RING GALAXIES—A REVIEW

Tapan K. Chatterjee

Centre of Advanced Study in Astronomy, Osmania University,
Hyderabad 500 007

Abstract

We review the theories proposed for the formation and evolution of ring galaxies.

I. INTRODUCTION

Many galaxies are observed which contain rings of various shapes and are accompanied by companions, nuclei, knots and debris. Sometimes empty rings are also seen. These galaxies contain a prominent bright ring-like structure which is quite fascinating. How did such strange shapes come about ? This is a fascinating current problem in Astronomy. We propose to shed some light on this question.

Ring galaxies or R-galaxies can be classified into three sub-classes :

(i) RE galaxies consisting of crisp empty rings;

(ii) RN galaxies consisting of a crisp ring, inside which lies an off-centred nucleus;

(iii) RK galaxies having single dominant knots or condensations in their rings.

Observations and statistics show that R-galaxies are true rings and not fortuitously aligned filaments or spherical shells. An examination of the photographs of R-galaxies indicate that almost all of them have at least a companion (sometimes more) that lies very close to the minor axis of the ring. The shape of the rings vary from highly elliptical to nearly circular. The RE galaxies are nearly circular and the RK galaxies are highly elliptical, the RN galaxies lie in between them. On the basis of photometric and spectroscopic observations it has been concluded that the rings have galactic sizes and masses (of the order of 10^{11} solar masses) and kinematical time scales of the order of 10^{11} years. The mean diameter of the ring is of the same order as the mean separation of the companion from the ring (Theys and Spiegel 1976).

Some examples of ring galaxies are Arp 4, 10, 11, 40, 104, 115, 128, 191, 318. (Arp 1966, 1967). Arp and Madore (1975) and Thompson (1977) have discussed the observational aspects of many ring galaxies.

A very interesting type of ring galaxy is A0035—the ‘ Cartwheel ’, which has a very complicated structure. Another interesting one is II Hz4 which is a double ring galaxy.

Thompson and Gregory (1977) have reported the discovery of a ring galaxy with a very low surface brightness. They suggest that it is a ring galaxy in its later stages of evolution, although its intrinsic luminosity and diameter tend to indicate that it may be a dwarf galaxy.

II. THEORETICAL MODELS

On the basis of these observations, several theories have been put forward on the formation and evolution of ring galaxies.

(i) FREEMAN AND DE VAUCOULEURS' THEORY

Freeman and de Vaucouleurs (1974) divide the ring galaxies into two broad categories :—(a) those consisting of a spheroidal system and a pure ring and (b) those consisting of a spheroidal system and a chaotic multi-nucleated object. The examples of types (a) and (b) are Arp 147 and Arp 143, respectively. The chaotic objects are frequently pear-shaped, almost triangular and often with one or more condensations near the centre.

The theory postulates the existence of large inter-galactic gas clouds (I.G.C.) of galactic masses (3 billion solar masses) and sizes (R = 15 kpc). Evidence of such clouds comes from H I clouds of galactic dimensions in M31 and M81 groups. Chamaraux, Heidmann and Lauque (1970) discuss dwarf galaxies which have a large fraction of their mass in the form of H I clouds.

When a disk galaxy collides with an intergalactic gas cloud (I.G.C.) of sufficient density and depth along a trajectory which is face-on, or near face-on, then two spectacular consequences follow :—

(1) The central spheroidal shaped component, known as the nucleus, which mainly consists of dense objects, and the stellar component of the disk pass almost undisturbed through the I.G.C.. This is on account o the fact that the distances between the stars in a galaxy are very large compared to their sizes, so that the mean free path is very large.

(2) The gaseous ring shaped disk component, however, collides violently with the I.G.C. This is, as is well known, because the mean free path is quite small in the case of the gaseous component. The result is that the gaseous ring shaped disk is slowed down, by the I.G.C., with respect to the stellar component, causing the two components to separate. Eventually the gaseous component is brought to rest with respect to the I.G.C. within a distance that depends upon the relative masses, densities and velocities; this distance is presumably less than the observed separation of several kiloparsecs between the two components of the system.

Calculations indicate that in a time of the order of 10^7 years, the gaseous component separates completely from the stellar component. This gaseous component will be further enriched in gas due to its interaction with the I.G.C.

The flat spinning gas ring which has been segregated from its spheroidal nucleus becomes unstable due to the lack of the presence of a central gravitational force. We can expect two main phases in its evolution :—

(1) **t less than 10^8 years**: The separation of the two components is less than the diameter of the ring. Due to the increased density of gas in the ring, a burst of star formation takes place. This leads to bright Population-I objects and H II regions, thus enhancing the brightness of the ring.

(2) **t greater than 10^8 years**: Due to the inherent instability in the ring, the ring collapses and a chaotic re-organisation of the material takes place, presumably, resulting in a centrally condensed object.

In the first phase (t less than 10^8 years) we have objects resembling (a) type objects, while in the second phase (t greater than 10^8 years) we have objects resembling (b) type objects.

This model predicts the following properties :—

(1) There are two main sources of light emission from the rings. During the first phase of the evolution (t less than 10^7 years) the main sources of luminosity are collisional excitation, ionisation and recombination of hydrogen. During the latter phase (t greater than 10^7 years) star formation becomes significant. Then the main sources of luminosity are thermal emission from OB associations, radiative excitation of giant H II regions, etc. For t greater than 10^8 years, the ring should be evolving towards a magellanic type irregular system. Spectroscopic and calorimetric data (Sandage 1963) confirm this.

(2) The model also predicts that the ring should be richer in hydrogen than the gas in the disk of the initial galaxy. Spectroscopic observations confirm this. Burbidge (1964) has made spectroscopic observations of Mayall's nebula, which give results consistent with this model.

(3) The model also predicts that after complete separation of the central spheroidal nucleus from the ring shaped gaseous component, the spinning gas ring should be expanding due to unbalanced centrifugal force. As the ring expands additional gas is swept up by it which slows down both rotation and expansion. As the angular momentum is conserved during expansion, the rotation velocity gets further reduced. The theoretical expansion velocity (about 40-80 km/sec) can be checked by detailed spectroscopic observations.

Depending on (i) the morphological type of the original galaxy (lenticular, spiral, ordinary or barred) and its stage along the Hubble sequence (early or late), (ii) the density distribution in its H I disk, (iii) the angle of incidence and the relative velocity of the disk with respect to the I.G.C. and (iv) the density structure of the I.G.C., a variety of appearances can be expected to result from the same basic encounter process.

We should note that there is a very strong resemblance between the isodensity contours of the rings and the equidensity contours of HI-regions of disk galaxies, VII ZW 466 being an example. This theory explains Arp No. 144 very well.

(ii) THEYS AND SPIEGEL'S THEORY

In this theory (Theys and Spiegel 1977), it is noted that the dynamical age of the ring galaxies is of the order of 10^8 years. On a longer time scale the ring becomes unstable. Self-gravitating rings are prone to what is known as the bead instability. In a time scale of the order of 10^8 years, rings of galactic masses and sizes should break up into beads, i.e., condensations should start to form at several points in the rings (Dyson 1893; Randers 1942; Wong 1974). The instability grows ,as do the density of the condensations, and the ring finally breaks up into about six smaller objects which subsequently collide and merge. It is speculated that this system forms a galaxy with a gas-enriched active nucleus. It is found that theoretical rings look most like the observed ones after a time of the order of 10^8 years.

From radial velocity determinations the separation time between the rings and their companions is found to be of the order of 10^8 years. This coupled with the fact that the spectroscopic observations indicate that a burst of star formation took place in the rings about 10^8 years ago, suggest that the companions are strongly implicated in the ring formation.

The crux of the theory for ring formation is that a disk galaxy, which is here approximated by a spheroidal nuclear component (N) and a disk or ring component (R), was struck by a centrally concentrated spherical galaxy, which now appears to be the companion of ring galaxy (C). The companion passed through the original disk at an angle from its axis of symmetry (minor axis in this case) and somewhere near the centre. The angle between the companion and the axis of symmetry was quite small. This caused the nucleus (N) to be deflected from its central position leading to a reduction of the central force. This caused a differential expansion. Different parts of the disk of the target galaxy expanded with different velocities. This caused overlapping and resultant crowding of the various constituents leading to the formation of a dense ring. Originally the component (N) probably contained much more than just the nucleus of the parent disk.

Collision simulation results indicate that for a collision between a disk galaxy and a spherical intruder galaxy, when the intruder approaches the target disk from without the disk's plane and scores a direct hit at the disk's centre, i.e, a normal, on-axis collision, (a) the general stellar population gets spread out i.e, the density of the nucleus decreases considerably and more stars are spread out in extent increasing the size of the galaxy (b) The low velocity and less massive stars i.e, Population-I component and the gaseous component form a very bright ring (of radius of the order of 8 to 10 kpc)

If we now consider the disk to be made up of Pure Population-I objects and approximate the galaxies (target and intruder) by two components each, a massive spherical nucleus and ' n ' rings of equal mass and equally spaced, and make collision simulations, we get excellent rings. The rings start forming in a time of the order 10^7 years and become extremely bright and prominent after about 10^8 years and then become unstable and disperse. Projection effects are also considered.

In this way good RN and RK galaxies are made, but RE galaxies pose a problem in the sense of explaining the missing nucleus.

The structures suggest two possible models of rings:

(1) We may suppose that the rings are nearly circular and that the companions lie on the symmetry axis but out of the planes of the rings In that case, every ring will be seen as an ellipse, and every companion will be on the projected minor axis. Occasionally there will be no apparent companion since it will appear in projection on the ring as a knot, or inside as a nucleus.

(2) The rings may be inherently elliptic; a preference of the companions for the projected minor axis would arise if the companions were in the planes of the rings and on their true minor axes.

RE galaxies are close to model (1) as they are nearly circular in shape. RK galaxies are close to model (2) in structure as they are quite elliptical. RN galaxies are intermediate between models (1) and (2).

We see that RE galaxies will be formed only when the nucleus is completely knocked off. This is possible only for very high energy collisions. Then the target core loses some mass to the intruding galaxy so that the remnant disperses due to loss of binding energy. But such high energy collisions are quite rare.

There is, however, a way of making RE galaxies without making unconceivable assumptions. In the case of an inelastic collision, where most of the energy is used in imparting Z-velocities to the stars, we get an RE galaxy. The nucleus is sufficiently knocked off to go outside the ring.

However in this case the results are very sensitive to the impact velocity. But even with a low impact velocity an RE can be produced in this case. It is found that halos, if present, affect the collision in a way that is favourable to the formation of RE's. Studies of Brownrigg and Hockney (1974), Ostriker and Peebles (1974), Hohl (1976) confirm this. Thus it is found that provided the inelastic nature of the collision is taken into account and there is dissipation of energy during collision, we get an RE galaxy even for a low impact velocity without assuming a very high energy collision which is very rare.

(iii) LYNDS AND TOOMRE'S THEORY

This theory (Lynds and Toomre 1976) explains the double ring galaxy II Hz4 very well. The basic process outlined requires one fairly concentrated galaxy to penetrate a disk-like second galaxy of comparable mass at roughly normal incidence and at some spot near its centre. The brief inward pull exerted by the galaxy in transit can convert an existing disk into a ringlike structure.

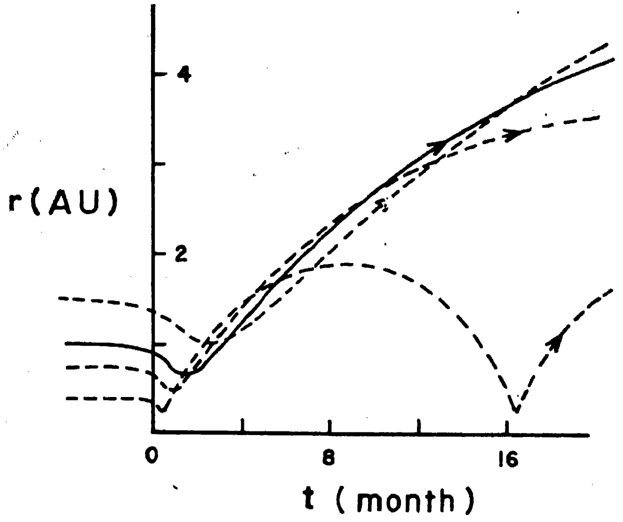

Fig. 1 : The analogy of the Solar System

To understand the process consider the following analogy. Suppose that another star wanders into the solar system exactly along the axis normal to the earth's orbit; assume that it starts from rest at infinity, and that it now falls unimpeded directly through the Sun and out the other side.

At first due to the increased radial gravitational force the Earth and the inner planets, Mercury, Venus and Mars are pulled towards the Sun. This causes their distances to decrease markedly during the first 5 or 6 weeks that the intruder spends within 1 Astronomical Unit of the Sun. This radial crowding is shown in Figure 1 by the small hump very close to the r-axis. After the intruder has passed away to quite an appreciable distance, the extra radial gravitational force caused by it diminishes. This causes the Earth and the inner planets (Mercury, Venus and Mars) to bounce back centrifugally. Actual calculations confirm this. The heavy curve in Fig. 1 shows how vigorous such a rebound would be if the mass of the intruding star was one solar mass. The spectacular point to be noted here is that during the rebound the independent trajectories of all these four inner planets crowd together for several months following the transit of the intruder. Thus all four inner planets would find themselves at about the same, but increasing distance from the Sun. This crowding is due to the fact that Keplerian radial dependence of the dynamical time scales of the various planets causes the 'oscillators' to drift out of phase. Thus we see that a ring is formed first when the planets are pulled inwards due to the extra radial gravitational force due to the intruder and crowd together. As the intruder passes by and the extra radial gravitational force decreases, the planets rebound back but still crowd together. Thus the dense ring formed, expands with lapse of time.

A very similar phenomenon arises when a spherical concentrated galaxy falls normally through the plane of a disk galaxy and scores a direct hit at the nucleus of the target galaxy. Due to the extra radial gravitational force the stars of the target galaxy are pulled inwards and crowd together to form a ring in the form of a density wave. As the intruder passes away, due to the decrease of the extra radial gravitational force the stars rebound back, and thus the ring expands outwards. The ring is a transient phenomenon of life-time of the order of 10^8 years and contains most of the gas and population-I objects of the disk. The density wave pushes interstellar matter before it. In effect it would produce a circular shock wave. Hence such a process would enhance the formation of young stars and bright H II regions, that indeed appear to accentuate many of the observed ring structures.

In the calculations the 'victim' disk plays the role of a galaxy one-third of whose total mass is ascribed to a central spheroidal nucleus, the other two-thirds of the mass is divided among 16 discrete rings spaced in radius so as to approximate a smooth Gaussian law of surface density $\mu(r) \propto \exp. (-r^2/2r^2_O)$ where r_O is a scale length. The gravitational potential of every mass element dM is softened from an exact -GdM/S to an artificial $-G(S^2+a^2)^{-\frac{1}{2}}dM$, where 'S' denotes the distance from that element, and 'a' is a fixed length, here set equal to $r_O/3$. This technique was earlier used by Miller (1974).

Now we consider the collision between two disk galaxies such that they interpenetrate each other normal to their disks and their nuclei collide with each other. We find that in that case a transient ring is formed in both the galaxies. We get a double ring galaxy like II Hz 4. Slight off-centre collisions produce better shapes, compatible with the shapes of II Hz 4, in which the nuclei of both the rings are drawn off-centre. It is to be noted that the shapes of II Hz4 and the model produced in the last theoretical simulation outlined are strikingly similar.

It appears that good rings are produced even if the impacts are not normal but are tilted by as much as 30° from the axis of the target and intruder. Restriction on the impact parameter are more stringent; in essence the intruding galaxy needs to pierce the target disk within 15% of its outer radius.

This theory has also given a suitable explanation of the morphology and velocity structure of a peculiar ring galaxy known as the 'Cartwheel' (A0035). Spectroscopic scans and direct photographs of this galaxy were obtained by Fosbury and Hawarden (1977), from which data they find many observational features of this remarkable system, like luminosity, element abundances, colours etc. This system consists of a bright large outer ring. At about the centre of the ring is a bright moderate nucleus which is surrounded by a smaller inner ring. The Hubble distance of this system is 150 Mpc, and diameter of the outer ring is 54 kpc. From rotation velocity of the ring, the mass of the nucleus of this galaxy comes out to be of the order of 4×10^{11} solar masses. Thus it is one of the largest and most massive of the ring galaxies whose Hubble distance is known. The velocity measurements show that the north-east side of the ring is nearest to us. The ring has two companions, out of which the most easterly companion is supposed to have taken part in the ring formation due to collision. This is because its radial velocity is about equal to that of the nucleus of the ring and it contains very little gas, while the more westerly companion which has a velocity lower by 400 km per sec, has a considerable amount of ionised gas and a rather normal undisturbed spiral structure. The distance of the companion galaxy corresponds to a time scale of about 2.5×10^8 years since closest approach which agrees quite well with the expansion time scale of the ring, of the order of 3×10^8 years, deduced from the measured expansion velocity and present radius of the ring. This ring consists of very bright, giant photoionised H II regions, whose integrated H_β luminosity implies the presence of about 3×10^5 O-stars providing Lyman continuum photons. But the energy distribution of the optical continuum implies that the number of O- and B-stars is of the order of 3×10^6, indicating an expected frequency of Type II supernovae of one per year. Elemental abundance measurements of two of the HII regions of the ring show deficiency in oxygen, nitrogen and neon as compared to the Orion nebula. This implies that either the whole system is young or that the gas that has been swept out of the original disk by the expansion of the ring has been mixed up with a massive halo of primordial gas. The electron temperature is higher than that of the Orion nebula, probably due to the low oxygen abundance resulting in reduced cooling efficiency.

As discussed by Toomre (1970), the basic phenomenon which resulted in the formation of the 'Cartwheel' is the bombardment of a disk galaxy by a very centrally concentrated spherical galaxy along a trajectory normal to the disk and penetrating the disk at a point very near to the nucleus of the disk. Toomre considers six different vertical bombardments of the disk galaxy (which consists of randomly set test particles) by a very centrally concentrated spherical galaxy which penetrates without any influence except its inward pull of gravity. In all the cases the spherical galaxy falls normally through the disk galaxy, but the impact parameter is different for the various cases. It is found that the closer is the point, at which the spherical galaxy penetrates the disk galaxy, to the nucleus of the disk galaxy, the better is the formation of the rings. When the penetration point is quite far from the nucleus (comparatively), a double armed spiral results due to the encounter. As the impact parameter decreases and the penetration point lies closer to the nucleus of the disk galaxy, the two arms of the double armed spiral, which is the aftermath of the encounter, join themselves forming a thin ring. The nucleus of the disk galaxy lies at one side of the ring giving the ring the shape of an RK galaxy, in which the nucleus is the dominant knot. As the impact parameter decreases, this ring becomes more thick and prominent. Finally, when the collision is on-axis, or near on-axis and normal, a beautiful transient outer ring is formed which expands with lapse of time and the nucleus lies inside this ring. At the same time, a secondary inner ring is formed surrounding the nucleus. The cause of this secondary ring is that many independent chunks of matter which were dragged inward by the intruder, fall back as the intruder moves away due to decreasing excess radial gravitational pull caused by the intruder. This can be compared to the secondary ripples, which develop after the first main ripple, when a stone is dropped in water. This inner ring is due to the different forms of relaxation followed by those orbits which feel the interaction over a time-scale which is long compared to an orbital period.

The aftermath of this last collision simulation has a striking resemblance to the 'Cartwheel'.

However, in these simulations, it is seen that between the inner and outer rings a sparse distribution of matter is there, but no dominant spoke-like structures are there, as is observed in the 'Cartwheel'. The distribution of matter between the inner and outer rings appears to be random according to the collision simulations of Toomre. Fosbury and Hawarden give an explanation for the 'spokes'. As the intruding galaxy moves away from the disk, the excess radial gravitational force caused by it decreases. This causes some of the stars and gases which were drawn in to fall back, causing violent relaxation of the orbits and severe radial bunching. These orbits, which were originally almost circular, become highly eccentric as a result of the interaction. The apogalaction of these orbits, which originally had a small radius, can be inside the present radius of the ring. Some of the stars, and also possibly gas, will have started falling back towards the nucleus and any original clumpiness could show up, after the effects of differential rotation, as the spiral spokes. The circular orbital period at the present radius of the ring is about 7 x 10^8 years, so that it is not yet expected that such a structure could be completely smeared out.

But this explanation of the 'spokes' of the 'Cartwheel' is disputable. The spokes are much too marked, both in brightness and structure, to be dismissed away by such a simple explanation. In fact they resemble a series of winding spiral arms connecting the inner and outer ring. Perhaps the target galaxy was a spiral galaxy with multiple spiral arms and the spokes are the dilapidated remains of these arms. This remains an interesting problem.

III. CONCLUSION

The observations and theoretical models tally quite well, as far as the observed shapes are concerned, for all the three theories.

Freeman and de Vaucouleurs' theory explains the formation of RE galaxies quite well but has the disadvantage of postulating the existence of mammoth intergalactic gas clouds. However, this theory gives a suitable explanation for the formation of chaotic multinucleated objects.

Theys and Spiegel's theory also explains the formation of RE galaxies quite well. If we consider an inelastic collision then even for moderate impact velocities the nucleus of the target galaxy is knocked off sufficiently to give rise to a RE galaxy.

The theory of Lynds and Toomre has the advantage that it neither postulates the existence of huge intergalactic HI clouds of galactic mass, (which if they existed would not have eluded detection) nor does it envisage the knocking out, or serious splattering of the nucleus of the disk or target galaxy by the intruder (such head on collisions are not frequent enough to explain the observed ring galaxies).

Detailed photometric and spectroscopic observations of ring galaxies and their spheroidal components and detailed evaluation of quantitative models are needed to decide between the various theories proposed.

All the theories however suffer from the effect of approximations at various stages. The galaxies are considered to consist of a spherical component, and 'n' equally spaced rings of equal mass or test particles representing the disk. The collisions are also somewhat idealised in the sense that we assume them to lie within a not too wide range of trajectories. The self-gravity of the rings has not been taken into account. Detailed collision simulations taking self-gravity into account are desirable.

In these models, only face on collisions of two galaxies are considered. When the disk of the intruder is oriented at random, its form after collision is a matter for more general calculations to decide.

Results obtained by Toomre for changes in structure of a disk galaxy in a vertical encounter with a spherical galaxy in off centre collisions have been discussed in the previous section. Studies of off-centre collisions with non-vertical trajectories are desirable.

Ring galaxies sometimes have two or more companions. Studies of the perturbing effects of a third galaxy on the structure of the ring formed by a collision of two galaxies, are also needed.

Another interesting question mentioned by Theys and Spiegel (1977) is that of the ultimate fate of ring galaxies, especially the RK and RN galaxies. These types have in the system a galactic core which has probably been relaxed by the encounter. The simulations indicate that this core will suffer further collisions with the gas enriched fragments of the ring in the course of some billion years. The fragment containing the original core would be exceptional and this is already suggested by the detection of the Seyfert nucleus in a ring (NGC 985 = VV 285) (de Vaucouleurs and de Vaucouleurs 1975). Simulations indicate that the fragments will collide and coalesce. Each collision causes further relaxation of the stars in the original core and pronounced enrichment of the gas content. It would seem, therefore, that many of the rings give rise to a reasonably condensed stellar core containing a large portion of the gas of the original rings. This core is embedded in a a diffuse envelope of Population-II stars. This seems to provide a possible origin for a configuration with a very gas rich core in a Population-II background, and this resembles certain radio galaxies. The study of the evolution of ring galaxies into active galaxies is one of the most interesting current problems,.

Though some mechanisms have been suggested for the formation of the 'Cartwheel', yet the detailed features need further elucidation.

As discussed in the earlier section, Toomre's (1978) paper indicates a mechanism for the formation of more than one ring in galaxies. On the observational side a a search for *multiple-ringed galaxies with a central nucleus* is of much interest.

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ERRATUM

PERIODOGRAM ANALYSIS OF THE LIGHT CURUES OF 44 TAU By S. K. Gupta

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Page 14, Column 2, Para 1, Line 13 **for** $\Sigma\ (C—O)^2$ **read** $\Sigma\ (O—C)^2$

Page 14, Column 2, Para 4, Line 7 **for** $—0\overset{m}{.}26$ **read** $—0\overset{m}{.}06$.