A high excitation H\textsc{ii} region in the faint dwarf elliptical galaxy A0951+68

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ABSTRACT

We present the results of BVRI imaging and optical spectroscopy of the dwarf galaxy A0951+68. The images reveal that, although this galaxy is classified as a dwarf elliptical, it has some properties that are similar to dwarf irregular galaxies. It contains two bright knots of emission, one of which is red and unresolved and the other blue and resolved. The blue knot also shows a high excitation emission line spectrum. The observed line ratios indicate that this is an H\textsc{ii} region, although with some line ratios that are border-line with those in AGN. The emission line luminosity is consistent with ionisation by a single, very luminous O star, or several smaller O stars, but the extended blue light in the knot shows that this has occurred as part of a substantial recent star formation event. We find that the metal abundance, while low compared to typical large galaxies, actually seems to be high for such a low luminosity dwarf. The position of A0951 in the literature is incorrect and we provide the correct value.

Key words: extragalactic H\textsc{ii} regions – dwarf irregulars and ellipticals

1 INTRODUCTION

The galaxy A0951+68 is in the Kraan-Korteweg and Tamman (KKT) catalogue of nearby galaxies\textsuperscript{[1,2]} (Kraan-Korteweg & Tamman1979, Kraan-Korteweg 1986), where it is classified as a dwarf elliptical in the M81 group of galaxies. From this catalogue we have selected a complete, distance-limited subset, with a declination cut-off and excluding irregulars. A multi-wavelength survey of this subset, which includes A0951, is in progress. During the optical imaging of A0951+68, it was realised that its position in the KKT catalogue was incorrect. The source of this incorrect position was a paper by Bertola and Maffei (1974). Using the photographs presented in that paper we were able to locate and image A0951+68 at the correct position, roughly 10 arcminutes from the KKT catalogue position (see section \textsuperscript{[1]}). Our images showed two bright knots surrounded by low surface brightness emission. A search in the literature for objects at the new position of A0951 revealed two observations prior to those of the “discovery” of Bertola and Maffei. Karachentseva (1968) discovered the galaxy and named it Kar61. It was also contained in the list of Mailyan dwarf galaxies\textsuperscript{[3]}, where it was called Mailyan 47.

It was no longer clear whether A0951+68 was really faint and nearby, or more distant and luminous, since the KKT distance was from an HI measurement at the incorrect position (Huchtmeier & Richter 1989). HI maps in the literature do show emission at the correct position but it is unclear whether this is just a positional coincidence as there is extensive HI emission in the region around M81. An independent measurement of distance was required and to this end we obtained optical spectra of the two bright knots in the galaxy. One of the spectra showed very high-excitation emission lines, from which we were able to confirm that this galaxy is indeed an M81 group dwarf, but showing interesting behaviour, atypical of a dwarf elliptical. We have therefore taken the A0951 distance to be 3.63 Mpc, the same as the M81 distance (Freeman 1994).

2 OBSERVATIONS AND DATA REDUCTION

Optical images in the B,V,R and I bands were obtained using the Jacobus Kapteyn Telescope (JKT) on La Palma in February 1994. The EEV7 CCD used gives a spatial scale of 0.31 arcsec/pixel and an image size of 6'.5 × 6'.0. The seeing on this night was poor, FWHM approximately 2'.0. The spectra were also taken on La Palma, in January 1995, using the Intermediate Dispersion Spectrograph (IDS) on the Isaac Newton Telescope (INT). We used a TEK CCD and the R300V grating which has a dispersion of 3.29 A/pixel\textsuperscript{-1}. The FWHM of the arc lines is 8.24±0.62 A. The slit width used was 1'.5.
The optical images were reduced using the IRAF software package. They were debiased and flat-fielded, and calibrated using Landolt photometric standards, which give Johnson B,V and Kron-Cousins R and I magnitudes (Landolt 1974). Extinction and colour corrections were determined from these standards. The spectra were reduced using the FIGARO software package. Each object and standard frame was debiased and flat-fielded, and the frames were cleaned of cosmic rays. The sky was removed from each frame was debiased and flatfielded, and the frames wereing the code 1983). Extinction and colour corrections were deter-

Table 1. Comparison of $\sigma$ (arcsec) of Gaussian fits to stars and knots

|        | $\sigma_{stars}$ | $\sigma_{A0951A}$ | $\sigma_{A0951B}$ |
|--------|------------------|-------------------|-------------------|
| B      | 0.98             | (1.1)             | 1.38              |
| V      | 1.02             | 0.94              | 1.30              |
| R      | 0.78             | 0.79              | 1.20              |
| I      | 0.69             | 0.76              | (0.8)             |

3 RESULTS

3.1 Morphology, position and colours

Figure 1 shows the R image of A0951. There are two bright knots of emission, A0951A and A0951B, superimposed on diffuse low surface brightness emission. The knot A0951A appears to be close to the peak of the diffuse emission, whereas A0951B is towards the edge of the galaxy. Figure 2 shows cuts through the galaxy and both bright knots in the sky subtracted R and B images. This also shows the central position of A0951A and highlights the difference in colour between the two knots. To see whether the two knots of emission were resolved we fitted Gaussian profiles to each knot and to three stars in each frame. Table 2 gives the average value of sigma in arcseconds for the stars and for the two knots. The brackets indicate an estimation since there was not enough signal-to-noise to enable a gaussian fit. A0951A is unresolved at all wavelengths, A0951B is clearly resolved in B,V and R.

Table 3 gives the magnitudes of the knots and the diffuse emission. To measure the knot magnitudes the images were first smoothed so that the p.s.f in each image was the same as that in the image with the worst seeing. The magnitudes for the knots were measured inside a circular aper-

|        | B-V   | V-R   | V-I   |
|--------|-------|-------|-------|
| Knot A | 0.96  | 0.61  | 0.91  |
| Knot B | 0.01  | 0.11  | -0.25 |
| Diffuse| 0.53  | 0.49  | 0.99  |

The strongest lines in the spectrum, H$_\alpha$, $[O\,iii]\lambda\lambda 4959, 5007$, and $H_{\alpha}$ were used to calculate the recession velocity of A0951. Applying a correction for the earth’s orbit gives a heliocentric velocity of -134.73 km s$^{-1}$ ± 30 km s$^{-1}$. The first error here is the root mean square fitting error on the calculated velocity, the second is a systematic error due to the shift in the wavelength calibration during the night mentioned in section 3.2.

3.2 Spectrum

Figures 3 and 4 show the spectra of the two bright knots. Both spectra have featureless continua, but A0951B contains strong high excitation emission lines. The observed value of 3.19 for the Balmer decrement in A0951B is greater than the Case B recombination value of 2.86 (for T$_e$=10000 K and N$_e$=100 cm$^{-3}$). Using the reddening law in Savage and Mathis (1979) this implies an E(B-V) of 0.1. The galactic reddening in this direction gives an E(B-V) of 0.01 (Burstein & Heiles 1982). Table 3 lists the line identification, the observed wavelengths and the observed and de-reddened (assuming E(B-V)=0.1) line fluxes in A0951B.

To provide checks of the spectrum and image measurements, the flux of the spectra in wavelength bands roughly corresponding to the Johnson B,V and Kron-Cousins R,I filters was calculated and converted to magnitudes. Taking into account that the area of the object covered by the slit is less than the aperture used for the photometry, these magnitudes are consistent with those calculated from the images.

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The measured FWHM of the H$_\alpha$ line is 9.02 Å. Recalling that the FWHM of the arc lines is 8.24±0.62 Å, this implies...
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Figure 2. Cuts through the galaxy in the B and R images

Table 2. Magnitudes

| filter | Knot A | Knot B | Diffuse | limiting contour mag arcsec\(^{-2}\) | approximate size (arcsec) |
|--------|--------|--------|---------|--------------------------------------|----------------------------|
| B      | 21.63  | 19.81  | 17.22   | 26.5                                 | 43 × 30                    |
| V      | 20.67  | 19.80  | 15.68   | 26.5                                 | 89 × 60                    |
| R      | 20.06  | 19.69  | 15.10   | 26                                    | 94 × 63                    |
| I      | 19.77  | 20.04  | 14.64   | 26                                    | 92 × 56                    |

that the H\textalpha{} line is unresolved, and that, at 1\sigma{}, the intrinsic FWHM of H\textalpha{} < 272 kms\(^{-1}\). This is consistent with values of < 120 kms\(^{-1}\) found in other H\textsc{ii} regions.

4 DISCUSSION

A0951+68 has previously been classified as a dwarf elliptical from its smooth and symmetric appearance on photographic plates. The presence of A0951B was not known and the nature of A0951A was unclear - Karachentseva et al. (1968) thought it was a foreground star, whilst Bertola & Maffei (1974) were unable to tell whether it was a star or the nucleus of the galaxy. The knot A0951A is close to the centre of the inner isophotes and this part of the galaxy has the appearance of a nucleated dwarf elliptical. However, A0951B is a high excitation H\textsc{ii} region (see section 4.3), and this and the outer isophotes look more like an Im type irregular galaxy. In their atlas of Virgo galaxies, Sandage and Bingelli (1984) note that there are a few cases of unsure classification between dE and Im galaxies, but are unable to say whether this is due to a real evolutionary link between the two types.

The absolute V magnitude of A0951 within \(\mu V = 26.5\) is -12.12. This is at the faint end of a sample of M81 dwarf irregulars observed by Miller and Hodge (1994), which have \(M_V\) between -11.9 and -16.7.

Another property of A0951 that is similar to dwarf irregulars is its probable HI content. Several groups have published maps of the neutral hydrogen emission in the vicinity of M81 which include the position of A0951 (van der Hulst 1973; Appleton et al. 1981; Yun 1994). These all show neutral hydrogen at the position of A0951. The paper by van der Hulst (1973) contains velocity channel maps which show HI at the position of A0951 with a velocity of -140 kms\(^{-1}\), consistent with the velocity measured from our optical spectrum. However the large amount of HI in this region and the low spatial resolution of the maps means we cannot be entirely sure that the gas is coincident with A0951.
Figure 3. Spectrum of A0951A

Figure 4. Spectrum of A0951B
Table 4. A0951B Line Fluxes

| Line ID | \( \lambda_{\text{obs}} \) | \( F(\lambda)/F(H\beta)_{\text{obs}} \) | \( F_r(\lambda)/F_r(H\beta) \) |
|---------|-----------------|-----------------|-----------------|
| H\alpha | 4102 | 0.992 | 0.40 | 0.42 |
| H\beta | 4861 | 4858.9 | 1.0 | 1.0 |
| [O\text{iii}] | 4959 | 4956.4 | 2.72 | 2.70 |
| [O\text{iii}] | 5007 | 5004.5 | 7.75 | 7.68 |
| [N\text{ii}] | 6548 | 6545.9 | 0.11 | 0.10 |
| H\alpha | 6563 | 6559.7 | 3.19 | 2.86 |
| [N\text{ii}] | 6584 | 6580.1 | 0.30 | 0.27 |
| [S\text{ii}] | 6717 | 6713.1 | 0.14 | 0.12 |
| [S\text{ii}] | 6731 | 6728.4 | 0.09 | 0.08 |

Upper limits on undetected lines

| [O\text{ii}] | 3727 | \( \leq 1.38 \) | \( \leq 1.52 \) |
| [O\text{iii}] | 4363 | \( \leq 0.17 \) | \( \leq 0.18 \) |
| He\alpha | 4686 | \( \leq 0.14 \) | \( \leq 0.14 \) |
| [O\text{ii}] | 6300 | \( \leq 0.11 \) | \( \leq 0.10 \) |

Observed H\beta flux = \( 2.63 \times 10^{-15} \) erg s\(^{-1}\)cm\(^{-2}\) 

Reddening corrected H\beta flux = \( 3.71 \times 10^{-15} \) erg s\(^{-1}\)cm\(^{-2}\)

Col 1 Line Identification, Col 2 observed wavelength
Cols 3 & 4 Observed and reddenning corrected line fluxes relative to H\beta=1

4.1 Diffuse emission

The colours of A0951 can be used as well as the morphology to pin down its type. Figure 3 shows the colours of the two knots and the diffuse emission. The ordinate gives the colour to pin down its type. Figure 5 shows the colours of the two knots. The colours of A0951 can be used as well as the morphology of A0951A are reminiscent of these dwarf elliptical nuclei.

4.2 A0951A

Knot A has much redder colours than Knot B. The V-I colour is similar to that of the diffuse emission; the other colours are somewhat redder. As we do not have a redshift for this knot there is the possibility that it is a superimposed foreground star - in Figure 5 it can be seen that the colours of A0951A are closest to those of a G star. The B-V colour of A0951A is at the far red end of the colours of dwarf ellipticals in the Virgo and Fornax clusters. The B-V, V-R and R-I colours of A0951A are similar to those in a sample of low luminosity early type galaxies observed by Prugniel et al (1993). Some dwarf ellipticals are nucleated and these nuclei have similar colours to the surrounding emission. The colours and morphology of A0951A are reminiscent of these dwarf elliptical nuclei.

The spectrum of A0951A is flat and featureless. Held and Mould (1994) show spectra of dwarf elliptical nuclei. On the whole they are not as flat as A0951A. The most prominent feature in these spectra is the 4000Å break, unfortunately at this wavelength the spectrum of A0951A has very low signal to noise and although there is a hint of a break it is impossible to say whether it is real. The signal to noise in our spectrum is too low to observe the absorption features seen in these spectra.

4.3 A0951B

The spectrum of A0951B is very striking. The value of the \([\text{O\text{iii}}] \lambda 5007/\lambda 3968\) ratio is as high as that seen in active galaxies, but the \([\text{N\text{ii}}] \lambda 6584/\lambda 6563\) ratio is much lower, suggesting low metallicity. The different types of emission line object, H\text{ii} regions and galaxies, active galaxies and planetary nebulae can be separated by their positions on emission line ratio diagrams such as those of Veilleux and Osterbrock (1987) and Baldwin, Phillips and Terlevich (1981). In these diagrams A0951 occupies the area populated by H\text{ii} regions and H\text{ii} galaxies, though the \([\text{O\text{iii}}] \lambda 5007/\lambda 3968\) ratio in this galaxy is amongst the highest seen. A0951B is somewhat peculiar in that the few other H\text{ii} galaxies and regions that have a similar \([\text{O\text{iii}}] \lambda 5007/\lambda 3968\) ratio have even lower \([\text{N\text{ii}}] \lambda 6584/\lambda 6563\) ratios. The value of \([\text{N\text{ii}}] \lambda 6584/\lambda 6563\) in A0951B puts it in the transition region between H\text{ii} regions and AGN. Also (see below), although its metal content is low compared to typical large galaxies, it is actually high compared to other H\text{ii} galaxies of the same luminosity.
Figure 5. Colour of A0951 knots and diffuse emission. The ordinate is the colour relative to I, i.e. at B the value is B-I. The stellar population models are those in Worthey (1994) and Leitherer & Heckman (1995) (see sections 4.1 and 4.3). Both models are low metallicity, 0.1Z⊙.

The observed emission line ratios in H ii regions depend upon the properties of the ionized gas and on the ionizing stars. Some of these properties can be calculated directly from the observations, others can be found by comparing the observations with models of H ii regions.

From the observed emission lines in A0951B we can deduce the electron temperature and density of the gas, and the number of ionizing photons. The electron temperature in the O++ region can be found from the ratio of the [O iii] λλ 4959, 5007 doublet and [O iii] λ4363. The fluxes in table 4 give an upper limit to the temperature of 15500 K. The electron density can be estimated from the [S ii] λλ 6717, 6731 doublet; however this loses sensitivity at typical H ii galaxy densities of less than ≈ 200 cm−3. The density in A0951B is in this low density limit. The number of hydrogen ionizing photons, Q(H), emitted by the ionizing stars is given by the relationship $Q(H)(s^{-1}) = 7.31 \times 10^{39} L_{H\alpha} (\text{ergs}^{-1})$ (Osterbrock 1989). Using the reddening corrected Hα luminosity for A0951B gives Q(H) = 1.20 × 10^{49} s^{-1}. This number of ionizing photons could be produced by one star of spectral type O7 (T_e = 45200 K) or several stars of later type.

Two of the most recent H ii region models are those of Cervino and Mas-Hesse (1994) and García-Vargas, Bressan and Díaz (1995). Both these models vary the ionization parameter, the effective temperature of the ionizing cluster (T_e), and the metallicity of the gas, and calculate the emission line ratios produced. The ionization parameter, U, is defined as the ratio between the density of the ionizing photons and the density of particles ($U = Q(H)/4\pi cn_H r^2$), where $n_H$ is the density of ionized hydrogen). This depends on the number of ionizing photons, the density of hydrogen atoms and the radius of the H ii region, so knowing the first two of these parameters would enable us to estimate the radius of the H ii region. In fact we only have an upper limit on the density, but the interesting thing to work out is how the radius of the H ii region compares to the Stromgren radius, and the ratio of these two radii only depends upon (density)^1/6.

The aim of Cervino and Mas-Hesse was to calculate the dependence of the most commonly observed emission lines, those of oxygen, on these parameters. From our limits on the oxygen emission line ratios in A0951 we can deduce from their models that T_e is between 45000 and 55000 K and the...
oxygen abundance, log(O/H), between -4.2 (1/12 solar) and -3.8 (1/5 solar). They do not say what value of ionization parameter they use. They show the parameters derived from their models for a sample of H II galaxies (Terlevich 1991). Comparison of A0951B with these galaxies shows that it has a similar metal content to the average H II galaxy, but a much lower luminosity.

García-Vargas et al. model the behaviour of more emission lines, and look at the line ratios for different ages of the ionizing star cluster (and hence different $T_e$) and for varying metallicity and ionization parameter. Their models suggest that A0951 has a metallicity, Z, between 0.001 (1/17 $Z_{\odot}$) and 0.008 (1/2 $Z_{\odot}$), an age between 2 and 5.2 Myrs (implying a $T_e$ between 40000 and 50000K), and an ionization parameter, log U, between -2.7 and -2.4. From this we can deduce that the radius of the H II region is the same as the radius of a Strömgren sphere of an O7 star. The range of effective temperatures implied by these models, combined with the number of ionizing photons is consistent with ionization by a single such O star, or a few, later-type O stars.

It is interesting to compare A0951 with GR8, a dwarf irregular in the local group (Skillman et al. 1988). While their total absolute magnitudes (-12.1 and -10.7) and H II region luminosities ($L(H\beta) = 1.4 \times 10^{36}$ and $5.8 \times 10^{36}$) are comparable, the metal content of A0951 seems to be much higher than that of GR8 or other star forming regions of the same total luminosity. This may suggest a different chemical evolution history for A0951, perhaps related to the fact that A0951 is not a dwarf irregular. Clearly a better estimate of the metal abundances is needed.

The Hα luminosity of A0951B is $1.64 \times 10^{37}$ erg s$^{-1}$. This is at the low end of the range of luminosities seen in dwarf irregulars. It is interesting to note that one of the dwarf irregular HII regions observed by Hunter and Gallagher (1983) has an ionizing source of a single O star, and similar line ratios to A0951B with $[OIII] \lambda 5007/\beta = 6.18$. The Hβ equivalent width in A0951B is 92.8 Å which is higher than the mean equivalent width in the Terlevich et al. (1991) sample of H II galaxies and is indicative of a young stellar population.

The emission-line region that we have been discussing occurs somewhere inside the resolved blue knot A0951B, which is clearly much bigger and more luminous than a single O star. The colours of knot A0951B are similar to those in resolved regions of star formation found in some Virgo dwarf irregulars by Bothun et al. (1982). A recent paper by Leitherer & Heckman (1993) shows the change in colours of a model starburst galaxy with metallicity and age. Their model for a metallicity of 0.1 $Z_{\odot}$ and an age of 4.4 Myr (chosen to be consistent with the values deduced from the spectrum) is shown in Figure 4. The solid line is for an instantaneous burst and the dashed line for continuous star formation. It can be seen that the model colours are reasonably similar to the colours of A0951B. We conclude that A0951B is a region of very recent star formation which in particular contains an H II region ionized by at most a few O stars, with an effective temperature of around 45000-50000K.

5 CONCLUSIONS

Optical images and spectroscopy of the M81 dwarf A0951+68 have provided a few surprises, not least that the published position of the galaxy was incorrect. We have calculated a new position. Another surprise was the presence in this supposed dwarf elliptical galaxy of an H II region, with very high excitation. H II region models suggest that the ionizing source is a single very luminous O7 star, or a few later-type O stars. The colours of the knot A0951B, which contains this H II region, are consistent with it being a star formation region. The colours of the diffuse emission in A0951, the presence of the star forming region and also the fact that it probably contains H I gas make A0951 more like a dwarf irregular than a dwarf elliptical. However, the knot of emission at the centre of the inner isophotes (A0951A) has colours that are similar to those of low luminosity ellipticals and is reminiscent of the nuclei seen in some dwarf elliptical galaxies.

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