DISCOVERY OF A TIDAL DWARF GALAXY IN THE LEO TRIPLET

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ABSTRACT

We report the discovery of a dwarf galaxy in the Leo Triplet. Analysis of the neutral hydrogen distribution shows that it rotates independently of the tidal tail of NGC 3628, with a radial velocity gradient of 35–40 km s⁻¹ over approximately 13 kpc. The galaxy has an extremely high neutral gas content, accounting for a large amount of its total dynamic mass and suggesting a low amount of dark matter. It is located at the tip of the gaseous tail, which strongly suggests a tidal origin. If this is the case, it would be one of the most confident and nearest (to the Milky Way) detections of a tidal dwarf galaxy and, at the same time, the object most detached from its parent galaxy (≈140 kpc) of this type.

Key words: galaxies: groups: individual (Arp 317, Leo Triplet) – galaxies: interactions – intergalactic medium

Online-only material: color figures

1. INTRODUCTION

The idea of dwarf objects forming from the tidal debris left by galaxy mergers was first proposed by Zwicky (1956), who suggested that interactions in systems of multiple galaxies can lead to an ejection of the tidal material and formation of an intergalactic structure, possibly even a dwarf galaxy. However, the “recycled” galaxies did not achieve much attention, apart from a symposium talk by Schweizer (1978). The first object of this type was discovered by Mirabel et al. (1992), who presented a photometric study of the Antennae galaxies, showing a tidal dwarf galaxy (TDG) formed from the collisional debris. Since then, many similar objects have been detected—see, e.g., Brinks et al. (2004) or Duc et al. (2007). Recently, Kaviraj et al. (2012) presented a study of a sample of 405 nearby TDG candidates, conducting a statistical analysis of their properties. Tidal dwarf galaxy candidates have also been found in the Local Volume (within 11 Mpc; Hunter et al. 2000). The M81 group hosts dwarf galaxy candidates have also been found in the Local Volume (within 11 Mpc; Hunter et al. 2000). The M81 group hosts some of the nearest examples of TDGs. The small distance allowed the authors to use HST-based color–magnitude diagrams (Makarova et al. 2002) to analyze the star formation history of the TDG candidates and search for additional signs of the tidal origin.

What makes the TDGs especially interesting is their mass composition. Whereas “normal” galaxies consist mostly of dark matter (DM), TDGs do not; the velocity of the DM particles in the galactic halo is much higher than the escape velocity of a TDG (Bournaud 2010), so they are not kinematically bound to it. Hence, such systems usually consist of only baryonic matter. Additionally, as they are formed in the outer parts of the galactic disks, their metallicity is higher than in non-tidal dwarfs.

Only a few TDGs were estimated to be heavy enough to contain a significant nonbaryonic fraction, but most estimates suggest that the DM content is similar to the baryonic mass—far below the typical order of magnitude of difference in non-tidal dwarf systems (Bournaud 2010). Lack of DM content and a specific environment cause the evolution of TDGs to be different from that of typical field galaxies, which still needs to be studied and described. With a low dark matter content, TDGs should also be more susceptible to the formation of galactic outflows driven by strong star formation. Alternately, a different mass distribution may lead to a lower overall star formation rate and therefore to low surface brightness of evolved TDGs.

TDGs are interesting, not only because of their mass composition, but also because of their influence on the intergalactic environment. Tidal debris can interact with other group members, like in the case of the Leo Triplet galaxy NGC 3627, known for its unusual magnetic field morphology (Soida et al. 2001). Recently, Weżgowiec et al. (2012) suggested these peculiarities could be the result of a past collision with a dwarf galaxy. Thus, TDGs might play an important role in the further evolution of their progenitors.

Galaxy systems with massive tidal tails and/or rings constitute favorable objects to use when searching for TDG candidates. One of the best examples of such objects is the Leo Triplet, a nearby group of galaxies known for a large tidal plume extending eastward from NGC 3628. Originally described by Zwicky (1956), the plume was later confirmed by photographic observations by Kormendy & Babcock (1974). Neutral hydrogen studies by Rots (1978) and Haynes et al. (1979) revealed a thick HI structure, longer and wider than its optical counterpart. A detailed analysis of the HI distribution (Stierwalt et al. 2009) suggested numerous candidates for nontidal dwarf satellites.

Recently, Nikiel–Wroczyński et al. (2013) presented a study of the magnetic field in the Triplet. The authors suggested that the HI clump at the tip of the tidal tail could be a TDG. Additionally, Karachentsev et al. (2008) have reported that it exhibits an unusually high $M_{HI}/L_B$ ratio. However, as pointed out in most of the TDG studies (see, e.g., Kaviraj et al. 2012), determining whether a candidate is self-gravitating (galaxy) or a larger part of the tidal debris (that will never become a self-bound, independent object) is crucial.

In this paper we use the archive neutral hydrogen and optical data to show that the velocity field of the TDG candidate detected in the Leo Triplet exhibits a velocity gradient and has a faint optical counterpart. These findings strongly support the idea of its independent rotation, thus confirming its identification as a galaxy.
2. OBSERVATIONS AND DATA REDUCTION

2.1. Neutral Hydrogen Observations

The 1.41 GHz spectral data, made with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO)\(^3\) in the D-array configuration, were taken from the NRAO Data Archive (Project AB1074, PI: A. Bolatto). Two intermediate frequencies were set, the first at 1.41527 GHz, the second at 1.41761 GHz, each with a bandwidth of 3.1 MHz. The corresponding velocity range is 269–1511 km s\(^{-1}\). The velocity resolution is 20.7 km s\(^{-1}\) (per spectral channel).

The resulting processed stack of images in the three most sensitive SDSS filter bands g′, r′, and i′ is presented in Figure 1. To improve on this tentative detection, we applied our stacking/filtering procedure, which increases the detectability of very low surface brightness structures (see Miskolczi et al. 2011, for details).

The resulting processed stack of images in the three most sensitive SDSS filter bands g′, r′, and i′ is presented in Figure 1.

3. RESULTS

3.1. Optical Emission Distribution

The processed SDSS image stack (Figure 1) shows a faint extended region at the position of the H\(_1\) plume (diffuse, low surface brightness patch at R.A.\(_{2000}\) = 11\(^{h}\)23\(^{m}\)15\(^{s}\), Decl.\(_{2000}\) = 13\(^{\circ}\)43\('\)15") and a (fainter) structure elongated along the east–west direction. This structure is also visible in a wide-field image showing the tail of NGC 3628, provided by S. Mandel (reproduced in Figure 4 in Miskolczi et al. 2011).

The detected patch shows an exponential brightness profile with a central surface brightness of 25.2 mag sqarcsec\(^{-1}\) (g′ filter) and a scale length of 120′ × 60′ (7 × 3.5 kpc). The total brightness of the structure is 17.1\(^{m}\) (16.65\(^{m}\) in the r′ filter). This means that g′−r′ is 0.45\(^{m}\). Using the conversion factors by Jester et al. (2005), these translate to an apparent B-band brightness \(m_B\) of 17.45\(^{m}\), \(B-V\) of 0.615\(^{m}\), and central surface brightness \(\mu_B\) of 25.55\(^{m}\) (\(\mu_V\) = 24.93\(^{m}\)). The distance modulus is 30.42, yielding an absolute B-band magnitude \(M_B\) of −12.97\(^{m}\).

We also check the color of the tidal tail at two separate positions, one closer (≈2′ to the southwest from the TDG), one more distant (≈13′ to the southwest from the TDG). The surface brightness of the more distant position in the tidal arm is comparable to that of the TDG, while the position closer to the TDG is fainter, which unfortunately limits the accuracy of the measurement. Measuring the TDG and both regions in the stream with different methods of background determination implied that the uncertainty of the color measurements of each of these structures is at least 0.1 mag. With that in mind, the colors of both the distant stream clump (g′−r′ = 0.3) and the fainter, closer one (g′−r′ = 0.4) are the same as the color of the TDG itself. With the data at hand, any difference in color between the stellar population mix in the TDG and the two analyzed regions in the stream remains within the uncertainties.

A detailed analysis of the stellar populations of the TDG and of the tidal stream must await much better data.

3.2. Neutral Hydrogen Distribution

Figure 2 presents the H\(_1\) total intensity (zeroth moment) map of the TDG candidate. It shows a luminous, well-resolved source

\(^3\)NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
of approximately ellipsoidal shape of a major axis of 300″ and a
minor axis of 275″ with a position angle of 35°. This corresponds
to a linear size of 17.5 × 16 kpc. The total intensity is ≈9.0 ±
0.5 Jy km s⁻¹. The neutral hydrogen data have clear counterparts
in the optical regime. Both optical and H I emitting media are
connected to the tidal tail.

The first moment (velocity) map is shown in Figure 3. The
velocity gradient runs from the northern (approaching)
to the southern (receding) side, where it sinks into the tidal
plume. The measured values of the radial velocity range from
860 to 900 km s⁻¹. The tail’s velocity is somewhat higher, with a
mean of 910 km s⁻¹. There is no observable trend along the
east–west direction. As the velocities of the dwarf system and
the tail are different, it appears likely that the dwarf is not bound
to the tail. This identifies the dwarf as a separate object, which
is self-gravitating—thus, a galaxy. This claim is also supported
by the morphology of the tidal tail, which bends strongly in
the direction of the TDG candidate in its close vicinity. Such
behavior suggests that the TDG’s gravitational influence on the
tail is higher than expected for the internal gravity of the tail.
This makes the existence of a self-gravitating object in the tip
of the tidal tail even more likely.

To illustrate the separation of the two components, we made
a contour plot of six channels in which the tail and/or the dwarf
system is visible. This map, included as Figure 4, shows that the
tidal tail and the dwarf galaxy are separated and there is at least
one channel in which only one of them is visible.

4. DISCUSSION

4.1. Stellar Mass and Age

Due to the very low surface brightness, the SDSS data do
not allow us to make a detailed fit to the spectral emission
distribution (SED) that could be used to derive the star formation
history and mass of the Leo TDG. Still, it is possible to
estimate some information from the photometry. Using the
scaling relation from Bell et al. (2003), we can use g’ and r’
magnitudes and the resulting color to get an estimate of the stellar
mass. With g’ = 17.1, r’ = 16.65, g’–r’ = 0.45, and the
values in Table 7 of Bell et al. (2003), we can calculate
the M/L ratio = 3.12. With the measured $L_r’$ of 2.39 × 10⁷ $L_\odot$, this
results in a stellar mass of $7.4 \times 10^7 M_\odot$.

A rough limit for the age of the dominant stellar population
can be derived from comparison with the model integrated
spectra. Assuming that the dwarf has at least some more or less
recent star formation (given its large H I mass), we decided to
use the starburst99 code (Leitherer et al. 1999, 2010; Vazquez
et al. 2005) to model basic properties of the stellar population
of the Leo TDG. Independent of the assumed metallicity (two
times solar to 1/20 solar) and star formation law (continuous
or instantaneous), for the measured $B−V = 0.62$ we get a lower age
limit of 1 Gyr (which is the limit of the published models).
If we assume a moderate internal reddening of 0.3 mag, the
age limits are from 3 × 10⁸ yr for a star formation burst and
solar metallicity to ≈10⁹ yr for 20% of the solar metallicity.
Obviously, while being relatively blue, the majority of the stars
formed significantly more than 10⁸ yr ago. For a more detailed
analysis much better photometry is required.

As estimated by Rots (1978), the closest encounter between
NGC 3627 and NGC 3628 may have happened ≈8 × 10⁸ yr ago.
Thus, most of the stars in the Leo TDG (and probably the tidal
dwarf itself) had to be formed shortly after the aforementioned
collision of these galaxies. It is not likely that these stars formed
in NGC 3628 and have been later dragged away, as the distance
from the parent object is very large.

4.2. Gas Content

The gas mass of the Leo TDG was estimated assuming $M_{\text{HI}}$
$[M_\odot] = 2.36 \times 10^5 D_{\text{Mpc}}^2 S_{\text{Jy}}$ dν, where $S_{\text{Jy}}$ dν is in Jy km s⁻¹
(van Gorkom et al. 1986). Using a distance of 12.15 Mpc
and total flux of 9.0 ± 0.5 Jy km s⁻¹ (see Section 3.2), we obtained
the total mass of the neutral hydrogen $M_{\text{HI}} = 3.0−3.3 \times 10^8 M_\odot$.
It is somewhat lower than the results from Stierwalt et al. (2009),
but still of the same order of magnitude. The differences are most
likely caused by the larger beam size of the Arecibo telescope.
used by the authors of the former study, which causes confusion of the emission from the dwarf candidate with that from the tail.

4.3. Mass-to-Light Ratio and the Total Mass

The dynamical mass \( M_{\text{DYN}} \) of the Leo TDG can be derived from the rotational velocity at a given radius. For the Leo TDG, the radial velocity (not corrected for the inclination) gradient is about 35–40 km s\(^{-1}\) over some 13 kpc (with the tail contribution subtracted). The neutral hydrogen data do not allow us to reliably estimate the turbulent component. Therefore, we decided to use a conservative assumption of 10 km s\(^{-1}\) for a one-dimensional turbulent contribution. If this is used to calculate the dynamical mass, one can obtain a total mass of some \( 7.9 \times 10^8 \) \( M_\odot \). With the inclination unknown, this value can be treated as a lower limit of the dynamical mass. For a reasonable inclination of about 60\(^\circ\) (based on the elongation of the optical and H\(_I\) shape of the dwarf), the total dynamical mass would rise to \( M_{\text{DYN}} = 1.41 \times 10^9 \) \( M_\odot \). It should be strongly indicated here that the dynamical mass estimate comes with a large uncertainty. As the dependence of the dynamical mass on the (unknown) inclination is given by \( M_{\text{DYN}} \propto 1/\sin(i)^2 \), the dynamical mass would largely increase if the Leo TDG was a more face-on-oriented system. In general, estimation of the masses of dwarf galaxies and their distributions is a complicated issue, as even if the inclination estimate is proper to some extent, the question of the finite disk thickness persists (Rhee et al. 2004). The total baryonic content of the Leo TDG can be calculated as a sum of the stellar mass (\( 7.4 \times 10^7 \) \( M_\odot \)) and gaseous component. Assuming a modest estimate of the molecular gas mass of 10\(^{-3}\)–30\% of the H\(_I\) mass (as \( M_{\text{BH}}/M_{\text{BH}} \) for NGC 3628 is equal to \( \approx 2\% \); Obruchek & Rawlings 2009), the total gas mass would be around 3.3–4.3 \( \times 10^8 \) \( M_\odot \), so the total baryonic content \( M_{\text{BAR}} \) is 4.0–5.0 \( \times 10^8 \) \( M_\odot \).

An estimate of \( M_{\text{DYN}}/L_B \) can also be derived. \( L_B \) [\( L_{\odot} \)] is equal to \( 10^{-0.4 \times (M - M_{\odot})} \). The \( B \)-band magnitude of the Sun is equal to 5.47 (Cox 1998). This yields a total \( B \)-band luminosity of 2.4 \( \times 10^7 \) \( L_{\odot} \). The \( M_{\text{DYN}}/L_B \) is then 33–59, and \( M_{\text{HI}}/L_B \) is 12–14.

4.4. Magnetic Field

The resolutions used in our previous study (Nikiel-Wroczyński et al. 2013), 4.3 in the radio continuum and 3.5 in the \( H_\alpha \) data of Stierwalt et al. (2009), gave no grounds to reject the coincidence of the \( H_\alpha \) and radio continuum emitting regions. There were also no reliable optical images available. All of this was suggestive of the existence of a magnetic field in the Leo TDG.

With an almost four times smaller beam of \( H_\alpha \) data analyzed in this work and using our optical image we could state that the radio peak is shifted by approximately 1° west from the neutral gas peak and seems to be located outside the optical emission. A large fraction of the radio continuum emission may be thus due to a background source. In light of the new data, we need to revise the estimate of the magnetic field strength. Setting an upper limit to the radio emission of 3.0 mJy beam\(^{-1}\) at the position of the gaseous and optical feature implies the total magnetic field in the TDG to be \( B_{\text{TOT}} \lesssim 2.8 \) \( \mu \)G. The magnetic and cosmic-ray energy density amounts therefore to \( E_{B+CR} \lesssim 6.8 \times 10^{-13} \) erg cm\(^{-3}\).

4.5. TDG, or a Non-Tidal LSB Galaxy?

The Leo TDG shares many of its characteristics with other TDGs (Kaviraj et al. 2012). It is rather bluer than its supposed progenitor (0.65 compared to 0.8 for NGC 3628; Paturel et al. 2003), it is located exactly at the tip of the tidal tail, and has a mass of some \( 10^8 \) \( M_\odot \), typical for such objects. On the other hand, if identified as a TDG, the discussed object would be the tidal dwarf most distant from its parent object, with a calculated separation of some 140–150 kpc, while 95\% of the TDG candidates do not lie more than 20 kpc from their progenitors (Kaviraj et al. 2012). Compared to the statistical sample, the Leo TDG is dim, as it contains less stars than typical TDG candidates. Among the most distinct features of this galaxy are its low surface brightness (\( \mu_B = 25.55 \) and very high abundance of neutral gas. Because of that, we compare its properties not only with the TDGs, but also Low Surface Brightness (LSB) galaxies. We decided to take a galaxy (F563–1) from the samples collected by de Blok et al. (1995, 1996) and the “dark” LSB NGC 3741 (Begum et al. 2005, 2008). As a comparison TDG, we have chosen the “old TDG” VCC 2062 (Duc et al. 2007). The data for the selected objects (TDGs and LSBs) are shown in Table 1.

The table clearly shows that the detected galaxy shares parameters of both TDGs and LSBs. In fact, it is not the

| Parameters of the Leo TDG Compared to TDGs and LSBs |
|-----------------------------------------------|
| Name                  | Leo TDG | F563–1 | VCC 2062 | NGC 3741 |
| Type          | TDG     | LSB     | TDG     | LSB (very dark) |
| Opt. size (kpc)  | 7.5     | 3.4\(^a\) | 0.7\(^a\) | 1.7       |
| H\(_\alpha\) size (kpc) | 13      | 16\(^a\) | 4.2     | 14.6    |
| \( \mu_B \) (mag arcsec\(^{-1}\)) | 25.55   | 23.79   | 24.85   | 24.91   |
| \( B-V \)        | 0.615   | 0.58    | 0.35    | 0.36\(^b\) |
| Total mass (\( M_\odot \)) | \( 7.9-14.1 \times 10^8 \) | \( 3.9 \times 10^10 \) | \( 3-4 \times 10^6 \) | \( 4 \times 10^9 \) |
| Gas content (\( M_\odot \)) | \( 3.3-4.3 \times 10^8 \) | \( 1.5 \times 10^9 \) | \( 0.8 \times 10^8 \) | \( 1.6 \times 10^8 \) |
| Stellar content (\( M_\odot \)) | \( 7.4 \times 10^7 \) | \( 2.3 \times 10^8 \) | \( 0.2-0.7 \times 10^8 \) | \( 1.4 \times 10^7 \) |
| \( M_{\text{HI}}/L_B \) | 12–14   | 2.06    | 3       | 6.26     |
| \( M_B \)         | –12.97  | –16.7   | –13     | –13.13   |
| \( M_{\text{DYN}}/M_{\text{BAR}} \) | 1.6–3.5 | \( \approx 17 \)\(^d\) | 2–4     | 24       |
| \( M_{\text{DYN}}/L_B \) | 33–59   | 50.1    | \( \approx 10 \) | 149     |

Notes:
\(^a\) Derived from its angular size.
\(^b\) From Taylor and Webster (2005).
\(^d\) Derived from the \( M/L \) ratio calculated based on Bell (2003).
only dwarf system that is considered to be either a TDG or an LSB—likewise is the VCC 2062 in the Virgo Cluster (Duc et al. 2007). Both galaxies share similar characteristics: they are dim, low-mass systems with low surface brightness. They have a significant neutral hydrogen halo, showing signs of rotation independent from the tidal arc movement. The velocity gradients are—to the limits of inclination—similar. However, the sizes of the H I halos are different, as the one of VCC 2062 is just 4.2 kpc—approximately three times smaller than that of the Leo TDG. The main difference between the Leo TDG and nontidal LSBs is the dominance of the gas content in the former. In most of the LSBs, gas is not a dominant component: and nontidal LSBs is the dominance of the gas content in the sizes of the H I halos. We obtained maps of the zeroth and first kinematic moments of the H I content as well as the distribution of the visible light in the SDSS g′, r′, i′ bands, yielding the following results.

1. There is a massive, star-forming H I clump at the tip of the tidal tail of the Leo Triplet.
2. The velocity field shows a nonnegligible gradient (approximately 35–40 km s⁻¹ over 13 kpc) along the north–south (declination) axis, strongly supporting that the detected clump is a self-gravitating TDG.
3. The dwarf galaxy is unusually distant from its host galaxy (approximately 140–150 kpc), which is more than seven times farther than the typical values.
4. The optical counterpart has been detected in the SDSS g′, r′, i′ bands, yielding the following results. In the Leo Triplet of galaxies. We obtained maps of the zeroth and first kinematic moments of the H I content as well as the distribution of the visible light in the SDSS g′, r′, i′ bands, yielding the following results.

5. SUMMARY

The optical counterpart has been detected in the SDSS g′, r′, i′ bands. The apparent B magnitude m_B is 17.45 m, B−V is 0.615 m, and the central surface brightness μ_B reaches 25.55 m. The absolute B-band magnitude is −12.97 m.
5. The total H I mass of the clump M_HI is 3.0–3.3 × 10⁸ M☉. The stellar content is about 7.4 × 10⁷ M☉. The stellar population age is 3 × 10⁸–10⁹ yr. This means that, despite a rather blue color, most of the stars are relatively old.
6. The estimated dynamical mass is just 1.6–3.5 times that of the total H I mass. The central surface brightness μ_B reaches 25.55 m. The absolute B-band magnitude is −12.97 m.

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