"Something strange is going on."

M.S. Roberts in Discussion V.2

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GALAXIES WITH LONG TAILS

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Today I would like to show you some animals from the zoo of Alar Toomre. These animals are all characterized by long tails and belong to two subspecies: The first consists of animals which always huddle in pairs, each individual having one long tail. The second, rarer subspecies comprises those strange animals which live alone but have two tails!

1. THE ANTENNAE GALAXIES

A prime example of a pair of the first subspecies are the well-known Antennae, NGC 4038/9. Their tails are long indeed, with an overall projected size (from tip to tip) of 160 kpc (20') at the redshift distance corresponding to $H_o = 50$ km s^{-1} Mpc^{-1}. The projected separation of the two main bodies is about 9 kpc and the absolute magnitude of each galaxy $M_V = -21$. The Toomres (1972, TT) proposed, through their tidal-interaction model for these galaxies, that during a close encounter some $7x10^8$ yr ago material from the outer fringes of the disks was ejected into the present-day tails. The narrow width of these tails is most remarkable. On Figure 1a the southern tail appears only 4-5 kpc wide, or about 1/20th of its length. The TT model reproduces this narrow width only by assuming a zero velocity dispersion for the test particles orbiting in the initial galactic disks. A reasonable velocity dispersion of, say, 10-20 km s^{-1} would broaden the tails substantially. A very deep photograph obtained with the CTIO 4-m telescope (Fig. 1b) does indeed show the tails to be about three times wider than previously seen; the projected width of the southern tail now appears to be ~15 kpc. By dividing half that width by the above interaction age, I estimate a velocity dispersion of 10-15 km s^{-1} for stars now at the edge of the tail, depending on the projection factor.

An especially interesting feature is the patch of luminous material near the tip of the southern tail. This patch appears to be a stellar system of very low surface brightness ($V \gtrsim 25$ mag $arcsec^{-2}$), similar to

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the dwarf irregular galaxy IC 1613 in the Local Group, but about twice as large (11x19 kpc). The integrated absolute magnitude is $M_V \approx -16.5$. There is good evidence (see below) that this dwarf system is physically associated with the southern tail.

What is the stellar and gaseous content of the tails? Photoelectrically measured UBV colors of five selected areas in the tails indicate stellar populations similar to those typically found in late-type spiral galaxies. If the stellar populations were coeval, the measured U-V indices would indicate ages of $1\text{-}3\times10^9$ yr, if one uses the cluster models by Searle et al. (1973). Since these ages are of the order of two to four times the interaction age, we conclude that the tail populations probably consist mainly of stars pulled out of the main bodies with only a sprinkle of stars possibly formed more recently out of the gas. One notable exception is an area measured towards the tip of the southern tail; its color is significantly bluer than the others, bluer in fact than the color of an average irregular galaxy. The associated age of 3×10^8 yr for a coeval population indicates that at the tip of the tail significant numbers of stars must have formed recently, *after* the closest approach of the two galaxies. This conclusion is supported by the

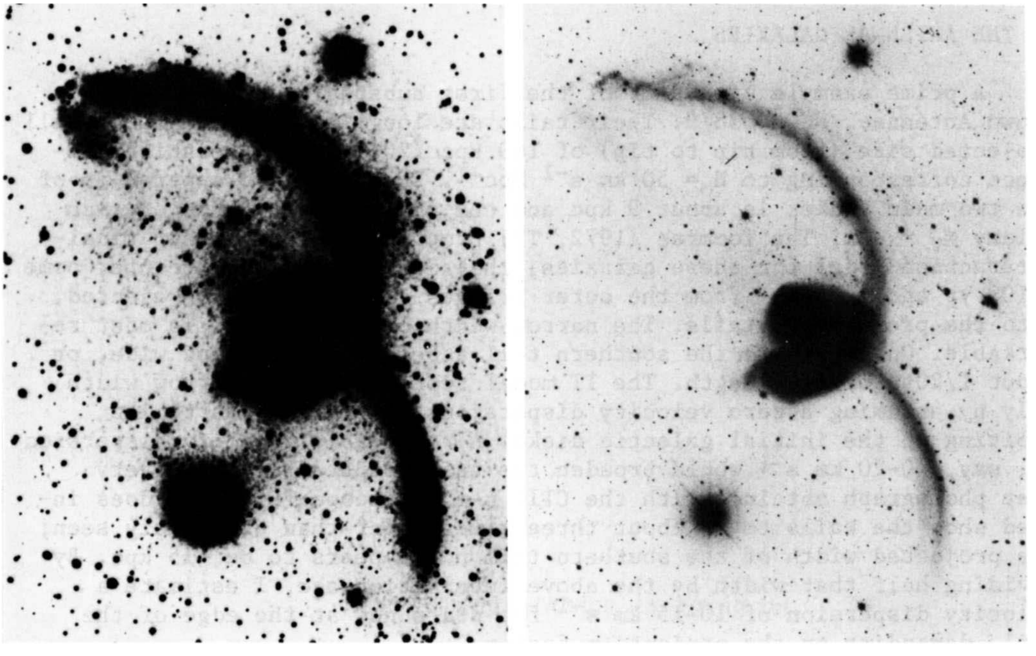

Figure 1. NGC 4038/9 on IIIa-J plates obtained with the CTIO 4-m telescope. North is at the top and east is at the left. (a) (left) Exposure of 50 minutes. (b) (right) Superposition print of two plates totalling 3.5 hours of exposure time. Note the dwarf stellar system near the tip of the southern tail.

appearance of the tails on the best CTIO 4-m plates and by spectroscopic observations. Whereas the whole northern tail and most of the southern tail appear smooth and unresolved even under 0".8 seeing, implying the absence of objects brighter than $M_B \approx -8.5$, the tip of the southern tail is resolved into bright stars (clusters?) and fuzzy knots. These knots are clearly H II regions, as shown by their emission-line spectra (Hα, [N II], [S II], and [O II] λ3727 lines on my spectrograms). The Hα fluxes are of the order of 100 times the Hα flux of the entire Orion nebula, and the line ratios indicate an excitation similar to that of, e. g., H II regions at intermediate radii in M 101. The remarkable fact which I wish to emphasize here is that *at about 100 kpc projected distance from the main bodies of NGC 4038/9, stars are still actively being formed as a consequence of some tidal interaction which took place 7x10^8 yr ago!* Furthermore, the gas out of which these stars are forming is not as metal-poor as one might expect from its remote location, but rather seems of a metallicity found typically at the outskirts of a giant disk galaxy. This, of course, fits in nicely with the tidal-interaction model for the Antennae.

The radial velocities of the four H II regions intersected by the spectrograph slit (1690, 1708, 1710, and 1711 km s^{-1}) agree closely with the 1710 km s^{-1} velocity of the H I gas observed by van der Hulst (this meeting). However, note that the H II regions are clearly located within the tip of the tail, whereas the H I gas seems to be more concentrated in that dwarf stellar system near the tip of the tail. The dwarf is therefore likely to be physically associated with the tail. Although nothing is known as yet about its stability, we should envisage the possibility that *tidal interactions may create dwarf galaxies* and that *these dwarfs may contain more metals than we would expect* if we somehow think of primordial material out there. This possible mechanism for the formation of dwarfs was emphasized already long ago by Zwicky (1956).

2. INTERGALACTIC RECYCLING

Large and even giant H II regions at the ends of tidal tails are a rather general phenomenon in interacting galaxies, providing direct evidence that (metal-enriched) gas is being returned to intergalactic space. To quote just a few examples: In NGC 4676 (the "Mice"), the northern tail consists of a young stellar population with a Balmer absorption-line spectrum, and H II regions occur out to 58 kpc (90") projected distance (Stockton 1974). The tidal model (TT) shows that most of this tail material will escape from the system. In NGC 2623 (= Arp 243), I have found, on spectra obtained with the Hale telescope, H II regions out to halfway along the northern tail (30", or only 16 kpc in that dwarfish system). In NGC 6621/2 (= Arp 81), several giant H II regions sit right at the tip of the tail, at 21 kpc (33") projected distance from the main galaxy, or 79 kpc (125") if one measures the projected distance along the tail. In NGC 3256, a southern system consisting of two partially merged galaxies, a complex of H II regions occurs at 39 kpc (154") projected distance along the eastern tail. Finally, in

NGC 2535/6 (= Arp 82), I have found H II regions at 58 kpc (147") projected distance from the main spiral, near the tip of the long tail to the Northwest. These examples show that we can expect to find in increasing numbers young stars of all degrees of metallicity in intergalactic space. These stars may well appear isolated, since the tidal filaments are often significantly fainter than the H II regions at their tips and are bound to dissipate into invisibility on a time-scale of $\sim 10^9$ yr. Why young stars should form preferentially at the ends of tidal tails is not clear at present, but perhaps this is due to a concentration of H I gas there, as observed in the Antennae by van der Hulst. The concentration of gas, in turn, might be explained by its exterior location in the pre-encounter galactic disks, since it is clear from the TT models that exterior particles fly farthest in any given time interval.

3. ON MERGING AND MERGED PAIRS OF GALAXIES

In 1972, the Toomres proposed a sequence of increasingly merged pairs of galaxies (see also Toomre 1977). This incited me to study observationally whether I could find an object in the last throws of merging, or perhaps even one which would recently have completed the merging process. As a start, I surveyed the Toomre sequence and some additional objects with near-infrared plates to see whether one or two nuclei were present. The technique is quite powerful, as illustrated in the case of NGC 4038/9. A near-infrared plate ($\lambda\lambda$ 7000-9000 Å) shows distinctly the two nuclei at 9 kpc projected separation, whereas plates obtained in the usual bandpasses show two messy bodies full of young stars and emission-line regions. This survey of "mergers" produced two results: (1) Either there were two well-separated nuclei (projected separations of 5-10 kpc and more), or there was only one nucleus to the resolution limit set by the seeing (corresponding to 0.25-1 kpc at the distances of the galaxies). This finding is compatible with the theoretical notion that the merging process should be rapid in its final stages. (2) There were five galaxies with single nuclei, but for a variety of reasons only two of these seemed good candidates for recent mergers: NGC 3921 and NGC 7252.

At this point, we should ask ourselves: What are the characteristics to be expected of a recently merged pair of galaxies? I can think of five characteristics to look for: (1) A pair of long tidal tails is the safest indicator of two participants. (Here "tidal" means that an explosive origin can be excluded.) (2) The candidate merger should be isolated to exclude the possibility of tidal damage from neighbors. (3) One might expect to see a single nucleus. (4) Relative to this nucleus, the two tails should move in opposite directions, since, after all, tides are symmetrical. (5) Motions in the main body might still be rather chaotic, if the merging took place recently.

NGC 3921 (= Arp 224), although located in a small group of galaxies, shows at least three of these characteristics: It has two massive tails, a single nucleus (with an unusually strong Balmer absorption-line spectrum indicative of young stars), and a chaotic body, whose internal motions I am still studying.

NGC 7252 shows just about all of the above characteristics to a striking degree (Fig. 2a). The galaxy has a beautiful pair of tails, each of which appears to be smoothly connected to one of a set of loops. (My wife says the object reminds her of a crumpled spider!) The loops probably consist mainly of stars, since I have been unable to pick up any emission lines (with one exception) with the powerful spectrograph of the CTIO 4-m telescope. The connection of stellar tails to stellar loops strongly implies that the tails are tidal. Explosive ejection of a large stellar aggregate seems difficult enough, but explosive ejection "around the corner" and into different orbital planes seems virtually impossible. Luckily, NGC 7252 is highly isolated. The first major galaxy of similar redshift lies at a projected distance of 2.5 Mpc away, whereas several nearby faint galaxies all turn out to be distant background objects. Quite apart from the fact that two long tails normally point to two interacting bodies of about equal mass (TT) rather than to one galaxy tidally damaged by another, there simply is no such other galaxy around! There is also only one nucleus, as sequences of exposures of decreasing length show. The resolution limit in 1" seeing corresponds to about 500 pc at the galaxy. Figure 2b shows that the tails move in opposite directions relative to the nucleus, as expected under the tidal hypothesis. In this galaxy as well as in the others mentioned earlier, tail velocities relative to the nucleus are of the order of 100 km s^{-1}. These low velocities, too, imply a tidal origin of the tails rather than an explosive origin. Note that the tail velocities of NGC 7252 could not have been determined if it weren't again for the presence of giant H II regions at the tip of each tail, at projected distances of 118 kpc and 70 kpc from the nucleus. By dividing these distances by the relative velocities (on the assumption that the transverse velocities

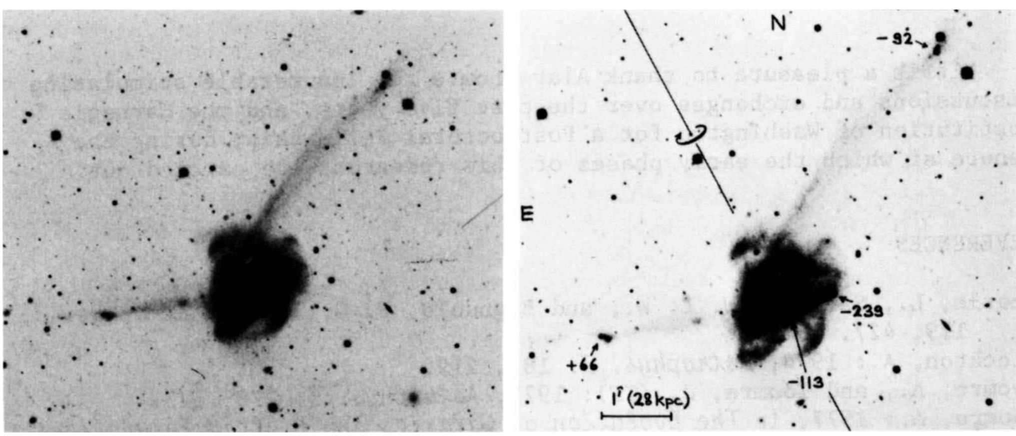

Figure 2. NGC 7252, a recent merger. (a) (left) IIIa-J plate obtained with the CTIO 4-m telescope. (b) (right) Rotation axis of inner gas disk, and tail and loop velocities (in km s^{-1}) relative to the nucleus.

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are of the same order as the radial velocities), we estimate an interaction age of 1×10^9 yr. Finally, the spectroscopic data indicate that the motions in the main body are chaotic indeed. The nucleus appears to be surrounded by a disk of gas, which rotates with $v \sin i \approx 100$ km s^{-1} around the axis shown in Figure 2b. Between this inner disk of about 4 kpc radius and the outer loops, the sense of rotation of the gas seems to reverse, if rotation is a proper description at all! However, farther out, in the one loop in which H II regions were detected (see Fig. 2b), the sense of motion has reversed again compared to the intermediate region and the material moves in the same sense as the inner disk.

In summary, NGC 7252 shows several characteristics which one would expect of a merger: a pair of tidal tails despite the splendid isolation, a single nucleus, tail motions in opposite directions relative to the nucleus, and chaotic motions in a strangely looped main body. This main body plus loops, by the way, has gigantic dimensions (~55 kpc) and a $M_V = -22.8$, which is about 1 mag brighter than an average Sc I galaxy. Certainly, this high luminosity is compatible with the idea that this heap of stars contains two former galaxies.

Finally, let me be so rash as to ask three provocative questions. Suppose that this IAU meeting were held not in Bad Münstereifel, but instead in NGC 7252 at some 10 kpc distance from the nucleus. Suppose also that we had studied the nearby galaxies in much the same way as we have discussed at this meeting. *Question 1:* What Hubble type would we give the galaxy we would live in? S0, as NGC 7252 has been classified, or E, Sa, Sb, or Sc? *Question 2:* What would our views be on galaxy evolution in general and, in particular, on chemical stratification as a consequence of that evolution? *Question 3:* How would we interpret the complicated velocity field in our galaxy? Especially, would considerations about the energetics coupled with observations of external, active galaxies lead us to believe that there was an explosion in the nucleus?

It is a pleasure to thank Alar Toomre for innumerable stimulating discussions and exchanges over the past five years, and the Carnegie Institution of Washington for a Postdoctoral Fellowship, during the tenure of which the early phases of this research were carried out.

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DISCUSSION FOLLOWING PAPER V.4 GIVEN BY F. SCHWEIZER

FREEMAN: The ages inferred from the Searle et al. colors are probably somewhat large; the stellar populations in the tails of the Antennae might have ages comparable to the interaction age.

The dwarf galaxy at the end of NGC 4038/9 tail would probably have a mass $\gtrsim 10^8$ $M_\odot$. Does that seem reasonable if this dwarf comes from the tidally produced tail?

TOOMRE: 10^8 $M_\odot$ is only about one thousandth of the total mass; that doesn't seem unreasonable.

SHU: Does your determination of a velocity dispersion of $\sim$ 15 km/s in the "disk" stars of the tail in the Antennae mean that this is a first encounter for the system?

TOOMRE: Presumably the motions slowed down since the previous encounter.

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