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We present H I spectral line images of the nearby dwarf galaxy NGC 3239. The galaxy’s curious morphology suggests that it is a post-merger system. We propose that NGC 3239 is a merger because it has multiple tidal tails, an enhanced velocity dispersion throughout the disk, and widespread star formation. We have produced kinematic moment maps corresponding to the H I column density, radial velocity, and velocity dispersion. Further, position velocity (P-V) slices of the galaxy were taken and three-color images were made using the SDSS G, R, and I, filters for comparison with the moment maps. These slices illustrate the complex neutral gas dynamics in the galaxy and support the interaction hypothesis.
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Cover Page Footnote
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This capstone is available in Macalester Journal of Physics and Astronomy: https://digitalcommons.macalester.edu/mjpa/vol7/iss1/2
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Abstract

We present H I spectral line images of the nearby dwarf galaxy NGC 3239. The galaxy’s curious morphology suggests that it is a post-merger system. We propose that NGC 3239 is a merger because it has multiple tidal tails, an enhanced velocity dispersion throughout the disk, and widespread star formation. We have produced kinematic moment maps corresponding to the H I column density, radial velocity, and velocity dispersion. Further, position velocity (P-V) slices of the galaxy were taken and three-color images were made using the SDSS G, R, and I, filters for comparison with the moment maps. These slices illustrate the complex neutral gas dynamics in the galaxy and support the interaction hypothesis.

Keywords: galaxies: evolution — galaxies: dwarf — galaxies: irregular — galaxies: individual (NGC 3239) — galaxies: kinematics (neutral hydrogen)

1. INTRODUCTION

Gas rich dwarf galaxies often are hosts sites for massive star formation. Ongoing star formation is often traced through Hα emission. Dwarf galaxies in particular are important laboratories for studying galaxy evolution. Previous studies (Tully et al. 1977) have shown that these small irreg-
ulars are neutral hydrogen rich, and that less luminous systems frequently contain smaller internal rotational motions. Using observations of the neutral gas component, a wealth of information such as the H I velocity field, velocity dispersion, column density, and galactic dynamical mass can be extracted through observations of the kinematics of dwarf irregulars.

Given the relatively small number of known tidal interaction between dwarf galaxies, it is imperative to ask how starburst regions form within these systems? Due to the redistribution of gas from tidal effects, mergers between dwarf pairs may aid in the triggering of starburst episodes. A detailed study of star formation in coupled systems versus isolated systems is critical for disentangling merger-driven starbursts and those due to stochastic processes (Stierwalt et al. 2014). NGC 3239 is one such dwarf merger located at a distance of $10.7 \pm 0.9$ Mpc (Rodriguez et al. 2014). We suggest that NGC 3239 is a merger because it has multiple tidal tails, an enhanced velocity dispersion, and ongoing star formation throughout the system. The disturbed stellar and gaseous structure of the galaxy noted by Krienke & Hodge (1991) supports the interaction hypothesis. These properties are unique to merging galaxies, as described in (Stierwalt et al. 2014).

The Arecibo Legacy Fast ALFA (ALFALFA) Extragalactic H I Source Catalog seeks to extend the faint end of the H I mass function and the overall abundance of low mass gas-rich halos. Star Formation can be tracked through several methods: 1) Hα observations, which give the number of ionizing photons if one assumes that all ionizing photons are absorbed and eventually re-emitted, 2) far-infrared (FIR) flux which assumes that a constant fraction of the emitted stellar energy is absorbed by dust, 3) radio continuum emission where only at radio and FIR wavelengths are the most obscured “starbursts” transparent, 4) far ultraviolet (FUV) flux which is primarily emitted by hot young stars, and 5) X-ray emission produced by high mass x-ray binaries. While Hα is one of the primary tracers of star formation, interstellar space is most abundantly populated with neutral hydrogen. Gas in the interstellar medium only converts from atomic to molecular in regions that are
well shielded from UV photons (Krumholz 2012). In these regions, the gas becomes sufficiently cool to undergo collapse. Neutral hydrogen contributes most of the cool gas mass, thus representing the fuel reservoir and potential for future star formation in these galaxies (Haynes et al. 2018).

2. OBSERVATIONS AND DATA HANDLING

This data-set for NGC 3239 was taken with the Karl G. Jansky Very Large Array (VLA) on March 14th, 1999 from 02:29:00 - 05:15:50. Reduction took place using ordinary command terminology from the Common Astronomy Software Applications (CASA) package. The primary calibrator and phase calibrator were the quasars 0538+498 and 1005+077 respectively. At a central frequency of 1416.8 MHz, the spectral window on the H I spectral line has channel width 48.8 kHz separated into 128 channels which delivers a velocity resolution of 0.381 kHz/channel. The observation period lasted a total of 10010 seconds and was divided into eleven integration scans. Imaging continuum subtracted visibilities was conducted through a multi-step procedure called CLEAN on the primary, phase, and source calibrators. A Briggs weighting scheme was employed with ROBUST = 0.5 and a width of 10.5 km s\(^{-1}\). A final deep clean was then conducted at a threshold of 1.5 * RMS. Using the \textit{fluxscale} command the phase calibrator flux density was measured to be \(S_\nu = 6.5308 \pm 0.0071 \text{Jy}\). Further physical properties of NGC 3239 are tabulated in Table 1; all parameters are intrinsic to this data-set save for the distance.

3. RESULTS AND INTERPRETATION

Figure 1 shows the three color image of NGC 3239 made with the Karma package KVis tool, using the SDSS G, R, and I filters with a logarithmic stretch. It is apparent from the presence of young, massive blue & white stars across the tidal arms as well as throughout the galaxy structure that there are current star forming regions. This is further supported by the co-spatiality of these regions with those of the high surface brightness \(H\alpha\) regions observed in (Krienkie & Hodge 1991). To produce
figures 2, 4, and 6, we collapsed our 3D data cube into 2 dimensions. The same methods were used to produce the contours seen in figures 3, 5 and 7. These three figures represent the un-blanked moment maps. Blanked comparisons of these (not shown) were also created by blanking at the 1.5σ level and smoothing the beam to 1.5 its dimensions (major=79.79", minor=66.47").

The moment zero map yields a flux integral of $S_{HI} = 71.13 \pm 7$ Jy km s$^{-1}$ that was further converted into units of column density $10^{20}$ cm$^{-2}$. The ALFALFA Extragalactic H I Source Catalog reports a flux integral of $S_{HI} = 60.73 \pm 0.09$ Jy km s$^{-1}$ (Haynes et al 2018). The mass of neutral hydrogen is then derived from its 21-cm emission spectrum. Using the ALFALFA recorded distance of $10.7 \pm 0.9$ Mpc, the aforementioned ALFALFA flux integral, and equation 1:

$$M_{HI} = 2.36 \times 10^5 \times (D/Mpc)^2 \times S_{HI} M_\odot$$

the calculated ALFALFA H I mass is $(1.46 \pm 0.27) \times 10^9 M_\odot$. Likewise, using the measured values from our data-set and the adopted distance, the H I mass is recorded to be $(1.92 \pm 0.25) \times 10^9 M_\odot$ which is in agreement with the ALFALFA result at the 2σ level. The distribution of the H I column density is visible in figures 2 and 3. There is no doubt that this orientation is co-spatial with the majority of the measured UV and optical flux from the galaxy. The first measurable data product that confirms the status of NGC 3239 status as the end product of two merging dwarf galaxies is evidenced by its column density profile. Shown in figure 2 are two over-dense regions of H I atoms. For dwarf irregulars, this feature is uncommon; typically only a central peak exists. The first over-density is visible in a region of star formation while the second is in an area devoid of any noticeable stellar flux. Around these regions, the number density of atoms decreases and becomes more uniform with increasing radius. The peak density was found to be $22.6 \times 10^{20}$ cm$^{-2}$. This value is peculiarly high as typical column densities range between $.5 \times 10^{19} - 2.3 \times 10^{21}$ with most dwarf irregulars having...
densities in the $10^{20}$ regime. These high density regions could thus be derived from the deposition of additional gas from a past merger.

Figures 4 and 5 show the intensity weighted velocity field of the galaxy, and the velocity field’s contours overlaid onto the SDSS optical image. On the lower end of the velocity field, one can see a clear extension of the kinematic morphology in the form of two visible tidal arms in the system. These attributes are suspected to have come from the merger of two previous dwarf galaxies. These tails are caused by the tidal forces between galactic bodies which drive the redistribution of stellar and gaseous content (Mundell et al. 2004). Along with this extension of gas, the presence of two unique over-densities separated by a high velocity gradient signifies regions of high mass undergoing solid body rotation. The major kinematic axis of this map spans roughly 110 km s$^{-1}$ of rotation.

Figures 6 and 7 represent the intensity weighted velocity dispersion of NGC 3239. This moment map shows the dispersion of the H I gas in km s$^{-1}$. Here, there is a clear central peak of the velocity dispersion, indicating complex kinematics in the surrounding H I gas. In a comparison with the moment 1 map, it is noticeable that the peak velocity dispersion occurs at the location of the highest velocity gradient. This is representative of highly turbulent motions within the H I gas.

To further explore the complex kinematics, three position-velocity slices were taken using the moment 1 map and the final un-blanked three dimensional data cube. Figure 8 shows the position of the three slices on the moment 1 map. Figure 9 corresponds to the northern slice, Figure 10 to the central slice, and Figure 11 to the southern slice. Using the central slice as demonstrative, the structure of solid body rotation is present; this is typical of dwarf irregular galaxies. This spans 5.75′. However, there are indications of more complex motions along both the northwestern and southeastern regions of the slices. These extensions of the gas have a maximum angular offset of about 5′ and 3′ respectively. A crude estimate of the dynamical mass of the galaxy is predicted from
this information via equation 2:

\[ M_{\text{dyn}} = \frac{V_{\text{rot}}^2 \times r}{G} \] (2)

We calculate \( M_{\text{dyn}} = (5.0 \pm 0.5) \times 10^{10} M_\odot \). This halo mass is typical of gas-rich, star-forming dwarf galaxies of similar luminosity.

4. CONCLUSIONS AND FUTURE WORK

The kinematic axis of the H I gas is not the same as the axis of the optical disc. The axes drawn on figure 8 to create the P-V slices are parallel to the major H I kinematic axis. Considering the presence of the tidal tails, the absence of an external interacting galaxy, the enhanced velocity dispersion, and the presence of multiple starburst regions, it is fair to conclude that NGC 3239 must already be a post-merger galaxy. The optical disc of the galaxy also appears to be very irregular; this is exacerbated by the H I disc being warped. The extent of the H I gas is also projected well beyond the scope of the optically luminous portions of the galaxy. These various properties imply that the present structure has deviated from one of higher stability and symmetry that may have been present prior to the merger event.

As presented, NGC 3239 is a galaxy worthy of more detailed analysis. The curious morphology, tidal tails, enhanced velocity dispersion and warped disc suggest it is a post-merger system. Future work could include observations of the resolved stellar populations, enabling color magnitude diagram and star formation history analysis. Further measurements of its Hα dynamics could also assist in probing the relationship between its H I gaseous content and its Hα star forming regions. The star formation within this galaxy is also a particular area which would be undoubtedly revealing. The arrangement of the star formation regions and gas within a galaxy can inform us about how much the star formation events disrupt the gas and how long it takes for these events to clear out clumps of atomic gas (Teich, et al.; 2016). Considering the merger status of NGC 3239, one would expect
traces of this in Hα. Gas consumption timescales can also be derived.

The author would like to thank John M. Cannon for his continued support and guidance. Appreciation also goes to Macalester College.

Facilities:

Facility: VLA
REFERENCES

[2018] Ranjan A., et al.; 2018, Molecular gas and star formation in an absorption-selected galaxy: Hitting the bulls eye at $z = 2.46$*
[2013] Tomasella L., et al.; 2013, Comparison of progenitor mass estimates for the Type IIP SN 2012A
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</tr>
<tr>
<td>Dec (J2000)</td>
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</tr>
<tr>
<td>Distance</td>
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<td>$N_{HI}$</td>
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</tr>
<tr>
<td>$S_{HI}$</td>
<td>$71±7$ Jy km s$^{-1}$</td>
</tr>
<tr>
<td>$M_{HI}$</td>
<td>$(1.92±0.37)\times10^{9}$ M$\odot$</td>
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**Table 1.** Full physical details of NGC 3239. The H I systemic velocity, column density, flux integral, and total H I mass were calculated from the moment maps.
Figure 1. SDSS color image of NGC 3239 made from G, R, and I filters with a logarithmic intensity scale. There is clear star formation in the inner most regions of the galaxy as well as extended star formation along the tidal arms.
Figure 2. Column density image of NGC 3239; contours are at levels of (0.05, 2.5, 5, 7.5...22.5) \times 10^{20} \text{cm}^{-2}.

The beam has dimensions major=79.79" and minor=66.47".
Figure 3. SDSS color image of NGC 3239 overlaid with contours of the H I column density distribution in units of $10^{20} cm^{-2}$; contours are of equal values as Figure 2.
Figure 4. Intensity weighted velocity field; the velocity gradients across the galaxy vary greatly by region and several kinematic axes are observed. The motion of the H I gas is dramatically unlike that of traditional dwarf galaxies which supports the notion that this is a post-merger system. The change in velocity across the steepest gradient is about 110 km s$^{-1}$. 

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Figure 5. SDSS color image of NGC 3239, overlaid with contours of the intensity weighted velocity field in units of km s$^{-1}$; contours are at levels of 680, 709, 738, 767, 796, and 820 km s$^{-1}$. The spread of the measured velocity extends well beyond the apparent extension of the baryonic mass distribution.
Figure 6. Intensity weighted velocity dispersion; the dispersion is peaked toward the center of the galaxy at a maximum value of 39 km s$^{-1}$. 
Figure 7. SDSS color image of NGC 3239 overlaid with contours of the intensity weighted velocity dispersion in units of km s$^{-1}$; contours are at levels of 1, 9, 17, 25, 33, and 39 km s$^{-1}$. The dispersion of the gas is of higher turbulent intensity toward the center of the galaxy away from the tidal arms. As expected, there is only one central turbulent core.
Figure 8. The first, second, and third position velocity slices of NGC 3239. Slices are shown on the moment 1 map. As a function of angular offset, the velocity field is extracted and imaged in Figures 9-11.
Figure 9. First position velocity slice of NGC 3239. This slice along the northern edge of the moment 1 map is not like the p-v solid body rotational structure that is expected of irregular dwarf galaxies. The extension of the H I gas velocity can clearly be seen in three different regions of varying angular offsets. This attribute is thought to be the H I velocity effect of the tidal arms.
Figure 10. Second position velocity slice of NGC 3239. This slice through the central kinematic axis of the moment 1 map is taken along the highest kinematic gradient. Presently, the solid body rotational structure is clearly defined; there are two noticeable velocity extensions of H I gas. On the left of the structure, offset is about 5′ while on the right side it is about 3′. Using this slice, the dynamical mass is estimated to be $M_{\text{dyn}} = (5.0 \pm 0.5) \times 10^{10} M_\odot$. 
Figure 11. Third position velocity slice of NGC 3239. This slice along the southern edge of the moment 1 map displays a characteristic p-v bar structure for irregular dwarf galaxies. However, the extended tail structure of the H I velocity is very prominent.