A COLLISIONAL ORIGIN FOR THE LEO RING*

LEO MICHEL-DANSAC1, PIERRE-ALAIN DUC2, FREDERIC BOURNAUD2, JEAN-CHARLES CUILLANDRE3, ERIC EMSELLEM1,4, TOM OOSTERLOO5, RAFFAELLA MORGANTI5, PAOLO SERRA6, AND RODRIGO IBATA6

1 Centre de Recherche Astrophysique de Lyon, Université de Lyon, Université Lyon 1, Observatoire de Lyon, Ecole Normale Supérieure de Lyon, CNRS, UMR 5574, 9 avenue Charles André, 69561 Saint-Genis-Laval cedex, France; leo@obs.univ-lyon1.fr
2 Laboratoire AIM, CEA/IRFU, CNRS, Université Paris Diderot, 91191 Gif-sur-Yvette cedex, France
3 European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei Muenchen, Germany
4 ASTRON, Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands
5 Observatoire Astronomique de Strasbourg (UMR7550), 11, rue de l’Université, 67000 Strasbourg, France

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ABSTRACT

Extended H i structures around galaxies are of prime importance for probing galaxy formation scenarios. The giant H i ring in the Leo group is one of the largest and most intriguing H i structures in the nearby universe. Whether it consists of primordial gas, as suggested by the apparent absence of any optical counterpart and the absence of an obvious physical connection to nearby galaxies, or of gas expelled from a galaxy in a collision is actively debated. We present deep wide field-of-view optical images of the ring region obtained with MegaCam on the CFHT. They reveal optical counterparts to several H i and UV condensations along the ring, in the g′, r′, and i′ bands, which likely correspond to stellar associations formed within the gaseous ring. Analyzing the spectral energy distribution of one of these star-forming regions, we found it to be typical for a star-forming region in pre-enriched tidal debris. We then use simulations to test the hypothesis that the Leo ring results from a head-on collision between Leo group members NGC 3384 and M96. According to our model which is able to explain, at least qualitatively, the main observational properties of the system, the Leo ring is consistent with being a collisional ring. It is thus likely another example of extended intergalactic gas made-up of pre-enriched collisional debris.

Key words: galaxies: evolution – galaxies: groups: individual (Leo group) – galaxies: individual (NGC 3384, M96) – galaxies: interactions

1. INTRODUCTION

The quest for primordial gas clouds that have never been involved in star-forming episodes in the local universe has motivated extensive H i surveys (e.g., HIPASS, Meyer et al. 2004; and ALFALFA, Giovanelli et al. 2005) but has yet been rather unsuccessful. Among the putative candidates are the so-called dark galaxies (e.g., Davies et al. 2004), which are, however, likely tidal debris from galaxy interactions (Duc & Bournaud 2008). Isolated H i clouds around early-type galaxies (ETGs; Morganti et al. 2006; Oosterloo et al. 2007; Serra & Oosterloo 2010) could either be accreting clouds or the collisional remnants of the violent merger events that are usually invoked for the formation of E TGs. Investigating the stellar populations associated or not with these clouds could discriminate these formation scenarios.

The Leo ring, in the Leo group of galaxies, is one of the most spectacular and mysterious intergalactic H i structures known in the nearby universe (Schneider et al. 1983, 1989; Schneider 1985; Stierwalt et al. 2009). It has a ring-like shape of diameter ~200 kpc, quite asymmetric and somewhat clumpy, apparently centered on the NGC 3384/M105 galaxy pair. Some radial filamentary structures are observed, in particular a bridge connecting the ring to the spiral galaxy M96. These have been numerous attempts to find counterparts to the H i emission at other wavelengths, which remained unsuccessful in the optical and Hα regime. This had suggested that the ring could consist of primordial gas. The only relatively bright optical counterparts correspond to H i-rich dwarf galaxies in the group (Stierwalt et al. 2009) whose velocities are discrepant from the ring velocity field (e.g., HGC 201970).7

Lastly, Thilker et al. (2009) reported a UV counterpart to some H i clumps along the ring from Galaxy Evolution Explorer (GALEX) observations. The UV knots with the highest far-UV (FUV) to near-UV (NUV) flux ratios are good candidates for being star-forming regions associated with the ring (and not background galaxies). The inferred star formation rate is very low but consistent with the H i column densities below 2 × 1020 cm−2. Based on the FUV–NUV color and upper limits on the FUV–r color, Thilker et al. (2009) estimated a very low gas metallicity and concluded that the H i ring is likely primordial.

More recently, Bot et al. (2009) reported a marginal detection of dust emission at 8 and 24 μm toward the densest H i condensation. If real, it implies that the metallicity of the H i ring is higher than the Z⊙/20 as estimated by Thilker et al. (2009). This would support scenarios where the gas has a galactic origin. Indeed, clouds expelled during galaxy interaction have been previously processed in the parent galaxies and are thus relatively metal-rich. Bekki et al. (2005) proposed that the disruption of a low surface brightness galaxy in the gravitational potential of a group forms gaseous arcs and rings with column density in agreement with observations, without providing a specific model for the Leo ring, though. Collisional rings are

7 One exception is HGC 202027, whose Sloan Digital Sky Survey (SDSS) redshift is close to that of the H i ring, but is not associated with an H i clump peak of the ring. It is most likely a pre-existing group member unrelated to the formation of the H i ring.

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a more classical example of such debris (Appleton & Struck-Marcell 1996; Bekki 1998; Bournaud & Combes 2003): a head-on galaxy collision disrupts a gaseous galactic disk into an expanding pre-enriched ring of gas, whose star-forming activity depends on the remaining gas density.

In this Letter, we present new optical images of the system and report the detection of counterparts in the $g'$, $r'$, and $i'$ bands (Section 2). We present a numerical model of the Leo ring as the result of a head-on collision in the Leo group (Section 3) and discuss this hypothesis in Section 4.

2. OBSERVATIONS OF AN OPTICAL COUNTERPART TO THE LEO RING

Deep optical observations of the Leo group of galaxies were obtained in 2009 January, November, and December with the MegaCam camera on the CFHT, as part of a survey of H\textsc{i}-rich ETGs from the ATLAS$^{3D}$ project (Serra et al. 2009).

The whole H\textsc{i} structure was covered with two MegaCam pointings of 1 deg$^2$ each. Each pointing consisted of individual exposures, offset with respect to each other typically by 10 arcmin. This allowed the creation of a master sky which was subtracted before recombining the images. Instrumental artifacts, such as diffuse light, could thus be removed down to a surface brightness limit of 28.2 mag arcsec$^{-2}$ in the $g'$ band. The total exposure times on the southern field (which contains the densest H\textsc{i} condensations) were 1764 s in the $g'$ band, 2760 s in the $r'$ band, and 714 s in the $i'$ band. Observations of the northern field were shallower: 882 s, 1380 s, and 71 s in $g'$, $r'$, and $i'$, respectively. Weather conditions were photometric. The data were processed using the Elixir-LSB software originally developed as part of the Next Generation Virgo Cluster Survey (L. Ferrarese et al. 2010, in preparation).

A true color image field is presented in Figure 1 together with close-ups toward three UV-detected H\textsc{i} condensations. New H\textsc{i} maps obtained with the Westerbork Synthesis Radio Telescope...
Note. 4 Our photometric measurement resulted in larger error bars than those listed in Thilker et al. (2009) and fluxes closer to the values listed in the GALEX online catalog. Aperture corrections and differences in the estimation of the background level might explain this.

The large error bars in the UV preclude a direct fit of the SED of this specific object with spectro-photometric models.

The multi-band aperture photometry on the UV clumps proved to be challenging: indeed, with an average seeing of 0.9 arcsec, our optical observations resolve the GALEX UV knots into several optical point-like sources displaying a variety of colors and thus possibly a variety of origins (see in particular clumps 1 and 2 in Figure 1). Clump 2E avoids these problems: the GALEX and optical emission coincide spatially and the MegaCam sources show a uniform blue color. We carried out a detailed photometric analysis on this condensation. Our measurements in the NUV and FUV GALEX bands, and g′, r′, and i′ MegaCam bands are presented in Table 1. They were obtained by using the POLYPHOT task of the IRAF package, with an aperture chosen to follow the external white contours shown in Figure 1. Local sky measurements were estimated manually to avoid nearby background/foreground sources.

The UV to optical spectral energy distribution (SED) of clump 2E is shown in Figure 2. We compare it to the SED of NGC 5291N, a luminous star-forming region in NGC 5291, which harbors an extended ring of confirmed collisional debris (Bournaud et al. 2007) with a morphology recalling that of the Leo ring. Accounting for a different flux and a difference in extinction of 0.2 mag in $A_V$, the two SEDs are strikingly similar (Figure 2). The metallicity of NGC 5291N, as estimated from a measure of the oxygen abundance in its ionized gas, is moderately high: 12+$\log$(O/H) = 8.4 (Duc & Mirabel 1998), suggesting that this could also be the case for clump 2E. As recently shown by Boquien et al. (2010), the SED of NGC 5291N, and thus of Leo clump 2E (see also Figure 2), is well fit by a model depicting an instantaneous starburst of age of about 5 Myr, within dust obscured pre-enriched gaseous material. Therefore, assuming that dust is present in the Leo H i structure, as suggested by the marginal Spitzer detections reported by Bot et al. (2009), the SED of clump 2E is consistent with the hypothesis that it was formed within pre-enriched material.

These results contradict the claim by Thilker et al. (2009) that the gas fueling the star-formation episode can only be very metal poor and thus primordial. Then, the extended H i structure probably results from a past interaction in the group.

We model a galaxy encounter using a particle-mesh sticky particle code (Bournaud et al. 2007, and references therein), with a softening length of 150 pc. The particle mass is $8 \times 10^4 M_\odot$ for gas, $4 \times 10^5 M_\odot$ for stars, and $7.2 \times 10^5 M_\odot$ for dark matter (DM). Gas dynamics is modeled through a sticky particle scheme with a Schmidt–Kennicutt law (Kennicutt 1998) with the star formation rate proportional to the gas density to the exponent 1.4.

Among a set of 50 simulations of head-on collisions, we present here a specific case that reproduces, at least qualitatively, the main properties of the Leo ring. It is a relatively low-velocity encounter, not because a high-velocity encounter is ruled out (high-velocity encounters can form rings and tidal debris, as shown by Duc & Bournaud 2008; Bournaud et al. 2007), but because this configuration seems more likely in the low velocity dispersion Leo group. Besides, initial tests showed that the interloper had to be very massive to form a giant ring. In our model, NGC 3384 is the target disk of a head-on collision with the massive galaxy M96. M96 appeared to be the most likely interloper, assuming that the H i bridge linking it to the ring was left over after the collision. Note that the key role played by M96 in the formation of the ring had already been envisioned by Rood & Williams (1985). As for the target galaxy, the S0 galaxy, NGC 3384 seemed a better candidate than the other central galaxy (M105): in the collision scenario, the target should initially be a gas-rich spiral, and an interaction without merger is more likely to convert it into a disky ETG (S0/Sa) than into a spherical elliptical such as M105 (Bekki 1998; Bournaud & Combes 2003).
Both the interloper and the target galaxy are modeled with a disk of gas and stars, a stellar bulge, and a DM halo. The target galaxy is a gas-rich spiral galaxy with an extended gaseous disk. The stellar disk has a mass $M_d = 1.92 \times 10^{10} \, M_\odot$ distributed according to a Toomre profile of scale length $r_d = 3.375 \, \text{kpc}$. The bulge is a Plummer sphere with a mass $M_b = 3.24 \times 10^8 \, M_\odot$ and a characteristic radius $r_b = 1.5 \, \text{kpc}$. The gaseous disk is a homogeneous disk with a mass $M_g = 4.8 \times 10^9 \, M_\odot$ truncated at $r_g = 18 \, \text{kpc}$. These components are embedded in a spherical DM halo with pseudo-isothermal profile, mass $M_h = 7.08 \times 10^{10} \, M_\odot$, and core radius $r_h = 24.75 \, \text{kpc}$.

The collision forms an expanding gas ring, mostly from NGC 3384 material. 1.2 Gyr later, the model reproduces, at least qualitatively, the main observational features: the size, mass, column density, and asymmetry of the H\textsc{i} ring; the bridge of H\textsc{i} linking the ring to M96; the projected systemic velocity of the two colliding galaxies; and the global kinematics of the gas along the ring and in M96, as shown in Figures 3 and 4.

The projected position of the target galaxy relative to the ring and the mass in the northern end of the ring are not exactly reproduced. There is also some mismatch between the gas velocities in the interloper and the ring. Nevertheless, the main intriguing properties of the Leo ring are reproduced, such as the strong asymmetry even if the exact orientation of this asymmetry is not just like that in the Leo ring itself. Our simulation should be seen as a proof of the concept that relatively common collisions with moderate velocities between two galaxies typical for the Leo group can easily form a “Leo ring-like” system. Matching all detailed properties accurately is not our purpose and would induce too many free parameters: the tidal field from other nearby galaxies (such as M105), and even of the whole Leo group can affect the result of a pair interaction (Martig & Bournaud 2008).

4. DISCUSSION AND CONCLUSIONS

The origin of the Leo ring has been actively debated for more than two decades. If made of primordial gas, it would be the only such giant H\textsc{i} structure known in the nearby universe.
The absence of an optical counterpart was often suggested to preclude a collisional origin. Our deep optical images have confirmed that indeed it is not associated with a diffuse stellar component brighter than $28 \text{ mag arcsec}^{-2}$. However, as shown by our numerical model of the Leo ring and previous simulations (Bournaud et al. 2007), collisional rings are not expected to systematically contain a significant populations of old stars expelled from the progenitor galaxy. Old stars can spread in a halo rather than along the ring, as is the case in our model with a predicted brightness fainter than $\sim 29 \text{ mag arcsec}^{-2}$.

The Leo ring is striking for not having managed to convert a significant fraction of its gas into stars. If primordial, this would require unexampled long-term stability conditions (stabilization by a deep potential such as the Leo group could nevertheless quench star formation; Martig et al. 2009). Our imaging program has revealed the presence of compact, optical counterparts to the far-ultraviolet sources detected by *GALEX*. These are likely young stellar associations formed in situ in the $\text{H}_1$ ring, with very low star formation rates that are consistent with the low $\text{H}_1$ surface densities. Thilker et al. (2009) had estimated a very low metallicity from UV data, suggesting the presence of primordial gas. Adding three data points in the optical bands to the SED of one of the UV clumps, we find it most consistent with that of a star-forming object in the NGC 5291 ring, known to be pre-enriched and of collisional origin (Bournaud et al. 2007). Thus, available data are actually consistent with the Leo ring being made-up of pre-enriched material. Obtaining a direct measurement of its metallicity would give the final word.

If the Leo ring is not made-up of primordial gas, its formation should involve pre-enriched gas expelled during galaxy–galaxy or galaxy–group interactions. Ram pressure would require a very dense intracluster medium to produce such a massive and extended structure, a condition not met in a relatively loose group like Leo. Note also that ram pressure usually forms one-sided tails attached to the parent galaxy, not ring-like structures (Tonnesen & Bryan 2009). The tidal potential of the group could also affect the gas content of galaxies, but is generally a second-order effect compared to direct collisions in galaxy pairs.

A more likely hypothesis is that the Leo ring has the same origin as the confirmed collisional ring around NGC 5291 (Longmore et al. 1979; Bournaud et al. 2007) or the famous Cartwheel ring (Horellou & Combes 2001)—the later being much denser and actively star forming. Our numerical model reproduces the main characteristics of the Leo ring, after a galaxy collision at a relatively moderate speed, quite plausible in the Leo group. The proposed progenitor galaxy, NGC 3384, does not show strong morphological disturbances, even in our deep imaging data. This is, however, expected in our model that produces a gaseous collisional ring, an extended and very faint (unobservable) stellar halo, but leaves little signs of collision such as classical tails and shells around the parent galaxy. *SAURON* observations of NGC 3384 (Emsellem et al. 2004; Kuntschner et al. 2006) revealed a barred rotating disk, with a low gas and dust content and without very recent star formation, which is also broadly consistent with our model where the pre-existing spiral is converted into a fastly rotating ETG by the 1.2 Gyr old collision.

Large collisional rings can form in groups of galaxies and take an appearance a priori suggesting primordial gas rather than tidal debris. The Leo ring appears to be fully consistent with being the result of such a process.

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REFERENCES

Angiras, R. A., Jog, C. J., Omar, A., & Dwarakanath, K. S. 2006, *MNRAS*, 369, 1849
Appleton, P. N., & Struck-Marcell, C. 1996, *Fundam. Cosm. Phys.*, 16, 111
Bekki, K. 1998, *ApJ*, 499, 635
Bekki, K., Koribalski, B. S., Ryder, S. D., & Couch, W. J. 2005, *MNRAS*, 357, L21
Boquien, M., et al. 2010, *AJ*, submitted
Bot, C., et al. 2009, *ApJ*, 138, 452
Bournaud, F., & Combes, F. 2003, *A&A*, 401, 817
Bournaud, F., Combes, F., Jog, C. J., & Puerari, I. 2005, *A&A*, 438, 507
Bournaud, F., et al. 2007, *Science*, 316, 1166
Calzetti, D., et al. 2000, *ApJ*, 533, 682
Davies, J., et al. 2004, *MNRAS*, 349, 922
Duc, P.-A., & Bournaud, F. 2008, *ApJ*, 673, 787
Duc, P.-A., & Mirabel, I. F. 1998, A&A, 333, 813
Emsellem, E., et al. 2004, MNRAS, 352, 721
Giovanelli, R., et al. 2005, AJ, 130, 2598
Horellou, C., & Combes, F. 2001, Ap&SS, 276, 1141
Kennicutt, R. C. 1998, ARA&A, 36, 189
Kuntschner, H., et al. 2006, MNRAS, 369, 497
Longmore, A. J., et al. 1979, MNRAS, 188, 285
Martig, M., & Bournaud, F. 2008, MNRAS, 385, L38
Martig, M., Bournaud, F., Teyssier, R., & Dekel, A. 2009, ApJ, 707, 250
Meyer, M. J., et al. 2004, MNRAS, 350, 1195
Morganti, R., et al. 2006, MNRAS, 371, 157
Oosterloo, T. A., Morganti, R., Sadler, E. M., van der Hulst, T., & Serra, P. 2007, A&A, 465, 787
Rood, H. J., & Williams, B. A. 1985, ApJ, 288, 535
Schneider, S. 1985, ApJ, 288, L33
Schneider, S. E. 1989, ApJ, 343, 94
Schneider, S. E., Helou, G., Salpeter, E. E., & Terzian, Y. 1983, ApJ, 273, L1
Schneider, S. E., Skrutskie, M. F., Hacking, P. B., Young, J. S., & Dickman, R. L. 1989, AJ, 97, 666
Serra, P., & Oosterloo, T. A. 2010, MNRAS, 401, L29
Serra, P., et al. 2009, in Proc. Panoramic Radio Astronomy: Wide-field 1–2 GHz Research on Galaxy Evolution, ed. G. Heald & P. Serra (Groningen: POS)
Stierwalt, S., et al. 2009, AJ, 138, 338
Thilker, D. A., et al. 2009, Nature, 457, 990
Tonneelen, S., & Bryan, G. L. 2009, ApJ, 694, 789