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Abstract

Studies of low-mass galaxies are important for populating the low-mass ends of funda- mental physical relations. Extremely metal-poor (XMP) galaxies are low-mass galaxies with gas-phase oxygen abundances of 12+log(O/H) ≤ 7.35 (1/20 Z⊙), and are especially interesting as proxies for studying the distant past, as their chemical makeup resembles those of galaxies in the early universe. AGC 198691, referred to as the Leoncino Dwarf, was discovered through the Arecibo Legacy Fast ALFA (ALFALFA) survey and found to have an oxygen abundance of less than 3% Z⊙. Presented here are the results of recent Karl G. Jansky Very Large Array (VLA) HI observations of Leoncino, with discussion of its apparently dispersion-dominated kinematics, level of agreement with mass-metallicity (MZ) and luminosity-metallicity (LZ) relations, current star formation, and theories regarding its extremely low metal content.

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THE LEONCINO DWARF: A NEUTRAL HYDROGEN ANALYSIS OF AGC 198691 AND ITS EXTREMELY METAL-POOR ENVIRONMENT

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ABSTRACT

Studies of low-mass galaxies are important for populating the low-mass ends of fundamental physical relations. Extremely metal-poor (XMP) galaxies are low-mass galaxies with gas-phase oxygen abundances of 12+log(O/H) $\leq$ 7.35 (1/20 $Z_{\odot}$), and are especially interesting as proxies for studying the distant past, as their chemical makeup resembles those of galaxies in the early universe. AGC 198691, referred to as the Leoncino Dwarf, was discovered through the Arecibo Legacy Fast ALFA (ALFALFA) survey and found to have an oxygen abundance of less than 3% $Z_{\odot}$. Presented here are the results of recent Karl G. Jansky Very Large Array (VLA) HI observations of Leoncino, with discussion of its apparently dispersion-dominated kinematics, level of agreement with mass-metallicity (MZ) and luminosity-metallicity (LZ) relations, current star formation, and theories regarding its extremely low metal content.

1. IMPORTANCE OF LOW-MASS GALAXIES AND XMPS

Though large galaxies are easily detected, smaller galaxies are significantly more abundant in the universe. Low-mass galaxies are actually the most numerous type of galaxy, but are also the most difficult to observe due to their intrinsic faintness. As a consequence of this, models relating parameters such as luminosity and metallicity to mass are woefully underpopulated in the low-mass regions, leaving current models unable to confidently predict galaxy behaviours across wide mass ranges. Low-mass also indicates that a galaxy has followed a rather solitary evolution, since

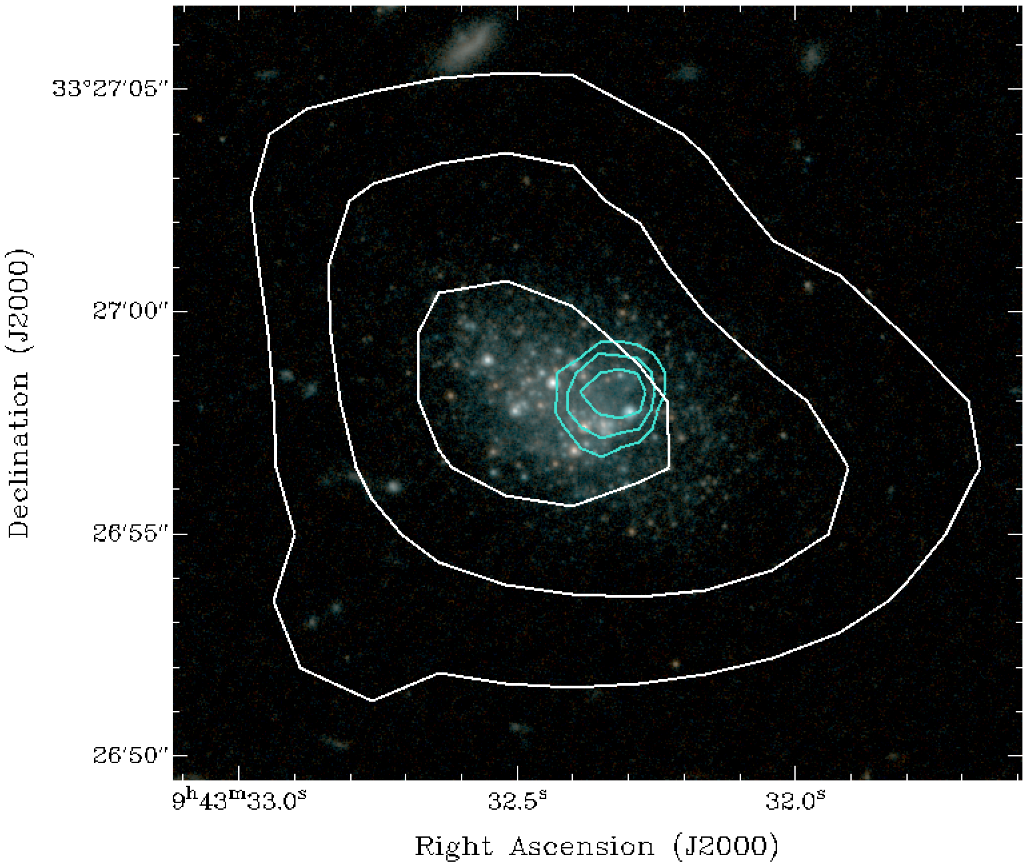

Figure 1. HST image of Leoncino with white contours showing column density contours at 5e20, 7.5e20, and 10e20 cm^{-2}. Blue contours show location of Hα emission at contours of 16, 32, and 58%.

interactions with other galaxies would have led either to the growth or destruction of the galaxy. Because they have remained relatively unperturbed since their formation, low-mass galaxies are suitable proxies for studying galaxy formation as well as stellar formation behaviors of the early universe.

As such, studies of low-mass galaxies were in high demand but low supply. In an attempt to remedy this, the Arecibo Legacy Fast ALFA blind HI survey (ALFALFA) was launched, casting a large observational net in the hopes of collecting substantial galaxy data (Giovanelli et al. 2005). From the resulting catalogue of 30,000+ sources, the Survey of HI in Extremely Low-mass Dwarfs (SHIELD; Cannon et al. (2011)) focused its study on 82 galaxies discovered by ALFALFA that fell within the $10^6 \sim 10^7$ M$_\odot$ range.

Parameter	Value
R.A. (J2000)	9:43:32.4
Decl. (J2000)	+33:26:58.0
12+log(O/H)	7.12±0.04
V_{helio}	514 km s^{-1}
V_{gsr}	481 km s^{-1}
M_{HI} / M_*	25.
m_V	19.53 ±0.03 mag
$F_{3.6}$ μm	(1.50±0.07) $\times 10^{-5}$ Jy
$m_{3.6}$ μm	18.8 mag
$B-V$	0.29±0.04 mag
A_V	0.04 mag
P.A.	80°
semi-major axis	6.″75
eccentricity	0.61
WFC3 F606W exp. time	15018 s
WFC3 F814W exp. time	18618 s

Table 1. Summary of properties for Leoncino.

Extremely Metal-Poor galaxies (XMPs) are objects of even greater interest than average dwarf galaxies. Low-mass galaxies are likely to be metal-poor, as their stellar population is neither large enough nor evolved enough to have flooded the galaxy with heavier elements, but XMPs are in their own league. A galaxy is considered extremely metal-poor when it has a gas-phase oxygen abundance of 12+log(O/H) $\leq$ 7.35, less than $\sim \frac{1}{20}$ $Z_\odot$ (McQuinn et al. 2020). Extremely metal-poor dwarfs are prime subjects of study, because their physics and chemistries mimic those of the first galaxies formed. As such, XMPs are extremely valuable for understanding the universe's evolution.

AGC 198691 (see Figure 1) was discovered through the ALFALFA survey and followed up on by SHIELD. Known colloquially as the Leoncino Dwarf, the galaxy is an XMP with an oxygen abundance of 12+log(O/H) $= 7.12 \pm 0.04$ (under 3% $Z_\odot$), the lowest recorded at its time of discovery (Hirschauer et al. 2016). Tabulated properties of Leoncino from Hirschauer et al. (2016) and McQuinn et al. (2020) can be found in Table 1. Here we analyse data gathered from these subsequent observations of Leoncino, with focus on its rotational dynamics, gas kinematics, and star formation behavior.

2. HI DATA REDUCTION AND IMAGING

HI spectral data was obtained with the Karl G. Jansky Very Large Array (programs VLA/15B-338 and 16A-134) in its D (maximum baseline length 1.03 km, nominal beam size of $\sim 40''$), C (maximum baseline length 3.4 km, nominal beam size of $\sim 15''$), and B (maximum baseline length 11.1 km, nominal beam size of $\sim 6''$) configurations. Total observation times in the order of D, C, and B were 5.8, 5.8, and 11.7 hours, with total on-source times approximating 3, 3, and 6 hours, respectively. Data was obtained through the VLA/15B-338 and 16A-134 programs and used primary calibrator 3C286 for one data set each from the D and B configurations, while using 3C147 for the rest. Phase calibrator J1006+3454 was used across all data sets.

Data was reduced using the Common Astronomy Software Application (CASA; McMullin et al. (2007)). Data cubes were created through cleans conducted on different combinations of configuration data sets, with a Briggs weighting scheme employed to maximise the data's sensitivities: a robust of 0.5 was applied to cubes containing B-configuration data to maximise angular resolution, and a robust of 2.0 was applied to cubes containing D-configuration data for maximum surface brightness sensitivity. In some cases, tapers in the UV plane were added to control the resulting beam size and resolution.

Data cubes were then cleaned to the 1.5σ level, determined by the rms in line emission-free channels, and then hand-blanked to contain only line emission. The resultant cubes were collapsed into two-dimensional moment maps showing surface gas density (moment 0), intensity-weighted velocity (moment 1), and intensity-weighted velocity dispersion (moment 2). Moment maps were generated for all three sensitivities (beam sizes of $8''$, $16''$, and $32''$). The HI flux integral recovered was $S_{HI} = 0.5 \pm 0.05$ Jy km s^{-1}, comparable to ALFALFA's recorded flux integral of $S_{HI} = 0.53$ Jy km s^{-1}.

Further data on Leoncino was gathered after these initial reductions, including new HST observations and photometric data, which we will reference in developing our analysis and can be found in detail in McQuinn et al. (2020).

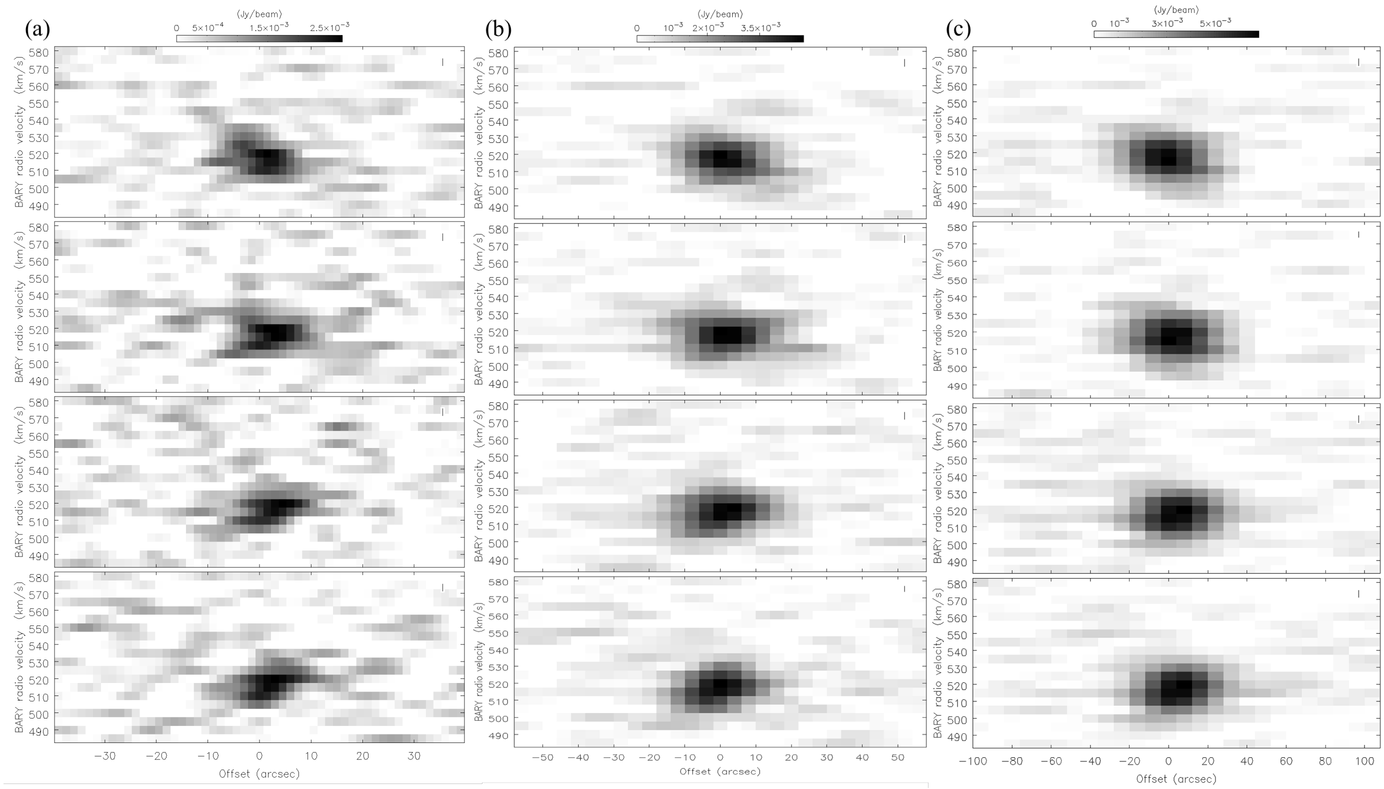

Figure 2. Slices through Leoncino's (a) highest (8″), (b) medium (16″), and (c) lowest angular resolution (32″). From top, primary axis angles were (a) 27.6°, 72.6°, 117.6°, and 162.6°; (b) 36.8°, 81.8°, 126.8°, and 171.8°; and (c) 54.0°, 99.0°, 144.0°, and 169.0°. Angles measured North of East.

3. RESULTS AND DISCUSSION

3.1. *Rotational Dynamics and Dispersion Kinematics*

From our analysis, it appears that Leoncino has no clearly defined rotational character. While the column density maps agree upon the location of its center of mass, the velocity field maps disagree on primary rotational axes. Slices were taken through the galaxy with KPVSLICE from the KARMA package, shown in Figure 2. Instead of taking slices beam-widths removed from the primary axis, they were taken through the primary axis and then rotated north of east by 45, 90, and 135 degrees for a total of four slices per resolution. Slice locations are marked on Leoncino's moment maps, found in Figure 3.

Referring to Figure 3, we see that Leoncino's primary axis appears to rotate as the angular resolution changes. If a galaxy has a definable rotational axis, this axis should not be altered by resolution. Since different resolutions of Leoncino appear to resolve morphologies that disagree on a common

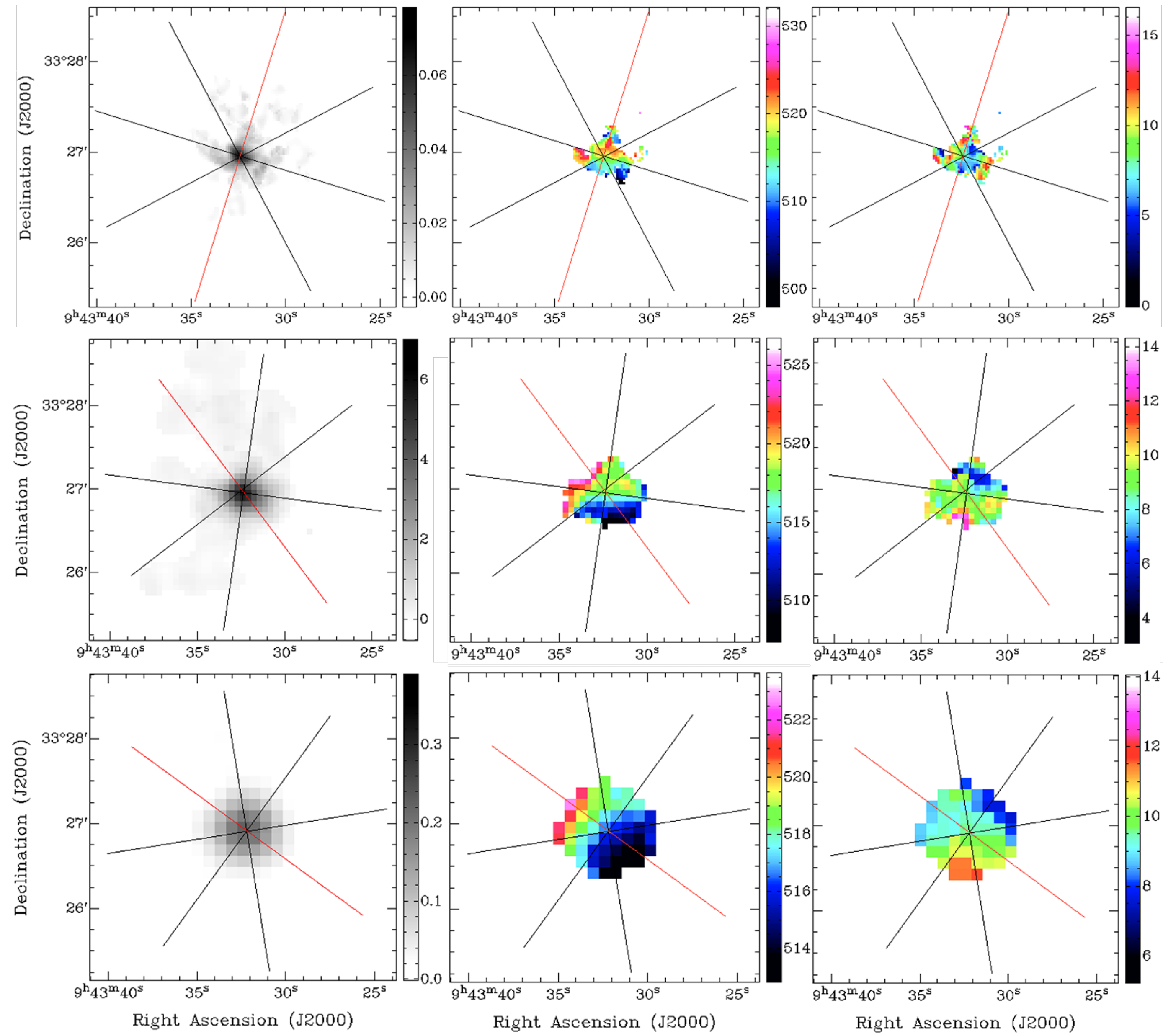

Figure 3. Slice locations for Leoncino moment maps. From left to right, moment 0, moment 1, and moment 2 maps per resolution. Moment 1 and 2 map values measured in km s^{-1}. Top row shows highest angular resolution with beam size 8″; middle row shows medium resolution with beam size 16″; bottom row shows lowest angular but highest surface brightness sensitivity at beam size 32″.

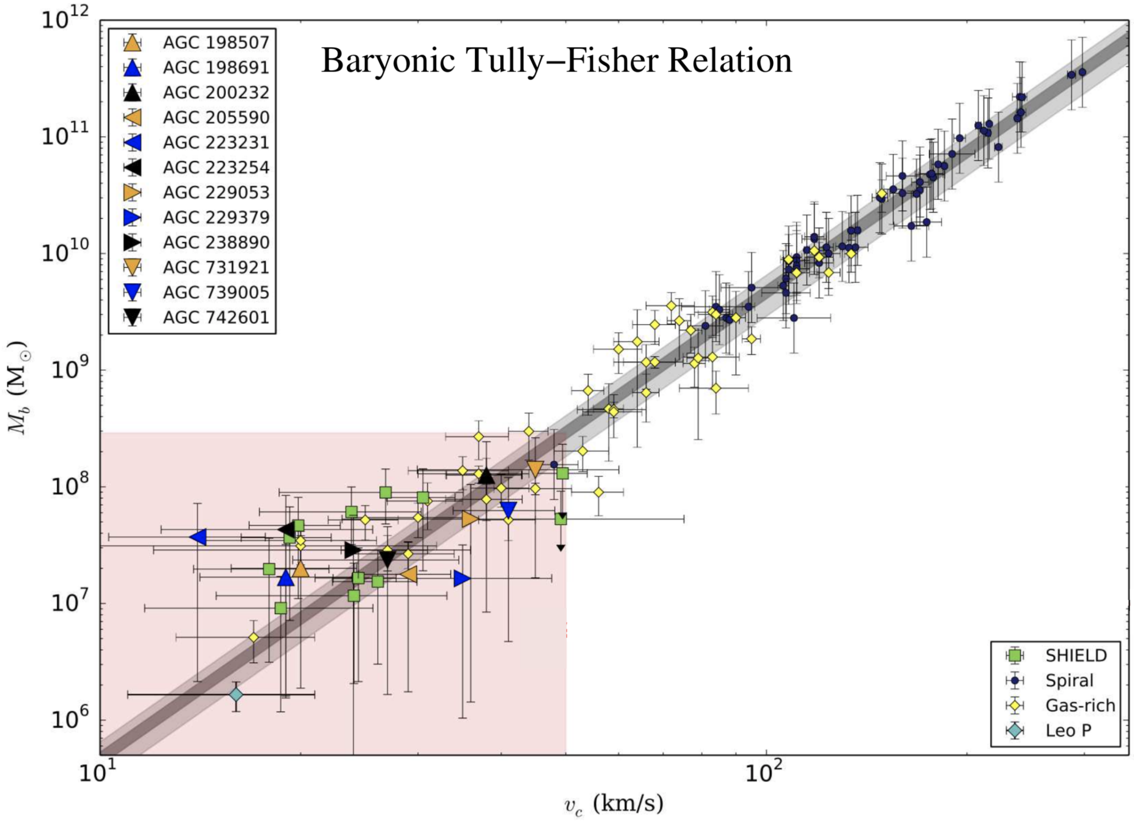

Figure 4. Baryonic Tully-Fisher relation, plotted baryonic mass by rotational velocity. Leoncino appears as the upright blue triangle marker in a preliminary location on the relation, with baryonic mass approximately 1.83 x 10^7 $M_\odot$. Figure from VLA/20A-330 observing proposal (PI: John Cannon, 2019).

primary axis, this warns us that Leoncino's gas kinematics may not be neatly rotational. When we observe the slices as well (Figure 2), we notice that Leoncino appears uniformly round across the cuts and resolutions, with no discernible rotation curve present.

This all seems to suggest that Leoncino has little to no rotational character. The maximum velocity dispersion seen in the moment 2 maps is approximately 15 km s^{-1} with average dispersions of 10 km s^{-1}, which is very near the 15-20 km s^{-1} velocity range seen in the moment 1 gradients. From this we might conclude that Leoncino is a dispersion-dominated galaxy with no rotational behaviour, however this conclusion may yet be false. When given a preliminary location on the baryonic Tully-Fisher relation as in Figure 4, we see that if Leoncino were to lie on the expected line, it would have a rotational velocity of just under 25 km s^{-1}. Up until now we have not considered the possibility of Leoncino being inclined to our line of sight; if we posit that Leoncino is inclined at just 45°, we would

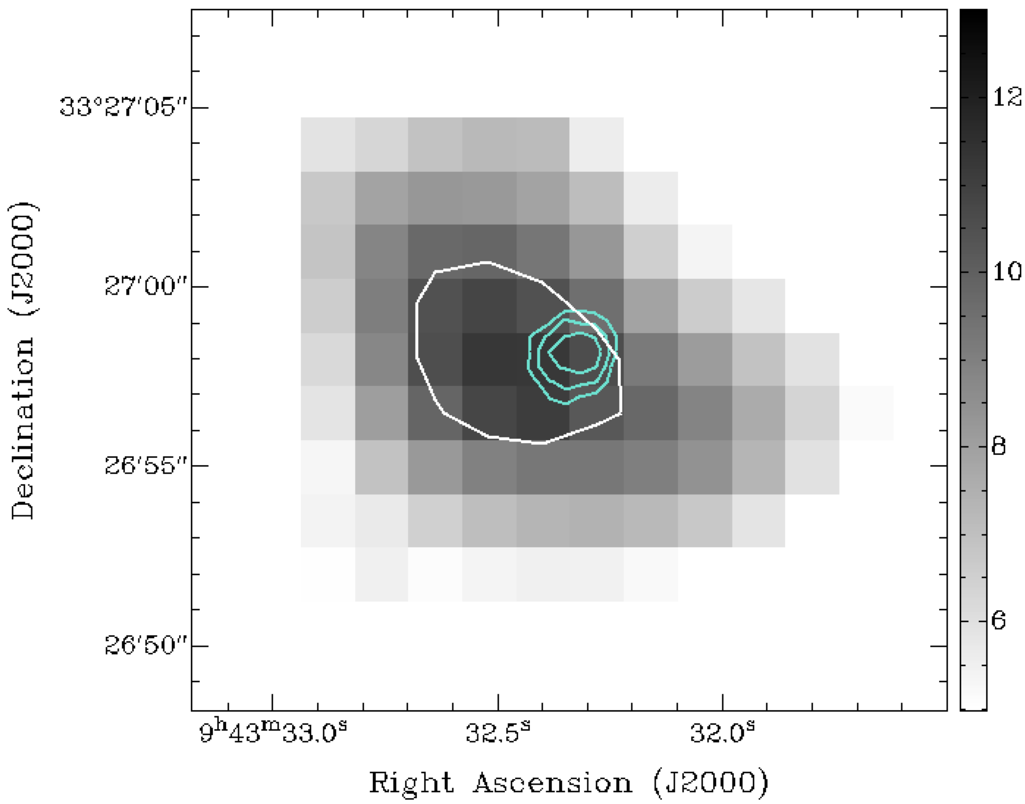

Figure 5. Highest angular resolution column density map blanked at 5e20 cm^{-2}, contoured at 1e21 cm^{-2} in white. Blue contour shows location of H emission at contour values 16, 32, and 58%. Color bar measures column density in units of 10^{20} cm^{-2}.

record a rotational velocity of 18 km s^{-1}, which lies well-within the velocity range we currently have recorded.

If the galaxy is indeed inclined it may explain our difficulty in resolving a clear gradient. Though increased resolution would certainly be helpful, at a distance of $12.1^{+1.7}_{-3.4}$ Mpc, a much more powerful telescope than those currently available would be needed to resolve Leoncino more than we currently have.

3.2. *Recent Star Formation in Leoncino*

Leoncino was found to agree with both the luminosity-metallicity (LZ) and the mass-metallicity (MZ) relations. Though it currently lies outside predicted values on the LZ scale, recent star formation marked by Hα emission was found to account for this offset. Hα measurements and LZ calculations are reported from McQuinn et al. (2020).

Figure 5 shows Leoncino's HI column density map blanked at 5e20 cm^{-2} and contoured at 1e21 cm^{-2}, with blue contours denoting where Hα emission was detected. A minimum column density of 1e21 cm^{-2} is expected for star formation (Skillman 1986), which agrees with the observations; however, the center of star formation is located near the edge of the expected region, offset from the location of highest column density. Measured from the center of the highest column density pixel, the center of the Hα emission is offset by approximately 10.7 pc. Why star formation is occurring near the minimum column density as opposed to areas of higher gas abundance currently remains a mystery; it may point to an external event (see Bartz et al., MJPA, this volume), or it may simply be a chance collapse that led to a chain of star formation around it, unrelated to location. As its cause remains undefined, this pocket of star formation may be worth further consideration in future studies.

3.3. *Leoncino's Low Metal Content*

Leoncino is rightly labeled as extremely metal-poor, with a surprisingly low gas-phase oxygen abundance even for an XMP. Though low metallicity is expected for dwarf galaxies, Leoncino's metal deficiency is significant, and does not appear to have been caused by some dramatic event. Rather, Leoncino's metal content appears to be evolutionary in nature, most likely influenced by its existence in a significantly under-dense environment, Void No. 12 (Pustilnik et al. 2019). Leoncino most likely experienced a very secular evolution; without many objects in its surroundings to interact with, Leoncino would have been permitted to remain an unperturbed low-mass galaxy with slow, inefficient star formation. One theory therefore is that Leoncino lost the majority of the metals its stars produced due to strong interstellar winds common in secular evolution models. Theories about Leoncino interacting with neighboring galaxy UGC 5186 are also worth considering, and will be addressed in Bartz et al 2020 (MJPA, this volume).

4. CONCLUSION

Low-mass galaxies are of great interest for current study as new technology better enables us to discover and meaningfully observe these dim but numerous objects. Surveys such as ALFALFA made leaps and bounds for dwarf galaxy research, but the lower end of mass relations are still markedly underpopulated. As such, the Leoncino dwarf is a source of great interest, with its low mass and extremely low gas-phase oxygen abundance. Working to understand Leoncino's past and present is of continuing importance, as there are few other environments that so closely simulate the state of the early universe.

Recently acquired VLA HI data cubes show Leoncino to have no easily discernable axis of rotation, and appears to be heavily dispersion-dominated; however, if the galaxy is at any appreciable inclination, calculations show that there may actually be some rotational character that is being lost in the moment maps. Leoncino agrees well with the predicted mass-metallicity relation, and was found to agree with the luminosity-metallicity relation if the young stars from a recent star formation burst were accounted for in the calculation. These stars were found to lie within the expected column density regions for star formation, but were offset from the areas of highest density. It is important to note that this offset is of a distance well-within one beam size and as such may not be entirely significant, but it remains an interesting observation. Finally, while Leoncino's extreme metal deficiency is still a surprise to find, its location in a void environment as well as its probable secular evolution offer plausible theories for its current state, though external factors may still be at play considering how dramatically low its metal count is. At present however, Leoncino remains a mysterious environment ripe with opportunities for continuing study.

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