The faint outer regions of the Pegasus dwarf irregular galaxy: a much larger and undisturbed galaxy

Alexei Y. Kniazev,¹,²* Noah Brosch,³ G. Lyle Hoffman,⁴ Eva K. Grebel,⁵ Daniel B. Zucker⁶,⁷,⁸ and Simon A. Pustilnik⁹,¹⁰

¹South African Astronomical Observatory, PO Box 9, 7935, Cape Town, South Africa
²Southern African Large Telescope Foundation, PO Box 9, 7935, Cape Town, South Africa
³The Wise Observatory and the Raymond and Beverly Sackler School of Physics and Astronomy, the Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel
⁴Department of Physics, Lafayette College, Easton, PA 18042, USA
⁵Astronomisches Rechen-Institut, Zentrum f¨ur Astronomie der Universit¨at Heidelberg, M¨onchhofstr. 12–14, D-69120 Heidelberg, Germany
⁶Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA
⁷Department of Physics, Macquarie University, North Ryde, NSW 2109, Australia
⁸Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia
⁹Special Astrophysical Observatory, Nizhnij Arkhyz, Karachai-Circassia, 369167, Russia
¹⁰Isaac Newton Institute of Chile, SAO Branch, Nizhnij Arkhyz, Russia

Accepted 2009 August 21. Received 2009 August 19; in original form 2009 January 18

ABSTRACT

We investigate the spatial extent and structure of the Pegasus dwarf irregular galaxy (PegDIG) using deep, wide-field, multicolour CCD photometry from the Sloan Digital Sky Survey (SDSS) and new deep H I observations. We study an area of ∼0.6 deg² centred on the Pegasus dwarf that was imaged by the SDSS. Using effective filtering in colour–magnitude space, we reduce the contamination by foreground Galactic field stars and significantly increase the contrast in the outer regions of the Pegasus dwarf.

Our extended surface photometry reaches down to a surface brightness magnitude $\mu_r \approx 32$ mag arcsec$^{-2}$. It reveals a stellar body with a diameter of $\sim 8$ kpc that follows a Sérsic surface brightness distribution law, which is composed of a significantly older stellar population than that observed in the $\sim 2$ kpc main body. The galaxy is at least five times more extended than listed in the NASA/IPAC Extragalactic Database. The faint extensions of the galaxy are not equally distributed around its circumference; the north-west end is more jagged than the south-east end. We also identified a number of stellar concentrations, possibly stellar associations, arranged in a ring around the main luminous body.

New H I observations were collected at the Arecibo Observatory as part of the Arecibo Legacy Fast ALFA survey. They reveal an H I distribution somewhat elongated in RA and about 0′:3 wide, with the region of highest column density coincident with the luminous galaxy. The H I rotation curve shows a solid-body rotation behaviour, with opposite ends differing by 15 km s$^{-1}$. There is a stream to lower velocities about 5 arcmin from the centre of the galaxy.

We were able to measure $ugriz$ colours in a number of apertures using the SDSS data and compared these with predictions of evolutionary synthesis models. The results indicate that the outermost regions of the PegDIG are 5–10 Gyr old, while the inner kpc contains stars $\sim 1$ Gyr old and younger. The colours correspond to K stars; earlier subclasses are located in the innermost parts of the galaxy. The PegDIG appears to be a relatively low-mass object, with

*E-mail: akniazev@saao.ac.za
1 INTRODUCTION

The Local Group (LG), our immediate neighbourhood, is the group of galaxies in which our Milky Way galaxy formed and is evolving. The Milky Way and M31 are the two dominant spiral galaxies in the LG, and each is surrounded by an entourage of lower mass companions. This kind of a binary structure is found in nearby galaxy groups as well (e.g. Karachentsev et al. 2002a,b, 2003). Apart from the late-type spiral M33, more than 50 galaxies forming the LG are either dwarf elliptical (dE), dwarf spheroidal (dSph) or dwarf irregular (dIrr) galaxies. Grebel (2001) characterized galaxies as dwarf galaxies if their total B- or V-band magnitude is fainter than −18 mag. While the primary distinguishing feature between dlrrs and dSphs is whether they have or do not have H I, there are other distinguishing features. dIrr galaxies typically have central surface brightnesses of $\mu_{V,0} \leq 23$ mag arcsec$^{-2}$ and total HI masses $M_{HI} \leq 10^9 M_\odot$. As their name suggests, their optical appearance is irregular, which tends to be caused by scattered HI regions for the more massive dlrrs. They are mainly found at larger distances from massive galaxies. dEs are spherical or elliptical in appearance, typically with $M_V \geq -17$ mag, and have $\mu_{V,0} \leq 21$ mag arcsec$^{-2}$ and $M_{HI} \leq 10^8 M_\odot$. Along with the dSphs, they are usually found in the vicinity of massive galaxies. dSphs tend to have $M_V \geq -14$ mag, $\mu_{V,0} \geq 22$ mag arcsec$^{-2}$ and $M_{HI} \leq 10^5 M_\odot$. See Grebel (2001) for further details.

Dwarf galaxies are, in principle, simpler systems than large galaxies. However, those objects studied in detail showed that even dwarf systems are complex in terms of their extended star formation (SF) histories and chemical evolution (e.g. Grebel 1997; Mateo 1998). Moreover, in the LG there is evidence for past interactions among some of its galaxies, including the accretion of dwarf galaxies by the two large spirals (e.g. Ibata, Gilmore & Irwin 1994; Ibata et al. 2001; Yanny et al. 2003; Zucker et al. 2004; Belokurov et al. 2007a; Bell et al. 2008).

The LG member galaxies reside currently in a volume with a radius of $\sim 1$–$1.2$ Mpc and their integrated mass is estimated to be between $(1.3 \pm 0.3) \times 10^{12}$ and $-(2.3 \pm 0.6) \times 10^{12} M_\odot$ (Courteau & van den Bergh 1999; Karachentsev et al. 2002c). The LG is the best-studied galaxy group thus far and includes the faintest dwarf galaxies ever detected (e.g. Belokurov et al. 2006, 2007b; Zucker et al. 2006). The dwarf, low-luminosity bodies in the LG all contain old populations (Grebel & Gallagher 2004) and may represent relics from the reionization epoch (Gnedin & Kravtsov 2006). Finally, there are persistent claims that dwarf galaxies are dark matter (DM) dominated. Studying their properties in the LG, the place where the most detailed work can be done, is a step towards understanding the nature of DM (e.g. Gilmore et al. 2007).

It is important to determine how large a galaxy is in any observational band. The apparent size alters the baryonic mass estimate and shows how extended the stellar component is in comparison to the gas. This also has implications on the possible evolution of the object, because the larger a galaxy’ cross-section, the higher are its chances of having interacted with other galaxies since its formation. The shape of the outer regions of a galaxy is a particularly sensitive indicator of past interactions; these tend to strip away stars and interstellar medium (ISM) creating tidal tails and spreading debris in the vicinity of a galaxy. However, it is very difficult to determine the morphology of the outer extremely faint surface brightness regions for galaxies in the LG. Their closeness implies a large angular extent. If the coverage of faint surface brightness levels over large areas is required, the necessary observing time for direct, wide-field imaging becomes prohibitive. In addition, it is important to note that distorted galaxy shapes at low-light levels can be an artefact of the Poisson scatter (Martin, de Jong & Rix 2008).

The availability of imaging data from the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002) offers a new and different way to approach this task. This data set is very uniform, covers a large fraction of the sky in five spectral bands, reaches objects as faint as 24 mag and is publicly available. The SDSS imaging data have already been used to explore the structural parameters of other LG objects (e.g. Draco, Odenkirchen et al. 2001b; And IX, Zucker et al. 2004; And X, Zucker et al. 2007; Ursa Major, Willman et al. 2005; Leo II, Coleman et al. 2007 and many others).

In this paper, we present a new interpretation of observational material of the Peg dSph galaxy (PEGDM; DDO 216 = UGC 12613) based on very deep and wide-field surface photometry using imaging data from the SDSS. The PegDmG is one of the faintest LG members and contains very few stars younger than 100 Myr (see also Gallagher et al. 1998). This object is not to be confused with the dSph galaxy Pegasus II = Peg dSph = Andromeda VI (Armandroff, Jacoby & Davies 1999; Grebel & Guhathakurta 1999; Karachentsev & Karachentseva 1999).

We trace the PegDmG across its entire angular extent in the optical to the lowest accessible surface brightness levels using SDSS data, since all previous studies either concentrated on stars near the centre of the galaxy (e.g. Gallagher et al. 1998) or presented surface brightness profiles (SBPs) covering only small fields (e.g. van Zee 2000). We combine these data with new HI maps derived from Arecibo Observatory1 data collected for the Arecibo Legacy Fast ALFA (ALFALFA) survey (e.g. Haynes 2008).

1 The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by the Cornell University under a cooperative agreement with the National Science Foundation.
2 THE PEGASUS DWARF IRREGULAR GALAXY

As discussed by Gallagher et al. (1998), the PegDIG exhibits many of the properties typical of dIrr galaxies, such as H\textsc{i}, young stars and H\textsc{ii} regions, and an irregular appearance due to recent SF. On the other hand, it is at the faint end of the luminosity range of dIrrs, its outer isophotes are fairly smooth, its gas content is comparatively low and its recent SF activity is low as well, prompting Gallagher et al. (1998) to suggest that it may be a dIrr/dSph transition-type galaxy.

2.1 Optical data, morphology, star formation and distance estimates

The basic parameters of the PegDIG, compiled from the literature, are listed in Table 1. There has been significant disagreement among the various distance estimators presented in the past, ranging from 1.75 Mpc derived from Cepheids to 760 kpc derived from the tip of the red giant branch (TRGB) in colour–magnitude (CM) diagrams. de Vaucouleurs (1975) quoted a distance of only 170 kpc to the PegDIG, considering the galaxy as one of our closest neighbours. The three most recent determinations all use ground-based photometric data and employ the TRGB (McConnachie et al. 2005; Tikhonov 2006a) or Cepheids (Meschin et al. 2009) as distance indicators. These studies converge to a value of about 1 Mpc, slightly larger than the distance of 760 ± 100 kpc derived by Gallagher et al. (1998) using data from the *Hubble Space Telescope* (HST). These distances render the PegDIG a peripheral, potential member of the M31 subgroup within the LG. We adopt here a nominal distance to the PegDIG of 1 Mpc.

Gallagher et al. (1998) studied the central region of the PegDIG using imaging in the *B, V and I* bands with the Wide Field Planetary Camera 2 (WFPC2) aboard the *HST*. Their field encompasses regions of recent SF in the PegDIG. These authors obtained the deepest photometry of the PegDIG so far, reaching objects down to *V* \approx 25. They identified a main sequence as well as blue loop stars younger than 0.5 Gyr. These young populations are clustered in two central clumps. Moreover, there are older, more widely distributed stars, Gallagher et al. (1998) and Dohm-Palmer et al. (1998) concluded that the model best fitting their measurements has a relatively constant SF rate over several Gyr, with a period of enhanced SF about 2 Gyr ago. The colours of the main-sequence stars measured by Gallagher et al. (1998) indicate a relatively high extinction of \(E(B-V) \approx 0.47\) or \(E(V-I) \approx 0.15\), and the stellar models could match the observations only for a distance of 760 kpc to the PegDIG. Gallagher et al. (1998) combined various measurements including the H\textsc{i} column density and *IRAS* dust maps in order to constrain the reddening and pointed out that these estimators do not yield consistent results. The adopted extinction is one of the main reasons for their shorter distance.

Krienke & Hodge (2001) used the colours and redshifts of background galaxies visible in the *HST/WFPC2* data of Gallagher et al. (1998) to estimate the internal reddening in the central region of the PegDIG. After correcting for the Galactic foreground reddening using the values of Schlegel, Finkbeiner & Douglas (1998), they found that the PegDIG itself contributes very little to the reddening and seems to have hardly any interstellar dust. Krienke & Hodge (2001) derived an internal reddening of \(E(B-V) \leq 0.03\) for the PegDIG, consistent with Gallagher et al. (1998). The total reddening of Krienke & Hodge (2001) is lower than that of Gallagher et al. (1998) by \(\geq 0.05\) in \(E(B-V)\).

Young et al. (2003) estimated a current SF rate of \(3 \times 10^{-5} \, M_\odot\, yr^{-1}\) from the H\textsc{r} flux, based on the broad-band and H\textsc{r} imaging in van Zee (2000). Hunter & Elmegreen (2004) listed the PegDIG as having the lowest SF rate among the 94 irregular galaxies of their sample \(4.4 \times 10^{-5} \, M_\odot\, yr^{-1}\) and the lowest SF rate per surface area \(8.3 \times 10^{-4} \, M_\odot\, yr^{-1} \, kpc^{-2}\).
The NASA/IPAC Extragalactic Database (NED) lists a major axis of 5 arcmin (~1.5 kpc at 1 Mpc) and a minor axis of 2.7 arcmin for the PegDIG. Tikhonov (2006a) found a 5 kpc thick disc (diameter ~16 arcmin at 1 Mpc) by tracing the red giant stars on images obtained with the 6-m BTA telescope and with HST. He wrote that the low-luminosity blue stars in the PegDIG are scattered throughout the 5 x 3 arcmin body of the galaxy. The HST image allowed the decomposition of the blue star distribution perpendicular to the disc; these stars ‘virtually disappear at 200 pc’ while the thick disc can be traced vertically to ~1 kpc.

Recently, McConnachie et al. (2007) compared the stellar structure of the PegDIG derived from Johnson V and Gunn i images from the INT Wide Field Camera with the H i maps produced by Young et al. (2003). They concluded that the H i distribution is different from that of the ‘regular, elliptical’ stellar distribution, and interpreted that as strong evidence for ram pressure stripping of the PegDIG by an intergalactic medium associated with the LG.

### 2.2 The interstellar matter: H\(\text{i}\) distribution, mass and dynamics

Fisher & Tully (1975) were the first to detect H\(\text{i}\) emission from the PegDIG and, based on its low radial velocity, suggested it is an LG member. The 21 cm line emission they measured had a width of 43 ± 7 km s\(^{-1}\). The neutral hydrogen in the PegDIG was mapped by Lo, Sargent & Young (1993) with the Very Large Telescope (VLA), and by Hoffman et al. (1996) with the Arecibo radio telescope. Lo et al. (1993) showed that the H\(\text{i}\) is concentrated in the main optical body and that it shows some clumps. Hoffman et al. (1996) found that the H\(\text{i}\) distribution was asymmetric, with the H\(\text{i}\) peak offset by ~1 arcmin from the centre of the outer isodensity contour. The rotation curve derived from the Arecibo observations becomes flat at about ~4.5 arcmin SE of the kinematic centre, which is itself offset by ~2.6 arcmin from the optical centre. On the NW side, the rotation curve falls off after peaking at ~2 arcmin from the kinematic centre. Note that Young et al. (2003) mention that the low velocity of the PegDIG very close to zero causes significant confusion with Galactic H\(\text{i}\), thus the interpretation of single-dish wide-beam H\(\text{i}\) measurements of this galaxy may be problematic.

Karachentsev, Karachentseva & Huchtmeier (2001) observed the PegDIG with the Effelsberg radio telescope as part of a programme to map the local galaxy population. They give only an upper limit of 11 mJy from the H\(\text{i}\) line flux, which they attribute to a low H\(\text{i}\) content and not to confusion from local H\(\text{i}\). Note that the 21-cm half-power beam at Effelsberg is 9.3 arcmin.

van Zee (2000) reported results of a study of isolated dwarf galaxies, where ‘isolated’ implies a distance of 100–200 kpc from the nearest neighbour, using \(UBV\) and \(H\alpha\) imaging, combined with VLA H\(\text{i}\) mapping. The PegDIG was included in her sample and yielded an integrated flux of 29.90 Jy km s\(^{-1}\) and an H\(\text{i}\) line width of 40 km s\(^{-1}\) for a recession velocity of ~183 km s\(^{-1}\), based on the VLA observations reported in Young et al. (2003). van Zee’ (2000) photometry showed that the PegDIG has the reddest colours of all galaxies in her sample. Evolutionary synthesis models indicate that the stellar population could be the result of a single major SF burst a few Gyr ago that ran out of material for further SF.

Further H\(\alpha\) mapping of the PegDIG was done at Westerbork by Stil & Israel (2002), as part of a project to study the hydrogen in a sample of dwarf galaxies. The PegDIG was considered by these authors as one of their most isolated objects. Stil & Israel (2002) found a 9.0 mJy upper limit to the 1.4 GHz continuum flux from the galaxy in the 1.35 MHz band, and a 21-cm line flux integral of 16.3 ± 0.5 Jy km s\(^{-1}\), implying a total H\(\text{i}\) content of \(4 \times 10^9\) M\(_\odot\) at the assumed 1 Mpc distance. The map they presented in their fig. 4 shows the H\(\text{i}\) concentrated at \(\alpha(2000) = 23^\text{h}26^\text{m}04^\text{s}\) and \(\delta(2000) = +14^\circ27^\prime40^\prime\), although the 13 arcsec synthesized beam was rather elongated in the north–south direction because of the declination of the object. The line profile shown in their fig. 2 is single peaked and very narrow, with a full width at half-maximum (FWHM) of less than 20 km s\(^{-1}\) and a weak ~80 km s\(^{-1}\) tail to higher recession velocities (the systemic H\(\text{i}\) velocity of the galaxy being ~189 km s\(^{-1}\)).

The most recent published H\(\text{i}\) map of the PegDIG was by Young et al. (2003) using the VLA and combining observations performed in the C and D configurations. Their integrated 21 cm profile has a 50 per cent full width of 24.6 km s\(^{-1}\) and a flux integral of 29.9 Jy km s\(^{-1}\). Young et al. (2003) display in their fig. 5 a contour map of the PegDIG with the lowest column density level at 10\(^{19}\) atoms cm\(^{-2}\) and an ~10 arcmin extent that shows the gas arranged in three main clumps. In addition, a region 1.5 arcmin north-west of the centre shows a double H\(\text{i}\) profile; this is interpreted as an expanding bubble with a radius of 1 arcmin (±200 pc at the 760 kpc assumed distance).

Jackson et al. (2006) presented spatially resolved maps of the PegDIG at 4.5 and 8 \(\mu\)m obtained with the Spitzer IRAC camera. These maps show only low surface brightness emission from the galaxy, indicating low amounts of hot dust grains and polycyclic aromatic hydrocarbons in the ISM. This, Jackson et al. (2006) propose, is the result of the destruction of grains by supernova shocks and the inability of the ISM to regrow them in a regime of low or zero SF rates.

### 3 THE SDSS DATA FOR THE PEGASUS DWARF IRREGULAR GALAXY

An image of the PegDIG was created by extracting the relevant area from the SDSS data release Data Release (Adelman-McCarthy et al. 2007) imaging data set. Owing to the distance of the PegDIG, the high stellar densities in its central regions, and an average seeing of ~1.5 arcsec in the SDSS imaging data, individual stars can no longer be resolved as point sources in this area. We performed surface photometry separately for the inner galaxy parts, and for the outer parts, where stars still can be resolved. The two independently derived surface photometry results were subsequently combined into a single, global surface photometry profile using areas of overlap. The results for the outer part were matched to those for the inner part, yielding a single SBP per band for the entire galaxy.

#### 3.1 Integrated photometry and surface brightness profiles

The PegDIG itself was not identified as a separate entity by the standard SDSS pipeline (see e.g. the SDSS Data Release 6 data base). The integrated photometry, the creation of SBPs and their analysis were done in the manner described in detail by Kniazev et al. (2004). First, \(g, r\) and \(i\) images for a wide region around the galaxy were extracted from the SDSS data base. These were combined with weights to form an image of the object that is deeper than any of the single SDSS bands could offer and that has essentially the same stellar point spread function (FWHM \(\approx 1\) arcsec) as the pipeline-reduced SDSS data. The central part of the combined \(gri\) image is shown in Fig. 1. The galaxy location was defined above the 3\(\sigma\) noise level on the smoothed combined image, and all background sources were subtracted using SDSS data base coordinates.
and using additional masking. The background was subtracted and SBPs for all ugriz filters were created in circular apertures with a uniform isophote step size of 2 arcsec. The calculated profiles were fitted on a logarithmic scale, following Sérsic (1968):

$$\mu(r) = \mu_0 + 2.5 \log \left( \frac{r}{a} \right)^n,$$

where \( R \) is the distance along the axis and \( n \) is an additional parameter.

To check the stability of our results, we performed additional two-dimensional (2D) modelling with the GALFIT program (Peng et al. 2002) using a one-component Sérsic function for all ugriz filters. To exclude all foreground stars from the fitting procedure, we used the same mask image that was calculated in the previous step, where the method of circular apertures was used.

The results for both methods are summarized in Tables 2 and 3. Table 2 presents all the model parameters for both methods, except for the total magnitudes. In case of circular apertures, the \( b/a \) axis ratio was calculated only once when building the mask for the galaxy location and was kept constant for the different filters. When GALFIT was used, the \( b/a \) axis ratio was allowed to vary as one of the parameters of the fitted model. GALFIT uses the following form for the Sérsic function:

$$\mu(r) = \mu_c + \left\{ -b_n \left( \frac{r}{r_e} \right)^n - 1 \right\}, \quad (2)$$

where \( \mu_c \) is the effective surface brightness and \( r_e \) is the effective (half-light) radius. Generally, \( \alpha = r_e/b_n \), but \( b_n \) is different for each \( n \) and can be only found numerically. A good approximation that can be used is \( b_n \approx 2/n - 0.324 \), but this is valid only for \( 0.07 \leq n \leq 1 \) (Trujillo, Graham & Caon 2001) and is not correct here, since \( n > 1 \). For this reason, our recalculations from \( r_e \) to \( \alpha \) are presented in brackets in Column 7 (\( r_e \)) of Table 2. The GALFIT solution for the \( u \) filter was unstable, and for this reason we fixed \( r_e \) to the same value it was for \( g \). This parameter is marked with a colon.

Table 3 presents the total magnitudes. In Column 2, the apparent magnitudes derived by integrating the luminosity within a circular aperture are not corrected for foreground Milky Way extinction, but extinction corrections calculated using

<table>
<thead>
<tr>
<th>Filter</th>
<th>Circular apertures</th>
<th>2D GALFIT</th>
<th>A_s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( b/a )</td>
<td>( \mu_0 ) (mag arcsec(^{-2}))</td>
<td>( \alpha ) (arcsec)</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>( u )</td>
<td>0.40</td>
<td>24.24 ± 0.10</td>
<td>89 ± 9</td>
</tr>
<tr>
<td>( g )</td>
<td>0.40</td>
<td>23.10 ± 0.05</td>
<td>98 ± 5</td>
</tr>
<tr>
<td>( r )</td>
<td>0.40</td>
<td>22.73 ± 0.04</td>
<td>114 ± 5</td>
</tr>
<tr>
<td>( i )</td>
<td>0.40</td>
<td>22.46 ± 0.05</td>
<td>118 ± 5</td>
</tr>
<tr>
<td>( z )</td>
<td>0.40</td>
<td>22.40 ± 0.07</td>
<td>127 ± 7</td>
</tr>
</tbody>
</table>

Table 3. Total magnitudes of the PegDIG.

Figure 1. The central part (\( \sim 13.5 \times 13.5 \) arcmin) of combined \( g \), \( r \) and \( i \) image of the Pegasus dwarf galaxy derived from a weighted combination of individual single-colour images from the SDSS. North is up and east is to the left. The oblique faint line is a satellite track that was registered on the SDSS \( r \) image. At the adopted distance of 1.0 Mpc, 1 arcsec = 4.85 pc.
the Schlegel et al. (1998) prescription are shown in Column 5 of this table.

The photometric parameters calculated with either of the methods are very similar, but the total magnitudes resulting from GALFIT are systematically larger. Comparing with the integrated photometry of van Zee (2000), we note that our 2D GALFIT values for $B_r$, $(B-V)$ and $(U-B)$ are very similar to those of van Zee.

### 3.2 The resolved outer part

#### 3.2.1 Photometric selection of PegDIG stars

Tracing out the PegDIG to much fainter surface brightness levels than allowed by the direct surface photometry described in the previous section is based on selecting stellar objects that probably belong to the galaxy and on rejecting those that likely belong to the foreground. This method of empirical photometric filtering was first described and used by Grillmair et al. (1995). It was first implemented for SDSS data by Odenkirchen et al. (2001a) for the globular cluster Pal 5 and was used by Odenkirchen et al. (2001b) to study the Draco dSph galaxy. Variants of this photometric filtering of resolved stellar point sources in the SDSS were also developed and used by Rockosi et al. (2002), Smolčić et al. (2007) and Coleman et al. (2007).

First, we selected all point sources imaged by the survey in an ~0.6 deg$^2$ region centred on the Pegasus dwarf galaxy. Approximately 8000 point sources in this area were classified by the standard SDSS pipeline as stars. Since the SDSS detects only the most luminous stars in the PegDIG, the number of identifiable stars belonging to the galaxy is quite limited. For this reason, we did not use any additional selection criteria, but rejected only the sources for which the photometric error in any of the three most sensitive passbands (gri) was larger than 0.4 mag. The spatial distribution of all the selected sources has a mean stellar density of ~2.85 stars arcmin$^{-2}$ for the foreground stars (all areas, excluding the central part of the field where the PegDIG is obviously located).

The crucial point in constructing a high-contrast map for the outer part of the Pegasus system is to achieve an efficient discrimination between the tracers of this system and the foreground field stars. Following Odenkirchen et al. (2001b), we created a training set by selecting ~1500 stars from the central part of the PegDIG (defined as an ellipse with a semimajor axis of 0.15, ellipticity 0.6 and position angle (PA) = −55$^\circ$, centred on ($\alpha$, $\delta$) = (352:15, +14:743).

In Fig. 2, we show a CM diagram of the point sources that are candidate members of the PegDIG as mentioned above. The diagram shows a fairly amorphous, extended plume of faint sources that resemble the distribution of stars in other distant dIrr galaxies from early CCD observations (e.g. Tosi et al. 1991; Greggio et al. 1993). The SDSS data share several characteristics with these early, ground-based CCD data: for a galaxy at the distance of the PegDIG, they are close to the detection limit and are strongly confusion and crowding limited. The extended plume of stars in the SDSS stellar point source catalogue is composed of young main-sequence stars, blue loop stars, red supergiants, luminous asymptotic giant branch stars and stars at the TRGB. In other words, we are sampling the most luminous stars in the PegDIG, which represent a range of different stellar populations and ages covering many billions of years. While these shallow data are not suited nor intended for detailed studies of the SF history of the PegDIG, they are very valuable for studies of its structure. The fact that stars on the upper red giant branch are included is particularly important, since this will be helpful when trying to trace the faint outer limits of the PegDIG, which are typically dominated by old(er) populations.

Following the procedure, described by Odenkirchen et al. (2001a,b), we calculated new colour indices $c_1$ and $c_2$:

\[
\begin{align*}
    c_1 &= 0.921(g-r) + 0.389(r-i), \\
    c_2 &= -0.389(g-r) + 0.921(r-i).
\end{align*}
\]

The relations in equation (3) are very close to those derived by Odenkirchen et al. (2001b) for the Draco dSph and similar to those derived by Odenkirchen et al. (2001a) for Palomar 5.

After constructing the colour index $c_1$, which is a linear combination of the $(g-r)$ and $(r-i)$ colours, the next step was to design an empirical filter mask in the $(c_1, c_2)$ CM plane that will allow the optimal separation of the CM distribution of sources belonging to the PegDIG population from that of the foreground field stars. The basic assumption is that the stars in the PegDIG are of specific types, based on their colours and apparent magnitudes, and will occupy a specific locus in the CM diagram. This is shown in Fig. 3. The region with maximal $s$ values in the right-hand panel of Fig. 3 delineates the locus in the CM plane with the highest fraction of PegDIG stars relative to field stars. This last figure indicates that the stars selected from the SDSS data set as probable PegDIG members are mostly between $21 \leq i \leq 23.5$ mag.

The next step was to identify a level $s_{opt}$ that yields the highest contrast for the selected area of the PegDIG compared to the field stars. This implies that a filter mask for the selection of PegDIG stars should include as many points as possible with $s \geq s_{opt}$, where $s_{opt}$ is a threshold value. To find the optimal number density threshold $s_{opt}$, we computed the signal-to-noise ratio (SNR) for a range of $s$ values, using the following equation from Grillmair et al. (1995) and Odenkirchen et al. (2001a,b):

\[
\text{SNR}(s) = \frac{N_p(s) - wN_p(s)}{\sqrt{N_p(s) + w^2N_p(s)}}
\]

where $N_p(s)$ is the total number of stars in the sample defined by $s$ and for the region of the PegDIG, and $N_p(s)$ is the number of stars in the same sample but for the region where the foreground population is probed. The $w$ parameter scales areas of these two regions. Since we are interested in the outer part of the PegDIG, the
SNR was optimized first for the elliptical annulus with a semimajor axis between 0.12 and 0.20 from the centre of Pegasus. After that, other areas and different foreground regions were tested; we found that $s_{\text{opt}}$ was practically identical in all those tests.

The final selection filter constructed here removed $\sim 76$ per cent of the contaminating field stars and reduced the mean density of the contaminating foreground stars from $2.85$ to $0.69 \pm 1.67$ stars arcmin$^{-2}$. The spatial distribution of stars identified as foreground sources is shown in the top panel of Fig. 4. It is clear that these stars are randomly distributed and do not show any strong concentration towards the bright core of the PegDIG; a concentration could be expected if the filtering operation had been inefficient. The spatial distribution of stars with characteristics matching our final selection filter is shown in the bottom panel of Fig. 4. A visual comparison of the top and bottom panels of this figure shows that the objects selected by the filter as candidate PegDIG members do concentrate around the known galaxy, implying that the filtering operation indeed selected preferentially PegDIG stars very distant from the unresolved inner body.

A stellar number density map of the central part of the studied field is shown in Fig. 5 as isopleths. The surface density was derived through counts on a $30 \times 30$ arcsec$^2$ grid and subsequent weighted averaging within a radius of one grid step. The thin lines show contours at the $1\sigma$ level above the mean background density, where $\sigma$ is the rms of the background stellar density fluctuations, showing the lowest level at which the PegDIG stars start to be recognizable. Since any significant detection of the PegDIG population requires a surface density of at least $2\sigma$ above the background, this level is marked by the thick contour in Fig. 5. Levels of $3\sigma$, $5\sigma$ and $10\sigma$ are plotted there with thick lines as well, to reveal the shape of the galaxy at different stellar number densities; the plot shows that the overall distribution of PegDIG stars is approximately ellipsoidal, but that the outer contours appear deformed. It is also obvious that the NW end of the galaxy seems to be much more irregular than the SE one. These deviations, at the NW end, are very strong, showing up even at the $3\sigma$ contour.

### 3.2.2 Structure of PegDIG

To quantify the size, shape and orientation of the PegDIG, we fitted a 2D model to the observed surface density distribution. For that the surface density was sampled on a $30 \times 30$ arcsec$^2$ grid of non-overlapping cells. We performed 2D modelling using GAlFIT with a one-component Sérsic function. The central part of the

---

**Figure 3.** Separation of foreground Milky Way stars from the stars in the PegDIG. Left-hand panel: density distribution $f_P$ of Pegasus stars in the $(c_1, i)$ CM plane that is shown as contour plot. Stars were taken from an elliptical annulus as described for Fig. 2. Middle panel: density distribution $f_F$ of field stars in the $(c_1, i)$ CM plane. Stars were calculated outside of an ellipse with similar parameters and with a semimajor axis of $0.25\degree$. Right-hand panel: lines of constant number ratio (the population contrast) $s = f_P/f_F$.

**Figure 4.** The spatial distribution of SDSS-selected point sources in the direction of the Pegasus dwarf galaxy. Top panel: stars selected by the algorithm as belonging to the Galactic foreground appear randomly distributed in this image. Contours of equal stellar surface density at a level of $1\sigma$ and $2\sigma$ are shown with thin lines ($\sigma$ is the rms background variation). There are some concentrations at only a $1\sigma$ level in the centre. Bottom panel: final spatial distribution of $\sim 3400$ photometrically selected stars in the PegDIG area. The stars selected as candidate PegDIG members are concentrated around the recognized location of the galaxy.
Table 4. Parameter values for the best-fitting model for the surface density distribution of the PegDIG.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\alpha_c$ (2000.0)</th>
<th>$\delta_c$ (2000.0)</th>
<th>$\beta_{la}$</th>
<th>PA (°)</th>
<th>$\alpha$ (arcsec)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D Sérsic</td>
<td>23:28:35.52</td>
<td>+14:44:29.04</td>
<td>0.39 ± 0.01</td>
<td>−55:7 ± 0:1</td>
<td>138 ± 2</td>
<td>1.11 ± 0.02</td>
</tr>
<tr>
<td>1D Sérsic</td>
<td></td>
<td></td>
<td></td>
<td>−55:7</td>
<td>192 ± 35</td>
<td>1.36 ± 0.21</td>
</tr>
<tr>
<td>Model</td>
<td>$\alpha_c$</td>
<td>$\delta_c$</td>
<td>$\beta_{la}$</td>
<td>PA</td>
<td>$r_c$</td>
<td>$r_t$</td>
</tr>
<tr>
<td>2D King 62</td>
<td>23:28:35.02</td>
<td>+14:44:28.30</td>
<td>0.38 ± 0.03</td>
<td>−55:9 ± 0:1</td>
<td>39 ± 20</td>
<td>957 ± 50</td>
</tr>
</tbody>
</table>

Figure 5. Top panel: contour plots of the observed distribution of stars in the PegDIG. Contours of equal stellar surface density are shown at 2σ, 3σ, 5σ and 10σ with a thinner contour at 1σ. The profiles in the centre of the galaxy show a ‘hole’ produced by missing information in the high-stellar-density part of the galaxy. Dot–dashed lines show the contours of the best-fitting exponential model (2D Sérsic profile) at 1σ, 3σ, 5σ and 10σ levels. Note the ‘dendritic’ extensions of the faint contours in the north-west part of the galaxy. Bottom panel: residuals of the fit shown in the top panel, rescaled to the level of the mean background counts. As before, the contour with thinner lines corresponds to levels of ±1σ. Short-dashed (blue) lines show negative levels of the residuals.

Although the statistical significance of any single feature may not be extremely high, we note that there seems to be a ring-like distribution of peaks (clumps) around the unresolved part of the galaxy. The peaks in the ring configuration encircling the inner, unresolved part of the galaxy are highly significant, more than 5σ above the background. The three peaks revealed to the north-west of the galaxy, between the 1σ and 3σ contours of the model, are of possibly even higher significance. These peaks could not be just artefacts of the Poisson noise, as suggested by Martin et al. (2008) for other faint nearby galaxies, but here they are sufficiently significant, namely 3σ or higher, as shown in the lower panel of Fig. 5. Such peaks are not seen at the opposite end of the galaxy and represent deviations of the faint outskirts of the galaxy from a pure Sérsic profile, which are restricted to the NW side.

As can be seen in Fig. 5, the highest density of detected stars in the area of the peaks (clumps) is about 10σ–20σ of the estimated background noise scatter. With the latter value 1.67 star arcmin$^{-2}$ (see Section 3.2), the 20σ level corresponds to a star density of...
3.35 star arcmin$^{-2}$ or $\sim0.009$ star arcsec$^{-2}$. In other words, the area with the highest density of detected stars in the SDSS Pegasus data corresponds to about one star in a circle with a radius of $\sim6$ arcsec. For an effective seeing of 1 arcsec and a pixel scale of 0.396 arcsec, there should not be any crowding problem in the regions with this and lower stellar density, either for detection or for object classification as a star/nebula.

To demonstrate the evidence for a much larger spatial extent of the PegDIG indicated by our data, we show in Fig. 6 the observed radial stellar density profiles. These were derived from star counts in elliptical annuli, with parameters of the ellipses taken from Table 4. The logarithm of the mean density above background is plotted versus the radius of each annulus. The radius refers to the distance along the fitted major axis. The central 2.7 arcmin region was not included in the fit and is not shown.

The best-fitting generalized Sérsic model, described by the parameters listed in Table 4, is characterized by a radial scalelength of $\alpha = 138$ arcsec and an exponent $n = 1.11$. Comparing these numbers with those shown in Table 2, one can see that both the exponent $n$ of the density distribution and the scale parameter $\alpha$ are very close to the values derived from the gri images. As Fig. 6 shows, the model profile fits our data very well over the entire region; there is no compelling evidence for a real cut-off in the radial profile of the PegDIG within the current observational limits. Using SDSS data for the unresolved part of the galaxy, we can trace the galaxy only up to an $\sim450$ arcsec radius along the major axis. Using star counts, and improving the contrast of our density map, we can trace the PegDIG up to $\sim800$ arcsec, but a distinct edge of the galaxy still remains undetected.

The model fits provide a useful, smooth reference against which to identify peculiarities in the shape of the observed distribution of stars. Such peculiarities are the above-mentioned ‘ring’ of stellar density peaks around the unresolved part of the galaxy, and the three peaks at the NW end of the faint galaxy extension revealed by our filtering procedure and subtraction of the fitted model. We note that there are no counterparts to these peaks in the SE part of the PegDIG. These features will be discussed below.

### 3.2.3 Surface brightness profiles from star counts

Our filtered star count data allow us to construct SBPs. Such SBPs can be derived using the filtered star count data, summing stellar magnitudes in elliptical annuli where the parameters of the ellipses are taken from Table 4, and normalizing them to the area of the annuli.

Assuming that the PegDIG stellar populations do not vary wildly in the outer parts of the galaxy (indeed they do not, as we show below), we can conclude that one sees the same profiles regardless of the method used. In the case of the unresolved part of the PegDIG these were calibrated correctly, but those constructed from the star counts were not, since stars below the detection limit of the SDSS would be excluded from the star counts. Using both data sets for the part of the galaxy where the two methods overlap, we can derive factors for the different filters and derive composite SBPs down to the faintest levels of the PegDIG. These SBPs can be used to understand the evolutionary history of the galaxy, since the SF in the outskirts of the galaxy presumably took place a long time ago.

The interpretation of these correction factors is that they compensate the SBPs in the galaxy part created by using resolved PegDIG stars for the missing light produced by the fainter stars that are not detected on SDSS images. The underlying assumption is that the slope and cut-offs of the initial mass function (IMF) are constant between the inner unresolved part of the PegDIG and the outer part where the brighter stars are resolved and recorded.

Composite SBPs in the gri bands were constructed from the unresolved part of the galaxy and from SBPs that were calculated from the star counts. Some of these composite SBPs are shown in Fig. 7. Fig. 8 shows the composite $(g - r)$ and $(r - i)$ colours. Both the $(g - r)$ and $(r - i)$ composite colours show very stable values for the outer parts of the galaxy, which justifies our previous statement.

The correction factors for the gri filters were estimated visually, using both the SBPs and the colour diagrams. Their final accuracy is presumably about $\pm0.1$ mag, since the colour diagrams are very sensitive to small photometric errors, and we estimate these to be $\sim0.05$ mag for each band used here. The correction factors themselves are 2.25 mag for $g$, 1.85 mag for $r$ and 1.65 mag for $i$ filter. They were obtained by vertically shifting the values for the outer part of the galaxy to match those for the inner, unresolved part of the PegDIG.

### 4 H I OBSERVATIONS

ALFALFA, the Arecibo Legacy Fast ALFA, extragalactic H I survey (Giovanelli et al. 2005a) is a blind neutral hydrogen survey that will ultimately cover 7074 deg$^2$ of the high galactic latitude sky visible from Arecibo. It provides an extragalactic H I line spectral data base covering the redshift range between $-1600$ and 18,000 km s$^{-1}$. The ‘fall’ part of the survey maps the sky region from RA $= 22^h$ to $3^h$ over most of the declination range accessible from Arecibo ($\delta = 0^\circ$–$36^\circ$). We collected the relevant H I observations covering the PegDIG from the ALFALFA archives as a grid containing the galaxy. The ALFALFA observations are conducted at
The faint outer regions of the PegDIG

Figure 8. Composite SDSS \((g - r)\) and \((r - i)\) colour distributions. One of the components of the colour distributions was calculated in circular apertures for the unresolved part of the PegDIG (blue points) and recalculated to the major axis using an ellipticity \(e = 0.61\). The other component was calculated from star counts (black points) in ellipses with parameters taken from the best fit to the stellar surface density map and corrected for the undetected part of the CM diagram. The red curves represent the best-fitting Sérsic models that were calculated for the SBPs created for the unresolved part of the Pegasus dwarf galaxy. The \((r - i)\) colour distribution was shifted by \(+1.5\) mag for clarity.

The Arecibo telescope with the seven-feed ALFA receiver. As described elsewhere (Giovanelli et al. 2005a,b, 2007), data acquisition for ALFALFA is done in a fixed azimuth, drift-scan mode. Each surveyed sky region is covered by two partly overlapping drift scans collected at two different epochs in order to sample at better than the Nyquist spatial frequency.

The two scan passes are separated in time by several months, thus comparing the data from the two epochs helps in ruling out spurious detections. When data acquisition is completed over a given region of the sky, the individual drift scans are assembled and regredded to form three-dimensional (3D) data cubes or ‘grids’. These grids are \(2.4 \times 2.4\) in size with 1 arcmin sampling and have 1024 channels along the spectral axis. Since the velocity resolution is \(\sim 5.3 \text{ km s}^{-1}\) (before Hanning smoothing), in order to cover the full ALFALFA velocity range which extends from \(-2000\) to \(18000 \text{ km s}^{-1}\) each grid is separated into four redshift subgrids, covering the velocity ranges: \(-2000–3300, 2500–7900, 7200–12800\) and \(12100–17900 \text{ km s}^{-1}\). For mapping the \(\text{H} \text{I}\) in the PegDIG, we used only the first velocity grid of the data cube at the PegDIG coordinates.

The ALFA beam used to produce these maps is plotted at the lower-right corner of the total \(\text{H} \text{I}\) map; this is a fairly elliptical beam elongated north–south, with major axes of \(3.3 \times 3.9\) arcmin. The higher level contours agree well with the previous map of Hoffman et al. (1996) derived from Arecibo observations with the flat feed. The lower contours in our map show some differences, partly because the 1996 map was not level of 10 per cent of the main beam, these extensions to the effective beams cause strong, extended sources like the PegDIG to have apparent emission reaching a few arcmin beyond the edge of the actual \(\text{H} \text{I}\) distribution at any declination where one of these extensions stretches towards the position of peak emission from the galaxy.

Figure 9. Effective ALFALFA beams at two representative declinations. Top panel shows declination 14°47′30″ and bottom panel shows 14°41′30″. The contours are spaced logarithmically, in steps of 3.33 dB down from the beam maximum.

The pronounced extensions shift in direction from one declination to another as little as 2 arcmin away as the dominant contribution to the received flux shifts from 1 ALFA pixel to the next. At a level of 10 per cent of the main beam, these extensions to the effective beams cause strong, extended sources like the PegDIG to have apparent emission reaching a few arcmin beyond the edge of the actual \(\text{H} \text{I}\) distribution at any declination where one of these extensions stretches towards the position of peak emission from the galaxy.

Fig. 10 shows the individual \(\text{H} \text{I}\) channel maps (averages of three ALFALFA velocity channels each) at the velocities \(-137.9, -153.4, -168.8, -184.3, -199.7, -215.1\) and \(-230.6 \text{ km s}^{-1}\). The contours are drawn at 2.15, 4.64, 10.0, 21.5, 46.4, 100, 215, 464 and 1000 mJy. The bottom-right panel in Fig. 10 presents the total \(\text{H} \text{I}\) map (integrated over velocity) with contour levels of 0.35, 0.74, 1.60, 3.5, 7.4 and \(16.0 \times 10^{19} \text{ atoms cm}^{-2}\). The ALFA beam used to produce these maps is plotted at the lower-right corner of the total \(\text{H} \text{I}\) map; this is a fairly elliptical beam elongated north–south, with major axes of 3.3 \(\times\) 3.9 arcmin. The higher level contours agree well with the previous map of Hoffman et al. (1996) derived from Arecibo observations with the flat feed. The lower contours in our map show some differences, partly because the 1996 map was not
Figure 10. Channel maps of the H I distribution and the integrated H I of the PegDIG, derived from the ALFALFA observations. The central velocities of each channel map are (from left to right) $-138, -153, -169$ km s$^{-1}$ in the top row, $-184, -200, -215$ km s$^{-1}$ in the middle row and $-231$ km s$^{-1}$ in the bottom row. The total H I map is shown in the bottom-right panel, which also displays the beam used to produce all the maps.

A complete one with points spaced along major and minor axes as opposed to a full grid, and because the sidelobe structure is very different between the flat feed and the seven-feed ALFA.

From an inspection of the gridview display of the individual channels in Fig. 10, we estimate that the structure in the lowest two contours to the north of the galaxy is possibly, as explained above, emission into the sidelobes of the beams that spanned that region and is probably spurious. The extensions to the east and south-west could also be sidelobe emission or could be real; this requires further observations.

The global spectrum (to the 100 mJy km s$^{-1}$ isophote level) for the PegDIG, derived from the ALFALFA observations, is shown in the bottom panel of Fig. 11. The systemic H I velocity is $-183.6$ km s$^{-1}$ and the width at 50 per cent of the peak is $23.4 \pm 2.4$ km s$^{-1}$. The corresponding quantities at 20 per cent of the peak are $-185.2$ and $38.6 \pm 2.4$ km s$^{-1}$. The H I profile is best fitted by a Gaussian centred at $-183.4$ km s$^{-1}$ with FWHM $= 23.6 \pm 0.3$ km s$^{-1}$. The total H I flux is $28.1 \pm 0.1$ or $27.83 \pm 0.06$ Jy km s$^{-1}$ if the integral under the best-fitting Gaussian is used. This corresponds to a total H I mass of $6.6 \times 10^6 M_{\odot}$ at the 1 Mpc nominal distance. There are no visible high-velocity H I wings. Also note that the signal from the PegDIG is clearly distinct from the Galactic emission between $-100$ and $0$ km s$^{-1}$ at this velocity resolution.

Fig. 11 shows the major axis position–velocity (PV) contour map of the PegDIG. To produce it, we rotated the declination (Dec.)–right ascension (RA) maps by $25^\circ$ (which we estimate to be the angle of the major axis of the H I distribution away from the RA axis), then summed along the minor axis. The result is plotted as a contour map in the position versus velocity plane, with contour levels 21.544, 46.416, 100.0, 215.44, 464.16, 1000.0 and 2154.4 mJy. The lowest two levels show the effects of the coma lobes, but the rest of the contours should be robust. The PV map indicates a solid-body rotation curve with opposite ends differing by 15 km s$^{-1}$, with a stream to more negative $cz$ about 5 arcmin from the centre of the galaxy. The positive direction of the position axis is towards the SE.

We measured a flux integral similar to that of Young et al. (2003) and almost twice that measured by Stil & Israel (2002). We conclude that, to a level of 2 mJy beam$^{-1}$, the galaxy is 0.3 wide in RA and 0.25 in Dec. The peak of the H I is at RA $= 23^h 28^m 55^s$, Dec. $+14^\circ 75$. 
in J2000 coordinates and at about $-184$ km s$^{-1}$. The FWHM of the H$\text{I}$ line is about 28 km s$^{-1}$, about 10 per cent wider that the width derived by Young et al. The H$\text{I}$ distribution does not show an obvious compression ridge to the SE, or a tail to the NW smoothed out by our wide beam. The slight crowding of the contours to the SE of the total compression ridge to the SE, or a tail to the NW smoothed out by our wide beam may be indicative of the innermost parts of the galaxy, might result from the depletion of the galaxy’s H$\text{I}$ reservoir. van Zee (2000) also mentioned that the H$\text{II}$ regions detected in her H$\alpha$ images are so faint that they would not have been detected if the PegDIG were more distant.

To estimate the distribution of stellar population ages in the PegDIG, we compared the derived integrated colours in its different parts with model tracks from the PEGASE2 package (Fioc & Rocca-Volmerange 1999) for metallicity values of $z = 0.02$ (solar), $z = 0.008$ (1/3 of solar) and $z = 0.004$ (1/5 of solar). Since the photometric systems $(u', g', r', i', z')$ used for the calculations of PEGASE2 evolutionary tracks and $(u, g, r, i, z)$ used in the real SDSS observations are slightly different, we applied the transformation formulae from Tucker et al. (2006) in order to correct theoretical values to the $(u, g, r, i, z)$ system. The PegDIG has been found to have a low present-day ISM metallicity of $\sim 1/5$ of solar (Skillman, Bomans & Koblunick 1997) and possibly has more metal-poor older stars (Gallagher et al. 1998). Based on the models we used, tracks of even lower metallicities ($<1/5$ of solar) would not match the red colours observed in the outer parts of the PegDIG, and thus these tracks are not plotted.

In Fig. 12, we plot model tracks of colour evolution in the $(g - r)_0$ versus $(u - g)_0$ and $(r - i)_0$ versus $(g - r)_0$ diagram for a standard Salpeter IMF, with lower and upper mass cut-off limits of 0.1 and 120 M$_\odot$. All observed colours are corrected for Milky Way foreground extinction. Different tracks in Fig. 12 represent the colour evolution for continuous SF with constant SFR (dashed lines) and for an aging instantaneous SF episode (solid lines) as two extremes of all possible SF histories. The hexagons on the evolutionary tracks with the respective numbers mark ages in Gyr since the beginning of SF.

We seek to constrain the mean age of the dominant population in different annuli by trying to fit simultaneously both colour–colour plots, the $(u - g)_0$ versus $(g - r)_0$ and the $(g - r)_0$ versus $(r - i)_0$ colours. Clearly, younger populations are more prominent in the central regions, where the mean colours agree relatively well with the 1 Gyr tracks. In the outermost regions, the averaged age is 5–10 Gyr or less. Our data do not allow us to prove or to disprove the presence of an old population (older than 10 Gyr), but the comparison of the integrated colours with population synthesis models suggests that the contribution of such an old population to the integrated light is fairly minor. Hence, the colour gradient appears to be consistent with an age gradient in the sense that younger populations are more centrally concentrated, while older populations show a more extended distribution. Of course, independent of the integrated colours, we know already from published earlier studies that an age gradient is present, as indicated by, for example, the centralized distribution of the H$\text{II}$ regions.
Figure 12. Two-colour diagrams with theoretical tracks from PEGASE2 for evolving stellar populations. The observed colours are corrected for Milky Way foreground extinction and are shown as red filled circles with error bars for the following major axis distances: 0–50, 50–100, 100–150, 150–250, 250–400, 400–600 and 600–800 arcsec. \((u - g)_0\) could be only calculated up to a major axis distance of 400 arcsec. The observed colours were averaged inside each major axis distance bin and the ±1σ errors also reflect the scatter of colour in each distance range. Redder colours correspond to an increased major axis distance: the lowest-leftmost point represents the centre of the PegDIG and highest-rightmost one corresponds to the outermost part. Top panels: tracks with a standard Salpeter IMF, for instantaneous (solid) and continuous (dashed line) SF laws using different metallicities: blue – \(z = 0.004 (1/5 Z_\odot)\); green – \(z = 0.008 (1/3 Z_\odot)\) and black – \(Z_\odot\). Filled black hexagons along the tracks, with respective numbers, mark the time since the beginning of SF: 1, 5 and 10 Gyr. Bottom panels: tracks for instantaneous (solid) and continuous (dashed line) SF laws with a standard Salpeter IMF (blue) for \(z = 0.004\) and non-standard Salpeter IMFs: slope is \(-1.6\) for green and \(-2.85\) for black.

As it is well known, colour gradients may be caused by either age, metallicity or reddening gradients (Harbeck et al. 2001; Hunter & Elmegreen 2006). We cannot unambiguously disentangle these three effects in our data, but we can at least attempt to qualitatively comment on their importance. Since the intrinsic reddening of the PegDIG seems to be low (Krienke & Hodge 2001), we discard extinction as a significant contributor to the observed colour gradients. We have insufficient data to constrain a potential metallicity gradient, but we note that the slope of the metallicity gradient has to have an opposite sign to the observable one: the more metal-poor track has bluer colours compared to the more metal-rich track. In other dwarf galaxies for which more detailed data are available, metallicity gradients tend to be small despite considerable scatter at a given age (e.g. Kniazev et al. 2005; Koch et al. 2006; Glatt et al. 2008). Altogether, it seems likely that our large-scale colour gradients are indeed primarily driven by age, although an age gradient may certainly also be linked with a metallicity gradient.

Population gradients have been identified in early- and late-type dwarf galaxies alike (e.g. Harbeck et al. 2001; Makarova et al. 2002, 2005; Parodi, Barazza & Binggeli 2002; Hunter & Elmegreen 2006; Lisker et al. 2006), although not all dwarf galaxies show such gradients. Generally seen as colour gradients, such variations are usually interpreted as age gradients. They appear to indicate longer-lasting SF in the deeper, inner parts of the potential well where the star-forming material accumulates more easily and/or can be retained more easily. The PegDIG seems to fit this trend as well.

6 DISCUSSION

One of the results of the present work is the derivation of SBPs for the PegDIG that extend about 1.6 times further out than what was found in the previous surface photometry studies (Tikhonov 2006a). Other deep optical surveys of dIrrs in the LG have found additional evidence for stellar distributions much more extended than previously thought: for example NGC 6822 (de Blok & Walter 2006), Leo A (Vansevičius et al. 2004) and IC 1613 (Battinelli, Demers & Artigau 2007). Tikhonov (2005, 2006b) also found such an effect for many nearby face- and edge-on dIrrs.

Our deep surface photometry, using stars identified as belonging to the PegDIG and eliminating Milky Way stars in the foreground, showed that it is possible to fit a Sérsic surface brightness distribution to the galaxy at least to a radius of 14 arcmin \(\simeq 4\) kpc. The stellar distribution shows some concentrations around the unresolved 2 kpc part, and some irregular extensions at the NW end.
of the major axis. Note that this region shows less H\textsc{i} than the SE part, when our maps are compared with those for neutral hydrogen from Young et al. (2003). The H\textsc{i} column density shown in their fig. 5 has a peak of \( \sim 10^{21} \) atoms \( \text{cm}^{-2} \) at RA = 23\textdegree88\textdegree35\textprime, Dec. = +14\textdegree44\textdegree15\textprime, identical to the peak of the ALFALFA maps.

Our results allow the derivation of some general properties of the PegDIG. The total H\textsc{i} flux and the total B-magnitude yield \( M(\text{H}\textsc{i})/L_B \approx 0.4 \). A rough estimate of the total dynamical mass can be derived from the PV plot in the bottom panel of Fig. 11. Assuming that the outermost gaseous regions of the PegDIG rotate with \( \sim 60 \) km s\(^{-1} \) at a Galactocentric distance of 4 kpc, the total dynamical mass is \( M_{\text{dyn}} \approx 3.3 \times 10^9 \) M\(_\odot\). The neutral hydrogen contributes only 2 per cent of this mass. The mass in stars can be roughly estimated from the SDSS colours plotted in Fig. 12; these correspond to main-sequence K stars. If the light were produced solely by K5 stars, the total mass in stars would be \( M_* = 1 \times 10^6 \) M\(_\odot\), about 30 per cent of the total dynamical mass. This indicates that while the PegDIG has a significant amount of DM, it is not a DM-dominated galaxy, contrary to the assertion of Aparicio, Gallart \& Bertelli (1997).

Wilkinson et al. (2004) interpreted the sharp drop in the SBP of the Draco dSph as the signature of a kinematically cold stellar population in the outer parts of the galaxy. They proposed two possible explanations for this phenomenon, which they presented along with arguments against accepting them. One is a two-population model with a hot bulge and a cold disc or halo that does not fit either the observed kinematics or the light distribution. The other is tidal reshaping by the Milky Way galaxy, which requires very tight constraints on the orbit of the dwarf galaxy. We mention this here since a similar phenomenon may be present in the PegDIG, even though the PegDIG is more than five times as distant from the nearest massive spiral as the Draco dSph (Grebel, Gallagher \& Harbeck 2003).

Karachentsev et al. (2004) mentioned that the major disturber galaxy for the PegDIG, in terms of tidal interactions, is M31, with a \( \theta \) parameter of 1.2. This parameter is the tidal index, which is defined as

\[
\theta_t = \max \left( \log \frac{M_k}{D_{\text{th}}} \right) + C,
\]

where \( \theta \) is the index of the specific galaxy, \( \theta_t \) is calculated for, \( k \) is the index of any other galaxy, \( M_k \) is the mass of the 4th galaxy and \( D_{\text{th}} \) is the 3D space distance between the 4th and the 4th galaxies (Karachentsev \& Makarov 1999). Galaxies with \( \theta \leq 0 \) can be considered to be undisturbed, while objects with \( \theta \geq 5 \) are considered to be highly disturbed. Based on the calculated value, the PegDIG could be somewhat affected by M31, but not by an extreme tidal interaction. Hunter \& Elmegreen (2004) listed M31 as the nearest neighbour to the PegDIG, at a projected distance of 450 kpc and a relative recession velocity of +117 km s\(^{-1} \). Note though that since the actual orbit of the PegDIG is not known, and it could even be on a fairly radial orbit around M31, a relatively strong tidal interaction in the past cannot be excluded.

McConnachie et al. (2007) plotted some of the PegDIG neighbours in their fig. 1 (lower-right panel). Their argument is that a comparison of the H\textsc{i} contours with the stellar distribution fits a morphology of gas being stripped away by ram pressure. They identify a 'compression front' on the SE end of the galaxy. In order for ram pressure stripping to take place, they require the LG to be filled by a tenuous \( \sim 10^{-5} \) cm\(^{-3} \), rather warm \( \sim 10^4 \) K gaseous medium. Ram pressure stripping would also modify the gas distribution in and around the galaxy. In fact, this is the main argument used by McConnachie et al. in bringing up the stripping possibility. The morphological modifications that should appear if the ram pressure stripping argument is valid are a leading edge compression region and the creation of a tail of stripped material following the galaxy.

The deep H\textsc{i} maps shown in Fig. 10 lack the signatures of either a strong tidal interaction or ram pressure stripping of the gas from the galaxy. On the contrary, the low-column-density gas observed at the outskirts of the PegDIG and the lack of disturbances in the distribution of this tenuous gas imply that any presumed interaction with an intergalactic medium, as proposed by McConnachie et al. (2007), can probably be discounted. Grebel et al. (2003) presented simple estimates of the efficiency of ram pressure stripping by a homogeneous LG intergalactic medium and concluded that the densities are too low to have a notable effect. However, Grebel et al. (2003) also argued that a putative clumpy medium could be rather effective. But the absence of disturbances in the PegDIG H\textsc{i} contours does not support stripping by a clumpy intergalactic medium.

With the present SF rate derived by Young et al. (2003) and the total H\textsc{i} mass measured in this work, the SF could last for another \( 2 \times 10^{11} \) yr. Such slow, continuous SF extending over a Hubble time or more is typical for dIrr galaxies (e.g. Hunter \& Gallagher 1986; van Zee 2001). The central H\textsc{i} column density is a bit short of the canonical threshold for SF, but this canonical limit is not always valid for low-mass galaxies (e.g. Hunter, Elmegreen \& Baker 1998). Is it possible that we are seeing the PegDIG during an extended lull in SF, while the gas is settling back after having been distended by, for example, supernovae in the last SF episode, akin to scenarios described by, for example, Dong, Lin \& Murray (2003)? Amplitude variations in the intensity of SF are commonly observed in dIrr galaxies, so here also the PegDIG would conform to the typical properties of these objects (e.g. Tosi et al. 1991; Grebel 1997).

Begum et al. (2006) discussed the SF threshold in very faint low-mass galaxies based on synthesis observations with the Giant Metrewave Radio Telescope. They found that while current SF (as traced by H\alpha emission) is confined to the regions with relatively large H\textsc{i} column density \( [N_{\text{H}\text{i}} > (0.4-1.7) \times 10^{21} \text{ cm}^{-2}] \), the morphology of the H\alpha emission is generally not correlated with that of the high H\textsc{i} column density gas. A high gas column density may be a necessary condition for SF, but it is not sufficient, for their sample at least, to ensure that SF does in fact occur.

We can also rule out tidal deformation, since such distortions are expected to be symmetric with respect to the centre, while for the PegDIG any distortions are relegated to the NW side. Our findings imply that the PegDIG might be a recent acquisition of the LG, now in the outskirts of the LG and far away from any nearby massive galaxies, that was formed in a comparatively empty region without major disturbances. However, without knowledge of its orbit we cannot rule out past interactions with M31.

7 CONCLUSIONS

We analysed images of the PegDIG collected by the SDSS and found that the unresolved part can be fitted by a Sérsic intensity profile down to \( \sim 30 \) mag arcsec\(^{-2} \). Using very effective filtering in the CM space of SDSS data, we reduced the contamination by foreground Galactic field stars and significantly increased the contrast for the outer part of the Pegasus dwarf where we identified resolved stars that belong to the PegDIG. This allowed the extension of the surface photometry to much fainter levels.
Our extended surface photometry, reaching down to a surface brightness of $\mu_B \simeq 33$ mag arcsec$^{-2}$, revealed an $\sim 8$ kpc wide stellar distribution following the same Sérsic profile as found for the unresolved part, composed of a stellar population similar to that in the $\sim 2$ kpc main body, but significantly older. The distribution of colours across the galaxy body shows that the innermost parts of the galaxy contain the youngest population. A comparison to population synthesis models suggests a mean age of $\sim 1$ Gyr for this part, and we know from earlier work at HST resolution that the youngest stars have ages of only a few $10^5$ Myr. The outermost parts of the PegDIG are much older with a mean age from integrated colours of at least 5 Gyr, indicating that there the contribution of younger populations is comparatively small. The total dynamical mass of the galaxy is $\sim 3 \times 10^9 M_\odot$, of which about 30 per cent is in stars and only 2 per cent is in $H_\alpha$.

We found that the stellar distribution of the PegDIG is considerably more extended than previously thought. Mapping the $H_\alpha$ distribution to very low-column-density levels at Arecibo revealed that the hydrogen distribution is slightly smaller than that of the stars revealed by the present study. The PegDIG is therefore yet another dlrw where the $H_\alpha$ is not much more extended than the stellar distribution, as it used to be in the classical picture of dlrws.

Our deep $H_\alpha$ map shows an extended and fairly regular gas distribution with solid-body-like rotation. We do not observe low-column-density tails extending beyond the edges of the neutral gas distribution shown in earlier synthesis array images (Young et al. 2003). Tidal stripping therefore seems unlikely. On the basis of the $H_\alpha$ observations alone, we cannot rule out ram pressure interaction with extragalactic gas, and the relatively small extent of the $H_\alpha$ distribution of stars may even support the hypothesis that the outermost gas has been stripped.

We identified faint extensions of the optical light distribution of the PegDIG at the north-west end that do not follow the expected distortions caused by a tidal interaction. We also showed that a number of stellar concentrations -- possibly extended stellar associations -- are located around the unresolved central galaxy body. Rings of stellar associations have been found in a number of dlrrs and could be a possible sign of outward-propagating SF but, on the other hand, the PegDIG also has very young stars in its innermost regions as shown by the HST data (Gallagher et al. 1998).

ACKNOWLEDGMENTS

We thank the anonymous referee for comments that improved the presentation of the manuscript. This paper makes extensive use of SDSS data products. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the participating institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS web site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the participating institutions. The participating institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max Planck Institute for Astronomy, the Max Planck Institute for Astrophysics, New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory and the University of Washington.

This work is based in part on observations collected at the Arecibo Observatory. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by the Cornell University under a cooperative agreement with the National Science Foundation.

This research has made use of the NED which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Moreover, this research has made extensive use of NASA’s Astrophysics Data System.

REFERENCES

de Vaucouleurs G., 1975, Stars Stellar Syst., 9, 557
Giovanelli R. et al., 2005a, AJ, 130, 2598
Giovanelli R. et al., 2005b, AJ, 130, 2613
Giovanelli R. et al., 2007, AJ, 133, 2569
Grebel E. K., 1997, Rev. Mod. Astron., 10, 21

@ 2009 The Authors. Journal compilation @ 2009 RAS, MNRAS 400, 2054–2069