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Letter to the Editor

Optical studies of the blue compact dwarf galaxy Tol 65 with the VLT

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Abstract. The photometric properties of the extremely metal-deficient ($Z_\odot$/24) i0–BCD Tol 65 are investigated using broad-band data obtained with VLT/FORS. A prime objective of this study is the detection and analysis of the structural properties of the putative low-surface brightness (LSB) stellar continuum underlying the extended starburst component. Our deep ($\mu_{\rm B} \gtrsim$ 28 mag/$\Box''$) VLT data reveal an unresolved irregular LSB host, dominating the light for surface brightness levels fainter than 25 B mag/$\Box''$. The intensity distribution as determined in its outskirts can be well approximated by an exponential fitting law and a flattening inside a radius of $\sim$0.6 kpc, equivalent to $\sim$2.4 exponential scale lengths. The age of this stellar component as inferred from radially averaged colour profiles is of the order of 10^8 yr. The luminosity of the starburst component of Tol 65 is contributed primarily by an assembly of at least five distinct luminous knots arranged over a projected linear scale of 1 kpc and giving rise to ample gaseous emission on scales of several hundred pc.

The properties of a faint LSB source discovered by the present observations in the immediate vicinity of Tol 65 are intriguing. Provided that it lies at the distance of the BCD, its absolute B magnitude and exponential scale length make it one of the most compact LSB dwarf galaxies detected so far. The properties of this source then prove remarkably similar to those inferred for a virtually inactive companion of another extremely metal-deficient young galaxy candidate, the i0–BCD I Zw 18. It will be important to explore whether such faint companions are common and may have formed in a preceding activity period from the same H I envelope as the currently active BCD.

Key words: galaxies: individual: Tol 65 – galaxies: compact – galaxies: dwarf – galaxies: starburst – galaxies: structure – galaxies: photometry

1. Introduction

There is compelling evidence that Blue Compact Dwarf Galaxies (BCDs) are in their overwhelming majority evolved (several Gyr old) dwarf galaxies undergoing brief ($\lesssim 10^7$ yr) starburst episodes, separated by longer quiescent (several 10^8 yr) phases. A strong argument in favour of a high age is the detection of a red low-surface-brightness (LSB) stellar envelope underlying the regions of active star formation (Loose & Thuan 1985, Kunth et al. 1988) with an isophotal radius typically twice of that of the starburst component (Papaderos et al. 1996b).

In a small fraction of BCDs, classified as "i0" type in the scheme of Loose & Thuan (1985), no LSB host galaxy was detected, thus the interpretation as old evolved systems being no longer compelling. The apparent lack of any conspicuous old stellar background along with strongly subsolar metallicity ($Z_\odot$/20) have been taken as indicators for young dwarf galaxies with ages $\lesssim 10^8$ yr (cf. Izotov & Thuan 1999).

We focus here on one of these rare nearby candidates, the BCD Tol 65 (D=36 Mpc; Thuan & Izotov 1997) with the low metallicity $Z_\odot$/24 (Kunth & Sargent 1983, Masegosa et al. 1994). CCD–imaging of Tol 65 was first presented by Kunth et al. (1988). They found a pair of bright starburst knots located close to the northeastern tip of a faint LSB host, while little became known concerning the detailed morphology and structural properties of any diffuse stellar population possibly underlying this starburst component. This knowledge is crucial, however, for an assessment of the evolutionary state of this BCD. As a first step, we study here the structure of the starburst together with that of the faint LSB host of Tol 65 by means of deep VLT surface photometry.

2. Observations and results

Exposures of Tol 65 in the broad-band filters Bessell U, B, R were obtained with the Focal Reducer and low dispersion Spectrograph (FORS 1) attached to the VLT UT1. The data were acquired under photometric conditions during a 6-night GTO run on May, 14th 1999 at an air mass ranging between 1.22 and 1.28. FORS was operating in the standard imaging mode yielding a final focal ratio of 3.13 and an instrumental scale of $0\farcs2$ pix^{-1}. The integration time, mean sky surface brightness and seeing for each exposure are included in Cols. 2–4 of Table 1. Details on the data processing may be found in Fricke et al.

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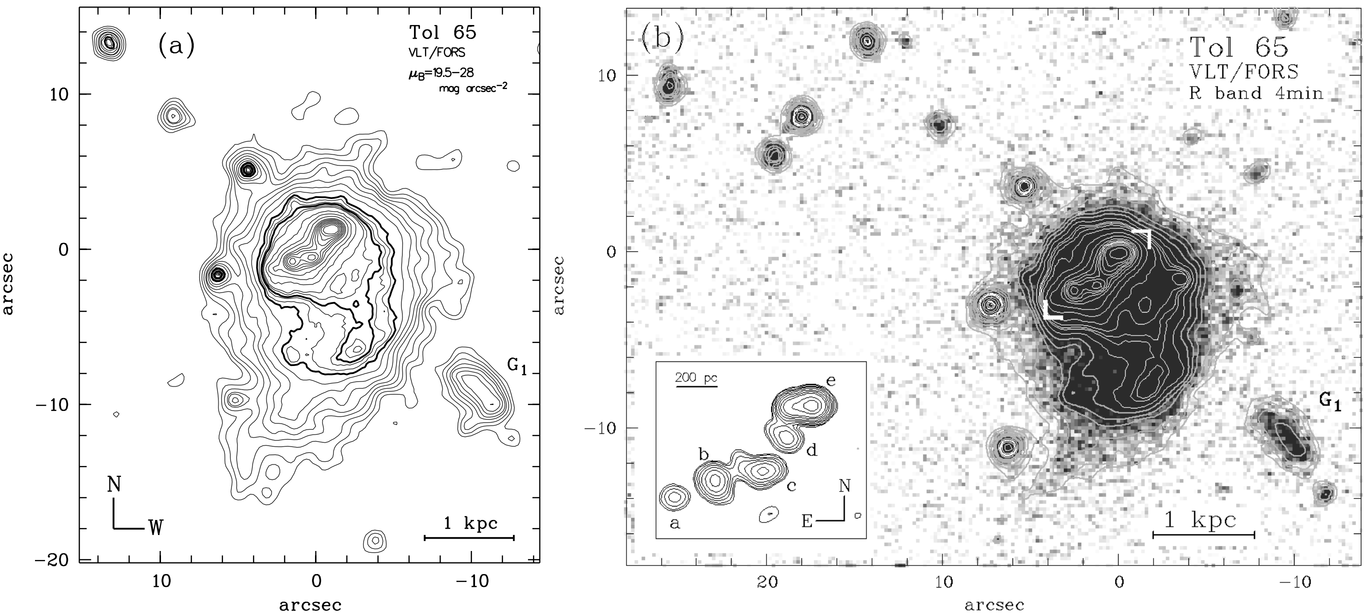

Fig. 1. a: Contour map of a B band exposure of the i0–BCD Tol 65 (D=36 Mpc) obtained with the VLT/FORS. Contours, corrected for galactic extinction, cover a range in surface brightness from 19.5 to 28 B mag/□$''$. The irregular arc–like pattern protruding $\sim$9$''$ to the southwestern direction of the starburst region (axis origin; $(\alpha,\delta)_{2000}$: $12^{\rm h}25^{\rm m}46^{\rm s}.5$, –36°14$'$ 1$''$) is delineated by the thick contours corresponding to 23.35 and 24.0 B mag/□$''$. The faint source G_1 ($(\alpha,\delta)_{2000}$: $12^{\rm h}25^{\rm m}45^{\rm s}.6$, –36°14$'$ 10$''$) located $\sim 14''$southwest of the intensity maximum of the BCD has not been detected previously. **b**: R band exposure of Tol 65. The inset at the lower-left displays a contour map of a contrast-enhanced 6$''\times$5$''$ subframe centered at the high-surface-brightness starburst component of the BCD (the region located between the rectangular brackets on the gray-scale map).

(1999) where the photometric properties of another extremely metal-deficient BCD, Tol 1214-277, observed during the same GTO run are investigated.

2.1. The starburst component of Tol 65

According to the classification scheme by Loose & Thuan (1985) Tol 65 belongs to the i0–BCD class. These rare objects are characterized, unlike the majority of iE/nE–BCDs, by the virtual absence of any low-surface-brightness (LSB) stellar component underlying the regions of active star formation. This holds at least down to a surface brightness level of $\lesssim$25 B mag/□$''$. The lack of an old extended LSB host down to this intensity limit may be interpreted in at least two ways: (i) the surface density of the diffuse stellar background is extremely low – a property compatible with a relatively young age, or (ii) the faint stellar host is “buried” within the extended emission region of a galaxy-wide starburst. Evidently, only very sensitive photometric studies reaching a surface brightness level well below the limit stated above (e.g. $\mu_{\rm B} \gtrsim 26.5$ mag/□$''$) are required for discriminating between the two possibilities.

Fig. 1a illustrates the irregular morphology of both, the high-surface brightness (HSB) component (<23 B mag/□$''$) and the LSB component (>25 B mag/□$''$) of Tol 65. The prime luminosity source in the HSB component is an assembly of intense starburst knots, moderately resolved in the contour map Fig. 1a. A modified unsharp-mask technique (Papaderos 1998) reveals within the starburst region of the BCD a chain of five compact ($1''\!.2 \lesssim \oslash \lesssim 1''\!.6$) HSB sources ($\overline{\mu} \lesssim 20$ B mag/□$''$) over a projected linear scale of $\sim$1 kpc along the SE-NW direction (cf. inset in Fig. 1b). The apparent B magnitudes of these knots, separated typically by $\sim$200 pc, range between 22.8 mag (a) and 19.3 mag (e) with an uncertainty of 0.15 mag. With the adopted distance modulus of m–M=32.78 to Tol 65 they translate into absolute B magnitudes from $\sim$–10 mag to –13.5 mag, respectively. These values put these knots in the luminosity range of Super-Star Clusters (SSC; O’Connell et al. 1994). It is worth noting that the integrated light of these five compact sources (18.4$\pm$0.17 B mag) amounts to $\sim$3/4 of the B luminosity of the starburst component within its isophotal radius at 25 mag/□$''$ (cf. Table 1; col. 8). The stellar luminosity output of the SSC candidates shown in Fig. 1b must therefore be accompanied by surrounding diffuse emission either from extended ionized gas or from point sources having low mean surface brightness. The latter will be hardly traceable in the presence of an intense local background (<22.5 B mag/□$''$).

Indeed, the presence of copious gaseous emission in the vicinity of the SSC candidates is confirmed by the colour maps of Tol 65 (Fig. 3). The (U–B) map (panel a) reveals two diffuse blue (–1.05$\pm$0.06 mag) regions located opposite to each other at the tips of the SSC sequence and having angular extents of 3$''\times$3$''$ (*nw*) and $6''\!.5\times2''\!.5$ (*se*), respectively. The (B–R) map (panel b) uncovers a strikingly different colour pattern. The bluest (B–R) colours (+0.15$\pm$0.05 mag) are observed midway of the chain, close to the sources b and c (cf. inset in Fig. 1b) while the detached regions *se* and *nw* were found to be partly redder

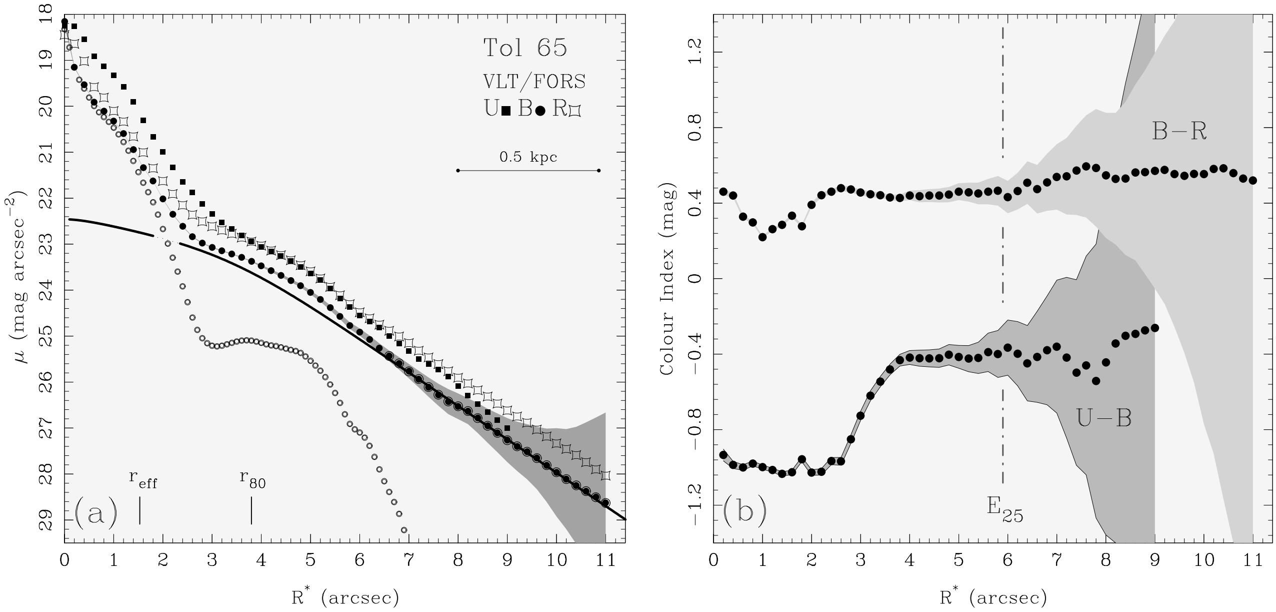

Fig. 2. a: Surface brightness profiles (SBPs) of Tol 65 in U, B, R corrected for extinction. The radii $r_{\rm eff}$ and r_{80} encircling, respectively, 50% and 80% of the total B band luminosity are indicated. Similar to the BCD Tol 1214-277 (Fricke et al. 1999) we adopted a modified exponential fitting law flattening at the center (thick curve) to approximate the radial intensity distribution of the underlying LSB component. The surface brightness distribution owing to the compact starburst source and to an assembly of compact and diffuse sources contributing to the light at intermediate (~ 24 B mag/□″) intensity levels (open circles) is being inferred from the luminosity in excess of the modelled intensity distribution of the LSB component. **b**: Radially averaged (U–B) and (B–R) colour profiles of Tol 65 computed by subtraction of SBPs displayed in panel a. The isophotal radius E_{25} of the LSB host at 25 B mag/□″ is indicated.

Table 1. Photometric properties of the starburst and LSB component of Tol 65.

Band	t	sky	seeing	$\mu_{\rm E,0}$	α	P_{25}	$m_{P_{25}}$	E_{25}	$m_{E_{25}}$	$m_{\rm SBP}$	$r_{\rm eff}$,r_{80}
	min	mag/□″	″	mag/□″	pc	kpc	mag	kpc	mag	mag	kpc
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
U	10	21.88±0.09	0.″69±0.″02	19.80±0.6	241±63	0.50	16.99	1.16	17.62	16.49±0.05	0.24, 0.50
B	6	22.49±0.04	0.″64±0.″02	20.71±0.4	261±27	0.48	18.00	1.03	18.50	17.34±0.04	0.27, 0.66
R	4	20.72±0.02	0.″62±0.″01	20.07±0.3	260±20	0.45	17.76	1.19	17.80	16.96±0.03	0.28, 0.70

All values listed in Table 1 are corrected for extinction ($A_{\rm U}$=0.34 mag, $A_{\rm B}$=0.28 mag, $A_{\rm R}$=0.16 mag). A distance of 36 Mpc to Tol 65 has been adopted throughout. Note that the central surface brightness $\mu_{\rm E,0}$ listed in col. 5 refers to the value one would obtain by extrapolation of the exponential profile slope observed for radii $R^* \geq 7''$ to $R^*=0''$. A more appropriate model for the intensity distribution of the LSB host (Fig. 2a; thick curve) implies for all bands a central surface brightness being by 1.75 mag fainter than the listed quantity $\mu_{\rm E,0}$.

than the LSB host with average colours of (+0.38±0.06) mag and (+0.54±0.04) mag, respectively. The colours observed at the northeastern part of Tol 65 bear witness to a significant contribution by ionized gas to the line-of-sight intensity on scales of $\sim$ 500 pc from the starburst knots. Here strong emission lines, such as [O II]$\lambda\lambda$3726,3729 and Hα, may conspiciously influence the colours. Krüger (1992) derives (U–B) and (B–R) indices of an H II region of –1.3 and +1.1 for solar metallicity and of –0.59 and +0.48 if a metallicity 1/20 $Z_\odot$ is assumed, i.e. colours in the range observed in regions *se* and *nw*.

From these findings the presence of a kinematically perturbed gaseous component in the vicinity of the starburst nucleus seems likely. Indirect support to this hypothesis is provided by UV observations of Tol 65 by Thuan & Izotov (1997) revealing a blueshifted O Iλ1302 absorption feature in the HST GHRS spectrum of the BCD. This absorption feature may be attributed to an expansion of the H I layer of the BCD with a velocity $\sim$ 200 km s^{-1} . The identification of Tol 65 with a damped Lyα system with an absorbing column density of (2.5±1)×10^{21} cm^{-2} (Thuan & Izotov 1997) indicates, however, that the starburst has not markedly disrupted the shielding H I halo.

2.2. Surface photometry

Surface brightness profiles (SBPs) were derived using methods outlined in Papaderos et al. (1996a; hereafter P96a). After correction for extinction they were interpreted in terms of a simplified starburst/LSB decomposition scheme (cf. Fig. 2a). Table 1 summarizes photometric quantities derived therefrom: Cols. (5&6) list the central surface brightness $\mu_{\rm E,0}$ and exponential scale length α of the LSB host as obtained from lin-

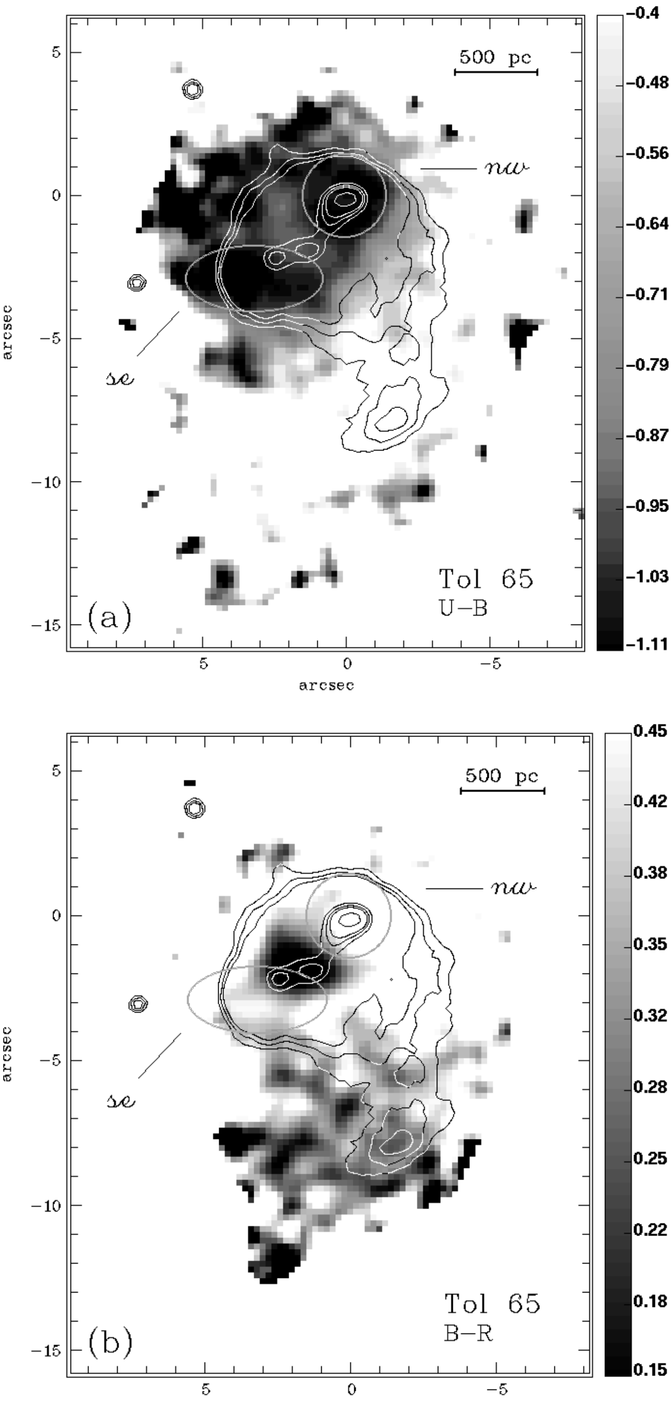

Fig. 3. a: (U–B) map of Tol 65. The overlaid contours correspond to surface brightness levels from 19.5 to 20.5 B mag/□″ (inner contours) and 23.1 to 23.55 B mag/□″ (outer contours). The bluest colours (U–B$\lesssim$–1 mag) are encountered within two diffuse regions labelled *se*&*nw*, located at the opposite tips of the putative SSC chain shown in Fig. 1b. **b**: (B–R) map of Tol 65. The contours have the same meaning as in panel a. At variance with the trend seen in the (U–B) map, the bluest region (B–R=0.15$\pm$0.05 mag) is confined to the central part of the elongated starburst region. The colours of the LSB host show a considerable scatter with –0.4$\lesssim$(U–B)$\lesssim$–0.26 and 0.3$\lesssim$(B–R)$\lesssim$0.6.

ear fits to the SBPs for $R^* \geq 7''$, weighted by the photometric uncertainty of each point. Cols. (7&9) list, respectively, the radial extents P_{25} and E_{25} of the starburst– and LSB components, both determined at a surface brightness level of 25 mag/□″. Cols. (8&10) contain the apparent magnitudes of the above mentioned photometric components within P_{25} and E_{25}, respectively, and col. (11) the apparent magnitude as derived from integration of each SBP out to the last measured point. Finally, col. (12) lists the effective radius $r_{\rm eff}$ and the radius r_{80}, encircling 80% of the galaxy's total flux. As it may be seen from the SBPs (Fig. 2a), an inwards extrapolation of the exponential intensity slope of the LSB host for photometric radii $R^*{\geq}7''$ implies for an intermediate galactocentric radius around 3″ a slightly higher intensity than the one observed. Thus, as in the case of the BCD Tol 1214-277 (cf. Fricke et al. 1999) the intensity distribution of the LSB host of Tol 65 was approximated by a modified exponential fitting law flattening for radii $R^*{\lesssim}r_{80}$. By fitting the latter distribution to the SBP of Tol 65 (Fig. 2a; thick curve) we obtain a parameter set (b,q)=(2.4,0.8) (cf. P96a; Eqs. 22&23) implying an intensity depression for radii smaller than 2.4 exponential scale lengths and a central intensity of 20% of the one predicted by the extrapolation of a pure exponential distribution to R^*=0″. Subtraction of the latter fit from the integral intensity profile reproduces adequately the central intensity excess as well as the more extended emission owing to the asymmetric luminosity pattern by compact and diffuse sources discernible out to 9″ southwest of the starburst region. The latter photometric component of the BCD having a medium surface brightness is reflected in the formation of a "plateau" in the residual surface brightness distribution for radii 3″ to 5.″5 (Fig. 2a; open circles). This feature, observed at varying strengths in the SBPs of iE–BCDs (cf. P96a), provides ∼20% of the line-of-sight B band emission of Tol 65 at the radius r_{80} and makes a non-negligible contribution (∼10%) even out to its isophotal radius E_{25}.

The impact of the starburst on the radially averaged colours of Tol 65 is evident from the (U–B) profile (Fig. 2b) showing a very blue index of ∼–1 mag within $R^*{\sim}3''$. With increasing radius the (U–B) index becomes gradually redder and for a galactocentric distance $\gtrsim$700 pc (4″) it levels off to a nearly constant value of ∼–0.4 mag. Thus, the ongoing burst effects a strong ($\lesssim$0.6 mag) colour shift within a region not exceeding 50% of the isophotal size of the BCD at 25 B mag/□″. In that respect Tol 65 differs markedly from another extremely metal-deficient i0–BCD, SBS 0335-052. Unlike Tol 65, the latter system shows a blue (∼–0.75 mag) nearly constant (U–B) index out to its periphery (Papaderos et al. 1998), a fact consistent with its overall more filamentary structure. The average (U–B) and (B–R) colours of the LSB host for radii $R^*{\geq}4''$ amount to (–0.4$\pm$0.08) mag and (+0.52$\pm$0.06) mag, respectively, being compatible with those of a stellar system having an age of the order of 10^8 yr, if an instantaneous formation process is assumed. On the other hand, as it was emphasized in Papaderos et al. (1998) no tight constraints on the age of such a system may be drawn lacking deep spectroscopic data. These are necessary for quantifying a potentially significant colour shift due to the emission by ionized gas possibly not being negligible even at the outskirts of Tol 65.

2.3. The nearby object G_1

The morphology and the (B–R) colour of (0.75±0.1) mag of the faint (22.4±0.06 B mag) compact ($r_{\rm eff}$=1.″2) source G_1 suggest that this source is an LSB satellite of Tol 65 rather than being a background galaxy. Indeed, its mean surface brightness of $\overline{\mu} = 25.4$ B mag/□″ is equal to the one derived by Thuan (1985) for a sample of LSB dIs within their Holmberg radii and by $\gtrsim$1 mag fainter than the average value for the underlying stellar hosts of iE/nE–BCDs ($\overline{\mu_{26.5}}$=24±0.1 mag/□″; Papaderos et al. 1996b). Its SBP shows for $R^*>1.''5$ an exponential intensity slope flattening-off to $\mu_{\rm B}\approx$24.5 mag/□″ for smaller radii. Assuming that the adjacent source G_1 lies at the same redshift as the BCD we derive an absolute B magnitude, corrected for extinction, of –10.7 mag and a very small exponential scale length of (90±30) pc.

It is worth comparing other BCDs for similar close companions. Such an example offers component B of the nE–BCD UM 465, for which Doublier et al. (1999) obtain an absolute B-magnitude of $M_{\rm B}$=–13.5 mag and an exponential scale length of ~ 150 pc. An even closer resemblance to feature G_1 may bear a faint, nearly inactive companion of the extremely metal-deficient i0–BCD I Zw 18. VLA-studies (van Zee et al. 1998) indicate that this detached constituent of I Zw 18, designated "C" (cf. Dufour et al. 1996), is a low-mass stellar system immersed within a common H I halo together with the well-known double starburst-nucleus. By the commonly adopted distance of 10 Mpc to I Zw 18, surface photometry studies by Izotov et al. (1999) imply for component C an absolute magnitude ∼–11 B mag and an exponential scale length of ∼87 pc, i.e. very close to the parameters we derive for G_1.

Such close companions which may so far have escaped detection in many BCDs, are not to be confused with the intrinsically brighter interaction candidates reported for a few BCDs, such as Tol 1214-416 (Östlin 1998) and II Zw 33 B (Walter et al. 1997); their origin and nature remains puzzling. A hypothesis worth investigating might be that such systems are gravitationally bound remnants of a preceding burst within the same H I-complex later forming the BCD. At a later evolutionary stage both components will possibly merge into one system. In this case such weak components, although difficult to detect, may generally not be uncommon in the vicinity of BCDs.

3. Discussion and summary

Tol 65 may be considered an outstanding example of an i0–BCD. The present studies show that discrete and diffuse luminosity sources attributable to the ongoing and recent star-formation activity are spread over a major fraction of its isophotal size at 25 B mag/□″ and provide more than one half of the optical emission encircled therein. An elaborated study of the diffuse stellar continuum supposed to underly the extended starburst component will therefore be a challenging task. The available deep ($\mu_{\rm B} \gtrsim 28$ mag/□″) VLT data definitely reveal an unresolved irregular LSB host dominating the light for surface brightness levels fainter than 25 B mag/□″. Its intensity distribution as determined in its outskirts can be well approximated by an exponential fitting law flattening inside a radius equivalent to ∼2.4 exponential scale lengths. The radially averaged colours of this asymmetric underlying host analyzed in the present study are consistent with an age significantly lower than 1 Gyr. Two-dimensional colour maps reveal conspicuous local departures from the radially averaged colour indices, indicating that extended emission by ionized gas may contaminate the observed light on scales of several hundred pc from the starburst region. These findings urge deep optical spectrophotometry combined with NIR imaging for better constraining the physical state of the unresolved LSB host in Tol 65.

The detection of a detached faint LSB source (G_1) in the immediate vicinity of Tol 65 is puzzling. Provided that it lies at the distance of the BCD, its absolute B magnitude (–10.7 mag) and exponential scale length (∼90 pc) make it one of the most compact LSB dwarf galaxies detected so far. If true, component G_1 proves remarkably similar to the virtually inactive companion (component C) of a further extremely metal-deficient and likewise young galaxy candidate, the i0–BCD I Zw 18. This prompts the question whether such faint companions are not interacting counterparts in the usual sense, but rather systems formed during a preceding activity episode within the H I halo shared with the currently active BCD. The further evolution or possible merging of such a stellar entity with the BCD may hold important clues for the build-up of the extended LSB component in the majority of BCDs. Owing to this possible evolutionary role of close LSB-companions it might be worthwhile to search for this phenomenon with a dedicated deep-imaging and spectroscopic survey.

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