SHELLS, RIPPLES AND TAILS

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1. Introduction

It has been known since the early simulations of Wright (1972), and Toomre & Toomre (1972), that interactions between galaxies can give rise to quite spectacular morphological features, including spiral structure in disk galaxies, and extensive tails. It appears that long tidal tails only arise from interactions involving disk galaxies (Toomre & Toomre 1972), and thus the presence of two opposed long tidal tails in a number of disturbed galaxies such as the Antennae (Whitmore & Schweizer 1995), NGC 3921 (Schweizer 1996), and NGC 7252 (Schweizer 1982), has led to the interpretation of these galaxies as disk-disk mergers in progress. These systems can be modeled rather successfully, as the work of Hibbard & Mihos (1995) has shown.

2. Shells and Ripples

The features that we know as shells were remarked upon by Arp (1966) in some peculiar elliptical galaxies such as NGC 474. They were found in large numbers by D.F. Malin (Malin 1979; Malin & Carter 1980, 1983) who had developed the techniques of photographic amplifaction and unsharp masking of photographic plates, which he applied to the plate collection of the UK Schmidt telescope at Siding Springs. Similar features were noted by Schweizer (1980) in the envelope of the peculiar elliptical NGC 1316, Schweizer used the term "ripples" to describe them. Malin & Carter (1983) found that some 10% of isolated elliptical galaxies have shells; Schweizer & Seitzer (1988) find rather higher percentages, using 4 meter rather than Schmidt telescopes, and they find shells around some S0 galaxies as well.

A striking feature of the most spectacular shell ellipticals, such as NGC 3923 and NGC 1344, later classified as Type I shell ellipticals by Prieur

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(1987, 1988) is the alternating appearance of the outer shells. These shells are aligned along the major axis, the outermost is on one side of the nucleus, the next one in on the opposite side, the third on the same side as the first and so on. This feature provided a most important clue to their origin. This alternating appearance breaks down at small radii for systems of many shells, as pointed out by Thomson (1991).

2.1. MERGER MODELS

Quinn (1982, 1984) proposed that shells result from mergers of a low mass galaxy with a giant elliptical. The shells result from phase wrapping in the potential of the elliptical. Quinn's original simulations were of radial mergers of a cold disk component with an elliptical potential, which gave rise to features rather like Type I shells.

These models were developed further by Dupraz & Combes (1986) and Hernquist & Quinn (1987, 1988, 1989) who show that shells can be formed in encounters with a variety of impact parameters, impact energies and progenitors. Indeed they can be formed by mass transfer in encounters which do not involve mergers. If the impact parameter of the encounter is large, then the shell system is formed by spatial wrapping around the nucleus, rather than phase wrapping, and has an "all around" appearance, represented in nature by NGC 474 and NGC 2865 which are classified as Type II shell systems by Prieur (1988). Dupraz & Combes (1986) investigated mergers in non-spherical potentials with a variety of shapes, and find that prolate potentials can focus the shells along the major axis, so that a prolate potential will form a Type I shell system with a greater range of impact angles than an oblate potential. The discovery of minor axis rotation in NGC 3923, the prototype Type I shell elliptical (Carter, Thomson & Hau 1997) supports a prolate potential for this galaxy and thus to some extent the merger model for shell formation in this galaxy.

The simulations of Dupraz & Combes (1986) suggest that there should be a few oblate galaxies with shells similar to Type I shells aligned along the minor axis, although this geometry does require a very particular impact angle. NGC 3051 (Malin & Carter 1983) may be an example of such a galaxy, although the geometry of this system changes with radius.

The merger model for shell formation has problems explaining some features, including the high surface brightness of the inner shells, the existence of shells deep in the potential of some galaxies, and the unexpected bi-symmetry of the innermost shells in NGC 3923 (Prieur 1990). Dupraz & Combes (1987), using the Chandrasekhar approximation, estimate the effect of dynamical friction and claim that dynamical friction can account for the small radii of the innermost shells. The applicability of the Chandrasekhar approximation is in some doubt, and a more detailed calculation of the effect of dynamical friction in shell formation is required urgently.

2.2. MAJOR MERGERS

Schweizer (1980), following a suggestion of A. Toomre, proposed that shells could be formed in near equal mass disk-disk mergers, giving rise to elliptical remnants. Indeed galaxies such as NGC 7252 (Hibbard & Mihos 1995) show shells which can be modeled very successfully by disk-disk mergers. NGC 3921 (Schweizer 1996) is another merger remnant which appears to show shells. Moreover Balcells (1997) finds two faint opposed tails, usually considered as a signature of a disk-disk merger, in the shell elliptical NGC 3656. This type of merger is probably only capable of making Type II shell systems, the issue of whether or not it can make an elliptical galaxy is addressed by Bender (1995) and many others.

2.3. THE WEAK INTERACTION MODEL

An alternative model of shell formation was proposed by Thomson and Wright (1990) and further developed by Thomson (1991), motivated by the problems with the merger model discussed above. According to their model the shells are formed in a thick disc component of an oblate galaxy during a mildly hyperbolic interaction with another galaxy. The passage of this galaxy excites a one-armed spiral density wave in the thick disc component. When viewed edge-on, this density wave naturally reproduces the interleaved pattern seen along the major axis in Type I shell galaxies. When viewed face-on or obliquely the wave forms a Type II shell galaxy. In this model the difference between Type I and Type II shell systems is one of viewing angle, whereas in the merger models it is driven by the shape of the primary potential and the impact parameter. One advantage of this model is that it has no trouble in producing the inner shells. A weakness of the weak interaction model is that there must be a thick disk component in the first place. This model does not require a rotating galaxy however, only a rotating component in which the density wave is excited.

The merger and weak interaction models make different predictions about the colours, distribution and velocities of the shells. The weak interaction model predicts that the shells will have the same colour as the body of the galaxy at that radius, whereas in the merger model the colour will depend upon the colours of the secondary progenitor. Fort et al. (1986) find shell colours somewhat bluer than the main body of the galaxy in two out of three galaxies studied. Turnbull (1997) presents the first results from a programme of much more accurate photometry of shells and the underlying galaxies.

The most clear-cut discriminant between these two models would be a measurement of the velocity of the material in the shells in a Type I shell system. In the interaction model these are composed of stars in a rotating thick disk component, even in an underlying galaxy which is not rotating. In the merger model they are an expanding density wave, and in a Type I system their velocity will be in the plane of the sky. This measurement has proved too difficult to make to date, owing to the low surface brightness of the shells and their low contrast against the underlying galaxy.

2.4. OTHER MODELS OF SHELL FORMATION

A rather different model for the formation of shells was proposed by Fabian, Nulsen & Stewart (1980) and expanded by Bertschinger (1985) and Williams & Christiansen (1986). In this picture shells are formed as a result of star formation in shocked gas in the interstellar medium of the galaxy, the shocks being caused by outflow from the nucleus. With the measurement of shell colours, which are not much bluer than the main body of the galaxy, the failure to detect either ionized or neutral gas associated with the shells except in a very few cases, and the discovery of the interleaving of shells on opposite sides of the nucleus in many shell galaxies, this picture has fallen into disfavor, although Lowenstein et al. (1987) reconcile this model with the last of these observations by proposing that the shells are composed of stars formed off-centre in an elliptical potential as a result of a blast wave, and that these stars then phase-wrap forming the same structures as in the merger models. The lack of very blue colours in the shells still argues against this model.

3. The Fate of Gas in Interactions

3.1. NUCLEAR GAS AND STARBURSTS

Gas of course behaves differently from stars in interactions, and when gas collects regions of star formation occur. Hernquist and Weil (1992) use a hybrid N-body and hydrodynamic code to model the behavior of a gas disk in a disk galaxy which merges with a much more massive elliptical. The gas collects quickly in a disk or ring in the centre of the potential well, whilst the stars form shells over a longer period. This explains the finding of Carter et al. (1988), that some 10% of shell ellipticals show strong Balmer absorption lines in their nuclei. Galaxies such as 0140−658 and 1241−339 have spectra similar to the most extreme of the "E+A" galaxies in distant clusters (Dressler & Gunn 1982; Zabludoff 1997). Lavery and Henry (1988) argued that interactions between galaxies were a major cause of this phenomenon in distant clusters.

Hau, Carter & Balcells (1998) examine the structure and nature of a starburst induced by a merger in NGC 2865 (Fig. 1), a Type II shell elliptical and a mild example of an "E+A" galaxy (Carter et al. 1988, Bica & Alloin (1987). This galaxy has a rapidly rotating central disk containing both young, metal-rich stars and gas. The starburst in this galaxy appears to be 0.4–1.7 Gyr old, rather older than the dynamical age of the shells. NGC 2865 appears to be the result of a merger between a gas-rich spiral galaxy and another galaxy, probably an elliptical, of 2 or 3 times the mass of the spiral. The metal abundance inferred for the starburst is higher, by a factor of between 2.5 and 5, than that of the underlying elliptical. This kind of abundance is not characteristic of a gas rich spiral, but it is possible to get around this problem if the star formation episode takes place over a period of time, so that some enrichment can occur.

3.2. GAS AT LARGE RADII

Schiminovich et al. (1994,1995), and Schiminovich (1997) find HI at large radii associated with NGC 5128, NGC 2865 and NGC 474. Curiously, in NGC 5128 and NGC 2865 the HI forms a ring or shell like structure displaced *outwards* from the optical shells. This is hard to explain in the merger and phase wrapping picture of shell formation, but may result from gas already at large radii in the secondary galaxy, which is stripped very early in the formation of a type II shell system (which all of these are) by spatial wrapping.

4. Kinematic Shells and Kinematically Decoupled Cores

In a few galaxies, such as NGC 7626 (Balcells & Carter 1993) kinematic shells can be seen at small radii. These are dynamically cold velocity anomalies, as if a sheet of cold material is wrapped around the nucleus. These would seem to be late stages in the formation of Kinematically Decoupled Cores, another signature of a recent merger in an elliptical (Bender 1990). There is a strong connection between shells and KDCs, Forbes (1992) finds that all of the 9 well established KDCs and a further 4 out of the 6 "possible KDCs" in his sample possess shells.

NGC 474 (Balcells, Hau & Carter 1998) is particularly interesting in that the velocity profiles are double-peaked near the nucleus, suggesting that the velocity structure of the components has survived. In this case both velocity components are comparatively narrow ($\sigma < 150\,\mathrm{km/s}$), possibly reflecting the nature of the progenitors. NGC 474 shows photometric shells, kinematic shells, double velocity peaks and a rapidly rotating kinematically decoupled core, and is a particularly interesting and complicated case.

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Figure 1. NGC 2865 - A type II shell elliptical with a mild E+A spectrum in its nucleus. This is a deep R band CCD image from the prime focus of the Anglo-Australian Telescope

5. Future Developments

Observationally the measurement of accurate colours and velocities of the material in the shells is of vital importance, the former is feasible with modern detectors, the latter will probably be a project for the next generation of ground-based telescopes, and even then only with extreme care in the background subtraction. Explanation of the inner shells and kinematic shells in galaxies such as NGC 474 will require a more detailed treatment of the effects of dynamical friction during shell formation, or if this doesn't work then we may be required to examine alternatives to the merger model, such as Thomson's (1991) weak interaction model, in more detail. Whilst there remains some doubt about whether mergers are required to explain

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shells, long tails are clear signatures of mergers involving disk galaxies. The relationship between these phenomena is vital to our understanding of the origin of shells.

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