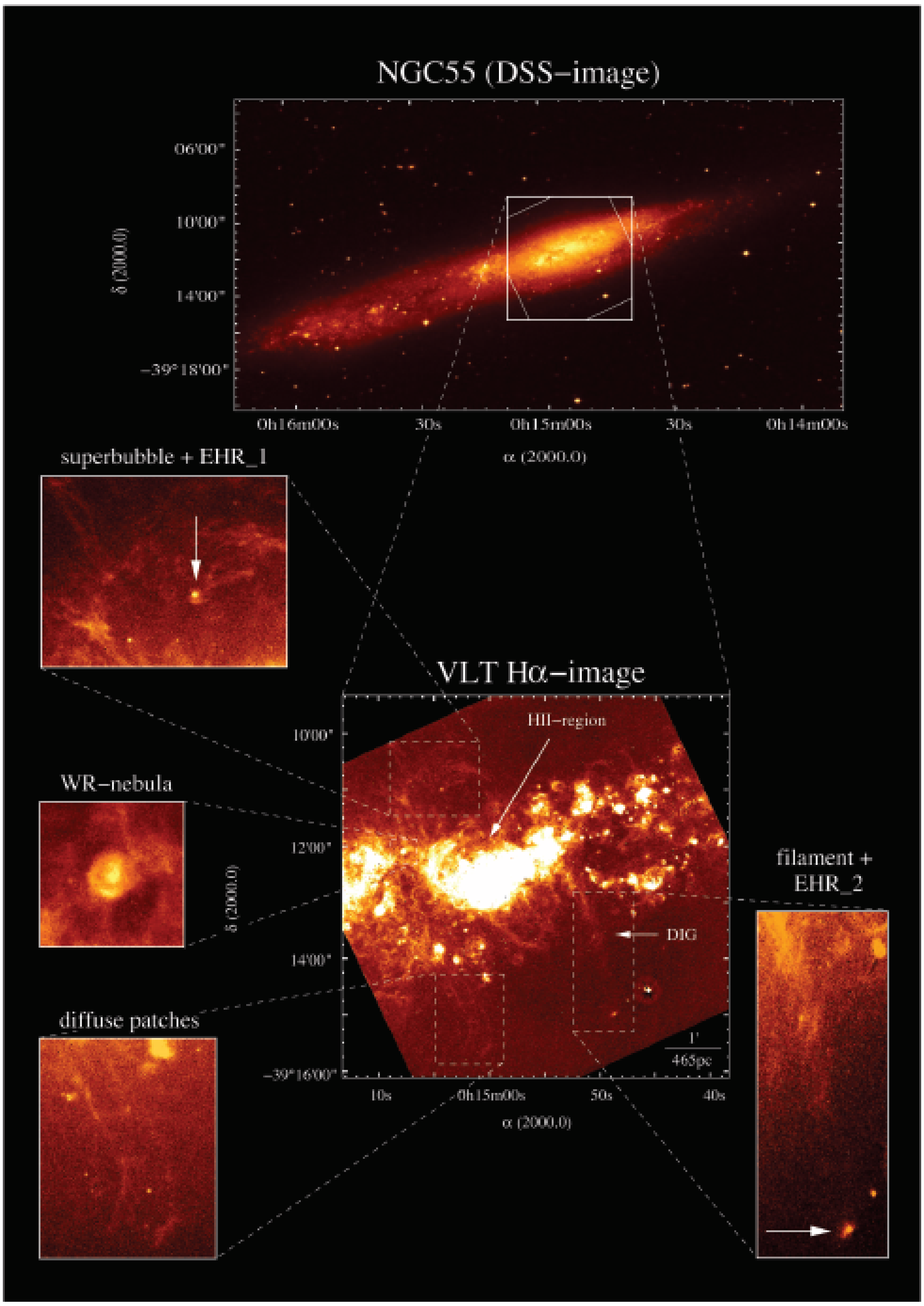


*Figure 1: Zooming into the centre of NGC 55. This Hα-image has been obtained with UT1+FORS1 at the VLT. It reveals various spectacular features, such as filaments, colliding shells, superbubbles, and a newly detected Wolf-Rayet nebula of surprisingly high temperature. Note the extraplanar HII-region (EHR_1) located within the extended northern SN shell and EHR_2 which sits on top of a huge elongated (1kpc) filamentary structure.*

During the last decades the formation of massive stars in galaxies of different Hubble-Types has been studied in great detail. For spirals this process is considered to be almost exclusively concentrated to the disc as the efficiency with which gas is converted into stars is highest there. On the other hand, the existence of a young and massive OB-star population in the halo of the Milky Way galaxy and other spiral galaxies, such as NGC253, is widely accepted.

However, as these stars are detected at large distances (~15 kpc) above the star forming disc, their creation and origin are rather poorly constrained. In order to clarify the origin of this young stellar component in the halo different scenarios have been proposed, such as ejection from the disc as a consequence of supernova (SN) explosions, ejection from stellar clusters as a result of gravitational encounters, and star formation in the halo itself (Keenan 1992, Ferguson 2002).

Estimates of the distance a star could travel at a given speed through the halo during its lifetime reveals that 'in situ' star formation in the halo is the most likely scenario for a large fraction of the studied sample of halo stars. If proper motions of these stars are reasonably low, it should be possible with future investigations to detect their stellar birthplaces, faint gaseous envelopes in the vicinity of these stars, and thus to further strengthen extraplanar star formation (ESF). Although the mechanism that triggers ESF still remains unclear, especially in view of low gas densities, we have increasing evidence that star formation occurs at rather unusual sites, such as in a galaxy halo.

In the following, we investigate the possibility of ESF and its triggering mechanism by analysing first VLT data of compact extraplanar gas clouds with embedded stellar sources located in the disc-halo interface of the edge-on galaxy NGC 55.

## Extraplanar HII-regions

There are fairly compact and isolated objects visible in H$\alpha$-imaging data for NGC 55 (Ferguson et al. 1996) which are located at distances of up to 1.5kpc above the disc of this galaxy. From a morphological point of view, these objects appear very much like a small scale disc HII-region with embedded clusters of massive stars formed recently. Interestingly, similar regions are also discernable in other well known edge-on galaxies, such as NGC891, NGC3628, or NGC5775. In order to detect these objects, the target galaxy should be nearby to ensure sufficiently high spatial resolution and seen close to edge-on (large inclination angles of $i > 70°$), as in this case the halo separates well from the disc.

What makes the barred spiral galaxy NGC 55, a member of the Sculptor Group, an ideal target to study ESF is its proximity of only ~1.6Mpc and its high inclination of $i = 80°$. Moreover, this galaxy reveals violent ongoing star formation in the centre and at least two prominent extraplanar HII-region (EHR) candidates. All these features can be seen very nicely from Figure 1 where the VLT H$\alpha$-image obtained with UT1+FORS1 is presented.

A huge curved filament of gas and dust, anchored to the disc, is protruding off the image plane, apparently pointing towards R.A.(2000): $00^h15^m07^s$ and Dec.(2000): -39°12′00″. Of particular interest are the two objects marked by arrows, whose magnifications are shown in Figure 2.

EHR_1 has a diameter of 17pc and is located 0.8 kpc above the disc, whereas EHR_2 reveals a projected distance of 1.5 kpc and spans 22 pc in diameter.

If effects along the line-of-sight are negligible, EHR_1 is located within an expanding oxygen-bright SN shell that was detected over 20 years ago by Graham & Lawrie (1982). It would be interesting to learn from similar observations in other galaxies if these extraplanar regions predominantly occur at points where such shells, created by OB stars and SNe, intersect and the gas is piled up. At least the compressed gas at R. A.(2000): $00^h15^m07^s$ and Dec.(2000): -39°11′00″ is in favour of this idea.

However, the most important immediate result is provided by optical multi-object-spectroscopy (MOS) and concerns the detection of spatially concentrated continuum emission, which originates

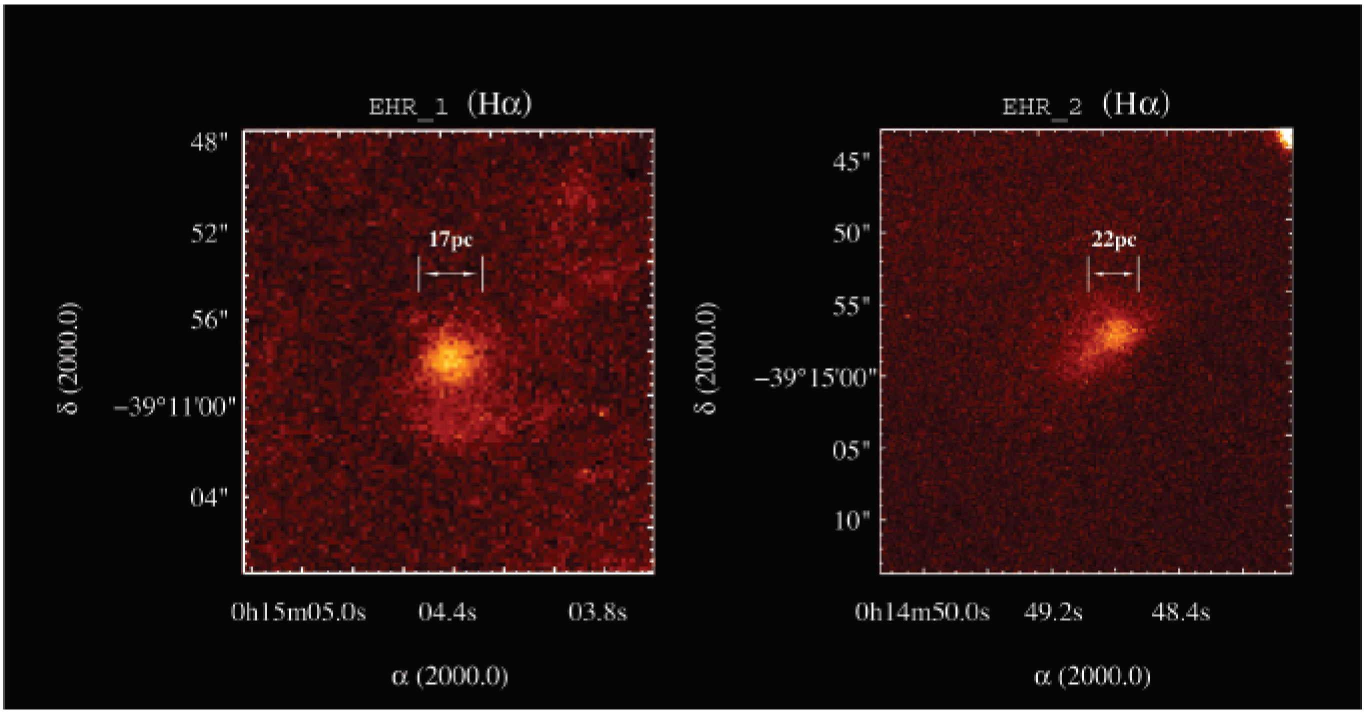


*Figure 2: Blow-up views of EHR_1 In the northern (left) and EHR_2 in the southern halo (right). Both objects show a dense central core with diffuse Hα-emission in their outskirts which is sharply bounded towards the halo.*

*Table 1: Element abundances for the HII-region and the EHRs as calculated by NAT for gas temperatures of 11500K. Values in brackets were derived with the empirical R23-calibration. Solar abundances are compiled from the most recent data including Christensen-Dalsgaard (1998) and Grevesse & Sauval (1998). The average metallicity* $\langle Z/Z_\odot \rangle$ *has been calculated from oxygen abundances as this element is the most abundant and efficient coolant.*

| Parameter | HII-region | EHR_1 | EHR_2 | Solar |
|---|---|---|---|---|
| $R_{23}$ | 0.88 | 0.68 | 0.72 | – |
| 12 + log(He/H) | 10.94 ± 0.02 (10.94) | (10.93) | 10.84 (10.93) | 10.98 |
| 12 + log(O/H) | 8.05 ± 0.10 (8.08) | 7.77 (7.61) | 7.81 (7.68) | 8.71 |
| log(N/O) | –1.26 ± 0.05 (-1.30) | –1.50 (-1.54) | –1.31 (–1.50) | –0.78 |
| log(Ne/O) | –0.85 ± 0.10 | – | – | –0.71 |
| log(S/O) | –1.41 ± 0.15 | –1.94 | –1.69 | –1.51 |
| log($O^+$/O) | –0.731 | –0.133 | –0.127 | – |
| log($S^+$/$S^{++}$) | –0.722 | – | – | – |
| $\langle Z/Z_\odot \rangle$ | 0.45 | 0.10 | 0.10 | 1.0 |

within the more diffuse body of the extraplanar objects (Figure 3).

The morphology of the continuum and the nebular emission-line distribution is direct evidence for stellar sources responsible for the excitation of these regions. Correspondingly, the flux-calibrated and background-subtracted spectra, integrated along their total spatial extent (Figure 4), are very similar to low excitation HII-regions.

For EHR_1, continuum emission is very weak and can hardly be seen in the spectrum presented in Figure 4. However, it is clearly visible in Figure 3. Figure 4 also shows the spectrum of EHR_2 which reveals a continuum much more prominent than that found in EHR_1.

A comparison with CLOUDY model simulations reveals that the ionisation mechanism of these compact objects is most likely photoionisation by single OB stars (O9.5 to B0). Further analysis of diagnostic diagrams unambiguously confirms the HII-region character.

## Constraining the Origin of the EHRs

The existence of HII-regions in the halo immediately raises the question whether these objects originated from the prominent extraplanar gas of this galaxy or have just been expelled from the disc into the halo.

Ejection from the disc can be ruled out by hydrodynamical considerations due to the enormous drag, the gas phase of these regions encountered on its way out of the disc into the halo. Even a small amount of interstellar matter located along the path would lead to a separation of cloud and embedded stars due to the enormous difference in impact parameters cloud vs. cloud as compared to stars vs. cloud. Therefore, we conclude that these objects must have formed within the halo.

In addition, knowledge of the gas phase abundances also helps to distinguish between different creation mechanisms of the extraplanar ionised regions. Rather low metallicities compared to the disc abundances would indicate that these regions have formed from almost pristine local halo material. Relatively high abundances would restrict the origin of the clouds to material processed in star-forming regions of the disc.

We therefore determined the element abundances of both EHRs and compared them to those measured in the disc using two independent methods (R23 and the nebular abundance tool (NAT), see Tüllmann et al. 2003 for details). The results are shown in Table 1.

A comparison between the average metal abundance of the central disc HII-region of NGC 55 (45% $Z_\odot$) and both EHRs reveals substantially lower [O/H] abundances of about 10% $Z_\odot$ and thus independently also supports the ESF scenario.

With metal abundances derived this way, we can visualise for the first time the strong differences in the metal content along the minor axis of this galaxy. From Figure 5 it is obvious that the gas phase of oxygen is less abundant in the halo by about a factor of 4.

In order to reach a better coverage of the oxygen abundance along the minor axis, Figure 5 also plots the metal abundance of the Diffuse Ionised Gas (DIG). This gas phase is pushed into the halo of a galaxy by multiple SNe where it is visible as a diffuse extended Hα-emitting gaseous layer surrounding the disc. The ionisation of the DIG is maintained most likely by photoionisation from stars

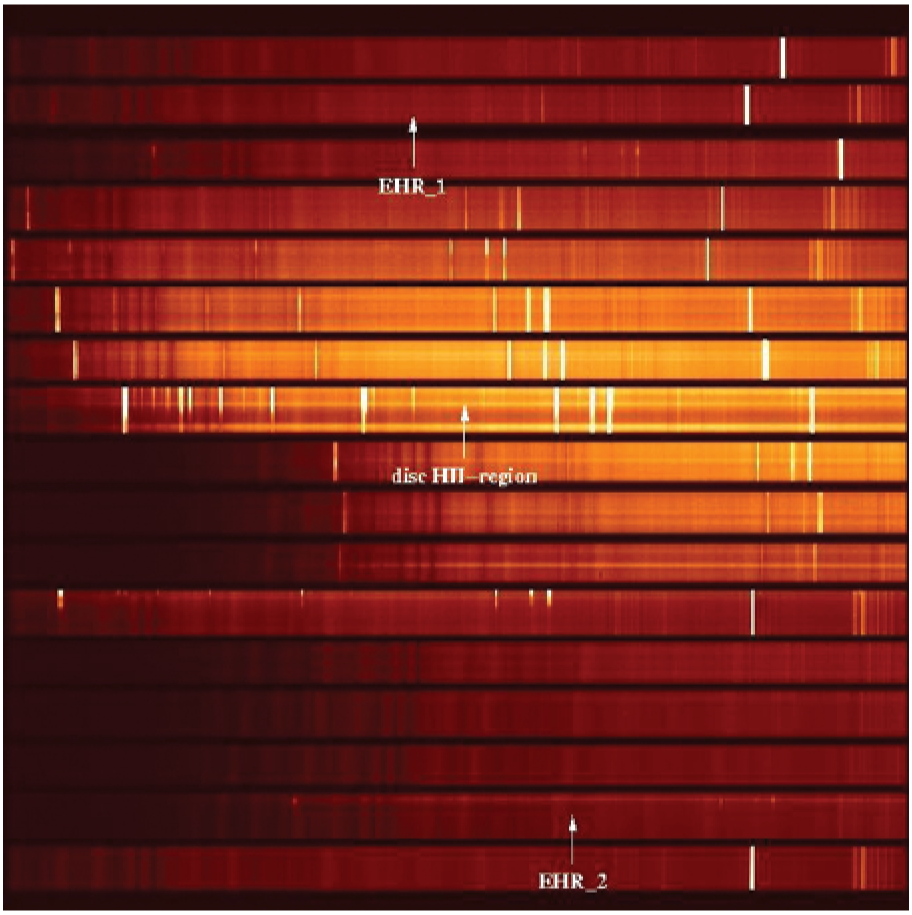


*Figure 3: MOS-frame covering the "blue" wavelength region from about 3500Å to 5600Å. Both EHR-spectra, reveal only faint stellar continuum and line emission contrary to the central HII-region in the disc.*

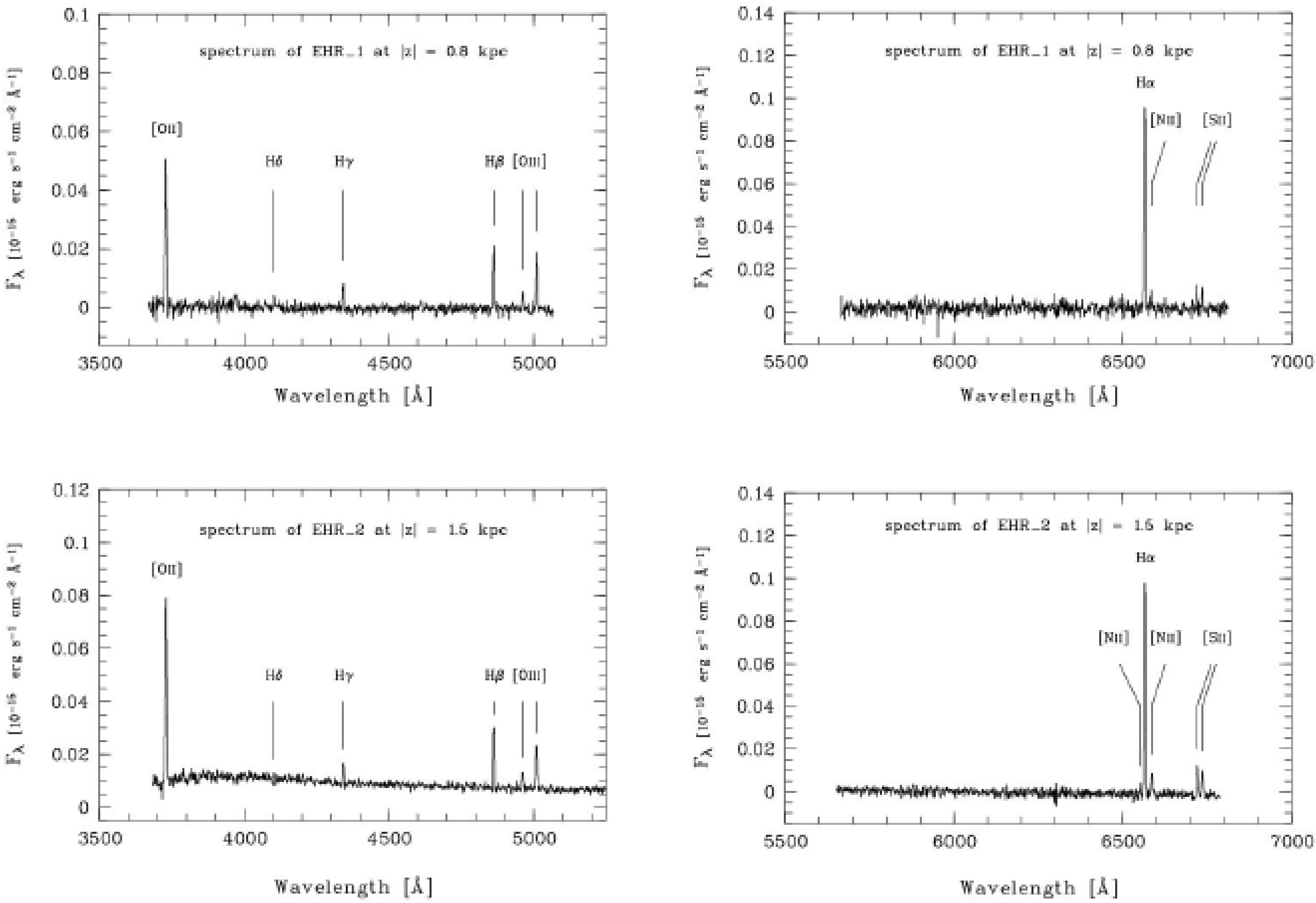


*Figure 4: Integrated spectra for both EHRs. Although their emission-line characteristics is similar to ordinary disc HII-regions, it appears that EHRs are ionised by a slightly softer radiation field, as implied by a significantly lower flux in the [OIII]λ5007 emission-line.*

located in the star forming disk below. As the DIG is no longer involved in star formation processes, it is expected to be also a good tracer of the metal content of the halo gas. The interested reader is referred to Dettmar (1992) for a comprehensive review.

## The Global Picture

Two important questions directly emanate from the ESF hypothesis: (a) how did gas reach the halo in a quantity to cool, collapse, and form neutral, dense clouds from which new stars were born, and (b) what triggered the collapse to actually form those stars?

The most simple and natural explanation is to assume that clustered SNe during an early burst of star formation ejected a significant amount of ionised material into the halo.

After star formation stopped the extraplanar gas had time to cool, collapse, and form dense molecular clouds. These molecular gas clouds, out of which EHRs have formed, can survive and collapse only in the period between two successive bursts of star formation.

Since both EHRs are located above the central part of NGC 55, it appears likely, that their formation was triggered by star formation activity in the disk below. In this global picture star formation in the disk could stimulate as well as terminate the creation of EHRs.

Future work will test the ESF scenario for a larger sample of galaxies, investigate initial formation conditions for EHRs, and check if the central stars can separate within their lifetime far enough from their birthplaces and contribute to the observed stellar halo population.

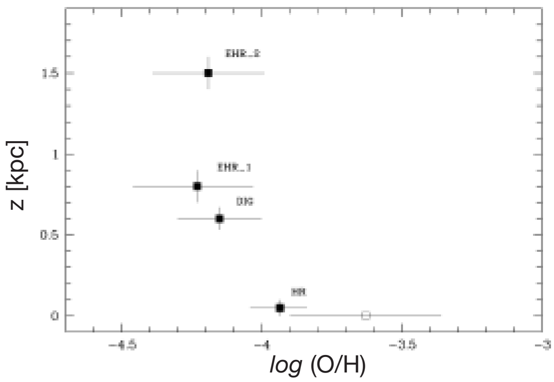


*Figure 5: Oxygen abundance as a function of |z|, the distance along the minor axis of NGC 55. The open symbol represents the averaged oxygen abundance for the disc, whereas the error bar represents data published by other authors. The data-point labelled "HR" has been slightly shifted along |z| to separate error bars. The one named "DIG" represents a special component of the ISM at intermediate |z|-distance (see text for details).*

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