The faint outer regions of the Pegasus Dwarf Irregular galaxy: a much larger and undisturbed galaxy

Aleksei Y. Kniazev,1 Noah Brosch,3 G. Lyle Ho, man,4 Eva K. G. Rebel,5 Daniel B. Zucker,6 Simon A. Postnikov7

1 South African Astronomical Observatory, PO Box 9, 7935, Cape Town, South Africa
2 Southern African Large Telescope Foundation, PO Box 9, 7935, Cape Town, South Africa
3 The 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
4 Department of Physics, Lafayette College, Easton, PA 18042, USA
5 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
6 Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia
7 Astrophysical Observatory, Nizhniy Arkhyz, Karachay-Cherkessia, 369167, Russia
8 Isaac Newton Institute of Chile, SAO Branch, Nizhniy Arkhyz, Russia

Abstract

We investigate the spatial extent and structure of the Pegasus dwarf irregular galaxy using deep, wide-field H I observations. We study an area of 0.6 square degrees centred on the Pegasus dwarf that was imaged by SDSS. Using effective imaging in colour-magnitude space we reduce the contamination by foreground Galactic stellar stars and increase significantly the contrast in the outer regions of the Pegasus dwarf.

Our extended surface photometry reaches down to a surface brightness magnitude $r' = 32$ mag arcsec$^{-2}$. It reveals a stellar body with a diameter of 8 kpc that follows a Sersic surface brightness distribution law, which is composed of a significantly older stellar population than that observed in the 2 kpc main body. The galaxy is at least 100 times more extended than listed in NED. 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 ALFA LFA survey. They reveal an HI distribution somewhat elongated in RA and about 0.3 kpc wide, with the region of high column density coincident with the main luminous galaxy. The HI rotation curve shows a solid-body rotation behaviour, with opposite ends differing by 15 km s$^{-1}$. There is a stream of low-velocity stars 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 Peg D II are 10 Gyr old, while the inner kpc contains stars 1 Gyr old and younger. The colours correspond to K stars; earlier sub-types are located in the innermost parts of the galaxy. Peg D II appears to be a relatively low-mass object, with a total dynamical mass of 3 $10^9$ M$_\odot$, of which only 30% in stars and 2% is in neutral gas.

The extended stellar distribution, the appearance of faint light extensions, and the lack of low column density HI tails rule out a possible tidal origin or a ram pressure stripping scenario. We propose that Peg D II is a fairly recent acquisition by the Local Group, following its recent growth.

Key words: galaxies: dwarf (galaxies: individual (Pegasus)) (galaxies: structure (Local Group))
1 INTRODUCTION

The Local Group (LG), our immediate neigbourhood, is the group of galaxies in which our Milky Way galaxy finds itself and is evolving. The Milky Way and M 31 are the two dominant spiral galaxies in the Local Group, and each is surrounded by an expanse of lower-mass companions. This kind of a binary structure is found in nearby galaxy groups as well (e.g., Katchaev et al. 2002a, b, 2002c). A part from the late-type spiral M 33, the three other low-mass companions. A kind of a binary structure is found in nearby galaxy groups as well (e.g., Katchaev et al. 2002a, b, 2002c). A part from the late-type spiral M 33, the three other low-mass companions.

As discussed by Gallagher et al. (1998), Peg D I G exhibits many of the properties typical of dIrr galaxies such as H i, young stars, and H II regions, and an irregular appearance due to recent star formation. 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 comparably low, and its recent star formation activity is low as well, prompting Gallagher et al. (1998) to suggest that it may be a dIrr/dSph transition-type galaxy.
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rate over several G yrs, with a period of enhanced SF about 2 G yrs ago. The colours of the main-sequence stars measured by Gallagher et al. (1998) indicate a relatively high extinction of $A_V \approx 0.47$ or $E(B-V) \approx 0.15$, and the stellar models could not match the observations only for a distance to PegDG of 760 kpc. Gallagher et al. (1998) combined various measurements including the H 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.

Kriek & Hodge (2001) used the colours and redshifts of background galaxies visible in the HST/WFC2 data of Gallagher et al. (1998) to estimate the internal reddening in the central region of PegDG. After correcting for the Galactic foreground reddening using the values of Schlegel et al. (1998), they found that PegDG itself contributes very little to the reddening and seems to have hardly any interstellar dust. Kriek & Hodge (2001) derived an internal reddening of $E(B-V) \approx 0.03$ for PegDG, consistent with Gallagher et al. (1998). The total reddening of Kriek & Hodge (2001) is lower than that of Gallagher et al. (1998) by $>0.05$ in $E(B-V)$.

Young et al. (2003) estimated a current star formation rate of $3 \times 10^5$ M yr$^{-1}$ from the H$_\alpha$ line, based on the broadband and imaging in van Zee (2000). Hunter & Elmegreen (2004) listed PegDG as having the lowest star formation rate among the 94 irregular galaxies of their sample (4 M $10^5$ M yr$^{-1}$) and the lowest star formation rate per surface area (83 $10^4$ M yr$^{-1}$ kpc$^{-2}$).

NED lists a major axis of 5 arc min ($1.5$ kpc at 1 M pc) and a minor axis of 2.7 arc min for PegDG. Khonon (2006) found a 5 kpc thick disk (diameter 16 arc min at 1 M pc) by tracing the red giant stars on $i$ images observed with the 6-m BTA telescope and with HST. He wrote that the low-$\lambda$ isocline blue stars in PegDG are scattered throughout the $5^\circ \sim 3^\circ$ body of the galaxy. The HST image allowed the decom position of the blue star distribution perpendicular to the disk; these stars \textit{virtually disappear at 200 pc} while the thick disk can be traced vertically to 1 kpc.

Recently, McConnachie et al. (2005) compared the stellar structure of PegDG with the known distance of Johnson V and Gunn $i$ images of 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 PegDG by an intergalactic medium associated with the Local Group.

2.2 The interstellar matter: H I distribution, mass, and dynamics

Fisher & Tuffs (1973) were the first to detect H I emission from PegDG, and based on its low radial velocity, suggested it is a Local Group member. The 21-cm line emission they measured had a width of 43 km sec$^{-1}$. The neutral hydrogen in PegDG was mapped by Lo, Sarment & Young (1991) with the VLA, and by Roman & Young (1994) with the Arecibo radio telescope. Lo et al. (1993) showed that the H I is concentrated in the main optical body and that it shows some clumpy gas. Roman et al. (1996) found that the H I distribution was asymmetric with the H I peak set

2.1 Optical data, morphology, star formation and distance estimates

The basic parameters of PegDG, 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 M pc derived from Cepheids to 760 kpc derived from the tip of the red giant branch (RGB) in colour-magnitude diagrams. de Vaucouleurs (1975) quoted a distance of only 170 kpc to PegDG, considering the galaxy one of our closest neighbours. The most recent determinations all use ground-based photometric data and employ the TRGB (McConnachie et al. 2005; Khonon 2006) or Cepheids (McConnachie et al. 2003) as distance indicators. These studies converge to a value of about 1 M pc, slightly larger than the distance of 760-100 kpc derived by Gallagher et al. (1998) using data from the Hubble Space Telescope. These distances render PegDG a peripheral, potential member of the M 31 subgroup within the LG.

We adopt here a nominal distance to PegDG of 1 M pc.

Gallagher et al. (1993) studied the central region of PegDG using imaging in the B, V and I bands with the Wide Field and Planetar y Camera (WFC2) aboard the Hubble Space Telescope (HST). Their data encompass regions of recent SF in PegDG. These authors obtained the deepest photometry of PegDG so far, reaching objects down to $V' \approx 25$. They identified a main sequence as well as blue loop stars younger than 0.5 G yr. These young populations are clustered in two central clumps. Moreover, there are older, more widely distributed stars (Gallagher et al. 1993) and Dohm-Palm et al. (1998) concluded that the model best fitting these emission lines has a relatively constant SF
Table 1. Basic Parameters of the Pegasus Dwarf Irregular Galaxy

| Parameter | Value | Reference |
|-----------|-------|-----------|
| (J2000.0) | 23h28m 16.25s | van Zee (2000) |
| B_v (m ag) | +14.44 | van Zee (2000) |
| B_V (m ag) | 12.50 0.15 | van Zee (2000) |
| U_B (m ag) | 0.00 0.09 | van Zee (2000) |
| a (arcsec) | 104.4 | van Zee (2000) |

Distance estimates

| Method | Distance Modulus | kpc | Reference |
|--------|------------------|-----|-----------|
| PN     | 200(1600)        |     | Jacoby & Lemen (1981) |
| TRGB   | 1700             |     | Hoessel & Mould (1982) |
| TRGB   | 700(1200)        |     | Christian & Fuller (1981) |
| Cepheid | 1700             |     | Hoessel & Mould (1990) |
| TRGB   | 950              |     | Apai & Lind (1994) |
| TRGB, RC | 1060             |     | Lee (1995) |
| TRGB   | 760(100)         |     | Gallaher et al. (1998) |
| TRGB, RC | 919              |     | McConnachie et al. (2005) |
| Cepheid | 1020             |     | Ilyin & Popov (2006) |
| Cepheid | 1070             |     | Merklin et al. (2000) |

Note: The abbreviations used here are as follows: a is the exponential scale length of the disk; t is the time by which evolution has occurred; the B surface brightness profile; PN refers to a distance estimate using planetary nebulae; TRGB is a distance using the tip of the red giant branch in the colour-magnitude diagram; RC is the same, but using the red clump.

by 1° from the centre of the outer iso-density contour. The rotation curve derived from the Arecibo observations becomes at about 45 arc min in the direction of the kine centre, which is itself set by 2.6 arc min in from the optical centre. On the NW side the rotation curve falls off after peaking at 2 arc min in from the kine centre. Note that Young et al. (2003) mention that the low velocity of Peg D I is very close to zero (causes significant confusion with Galactic H i, thus the interpretation of single-dish wide-beam H i measurements of this galaxy may be problematic.

Karaschev, Karaschev, & Huchm e 2003 observed Peg D I with the Eclisberg radio telescope as part of a program to map the local galaxy population. They have only an upper limit of 11 m Jy from the H i line, which they attribute to a low H i content and not to confusion from local H i. Note that the 21-cm half-power beam at Eclisberg is 9.3 arc min. Van Zee (2000) reported results of a study of isolated dwarf galaxies, where isolated means a distance of 100 kpc from the nearest neighbour, using UV and H imaging, combined with VLA H imaging. Peg D I was included in her sample and yielded an integrated 10 mm of 29.9 Jy km s^-1 and an H i line width of 40 km s^-1 for a recession velocity of 183 km s^-1, based on the VLA observations reported by Young et al. (2003). Van Zee's (2000) photometry showed that Peg D I 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 star formation (SF) burst a few Gyr ago that ran out of material for further SF.

Further H i mapping of Peg D I was done both at VLA and with the Spitzer IRAC cam era. Their integrated maps show only low surface brightness emission from the galaxy, indicating low amounts of hot dust grains and PAHs in the ISM. This, Jackson et al. (2004) propose, is the result of the destruction of grains by super-wind activity from the galaxy. The most recent published H i map of Peg D I was by Young et al. (2003) using the VLA and combination observations performed in the C and D configurations. Their integrated 21-cm profile has a full width of 24.5 km s^-1 and an H i integral of 25 Jy km s^-1. Young et al. (2003) display in their Fig. 5 a contour map of Peg D I with the lowest column density level at 10^10 atoms cm^-2 and a 10 arc min extent that shows the gas arranged in three main clumps. In addition, a region 1.5 arc min in the northwest of the centre shows a double H i profile; this is interpreted as an expanding bubble with a radius of one arc min (~ 200 pc at the 760 kpc assumed distance).

Jackson et al. (2004) presented spatially-resolved maps of Peg D I at 4.5 and 8 m obtained with the Spitzer IRAC cam era. These maps show only low surface brightness emission from the galaxy, indicating low amounts of hot dust grains and PAHs in the ISM. This, Jackson et al. (2004) propose, is the result of the destruction of grains by super-wind activity from the galaxy.
nova shocks and the inability of the ISM to re-grow them in a regime of low or zero star formation rates.

3 THE SDSS DATA FOR THE PEGASUS DWARF IRREGULAR GALAXY

An image of PegD I G was created by extracting the relevant area from the SDSS data release DR5 [Ade10] imaging data set. Owing to the distance of PegD I G, 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 attached to those for the inner part, yielding a single surface brightness profile (SBP) per band for the entire galaxy.

Table 2. Photometric parameters for the unresolved part of PegD I G in the SDSS

| Filter | Circular Apertures | 2D GALFIT | A |
|--------|--------------------|-----------|---|
|        | Apparent           | Total     | Total | |
|        | [m ag]             | [m ag]    | [m ag] | [m ag] |
|        | (1)                | (2)       | (3)   | (4) |
| u      | 13.64 ± 0.03       | 13.20 ± 0.03 | 0.34 |
| g      | 12.26 ± 0.02       | 12.01 ± 0.02 | 0.18 |
| r      | 11.67 ± 0.02       | 11.48 ± 0.02 | 0.14 |
| i      | 11.35 ± 0.02       | 11.16 ± 0.02 | 0.10 |
| z      | 11.37 ± 0.03       | 11.32 ± 0.09 | 0.03 |

3.1 Integrated photometry and Surface Brightness Profiles

PegD I G itself was not identified as a separate entity by the standard SDSS pipeline (see, for example, the SDSS DR6 database). The integrated photometry, the creation of SBPs, and their analysis were done in the manner described in detail by [niziev et al. 2004]. First, for the entire region around the galaxy, were extracted from the SDSS database. These were combined with widths to form an image of the object that is deeper than any of the single SDSS bands could cover and that has essentially the same stellar point spread function (FWHM ≈ 1 arcsec) as the pipeline-reduced SDSS data. The central part of the combined gri image is shown in Figure 3. The galaxy location was defined above the 3σ noise level on the smoothed combined image, and all background sources were subtracted using SDSS database coordinates and using additional masks. The background was subtracted and SBPs for all gri images were created in circular apertures with a uniform isophote step size of 20 arcsec. The calculated profiles were fitted on a logarithmic scale, following [Sersic 1968]:

\[(r) = e^{*} + 10^{0.4(b)} (r = 1)\]

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 modelling with the GALFIT program [Peng et al. 2002] using a one-component Sersic function for all gri images. To exclude all foreground stars from the fitting procedure, we used the same mask image that was calculated on 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 images. When GALFIT was used, the b/a axis ratio was allowed to vary as one of the free parameters of the fit. GALFIT uses the following form for the Sersic function:

\[ n \frac{h}{r_{e}} \frac{1}{10^{-n}} \]

where \( n \) is the effective surface brightness and \( r_{e} \) is the effective (half-light) radius. Generally \( r_{e} = h_{e} \), but \( h_{e} \) is different for each \( n \) and can be only found numerically. A good
approximation that can be used is \( r_0 = 2n = 0.324 \), but this is valid only for \( 0.76 \leq n \leq 1 \) (Trujillo, Graham, & Casoli 2001), and is not correct here, since \( n > 1 \). For this reason, our recalculations from \( r_0 \) to \( r \) are presented in brackets in column 7 (\( r_0 \)) of Table 2. The GALFIT solution for the outer part (Table 2) presents the total magnitudes. In column 2, the apparent magnitudes derived by integrating the luminosity within a circular aperture out to the limiting isophotal level of the SDSS data are listed. The total magnitudes presented in Table 2 were calculated extrapolating out to \( r = 1 \) using equation (9) from Kniazev et al. (2004) and the parameters of the Sersic function listed in Table 2. The rather large errors of these magnitudes result from the big errors of the input parameters in Table 2. The total magnitudes from GALFIT are also a result of \( u \)-integration out to \( r = 1 \). In the case of GALFIT, the total magnitude is a free parameter of the \( u \)-model, and the magnitudes that were recalculated from the \( u \)-griz magnitudes using the equations from Jordi, Grebel, & Ammon (2006). The magnitudes in Table 2 are not corrected for foreground Milky Way extinction, but extinction corrections calculated using 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 photometric data of van Zee (2000) we note that our 2D GALFIT values for \( B \) and \( V \) are very similar to those of van Zee.

3.2 The Resolved Outer Part

3.2.1 Photometric selection of PegD I G stars

Tracing out PegD I G 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 binning was first described and used by Kuijken (1992). 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 dwarf spheroidal galaxy. Variants of this photometric binning of resolved stellar point sources in the SDSS were also developed and used by Rockosi et al. (2003), Smolčič et al. (2007), and Coleman et al. (2007).

First, we selected all point sources in a region of \( 0.5 \) square degree region centered on the Pegasus dwarf galaxy. An approximate 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 PegD I G, the number of identical stars belonging to the galaxy is 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 \( m \) 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

![Figure 2.](image-url)
and with a semi-major axis of 0.25 deg.

and similar to those derived by Odenkirchen et al. (2001a).

Figure 3. Separation of foreground Milky Way stars from the stars in PegD I G. Left: Density distribution $f_0$ of Pegasus stars in the ($c_i; l_i$) colour-magnitude plane that is shown as contour plot. Stars were taken from an elliptical annulus as described for FkII M. Kiddle: Density distribution $f_5$ of eld stars in the ($c_i; l_i$) colour-magnitude plane. Stars were calculated outside of an ellipse with similar parameters and with a semi-major axis of 0.25 deg. Right: Lines of constant num ber ratio (the population contrast) $s = f_0 / f_5$.

$c_i = 0.921 (g - r) + 0.289 (r - i)$

$c_o = 0.921 (g - r) + 0.289 (r - i)$

The relations in the equations are very close to those derived by Odenkirchen et al. (2001b) for the Daco dSph and similar to those derived by Odenkirchen et al. (2001) for Pegasus 5.

A finder constructing the colour index $c_i$, which is a linear combination of the ($g - r$) and ($r - i$) colours, the next step was to design an empirical mask in the ($c_i; l_i$) colour-magnitude (CM) plane that will allow the optimal separation of the colour-magnitude distribution of sources belonging to the PegD I G population from that of the foreground eld stars. The basic assumption is that the stars in PegD I G 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 Figure 3. The region with maximum values in the right panel of Figure 3 delineates the locus in the CM plane with the highest fraction of PegD I G stars relative to eld stars. This last panel indicates that the stars selected from the SDSS data set as probable PegD I G members are mostly between 216.6 and 235.5 mag.

The next step was to identify a level $S_{opt}$ that yields the highest contrast for the selected area of PegD I G compared to the eld stars. This implies that a mask for the selection of Pegasus stars should include as many points as possible with $s > S_{opt}$, where $S_{opt}$ is a threshold value. To nd 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. (1999) and from Odenkirchen et al. (2001a):

$$\text{SNR}(s) = \frac{N_p(s)}{N_f(s) + w^2 N_f(s)}$$

Here $N_p(s)$ is the total number of stars in the sample defined by $s$ and for the region of PegD I G, and $N_f(s)$ is the number of stars in the same sample, but for the region where the foreground population is probed. The $w$ parameters scales areas of these two regions. Since we are interested in the outer part of PegD I G, the SNR was optimized rst for the elliptical annulus with a semi-major axis between 0.12 and 0.20 deg from the centre of Pegasus. A user that, other areas and different foreground regions were tested; we found that $S_{opt}$ was practically identical in all those tests.

The n selection here removed 76% of the contaminating eld stars and reduced the mean density of the contaminating foreground stars from 2.85 stars arcmin$^2$ to 0.59 stars arcmin$^2$. The spatial distribution of stars identified as foreground sources is shown in the top panel of Figure 4. It is clear that these stars are randomly distributed and do not show any strong concentration toward the bright core of PegD I G; a concentration could be expected if the limiting operation had been ine cient. The spatial distribution of stars with characteristics matching our n selection is shown in the bottom panel of Figure 4. A visual comparison of the top and bottom panels of this figure shows that the objects selected by the n as candidate PegD I G members do concentrate around the known galaxy, implying that the limiting operation indeed selected preferentially PegD I G stars very distant from the unresolved inner body.

A stellar number density map of the central part of the studied eld is shown in Figure 5 as isophotes. The surface density was derived through counts on a 30’ by 30’ grid and subsequent weighted averaging within a radius of one grid step. The thin lines show contours at the 1 level above the mean background density, where is the mean of the background stellar density fluctuations, showing the lowest level at which the PegD I G stars start to be recognizable. Since any signi cant detection of the PegD I G population requires a surface density of at least 2 above the background, this level is marked by the thick contour in Figure 4. Levels of 3, 5 and 10 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 PegD I G stars is approximately elliptical, but that the outer contours appear deformed ed. 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 contour.

3.2.2 Structure of PegD I G

To quantify the size, shape, and orientation of the Pegasus dwarf irregular galaxy we used a two-dimensional model.
Table 4. Parameter values for the best-fit model for the surface density distribution of PegDIG

| Model   | c     | c     | b/a | PA      | n     |
|---------|-------|-------|-----|---------|-------|
|         | [2000.0] | [2000.0] |     | [degree] | [arcsec] |
| 2D Sersic | 23:28:35.52 | +14:44:29.04 | 0.39 | 0.01 | 55:7 | 0:1 | 138 | 2 | 1.11 | 0.02 |
| 1D Sersic | 0.40 | 55:7 | 192 | 35 | 1.36 | 0.21 |

| Model   | c     | c     | b/a | PA | rc | rt |
|---------|-------|-------|-----|----|----|----|
| 2D King | 23:28:35.02 | +14:44:29.30 | 0.38 | 0.03 | 55:9 | 0:1 | 39 | 20 | 957 | 50 |

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 and 2 are shown with thin lines (is the rms background variation). There are some concentrations at only 1 level in the center. Bottom panel: Final spatial distribution of 3400 photometrically selected stars in the PegDIG area. The stars selected as candidate PegDIG members are concentrated around the recognized location of the galaxy.

Figure 5. Top: Contour plots of the observed distribution of stars in PegDIG. Contours of equal stellar surface density are shown at 2, 3, 5, and 10 with a thinner contour at 1. 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-fit exponential model (2D Sersic profile) at 1, 3, 5, and 10 levels. Note the "dendritic" extensions of the faint contours in the north-west part of the galaxy. Bottom: 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 1. Short-dashed (blue) lines show negative levels of the residuals.
Figure 6. Radial profile of the surface density of stars in PegD IG. Data points with error bars show the profile of the observed distribution (star counts in elliptical rings around the center of PegD IG with parameters of the best-fit model shown in Table 4) and with the mean background ( edm stars arcmin^-2 subtracted). The red solid line shows the major axis model distribution for the GALFIT 2D Sersic model (see Table 4 for parameters). The blue long-dashed line shows the best-fit 1D Sersic model, where the point at 12 arcmin is excluded since it represents the extension visible in the bottom panel of Figure 5. When doing a twi with this point included, the result of the 1D twi is very close to the result of 2D with GALFIT. The green dotted line shows the major axis model distribution for the GALFIT 2D King model (Table 4 for parameters). Points located to the left of the vertical dotted line at R = 4 arcmin were not included in the fit for either model. The vertical short-dashed line indicates a radial distance of 450 arcsec, where our SBP profile is in the ugriz filters term inate.

to the observed surface density distribution. For that, the surface density was summed on a 30" x 30" grid of non-overlapping cells. We perform ed a two-dimensinal m outing using GALFIT with a one-component Sersic function. The central part of the galaxy (which looks like a hole in our data) was excluded from them outing with the special warning allowed by GALFIT. The best-fit parameters are shown in Table 4 and the best-fit model is shown in Figures 4 and 5. The lower panel of Figure 6 shows the difference between the actual data and the best model.

As can be seen in Figure 5, the highest density of detected stars in the area of the peaks (clump) is about 10^3 stars arcmin^-2 of the estimated background noise scatter. With the latter value 1.67 stars arcmin^-2 (see Section 3.2), the detection limit corresponds to a star density of 33.5 stars arcmin^-2 or 0.009 stars arcsec^-2. In other words, the area with the highest density of detected stars in the SDSS PegD IG data corresponds to about one star in a circle with a radius of 6 arcsec. For an effective seeing of one 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 PegD IG indicated by our data, we show in Figure 6 the observed radial stellar density profile. 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 tted major axis. The central 20" region was not included in the fit and is not shown.

The best-ﬁtting generalized Sersic model described by the parameters listed in Table 4 is characterized by a radial scale length of ~1.38 arcsec and an exponent n = 1.1. Comparison of the numbers with those shown in Table 4 one can see that both the exponent n of the density distribution and the scale parameter are very close to the values derived from the ground images. As Figure 6 shows, the model profile fits our data very well over the entire region; there is no compelling evidence for a malcuto in the radial prole of PegD IG within the current observational limits. Using SDSS data for the unresolved part of the galaxy we can trace the galaxy only up to a 450" radius along the major axis. Using star counts, and im proving the contrast of our density map, we can trace PegD IG up to 800", but a distinct edge of the galaxy still remains undetected.

The model provides 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 twiuing procedure and subtraction of the tted model. We note that there are no counterparts to these peaks in the SE part of PegD IG. These features will be discussed below.

3.2.3 Surface Brightness Profiles from Star Counts

Our measured star counts allow us to construct surface brightness profiles (SBPs). Such SBPs can be derived using the measured star counts, 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 annulus.

A summing that the PegD IG 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 profile regardless of the method used. In the case of the unresolved part of PegD IG these were calculated 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
Figure 7. Composite SDSS gr-band SBPs. The SBPs were calculated in circular apertures for the unresolved part of the Pegasus dwarf irregular galaxy (blue points) and recalculated to the major axis using an ellipticity of $e = 0.61$. The other data points for the SB were calculated from star counts (black points) in ellipses with parameters taken from the best-fit model for the stellar surface density map and corrected for the part of the colour-magnitude diagram that is not detected in the SDSS data. The red curves represent the best-fit Sersic model calculated from the SBPs for the unresolved inner part of Pegasus dwarf galaxy. The curves indicate that this model also fits the outer, fainter parts of this object reasonably well. The SB profile for the r band was shifted by an additional 2 magnitudes for clarity.

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 PegD I G (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 colour-magnitude diagram. The red curves represent the best-fit Sersic models that were calculated for the SBPs created for the unresolved part of Pegasus dwarf galaxy. The $(r - i)$ colour distribution was shifted by +1.5 magnitudes for clarity.

Figure 9. Effective ALFA beam at two representative declinations. Top shows a declination $14^\circ 47^m 30^s$ and bottom shows $14^\circ 41^m 30^s$. The contours are spaced logarithmically, in steps of 3.33 dB down from the beam maximum.

...part of the galaxy where the two methods overlap we can derive factors for the different layers and derive composite SBPs down to the faintest levels of PegD I G. These SBPs can be used to understand the evolutionary history of the galaxy, since the star formation in the outskirts of the galaxy presumably took place a long time ago.

The interpretation of these correction factors is that they can penetrate the SBPs in the galaxy part created by using resolved PegD I G 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 cutoffs of the IMF are constant between the inner unresolved part of PegD I G and the outer part where the brighter stars are resolved and recorded.

Composite SBPs in the gr 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 Figure 7. Figure 8 shows the composite $(g - r)$ and $(r - i)$ colours. Both the $(g - r)$ and $(r - i)$
Figure 10. Channel maps of the H I distribution and the integrated H I of PegD I G, derived from the ALFA LFA 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.

com posite colours show very stable values for the outer parts of the galaxy, which justify our previous statement.

The correction factors for the grid lines were estimated visually, using both the SBPs and the colour diagrams. Their mean accuracy is presumably about \(0.1\) mag, since the colour diagrams are sensitive to small astrometric errors, and we estimate these to be \(0.05\) 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 bands. They were obtained by shifting vertically the values for the outer part of the galaxy to match those for the inner, unresolved part of PegD I G.

4 H I OBSERVATIONS

ALFA LFA, the Arecibo Legacy Fast ALFA extragalactic H I survey (Giovanelli et al. 2002) is a blind neutral hydrogen survey that will ultimately cover 7074 square degrees of the high galactic latitude sky visible from Arecibo. It provides an extragalactic H I line spectral database covering the redshift range between 1600 km s\(^{-1}\) and 18,000 km s\(^{-1}\). The "full" part of the survey maps the sky region from RA = 22\(^{h}\) to 3\(^{h}\) over most of the declination range accessible from Arecibo (\(= 0(36)\)). We collected the relevant H I observations covering PegD I G from the ALFA LFA archives as a grid containing the galaxy. The ALFA LFA observations are conducted at the Arecibo telescope with the 7-m Arecibo ALFA receiver. As described elsewhere (Giovanelli et al. 2005a, 2005b, 2007), data acquisition for ALFA LFA is done in a xed 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 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 regridded to form three-dimensional data cubes or "grids". These grids are 2.4 \(\times\) 2.4 in size with 1 arcmin in sampling, and have 1024 channels along the spec-
Dowell et al. (2008) Using this procedure, we have seven separate beam maps (Irwin et al. 2009) was written by J. Dowell et al. (2008). Using this procedure, we have constructed effective beam m maps of the seven separate beam maps (Irwin et al. 2003) at the received beam m. At a level of 10% of the main beam, these extensions to the effective beam m cause strong, extended sources like PegD I G to have apparent emission reaching a few arcmin beyond the edge of the actual H I distribution at any declination where one of these extensions stretches toward the position of peak emission from the galaxy.

Figure 10 shows the individual H I channel maps (averages of 3 ALFA ALFA velocity channels each) at the velocities 136.9, 153.4, 168.8, 184.4, 199.7, 215.1, and 230.6 km s\(^{-1}\). The contours are drawn at 2.15, 4.64, 10.0, 21.5, 46.4, 100, 215, 464, and 1000 m Jy. The bottom-right panel in Figure 10 presents the total H I map (integrated over velocity) with contour levels of 0.35, 0.54, 1.60, 3.5, 7.4, and 16.0 \(10^{16}\) atom cm\(^{-2}\). The ALFA beam used to produce these maps is plotted at the lower-right corner of the total H I map; this is a fairly elliptical beam elongated north-south, with major axes of 3.7, 4.1 km s\(^{-1}\). The higher level contours agree well with the previous map of Homan et al. (1996) derived from Arecibo observations with the at fixed. The lower contours in our map show some differences, partly because the 1996 map was not a complete one with points spaced along major and minor axes as opposed to a full grid, and because the side-lobe structure is very different between the at fixed and the seven-fixed ALFA.

From an inspection of the gridview display of the individual channels in Figure 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 side lobes of the beam that spanned that region and is probably spurious. The extensions to the east and southwest could also be side-lobe emission or could be real; this requires further observations.

The global spectrum (to the 100 m Jy km s\(^{-1}\) isophote level) for PegD I G, derived from the ALFA ALFA observations, is shown in the left panel of Figure 11. The system b H I velocity is 1836 km s\(^{-1}\) and the width at 50% of the peak is 23.4 km s\(^{-1}\). The corresponding quantities at 20% of the peak are 1852 and 38.6 km s\(^{-1}\). The H I profile is best-fit by a Gaussian centered at 1834 km s\(^{-1}\) with FWHM = 23.6 km s\(^{-1}\). The total HI ux is 281.0 1.0 Jy km s\(^{-1}\), or 278.3 0.6 Jy km s\(^{-1}\) if the integral under the best-fit Gaussian is used. This corresponds to a total HI mass of 6.5 \(10^{10}\) M\(_{\odot}\) at the 1 M pc nominal distance. There are no visible high-velocity H I wings. Note also that the signal from PegD I G is clearly distinct from the Galactic emission between 100 and 0 km s\(^{-1}\) at this velocity resolution.

Figure 11 shows the major axis position-velocity (PV) contour map of PegD I G. To produce it we rotated the declination (DEC) (right ascension (RA)) maps by 25° (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 vs. velocity plane, with contour levels 21.54, 46.416, 100.0, 215.4, 464.16, 1000.0, and 2154.4 m Jy. The lowest two levels show the e folds of the con a lobes, but the rest of the contours should be robust. The PV map indicates a solid-body rotation curve with opposite ends di ering 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 toward the SE.

We measured a ux integral similar to that of Young et al. (2003) and also twice that measured by Stil & Israel (2002). We conclude that, to a level of 2 m Jy beam, the...
galaxy is 0.3 degrees wide in RA and 0.25 degrees in DEC. The peak of the H I is at RA = 23°28'55", DEC = +14°75' in J2000 coordinates and at about 184 km s⁻¹. The FW HM of the H I line is about 28 km s⁻¹, about 10% wider than the width derived by Young et al. The H I distribution does not show an obvious con pressure ridge to the SE, or a tail to the NW, as expected by our wide beam. The slight crowding of the contours to the SE of the total H I distribution and slight elongation to the NW may be indicative of a con pressure ridge and tail inferred by Young et al. (2003) from their VLA maps, but lacking a procedure to deconvolve the multiple asymmetric beam sizes, we cannot be certain. However, we do not see any extension of the H I signal beyond the outermost YOUNG et al. contour even though ALFA ALFA is sensitive to column densities 4 or 5 times lower than the sensitivity limit of the Young et al. map.

5 THE STELLAR POPULATIONS

van ZEE (2000) presented B and (B V) profiles that extend only 300 arcsec from the centre; these show that the stellar population changes from (B V)’0.6 arcmin from the centre (a’24) to 0.8 arcmin from the centre. This is similar to the colour gradient found here for the unresolved part of the galaxy.

Hierarchical galaxy formation scenarios predict that dwarf galaxies should show traces of an old stellar population. And indeed, all nearby dwarf galaxies show clear evidence for the presence of old stellar populations (CRebe and GALLAGHER 2004), i.e., populations older than 10 Gyr, as traced by, e.g., the presence of a horizontal branch. This may also be the case for Peg D I G, where traces of present-day very low level star formation (4.4×10⁻⁵ M_☉ yr⁻¹) were found (e.g., Hunter & Elsner 2004) while most of the stars belong to earlier generations. Indeed, the deepest existing HST data show clear evidence for substantial populations with ages of 9 Gyr and younger as traced by a very prominent red clump (GALagher et al. 1998). Those data approach the detection limit just below the intergalactic age red clump, making it very difficult to establish the presence of a horizontal branch (Although there are indications of a density enhancement in the corresponding red clump, the mean gradient in Fig. 15 of GALLAGHER et al. 1998)

van ZEE (2000) found that Peg D I G had the reddest (B V) and (B V) colours of all the galaxies in her sample. She could not trace these with a constant star formation model, but could institute a continuous decreasing star formation rate, and with an aging, a few Gyr old starburst. She proposed that the very low level star formation rate, now relegated to the innermost parts of the galaxy, might result from the depletion of the galaxy’s H I reservoir. (van ZEE 2000) mentioned also that the H II regions detected in the H I in ages are so faint that they would not have been detected if Peg D I G were more distant.

To estimate the distribution of stellar population ages in Peg D I G, we compare the derived integrated colours in its di erent parts with model tracks from the PEGASE2 package (Finck & ROCHA-VONRAHME 1993) 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 system (u’ g’ r’ i’ z’, u’ r’ i’ z’) used for the calculations of the PEGASE2 evolutionary tracks and (i’ z’ j’ y’ j’) used in the real SDSS observations are slightly di erent, we applied the transformation formulae from Tucker et al. (2004) in order to correct theoretical to values of the (i’ z’ j’ y’ j’) system. Peg D I G has been found to have a low present-day ISM metallicity of 1/5 of solar (Skillman, ROMANs & KOBULNICKY 1999), and possibly has more metal-poor older stars (GALagher 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 Peg D I G and thus these tracks are not plotted.

In Fig. 12, we plot model tracks of colour evolution in the (g r), versus (u g) and (r i), versus (g r) diagram for a standard Salpeter IMF, with lower and upper mass cutoff limits of 0.1 and 120 M_☉. 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 extreme cases of possible SF histories. The hexagons on the evolutionary tracks with the respective num bers 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 ts in ultravioletly both colour-colour plots, the (u g), vs. (g r), and the (g r), vs. (r i), colours. Clearly, younger populations are more prominent in the central regions, where the mean colour ages 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, e.g., by the centralised distribution of the H II regions.

As is well known, metallicity and age may be either either age, metallicity, or reddening gradient (HARBEEK et al. 2003), Hunter & Elsner 2008). 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 Peg D I G seems to be low (Kunsche & HODA 2003), 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: more metal-poor objects have bluer colours compared to the more metal-rich objects. In other dwarf galaxies for which more detailed data are available, metallicity gradients tend to be small at the cluster of a given age (e.g., Knapov et al. 2005, GLAT et al. 2008, KOCHE 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-type and late-type dwarf galaxies alike (e.g., Barbeau et al. 2001, Parodi et al. 2002, Makarov et al. 2002, 2005, Huterer & Elmegreen 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 star formation in the deeper, inner parts of the potential well where the star-forming material accumulates more easily and/or can be retained more easily. PegD I G seems to support this trend as well.

6 DISCUSSION

One of the results of the present work is the derivation of surface brightness profiles for PegD I G that extend about 1.6 times further out than what was found in previous surface photometry studies (Young et al. 2003). Other deep optical surveys of dIrrs in the Local Group have found additional evidence for stellar distributions much more extended than previously thought: e.g., NGC 6822 (de Blok & Walter 2004), Leo A (van de Ven et al. 2004), and IC 1613 (Battinelli et al. 2007). Ti Khonon (2005, 2006b) also found such an effect for many nearby face-on and edge-on dIrrs.

Our deep surface photometry, using stars identified as belonging to PegD I G and eliminating Milky Way stars in the foreground, showed that it is possible to have a single surface brightness distribution for the galaxy at least to a radius of 14 arcmin (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 I than the SE part, when our maps are compared with those for neutral hydrogen from Young et al. (2003). The H I column density shown in their Fig. 5 has a peak of $10^{21}$ atoms cm$^{-2}$ at RA $= 23^h 28^m 35^s$, DEC $= +14^\circ 44^\prime 15^\prime\prime$, identical to the peak of the ALFA LFA maps.
The faint outer regions of the Pegasus Dwarf Irregular Galaxy

Our results allow the derivation of some general properties of PEGD I. The total H I flux and the total B magnitude yield M(H I)/L_B = 0.4. A rough estimate of the total dynamical mass can be derived from the PV plot in the left panel of Figure 11. Assuming that the outermost gaseous regions of PEGD I rotate with 60 km s^{-1} at a galactocentric distance of 4 kpc, the total dynamical mass is M_dyn = 33 \times 10^8 M_\odot. The neutral hydrogen contributes only 2% of this mass. The mass in stars can be roughly estimated from the SDSS colors plotted in Figure 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 10^8 M_\odot, about 30% of the total dynamical mass. This indicates that while PEGD I has a significant amount of dark matter, it is not a dark matter-dominated galaxy, contrary to the assertion of [Apparicio et al. 1997].

Winkelman et al. (2004) interpreted the sharp drop in the surface brightness profile of the Draco dSph as the signature of a kine tically 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 one. One is a two-population model with a hot bulge and a cold disk or halo that does not exist either the observed kinematics nor the light distribution.

The other is tidal reshaping of 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 PEGD I, as PEGD I is more than 3 Mpc distant from the nearest massive spiral as the D raco dSph (C. Rebolo et al. 2003).

Karakashev et al. (2004) mentioned that the major disturbing galaxy for PEGD I, in terms of tidal interactions, is M 31, with a parameter of 1.2. This parameter is the tidal index, which is defined as:

$$ i = \frac{u}{a} = \frac{M_{k}}{D_{k}} \times \frac{\log M_{k}}{D_{k}} + C $$

Here i is the index of the Galactic galaxy, k is the index of any other galaxy, M_k is the mass of the k-th galaxy and D_k is the 3D space distance between the i-th and the k-th galaxy (Karakashev & Makarov 1999).

Galaxies with $>60$ can be considered to be undisturbed, while objects with $>50$ are considered to be highly disturbed. Based on the calculated value, PEGD I could be somewhere acted by M 31, but not by an extreme tidal interaction (Hunter & Elmegreen 2004) listed M 31 as the nearest neighbor of PEGD I, at a projected distance of 450 kpc and a relative recession velocity of 117 km sec^{-1}. Note that since the actual orbit of PEGD I is not known, and it could even be on a fairly radial orbit around M 31, a relatively strong tidal interaction in the past cannot be excluded.

Macon et al. (2007) plotted some of the PEGD I neighbors in their Fig. 1 (lower right panel). Their argument is that a comptonization of the H I contours with the stellar distribution is a morphology of gas being stripped away by ram pressure. They identify a "com pression front" on the SE end of the galaxy. In order for ram pressure stripping to take place, they require the Local Group to be led by a tenuous (10^5 cm^{-3}), rather warm (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 McCook 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 I maps shown in Figure 10 lack the signatures of either a strong tidal interaction or of ram pressure stripping of the gas from the galaxy. On the contrary, the low column density gas observed at the outskirts of PEGD I and the lack of disturbances in the distribution of this tenuous gas imply that any previous interaction with an intergalactic medium, as proposed by McCook et al. (2007), probably can be discounted. C. Rebolo et al. (2003) presented simple estimates of the efficiency of ram pressure stripping by a homogeneous Local Group intergalactic medium and concluded that the densities are too low to have a noticeable effect. However, C. Rebolo et al. (2003) also argued that a putative clumpy medium could be rather effective. But the absence of disturbances in the PEGD I H I contours does not support stripping by a clumpy intergalactic medium.

With the present star formation rate derived by Young et al. (2004) and the total H I mass measured in this work, the star formation could last for another $2 \times 10^{11}$ years. Such slow, continuous star formation extending over a Hubble time or more is typical for d IIR galaxies (e.g., Hunter & Gallagher 1988; van Zee 2003). The central H I column density is a bit short of the canonical threshold for star formation, but this canonical threshold is not always valid for low-mass galaxies (e.g., Hunter et al. 1998). Is it possible that we are seeing PEGD I during an extended tail in star formation, while the gas is setting back after having been disturbed by, e.g., supernovae in the last star formation episode, akin to scenarios described by, e.g., Dong et al. (2003)? Amplitude variations in the intensity of star formation are common only observed in d IIR galaxies, so here also PEGD I would confirm to the typical properties of these objects (e.g., Pisano et al. 1997; Rebolo 1997).

C. Rebolo et al. (2004) discussed the SF threshold in very faint low-mass galaxies based on synthesis observations with the Giant Metrewave Radio Telescope (GMRT). They found that while current star formation (as traced by Hα emission) is confined to regions with relatively large H I column density ($N_{H I} > 1 \times 10^{12}$ cm^{-2}), the morphology of the H I emission is generally not correlated with that of the high H I column density gas. A high gas column density may be a necessary condition for star formation, but it is not sufficient, for their sample at least, to ensure that star formation does in fact occur.

We can also rule out tidal deformations, since such distortions are expected to be symmetric with respect to the center, while for PEGD I any distortions are relegated to the NW side. Our results imply that PEGD I might be a recent acquisition of the Local Group, now in the outskirts of the LG and far away from any nearby massive galaxy, which was formed in a comparatively empty region without major disturbances. However, without knowledge of its orbit, we cannot rule out past interactions with M 31.
7 CONCLUSIONS

We analyzed ages of the Pegasus dwarf irregular galaxy collected by the SDSS survey and found that the unresolved part can be fitted by a Semic intensity profile down to 30 mag arcsec$^{-2}$. Using very effective imaging in the color-magnitude space of SDSS data, we reduced the contamination by foreground Galactic disk stars and significantly increased the contrast for the outer part of the Pegasus dwarf where we identify resolved stars that belong to PegD I. This allowed the extension of the surface photometry to much fainter levels.

Our extended surface photometry, reaching down to a surface brightness of $g' = 33$ mag arcsec$^{-2}$, reveals a 8 kpc wide stellar distribution following the same Semic profile as for the unresolved part, composed of a stellar population similar to that in the 2 kpc main body, but smaller than the innermost parts of the galaxy. A comparison to population synthesis models suggests a mean age of 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 Myr. The outermost parts of PegD I have much older with a mean age from integrated colours of at least 5 Gyr, indicating that most of the contribution of younger populations is concentrated in a small area around the galaxy center. The total dynamical mass of the galaxy is 3 $10^8 M_{\odot}$, of which about 30% is in stars and only 2% is in H I.

We found that the stellar distribution of PegD I is considerably more extended than previously thought. Mapping the H I 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. PegD I is therefore yet another dimmer where the H I is not much more extended than the stellar distribution, as it is used to be in the classical picture of dIrrs.

Our deep H I 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). The tidal stripping therefore seems unlikely. On the basis of the H I observations alone, we cannot rule out ram pressure interaction with extragalactic gas, and the relatively small extent of the H I vis-a-vis the 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 PegD I 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 associations (possibly extended stellar associations) are located around the unresolved central galaxy body. Rings of stellar associations have been found in a number of dIrrs and could be a possible sign of outward-propagating star formation, but, on the other hand, PegD I also has very young stars in its innermost regions as shown by the HST data (Gallagher et al. 1993).

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REFERENCES

Adeleman-McCarthy J.K., et al., 2007, ApJS, 172, 634
Aparicio A., 1994, ApJ, 437, L27
Aparicio A., Gallart C., Bertselli G., 1997, AJ, 114, 669
Aparicio A., Tikhonov N., Karachentsev I., 2000, AJ, 119, 177
Ammon T.E., Jacoby G.H., & Davies J.E. 1999, AJ, 118, 1220
Battinelli P., Demers S., & Artigau E. 2007, A&A, 466, 875
Begum A., Chengalur J.N., Karachentsev I., Kaisin S.S., Sharina M.E., 2006, MNRAS, 365, 1220
Bell E.F., et al. 2008, ApJ, 680, 295
Belokurov V., et al. 2006, ApJ, 647, L111
Belokurov V., et al. 2007a, ApJ, 658, 334
Belokurov V., et al. 2007b, ApJ, 654, 897
Christian C.A., Tully R.B., 1983, AJ, 88, 334
Colin M.G., Joridi R., H.W., G. Rebhun E.K., Koch A., 2007, AJ, 134, 1398
Courteau S., van den Bergh S., 1999, AJ, 118, 337
de Blok W.J., 2006, AJ, 131, 343
de Vaucouleurs G., 1975, SSS, 9, 557
Dohn-Palm R.C., et al., 1998, AJ, 116, 1227
Dong S., Lin D.N.C., Murray S.D., 2003, ApJ, 596, 930

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Kriek K., Hodge P. W. 2001, PASP, 113, 1115
Koch A., Grabel E. K., Wyse R. F. G., Kleya J. T., Wilkinson M. I., Harbeck D. R., G healthcare G. F., Evans N. W., 2006, AJ, 131, 895
Lee M. G., 1995, JAS, 28, 169
Linker T., Li a m. K., W estem P., G rebel E. K., 2006, AJ, 132, 2432
Lo K. Y., Sargent W. L. W., Young K., 1993, AJ, 106, 507
Lupton R., Gunn J. E., Ivezić Z., Kapp G. R., Kent S., Yasuda N., 2001, in Astromoncal Data Analysis Software and System X, ASP Conf. Ser. 238, eds. F. R. Hamden, Jr., F. A. Primini, & H. E. Payne (San Francisco: ASP), 269
Makarova L. N., Karachentsev I. D., Grabel E. K., Barisunova O. Y., 2002, A & A, 384, 72
Makarova L. N., Karachentsev I. D., Grabel E. K., Harbeck D., Kormtкова G. G., G. eisler D., 2005, A & A, 433, 751
M. artin N. F., de Jong J. T. A., R. H. W., 2008, ApJ, 684, 1075
M. ateo M. L., 1998, A & A, 36, 435
M. c. onnachie A. W., Inv in M. J., Ferguson A. M. N., Ibata R. A., Lew in G. F., Tanvir N., 2005, MNRAS, 356, 979
M. c. onnachie A. W., Inv in M. J., 2005, MNRAS, 365, 1263
M. c. onnachie A. W., Venn, K. A., Inv in, M. J., Young, L. M. & G. eesha, J. J., 2007, ApJ, 671, L33
M. ehrin I., Gallart C., Aparkin A., Cassisi S., Rosenberg A., 2009, AJ, 137, 3619
Odenkirchen M. et al., 2001a, ApJ, 548, L165
Odenkirchen M. et al., 2001b, AJ, 122, 2538
Porudzi B. R., Barazza F. D., Bingelli B., 2002, A & A, 388, 29
Peng C. Y., Ho L. C., Imp ey C. D., R. H., 2002, AJ, 124, 266
Pockesi C. M. et al., 2002, AJ, 124, 349
Sessick J. L., 1968, Atlas de Galaxies Australes, (Cordoba, Argentina: Observatorio Astronomico)
Schlegel D. J., Finkbeiner D. P., Douglass M. J., 1998, ApJ, 500, 525
Skilling a. E. D., Bon ans a. D., G. Kondinsky H. A., 1997, ApJ, 474, 205
Smolovi V., Zucke r D. B., Belf E. F., Collin a. M. G., R. H., Schinnerer E., Ivezić Z., Kniazev A., 2007, AJ, 134, 1901
Still J. M., Israel F. P., 2002, A & A, 389, 29
Stoughton C. et al., 2002, AJ, 123, 485
Tkho nov N. A., 2005, A. stronomy R. eports, 49, 501
Tkho nov N. A., 2006a, A. stronomy Y. Letters, 32, 149
Tkho nov N. A., 2006b, A. stronomy Y. Reports, 50, 517
Tosi M., G. regele L., M. arconig G., Focardi P., 1991, AJ, 102, 951
Trujillo I., Graham A. W., Caon N., 2001, MNRAS, 326, 869
Tucker D. L., Kent S., Richon M. N., et al., 2006, AN, 327, 821
van den Bergh S., 2000, PASP, 112, 529
van Zee L., 2000, AJ, 119, 2757
van Zee L., 2001, AJ, 121, 203
Veness R. V. et al., 2004, ApJ, 611, L93
V. ikkinn M. I., K. leyton J. T., Evans N. W., G healthcare G. F., Inv in M. J., G. rebel E. K., 2004, ApJ, 611, L21
W. ilk a. et al., 2002, AJ, 124, 2600
W. ilk a. et al., 2005, ApJ, 626, L85
A.Y. Kniazev et al.

Yanny B. et al., 2003, ApJ, 588, 824
York D. G., Adelman, J., Anderson J. E. et al., 2000, AJ, 120, 1579
Young L. M., van Zee L., Lo K. Y., Dohm-Palm er R. C.,
Beierle M. E., 2003, ApJ, 592, 111
Zucker D. B. et al., 2004, ApJ, 612, L117
Zucker D. B., et al., 2004, ApJ, 612, L121
Zucker D. B., et al., 2006, ApJ, 650, L41
Zucker D. B., et al., 2007, ApJ, 659, L21

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