TAURUS observations of the ring galaxy in Vela

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Summary. Two-dimensional velocity field mapping of the ring galaxy in Vela (1008 – 3814) is reported. TAURUS, an imaging Fabry–Perot interferometer, attached to the Cassegrain focus of the AAT and employing the IPCS as an area detector, was used to obtain the data. The resultant velocity field is found to be incompatible with the simple expanding, rotating ring anticipated from previous ring galaxy studies. The appearance and kinematics favours a folded ring structure, similar to, but not as extreme as, the classic folded ring, Arp 144. The relevance to ring galaxy formation is discussed.

1 Introduction

At the present time there are two competing hypotheses regarding the formation of the small but intriguing subgroup of peculiar galaxies known as ring galaxies. The first, originally advanced by Freeman & de Vaucouleurs (1974), proposed that the rings were formed as a result of the collision between a normal spiral galaxy and a large intergalactic cloud (IGC). The bulk of the spiral disc is assumed to be relatively deficient in gas, due to normal star formation processes, but is surrounded by an outer ring of unprocessed H\textsc{i}. As the galaxy advances into the IGC, this ring of H\textsc{i} snow-ploughs up sufficient of the IGC to trigger star-formation within the outer ring, while the progress of the stellar component of the nucleus and inner disc are unimpeded by the interaction. Within time-scales of the order of $10^8$ yr, an intense burst of star formation is visible as H\textsc{ii} regions in a ring detached by a few ring radii from the original stellar nucleus.

Although this scheme was able to account in a qualitative fashion for many of the structures observed, it required a mean density of IGCs approximately 4 orders of magnitude larger than the upper limit set by H\textsc{i} emission measures (Silvergate & Krumm 1978; Roberts & Steigerwald 1977).

The alternative and now more widely accepted hypothesis, is that put forward independently by Lynds & Toomre (1976) and Theys & Spiegel (1977). Here an almost head-on (distance of closest approach < 2 kpc) collision, between a spiral galaxy and an early-type,
gas-free, system is postulated. In elegant computer simulations of this process Lynds & Toomre (1976) and Toomre (1978) were able to get very close agreement between their models and the appearances of some ring galaxies.

Indeed, the success of such models to account, in particular, for the double ring system Hz4, postulated to be the result of a collision between two gas-rich spirals (Lynds & Toomre 1976) and the Cartwheel Galaxy, A0035 – 34 (Toomre 1978), where the offending elliptical is assumed to be that seen in projection along the minor axis of the ring, has led to a general acceptance of this model in the foregoing literature.

We should note, however, that this spiral-elliptical encounter is not without its problems. There exists a small but not insignificant number of empty ring galaxies (REs as classified by Theys & Spiegel 1976) which appear to have lost their nuclei altogether. This may present a problem for Toomre-type collisions which are expected to leave a remnant nucleus inside the ring, even though it is often displaced from the centre and is indeed not necessarily exactly coplanar with the ring. The IGC–galaxy collision, on the other hand, would naturally give empty rings, with the original nucleus appearing as a companion seen in projection along the minor axis, but has difficulty when accounting for rings which still possess a nucleus.

Furthermore, Dostal & Metov (1979) have attempted a rigorous treatment of the collision probabilities between two galaxies which would be expected to give ring systems of the Toomre variety. They find that an absolute upper limit to the probability would give approximately 3 orders of magnitude fewer rings than are actually observed. An enhanced encounter probability can be obtained by supposing that each member of the collision is gravitationally bound such that tidal disruption of their orbits eventually leads to a close encounter. However, this possibility may be used to support both hypotheses.

2 Previous observational work

The development of ring galaxy models was soon to be followed by spectroscopic observations of the velocity field of two classic ring systems.

Fosbury & Hawarden (1977) observed A0035 – 34, a system with both an inner and outer ring structure. As well as achieving a reasonable understanding of the physical conditions and abundances in the individual H II regions making up the outer ring, they were able to fit their six velocity points to motions which combined expansion and rotation of the outer ring in a way compatible with Toomre’s (1978) predictions. Unexplained however, are the curved spokes connecting the inner and outer rings, which give the Cartwheel its name; these were seen to have primarily continuous spectra and hence could not be readily velocity mapped.

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<th>Table 1. Observational characteristics.</th>
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Plate 1. (Left) Reproduction of an ESO 3.6-m prime focus plate of the Vela ring, kindly supplied by Dennefeld, Launstein & Materne. The scale and orientation have been matched to the velocity field data on the right. (Right) Representation of the twodimensional velocity field (km s⁻¹) of the Vela ring galaxy relative to the systemic velocity of the inner ring. North to the top, east to the left. The accurate pixel scale and orientation is given in Table 1.
More recently, Dennefeld, Lausten & Materne (1979) investigated the ring galaxy in Vela at 1008 – 3814. They took several direct plates of the object and showed, for the first time, its complex morphology. Like the Cartwheel, the Vela ring itself has multiple ring structures but no spikes are visible for this object. They were able to measure radial velocities from spectra obtained on one position in the outer ring and one in the inner ring. A difference of approximately 100 km s$^{-1}$ was obtained from which a rough estimate of the expansion velocity was deduced.

Clearly, in both cases, only a minimum of observational verification of theory has been achieved, primarily because of the time consuming nature of the spectrographic technique, a problem overcome by the advent of a new observational method.

3 Interferometric observations

We present here the results concerning the H$\alpha$ velocity field of the Vela ring galaxy, as shown in Plate 1 (left), obtained during the first AAT observations using a new imaging Fabry–Perot system known as TAUROS (Taylor 1978; Taylor & Atherton 1980; Atherton et al. 1982). The system is designed to give seeing-limited (1.4 arcsec) radial velocity fields of extended emission-line objects, using the Image Photon Counting System (IPCS: Boksenberg 1972) as the area detector. It creates a three-dimensional array of data values, (2 spatial dimensions of 4.5 arcmin diameter and 1 spectral dimension of 96 increments) from which the velocity field of the object can be obtained directly over the whole field. The observational characteristics are listed in Table 1.

The data are acquired in a ‘rapid-scan’ mode, whereby the full three-dimensional data set is refreshed every 216 s of observing time, and hence seeing and transparency variations throughout an integration are averaged out to be approximately constant within each spatial frame of the array.

The observational procedure was to place the object in the approximate field centre of TAUROS and to offset guide using one probe of the acquisition and guider unit to which the interferometer was mounted. An integration time of approximately two hours was used.

In order to fully reduce the data thus obtained two further three-dimensional data sets were required. First a white light flat-field scan was obtained by illuminating the inside of the AAT dome. This allows a relative wavelength dependent sensitivity map of the interference filter pre-monochromator to be created. Also, when reduced to a two-dimensional spatial flat-field map, through integration of each pixel scan in the wavelength direction, the white-light scan gives a combined IPCS, interference filter pixel sensitivity map.

Secondly a calibration three-dimensional array is obtained by illuminating the entrance aperture by a monochromatic source. This gives the phase map (Taylor & Atherton 1980; Atherton et al. 1982) which allows us to re-structure the three-dimensional object array into a set of normalized two-dimensional images of the field at different, but equally spaced, spectral intervals, the transmitted wavelength being constant across each individual two-dimensional image. In this way, each pixel of the image contains a spectral line profile of the source at that particular location, which is then used to determine its velocity. A velocity map of the object is then constructed as described by Pike et al. (1980).

4 Results

The velocity field created by this technique is given in Plate 1 (right). It should be noted that both the inner and outer ring structure have been velocity mapped, although the outer ring is
incomplete since our limiting flux level corresponds approximately to the structure seen in the 20-min exposure of Dennefeld et al. 1979. Further, the structure of the outer ring has been somewhat smoothed by the process of spatial binning. In regions where the signal-to-noise ratio is low, the spatial resolution was degraded to 2² pixels (~3 arcsec) while the single pixel resolution was maintained for the higher signal regions.

The inner ring structure is more readily visible in Fig. 1 where the individual line profiles are displayed. The nucleus itself is seen to possess a high, presumably stellar, continuum with little emission flux from which its velocity can be derived. The internal accuracy of the velocities is, of course, a function of signal-to-noise, but is in general better than 3 km s⁻¹, as estimated from these and similar results obtained on other sources.

The radial velocity measures in the inner ring have been fitted to a deprojected expanding and rotating circular ring. The results are shown in Fig. 2(a). The major axis on the inner ring is at a position angle (PA) of 90° ± 10°, with its ellipticity implying an orientation to the
Figure 2. Deprojected velocity measurements. (a) The inner ring. The solid line represents the best fit sine-wave to these points. (b) The outer ring. The squares represent measures to the east of the major axis (PA = 160°), the solid dots are to the west. The solid line is a sine-wave freely fitted to all points, whereas the broken line is fitted just to the western points and has a constrained systemic velocity equal to that of the inner ring.

line-of-sight of approximately 30°. A least-squares fit, using these projection angles, indicates a pure rotational component to the velocities of $15.3 \pm 1\, \text{km}\,\text{s}^{-1}$. An inner ring radius of 5 arcsec (equivalent to 1.6 kpc at a Hubble distance of 65 Mpc) leads to a nuclear mass, internal to this ring, of approximately $8 \times 10^8 \, M_\odot$.

The least-squares fit also gives a well-determined value for the systemic velocity (heliocentric) of $4852 \pm 5\, \text{km}\,\text{s}^{-1}$ (where the error, here, is systematic in nature; the formal error in the fit being < 1 km s$^{-1}$), in excellent agreement with the figure of 4845 km s$^{-1}$ given by Dennefeld et al.

In contrast to the quiescent kinematics of the inner ring the outer ring structure shows a marked velocity trend in its western arm, as represented in Plate 1 (right).

The velocity curve of the outer ring is plotted in Fig. 2(b), the squares representing the western, more pronounced region, while the circles are those regions to the east of the major axis.

The least-squares sine-wave fit to all the velocity measures, assuming a PA of 160° and a projection angle to the line-of-sight of 56°, is shown as solid curve in the diagram and, to within the errors, this result might be seen as satisfactory. The formal results of this solution give $13 \pm 2\, \text{km}\,\text{s}^{-1}$ and $39 \pm 1\, \text{km}\,\text{s}^{-1}$ for the rotational and expansion velocities, respectively. However, the systemic velocity of the outer ring is $22 \pm 1\, \text{km}\,\text{s}^{-1}$ larger than
the systemic velocity of the inner ring, and indeed the velocity measures to the east of the major axis show a fairly random scatter whose average velocity is identical to that of the inner ring, in marked contrast to the well behaved rotation curve shape of the regions to the west.

To highlight this feature of the results, we have fitted a sine-wave to just those points to the west of the major axis, keeping the systemic velocity fixed at a value of 4852 km s\(^{-1}\), the value obtained for the inner ring. This fit is shown as a dotted curve in Fig. 2(b). It is clear that this fit better represents the points to the west of the major axis than does the fit which includes, in its solution, all the points around the ring.

5 Interpretation

At first sight the Vela ring system appears to be a classic example of a ring galaxy formed by the Toomre-type collision of a disc system with an early-type galaxy. However, a detailed inspection of the morphology of the system, together with considerations of the kinematics as presented in this paper, lead to serious problems.

First the companion early-type galaxy, which is the only candidate for such a collision, does not lie close to the minor axis of the outer ring, as generally expected of Toomre-type ring systems but is, in fact, approximately 45° from it. Furthermore the radial velocity difference between the ring and its companion is 336 km s\(^{-1}\) (Dennefeld et al. 1979) implying a lower limit to the mass of the system of approximately \(6 \times 10^{11} M_\odot\) which is to be compared to the \(6.2 \times 10^9 M_\odot\) estimate for the ring galaxy alone as derived from the motions in the outer ring. Although neither of these arguments is conclusive, clearly we have to face the possibility that the apparent companion is not associated with the ring galaxy but is simply a background field elliptical.

The structure of the outer ring, as determined from its appearance and kinematics, also creates interpretational problems. As shown in the previous section, a single sine-wave fit to all the velocity points around the outer ring not only implies that, if circular geometry is assumed, then the expansion of the ring is significantly larger than its rotation, a result which is again in contradiction to theoretical expectations of the Toomre-type models, where the ratio of rotational to expansion motion is predicted to be approximately 5 (Toomre 1978), but also gives a systemic velocity 22 km s\(^{-1}\) different from that determined from the inner ring. Of course the outer ring need not be circular; however, in abandoning this assumption we are no longer able to estimate the ratio of expansion-to-rotation.

The fact that the trend of velocities in the western sector of the outer ring shows a very regular systematic behaviour, in contrast to the rather chaotic motions of the eastern sector, leads one to consider the possibility that there is a distinct difference between the two halves of the ring. This notion is further strengthened by a close inspection of the 60-min exposure of Dennefeld et al. (1979) as reproduced in Fig. 1, which reveals evidence for two separate semi-elliptical structures, joined or overlapping at positions A and B as marked, and seen at different orientations to the line-of-sight. This, of course, implies that the ring galaxy is not a plane two-dimensional structure but that it represents a ring, folded along a line close to its diameter.

This idea of a folded ring is not new. Freeman & de Vaucouleurs (1974) adopted a similar model from considerations of Arp 144, which is a much clearer example of such a geometry. They used Arp 144 to support their arguments for galaxy—IGC collisions, imagining the object to originate as a ring surrounding a stellar nucleus which has been stripped from one end and folded over to form the structure we now observe. Indeed from such a model one
might expect that the sector of the ring in contact with the IGC (i.e. the eastern half) would have lost most of its original rotation motion.

The fact that the eastern sector appears to have chaotic velocities scattered about the systemic velocity of the inner ring also implies that the inner ring is in contact with the IGC and is quite probably a result of the collision of the nucleus with it.

The major observational problem with this scenario is that the strongest H\textsc{ii} regions appear on the western sector which has not experienced the full force of the interaction. Furthermore, the reason for the sharp discontinuity at the interface of the IGC, implied by this model and further accentuated by the more extreme example of Arp 144, together with the problem of the nature of the unobserved IGC, remain to be explained.

6 Conclusions

The following problems have been revealed by the detailed study of the velocity field of the Vela ring galaxy.

(i) It is difficult to reconcile the velocity field of the outer ring with a simple rotating, expanding ring sharing the systemic velocity of the nuclear region.

(ii) The appearance and velocity structure of the outer ring are shown to be in rough accord with a folded ring geometry not dissimilar from Arp 144, but showing a less extreme degree of folding.

(iii) The apparent companion elliptical is probably not the galaxy responsible for the head-on collision necessary for the Toomre-type interpretation.

Although there appears to be good reason for assuming that the probability of encounters between galaxies and IGCs is too small to explain the occurrence of ring galaxies (Lo & Sargent 1979), there is evidence, both from our study and from the original work of Freeman & de Vaucouleurs (1974), that events of this nature do occur. The explanation for this would be either that H\textsc{i} IGCs are gravitationally bound to the parent galaxy which does not impose severe restrictions on the overall field volume density of IGCs, or that the compositions of the IGCs involved in the collision are not H\textsc{i} at all, but are in some other state (such as molecular H\textsc{2} or hot 10\textsuperscript{7} K plasma). Toomre's calculations have given us confidence that certain rings may be explained on the basis of galaxy—galaxy collisions, but it remains to be seen whether folded ring structures, encountered in this study, can be produced by similar encounters. Perhaps two separate mechanisms are required to explain the ring phenomenon in its entirety.

References


