Thick gas discs in faint dwarf galaxies

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ABSTRACT
We determine the intrinsic axial ratio distribution of the gas discs of extremely faint $M_B < -14.5$ dwarf irregular galaxies. We start with the measured (beam corrected) distribution of apparent axial ratios in the HI 21-cm images of dwarf irregular galaxies observed as part of the Faint Irregular Galaxy GMRT Survey (FIGGS). Assuming that the discs can be approximated as oblate spheroids, the intrinsic axial ratio distribution can be obtained from the observed apparent axial ratio distribution. We use a variety of methods to do this, and our final results are based on using Lucy’s deconvolution algorithm. This method is constrained to produce physically plausible distributions, and also has the added advantage of allowing for observational errors to be accounted for. While one might a priori expect that gas discs would be thin (because collisions between gas clouds would cause them to quickly settle down to a thin disc), we find that the HI discs of faint dwarf irregulars are quite thick, with mean axial ratio $q \sim 0.6$. While this is substantially larger than the typical value of $\sim 0.2$ for the stellar discs of large spiral galaxies, it is consistent with the much larger ratio of velocity dispersion to rotational velocity ($\sigma/v_c$) in dwarf galaxy HI discs as compared to that in spiral galaxies. Our findings have implications for studies of the mass distribution and the Tully–Fisher relation for faint dwarf irregular galaxies, where it is often assumed that the gas is in a thin disc.

Key words: galaxies: dwarf – galaxies: irregular – radio lines: galaxies.

1 INTRODUCTION

The observed shape of a galaxy differs from the intrinsic shape because of projection effects. If one has a sample of galaxies drawn from a population with a well-defined intrinsic axial ratio distribution and with random orientations with respect to the earth, then one can determine the distribution of intrinsic axial ratios from the observed axial ratio distribution (for e.g. Noordlinger 1979; Binney & de Vaucouleurs 1981; Lambas, Maddox & Loveday 1992; Ryden 2006). It is worth noting that most of these studies have focused on large galaxies, and that there have been relatively few that focused on dwarfs. For bright spiral galaxies, $q_0$ is often taken to be $\sim 0.2$ (see e.g. Haynes & Giovanelli 1984; Verheijen & Sancisi 2001). Also, it has long been appreciated that the axial ratio is a function of Hubble type. For example, Heidmann, Heidmann & de Vaucouleurs (1972) found that while discs get thinner as one goes from galaxies of morphological type Sa to Sd, there is a rapid increase in disc thickness as one goes from Sd to dwarf irregular galaxies. Similarly, Staveley-Smith, Davies & Kinman (1992) found that dwarf galaxies from the UGC catalogue have $q_0 \sim 0.5$. Axial ratio is also a function of the wavelength of observation. For example, Ryden (2006) showed that older populations as traced by redder stars have thicker ratios that the corresponding B-band disc. But all of these studies refer to the stellar discs of the galaxies. Due to collisions between gas clouds, one would expect that the gas discs would be intrinsically quite thin, for example, for our Galaxy, the scale height of the middle disc is only $\sim 300$ pc. In extremely gas-rich dwarf galaxies, one might then expect that the gas discs are
2 SAMPLE SELECTION, ANALYSIS AND RESULTS

The FIGGS sample was selected to satisfy the following criteria: (i) absolute blue magnitude $M_B > -14.5$, (ii) integrated H I flux $> 1$ Jy km $s^{-1}$ and (iii) optical major axis $> 1$ arcmin. There are in total 62 galaxies in the FIGGS sample, for all of which we have axis ratios available. We discuss the implications of the selection criteria on our derived axis ratio in Section 3; here, we merely note that any bias in the sample is likely to be towards having a preference for edge on systems. The FIGGS survey presents H I images at a range of angular resolutions. Since we are interested in the overall shape of the disc, we measured the axis ratio of the disc using the coarsest resolution H I maps. This was done because we wanted to avoid the fine structure which shows up at higher resolutions, and instead trace the complete spatial spread of H I which requires observing the less dense gas using coarser resolution. For all of these galaxies, elliptical isophotes were fit to the H I image using the STSDAS package in IRAF. The axis ratio that we use in this Letter was measured for the isophote with mean column density $10^{19}$ cm$^{-2}$ for all galaxies. The measured axial ratio was corrected for the finite beam size before being used.

For a sample of randomly oriented axisymmetric oblate spheroids, with intrinsic axial ratio distribution $\psi(q)$, where the axial ratio $q$ is defined as $q = c/a$, with $c$ being the short axis (‘thickness’) of the spheroid and $a$ the long axis (‘diameter’), the observed distribution of axis ratios $\phi(p)$, where $p$ is the observed axial ratio is given by (see e.g. Binney 1978)

$$\phi(p) = p \int_0^p \frac{\psi(q) \, dq}{\sqrt{(1 - q^2)(p^2 - q^2)}}$$  \hspace{1cm} (1)

What is available to us is $\phi(p)$, the observed axial ratio distribution; in order to derive the intrinsic axial ratio distribution $\psi(q)$, we have to invert equation (1).

Fall & Frenk (1983) provide an integration formula (equation 7 in their paper) in the case that $\phi(p)$ is a polynomial function. This allows for a direct inversion of equation (1). The binned data (Fig. 1) were hence fit by a polynomial, using a weighted least-squares fit. The errors were assumed to be Poisson distributed (with the error for bins with zero counts taken to be that for a single count). The errors were also estimated using bootstrap resampling. 10 000 different realizations of the data were constructed using bootstrap resampling. The 80 per cent confidence limits histograms determined in this way are also shown in Fig. 1. As it can be seen, the two error estimates are in good agreement. The direct inversion of the best-fitting polynomial is shown in Fig. 2. It has a broad peak around $q_0 \sim 0.6$, but also falls to negative values beyond $q \sim 0.8$, which is unphysical.

While there may exist an acceptable polynomial fit to $\phi(p)$ which does not produce negatives on inversion, we do not investigate this possibility directly. Instead, we choose to try to invert equation (1) using Lucy’s deconvolution algorithm (Lucy 1974). This approach has the added advantage of also being able to account for measurement errors. The Lucy deconvolution method is an iterative algorithm for estimating the intrinsic frequency distribution from an observed distribution, subject to the constraints that the deduced distribution should be normalized as well as positive for all values of the intrinsic quantity ($q$ in our case). One starts with an initial guess for the intrinsic distribution ($\psi(q)$), and uses a kernel $[k(p|q)$, defined by equation 2 below] to iteratively find better approximations to both the apparent distribution and the intrinsic distribution.

Axial ratio of faint dwarfs

![Figure 1](https://academic.oup.com/mnrasl/article-abstract/404/1/L60/998234/fig1)

Figure 1. Histograms of the measured apparent axial ratios (after correction for the finite beam size). There are a total of 15 bins, the error bars were determined assuming Poisson statistics. The shaded area represents the 80 per cent confidence limit histograms generated by bootstrap resampling of the data (see text for details). The dashed line shows the best-fitting (i.e. using the weighted least square) polynomial to the binned data. The solid black line is the reconstructed distribution ($\Phi(p)$) given by Lucy deconvolution (see text for details). All values have been normalized so that the area under the curves and histogram is unity.

![Figure 2](https://academic.oup.com/mnrasl/article-abstract/404/1/L60/998234/fig2)

Figure 2. The frequency distribution of intrinsic axial ratios. The dashed line indicates $\psi(q)$ as obtained from the direct inversion of the polynomial fit to the binned data. The solid line is the final $\psi(q)$ obtained after Lucy deconvolution (see text for details). The shaded area represents the region between the $\psi(q)$’s obtained by applying Lucy deconvolution to the polynomial fits to the 80 per cent confidence interval histograms (see text for details).
If we rewrite equation (1) as

\[ \phi(p) = \int \psi(q) k(p|q) dq, \]  

then the rth loop of the iterative algorithm will be

\[ \Phi'(p) = \int \psi'(q) k(p|q) dq, \]  

\[ \psi'^{(q+1)} = \psi'(q) \int \frac{\phi(p)}{\Phi'(p)} k(p|q) dp, \]  

Equation (4) neglects the measurement errors in determining the observed axial ratio. Following Binney & de Vaucouleurs (1981), we can account for these errors by assuming the following form for the probability \( E(p|p') dp \), that a galaxy of actual apparent axial ratio \( p' \) is instead measured to have an axial ratio \( p \):

\[ E(p|p') = \frac{1}{\sqrt{2\pi} \sigma} \left[ \exp \left( -\frac{(p - p')^2}{2\sigma^2} \right) + \exp \left( -\frac{(2 - (p + p'))^2}{2\sigma^2} \right) \right]. \]  

In our case, we estimate the measurement errors by fitting a straight line to the distribution of errors in the axial ratio \( p \) as reported by the isophote fitting package. This gives

\[ \sigma(p') = 0.029p' + 0.0006 \]  

and projection kernel hence becomes

\[ K(p|q) = \int E(p|p') k(p|q) dp'. \]  

The algorithm now involves using \( K(p|q) \) instead of \( k(p|q) \) in equations (3) and (4), for which the range of integration now becomes 0 to 1, since now \( K(p|q) \neq 0 \) for \( p < q \). One would expect that in successive iterations, the approximation \( \Phi(p) \) to the observed distribution \( \phi(p) \) improve, and this can be used to decide when to terminate the algorithm.

Two different initial guesses for \( \psi(q) [\psi(q)] \) were tried, the first was peaked around \( q \sim 0.6 \), the second was constant for all \( q \). These two initial guesses thus cover two extremes of possible \( \psi(q) \). For both initial guesses, \( \psi(q) \) quickly converges to the form shown in Fig. 2. To determine the indicative errors in the determination of \( \psi(q) \), the 80 per cent confidence limit histograms shown in Fig. 1 were fit with polynomials and Lucy deconvolution was applied to these polynomials. The resulting intrinsic distribution functions are also shown in Fig. 2, and the shaded area hence represents the \( \sim 80 \) per cent confidence interval for \( \psi(q) \). The final \( \Phi(p) \) (i.e. the final approximation to the observed distribution function) is shown in Fig. 1, and as it can be seen, it fits with the observed distribution within the error bars. The \( \psi(q) \) shown in Fig. 2 has \( q = 0.57 \), standard deviation \( \sigma = 0.164 \) and skewness \( \gamma_1 = q^3/\sigma^3 = -0.62 \).

3 DISCUSSION

Equation (1) (and hence results obtained from inverting it also) applies only for a sample of randomly oriented oblate spheroids. The basic assumption hence is that the galaxy sample we are working with has an unbiased distribution of inclination angles. The selection criteria for the FIGGS sample (from which the current sample is drawn) includes a requirement that the optical major axis of the galaxy be \( >1 \) arcmin. Dwarf galaxies are generally dust poor (for e.g. see Walter et al. 2007; Galametz et al. 2009), and hence to a good approximation have optically thin discs. Highly inclined galaxies will hence be overrepresented in a diameter limited sample, i.e. our sample is biased towards edge on discs. This means that the true mean intrinsic axial ratio would be even larger than what we have estimated above. It is worth noting that as the intrinsic axial ratio gets closer to 1.0, the magnitude of this bias decreases, and hence the bias in our estimate should not be large.

The mean intrinsic axial ratio that we obtain, viz. \( \langle q \rangle \sim 0.57 \) is substantially larger than the value of 0.2 usually adopted for the stellar discs of large spiral galaxies. The value from our sample is more than twice as large as older measurements of \( \langle q \rangle \) in stellar discs of Magellanic irregular galaxies by Heidmann et al. (1972) (ranging from 0.20 to 0.24). Consistent with this, our sample contains no very flat galaxies. In fact, as it can be seen from Fig. 1, there are no galaxies with apparent axial ratio \(<0.2 \) in the sample. Further, if we look at the distribution of the observed axial ratio of different classes of galaxies in the Automated Photographic Measuring (APM) survey as in Lambas et al. (1992), then our histogram resembles those for ellipticals and S0s more closely than that for spirals. This is another qualitative indication that the underlying intrinsic distribution of axial ratios has a higher mean than is typical for spirals. Interestingly, the value of \( \langle q \rangle \) we obtain matches well with what Staveley-Smith et al. (1992) and Binggeli & Popescu (1995) derived for the stellar discs in dwarfs.

The thickness of the gas discs of dwarf galaxies is contrary to what one might have naively expected for a gas disc, since, in general, collisions between gas clouds should cause them to quickly settle into a thin disc. However, this large axial ratio is probably consistent with the large gas dispersion in comparison to the rotational velocity observed in dwarf galaxies. For example, Kaufmann, Wheeler & Bullock (2007) did particle hydrodynamics simulations to show that dwarf galaxies with rotational velocities \( \sim40 \) km s\(^{-1} \) did not originate as thin discs but thick systems. This still leaves open the question of where the large velocity dispersion comes from. Dutta et al. (2009) find good evidence for a scale-free power spectrum of H\(_I\) fluctuations in dwarf galaxies, consistent with what would be expected from a turbulent medium. Interestingly, they also find that that the dwarfs must have relatively thick gas discs, similar to the conclusions reached here.

Assuming that the origin of the velocity dispersion is turbulent motions in the interstellar medium (ISM), the time-scale for dissipation is given by \( \tau \sim L/v_{\text{turb}} \sim L/\sigma \) (e.g. Shu, Adams & Lizano 1987). The total turbulent energy is \( E_{\text{turb}} \sim 1/2 M_{HI} \sigma^2 \). For our sample galaxies, the typical H\(_I\) mass is \( \sim3 \times 10^9 \) M\(_{\odot}\), while the length-scale \( L \sim 1 \) kpc. The rate of turbulent energy dissipation is therefore \( \sim10^{39} \) erg yr\(^{-1} \). On the other hand, the star formation rate is \( \sim10^{-3} \) M\(_{\odot}\) yr\(^{-1} \) (Roychowdhury et al. 2009), for which the expected supernova rate for a Salpeter initial mass function (IMF) is \( \sim7 \times 10^{-4} \) yr\(^{-1} \) (Binney 2001). Assuming that each supernova explosion deposits \( \sim10^{51} \) ergs of energy into the ISM, the energy input from star formation is \( \sim10^{46} \) ergs yr\(^{-1} \), more than sufficient to balance the turbulent energy loss. Thus, star formation driven turbulence in the ISM is a plausible cause for the thick gas discs that we observe.

We have assumed throughout that the H\(_I\) discs of dwarf galaxies can be approximated as oblate spheroids. On the other hand, in Section 2, we saw that the inversion based on the best-fitting polynomial to the observed histogram of axial ratios actually gives unphysical results, i.e. that the derived intrinsic axial ratio distribution \( \psi(q) \) becomes negative. Lambas et al. (1992) found a similar pattern for the axial ratio distribution of spiral and S0 galaxies in the APM catalogue, and hence relaxed the assumption that the discs are oblate...
spheroids. Adequate fits to their data could be obtained assuming that the galaxies have a triaxial shape. Similarly, Ryden (2006) from a study of large galaxies in the Two Micron All Sky Survey catalogue concluded that spiral galaxies are mildly triaxial. The fact that the polynomial approximation gives unphysical results for our sample also suggests that triaxial models may provide a better fit. On the other hand, the Lucy deconvolution gives a physically plausible (as indeed it is designed to) intrinsic axial ratio distribution, that fits the observed data within the error bars. It is worth noting that the distribution found by Lucy deconvolution is in excellent agreement with that found by direct inversion of the polynomial fit for the entire range for which the latter is >0. Interestingly, if we assume the gas discs to be prolate instead of oblate spheroids, Lucy deconvolution produces an equally acceptable \( \Phi(p) \) as can be seen from Fig. 3. The \( \psi(q) \) obtained from Lucy deconvolution with a prolate spheroid assumption (see Fig. 4) indicates that such gas discs should be more cylindrical than spherical. However, the observed kinematics of gas in these galaxies (see Begum, Chengalur & Hopp 2003; Begum, Chengalur & Karachentsev 2005a; Begum et al. 2005b; 2006, 2008 etc.), shows that the gas has a significant rotational support. As discussed earlier, a gravitationally bound rotating disc of gas forms an oblate and not a prolate spheroid. Thus, although from the axial ratio data alone, one cannot distinguish between a prolate and oblate shapes, in conjunction with the kinematical data, it is clear that the gas is distributed in the form of a thick disc.

In summary, we find that the gas discs of dwarf galaxies are relatively thick, in sharp contrast to the gas discs of spiral galaxies. This has implications both for the internal dynamics of the gas, as well as for studies of the mass distribution and the Tully–Fisher relation in faint dwarfs, in which it is generally assumed that the gas is in a thin disc.

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