LETTERS

An almost head-on collision as the origin of two off-centre rings in the Andromeda galaxy

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The unusual morphology of the Andromeda galaxy (Messier 31, the closest spiral galaxy to the Milky Way) has long been an enigma. Although regarded for decades as showing little evidence of a violent history, M31 has a well-known[1–7] outer ring of star formation at a radius of ten kiloparsecs whose centre is offset from the galaxy nucleus. In addition, the outer galaxy disk is warped, as seen at both optical[8] and radio[9] wavelengths. The halo contains numerous loops and ripples. Here we report the presence of a second, inner dust ring with projected dimensions of 1.5 × 1 kiloparsecs and offset by about half a kiloparsec from the centre of the galaxy (based upon an analysis of previously-obtained data[10]). The two rings appear to be density waves propagating in the disk. Numerical simulations indicate that both rings result from a companion galaxy plunging through the centre of the disk of M31. The most likely interloper is M32. Head-on collisions between galaxies are rare, but it appears nonetheless that one took place 210 million years ago in our Local Group of galaxies.

Newly acquired images[10] of M31 secured by the Infrared Array Camera[11] (IRAC) onboard the Spitzer Space Telescope span the wavelength regime of 3.6–8.0 μm. These images offer unique probes of the morphologies of the stellar distribution and interstellar medium with no interference from extinction. Figure 1 shows the emission map of the interstellar medium at 8 μm, generated by subtracting a scaled 3.6 μm image (dominated by starlight) from the 8 μm image. The subtraction removes the contribution from stellar photospheres and leaves only the emission from dust grains[10], which trace the interstellar medium of M31.

What is most striking in Fig. 1 (and in the enlarged inset) is the presence of a complete—although asymmetric—inner ring of dust 6.9 by 4.4 arcmin in extent, translating to linear dimensions of about 1.5 by 1 kpc (assuming a distance[12] of 780 kpc). The inner ring lies between the two well-known Baade spiral dust arms[13], both of which are clearly seen in emission. The inner ring is elongated in a direction close to the minor axis and belongs to the central gas disk, which appears to be more face-on[14]. It is therefore not possible to know the inner ring's precise ellipticity, but it is unlikely to be circular.

IRAC imaging thus reveals two rings. The outer ring is offset by approximately 10% of its radius, while the inner ring is offset by about 40% or ~0.5 kpc. The inner elliptical ring has been alluded to in earlier studies[15,16], but all investigators have hitherto believed it to be a mini-spiral, related to a bar. Published Spitzer 24 μm images[5] of M31 show centrally concentrated dust emission; the ring morphology is therefore disguised at these longer wavelengths. The IRAC images beautifully show the inner ring at high spatial resolution and furthermore confirm that this feature is a complete and continuous ring, even though it is offset and asymmetrical.

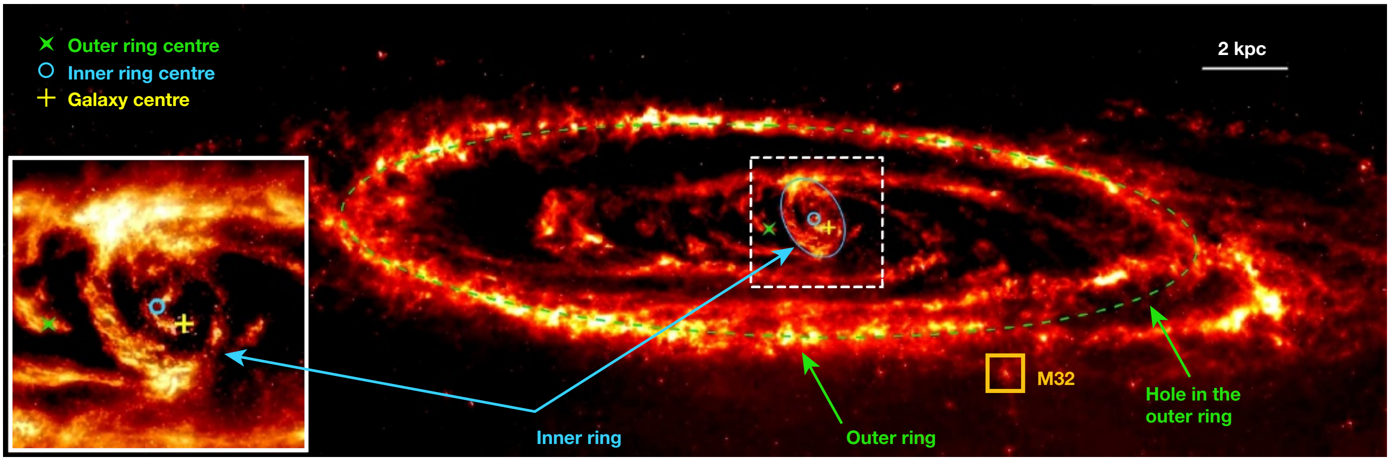

Figure 1 | The Andromeda galaxy M31 observed with IRAC[11] on board the Spitzer Space Telescope at a wavelength of 8 μm. A scaled version of the 3.6 μm image was subtracted from the 8 μm image to remove light from stellar photospheres. The remaining emission therefore traces the emission of warm dust grains and macromolecules in the interstellar medium. M31 clearly possesses two rings. Apart from the famous outer dust ring seen at a radius of ~10 kpc, this map reveals a second 1.5 kpc by 1 kpc inner dust ring offset by approximately 0.5 kpc from the galaxy nucleus. Both rings are interpreted to be density waves induced by an almost head-on collision. The most likely candidate is the dwarf companion galaxy M32, which appears faint in this image because it has little dust. The starlight of M32 is, however, prominent in the separate 3.6 and 8 μm images[10].

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There are two known scenarios whereby disk systems form rings: by head-on galaxy collisions or by rotating bars. Head-on collisions differ from common tidal interactions between galaxies because the pericentric distance of the orbit of the companion is small, and its orbit is almost perpendicular to the target disk. Such collisions produce expanding ring-shaped waves[17]. Rotating bars in spiral disks produce inner, outer and sometimes nuclear rings in barred spiral galaxies. The rings occur at orbital resonances and arise from the galaxy's internal dynamics (unlike collisional rings). Many examples of bar-induced rings are known[18].

Infrared imaging of spiral galaxies in the local Universe confirms the ubiquity of the bar phenomenon; about 80% of spiral galaxies are barred[19], even if many are classified as unbarred at visible wavelengths. M31 is no exception; although Hubble classified it as normal type Sb, it is likely to possess a stellar bar. The presence of a bar in M31 is suggested by its boxy bulge, which is conspicuous in infrared imaging[5,20] and is aligned almost parallel to the galaxy's major axis. The boxy bulge might be an inflated bar, or it may hide a thinner parallel bar (at about 10° from the major axis). There is, however, no bar parallel to the minor axis, along which the major axis of the inner dust ring lies. Had there been a stellar bar along the minor axis, it would surely have been detected in the IRAC 3.6 μm image[10], which is much deeper than the 2.2 μm Two-Micron All-Sky Survey (2MASS) images and less affected by dust attenuation. The double-ring system of M31 therefore appears to be unrelated to any possible central bar, because the elliptical inner ring does not have the typical orientation of most bar-induced gas rings (which are generally aligned along the bar's major axis). Moreover, the off-centre ring strongly supports the collision interpretation. Resonant rings generated from rotating bars are rarely as off-centre as the rings of M31, and the amount of decentration increases with radius. In M31, however, the inner ring is off-centre by 40% of its radius, whereas the outer ring is off-centre by only 10%.

The relative brightness of the inner and outer rings further supports a collision origin. When a bar induces a strong pair of rings, the most prominent one is generally the inner, located just beyond the extremity of the bar at the so-called 4:1 resonance. In M31, the outer ring is much brighter than the inner one. This makes the interpretation of bar-induced resonance rings highly unlikely except under the unrealistic hypothesis of a very slowly rotating bar extending up to the outer ring (contrary to observations). The dual-ring morphology of M31 strongly indicates expanding density waves triggered by a head-on galaxy collision with a companion.

The dwarf companion galaxy M32 is very likely to be the impactor. To investigate whether a collision of M32 with the disk of M31 could induce the two ring-shaped density waves identified in the IRAC images, *N*-body simulations were performed[21]. The simulations include stars, gas and dark matter in M31 and M32 with one million particles and a spatial resolution of 350 parsecs. Our simulations differ from all previous ones in that the initial orbit of M32 is close to the polar axis of M31, and the mass ratio is larger. Previous simulations[5] have assumed that the impact occurred several kiloparsecs away from the centre of M31 and not along the rotation axis (nearly head-on). Our new simulations start with an axisymmetric disk, proceed for approximately one gigayear while a bar and spiral arms form, then introduce a collision with M32. We take into account not only the mass stripped during the collision but also the dark matter associated with M32 itself. We assume an initial mass ratio for M32 of a tenth that of M31 (including dark matter). Current-epoch mass estimates of M32 are lower, but much mass is likely to have been stripped[22] during the collision. The final mass of M32 in our model is 1/23 that of M31, which is compatible with present-day mass estimates.

The simulation of a head-on collision (Fig. 2) beautifully reproduces the observed global morphologies of M31 reported in this Letter. The model produces two striking density wave rings offset from the galaxy centre. The outer density wave propagates through the M31 disk, resulting in a perturbed interlacing of spiral features with an outer ring. This produces the conspicuous hole observed in the outer 10 kpc ring of M31 (compare Figs 1 and 2). Our model reproduces this very striking (but transient) feature and adds evidence that the two rings have been induced by a collision 210 million years ago close to the rotation axis of M31. The non-zero (but small) impact parameter makes the inner ring off-centre, and the inclination of the orbit with respect to the rotation axis produces the ring elongation. In the simulations, the head-on collision does not destroy the pre-existing boxy bulge in the barred target disk but merely weakens it.

Collisional ring galaxies are expected to show local radial and tangential perturbed motions in the vicinity of the rings, which will be observed as 'streaming motions'. When the intruder is a quarter the mass of the disk galaxy or less, the ring behaves like a wave which propagates through the disk[23], as opposed to the large-scale bulk

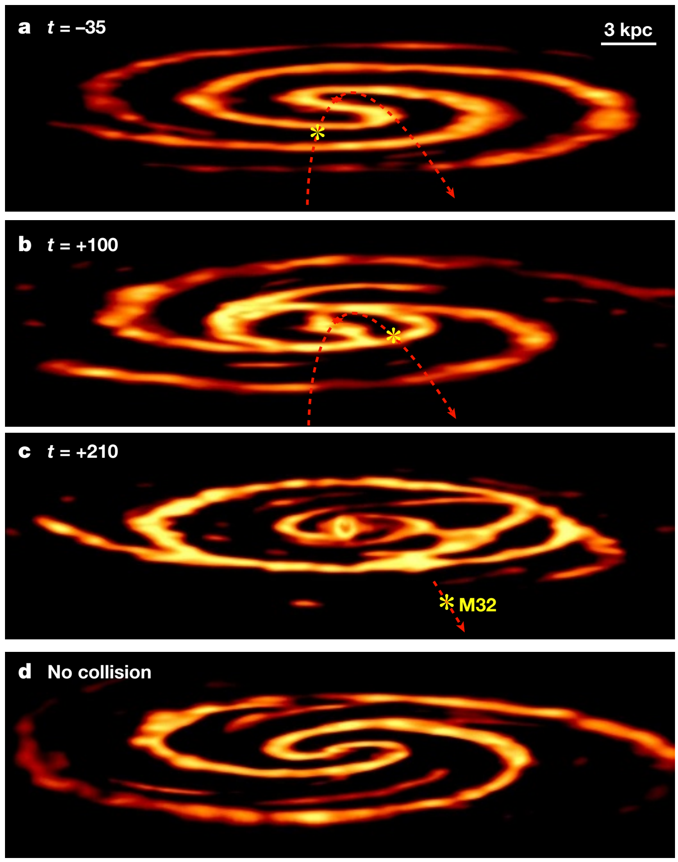

Figure 2 | Gas morphology produced by simulations[21] of a head-on encounter between M31 and M32. These *N*-body models include the gravitational dynamics of stars, interstellar matter, and dark matter in both M31 and M32. A 'sticky-particle' scheme accounts for the dissipative nature of the interstellar medium, and star formation is also included[21]. The dashed red line demarcates the orbit of M32; the locale of impact lies very close to the polar axis of M31. Snapshots **a**, **b** and **c** occur at $t = 35$ million years before collision and at 100 and 210 million years post-impact; **c** also shows the position of M32 as we see it today. All snapshots are taken with the disk viewed at an inclination angle of 77° for direct comparison with Fig. 1. **c** shows the central region of M31 warped by a tilt angle of 30° with respect to the main disk plane in accord with observations[14]. The two ring-like waves (both offset from the galaxy centre) are seen, as is the hole in the outer ring. **d** shows the gas morphology at $t = 210$ million years, starting from the same initial disk conditions but modelled without a collision; no density-wave rings are generated. The initial mass of the companion M32 is a tenth that of M31 (or 1/13$^{\text{th}}$ excluding dark matter). The companion is assumed to have struck the M31 disk at a velocity of 265 km s^{-1} and 1.2 kpc from the centre of M31. It would now be located at a distance of 35 kpc and at a galactic latitude of about 45°, which is fully compatible with the present position[30] of M32.

motion of material that occurs when the mass of the intruder is larger. Our model predicts radial velocities in the gas of $10\,\mathrm{km\,s^{-1}}$ at the outer (10 kpc) ring. Unwin[24] found local streaming velocities in neutral hydrogen gas of $30\,\mathrm{km\,s^{-1}}$ at that radius; our predicted radial velocities constitute 30% of the total observed streaming velocity. The inner ring is predicted to show lesser radial velocities, which are more difficult to probe because of the vertical tilt of the central gas disk. There is an interesting kinematic signature of a ring induced by collision: the resulting positive radial velocity in the ring is predicted to be associated with a depression in the rotational velocity towards the outer parts of the ring (with a corresponding increase in the inner parts of the ring). This is indeed seen in isovelocity contours in neutral hydrogen[24]. The predicted tangential streaming motions for spiral arm density waves[25] would have the opposite sense. (See the Supplementary Information.)

The most striking analogue of the disk morphology observed in M31 is the Cartwheel galaxy. The Cartwheel galaxy is the archetype of a double-ringed morphology produced by collision. Two distinct density wave rings are observed: a conspicuous outer ring, associated with massive star formation, and an elliptical inner ring, offset from the centre of the galaxy. In between the two rings lie several spiral arms, termed 'spokes', which have developed in a trailing pattern. Several models have been computed of the Cartwheel galaxy, simulating the almost head-on collision with one of its companions[26,27].

M31 differs from the Cartwheel galaxy in that we do not see the inner ring in starlight but only in gas and dust. In other words, the inner ring in the Cartwheel galaxy shows a much greater degree of contrast (compared to the parent disk) than does the inner ring in M31. The explanation is that the impactor in the Cartwheel galaxy must have been more massive than M32, resulting in two density-wave rings of stars. Our simulations match the lower contrast seen in M31: the primary ring wave propagates outward in the disk, being created by a crowding of particle trajectories and made prominent by massive star formation triggered at the peak of the wave. The second elongated density-wave ring begins to propagate in the central regions of the galaxy, most probably in a tilted central disk. At the present epoch, the gas morphology of the model agrees with the double-ring structure of the M31 interstellar medium as revealed by IRAC.

The morphology of M31 has been mysterious for many years, but the discovery of the offset inner ring may be the clue needed to offer an explanation: a recent head-on collision could have produced both the inner ring and the previously known outer one. The rings are unlikely to have been created by bar resonances because of the rings' relative brightness and their offsets from the galaxy centre and also because they show no relationship to the spiral structure; in particular, no minor axis bar is observed. While head-on collisions between galaxies may have been common in the early Universe[28,29], only a handful are known nearby. The discovery of one in our near-neighbour M31 affords the unique opportunity of studying such a collision at unprecedented spatial resolution.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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