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# Status of shell galaxies

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# Introduction

“Shells” or “ripples” around galaxies have been known for a few decades. A set of peculiar galaxies classified as “shell galaxies” appeared in Arp’s catalogue (Arp, 1966). But only recently has special attention has been drawn to them. The improvement of photographic emulsions, and the application of new photographic techniques such as “unsharp masking” and “contrast enhancement” by Malin (1977, 1981) has led to the discovery of shells and other peculiar features in a substantial fraction of early-type galaxies. The publication of Malin and Carter’s (1983) catalogue of 137 shell galaxies found in the SRC/ESO Southern Sky Survey clearly established the importance of this phenomenon and showed that about 10% of ellipticals are surrounded by shells. They define this class of objects as: “*These galaxies appear at first sight to be normal ellipticals, but closer inspection reveals one or more edged-brightened structures*”.

The first photometric observations (Carter *et al.*, 1982) with IPCS and photomultipliers showed that the shells were made of stars.

Shells are faint structures and are difficult to detect since they are superimposed upon the bright background of the galaxy. The luminosity contrast of the shells is very small, and sometimes comparable to the deviations of the isophotes to perfect ellipses. Processing the images (e.g., Fig 1) is generally necessary to detect the shells: for example with unsharp masking, developed by Malin (1981) to process photographically large plates, or with gradient maps (Wilkinson *et al.*, 1987a).

I will briefly present here the main results which have been published in the last four or five years. I will also refer to the statistical study of Malin and Carter’s catalogue which I have been doing in collaboration with A. Wilkinson, D. Carter, W. Sparks, and D. Malin (referenced as Prieur, 1988b, and Wilkinson *et al.*, 1989a).

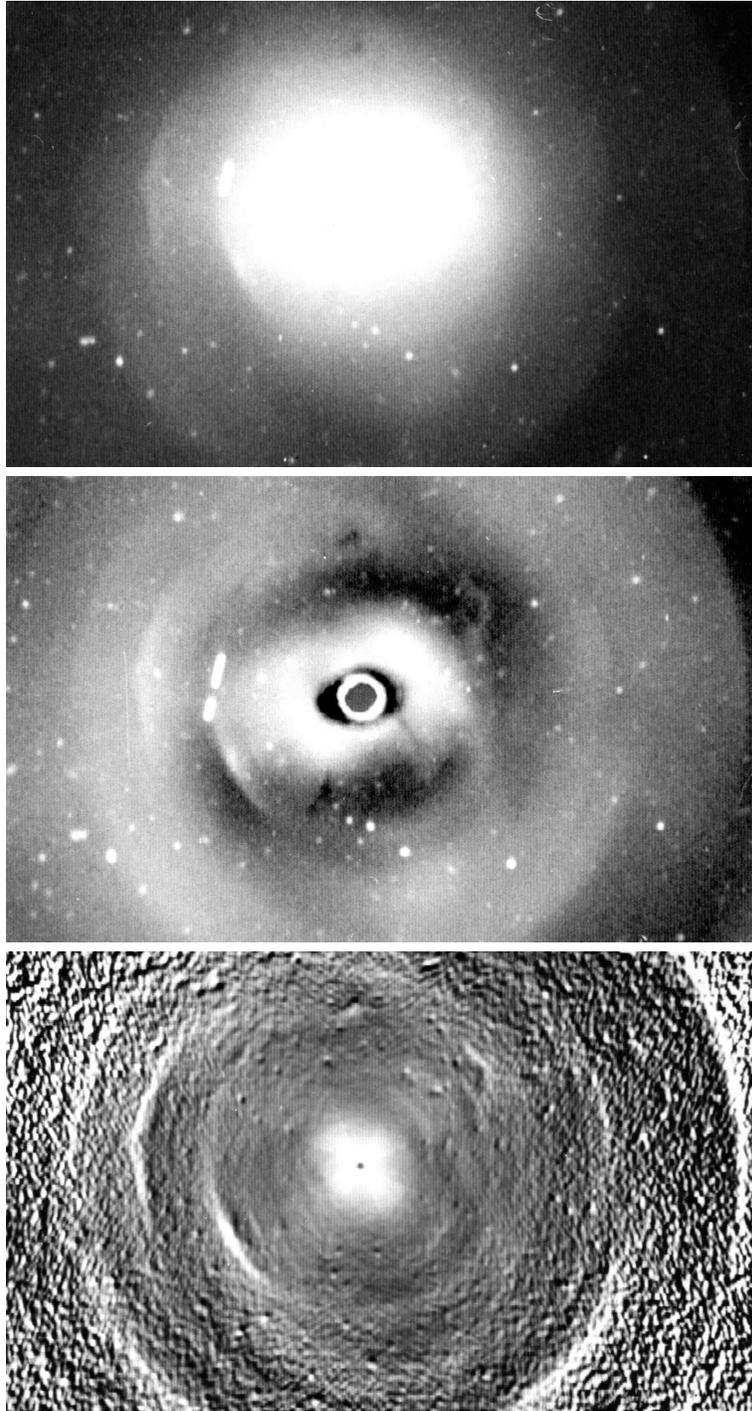


Figure 1: CCD picture of NGC 474 in R, taken at the prime focus of CFHT (from Prieur, 1988b). Top, image non processed; middle, a model of the galaxy has been removed; bottom, gradient map. North is on the left, East on the bottom. The bright trail on the left is probably due to an asteroid. The field is about  $2' \times 3'$ .

# Chapter I

## Models

The models which have been proposed to account for the properties of the shells since the beginning of the 1980's can be sorted into two classes according to the origin of the stars forming the shells: internal (formation *in situ*) or external (accretion of stars from a companion galaxy).

### I.1 Internal models

Following Fabian *et al.* (1980), Williams and Christiansen (1985) proposed that shell stars have formed within a giant shell of intra-galactic gas compressed with a shock wave, and have been orbiting in phase since. A few authors have published different versions of this model: Bertschinger (1985), Umenura and Ikeuchi (1987), and Lowenstein *et al.* (1987).

All these models try to explain a rather odd geometry for this star formation, which has to be quick and massive. Then this scenario must cease to be effective rather soon after the galaxy formation, to account for the old population of stars which is observed. But the sharpness of these structures, which should last over a Hubble time (hundreds or thousands of orbits) may be a real problem. No study has been done about this, but I doubt that a family of stars formed a Hubble time ago with *approximately* the same initial conditions will remain orbiting in phase with the accuracy needed to make the edges of the shells very sharp, sometimes not even resolved (cf section III.3).

I may also mention a peculiar model by Kundt and Krause (1985) where the shells would be filaments of plasma... I think that the spectroscopy alone is sufficient to discard this hypothesis (cf section IV.1).

## I.2 Merging models

The idea that shells would result from a merger was first proposed by Schweizer (1980) and based on the observation of NGC 1316. Following this, Quinn (1984) proposed a model based on wrapping the location of the companion stars in phase space and numerical simulations. When a small disk merges with a big elliptical in a radial orbit, the companion stars form density waves with sharp edges, at a location close to their apocenter. Dupraz and Combes (1986) showed that small ellipticals could also form shells, and studied the effects of non spherical potentials. Hernquist and Quinn (1988, 1989) presented a comprehensive set of simulations to explore the space of parameters. They showed that both wrapping in phase and real space can be involved in shell formation, and that mass transfer during interactions can also generate shells.

Recently Nulsen (1989) studied analytically the process of shell formation in 3 dimensions with phase wrapping (“shear shells”). According to him, the shape of shear shells materializes the invariant surfaces (orbits) in an integrable potential, and can be used to describe the potential of the galaxy.

Nevertheless there is a point which deserves some discussion. He claims that shear shells cannot be visible in a spherical potential, and that Hernquist and Quinn’s (1988) simulations introduced an additional constraint for the initial conditions (no dispersion in the module of the velocity for the stars at a given radius) which made them *artificially* visible. This is very serious since this remark would invalidate the results of their paper, often quoted in the literature. I have done some simulations to check this and not found significant differences when adding dispersion in the velocity module. Nulsen (1989) also says that no shells should be visible in Keplerian potential when the stars have non radial orbits. The tests I have done seem also to contradict this. So I think that Hernquist and Quinn (1988)’s results are valid, and that something is missing in Nulsen’s analytical modelling.

Numerical simulations have shown that collisions of galaxies produce very easily transient sharp-edged structures similar to the shells observed around early-type galaxies. Real space wrapping gives birth to short time lived shells with complex structures whereas phase wrapping shells produce simpler structures which can last for a few free fall times. The companion can be a spiral or a spheroid, and its mass can range from a few hundredths to a few tenths of that of the galaxy. New N-body simulations of collisions of galaxies of comparable size have also produced shells (Barnes, 1989, Salmon *et al.*, 1989), but they tend to be less “organized” than the shells created with smaller companions.

# Chapter II

## Morphology

To quantify things it is convenient to fit arcs of ellipses to the shells, since they are generally very close to being arcs of ellipses. (Prieur, 1988a, 1988b, Wilkinson *et al.*, 1989a). When the angular extension is large enough, ellipses with a free center can be fitted to these arcs, and in most cases the centre of the ellipses can be taken equal to the centre of the galaxy, within the error bars. We have not observed cases where the convexity is orientated towards the center of the galaxy as in some simulations generated by spatial wrapping (cf. fig 2 of Hernquist and Quinn, 1988). This does not mean that spatial wrapping should be excluded, and for instance the “spiral-like” structure very close to the center of 0422-476 (Wilkinson *et al.*, 1989b) suggests that spatial wrapping takes place there.

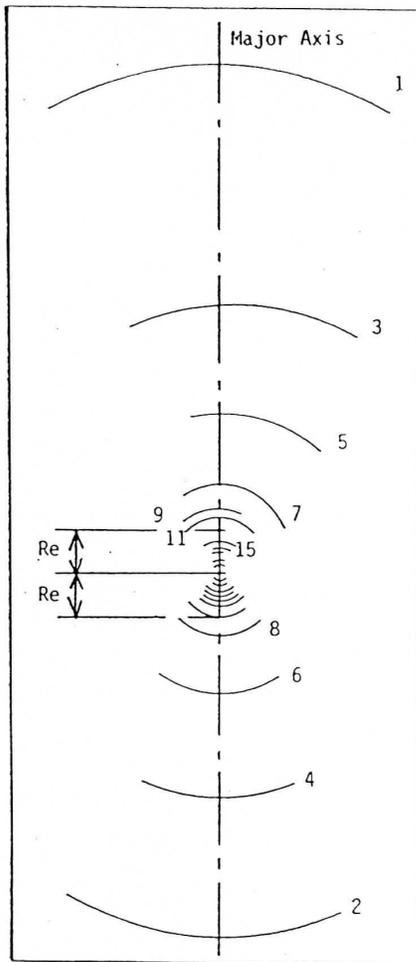
It should also be noted that for all the systems we know, when shells are well aligned along a certain axis, this axis is always very close to the major axis of the galaxy (Wilkinson *et al.*, 1989a). This is probably due to the constraints on the orbits of the stars in a non-spherical potential (box orbits).

### II.1 Classification in 3 types

Shell systems can be classified in three types according to their morphology (Prieur, 1988b, Wilkinson *et al.*, 1989a): type 1 are constituted by the aligned systems (ex: NGC 3923), type 2 by the systems where the position angles of the shells are randomly distributed around the galaxy (“all-round” systems, ex: 0422-476) (see Fig. II.1, and type 3 class by all the remaining objects which cannot be classified as type 1 or type 2, either because the small number of shells does not allow their classification, or because shells do not appear in their “usual way”, as sharp-edged concentric structures (ex: 0201-196).

It appears that these 3 types are observed in equal proportions in Malin and Carter’s catalogue (Prieur, 1988b, Wilkinson *et al.*, 1989a).

SHELLS OF NGC 3923



0422-476

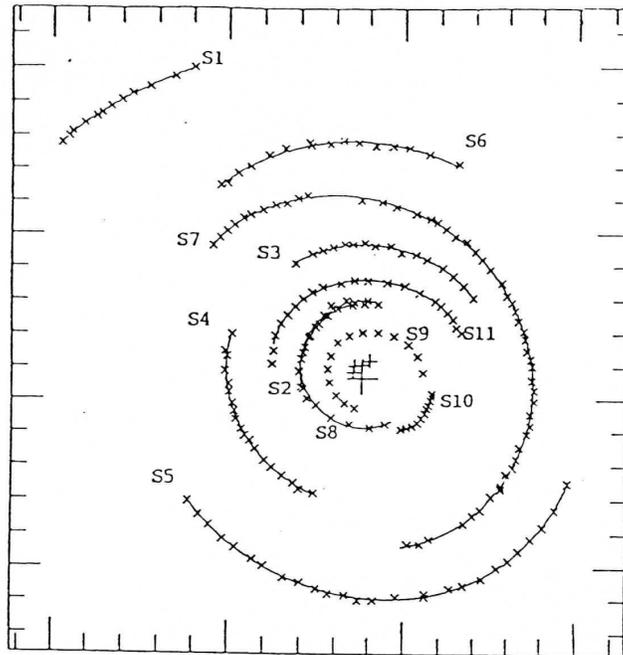


Figure II.1: Example of an aligned system (type 1), NGC 3923 on the left, and of an "all-round" system (type 2), 0422-476 on the right (from Prieur, 1988b).

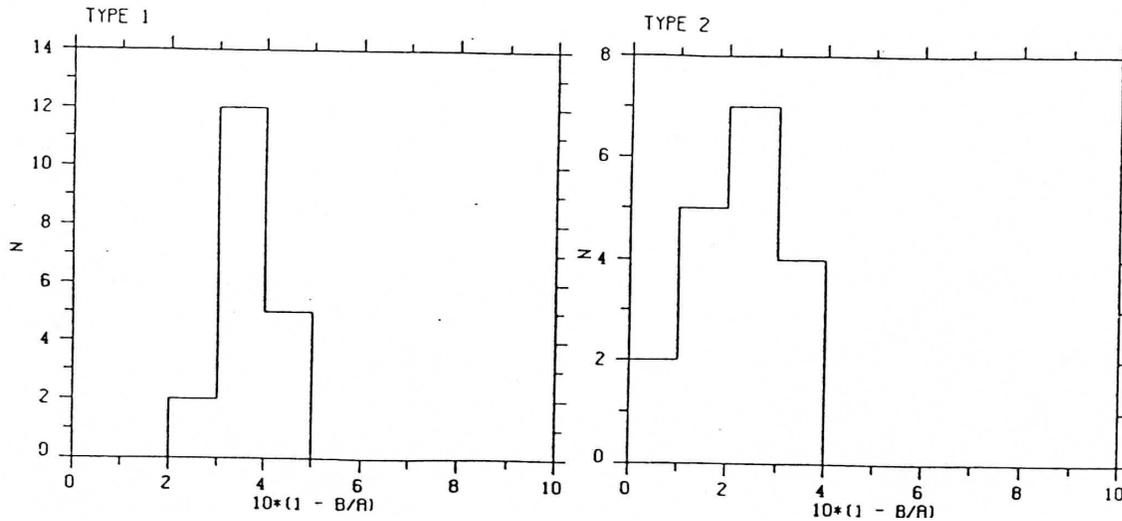


Figure II.2: Histogram of the shell galaxies versus the apparent ellipticity of the galaxy: type 1 systems on the left, type 2 on the right (from Prieur, 1988b).

## II.2 Correlation type-ellipticity

A correlation has been found between the morphological types previously defined and the apparent ellipticity of the galaxy (Prieur, 1988b). Elongated galaxies are preferentially surrounded by aligned systems of shells (type 1), and round-like galaxies by type 2 shell systems (see Fig II.2). There is no specific trend for type 3 systems.

One could think that this is only a projection effect. Type 1 systems would appear as type 2 system when seen face on, and/or inversely for type 2 systems when seen edge on. Numerical simulations have shown that aligned systems could not appear like type 2 systems, even seen face-on (Dupraz and Combes, 1986, Hernquist and Quinn, 1989). But the question is still open to know whether “all-round” systems can look like aligned systems when seen edge-on. Hernquist and Quinn (1989) say it is possible, but Dupraz and Combes (1986) disagree.

This correlation could also be real and intrinsic to the systems in 3 dimensions, as expected by Dupraz and Combes (1986). According to them aligned systems can only form in prolate potentials and “all-round” systems in prolate potentials. This is due to a “focusing” effect of the potential on the shell geometry.

Dupraz and Combes (1986) used an elliptical potential with a constant ellipticity for the equipotentials, which could be a too crude approximation. They have changed this since, and allowed the ellipticity to become spherical at large radii, but they found the same results (Dupraz, private communication). For them the geometry in the central parts, where the deflection occurs (nearly radial orbits), is essential, and the outer parts play a negligible role.

Table II.1: Total luminosity of the shell systems as a fraction of the luminosity of the galaxy (col. 2 and 3) (references: \*Fort *et al.*, 1986, †Pence, 1986, ‡Schombert and Wallin, 1987, •Prieur, 1988a, ◊Wilkinson *et al.* 1989b), total number of shells (col. 4), distance of the closest shell as a fraction of  $r_e$  (col. 5), morphological type as defined in sect. II.1 (col. 6), and colours of the shells compared to that of the galaxy (col. 7).

Name (1)	Total lum. (%) (2)	Total lum. (%) (3)	$N_{shells}$ (4)	$d_{min} (r_e)$ (5)	Type (6)	Shell colours (7)
NGC 474	6–7 <sup>‡</sup>	$> 3.3 \pm 1$ $\approx 6-8^\circ$	13	—	2	bluer, same col.
0140-658	—	$> 3. \pm 1$ $\approx 3-4^\circ$	6	2.7	2	same col.
NGC 1210	—	$> 1.2 \pm 0.5$ $\approx 1.5-2.^\circ$	11	0.7	2	bluer, same col.
0422-476	—	$> 3. \pm 0.5$ $\approx 3.-4.^\circ$	10	1.8	2	big scatter
NGC 2865	11–22*	—	7	—	2	bluer
NGC 3051	5 <sup>†</sup>	—	$> 5$	—	1?	same col.
NGC 3923	3–8*	$> 3. \pm 1$	22	0.2	1	same col.
NGC 5018	$> 0.5^\dagger$ 9–18*	$\approx 5 \pm 1.5^\bullet$ —	10	—	2	bluer

Hernquist and Quinn (1989) disagree with this view. They admit that there is a focusing effect in prolate potentials, but that this effect disappears when the potential becomes spherical at large radii, which is a more realistic case, and argue that other parameters of the collision play also an important role. They generate aligned systems in oblate potentials (cf. their fig. 5), and “all-round” systems in prolate potentials (cf. their fig. 4). This would preclude the correlation that we see.

The model 3 of Hernquist and Quinn (1989) with a potential elliptical even at large radius, shows a very efficient “locking” of the shells along the major axis, very similar to the simulations of Dupraz and Combes. The correlation we observe may be an indication that the potential remains elliptical, even at large radii and therefore that there would be dark matter around these objects, and that the dark haloes would have the same shape as the luminous components...

Another reason for this correlation could be that the mass of the companion was not negligible, and that the potential of the host galaxy has been seriously modified during the merging. Radial encounters would have “stretched” the host galaxy along the direction of impact as shown by recent N-body simulations (Salmon *et al.*, 1989). As encounters with a small impact parameter are more favourable for shell formation, this effect could explain why galaxies with small ellipticity are much less numerous in our histograms (Fig II.2), than what is expected for early-type galaxies (cf. Sandage *et al.*, 1970, de Vaucouleurs and Binney, 1981).

### II.3 Radial distribution of the shells

With Quinn’s (1984) assumptions of a quick and total disruption of a small companion and no significant loss of energy for the stars after this event, the radial distribution of the shells depends only on the potential of the host galaxy, and can be computed in a simple way. A series of papers have been published about the interpretation of the shell distribution of NGC 3923, NGC 3051, and NGC 1344: Quinn (1984), Dupraz *et al.* (1987), and Hernquist and Quinn (1987a, 1987b). It was found that the shell distribution of NGC 3923 (the best studied system) could not be fitted with a potential corresponding to the luminosity profile. A few attempts (Dupraz *et al.* 1987, Hernquist and Quinn, 1987b) have been done, without success, to explain this distribution by alternatives to Newton’s laws: MODified Newtonian Dynamics (MOND, Milgrom, 1983), Finite Length-scale Anti-Gravity (FLAG, Sanders, 1984), and REM (REvised MOND, Sanders, 1986). It appeared that dark matter provided a good alternative and with slightly different values for the number of shells and the radii, different authors obtained a good fit for NGC 3923 when adding a dark halo, less concentrated than the luminous component, and a mass ratio of about 40 for the dark/luminous components (Quinn, 1984, Hernquist and Quinn, 1987a, Prieur, 1988b). But even in the best fits with dark matter, the inner shells are discrepant by being too close to the center.

In the last few years, it has been established that shells can be found frequently very close to the nucleus (see Table II.1, Wilkinson *et al.* 1987a, and Prieur 1988a, 1988b) at only a few kpcs, which implies that a dissipative process has played a role in the formation of shells.

Dupraz and Combes (1987) presented an analytical model where the companion has a high central density and is disrupted very slowly. Only the outer stars of the companion are lost in the first passage through the central regions of the galaxy, and the remaining core loses slowly its stars while orbiting in the potential of the galaxy, and being slowed down by dynamical friction. They showed that the radial distribution of shells around NGC 3923 could be explained without adding a dark halo. The disruption of the companion was unfortunately very simplified to be treated analytically.

In a recent paper, Heisler and White (1990) emphasize the importance of treating correctly the self-gravity of the companion in the collision. As already shown by Dupraz (1984), self-gravity increases the range of orbits used by the companion stars. Heisler and White find that the maximum range in radius they can obtain with reasonable collision parameters is about 10, without dynamical friction. The observations have shown that this range can be higher for some systems (0351-550, 0422-476, 1252-266, NGC 1344, and NGC 3923 for instance), and dynamical friction would have to be invoked for these objects.

Full N-body simulations should provide a definitive answer to the problem of shell distribution by answering the fundamental question: *“how is the companion disrupted and what is the role of dynamical friction?”*

Salmon *et al.* (1990) have recently done such a simulation involving 160 000 stars. The companion survived for a few oscillations and generated multiple systems of shells (one at each passage in the dense regions of the galaxy). The final range in radii was about 60, which is what we observe for NGC 3923. This shows clearly that we are not far from being able to model shell systems such as NGC 3923, in a very simple way.

One of the direct implications of the scenario involving a slow disruption of the companion (i.e. its central density is larger or comparable to that of the galaxy) is that we should observe multiple nuclei. There is already one example (4C 29.30, van Breugel *et al.*, 1986), but no real investigation to study this point has been done so far. We have not found clear evidence for multiple nuclei in the objects of Malin and Carter’s catalogue we have studied up to now (Wilkinson *et al.*, 1989a).

I have fitted theoretical radial distribution of shells based on Quinn’s (1984) model to 8 aligned systems, and found that it worked well for 6 systems without adding dark matter (Prieur, 1988b). A dark halo was needed only for NGC 3923 and 0351-550, which happened to be the shell systems with the lowest radii of the innermost shell (Prieur, 1988b). This may be an indication that the radial distribution is curved by the dynamical friction and not by dark haloes. This would not imply that dark matter is not present, but simply that it is not required explicitly, as thought before.

# Chapter III

## Photometry

### III.1 Integrated luminosity

A lower limit of the total luminosity of the infalling companion can be obtained by integrating the luminosity of the shell system (see Table II.1). According to numerical simulations, about half of the companion stars are “lost” in an average merger (Hernquist and Quinn, 1988). Observations suggest therefore that shells can be formed even when the mass ratio companion/galaxy is as high as a few tenths, which was not expected by Quinn (1984). In the last few years, observations and simulations (cf. section II.2) have been going in the same direction in showing that even major collisions where the two components are considerably modified can lead to shell formation. The detection of shells around NGC 7252 (Schweizer, 1982), was already a very good observational argument in showing this.

We can also have an idea on how the companion was disrupted by examining the radial distribution of the integrated light contained in each shell. For NGC 3923 (which has more than 22 shells) the four outer shells contain about half of the total luminosity. This suggests that the companion has lost most of its stars at its first passage in the central regions of the galaxy (Prieur, 1988a).

### III.2 Colour indices

Shell colours are difficult to measure even in wide band photometry, and the results have generally large error bars. Only a few studies have been published on this subject so far (Fort *et al.*, 1986, Schombert and Wallin, 1987, Prieur, 1988b).

Because of the low contrast of the shells, the contribution of the galaxy has to be subtracted from the different images taken with different filters. The colour gradients which are intrinsic to the galaxy are sometimes of the same order as the difference in colours of the shells relative to the galaxy. Therefore it is not possible to subtract the galaxy in

exactly the same way in different colours when the galaxy itself exhibits differences in these colours.

Fort *et al.* (1986) studied NGC 2865, NGC 3923, and NGC 5018, and found that shells can be bluer (for NGC 2865, NGC 5018), or of the same colour of the galaxy (NGC 3923). Schombert and Wallin (1987) found that the outer shells of NGC 474 had the same colour as the galaxy. I have done some measurements of the inner shells of NGC 474 (only the inner because of the small field of the CCD we used), and found a large scatter, but colours in average bluer than the galaxy.

So far we have done measurements of about 60 shells (Prieur, 1988a, Wilkinson *et al.*, 1989a) and found that the mean of the shell colours is generally close to that of the galaxy, sometimes bluer ( $\Delta_{B-R} \approx 0.1-0.2$ ) but that the scatter varies a lot from one system to the other. Some shells can even be much redder than the galaxy ( $\Delta_{B-R} \approx 0.2$ ) in systems with large scatter (see Table II.1 and Prieur, 1988b).

An unexpected result has been the finding of a significant azimuthal colour differences in some of the shells:  $\Delta_{B-V} \approx 0.3$  for 1A and 1B of NGC 5018, and  $\Delta_{B-V} \approx 0.3$  for 2A and 2B of NGC 2865 (Fort *et al.*, 1986) and even  $\Delta_{B-R} \approx 0.4$  for 10A and 10B of NGC 474 (Prieur, 1988b). Schombert and Wallin (1987) have also noticed a scatter intrinsic to the shells. As I said previously, one has to be careful since the subtraction of the galaxy plays a key role in deriving the colour indices. Error bars are difficult to estimate and may be of the order of 0.2, but we still think that this effect is real, at least for NGC 474 for which we can see this effect directly on the ratio of B and R images (cf. photo 8, Prieur, 1988b).

I have done some simulations to see how the different components of the companion (bulge-disc for example) behaved in the shell formation process (Prieur, 1988b). I found that they can account for colour gradients within the shells, but that this effect fades with time. Nevertheless more realistic simulations than mine are needed to conclude about this and check if this effect can account *quantitatively* of the differences in colours that we have measured (dust also could provide a simpler explanation...).

### III.3 Profiles

Shell profiles can have very sharp edges (see Fig III.1), even sometimes unresolved, which is well explained by phase space or real space wrapping. The inner slope is much shallower but we have never observed plateau-like shells as mentioned by some observers (Pence, 1986, Schombert and Wallin, 1987). We are not sure that the profiles mentioned in these two papers have not been affected by a bad subtraction of the galaxy since this shape is only observed for *inner* shells.

In Quinn's (1984) model, the gradient in periods wraps the location of the companion stars in phase space around the center and thins it progressively with time, so that it can be assimilated to a thin surface. Shells appear where this surface has a fold when projected

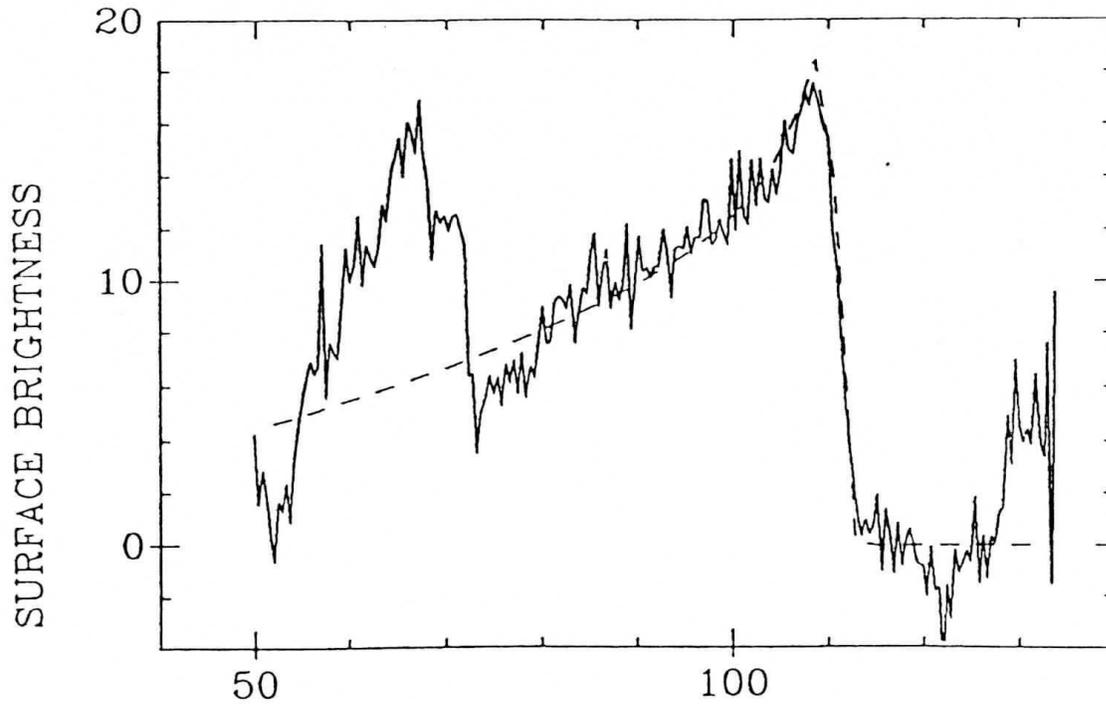


Figure III.1: Profile of shell n° 5 of NGC 474 (close to the left edge of fig 1), and fit with a radial distribution in  $x^{-0.2}$ . Radius in arcsec, and arbitrary units for the surface brightness (from Prieur, 1988ba).

on the plane of the sky. For a shell resulting from wrapping in real space, the shell surface brightness should decrease as  $x^{-1/2}$  in the inner part, whereas for a phase space wrapping, the radial density distribution would decrease as  $x^{-1/2}$  and the projected surface brightness should show a *plateau-like* shape. (Hernquist and Quinn 1988, Nulsen, 1989). This property is independent of the potential in which the particles evolve, but should be valid only very close to the edge, as it is an asymptotic behaviour. This could be a very nice way of distinguishing between wrapping in phase space or in real space

We have observed around 100 shell profiles and not found clear “plateau-like” profiles. I have done some simulations and found a very good agreement with the profiles we have observed, but not any plateau-like profile, again (Prieur, 1988b). I think that even the simulations given as an example by Hernquist and Quinn (1988) to illustrate the plateau shape show clearly that the profiles do not have this shape (!) (cf. their fig 10).



# Chapter IV

## IV. Spectroscopy of the shells

### IV.1 Nature of the stellar population

All the spectroscopic attempts to show that the stellar population of the shells was different from that of the underlying galaxy have failed until now: Quinn (1982) with NGC 3923 and NGC 1344, and Pence (1986) with NGC 3923 and NGC 3051 (for NGC 3923, this is in agreement with the CCD photometry of NGC 3923 by Fort *et al.*, 1986). So the spectroscopy confirms the first photometric measurements in visible and infra-red (Carter *et al.*, 1982), and shows that *shells are formed from an old population of stars, very similar to that of the underlying galaxy*. It would be interesting to observe in spectroscopy some of the shells for which the wide-band photometry has shown differences in colours.

### IV.2 Kinematics

Kinematic differences between two stellar subsystems formed with the same kind of population without any emission lines, and only broad absorption lines are difficult to detect. Bosma *et al.* (1985) observed NGC 1316 with long-slit spectroscopy and found a jump in the radial velocity of about 30 km/s at the location of a shell. But it was only a two-sigma detection, and new observations are needed to confirm this.

Hui *et al.* (1989) have observed the planetary nebulae of NGC 5128, and found that at the the location of shells numbered 12 and 13 by Malin *et al.* (1983), the velocity dispersion dropped to about 60 km/s and the rotation velocity to about 30 km/s. This is the first clear evidence that shells are kinematically independent from the rest of the stars forming the galaxy. In phase space wrapping, shells are density waves which propagate slowly towards the outer parts of the galaxy. We expect a lower velocity dispersion (population of stars close to their apocenter) and a small expanding velocity of typically 20–50 km/s. The observed values for NGC 5128 are therefore in good agreement with the merging predictions.



# Chapter V

## Study of the host galaxy

### V.1 Spectroscopy: recent star formation

Carter *et al.* (1988) have found evidence of recent star formation in the center of 20 out of 100 shell galaxies of Malin and Carter's (1983) catalogue. The spectra do not go far enough to see if there are some changes with the radius, but the integrated colour indices which we have for some of them, are rather red and suggest that this star formation took place in the central regions. A recent study of 0140-658 support this conclusion: this "post star burst" (PSB) shell galaxy exhibits a strong colour gradient, bluer in the center with  $B-R=1.0$  at  $r=2''$  and  $B-R=1.3$  at  $r=8''$  (Wilkinson *et al.*, 1989a). For NGC 7252 also, Schweizer (1982) found evidences of a recent burst of star formation in the center, associated with an ongoing merger.

The spectra of the PSB shell galaxies are similar to the "E+A" active galaxies found in some remote clusters of galaxies (Dressler and Gunn, 1983). These observations suggest therefore that the accretion of a companion is an efficient process to reactivate star formation in elliptical galaxies, and that galaxy interactions may be the origin of the abnormally high rate of PSB galaxies in remote clusters.

### V.2 Correlation with other properties

Since the publication of Malin and Carter's (1983) catalogue, many studies have been done to find a correlation between the presence of shells and other properties. Except for the star formation detection (cf previous section), all these studies have failed. No significant correlation was found with the presence of dust and gas (Sadler and Gehard, 1985, Athanassoula and Bosma, 1985), the detection by IRAS (Wilkinson *et al.*, 1987c), or the radio-emission (Wilkinson *et al.*, 1987b).

### **V.3 Correlation with other properties, repartition in the Hubble sequence**

Schweizer and Seitzer have undertaken a survey with deep CCD frames to search for shells and other features in a sample of about 200 nearby early type galaxies. The final results have not been published yet, but they have found sharp edged structures (that they call “ripples”) around 50 % of ellipticals and 30 % of lenticulars (Schweizer and Seitzer, 1989). They have also presented an estimate of the fraction of shell detection in the Hubble sequence (Schweizer and Seitzer, 1988) and found about one percent for disk galaxies. The lower rate of detection of shells in disk galaxies, can be explain by the difficulty to detect faint sharp edged structures in the background of spiral arms and gas clouds. Also, according to simulations, the domain of the collision parameters which generate shells is smaller with disks than with ellipticals (Dupraz and Combes, 1986, Hernquist and Quinn, 1989).

In a famous paper, Toomre (1977) proposed that ellipticals could have been formed with the merging of spirals, and that the observed present rate of interacting spirals could even account for the fraction of ellipticals in the universe (about 10 %). The formation of ellipticals from mergers has been a matter of (sometimes passionate) debates and I will not discuss this here. Nevertheless the estimated short lifetime of the shell systems (about 1–2 billion years) and the high rate of shell detection in ellipticals (about 10 % according to Malin and Carter, 1983) implies that nearly all the ellipticals have undergone at least one merger which has lead to shell formation (though this may be not true for cluster ellipticals where the shell detection rate is much smaller). The higher detection rate found by Schweizer and Seitzer (1989) reinforces this statement and increases the number of mergers to a few events per galaxy...

# Chapter VI

## Discussion

Now let us examine briefly some arguments for and against the main classes of models we mentioned in the introduction.

One of the objections against internal models that we have not mentioned in section I.1, has been the interleaving of the shells in aligned systems. When sorting the shells according to their radius, two successive shells are located in opposite sectors. This property has been observed by many authors (Malin and Carter, 1983, Quinn, 1984, Prieur, 1987,...), and is naturally explained by wrapping in phase space or real space. Most of internal models simply ignored this point (“pure coincidence...”), except Lowenstein *et al.* (1987) who associate a massive star formation with phase wrapping. If a substantial quantity of hot gas turns into stars in a short time scale, and in a small region of space, it can generate shells in the same way as a companion galaxy. But as the lifetime of wrapping systems is rather short (a few billion years at most), this star formation has to be recent, and then the photometry and spectroscopy disagree...

The main argument against the merging origin for the shells put forward by some authors, has been the very low frequency of shell galaxies in clusters. It is still not completely clear why we observe so few shell galaxies in clusters or small groups, where common sense would say that galaxies have greater chances of collisions. Only 4 % of the objects of Malin and Carter’s catalogue belong to rich clusters.

One reason could be that outer shells are destroyed by close encounter with other cluster members. Since inner shells are difficult to detect by visual inspection on the sky survey, there could be such an artefact causing a lower detection of systems with inner shells only. Malin and Carter processed photographically some plates of nearby clusters with unsharp masking, but they did not find any significant result. We are waiting for the results of Schweizer and Seitzer’s deep survey which is free of such a bias, to see if they come to the same conclusions.

I think that the main reason is that the collisions in clusters occur with high relative velocities, which is not favourable to mergers and shell formation (Quinn, 1984, Dupraz and Combes, 1986). Numerical simulations would be welcome to quantify this.



# Conclusion

Observations have been converging in the last few years to establishing that the merger scenario was the only one which accounted for the observed properties of the shells. Nevertheless it is not as clear as a few years ago that shell stars behave like test-particles launched at the same time in the potential of the galaxy, and that they may be used for detecting dark matter around galaxies. The companion galaxy may have been rather massive (a few tenths of the mass of the galaxy), progressively disrupted, and slowed down by dynamical friction.

There is some hope that N-body simulations will soon provide a definitive answer to the problem of the companion disruption and the role of dynamical friction. I think it would be very interesting to simulate NGC 3923, for which comprehensive data about the shell system and the galaxy are available.

With numerical simulations we are doing a sort of experimental astronomy, and I think it is essential to make a big effort to dominate these simulations, and try to model analytically the results. Before any extrapolation, we must first understand what is generated by the simulations for which we can change all the parameters. The debate about the influence of the potential of the galaxy on shell morphology which has been going on for the last two years, has been a good illustration that this is not an easy task, but nevertheless essential.

The very high detection rate of shells in early type galaxies (30—50 %) suggests that nearly all the early type galaxies from the field or belonging to small groups have undergone at least one merger with a companion since the beginning of the universe. This striking result emphasizes the key role of gravitational interactions for galaxy formation and evolution.

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