Astron. Astrophys. 256, L19–L22 (1992)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Genesis of a dwarf galaxy from the debris of the Antennae

I. F. Mirabel[1], H. Dottori[2], and D. Lutz[3]

[1] Service d'Astrophysique, Centre d'Etudes de Saclay, F-91191 Gif-sur-Yvette, France
[2] Instituto di Física, UFRGS, Campos do Vale, C.P. 15051, 91500 Porto Alegre, R.S., Brazil
[3] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D/W-8046 Garching bei München, Germany

Received December 5, 1991; accepted January 17, 1992

Abstract. We show that a dwarf irregular galaxy has formed out of the tidal remnants that were ejected to intergalactic space during an encounter of the disk galaxies NGC 4038/39 (the Antennae). The tidal dwarf consists of a chain of nebulae ionized by recently formed massive stars, which are embedded in an envelope of HI gas and low surface brightness optical emission. Since this object is at the tip of one of the tidal tails, star formation on a scale similar to star forming galaxies is taking place at $\sim$ 100 kpc from the merging disks.

Key words: Galaxies: formation - irregular - NGC 4038/39 - HII regions: general

1. Introduction

Collisions between giant disk galaxies may eject dwarf galaxies to intergalactic space. This idea which was first proposed by Zwicky (1956), and later followed up by Schweizer (1978), has remained until these days as an anecdote. We became interested on it after a close inspection of NTT images of a sample of ultraluminous merging galaxies (Melnick and Mirabel, 1990). Patches of optically emitting material usually appear along the tidal tails that emanate from the merging disks. In the particular case of the Superantennae, Mirabel, Lutz and Maza (1991) find that the knots along the tails stretching to a total extend of 350 kpc become bluer towards the far-ends. These condensations of gas and stars are likely to become detached systems, namely, isolated dwarf galaxies or star clusters.

In this Letter we present further evidence for this phenomenon by means of CCD optical imaging and spectroscopy of the nearby prototype merger galaxy NGC 4038/39 (The Antennae = Arp 244 = VV 245). We show that the properties of a detached condensation of gas and stars at the tip of a tidal tail are consistent with those of a dwarf galaxy forming massive stars.

2. Massive star formation at the tip of the antenna

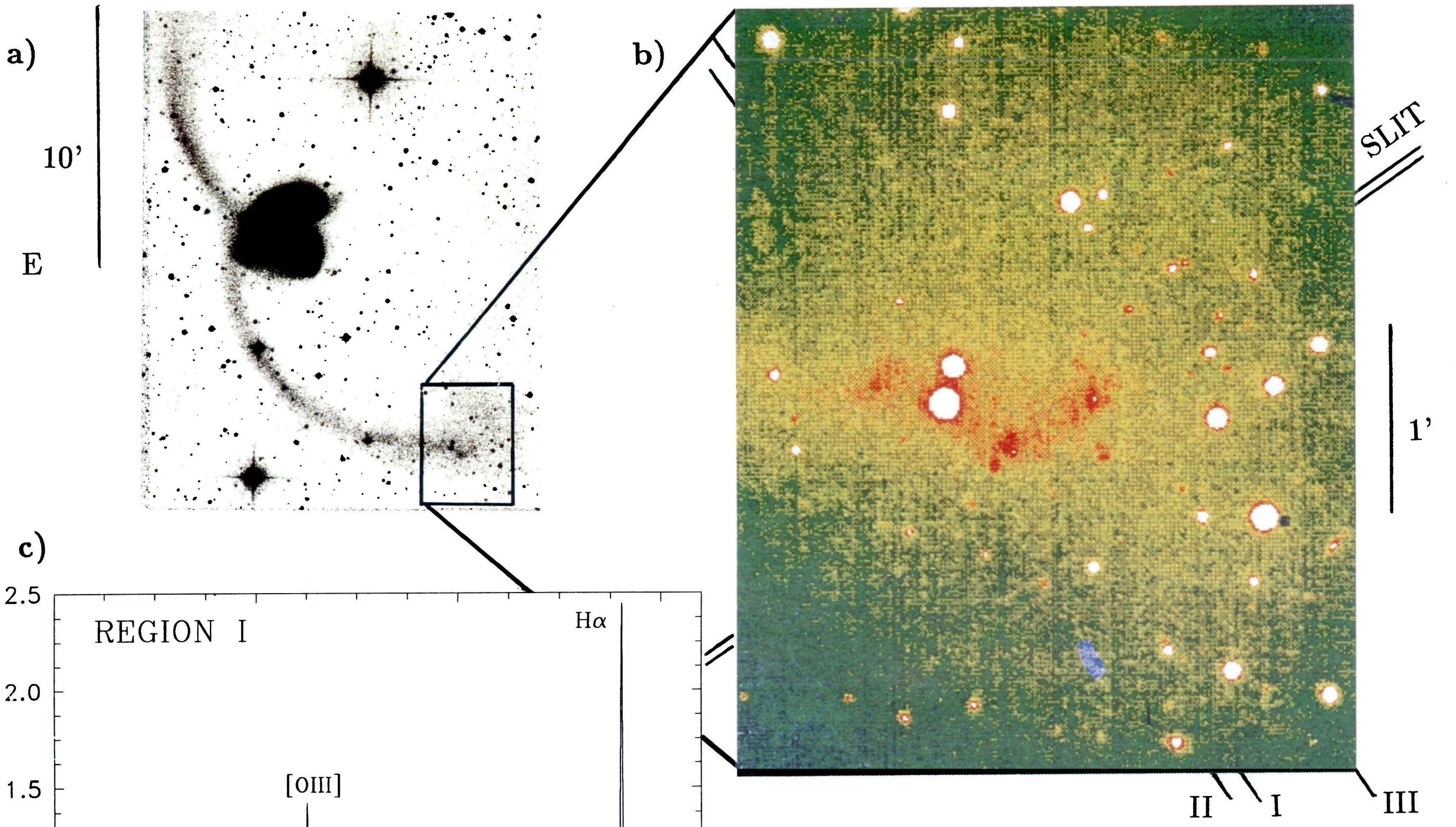
In Figure 1a is shown an optical photograph of the Antennae. For H_o = h 50 km s^{-1} Mpc^{-1} the total projected size of the tails is h^{-1} 170 kpc. The peculiar morphology of this system has been modeled by Toomre and Toomre (1972) and more recently by Barnes (1988), as a consequence of the tidal interaction between the disk galaxies NGC 4038/39. Schweizer (1978) noted that there is a region of exceptionally blue colors at the tip of the southern tail, which is at a distance of h^{-1} 100 kpc from the merging disks. In Figure 1b is shown a false color V filter image of this region obtained with EFOSC on the 3.6m ESO telescope during June 1991. In addition to the foreground field stars shown in white, there are bright fuzzy knots of luminous material that in the false color image of Figure 1b appear as red patches. These condensations delineate a twisted bar that is embedded in an envelope of diffuse optical emission. The latter widens toward the western end of the tail. After substraction of the stars in the field, four frames of 10 minutes each were added reaching an isophotal limit of 27.4 mag sec^{-2}. For this object we estimate a total integrated magnitude m_v = 17.3 mag, with an error of 0.3 mag.

To analyze the light comming from the fuzzy optical patches we have taken with EFOSC on the 3.6m telescope a four hours spectrum using a slit width of 1.5". As we discuss below, this spectrum shows that the objects of ragged appearance in figure 1b are, as was claimed by Schweizer (1978), emission line nebulae ionized by massive stars. The spectrum of one of these regions that is shown in Figure 1c is typical of a highly excited HII region.

The observational results of the spectrophotometry of the three emission-line complexes indicated in Figure 1b are presented in Table 1. We point out that the slit was oriented to contain the center of region I. Because the centers of the three complexes are not perfectly aligned along a straight line, regions II and III were not completelly introduced in the slit. This implies that the H_β equivalent widths and intensities for the last two regions that are listed in Table 1 must be considered lower limits.

The equivalent width $W_{H\beta}$ observed in region I is larger than that observed in 30 Doradus ($\sim$ 270 Å, Dottori and Bica, 1981) and comparable to that observed in IIZw40 ($\sim$ 370 Å, Baldwin, Spinrad, and Terlevich, 1981), one of the most excited extragalactic HII regions. The high equivalent width of the H_β line implies that the stellar population in this region is in a very early state of evolution. The electron temperature is $\sim$ 8000 K and the ratio of the [SII] lines is consistent with a low electron density. Using standard synthesis models of stellar populations (e.g. Cid-Fernandez et al. 1991) we find that the stars ionizing

Send offprint requests to: I.F. Mirabel



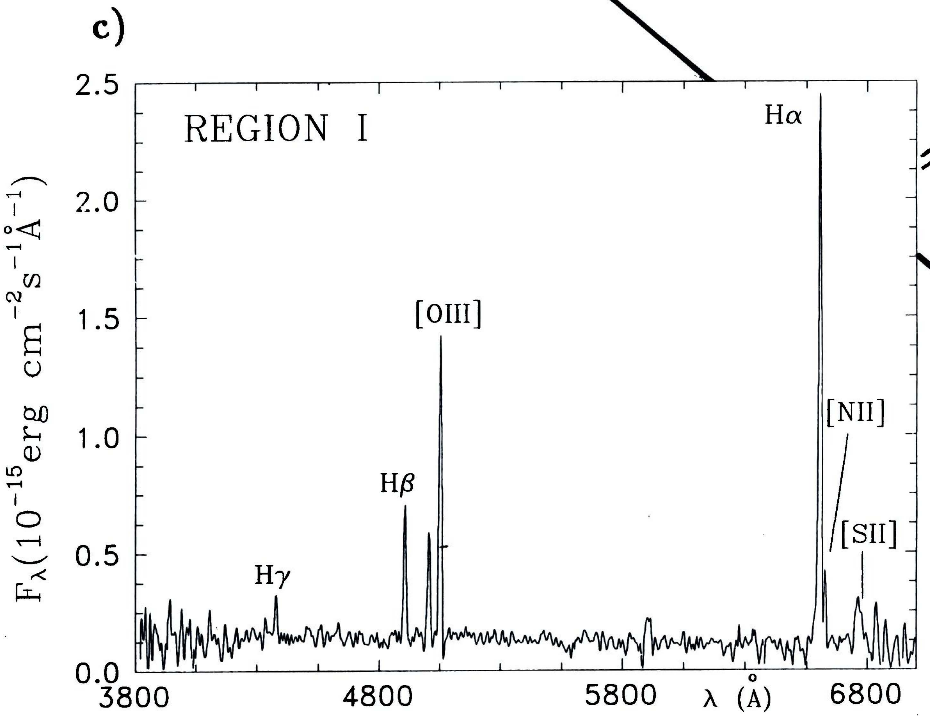


Fig. 1. a) Optical photograph of the interacting galaxies NGC 4038/39 (the Antennae) reproduced from an ESO Schmidt plate (Lautsen, Madsen, and West, 1987). b) V filter CCD image of the southern tip of the Antennae. This false color image shows a chain of HII regions (red patches) embedded in a diffuse low surface brightness envelope. The white dots are foreground stars. The position of the long slit is indicated at the edges of the color image. The HII regions I, II, and III that are listed in Table 1 are the bright fuzzy knots at the intersections of the slit with the extensions of the lines labeled "I, II, and III" at the bottom margin. c) Spectrum of the HII region I. This nebula has a luminosity ~ 300 times that of Orion and it is ionized by stars younger than 2 10^6 years.

the nebula of region I are younger than 2 x 10^6 yrs. The nebulae of regions II and III are ionized by stars younger than 6 x 10^6 yrs.

Table 1: Spectrophotometry of HII regions [a]

Region	I	II	III
$W_{H\beta}$ (Å)	417	$\geq$ 25	$\geq$ 12
$C_{H\beta}$	0.42	0.31	
Log $I_{H\beta}$(erg $s^{-1}cm^{-2}$)	- 13.68	$\geq$ - 14.5	$\geq$ - 14.77
$I_{H\alpha}/I_{H\beta}$	4.2	3.4	2.9
$h^{-2}L_{H\alpha}$(erg s^{-1})	2.92 10^{39}	$\geq$ 8.02 10^{38}	$\geq$ 1.64 10^{38}
T_e (K)	8000	6000	6000
Age (10^6 yrs)	$\leq$ 2	$\leq$ 6	$\leq$ 6

[a] H_o = h 50 km s^{-1} Mpc^{-1}

Table 2: The tidal dwarf galaxy

m_V (mag)	17.3±0.3
V_{hel} (km s^{-1})	1,660
Dist. from NGC 4038/39 (kpc)	h^{-1} 100
Diameter (kpc)	h^{-1} 15
M_V (mag)[a]	-15.3
$L_{H\alpha}$ (erg s^{-1}) of three HII regions	h^{-2} 3.9 10^{39}
12 + log [O/H]	8.4
M_{HI} ($M_\odot$)	h^{-2} 10^9
Dynamic Mass ($M_\odot$)[b]	h^{-2} 8.3 10^9

[a] Assuming h = 1
[b] Assuming σ_v = 40 km s^{-1}

3. The tidal dwarf galaxy

We now show that the integrated properties of the object at the tip of the southern antenna given in table 2 are consistent with those of a low surface brightness dwarf galaxy.

The absolute visual magnitude M_v = - 15.3 we estimate for this object is strikingly close to the mean absolute magnitude of M_v = - 15.5 mag of dwarf irregular galaxies estimated by Hunter and Gallagher (1985). The absolute magnitude is between those of the Local Group dwarf irregular galaxies IC 1613 (M_v = - 14.6, Hodge et al. 1991a) and NGC 6822 (M_v = -15.8, Hodge et al. 1991b).

It is also interesting to compare the HII region luminosity of this object with that of NGC 6822 and IC 1613. Using the H_α luminosities of these galaxies given by Hodge et al. (1991b), we find that the integrated H_α luminosity of the three HII regions at the tip of the Antennae is about the same as that of the integrated H_α flux from NGC 6822, and about one order of magnitude larger than that of IC 1613.

From atomic hydrogen observations at λ21 cm van der Hulst (1979) finds h^{-2} 10^9 $M_\odot$ of HI at the tip of the southern antenna. The HI column density at the extreme end of the southern tail increases by a factor of two and seems to have detached from the HI that is closer to the merging disks. We point out that the mass of HI is strikingly close to the mean value of 4 x 10^8 $M_\odot$ for this type of galaxies (Hunter and Gallagher, 1985). If one assumes that the mass of this object is virialized, a velocity dispersion of 40 km s^{-1} from the λ21 cm data, would imply a dynamic mass of h^{-2} 8.3 x 10^9 $M_\odot$. In this context, the HI mass would be about ~ 10% of the total mass.

The chemical composition of the three HII regions listed in Table 1 is typical of some dwarfs of low surface brightness (Kunth, 1985). In the spectra we identify the classical forbidden lines [OIII]5007+4959, [NII]6584 and [SII]6717+6732. Using the empirical method of Pagel, Edmunds and Smith (1980), who showed that in the absence of [OII] λ3727/29 the free excitation parameter [OIII]/H_β is a reliable indicator of the [O/H] abundances, we obtained an oxigen abundance 12+log[O/H] = 8.4, which is similar to that of the LMC (= 8.4) and to that of NGC 6822 (= 8.3). Since the emitting gas has come from the outer parts of the colliding galaxies NGC 4038/39, it is not surprising that the metallicity is typical of HII regions in the outskirts of galactic disks.

4. Discussion

Toomre and Toomre (1972) and more recently Barnes (1988), have shown that the gigantic streamers of the type seen in the Antennae are likely to be provoked by gravity during a direct encounter of similarly massive disk galaxies. The remarkable slender tails would have been caused during a previous encounter that took place ~ 7 x 10^8 years ago. Since the age of the stars that ionize the HII nebulae at the tip of the stream is $\leq 10^7$ years, these stars were borned well after the ejection of the material from which they have been formed.

Although the computer models of the Antennae successfully simulate the major features of this system, they do not reproduce the presence of gas condensations at the ends of the tidal tails. Numerical simulations of interacting galaxies predict density enhancements that seem to propagate along the tidal arm (e.g. Walin, 1990). In these models the condensation is produced by compression of matter to a linear feature at its position, whereas it is more sheetlike outside of it. However, Wallin (1990) finds that these purely kinematical density enhancements decrease in amplitude towards the tip of the tails. Perhaps the computer models of the Antennae do not reproduce condensations at the ends of the tidal tails because they assume equal initial space distributions for the gas and stars in the pre-encounter disks. This is not a realistic assumption since it is well known that the HI in the disks of spiral galaxies extends far beyond the stars.

At present we don't know how massive stars can be formed in the intergalactic space out of the scattered debris of galaxy-galaxy collisions. It is possible that thermal pressure from a hot intergalactic medium produces density enhancements in the stripped gas, with subsequent gravitational collapse that leads to the formation of massive stars. The increase of star formation activity at the end of the tail may hence be due to the high gas content of the material coming from the outskirts of the pre-encounter disks, and to the trigger given by the density enhancement discussed above.

5. Conclusion

The observations reported here on NGC 4038/39 show that not all dwarf galaxies and halo star clusters are delayed condensations from isolated primordial gas clouds left-over from the formation of luminous galaxies. In fact, some fraction of dwarf galaxies and star clusters may be formed out of the debris of galaxy-galaxy collisions. The discussion of the statistical importance of tidaly formed objects and the astrophysical implications of this phenomenon are beyond the scope of this letter and must wait to the results from extended observational programs.

Acknowledgements. We thank Laurent Vigroux, Miguel Mas-Hesse, Pierre-Alain Duc, and James Lequeux for discussions. We also are grateful to Jorge Melnick and Daniel Golombek for their assistance with technical aspects of this work, and to Dietrich Baade for the the photographic copy of NGC 4038/39.

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