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Galaxy shredding – I. Centaurus A, NGC 5237, and the Fourcade–Figueroa shred

R. C. Thomson
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

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SUMMARY

Galaxy shredding occurs when a spiral galaxy undergoes a strong prograde interaction with a massive galaxy. The fragile disc of the spiral galaxy is disrupted (shredded) during the encounter and the massive galaxy captures up to half of the disc material. The rest is ejected from the system as a non-rotating shred of dusty, gas-rich disc material which appears as a blue irregular/starburst galaxy. The robust bulge of the spiral progenitor is relatively undisturbed by the encounter and emerges from the shredding episode as a dwarf elliptical galaxy. Numerical simulations are presented together with a case study of the nearby active galaxy Centaurus A.

Key words: galaxies: individual: Centaurus A – galaxies: individual: NGC 5237 – galaxies: interactions – galaxies: irregular – galaxies: kinematics and dynamics.

1 INTRODUCTION

Since their discovery by Malin & Carter (1980), shell galaxies have been studied in detail by many authors and several models proposed to explain these structures. Of these, the merger model (Quinn 1984; Dupraz & Combes 1986; Hernquist & Quinn 1988, 1989) was favoured because it was the only model which could naturally explain the observed interleaving of shells. According to this model, shells are formed by the disruption of a low-mass companion whose stars now form the observed shells.

Recently, Thomson & Wright (1990) have proposed an alternative model of shell formation wherein shells are formed as density waves induced in a thick disc population of stars by a weak interaction with another galaxy. Only weak interactions (i.e. mass ratios of about 10:1) produce shells by this mechanism, since the thick disc particles must remain on nearly circular orbits. Stronger interactions produce too much random motion and any shells which are then formed disappear on a relatively short time-scale. Thomson (1991) has shown that the weak interaction model can explain all the known characteristics of shell galaxies (including the interleaving) and gives a more accurate and robust description of the observations than does the merger model.

One consequence of the weak interaction model is that the secondary galaxy does not merge with the primary galaxy and re-emerges after the interaction. Since shell galaxies tend to be found in the field or in small groups, spiral galaxies are expected to be the most likely secondary candidates. More specific evidence that spiral galaxies are involved includes the detection of dust, A-type stars and emission lines in a significant fraction of shell galaxies (Carter *et al.* 1988).

It is important to realize that an apparently weak interaction for the massive galaxy can represent a strong interaction for the smaller galaxy. The simulations presented here show that the fragile disc of a spiral galaxy can be completely disrupted during a strong prograde interaction with a massive galaxy. This disruption process is suitably described as galaxy shredding – a terminology which is derived from Arp's (1967) description of a class of irregular galaxies as shreds.

Computer simulations of shred-forming interactions as seen by the smaller spiral galaxy are presented in Section 2. A case study of Centaurus A is presented in Section 3, followed by a more general discussion in Section 4. Further case studies will be presented in subsequent papers in this series.

2 COMPUTER SIMULATIONS

The gravitational field of the spiral galaxy is modelled by a rigid Plummer potential with a unit core radius. Test particles are distributed out to a maximum radius of 4 length units to form a thin exponential disc with a scalelength of 1.5 length units. The orbits are initially set up to be circular and rotate in the anticlockwise sense when viewed from above in the figures presented here. The stars which form the pressure-supported bulge in the central region of the spiral galaxy are assumed to remain tightly bound to the underlying galaxy potential and are not modelled here. The position of their centre of mass, however, is given by the location of the core of the spiral galaxy potential.

The gravitational field of the massive galaxy is also modelled by a rigid Plummer potential with a unit core radius. Its mass is set to be 10 times that of the smaller galaxy in all the simulations presented here, and the total system mass is normalized to unity. The encounter is modelled by either a parabolic or a hyperbolic passage of the spiral galaxy around the massive galaxy with a perigalactic distance of 4 length units. The equations of motion are integrated using a Predictor–Corrector scheme as described by Wright (1972). The simulations start at $t=0$ and stop after 500 time units have elapsed with closest approach occurring at $t=100$ time units. Each simulation comprises 10^5 particles and takes about 8 hr of CPU time on a Sparcstation 1+.

Fig. 1 shows the evolution of a shred-forming encounter in which the smaller spiral galaxy interacts with the massive galaxy on a prograde parabolic orbit inclined at 15° with respect to the simulated disc. The disc is almost completely disrupted by the strong interaction. About one quarter of the disc particles are captured by the massive galaxy, and a similar fraction remain bound to the bulge remnant. The rest are thrown out of the system to form a shred of dusty, gas-rich disc material which is initially linked to the progenitor bulge by a low surface brightness bridge. It is proposed that the knot at the tip of the shred is gravitationally bound and appears as a non-rotating gas-rich irregular/starburst galaxy; the associated bulge remnant reappears as a dwarf elliptical galaxy.

The bifurcation of the spiral progenitor is caused by the distinctly different dynamics and response of the loosely bound rotationally supported disc and the tightly bound pressure-supported bulge during the encounter. Only strong prograde interactions cause galaxy shredding and a mass ratio of about 10:1 or more is required for this process to be effective. The shred is essentially a disembodied tail which is no longer bound to the disrupted spiral galaxy.

Fig. 2 shows a shred-forming encounter in which the disc of the spiral progenitor is inclined at an angle of 90° with respect to the orbital plane. As the inclination angle of the encounter is increased, galaxy shredding still occurs, but is less efficient and becomes essentially ineffective when the encounter becomes retrograde.

Fig. 3 shows a shred-forming encounter in which the spiral progenitor interacts with the massive galaxy on a prograde hyperbolic orbit inclined at 15° with respect to the simulated disc. In this case, the velocity at closest approach is 30 per cent faster than the equivalent parabolic orbit. As in Fig. 1, a well-defined shred is formed but the angle between the shred and bulge remnant subtended at the massive galaxy is smaller than for a parabolic encounter. This is purely due to the extra speed of the progenitor spiral and hence of the remnants relative to the massive galaxy. More extreme hyperbolic encounters produce a correspondingly smaller effect due to the relatively large difference between the orbital velocity and the rotation velocity of the spiral disc. Galaxy shredding occurs most effectively when the orbit is close to being parabolic.

A notable limitation of these test particle simulations is the lack of any self-gravity. The motion of the bound particles is expected to be modelled reasonably well without including self-gravity, but the dynamics of the particles which form the shred are not expected to be accurately modelled once they escape from the gravitational field of the massive galaxy. Further simulations, which include the effect of self-gravity, need to be carried out in order to model the shred dynamics more accurately. Although lacking self-gravity, these test particle simulations do show, however, that galaxy shredding can take place and this process is investigated further here by considering a specific example – Centaurus A.

3 CENTAURUS A (NGC 5128)

At 5 Mpc, Centaurus A is the nearest active galaxy. It is also the nearest known shell galaxy. Understanding the physics of Centaurus A could therefore unlock some of the mysteries of the more remote active galaxies and quasars which are not so conveniently placed.

The idea that Centaurus A may be the product of a collision between an elliptical and a spiral galaxy was originally put forward by Baade & Minkowski (1954). They suggested that the dust lane was actually an edge-on spiral galaxy seen in silhouette against the background elliptical galaxy and perhaps actually in collision. This model is no longer viable, since the dust lane is now known to form a rotationally supported ring around Centaurus A. The more realistic model described here implies that the dust lane was probably formed during a strong interaction with a spiral galaxy about 5×10^8 yr ago.

Like all shell galaxies, Centaurus A has been described most recently as a merger remnant. If the shells were formed by a weak interaction, however, then the secondary remnant(s) should be identifiable. Plate 1(a) shows the region south and east of Centaurus A. The most likely secondary remnants of the shell-forming encounter have been identified as the nearby dwarf elliptical galaxy NGC 5237, shown in Plate 1(b), and the Fourcade–Figueroa shred (Dottori & Fourcade 1973) – a low surface brightness irregular galaxy, shown in Plate 1(c).

Spectra of the Fourcade–Figueroa shred (Dottori & Fourcade 1973; Graham 1978) reveal a rich emission-line system with a mean galactocentric velocity ($V_0=V_\odot+300 \sin l \cos b$) of $+607$ km s^{-1} (Graham 1978; Hesser, Harris & van den Bergh 1984). Since the galactocentric velocity of Centaurus A is $+318$ km s^{-1} (Graham 1979; Hesser *et al.* 1984), the Fourcade–Figueroa shred has a relative velocity of approximately $+300$ km s^{-1} with respect to Centaurus A. The galactocentric velocity of the dwarf elliptical galaxy NGC 5237 is $+116$ km s^{-1} (Fairall 1981), and hence has a relative velocity of approximately -200 km s^{-1} with respect to Centaurus A. The encounter geometry then requires that the progenitor spiral followed a nearly parabolic orbit in a plane tilted at about 35° with respect to the line of sight, starting NE and in front of Centaurus A to reach perigalacticon approximately 10 kpc to the rear and on the west side some 5×10^8 yr ago. During closest approach, a large fraction of the disc material was captured by Centaurus A; a non-rotating shred was thrown off in a direction away from the Sun toward the SE, and the bulge remnant continued on its orbit east of Centaurus A.

A simulation of this system is shown in Fig. 4. Assuming the mass of Centaurus A to be 2×10^{12} $M_\odot$ (Hesser *et al.* 1984), and the perigalactic distance of the encounter was 10 kpc, the time unit for this simulation is 1.3×10^6 yr. The current configuration of this system therefore corresponds to the simulation at approximately $t=500$ (i.e. about 400 time units after the encounter). With a mass ratio of 10:1, the mass of the spiral progenitor is estimated to have been 2×10^{11} $M_\odot$ – about the same size as our own Galaxy, the Milky Way.

According to this model, the prominent dust lane seen in Centaurus A is composed of dusty, gas-rich disc material captured during the encounter. In the simulation, a signifi-

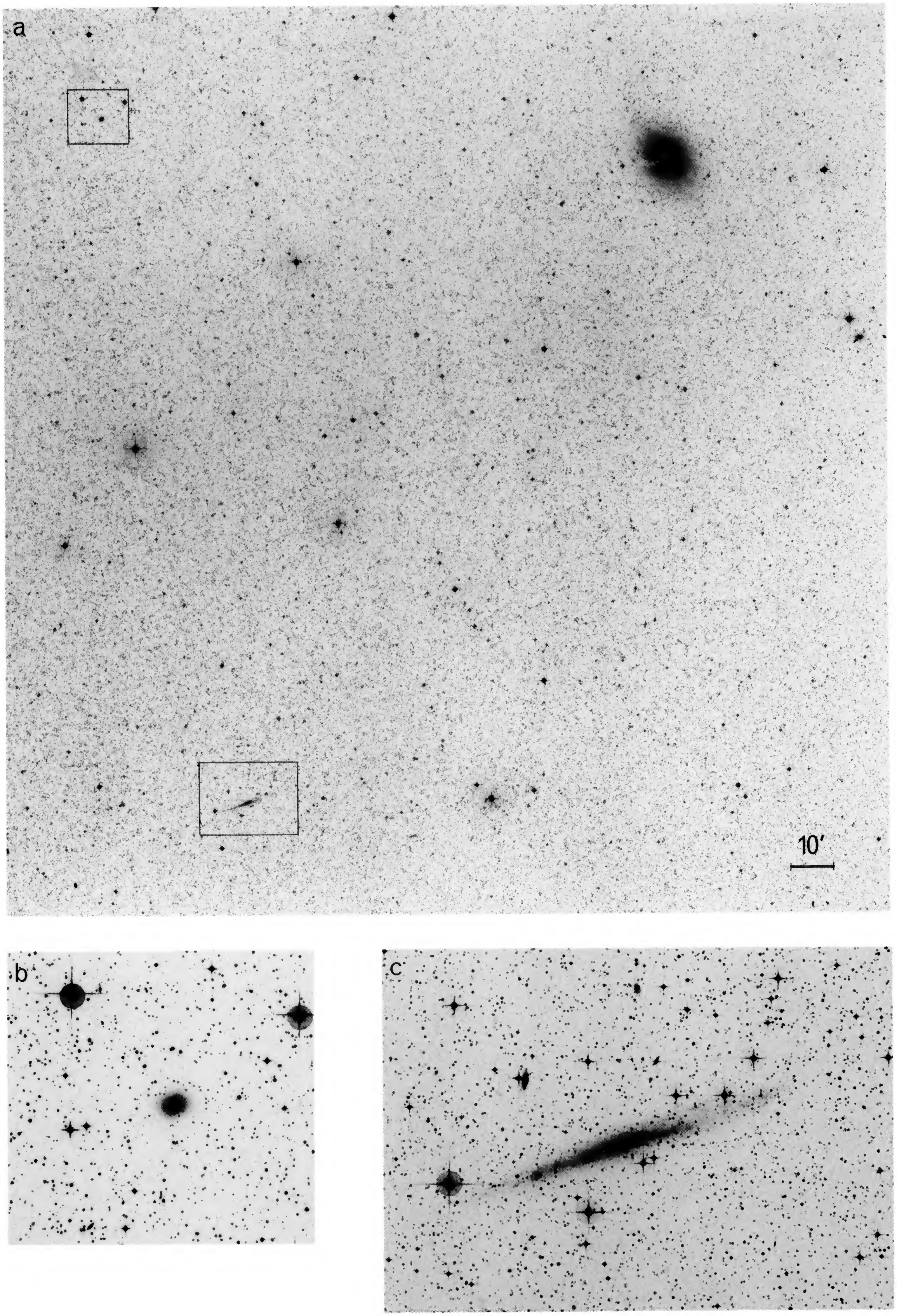

Plate 1. (a) Region south and east of Centaurus A (reproduced from the SRC Southern Sky Survey IIIaJ plate No. 270). (b) Close-up of the dwarf elliptical galaxy NGC 5237 [marked upper left in (a)]. (c) Close-up of the Fourcade–Figueroa shred [marked lower middle in (a)]. North is at the top, and east is to the left.

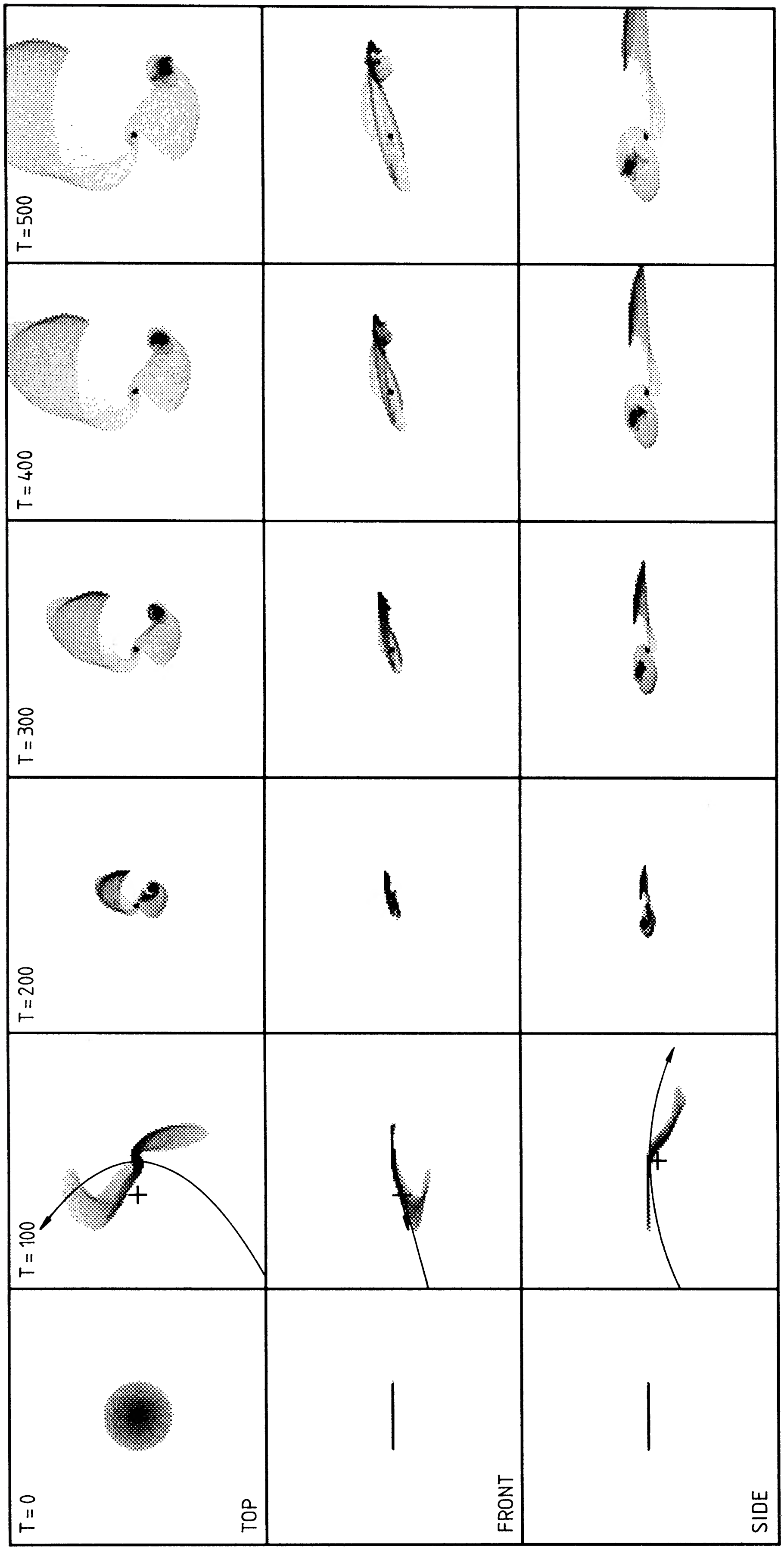

Figure 1. Shred-forming encounter viewed in the reference frame of the spiral galaxy. In this simulation, the spiral galaxy moves on a prograde parabolic orbit inclined at 15° with respect to the plane of the disc, as shown in the second frame set ($t = 100$). Top row – view from above; middle row – view from front; bottom row – view from side. The first two frame sets are 30×30 length units, and the last four frame sets are 300×300 length units.

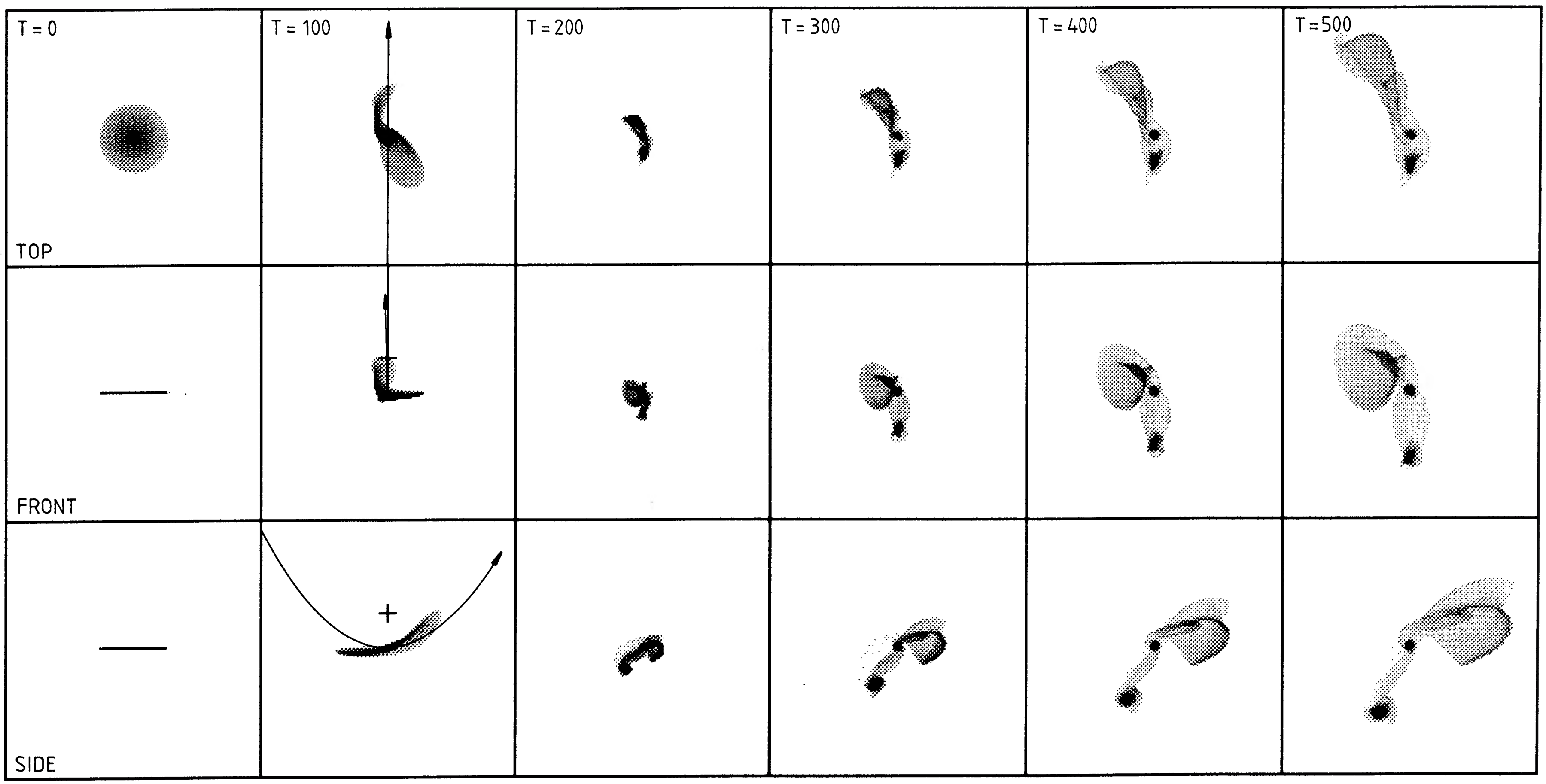

Figure 2. Shred-forming encounter viewed in the reference frame of the spiral galaxy. In this simulation, the spiral galaxy moves on a prograde parabolic orbit inclined at 90° with respect to the plane of the disc, as shown in the second frame set ($t = 100$). Top row – view from above; middle row – view from front; bottom row – view from side. The first two frame sets are 30×30 length units, and the last four frame sets are 300×300 length units.

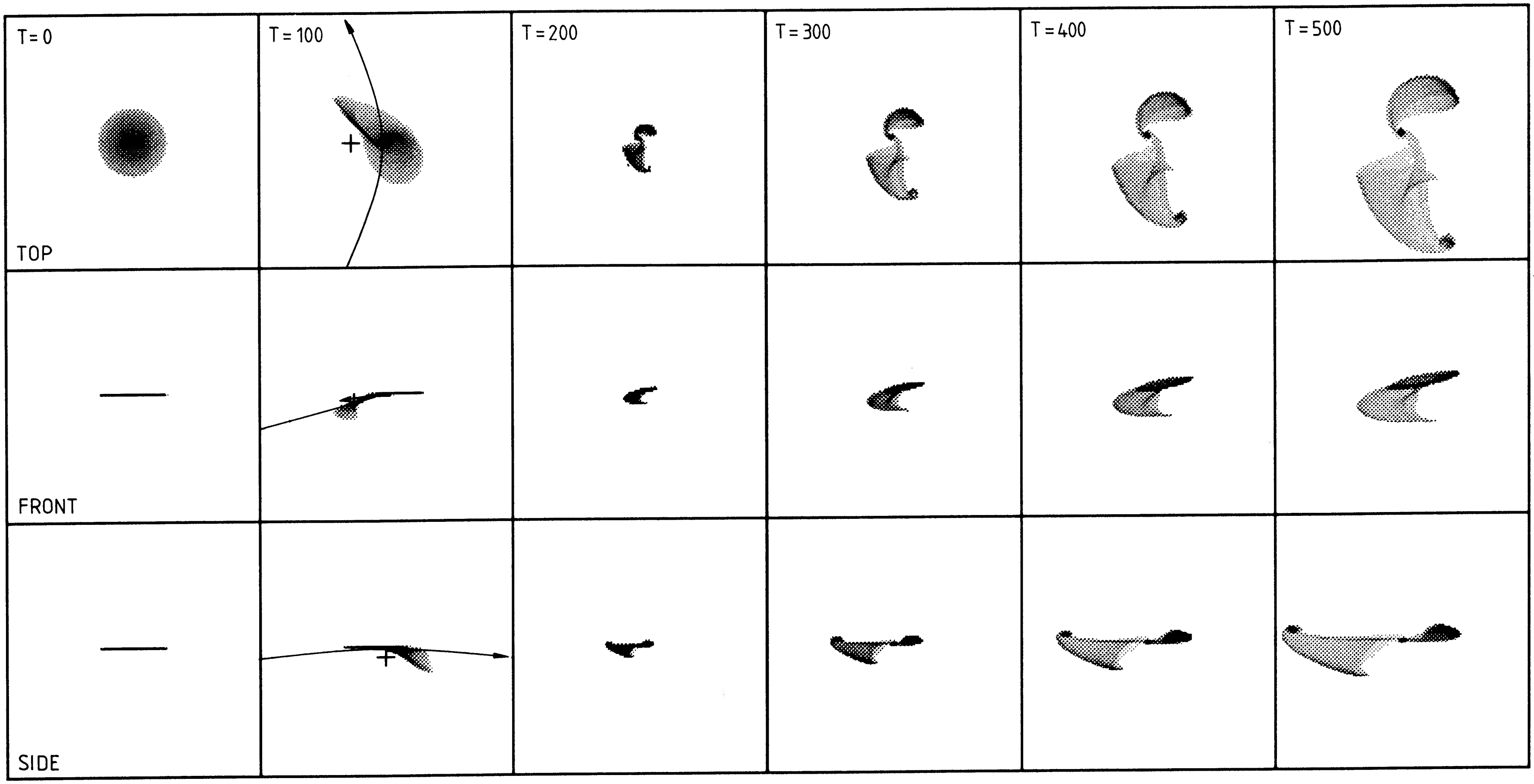

Figure 3. Shred-forming encounter viewed in the reference frame of the spiral galaxy. In this simulation, the spiral galaxy moves on a prograde hyperbolic orbit inclined at 15° with respect to the plane of the disc, as shown in the second frame set ($t = 100$). Top row – view from above; middle row – view from front; bottom row – view from side. The first two frame sets are 30×30 length units, and the last four frame sets are 500×500 length units.

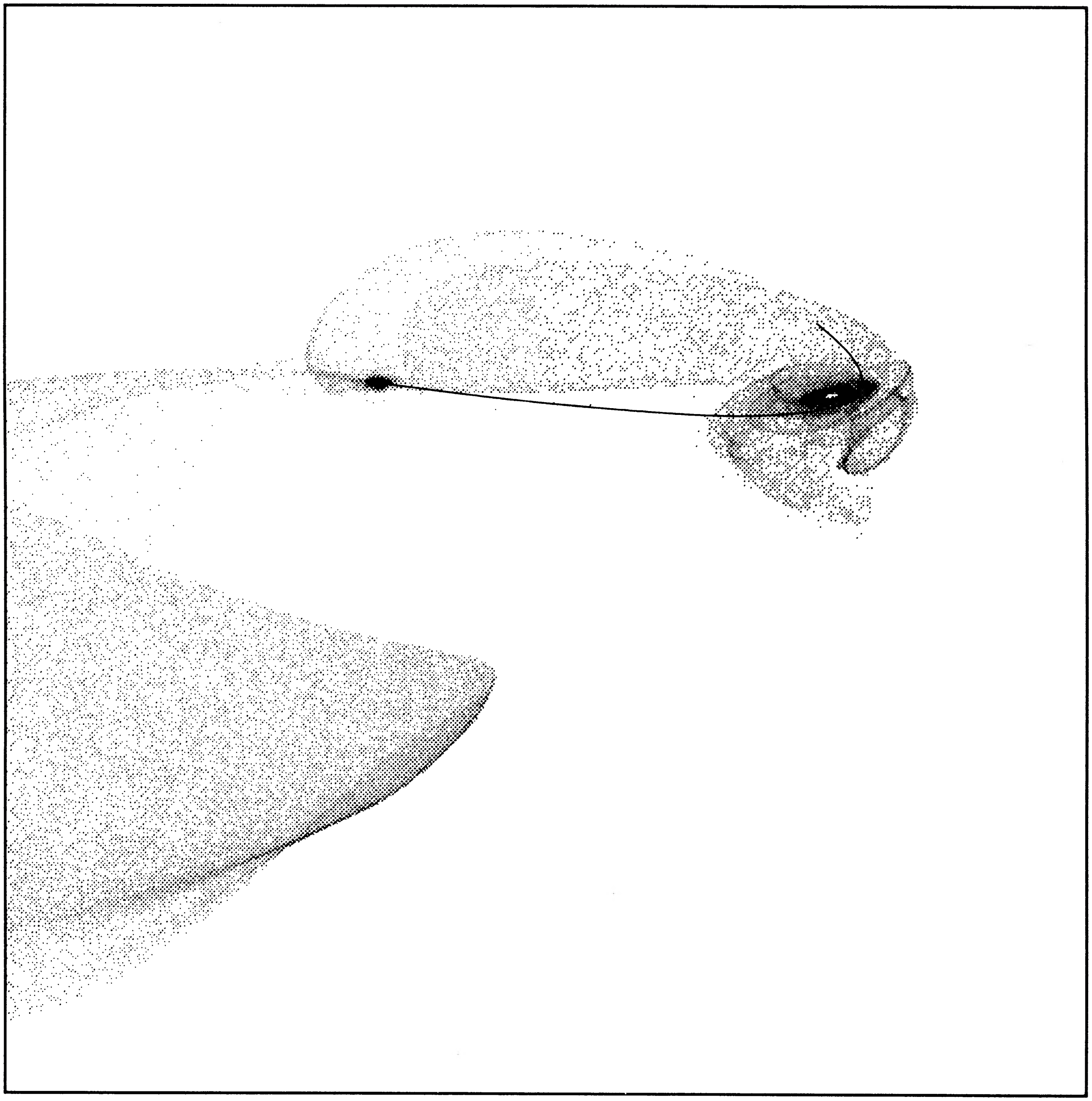

Figure 4. Simulation of the Centaurus A system as seen from the direction of the Sun. In this case, the spiral galaxy moves on a prograde parabolic orbit which is inclined at 15° with respect to the plane of the disc, and viewed from below the orbital plane at an angle of about 35° (from Fig. 1, $t = 500$). The solid line traces the orbit of the centre of mass of the progenitor spiral galaxy. The frame size is 200×200 length units.

cant fraction of the captured material forms a rotationally supported accretion ring, very similar to the observed distribution of gas and dust in Centaurus A. The model requires that the captured material is rotating in such a manner that the east side is blueshifted and the west side redshifted, which is as observed (Bland, Taylor & Atherton 1987).

The model predicts that the Fourcade–Figueroa shred is not rotationally supported. This is in good agreement with the result obtained by Graham (1978) who found a remarkably small velocity gradient along the major axis amounting to only about 10 km s^{-1} $arcmin^{-1}$ with an uncertainty of the same order. Graham argued that the small velocity gradient could be explained if the observed Hα emission originates from H II regions in the outer part of the galaxy only, with emission from the faster moving inner regions obscured by dust. Such dust lanes are common in the planes of spiral galaxies and are clearly visible when viewed edge-on. No such dust lane can be seen in this case. This explanation is therefore unlikely. The observed kinematics are not consistent with this galaxy being an edge-on late-type spiral, but are in good agreement with the shred model described here.

The discovery of an emission-line region in the dwarf elliptical galaxy NGC 5237 was particularly noted by Fairall (1979), who thought it may be a 'possibly active elliptical with ejected material'. Subsequently, Fairall (1981) argued that NGC 5237 may be a member of the Local Group in view of its low radial velocity relative to the Centaurus group, although he admitted that it cannot be nearer than 1 Mpc otherwise individual stars would be resolved. Fairall notes that the average level of excitation is that of an H II region. In terms of the shred model presented here, such a star-forming region would not be unexpected and probably represents the residual spiral disc material left in the bulge remnant after the encounter with Centaurus A. This interpretation is also consistent with the indications of spiral structure in NGC 5237 reported by Borchkhadze & West (1977).

4 DISCUSSION

Galaxy shredding offers a viable and consistent model for the origin of at least some dwarf elliptical and irregular type galaxies from progenitor spiral galaxies. The disc material accreted by the massive galaxy during a shred-forming encounter can also explain the presence of gas and dust in elliptical galaxies otherwise devoid of such material, and in some cases this may provide the fuel to power an active galactic nucleus (AGN). Immediately post-encounter, it is likely that massive star formation will take place in all parts of the progenitor spiral disc. Eventually, the three progeny of the collision will appear as a gas-rich irregular galaxy (the shred), a dwarf elliptical galaxy (the bulge remnant), and a dusty, possibly active relic of the massive (elliptical or spiral) galaxy.

Massive spiral galaxies as well as elliptical galaxies can produce shred-forming encounters – it is only necessary for the mass ratio to be about 10:1 and that the smaller spiral galaxy be on an approximately parabolic prograde orbit. Hence a dwarf spiral galaxy may be shredded by a giant spiral just as effectively as by a giant elliptical.

4.1 The accretion ring

There are many indications that nuclear activity is associated with galaxy interactions (Osterbrock 1991). Noguchi (1988) and Hernquist (1989) both describe a mechanism for fuelling AGN in Seyfert galaxies where *in situ* material in the gas-rich disc of the host spiral galaxy gradually loses angular momentum and spirals into the nucleus through non-axisymmetric perturbations caused by bars or by interaction with relatively low-mass companions.

Galaxy shredding provides a corresponding mechanism for fuelling AGN in gas-poor elliptical and other early-type galaxies. In this case, a large quantity of gas-rich disc material can be captured by a massive elliptical galaxy to fuel a sudden onset of activity, including star formation and radio emission such as that seen in Centaurus A.

Fig. 5 shows the evolution of the Centaurus A system as seen from the direction of the Sun. The long-term dissipationless evolution of the accretion ring is also shown in Fig. 5, together with a more detailed view of the collision around $t = 100$ time units showing the formation of the shred and the accretion ring. It can be seen that most of the accreted material initially moves on relatively high angular momentum orbits, to form a ring of dusty, gas-rich material which probably undergoes a strong burst of star formation during and immediately after the collision. Subsequently, material in the accretion ring will lose angular momentum due to dissipational collisions, as in the Noguchi–Hernquist model, to fuel the AGN.

The orientation and appearance of the accretion ring is consistent with the description given by Wilkinson *et al.* (1986) who concluded that we must be seeing the underside of the ring and therefore that the angular momentum axis is directed away from us. Fig. 5 also shows some warping of the accretion ring (especially in the outer regions) which is caused by the small but significant inclination (15°) of the spiral progenitor disc with respect to the orbital plane. This warping can help to explain the ragged southern edge of the dust lane in Centaurus A where it appears to be pulled down over the face of the galaxy, as described by Wilkinson *et al.* Additional warping may be produced by the non-spherical potential of Centaurus A, but this is not modelled here since the potential is assumed spherical. It might be interesting to investigate the effect of a non-spherical potential as well as other parameters on the evolution of the accretion ring, but this is beyond the scope of this paper.

The formation of such an accretion ring by mass transfer has been modelled previously by Toomre & Toomre (1972) who originally suggested that such a mechanism may be responsible for fuelling AGN. Their simulation involving a heavy companion was redone by Toomre using many more particles and this was later presented and discussed by Hernquist & Quinn (1988) as a possible shell-forming mechanism. Hernquist & Quinn did point out, however, that the flattened disc-like nature of the accreted material was not compatible with the morphology of shell structures in general, which are known to be three dimensional. It is possible that the sharp-edged features formed in the accretion ring could appear as complex shells when viewed at an appropriate angle, but not when viewed close to edge-on.

According to the weak interaction model of shell formation, shells are density waves induced in a thick disc population of stars by a weak interaction with another galaxy. For Centaurus A, it is suggested that *in situ* density wave shells were formed along and perpendicular to the major axis during the shred-forming encounter, and sharp-edged features in the accretion disc may form an additional low surface brightness component (Fig. 4).

4.2 The shred

Assuming that the Fourcade–Figueroa shred is typical of its class, then shreds are expected to appear as an apparently bulgeless edge-on spiral or irregular galaxy inclined at an acute angle with respect to a nearby (~few hundred kpc) massive galaxy. Shreds are blue and have a rich emission-line spectrum typical of star-forming regions. As such, shreds are expected to be infrared sources, like the Fourcade–Figueroa shred (IRAS 13317 – 4517). Shreds are best described as Magellanic Irregulars (IrI), and the Fourcade–Figueroa shred is similar to the Large Magellanic Cloud, albeit somewhat larger.

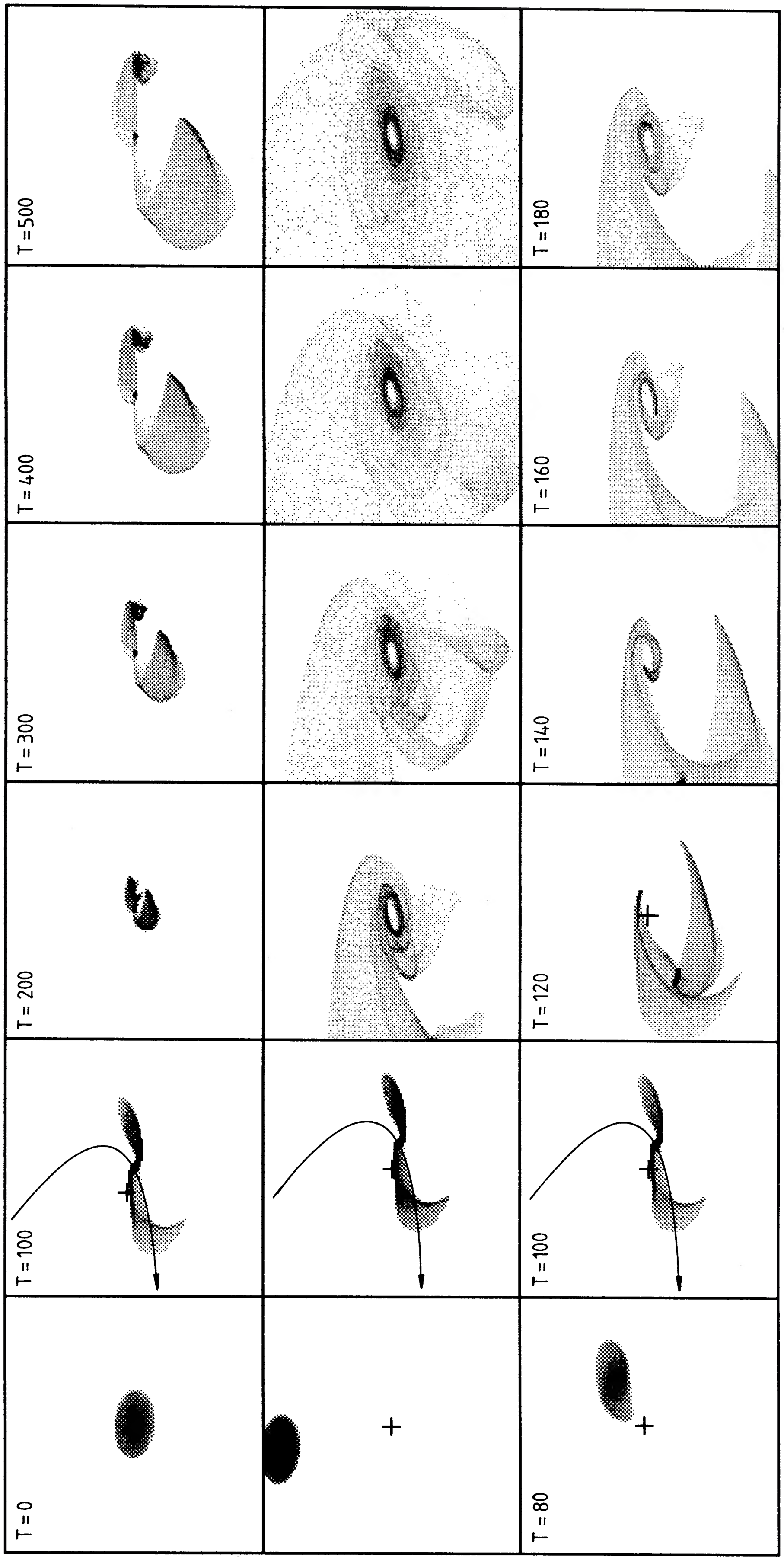

Figure 5. Evolution of the Centaurus A system as seen from the direction of the Sun. Top row – evolution of the whole system in the reference frame of the spiral galaxy (the first two frames are 30×30 length units and the last four frames are 300×300 length units); middle row – contrast-enhanced evolution of the accretion ring in the reference frame of the massive galaxy (each frame is 30×30 length units); bottom row – detail of the collision from $t = 80$ to 180 time units showing the formation of the shred and accretion ring in the reference frame of the massive galaxy (each frame is 30×30 length units).

Most characteristically, shreds are not rotationally supported and long-slit spectra could be used to distinguish them from edge-on late-type spirals. Immediately post-encounter, shreds are not in equilibrium and expand freely along the major axis, as seen in the non-gravitating simulations presented here. This major axis expansion will appear as solid-body rotation when viewed at an angle, even though the shred is not actually rotating at all. The expansion continues until self-gravity becomes effective on the dynamical time-scale of the shred. For the Fourcade–Figueroa shred, this is approximately 100 simulation time units (i.e. $\sim 1.3 \times 10^8$ yr). After this time, it is proposed that a stable self-gravitating bar-like system forms which does not appear to rotate along the major axis. Self-consistent simulations are required to determine more accurately the dynamical evolution of shreds.

The possibility that dwarf galaxies can be formed at the end of tidal tails was discussed by Schweizer (1978) who commented on the star-forming region seen at the end of the southern tail of the interacting pair of galaxies NGC 4038/4039 (the 'Antennae'). This system was originally modelled by Toomre & Toomre (1972) as a close encounter between two equal-mass spirals. A more sophisticated simulation by Barnes & Hernquist (1991), which includes self-gravity and dissipation in a gaseous component, shows the gas at the tip of the tail breaking up into dense knots. In fact, Schweizer (1978) cites several cases of H II regions at the end of tidal tails: NGC 4676 (the 'Mice'); NGC 2623 (Arp 243); NGC 6621/2 (Arp 81); NGC 3256; and NGC 2535/66 (Arp 82). He suggested this could be due to a higher concentration of H I gas in the outer regions of the spiral galaxy which now forms the tip of the tail. It is likely that shreds behave in a similar manner, and could sustain star formation at much greater distances from the progenitor spiral – far enough in fact for the connection to be previously unsuspected.

Shreds are not necessarily low surface brightness galaxies. As can be seen in the simulations, the surface brightness can be much higher immediately post-encounter. Clearly, the surface density of particles is higher at this stage, before being diluted by the expansion of the shred. In addition, massive star formation will take place at this epoch, further increasing the surface brightness. Newly formed shreds may therefore appear as relatively high surface brightness irregular/starburst galaxies. It is likely that the Fourcade–Figueroa shred was much brighter in the past than it is now.

4.3 The bulge remnant

Assuming that NGC 5237 is at the distance of Centaurus A, then its diameter is ~ 2 kpc and the size of the emission-line region is ~ 500 pc – somewhat larger than the giant H II region 30 Doradus (which has a diameter of 230 pc) in the Large Magellanic Cloud, but smaller than the whole 30 Doradus complex. Borchkhadze & West (1977) described NGC 5237 as a dwarf interacting system, and the emission-line region, also reported by Fairall (1979), is most clearly seen in their fig. 3D. Fairall (1981) described the galaxy as a low surface brightness dwarf elliptical with a slightly irregular profile. The average level of excitation is that of an H II region and the source of excitation is ultraviolet radiation from hot young stars.

The description of NGC 5237 as an interacting dwarf elliptical is consistent with the shredding model presented here. The residual disc material may be capable of sustaining star formation for a considerable time after the interaction, but once this fuel has been used up NGC 5237 will then appear as a normal dwarf elliptical galaxy. It seems likely that at least some dwarf elliptical galaxies can be formed in this manner. Whether or not this mechanism can explain the formation of a large fraction of dwarf ellipticals is not yet known.

5 CONCLUSIONS

Galaxy shredding occurs when a spiral galaxy undergoes a strong prograde interaction with a massive galaxy. Mass transfer takes place, and a significant fraction of the disc material is captured by the massive galaxy. It is suggested that this material may provide the fuel needed to power AGN in otherwise gas-poor elliptical galaxies. Most of the remaining disc material is thrown out of the system as a shred of dusty, gas-rich disc material which appears as a blue irregular/starburst galaxy. The progenitor bulge reappears relatively unscathed as a dwarf elliptical galaxy.

A case study of Centaurus A suggests that a shred-forming encounter with a spiral galaxy (about the same size as our own Galaxy) took place some 5×10^8 yr ago. The associated bulge and shred remnants have been identified as the nearby dwarf elliptical galaxy NGC 5237, and the Fourcade–Figueroa shred respectively. The captured disc material now forms the conspicuous ring of gas and dust which girdles Centaurus A, and probably provides the fuel that powers the radio emission we see today.

The shredding model described here provides a consistent picture of many aspects of the Centaurus A system, including: the relative positions and velocities of Centaurus A, NGC 5237, and the Fourcade–Figueroa shred; the orientation and sense of rotation of the dust lane in Centaurus A; the peculiar nature of the interacting dwarf elliptical galaxy NGC 5237; and the orientation and observed non-rotation of the Fourcade–Figueroa shred. The complex shell system of Centaurus A can also be understood in terms of a two-component model: density waves in a thick disc induced by the interaction, plus sharp-edged features in the accretion disc.

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