Resolving the mystery of the dwarf galaxy HIZSS003

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ABSTRACT

The nearby galaxy HIZSS003 was recently discovered during a blind H I survey of the Zone of Avoidance. Follow-up Very Large Array (VLA) observations as well as optical and near-infrared imaging and spectroscopy confirm that it is a low-metallicity dwarf irregular galaxy. However, there are two puzzling aspects of these observations: (i) current star formation, as traced by Hα emission, is confined to a small region at the edge of the VLA H I image; and (ii) the metallicity of the older red giant branch stars is higher than that of the gas in the H II region. We present high spatial and velocity resolution Giant Metrewave Radio Telescope observations which resolve these puzzles by showing that HIZSS003 is actually a galaxy pair and that the H II region lies at the centre of a much smaller companion galaxy (HIZSS003B) to the main galaxy (HIZSS003A). The H I emission from these two galaxies overlaps in projection, but can be separated in velocity space. HIZSS003B has an H I mass of \(2.6 \times 10^6\) M⊙, and a highly disturbed velocity field. Since the velocity field is disturbed, an accurate rotation curve cannot be derived; however, the dynamical mass indicated is \(~5 \times 10^7\) M⊙. For the bigger galaxy HIZSS003A we derive an H I mass of \(1.4 \times 10^7\) M⊙. The velocity field of this galaxy is quite regular, and from its rotation curve we derive a total dynamical mass of \(~6.5 \times 10^8\) M⊙.

Key words: galaxies: dwarf – galaxies: individual: HIZSS003 – galaxies: kinematics and dynamics – radio lines: galaxies.

1 INTRODUCTION

The galaxy HIZSS003 was discovered in the course of a blind H I 21-cm survey of the Zone of Avoidance (ZOA) (Henning et al. 1998, 2000). Its very low Galactic latitude (\(b = 0.09\)) made identification of the optical counterpart in the Palomar Sky Survey images difficult; however, the H I properties derived from the single-dish data were consistent with it being a dwarf irregular galaxy. This was later confirmed by follow-up Very Large Array (VLA) D-array and optical observations (Massey et al. 2003). The VLA map showed two peaks in the H I distribution, a resolved peak at the centre of the galaxy and an unresolved secondary peak close to the edge of the H I distribution. While broad-band \(BVRI\) imaging failed to detect any stars in the galaxy, narrow-band Hα imaging detected an H II region spatially coincident with the unresolved secondary H I peak in the VLA map. Spectroscopy of the H II region confirmed that its radial velocity agreed with that of the H I emission. Although the identification of an H II region strengthens the conclusion that HIZSS003 is a dwarf irregular galaxy, it is puzzling that the current star formation should be concentrated at the edge of the H I disc. Very Large Telescope (VLT) near-infrared images as well as Multiple Mirror Telescope (MMT) spectroscopic data of the H II region were presented by Silva et al. (2005). The near-infrared images revealed a resolved stellar population and allowed the distance to the galaxy to be derived based on the \(K\) magnitude of the tip of the red giant branch (TRGB). The derived distance of 1.69 ± 0.07 Mpc agrees well with the previous estimate of 1.8 Mpc by Massey et al. (2003) (based on the assumption that HIZSS003 has zero peculiar velocity with respect to the Local Group centroid).

From their spectroscopic data, Silva et al. (2005) estimate the metallicity ([O/H]) of the H II region in HIZSS003 to be \(~ -0.9\), comparable to that of other nearby metal-poor irregular galaxies. On the other hand, the metallicity ([Fe/H]) of the RGB stars (as derived from their colours) is somewhat higher, namely \(~ -0.5 \pm 0.1\). That the older RGB stars in the galaxy are more metal-rich than the gas associated with ongoing star formation in the H II region is puzzling. Silva et al. (2005) speculate that the lower metallicity of the H II region is caused by low-metallicity gas that is falling into HIZSS003 for the first time. Here we present high-resolution Giant Metrewave Radio Telescope (GMRT) H I images of HIZSS003, which resolve the puzzles of the H II region location and metallicity by showing that HIZSS003 is in fact a galaxy pair, with the H II region being located at the centre of a much smaller companion to the main galaxy. Throughout this paper we adopt the Silva et al. (2005) TRGB distance estimate of 1.69 Mpc for HIZSS003.

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2 OBSERVATIONS AND DATA ANALYSIS

The GMRT (Swarup et al. 1991) observations of HIZSS003 [RA (2000): 07h00m29.3s, Dec.(2000): −04°12’30”] were conducted on 2004 August 23. An observing bandwidth of 1 MHz centred at 1419.1 MHz (which corresponds to a heliocentric velocity of 290 km s\(^{-1}\)) was used. The band was divided into 128 spectral channels, giving a channel spacing of 1.65 km s\(^{-1}\). Flux calibration was done using scans on the standard calibrators 3C 147 and 3C 286, which were observed at the start and end of the observing run. Phase calibration was done using 0744−064, which was observed once every 40 min. Bandpass calibration was done in the standard way using 3C 286. The total on-source time was ∼4 h.

The data were reduced using standard tasks in classic AIPS. The GMRT has a hybrid configuration which simultaneously provides both high angular resolution (∼2 arcsec if one uses baselines between the arm antennas) and sensitivity to extended emission (from baselines between the antennas in the central array). Data cubes were therefore made at various resolutions including 42 × 39, 28 × 26, 23 × 18, 18 × 11, 8 × 6 and 4 × 3 arcsec\(^2\), using uniform weighting. The rms noise per channel for these resolutions is 2.2, 2.0, 1.8, 1.6, 1.4 and 1.2 mJy respectively. All the data cubes, except 8 × 6 and 4 × 3 arcsec\(^2\), were deconvolved using the task IMAGR.

For the two highest resolution data cubes, the signal-to-noise ratio was too low for clean to work reliably. A continuum image was made using the average of the line-free channels. No continuum was detected from the galaxy to a 3σ flux limit of 1.0 mJy beam\(^{-1}\). A high-resolution continuum map (4 × 3 arcsec\(^2\) resolution) was also made to search for any compact continuum sources. The only continuum source of note detected is NVSS J070023 − 041255. The H I column density (as derived from the 42 × 39 arcsec\(^2\) resolution image) along the line of sight to this source is 5.7 × 10\(^{20}\) atom cm\(^{-2}\). A search for HI absorption, in the direction of this source, gave negative results at all resolutions. The implied lower limit on the spin temperature of the gas (assuming a velocity width of 10 km s\(^{-1}\)) is 723 K. For reference we note that NVSS J070023 − 041255 lies towards the source that we call HIZSS003B below, and that it is close to, but not coincident with, the H I region detected by Massey et al. (2003). It appears likely that it is a background source, with no connection to the H I emission. The continuum source was subtracted using the task UVSUB.

3 RESULTS AND DISCUSSION

Channel maps of the H I emission at a resolution of 42 × 39 arcsec\(^2\) are shown in Fig. 1. H I emission is spread over 63 channels and consists of two distinct sources, one spanning 59 channels and the other spanning 26 channels. At this spatial resolution some channels show H I emission connecting the two sources; however, it is not clear whether this is due to beam smearing. A H I feature connecting the two sources is also seen in the 28 × 26 and 23 × 18 arcsec\(^2\) resolution data cubes. However, at higher resolutions no such connecting emission is seen in the channel maps. Further, as discussed in more detail below, the velocity field of the bigger source does not appear to be particularly disturbed, and neither source shows signs of two armed tidal distortions. It is possible that the connecting emission seen in Fig. 1 is due to beam smearing. In order to disentangle the H I emission, one spectral cube was made for each galaxy in which emission from the other galaxy was blanked out. In the case of channel maps that showed connecting H I, the blanking was done mid-way between the two sources. Figs 2(a) and (b) show H I images of the two sources at 23 × 18 arcsec\(^2\) resolution made from these blanked cubes. In the rest of the paper, we refer to the bigger (eastern) galaxy as HIZSS003A and the smaller (western) one as HIZSS003B. The entire H I distribution will be referred as the ‘HIZSS003 system’. The sources HIZSS003A and HIZSS003B correspond to the main H I peak and the secondary unresolved peak in the VLA map of Massey et al. (2003). The combination of poor spatial (∼60 arcsec) and velocity (∼10 km s\(^{-1}\)) resolution of the VLA observations prevented Massey et al. (2003) from separating the two galaxies, although the near-infrared VLT images do show two separate stellar concentrations, i.e. one for each galaxy. Fig. 2(c) shows the high-resolution H I map (8 × 6 arcsec\(^2\) resolution) of HIZSS003. The more diffuse emission is resolved out, and the remaining emission from the two galaxies can be disentangled without having to resort to channel-by-channel blanking. As can be seen in Fig. 2, the H I distribution in both the galaxies is clumpy, with three main peaks seen in the H I distribution of HIZSS003A, whereas the H I distribution of HIZSS003B is resolved into two peaks. No signature of tidal interaction is evident in the H I distribution of either galaxy. The H II region detected in the HIZSS003 system is located close to one of the peaks of the H I distribution in HIZSS003B (shown by a cross in Fig. 2c). The H α emission is approximately aligned with the H I contours of the galaxy (i.e. from north-west to south-east), and its heliocentric velocity (335 ± 15 km s\(^{-1}\) − Massey et al. 2003) matches within the error bars with the systemic velocity of 322.6 ± 1.4 km s\(^{-1}\) for HIZSS003B derived from the H I global profile (see below).

Fig. 3 shows the global H I emission profiles of the two galaxies obtained from the 42 × 39 arcsec\(^2\) resolution data cubes. As discussed above, emission from one galaxy was blanked before obtaining the H I profile for the other one. Gaussian fits to the H I profiles give systemic velocities of 288.0 ± 2.5 and 322.6 ± 1.4 km s\(^{-1}\) for HIZSS003A and HIZSS003B respectively. The corresponding velocity widths at 50 per cent of peak emission are 55 and 28 km s\(^{-1}\), while the integrated fluxes are 20.9 ± 2.1 and 3.8 ± 0.3 Jy km s\(^{-1}\). The H I masses corresponding to these integrated fluxes are 1.4 × 10\(^5\) and 2.6 × 10\(^4\) M\(_\odot\). The combined flux of both galaxies is 24.7 Jy km s\(^{-1}\), which is in excellent agreement with the value of 24.9 Jy km s\(^{-1}\) obtained from the VLA observations by Massey et al. (2003). However, both these values are somewhat lower than the flux integral of ∼32 Jy km s\(^{-1}\), estimated from the single-dish observations by Henning et al. (2000). The H I diameters of the two galaxies, measured at a level of ∼10\(^{-19}\) atom cm\(^{-2}\) (from the 42 × 39 arcsec\(^2\) images), are ∼6.5 arcmin (3.2 kpc) and ∼3 arcmin (1.5 kpc).

Figs 4(a) and (b) show the velocity fields of the two galaxies derived from the moment analysis of the 28 × 26 arcsec\(^2\) resolution data cube. The velocity field of HIZSS003A (Fig. 4a) is regular and a large-scale velocity gradient, consistent with systematic rotation, is seen across the galaxy. The velocity field is also mildly lopsided – the isovelocity contours in the southern half of the galaxy are more curved than in the northern half. Kinks are seen in the eastern isovelocity contours, close to the location of HIZSS003B. These kinks are more prominent in the higher resolution velocity fields (not shown).

Rotation curves of HIZSS003A were derived using 42 × 39, 28 × 26, 23 × 18 and 18 × 11 arcsec\(^2\) resolution velocity fields, using tilted ring fits. The centre and systemic velocity for the galaxy obtained from a global fit to the velocity fields at various resolutions matched within the error bars; the systemic velocity of 291.0 ± 1.0 km s\(^{-1}\) also matched with the value obtained from the global H I profile of the galaxy. Keeping the centre and systemic velocity fixed, we fitted for the inclination and position angle (PA) in each ring.
The dwarf galaxy HIZSS003

Figure 1. H I channel maps of HIZSS003 at 42 × 39 arcsec² resolution. The contour levels are 7.5, 22.5, 45 and 75 mJy km s⁻¹. The heliocentric velocity in km s⁻¹ is marked on the upper left-hand corner of every pane. The channel spacing is 1.65 km s⁻¹.

Figure 2. Integrated H I emission maps (grey-scales and contours) of (a) HIZSS003A and (b) HIZSS003B at 23 × 18 arcsec² resolution. The contour levels are 0.2, 3.9, 7.8, 11.6, 15.4, 19.1, 31.4 and 24.9 × 10²⁰ atom cm⁻². The angular scale for panel (b) has been expanded for clarity. (c) Integrated H I emission map of the HIZSS003 system (grey-scale and contours) at 8 × 6 arcsec² resolution. The contour levels are 0.03, 0.05, 0.10, 0.17, 0.21, 0.27, 0.34 and 0.36 Jy beam⁻¹ km s⁻¹. The location of the H II region in HIZSS003B is marked by a cross.


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For all resolution velocity fields, the PA was found to vary from \(\sim 4^\circ\) to \(4^\circ\) and the inclination varied from \(\sim 70^\circ\) to \(55^\circ\). Keeping the PA and inclination fixed to \(3^\circ\) and \(65^\circ\) in the inner regions (up to 90 arcsec) and \(0^\circ\) and \(60^\circ\) in the outer regions respectively, the rotation curves at various resolutions were derived. Fig. 4(c) shows the rotation curves of the galaxy derived at various resolutions – as can be seen, they match within the error bars. The solid line shows the final adopted rotation curve. The total dynamical mass of HIZSS003A (at the last measured point of the rotation curve) is found to be \(6.5 \times 10^8 M_\odot\).

The velocity field of HIZSS003B (Fig. 4b) shows a large scale gradient in the south-east–north-west direction with a magnitude of \(\sim 5\) km s\(^{-1}\) kpc\(^{-1}\). This gradient is aligned along the direction of elongation of the H\textsc{i} contours and also with the H\textsc{ii} region in the galaxy (Fig. 2b). However, the observed velocity pattern is clearly not rotation since the velocity gradient is not monotonic. Both ends of the galaxy are at a higher velocity than the central region. Similar kinematics are seen in other very low-mass dwarf galaxies, e.g. Sag DIG and LGS 3 (Young & Lo 1997). The disturbed kinematics may be due to a combination of tidal perturbation from the companion galaxy and energy input from the ongoing star formation (see e.g. GR8, Begum & Chengalur 2003). The inclination of HIZSS003B derived from the ellipse fit to the H\textsc{i} distribution (assuming an intrinsic axial ratio \(q_\theta = 0.25\)) is \(\sim 50^\circ\), which means that the upper limit to the inclination-corrected rotation velocity is \(5/\sin 50^\circ \sim 6.5\) km s\(^{-1}\).

Assuming that the gas has a velocity dispersion (\(\sigma\)) of 8 km s\(^{-1}\) [which is a typical value for low-mass dwarf irregular galaxies (e.g. Lake, Schommer & van Gorkom 1990; Begum, Chengalur & Hopp 2003)] implies that the systematic rotation, if any, in the galaxy is smaller than the velocity dispersion. Given the lack of any systematic rotation, it is difficult to determine the total dynamical mass for the galaxy accurately. From the virial theorem, assuming the H\textsc{i} distribution to be spherical with an isotropic velocity dispersion and negligible rotation, the mass indicated is (Hoffman et al. 1996)

\[
M_{VT} = \frac{5 \sigma^2}{G}.
\]

Assuming a \(\sigma\) of 8 km s\(^{-1}\), and taking the diameter of the galaxy as \(\sim 1.5\) kpc, gives the total mass of HIZSS003B to be \(\sim 5.3 \times 10^7 M_\odot\). For the entire HIZSS003 system, if we assume the two galaxies to be in a bound circular orbit, then the orbital mass indicated is

\[
M_{orb} = \frac{32}{3\pi G} r_p \Delta V^2,
\]

where \(r_p\) is the projected separation and \(\Delta V\) the radial velocity difference (Karachentsev et al. 2002). For a projected separation of \(\sim 0.7\) kpc and a velocity difference of \(\sim 34.6\) km s\(^{-1}\), the orbital mass indicated is \(\sim 6.7 \times 10^8 M_\odot\), in good agreement with the total mass derived from the internal kinematics.

Silva et al. (2005) highlight a puzzle regarding the metallicity of HIZSS003. The metallicity of the HIZSS003 system calculated from the younger H\textsc{ii} region is smaller than that estimated from the colour of the older RGB stars. Given that the bulk of the stars are associated with the bigger galaxy but that the H\textsc{ii} region is in the smaller galaxy, the inconsistency in the derived metallicities is not surprising. The low metallicity of the gas in the H\textsc{ii} region of the smaller galaxy HIZSS003B is also qualitatively consistent with what one would expect from the metallicity–luminosity relation. Further, going by the stars identified as belonging to the H\textsc{ii} region (fig. 6 of Silva et al. 2005), there is a trend for these stars to have a slightly smaller \(J – K\) colour (consistent with a lower metallicity: Valenti, Ferraro & Origlia 2004) than the median colour of all stars identified as belonging to HIZSS003. The HIZSS003 puzzle thus seems (at a qualitative level at least) resolved. However, as is well
known, an observed colour difference cannot be uniquely ascribed to a difference in the metallicity, but could also be due to a difference in the age of the stars (‘age-metallicity’ degeneracy) or a temperature difference. A more quantitative consistency check will have to await a detailed reanalysis of the near-infrared data.

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REFERENCES


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