H\textsubscript{i} in the Arp 202 system and its tidal dwarf candidate

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ABSTRACT

We present results from our Giant Metrewave Radio Telescope (GMRT) H\textsubscript{i} observations of the interacting pair Arp 202 (NGC 2719 and NGC 2719A). Earlier deep UV(GALEX) observations of this system revealed a tidal tail like extension with a diffuse object towards its end, proposed as a tidal dwarf galaxy (TDG) candidate. We detect H\textsubscript{i} emission from the Arp 202 system, including H\textsubscript{i} counterparts for the tidal tail and the TDG candidate. Our GMRT H\textsubscript{i} morphological and kinematic results clearly link the H\textsubscript{i} tidal tail and the H\textsubscript{i} TDG counterparts to the interaction between NGC 2719 and NGC 2719A, thus strengthening the case for the TDG. The Arp 202 TDG candidate belongs to a small group of TDG candidates with extremely blue colours. In order to gain a better understanding of this group we carried out a comparative study of their properties from the available data. We find that H\textsubscript{i} (and probably stellar) masses of this extremely blue group are similar to the lowest H\textsubscript{i} mass TDGs in the literature. However the number of such blue TDG candidates examined so far is too small to conclude whether or not their properties justify them to be considered as a subgroup of TDGs.

Key words: galaxies: spiral - galaxies: interactions - galaxies: kinematics and dynamics - galaxies: individual: Arp 202 - radio lines: galaxies galaxies: tidal dwarfs

1 INTRODUCTION

Tidal interactions between galaxies, where at least one of them is gas rich, can result in tidal stripping of large amounts of H\textsubscript{i} from the potential of the parent galaxy(s). Most of this stripped H\textsubscript{i} will eventually fall back into the potential of one or other of the interacting galaxies or be incorporated into the intra–group medium (IGM). But if the H\textsubscript{i} densities are sufficient and environmental conditions are favourable, self-gravitating bodies with masses typical of dwarf galaxies, called Tidal Dwarf Galaxies (TDG), may form within the tidally stripped gas (Duc & Mirabel 1999; Duc et al. 2000). Apart from establishing that these are indeed self-gravitating objects, a key observational problem is to distinguish TDGs from older standard dwarfs because some TDGs contain old stars stripped from their parent galaxies. Other TDGs consist almost entirely of young stars formed in situ from H\textsubscript{i} stripped from the parents during the interaction (Duc & Mirabel 1999; Duc et al. 2000; Braine et al. 2001). A combination of evidence linking the TDG candidate to interacting parents and stellar population studies is normally used to identify TDG candidates, although indisputable criteria remain to be accepted.

TDGs are usually observed during an active star forming stage thus allowing tests of star formation criteria and stellar to gas relationships in low gas density environments. As TDGs form from stripped gas they are expected to contain little or no dark matter (Elmegreen et al. 1993). This makes them valuable in studying the role and importance of dark matter in galaxy formation. TDGs are also expected to be metal rich in comparison to normal dwarfs, because the gas from which TDGs form originates from more evolved, usually large, late–type galaxies. The lack of dark matter in TDG’s implies they are more vulnerable to disruption by further tidal interactions than normal dwarfs. Thus TDGs provide a unique environment to investigate the processes governing formation and evolution of galaxies.

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Figure 1. Arp 202 field: Left: Low-resolution integrated H\textsc{i} emission contours overplotted on a SDSS g, r, i-band false colour image. The contours are H\textsc{i} column density levels of $10^{19}$ atoms/cm$^2 \times (4.4, 9.3, 15.5, 21.7, 34.1, 46.5, 61.9, 71.2, 105.3, 185.8, 247.7, 309.7)$. The first contour is at 3$\sigma$. The beam size (47.5$''$ x 37.4$''$) is indicated by the ellipse at the bottom left of the image. Names of galaxies detected in H\textsc{i} are shown adjacent to their optical positions. Right: GMRT H\textsc{i} spectra, with a velocity resolution of 27 km s$^{-1}$, for each of the detections. The Arp 202 spectrum is from the integrated emission from NGC 2719, NGC 2719A, the tidal tail and the TDG candidate.
To address the issue of in-situ star and TDG formation in tidal gas debris, a multi-wavelength study of a sample of Arp interacting galaxies (the Spirals, Bridges, and Tails (SB&T) sample) is being carried out by Smith et al. (2007, 2010a). GALEX, Spitzer and Hα observations of these systems have revealed evidence of in-situ star formation and TDG candidates. One such system is the Arp 202 close pair of galaxies, NGC 2719 and NGC 2719A, which have radial velocities 3077 km s$^{-1}$ and 3117 km s$^{-1}$ respectively and signs of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2). Deep UV (GALEX) observations of a tidal interaction at optical and UV wavelengths (Figures 1 and 2).

In this paper, we present results from our Giant Metrewave Radio Telescope (GMRT) H$i$ observations of the Arp 202 system including at the position of the proposed TDG. The paper also utilises publicly available SDSS  Spitzer and GALEX data and images. Section 2 sets out details of our observations, and the results are given in section 3. We discuss the results in section 4. A summary and concluding remarks are set out in section 5. The average of the radial velocities of NGC 2719 and NGC 2719A is 3097 km s$^{-1}$. Using this average velocity and assuming H$_0$ to be 75 km s$^{-1}$ Mpc$^{-1}$, we adopt a distance of 41.3 Mpc for NGC 2719 and NGC 2719A and the TDG. At this distance the spatial scale is 12 kpc / arcmin. J2000 coordinates are used throughout the paper, including in the figures.

2 OBSERVATIONS

H$i$ observations of Arp 202 were carried out with the GMRT on April 30th, 2008. Further details of the observations are given in Table 1. The baseband bandwidth used was 8 MHz for the H$i$ 21-cm line observations giving a velocity resolution of ∼13 km s$^{-1}$.

The Astronomical Image Processing System (AIPS) software package was used for data reduction. Bad data from malfunctioning antennas, antennas with low gain and/or radio frequency interference (RFI) were flagged. The flux densities are on the scale of 5.0 Jy beam$^{-1}$, with flux density uncertainties of ∼5%. Following calibration, continuum subtraction was carried out in the $uv$ domain using the AIPS tasks $uvsub$ and $uvlin$. To analyse the H$i$ structures, image cubes of different resolutions were produced by applying different ‘tapers’ to the data with varied $uv$ limits. The task $imomnt$ was then used to obtain the final cleaned H$i$ image cubes. The integrated H$i$ and H$i$ velocity field maps were extracted from the cubes using the AIPS task $moment$. Details for the final high and low-resolution cubes are given in Table 1.

3 OBSERVATIONAL RESULTS

The contours in Figure 1 are from the low-resolution (47.5" x 37.4") integrated H$i$ GMRT map for the Arp 202 field overlaid on a SDSS $g$, $r$, $i$-band false colour image. H$i$ properties of the objects for the Arp 202 field are set out in Table 2. The two principal H$i$ detections are, the large SABc spiral, NGC 2724, in the north-east and the Arp 202 system in the west detected in the velocity range 2942 km s$^{-1}$ to 3238 km s$^{-1}$. Within the Arp 202 system the main features are the H$i$ counterparts of the NUV (GALEX) tidal tail and TDG candidate. Figure 2 shows the high-resolution (23.5" x 16.3") H$i$ integrated map contours overlaid on a NUV (GALEX) image of the two principal galaxies in Arp 202 system and the TDG candidate. Figure 2 shows the tidal tail – TDG connection at H$i$ column densities ≥ 4.3×10$^{20}$ cm$^{-2}$. The peak H$i$ column density found at the position of the TDG candidate is ∼7.5×10$^{20}$ cm$^{-2}$. In the channel images (Figure 2), the H$i$ tail is visible from velocities 2995 km s$^{-1}$ to 3076 km s$^{-1}$ and the H$i$ peak emission in the tail coincides with the TDG in the velocity range of 3022 km s$^{-1}$ to 3049 km s$^{-1}$. The projected length of the H$i$ tidal tail which appears to originate from NGC 2719A, is ∼1.5" (20 kpc).

Apart from the galaxies referred to in the previous paragraph, two further galaxies were detected in H$i$ within the FWHM of the GMRT primary beam: SDSS J090028.22+354009.8 projected ∼4.1" to the south-east of the Arp 202 and SDSS J090029.37+354840.6 projected ∼5.9" to the north-east of Arp 202. SDSS J090029.37+354840.6 was marginally detected (Figure 1), however the spectrum and channel maps show the H$i$ signal to be correlated in consecutive channels at the optical position of the galaxy. We therefore conclude the H$i$ is associated with optical galaxy.

The GMRT spectrum for each of the galaxies detected in H$i$ and the Arp 202 system is plotted on the right side of Figure 1. The GMRT integrated flux density from the Arp 202 system is 17.55 Jy km s$^{-1}$, which compares well with the uncorrected single dish flux density of 16.70 Jy km s$^{-1}$ for NGC 2719 (Huchtmeier & Richter 1989). The H$i$ mass derived from the GMRT for the Arp 202 pair, tidal tail and the candidate TDG is 7.1±0.3×10$^9$ M$_{\odot}$. We extracted an H$i$ spectrum from within approximately a 23 by 16 arcsec region (similar to the beam) centred on the TDG (Figure 2) and derived an H$i$ mass for the TDG of ∼1 ± 0.5×10$^9$ M$_{\odot}$. The integrated flux density from the GMRT spectrum of NGC 2724 is 13.9 Jy km s$^{-1}$ which compares well with the single dish value of 13.8 Jy km s$^{-1}$ (Springob et al. 2005). SDSS J090028.22+354009.8, which is ∼49 kpc to the south-east of the Arp pair, shows signatures of interaction in H$i$ maps and is connected to the pair by a very faint and fragmented H$i$ bridge. The bridge can be traced in the channel images (Figure 2), although the signal to noise ratio is poor.

Figure 2 right panel shows the velocity field of the Arp 202 system from the high-resolution cube. The contours between 3050 km s$^{-1}$ to 3200 km s$^{-1}$ indicate the H$i$ in the central and NW parts of the NGC 2719 disk are in a regularly rotating edge on disk, although with indications of a warp. This rotation pattern is broken at south-eastern end of the NGC 2719 H$i$ disk at velocities below 3050 km s$^{-1}$. The abrupt change of rotation pattern in the contours.

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1 Galaxy Evolution Explorer
2 Sloan Digital Sky Survey
3 Galaxy Evolution Explorer

Table 1. GMRT observation details

| Frequency       | 1420.4057 MHz |
|-----------------|--------------|
| Observation Date| 30th April, 2008 |
| Primary calibrator | 3C147 |
| Phase Calibrator | 0741+312 (2.00 Jy) |
| (flux density)   |              |
| Integration time | 8.0 hrs |
| primary beam     | 24' at 20 cm |
| Low resolution beam | 47.5" × 37.4" (PA = 5.9°) |
| High resolution beam | 23.4" × 16.3" (PA = 17.8°) |
| rms for low-resolution map | 1.24 mJy beam$^{-1}$ |
| rms for high-resolution map | 0.81 mJy beam$^{-1}$ |
| RA (pointing centre) | 09h 00m 17.17s |
| DEC (pointing centre) | 35° 43′ 33.12 |

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NGC 2719 and 2719A are expected to have H\textsubscript{i} lost most of its H\textsubscript{i} through interactions between NGC 2719 and NGC 2719A. The narrow range of H\textsubscript{i} velocities, ~60 km s\textsuperscript{-1}, in the tidal tail running westward from NGC 2719A to and including the TDG candidate provide clear evidence linking the both the tidal tail and TDG candidate to the interaction between NGC 2719 and NGC 2719A.

### 4 DISCUSSION

#### 4.1 Arp 202 – major interactions

The pre-merger interacting pair, NGC 2719 and NGC 2719A, have an optical radial velocity separation of 40 km s\textsuperscript{-1} and D\textsubscript{25} of 1.3 arcsec (17.5 kpc) and 0.9 arcsec (12 kpc) respectively. We estimate the stellar mass for NGC 2719 at ~3.4 x 10\textsuperscript{8} M\textsubscript{⊙} and NGC 2719A at 5.0 x 10\textsuperscript{8} M\textsubscript{⊙} (a stellar mass ratio of ~1:1.4), based on the parameters from [Bell et al. (2003)] and [Blanton et al. (2003)] for SDSS g–band magnitudes and g–r colours. The sizes, SDSS colours and stellar masses indicate these are relatively small late-type galaxies (Im pec per NED). In optical images NGC 2719 presents as an essentially intact high inclination disk. While both galaxies are designated as late-types, the high-resolution H\textsubscript{i} channel maps in Figure 4 show that almost all of the H\textsubscript{i} emission is projected against the NGC 2719 disk. Despite NGC 2719 having the optical appearance of an edge-on spiral, the GMRT H\textsubscript{i} spectrum lacks double horned structure expected from a rotating H\textsubscript{i} disk. This and the tidal perturbation parameter\textsuperscript{[4]} $p_{\text{EE}} = 0.6$, suggests the NGC 2719 H\textsubscript{i} disk may have been severely perturbed by the interaction between the pair. NGC 2719A has a more irregular optical morphology, and the UV tail (Figure 4) appears to originate from this galaxy. It seems likely the H\textsubscript{i} and stellar material in the tidal tail has its origin in a close interaction between NGC 2719 and NGC 2719A, where NGC 2719A has lost most of its H\textsubscript{i} to NGC 2719 and the IGM.

The Arp 202 pair are H\textsubscript{i} rich, with a combined H\textsubscript{i} mass of 7.1 x 10\textsuperscript{9} M\textsubscript{⊙}. Galaxies of same size and morphological type as NGC 2719 and 2719A are expected to have H\textsubscript{i} masses of ~2.8 x 10\textsuperscript{9} M\textsubscript{⊙} and ~1.7 x 10\textsuperscript{9} M\textsubscript{⊙} respectively.\textsuperscript{[4]} Sengupta et al.\textsuperscript{[1984]}, making a total of 4.5 x 10\textsuperscript{9} M\textsubscript{⊙} for the pair. The presence of excess H\textsubscript{i} mass may be due to the system acquiring H\textsubscript{i} through interactions and/or accretion of small neighbours. A 60' radius (720 kpc at that distance) search around the Arp 202 system, within a velocity range of 2000 km s\textsuperscript{-1} to 4000 km s\textsuperscript{-1}, yields only one similar sized neighbour (NGC 2724) and two small dwarfs (SDSS J090028.22+354009.8 and SDSS J090029.37+354840.6). The projected distance between Arp 202 and NGC 2724 is 9.6' (115 kpc). Assuming galaxies are moving at ~150 km s\textsuperscript{-1}, a typical number for velocity dispersion in loose groups, we estimate that if they have crossed paths, then the last interaction could have occurred about 3.6 x 10\textsuperscript{8} years ago, less than the dynamical time scales of NGC 2719 and NGC 2724, which are estimated to be 4.2 x 10\textsuperscript{8} years and 5.2 x 10\textsuperscript{8} years respectively. Had there been an interaction involving a massive transfer of H\textsubscript{i} between these two galaxies, extended tidal features would have remained in the H\textsubscript{i} disks for at least one dynamical timescale. While the H\textsubscript{i} in Arp 202 is heavily perturbed, the NGC 2724 H\textsubscript{i} disk is relatively undisturbed and shows no significant H\textsubscript{i} deficiency. The expected H\textsubscript{i} mass of NGC 2724 is 2.9 x 10\textsuperscript{8} M\textsubscript{⊙} compared to the observed mass of 5.6 x 10\textsuperscript{8} M\textsubscript{⊙}, making it an H\textsubscript{i} rich spiral. Thus even if it has interacted with the Arp 202 system, it seems unlikely that any massive gas exchange has taken place between them. We conclude that the perturbation signatures in the Arp 202 are primarily the result of the interaction between NGC 2719 and 2719A.

#### 4.2 SDSS J090028.22+354009.8 and SDSS J090029.37+354840.6 – minor interactions

Apart from NGC 2724, there are two dwarfs close to the Arp 202 system. SDSS J090028.22+354009.8, to the south-east is ~4.1' (49 kpc) away and SDSS J090029.37+354840.6 to the north east is ~5.8' (69 kpc) away. Their stellar masses were estimated from the SDSS photometric measurements quoted in NED and using the mass to light ratio to colour relation prescribed in [Bell et al. (2003)]. The value for solar absolute magnitude in g – band was taken from [Blanton et al. (2003)]. The stellar masses for SDSS J090028.22+354009.8 and SDSS J090029.37+354840.6 are estimated to be 3.9 x 10\textsuperscript{8} M\textsubscript{⊙} and 1.1 x 10\textsuperscript{8} M\textsubscript{⊙} respectively. Their H\textsubscript{i} masses from the GMRT data are estimated to be ~1 x 10\textsuperscript{8} M\textsubscript{⊙}. The upper limit was applied as they both are not unambiguously three sigma detections. Both the galaxies are beyond the fields imaged by [Spitzer] and only SDSS J090028.22+354009.8 is within the GALEX Medium Imaging Survey (MIS) field. The galaxy is bright in the GALEX map indicating star formation activity within the

| Table 2. GMRT H\textsubscript{i} detections |
|------------------------------------------|
| Object       | RA          | Dec         | Velocity | M(H\textsubscript{i}) |
|--------------|-------------|-------------|----------|---------------------|
| Arp 202 pair |             |             |          |                     |
| – NGC 2719   | 09:00:15.4  | +35:43:40   |          |                     |
| – NGC 2719A  | 09:00:15.9  | +35:43:12   |          |                     |
| – TDG candidate | 09:00:09.3 | +35:43:38   | 3047 ± 13.6 | 0.1 ± 0.05         |
| NGC 2724     | 09:01:18    | +35:45:43   | 3220 ± 13.6 | 5.6 ± 0.4          |
| SDSS J090028.22+354840.6 | 09:00:29.4 | 3081 ± 13.6 | -0.1        |
| SDSS J090029.37+354840.6 | 09:00:28.2 | 3301 ± 13.6 | -0.1        |

Uncertainties on H\textsubscript{i} masses quoted here are for an adopted distance and inclination angle, estimated using uncertainty on the line flux. Actual uncertainties on the masses can be higher.
last $10^8$ yr. This is not unexpected as SDSS J090028.22+354009.8 shows signs of recent interaction with the Arp 202 system. We have detected fragments of an H I bridge connecting Arp 202 and SDSS J090028.22+354009.8. We see no similar H I connection between Arp 202 and SDSS J090029.37+354840.6. But we notice an offset between the optical and the H I radial velocities for both these galaxies. While SDSS J090028.22+354009.8 and SDSS J090029.37+354840.6 have optical velocities of $3301$ km s$^{-1}$ and $3081$ km s$^{-1}$ in NED, the H I is detected at velocities $\sim 3181$ km s$^{-1}$ and $3011$ km s$^{-1}$ respectively. The H I velocities quoted here correspond to the peak intensities. The H I line widths at 20% of the peak flux value of SDSS J090028.22+354009.8 and SDSS J090029.37+354840.6 are 109 km s$^{-1}$ and 82 km s$^{-1}$ respectively. This shift of the H I velocity could be due to interactions with the Arp 202 system, during which the gas disks of the smaller galaxies have been disturbed. Also H I loss from these galaxies to the Arp 202 system cannot be ruled out.

Since it is difficult to establish if such nearby dwarfs are indeed TDGs, we compared the available information on these galaxies to those of TDGs and probed the chances of them being Arp 202 system detached TDGs. Judging by the optical and H I masses and the SDSS g–r colours, SDSS J090028.22+354009.8 seems to be an old dwarf galaxy associated with the Arp 202 system. Its g–r colour is an extreme 1.65, much higher than usual early type dwarfs making it an unreliable number to derive concrete conclusions. SDSS J090029.37+354840.6 on the other hand is a bluer dwarf, with g–r value as 0.19, which is considered low in dwarf galaxy samples (Barazza et al. 2006) and similar to blue compact dwarf galaxies (BCDG) (Zitrin et al. 2009). In terms of stellar populations, tidal dwarf galaxies are known to be of two types, one with extremely new stars, with optical colours similar to BCDGs and the other dominated by an older population, mostly derived from the fragments of the parent galaxies (Duc & Mirabel 1999). However the dynamical mass to gas mass ratio of SDSS J090029.37+354840.6 is $\sim 8$. Because of the predicted absence of dark matter, this ratio is expected to be closer to 1 in TDGs. Additionally, the galaxy is about 70 kpc away from the main system and previous studies about TDG detachment shows that 95% of TDGs are found within 20 kpc of their parent system (Kaviraj et al. 2012). Thus from the information available we conclude these dwarfs are not detached TDGs, but rather old satellites of the system. Metallicity and CO data for these dwarfs could further constrain the origin of these dwarfs.

4.3 The candidate TDG of the Arp 202 system

Smith et al. (2010b) first reported the presence of a clumpy star forming tidal tail terminating in the TDG candidate from NUV (GALEX) observations and confirmed the candidate was part of the Arp 202 system with optical spectroscopy. Our GMRT H I morphology and kinematic results, set out in section 3, clearly show that the H I tidal tail/bridge links the H I TDG counterpart to the interacting Arp 202 pair.

The tail and TDG candidate are faintly visible in individual SDSS images but are much more apparent in the UV (GALEX) images. Neither were detected in either the Spitzer 8 $\mu$m or SARA Hα images. This lead Smith et al. (2010b) to suggest that the TDG may be in a post–starburst stage, i.e. dominated by a stellar population with age between 10$^7$ yr to 10$^8$ yr. Schechtman-Rook & Hess (2012) presented a FUV–g vs g–r plot (their figure 11) for the UV detected TDG candidates from the Smith et al. (2010b) and two other candidates, Holmberg IX and NGC 4656UV. The Arp 202 TDG candidate appears in their plot as one of the candidates with extreme blue colour, together with NGC 4656UV, Arp 305 and Holmberg IX, one of the strongest TDG candidates (Sabbi et al. 2008). The mean FUV–g colour of these four TDG candidates (blue candidates) is close to 0, $\sim 1$ mag lower than the rest of the Smith et al. (2010b) sample. But as Schechtman-Rook & Hess (2012) point out a larger sample is needed to determine whether the blue candidates are part of a separate category of TDGs. While acknowledging this limitation, in Table 3, we compare selected properties of SDSS J090028.22+354009.8 and SDSS J090029.37+354840.6 with those of known TDGs, to set limits on their classifications.

Figure 2. Arp 202: Left panel High resolution H I integrated map contours (white) overlaid on a NUV (GALEX) image. The H I column density contour levels are 10$^{20}$ atoms cm$^{-2}$ x (4.4, 7.5, 14.5, 26.0, 43.4, 66.6). Right panel H I velocity with contours at velocity separation of 30 km s$^{-1}$. The H I beam (23.4\arcsec x 16.3\arcsec) is shown as white ellipse at the bottom left of each panel.
of the Arp 202 TDG candidate with those of the other three blue candidates and statistics from larger samples of TDG candidates (Kaviraj et al. 2012; Duc & Mirabel 1999). The aim of compiling the data in the table was to determine if the blue candidates share any additional distinguishing features. In the following paragraphs we briefly comment sequentially on each row in Table 3.

In Table 3, the mass and size estimates, in particular, are highly uncertain, so we are only able to draw order of magnitude conclusions from their comparative data. The uncertainties are particularly acute for the estimates of stellar mass (M*). M* in units of 10^9 M_☉ for Arp 202 (0.2) and NGC 4656UV (0.4) were estimated using g and r band colours following the method described in note a to Table 3. M* for Holmberg XI (0.02) and Arp 305 (0.04) are taken from the literature (see Table 3 for references) and they were determined from SED fitting in the respective papers. For Arp 305 M* determined with the g and r band colour method is 1.1 × 10^9 M_☉ suggesting this method may overestimate M* by at least an order of magnitude. The g and r colour M* method assumes the galaxy has a standard mix old and young stellar populations but we have evidence from the non–detections of the Arp 202 TDG candidate in Spitzter 3.6, 4.5 and 8 μm images (and only marginal equivalent detections for Arp 305) that these two candidates are relatively deficient in old stellar populations compared to standard galaxies.

From the GMRT spectrum for the Arp 202 TDG candidate (Figure 1 – Bottom right panel) we estimate its H i mass to be ~ 1.0 × 10^8 M_☉. The mean M_Hi of the blue candidates is 2.2 ± 1.6 × 10^8 M_☉ which is an order of magnitude lower than the mean value from [n=20] Duc & Mirabel (1999) sample (16 × 10^8 M_☉). M_Hi for all the blue candidates is close to the minimum M_Hi of 2.0 × 10^8 M_☉ in Duc & Mirabel (1999) sample. So even allowing for the uncertainties in the estimates of M_Hi, the blue candidates have a significantly lower M_Hi than a typical TDG candidate. Moreover if our interpretation of stellar mass in the previous paragraph is correct then Arp 202 probably shares a M_Hi / M* ratio, of several tens to a hundred or so, with the other blue candidates.

For the Arp 202 TDG candidate, M_dyn is estimated at 3.9 × 10^8 M_☉ using the method described in Table 3. This is ~ 4 times the M_Hi / M* with a ratio of the same order as in NGC 4656UV. We have no M_dyn for Holmberg IX or Arp 305. As for the Arp 202 TDG candidate, we see no clear indication of the presence of significant amounts of dark matter.

Table 3 shows the estimated extent of each of the blue candidates, which range from 2.2 kpc to 11 kpc. Because of the wide range in angular scales and distances to the blue candidates it is difficult to properly compare the extent of these candidates. Moreover there is also a problem of separating the TDG and tail. We have estimated the extent of the blue candidates from inspection of UV (GALEX) images, except for the nearest candidate, Holmberg IX, where we use the value from NED. We concluded that the extent of the blue candidates is typically a few kpc.

From the FUV (GALEX) magnitudes (Smith et al. 2010a) and using the star formation rate (SFR) vs FUV luminosity relation in Salim et al. (2007), the estimated SFR of the Arp 202 TDG is 0.039 M☉ yr⁻¹. This is lower than the mean value of SFRs found in TDGs (Duc & Mirabel 1999). With its gas reserve, at this SFR, the Arp 202 TDG can form stars for more than 2 Gyr. Using the Hα luminosity quoted in Hancock et al. (2009) and the SFR recipe in Kennicutt (1998), we also estimated the SFR for Arp 305 TDG as 0.025 M☉ yr⁻¹. The SFR values of other blue TDG candidates were taken from the literature (Schechtman-Rook & Hess 2006; Courteau et al. 2008). The mean SFR for the blue candidates is ~ 0.025 M☉ yr⁻¹, lower than the mean of the Duc & Mirabel (1999) sample. However we note here that the SFR estimates can significantly change depending on the wavebands. This prevents us from suggesting that the SFRs of the blue candidates are actually lower than the TDG average.

The metallicity for the Arp 202 TDG candidate from Smith et al. (2010a) is log(O/H)+12=8.9, approximately solar metallicity and above the log(O/H)+12 mean value of the Duc & Mirabel (1999) sample (8.5). We note here that the Arp 202 TDG candidate’s spectrum from which the metallicity is quoted, is as yet unpublished. Holmberg IX has a similar metallicity to Arp 202 and the Duc & Mirabel (1999) sample but NGC 4656UV is significantly sub–solar. Metallicity is one of the strongest tests to distinguish TDGs from standard dwarfs. Higher metallicities are expected if a dwarf formed from metal rich disk material from a parent galaxy as opposed to the poor metallicities for standard dwarfs formed from pristine gas. Thus the Arp 202 candidate’s metallicity provides strong support for it being a TDG , while the NGC 4656UV metallicity value raises a question.

The SDSS g – r colour was calculated using the data from the sources referred to in note j to Table 3. The g – r colour for the Arp 202 candidate is 0.21. As expected from Schechtman-Rook & Hess (2012) results, the mean g–r colour of the blue candidates (0.06 ± 0.13) is bluer than the mean of the 6 TDG candidates in the Smith et al. (2010a) sample (0.41 ± 0.20). Unfortunately this is not directly comparable to B–V of 0.3 for the 20 TDG candidates in the Duc & Mirabel (1999) sample. The FUV–g colour of the Arp 202 TDG is -0.47, the bluest FUV–g colour amongst the blue candidates.

From a study of TDGs, Kaviraj et al. (2012) concluded that 95% of TDG progenitors are spirals involved in binary mergers where the parent galaxies’ mass ratio is less than 1:7 (median 1:2.5). They also concluded TDGs are not produced in interactions where the parent mass ratios exceed 1:11 and for 95% of the time the physical separation between the parent galaxies and the TDG is < 20 kpc. These values are consistent with simulations by Bournaud & Duc (2006). For all of the blue candidates, including the Arp 202 the progenitor pair mass ratios are within the ratio observed by Kaviraj et al. (2012). Table 3 shows the protected distance to the nearest gas rich parent galaxy for three of the blue candidates is within 20 kpc , but the Arp 305 TDG candidate is projected 36 kpc from NGC 4017.

Allowing for the small sample size and measurement uncertainties we see indications that, in addition to the extreme blue colour reported by Schechtman-Rook & Hess (2012), the blue candidates have significant smaller H i masses (2.2 ± 1.6 × 10^8 M_☉) than the Duc & Mirabel (1999) sample. It seems likely that the stellar masses (M*) of the blue candidates are considerably smaller than the Duc & Mirabel (1999) sample but NGC 4656UV is significantly sub–solar. Metallicity is one of the strongest tests to distinguish TDGs from standard dwarfs. Higher metallicities are expected if a dwarf formed from metal rich disk material from a parent galaxy as opposed to the poor metallicities for standard dwarfs formed from pristine gas. Thus the Arp 202 candidate’s metallicity provides strong support for it being a TDG , while the NGC 4656UV metallicity value raises a question.

5 SUMMARY AND CONCLUDING REMARKS

Our GMRT H i morphology and kinematic results clearly link the H i tidal tail and the H i TDG counterpart to the interaction between NGC 2719 and NGC 2719A. This and the similarity of the Arp 202 candidate’s properties to other TDG candidates with extreme blue colours (Table 3), and in particular Holmberg IX, strengthens the case for the Arp 202 candidate being a TDG formed under the stan-
Table 3. Properties of extremely blue TDGs compared to average properties from literature.

| Property                          | Statistic from TDG candidate samples | Arp 202 | NGC 4656UV | Holmberg IX | Arp 305 |
|----------------------------------|------------------------------------|---------|------------|-------------|---------|
| TDG M* (10^8 M_☉)               | 2.1                                | 0.2     | 0.4        | 0.02        | 0.04    |
| TDG M_HI (10^8 M_☉)              | 16.0                               | 5.0     | 3.2        | 3.3         | 0.6     |
| TDG Mdyn (10^8 M_☉)              | 3.9                                | 9.0     | 3.2        | –           | –       |
| TDG extent (kpc)                 | 4.0                                | 5.0     | 2.3        | 2.25        | 11.0    |
| TDG SFR (10^-3 M_☉/yr)           | 7.8                                | 2.0     | 0.27       | 8.0         | 25.0    |
| TDG Metallicity (Fe/H)           | 8.3                                | 9.0     | –0.21      | –0.07       | 0.13    |
| Parent pair mass ratio           | >1:7, median = 2.5                  | 1:1.4   | 1:2.6      | 1:1.5       | 1:2.9   |
| TDG projected distance from parent (kpc) | <2.0                             | 18      | 11         | 13          | 36      |
| TDG estimated age (Myr)          | 292                                | 200     | –          | –           | –       |

a M* for Arp 202 and NGC 4656UV are estimated from SDSS g and r band colours following log(M*/L_g)=a_g+b_g (Bell et al., 2003) and g–r band solar luminosity from parameter from Blanton et al., 2003, using colours from Smith et al., 2010 and Schectman-Rook et al., 2012 respectively. For Holmberg IX M* is from Sabbi et al., 2008 and M* for Arp 305 is from Hancock et al., 2009.

b M_HI for Arp 202 from Table 2 and NGC 4656UV from Schectman-Rook & Hess, 2012, Holmberg IX from Swaters & Balcells (2002) and Arp 305 van Moorsel (1983).

c M_dyn for Arp 202 = 3.39 × 10^5 × a_HI × d × (W_20/2), where a_HI = diameter in arcmin, d = the distance to the object and W_20 = the line width at 20% of the peak (Giovanelli & Haynes, 1988). The HI beam major axis of the high-resolution map was used as a_HI and since the signal is present in only two channels in our high-resolution cube, the net width of the two channels was used as W_20, NGC 4656UV from Schectman-Rook & Hess, 2012 and the SFR in Arp 305 is from Hancock et al., 2009 and the SFR recipe in Kennicutt, 1998.

d Extents were measured from UV (GALEX) images except for and Holmberg IX which is from NED.

e SFR for the Arp 202 TDG candidate is estimated using the UV luminosity quoted in Smith et al., 2010 and the SFR recipe in Salim et al., 2007, NGC 4656UV is from Schectman-Rook & Hess, 2012, Holmberg IX from Sabbi et al., 2008 and SFR for Arp 305 is estimated using the UV luminosity quoted in Hancock et al., 2009 and the SFR recipe in Kennicutt, 1998.

f M_HI for Arp 202 from Table 2 and NGC 4656UV from Schectman-Rook & Hess, 2012, Holmberg IX from Sabbi et al., 2008 and SFR for Arp 305 is estimated using the UV luminosity quoted in Hancock et al., 2009 and the SFR recipe in Kennicutt, 1998.

We compared properties of the Arp 202 candidate and three other extremely blue TDG candidates identified by Schectman-Rook & Hess, 2012 to larger samples of TDG candidates. All four of these extremely blue candidates have H_I (and probably M*) masses comparable to the smallest TDGs found in the literature. These lower masses are probably at least partially responsible for the low SFR compared to the Duc & Mirabel, 1999 TDG sample. All of the extremely blue candidates are H_I rich, with the M_HI/M* ratios ranging approximately between 5 and 150. The number of extremely blue TDG candidates examined is too small to conclude whether or not they are a distinct subgroup with TDGs.

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Figure 3. Channel images from the high resolution cube (beam is $23.4'' \times 16.3''$) showing the Arp 202 pair, the candidate TDG (indicated by green circle) and the fragmented $\text{H}_i$ bridge between Arp 202 and SDSS J090028.22+354009.8 (indicated by blue circle). The contour levels are $0.7 \text{ mJy} \times (3,5,7,10,15)$. The $\text{H}_i$ contours are overlayed on the SDSS $r$–band image.