DDO 88: Inner Turmoil, Outer Calm

Caroline Simpson, Florida International University
Deidre Hunter, Lowell Observatory
Patricia M. Knezek, WIYN Observatory

Abstract

We present an HI and optical study of the gas-rich dwarf irregular galaxy DDO 88. Although DDO 88's global optical and HI parameters are normal for its morphological type, it hosts a large (2-3 kpc diameter) and unusually complete ring of enhanced HI emission located at approximately one-third the total HI radius and one-half the optically-defined Holmberg radius. The ring surrounds a central depression in the HI distribution. The HI ring is not expanding and does not appear to be related to any recent large-scale star formation. The star-formation rate is modest and is normal for Im/Sm galaxies. There is no star formation in the outer regions of the galaxy beyond the ring. The normal appearance of this galaxy in the optical and in the outer regions of the HI, which exhibits no unusual features, give no hint of the presence of the striking HI ring in the inner regions. This may place constraints on what the outer regions of dIrr galaxies can tell us about their evolution.

Introduction

DDO 88 (NGC 3377A; UGC 5889), is a gas-rich dwarf irregular galaxy located in the Leo I group (M96). Although located only 7′ (15 kpc) to the northwest of the E6 elliptical NGC 3377 and separated in velocity by only 93 km s^{-1}, there is no evidence in either system of disturbance, and so it is unlikely that they are interacting.

DDO 88 came to our attention when 21 cm observations taken with the VLA[1] indicated the presence of an apparent ring of HI surrounding the optical body of the galaxy (Simpson & Gottesman 2000). Although these data suffered from a lack of sensitivity, the suggestion of a large hole (2 – 3 kpc; D = 7.4 Mpc) in the HI distribution was intriguing. There are examples of other large holes in similar galaxies (Walter & Brinks 1999; Wilcots & Miller 1998; Puche et al. 1992; Sargent et al. 1983), but this seemed extreme.

Energy deposited in the interstellar medium (ISM) by vigorous episodes of star formation have been invoked to explain the presence of shells, holes, and filaments observed in low-mass galaxies (e.g. Stewart et al. 2000; Walter & Brinks 1999; Martin 1998; Meurer et al. 1998; Young & Lo 1996; Meurer et al. 1992; Puche et al. 1992; but see Rhode et al. 1999). The ISM in the star-forming region is depleted and/or heated up and dispersed; the surrounding cold, dense material is swept up and compressed around the edges, possibly triggering further star formation. This effect should be particularly strong on low-mass systems such as dwarfs (Mac Low & Ferrara 1999; de Young & Heckman 1994). We would then expect to see the outer regions of the galaxy to be perturbed as well.

To investigate the interplay between the inner and outer regions of low-mass irregular galaxies, we present new 21cm and optical (U, B, V, R, and Hα) observations of DDO 88.

[1]The VLA is a facility of the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation

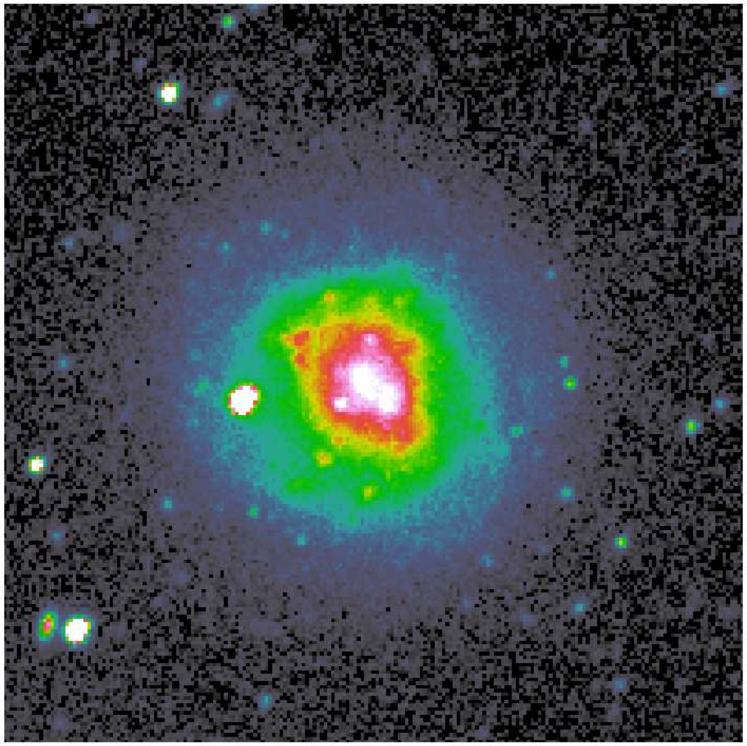

Figure 1: False-color logarithm representation of the V-band image to allow comparison of the inner and outer parts of the galaxy.

Optical Morphology

We obtained UBV images of DDO 88 using the Lowell Observatory 1.1 m Hall telescope March 1999 and April 2000. We also obtained Hα images of DDO 88 during April 1995 with the Perkins 1.8 m telescope at Lowell Observatory. We also employ B, R, and Hα images of DDO 88 obtained with the Michigan-Dartmouth-MIT Observatory 1.3 m telescope (Knezek, Sembach, & Gallagher 1999).

Our V-band image of DDO 88 is shown in Figure 1. DDO 88 changes shape slightly becoming more round in the outer parts, with the ellipticity (1 – b/a) changing from 0.13 in the inner galaxy to 0.03 in the outer parts. If the intrinsic $(b/a)_0$ is 0.3 (Hodge & Hitchcock 1966), the observed outer (b/a) implies an inclination of 16°. Thus, the galaxy is observed close to face-on.

There is also an asymmetry at low surface brightness levels, with the galaxy slightly more extended to the north and northwest than to the south and southeast. However, this kind of optical asymmetry is seen in other irregular galaxies (e.g. NGC 2366; Hunter, Elmegreen, & van Woerden 2001). Except for this small optical asymmetry, we see no signs of disturbance in DDO 88 that could be ascribed to an interaction with its larger neighbor NGC 3377.

Table 1: Integrated Properties

Parameter	Value
D (Mpc)[a]	7.4
$E(B-V)_f$[b]	0.01
R_{25} (arcmin)	0.83
R_{25} (kpc)	1.8
R_H (arcmin)	1.2
R_H (kpc)	2.6
$\mu_{V,0}$ (mag arcsec^{-2})	21.97 ± 0.04
α_V (kpc)	0.70 ± 0.01
$M_{B,0}$ (r=79″)	-15.34 ± 0.02
$(U-B)_0$ (r=79″)	-0.03 ± 0.09
$(B-V)_0$ (r=79″)	0.52 ± 0.02
log $L_{H\alpha,0}$ (ergs s^{-1})	38.89
SFR[c] ($M_\odot$ yr^{-1})	0.0055
log SFR/area[c] ($M_\odot$ yr^{-1} kpc^{-2})	−3.26

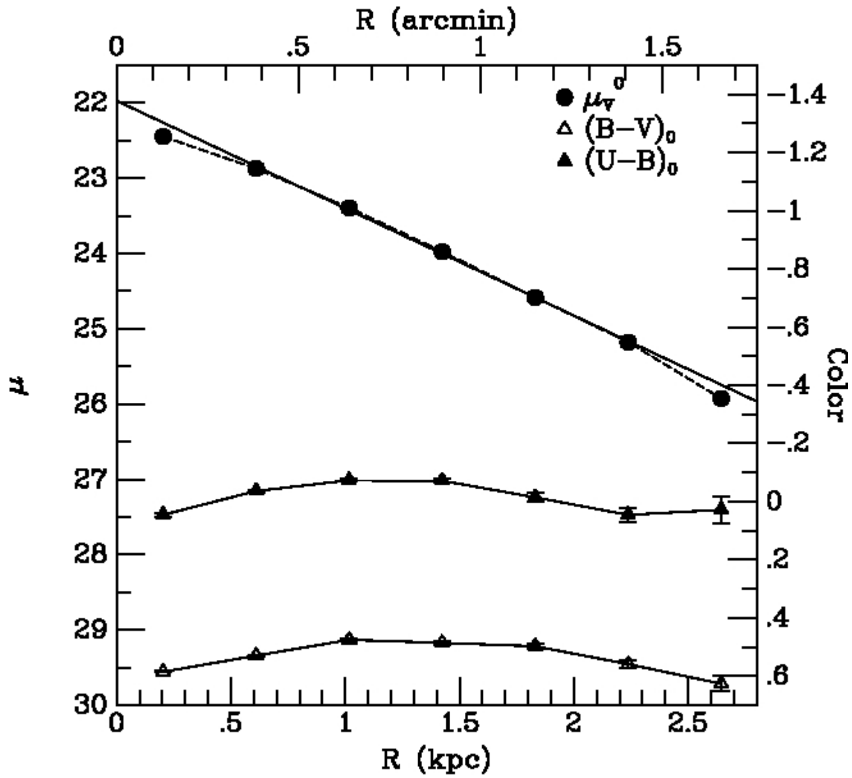

Figure 2: UBV surface photometry corrected for internal reddening (0.05 mag) and external reddening (0.01 mag). The exponential fit to the V-band surface brightness profile is shown as a solid line.

Surface Photometry

UBV surface photometry corrected for reddening is shown in Figure 2. Because the galaxy is nearly face-on, we used circular apertures increasing in radius from 11.3″ to 79.4″ in steps of 11.3″. Integrated magnitudes and colors are given in Table 1 and agree well with values in the literature. The integrated colors show that DDO 88 lies at the red end of the distribution of a large sample of Im and Sm galaxies in a UBV color-color plot (see Figure 2 of Hunter 1997).

In Figure 2, a linear fit to to $\mu_{V,0}$ in the inner 17″– 62″ is shown as the solid line. DDO 88 is fit well with an exponential disk profile having a central V-band surface brightness $\mu_{V,0}$ of 21.97 ± 0.04 magnitudes arcsec^{-2}. Corrected to the B passband, DDO 88 has a central surface brightness that is a little high and a disk scale length that is a little low compared other late-type galaxies (de Jong 1996). Figure 2 indicates that as in most irregulars, DDO 88 does not exhibit any major color gradient with radius. There are no regions other than star-forming regions associated with HII regions that are significantly different in color from the rest of the galaxy.

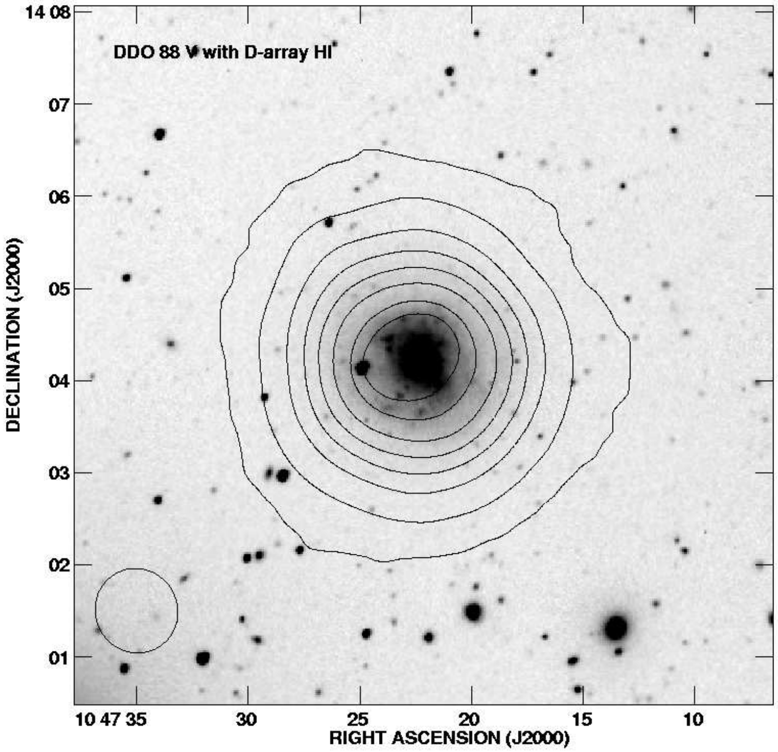

Figure 4: V-band image with HI contours from the D-array flux map. Contour levels are 02, 3.7, 11.1, 18.5, 25.9, 33.3, 40.8, 44.5 × 10^{19} atoms cm^{-2}. Beamsize is indicated in the lower left corner.

HI Morphology

DDO 88 was observed using the D-array and CS- array configurations of the VLA for 7.5 and 2.5 hrs, respectively. The separately edited, calibrated, and continuum-subtracted data sets were then combined in the *u-v* plane and imaged using uniform weighting with a ROBUST factor of –1 to produce a data cube with both good sensitivity and high resolution. See Table 2.

The D-array data lack the resolution to detect any structure in the HI distribution, and the map shows essentially circular contours of smoothly increasing density towards the center of the system. The HI contours on the V band image are shown in Figure 4.

Table 2: VLA Observations

	D-array	CS-array	C+D
Observation Date	1996 Sept 20, 24	1997 Sept 19	...
Time on Source	449 min	161 min	...
Bandwidth	1.56 MHz	1.56 MHz	1.56 MHz
No. of Channels	128	128	128
Velocity Resolution	2.6 km s^{-1}	2.6 km s^{-1}	2.6 km s^{-1}
Beamsize	55.6″ × 53.6″	14.5″ × 13.1″	16.8″ × 14.6″
Single channel r.m.s.	0.71 mJy B^{-1}	1.26 mJy B^{-1}	0.98 mJy B^{-1}

HI Ring

The higher resolution C+D-array data is better able to resolve the structure in the higher density HI gas (Figure 5). The most striking feature in this flux map is a high density ($N_{HI} \geq 4.5\times10^{20}$ atoms cm^{-2}) ring in the HI distribution. The ring contains 30% of the total HI mass as measured from the D-array data. This ring surrounds a central depression or hole in the HI which apparently surrounds the bulk of the V-band emission, as demonstrated in Figure 6.

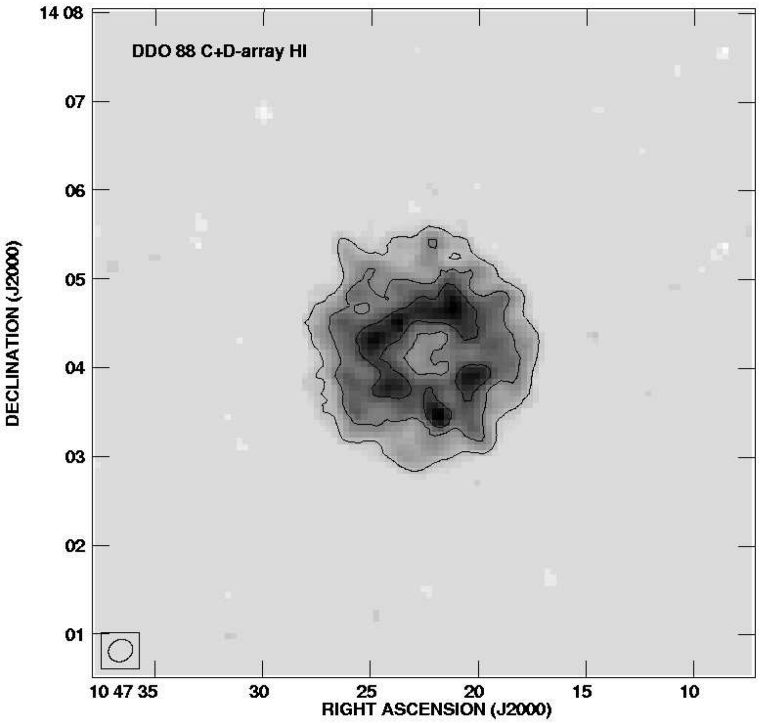

Figure 5: Integrated HI flux from the C+D-array. Contour levels are at 1, 3, 5, 7 $\times 10^{19}$ atoms cm^{-2}. Beamsize is indicated in the lower left corner.

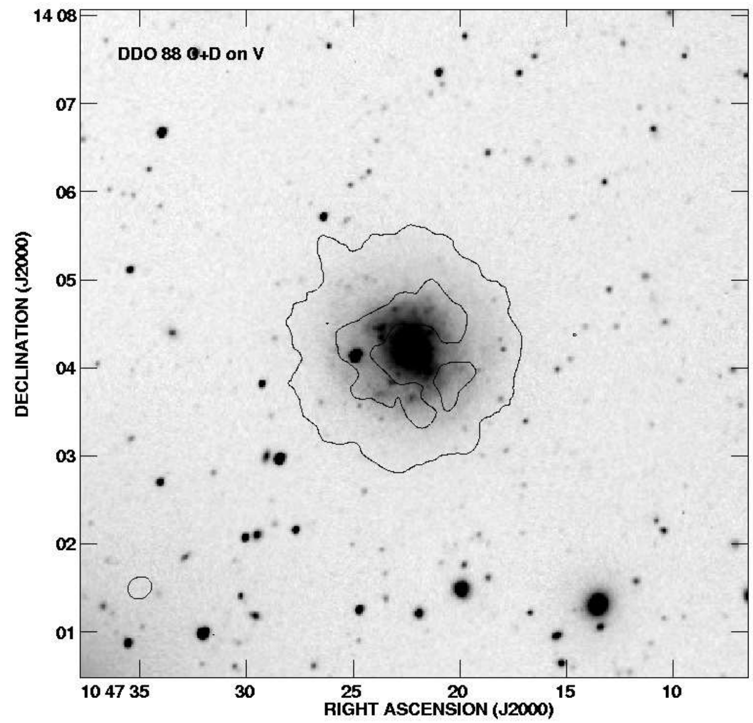

Figure 6: V-band image with HI contours from the C+D-array. Contour levels are at 1, 5 $\times 10^{20}$ atoms cm^{-2}. Beamsize is indicated in the lower left corner.

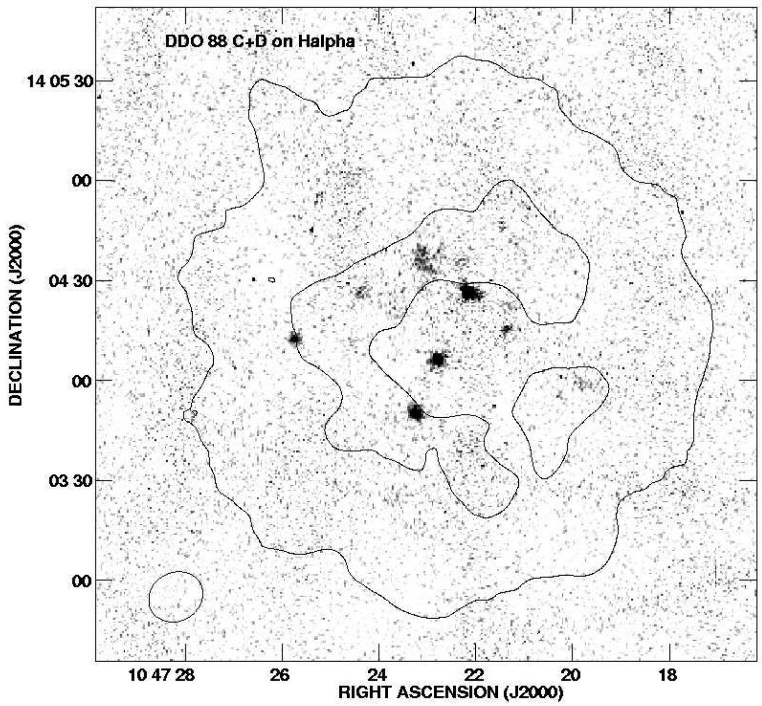

Figure 7: Hα image with HI contours from the C+D-array. Contour levels are at 1, 5 × 10^{20} atoms cm^{-2}. Beamsize is indicated in the lower left corner.

HI Knots

There are several discrete clumps of HI with masses of 1 – 3 × 10^6 $M_\odot$ embedded in the ring which are not resolved. These knots do not appear to coincide with any noticeable optical features in either the V or Hα images. Instead, two of the bright Hα regions are located on either inside edge of the ring in the southeast and the northwest, and the third is inside the hole in the HI ring (Figure 7).

Table 3: HI Properties

Parameter	Value
M_{HI}	7.8 × 10^7 $M_\odot$
V_{max}	41 km s^{-1}
R_{HI}	2.1′ = 4.4 kpc
R_{HI}/R_{25}	1.7
Outer diameter of ring	1.6′ = 3.4 kpc
M_{HI} of ring	2.3 × 10^7 $M_\odot$
Diameter of central hole	0.8′ = 1.8 kpc

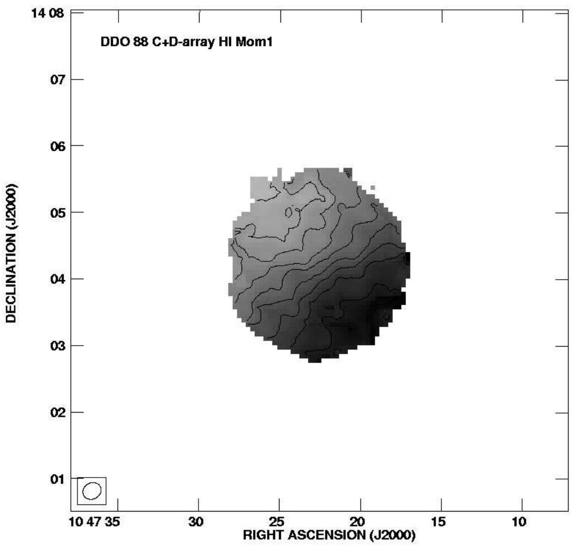

Figure 8: Velocity map from C+D array data. Contour levels are 550, 555, 560, 565, 570, 575, 580, 585, 590, 595 km s^{-1}.

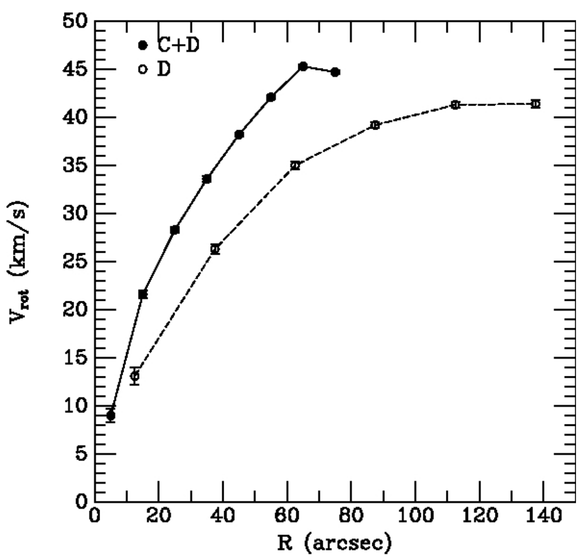

Figure 9: Rotation curve from low-resolution D-array data (○) and the higher-resolution C+D-array data (●).

Kinematics

DDO 88 shows mostly ordered, largely solid body rotation over its velocity field (Figure 8). Many dwarf galaxies exhibit solid body rotation over much of their areas, and DDO 88 would seem to be no exception. We have fit a rotation curve (Figure 9) to the galaxy; the rotation curve and maximum rotation speed observed in DDO 88 are normal for its luminosity (Hunter, Hunsberger, & Roye 2000). The shape of the rotation curve is also fairly normal (Swaters 1999).

The average velocity dispersion in the second moment map is on the order of 5 km s^{-1}, with one higher dispersion (up to 12 km s^{-1}) knot associated with the brightest HI knot in the ring. Interestingly, this knot is not associated with any significant optical feature in either the V or Hα images. On average, the gas dispersions are slightly higher in the area of the ring: 7 – 9 km s^{-1} vs. 4 – 5 in the outer regions.

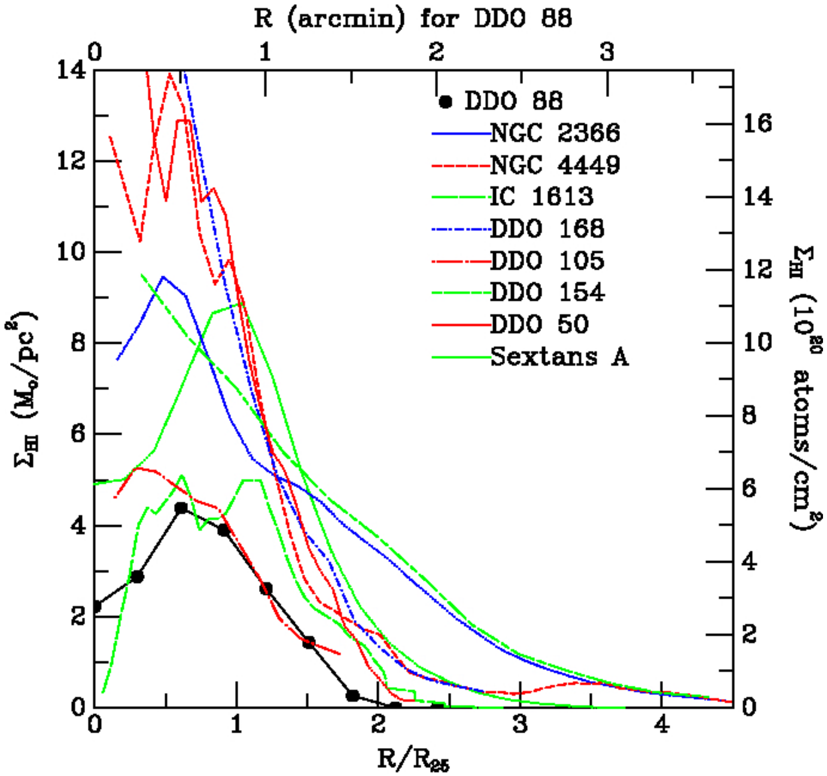

Figure 10: Surface density of HI in DDO 88. For comparison we show the HI surface density profiles of a sample of other Im galaxies (NGC 2366: Hunter, Elmegreen, & van Woerden 2001; NGC 4449: Hunter, van Woerden, & Gallagher 1999; IC 1613: Wilcots 2001; DDO 105 and DDO 168: Broeils 1992; DDO 154: Carignan & Beaulieu 1989; DDO 50: Puche et al. 1992; and Sextans A: Wilcots & Hunter 2002).

HI Surface Density Profile

In Figure 10 we show the azimuthally-averaged surface density of the HI gas in DDO 88, integrating in 15″ radial steps using a position angle of 215° and inclination of 28°. Along with DDO 88, we plot other irregular galaxies for comparison. In all, the azimuthally-averaged drop-off of the HI surface density with radius appears to be well within the range of what is observed in other irregular galaxies. The central hole is also common.

The extent of the HI relative to the optical as measured by R_{25} is a little low compared to the collection of irregulars in Figure 9, but cannot be considered too unusual. In addition the ratio of R_{HI}/R_H in DDO 88 is 1.7, which is seen to lie at the peak in the number distribution for various irregulars from data in the literature (Hunter 1997).

The overall level of the HI surface density is low compared other Im galaxies in Figure 10; this may explain why the star formation activity in this galaxy is so modest, although generally there is no correlation between maximum gas surface density and integrated star formation activity in irregulars (Hunter, Elmegreen, & Baker 1998). Furthermore, it is interesting and puzzling that we see HII regions in DDO 88 in the central and outer parts of the galaxy where the HI surface density is low.

Formation of Hole

Other irregulars (DDO 81, Walter & Brinks 1999; Holmberg II, Puche et al. 1992; M81dwA, Sargent et al. 1983) do have holes in their ISM created by the winds and supernova explosions of concentrations of massive stars or by instabilities in the multi-phase ISM (Wada, Spanns, & Kim 2000). However, holes this large are rare and may be especially unusual in a galaxy of this low luminosity. Using the shell models of McCray & Kafatos (1987), we conservatively estimate that number of massive stars required to produce DDO 88's hole would be approximately 400, with a total stellar mass of 0.2 – 2 $\times$ 10^6 $M_\odot$. Assuming constant star formation over the past 10 Gyr, as indicated by the integrated UBV colors (Larson & Tinsley 1978), the mass-to-light ratio is 1 $M_\odot/L_{V\odot}$. Thus, the total mass of stars in the galaxy is of order 2 $\times$ 10^8 $M_\odot$. This means the star-forming event required to make the central hole in the HI is of order 0.1 – 1%. Therefore, this star-forming event would be a minor blip in the evolution of the galaxy.

If instead of being the result of star formation, the central minimum in HI is due to the HI being replaced by molecular gas, we estimate the amount of "missing" HI mass converted to H_2 to be 3 $\times$ 10^6 $M_\odot$. The consequences of such a large molecular complex should be observable in embedded star formation, the ratio of molecular-to-atomic material, and optical extinction. We do see a few small HII regions, but not at a level that would indicate massive amounts of molecular gas. Is also unlikely that there is optically shrouded star formation, as the upper limit to $L_{FIR}/L_{H\alpha}$ for DDO is consistent with very little embedded star formation (Hunter et al. 1989).

The observed HI mass in the central depression is 5.5 $\times$ 10^6 $M_\odot$, giving a ratio of M_{H2}/M_{HI} of 0.7, or 0.1 if we include the HI ring. These estimates are within the range of 0.1 – 1.8 found in the star-forming regions of NGC 4449 (Hunter, Walker, & Wilcots 2000). However, the azimuthally-averaged surface photometry of the galaxy does not indicate significant extinction in the center of the galaxy, which we would expect if the central region is filled with molecular gas.

So although the ratio of molecular-to-atomic gas would be reasonable, we think it unlikely that the central depression in HI is due to conversion to molecular gas. There is no evidence for the extensive star formation (even if shrouded) that would be expected, and no significant extinction is detected.

Summary

DDO 88 appears to be a fairly normal low-luminosity dwarf galaxy in the optical, with no large scale star formation occurring. There is a slight asymmetry in the outer low-level isophotes, but this is not unusual for its morphological type. Its integrated UBV colors put it at the red end of the distri\bution for Im/Sm galaxies, reinforcing the idea that there has been no recent extensive star formation. It is well fit by an exponential disk, and there are no major color gradients detected across the disk. Again, this is typical of Im/Sm galaxies.

In HI, DDO 88's outer regions also appear quite normal, with the ratio of HI-to-optical radius in the normal range. Its azimuthally-averaged surface is low overall when compared to a sample of irregulars, and drops off at an average rate.

The normal appearance of the optical and outer regions of the HI in DDO 88 give no hint that the center of the galaxy hosts a large central HI hole or depression. The HI surrounding the hole is distributed in a high column density ring, the inner edges of which roughly correspond to the outer edges of the V band emission. The hole is unusually large for a galaxy of this size, and does not appear to be expanding. DDO 88's integrated colors are consistent with a constant star formation event over the last 10 Gyr. The stellar mass required to produce a hole of this size (via energy injection from stellar winds and supernova) is on the order of 0.1 – 1% of the total stellar mass of the galaxy, and so would not be a significant event in its evolution if this is, indeed, how the hole formed.

DDO 88 provides a cautionary tale when investigating how the outer regions of irregular galaxies affect their evolution. In this case, you cannot tell the book by its cover.

References

Broeils, A. 1992, Ph.D. thesis, Rijksuniversiteit Groningen

Carignan, C., & Beaulieu, S. 1989, ApJ, 347, 760

de Jong, R. S. 1996, A&A, 313, 45

de Young, D. S., & Heckman, T. M. 1994, ApJ, 431, 598

Hodge, P. W., & Hitchcock, J. L. 1966, PASP, 78, 79

Hunter, D. A. 1997, PASP, 109, 937

Hunter, D. A., Elmegreen, B. G., & Baker, A. L. 1998, ApJ, 493, 595

Hunter, D. A., Elmegreen, B. G., & van Woerden, H. 2001, ApJ, 556, 773

Hunter, D. A., Gallagher, J. S., III, Rice, W. L., & Gillett, F. C. 1989, ApJ, 336, 152

Hunter, D. A., Hunsberger, S. D., & Roye, E. W. 2000, ApJ, 542, 137

Hunter, D. A., Walker, C. E., & Wilcots, E. M. 2000, AJ, 119, 668

Hunter, D. A., van Woerden, H., & Gallagher, J. S. 1999, AJ, 118, 2184

Knezek, P. M., Sembach, K. R., & Gallagher, J. S., III 1999, ApJ, 514, 119

Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, 46

Mac Low, M.-M., & Ferrara, A. 1999, ApJ, 513, 142

Martin, C. L. 1998, ApJ, 506, 222

McCray, R., & Kafatos, M. 1987, ApJ, 317, 190

Meurer, G. R., Freeman, K. C., & Dopita, M. A. 1992, AJ, 103, 60

Meurer, G. R., Staveley-Smith, L, & Killeen, N. E. B. 1998, MNRAS, 300, 705

Puche, D., Westpfahl, D., Brinks, E., & Roy, J.-R. 1992, AJ, 103, 1841

Rhode, K. L., Salzer, J. J., Westpfahl, D. J., & Radice, L. A. 1999, AJ, 118, 323

Sargent, W. L. W., Sancisi, R., & Lo, K. Y. 1983, ApJ, 265, 711

Simpson, C. E., & Gottesman, S. T. 2000, AJ, 120, 2975

Stewart, S. G., et al. 2000, ApJ, 529, 201

Swaters, R. 1999, PhD thesis, Rijksuniversiteit Groningen

Wada, K., Spaans, M., & Kim, S. 2000, ApJ, 540, 797

Walter, F., & Brinks, E. 1999, AJ, 118, 2734

Wilcots, E. M., & Hunter, D. A. 2002, AJ, in press

Wilcots, E. M., & Miller, B. W. 1998, AJ, 116, 2363

Wilcots, E. M., 2001, private communication

Young, L. M., & Lo, K. Y. 1996, ApJ, 462, 203