INTERACTING SYSTEMS

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I will confine this brief review to just two examples of galaxies that seem to have interacted recently with impressive consequences: (1) the well-known Messier 51 system NGC 5194/5 = deservedly VV 1, and (2) the so-called Cartwheel, a ring within a ring, separated by vaguely spokelike features and accompanied by two smaller galaxies.

These two situations deserve special emphasis, not only because of the presence in Tallinn of Vorontsov-Vel'yaminov who at least two years ago still regarded both as "enigmatic", but perhaps especially because they long fascinated also that other grand pioneer of our subject, the one whom we abbreviate as Zw. Indeed the Cartwheel was discovered by Zwicky (1941) himself — from Palomar with a 46-cm Schmidt telescope, despite its -34° declination — who then thought it "one of the most complicated structures awaiting its explanation on the basis of stellar dynamics". And in the very next paragraph of that old article, Zwicky went on to remark about M51 that "tidal actions operative during this encounter may have caused the two spiral arms in the big nebula" and, more significantly, "notice also an indication of a tidal effect in the small nebula, which has the aspect of a closed barred spiral".

Even I do not pretend that these two rich examples have yet shed all of their mystery. However, I do believe that modern observations offer some unusually clear and instructive signs of recent tidal damage in both cases — and also that the explanation of the Cartwheel as a tidal remnant has turned out to be almost embarrassingly simple.

1. THE NGC 5194/5 PAIR

The main evidence for tidal interplay between the two partners in this classic system has now grown to four items: two still refer to their *outer shapes*, and the other two to some newly-measured *velocities*. Those shapes and their orientations are shown beautifully in Figure 1, where a fairly standard (but already integrated) photograph has been superposed by M.S. Burkhead upon the photographic sum of five (!) deeply

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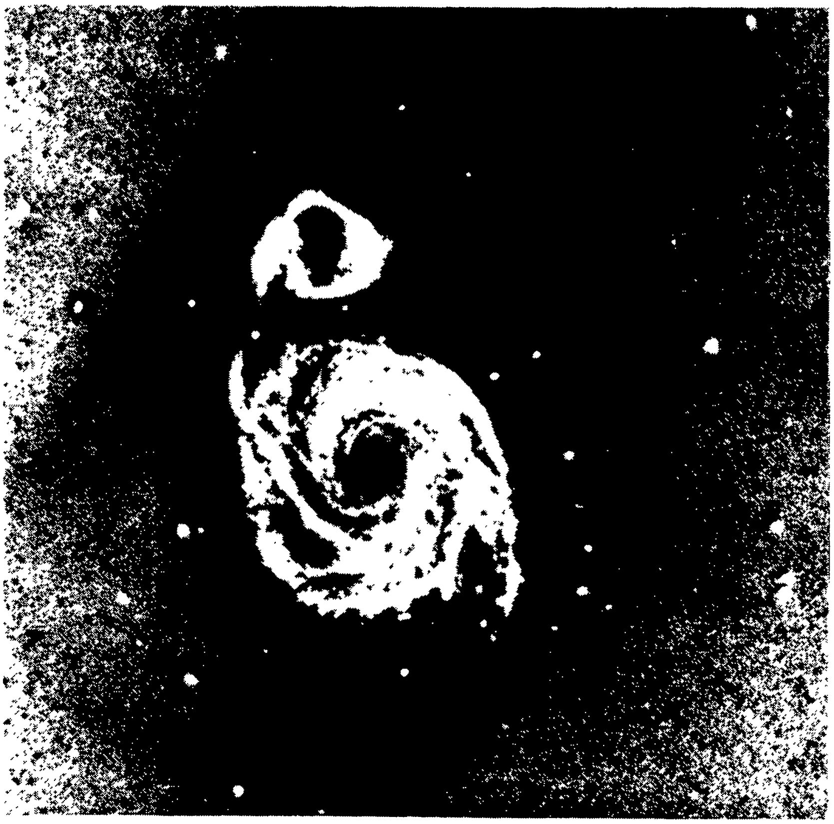

Figure 1. Recent composite photograph of NGC 5194/5, by Burkhead

exposed IIIaJ negatives, all taken by himself using the Palomar 122-cm Schmidt telescope. Very distinctive here — as in the older IIIaJ photograph by van den Bergh (1969; reprinted slightly darker by Toomre 1974) and in others which Schweizer and especially Lynds have kindly shown me in the past few years — is the almost comma-like lower outline of 5194, including its abrupt western edge that curves smoothly all the way from the northwest to the broad extremity in the south. And even more telltale, as I have stressed before, are the faint long plumes or streamers which seem to extend from 5195 toward the 2 and 8 o'clock directions.

I doubt that these long streamers could have been known to Zwicky (1941), since his sketches of various faint details even in the 1959 *Handbuch* article seem rather fanciful when compared with Figure 1. His "indication of a tidal effect in the small nebula" must have referred more to the strange impression of three spikes of a crown immediately to the north of 5195 that can be had from photographs not quite as burnt-out as the one above. On the other hand, I am afraid that Vorontsov-Vel'yaminov (1975a,b, 1977) was quite seriously mistaken when he wrote repeatedly that 5195 "does not exhibit the slightest evidence of the 'tail' and 'bridge' shown in the model" constructed by Toomre and Toomre (1972 = TT; see esp. Fig. 21), and that "none of the filaments ... predicted by the theory are observed, at least on the photographs published so far". If from nothing else, this last remark suffers from the oversight that, far from *predicting* any tidal plumes from 5195, my brother

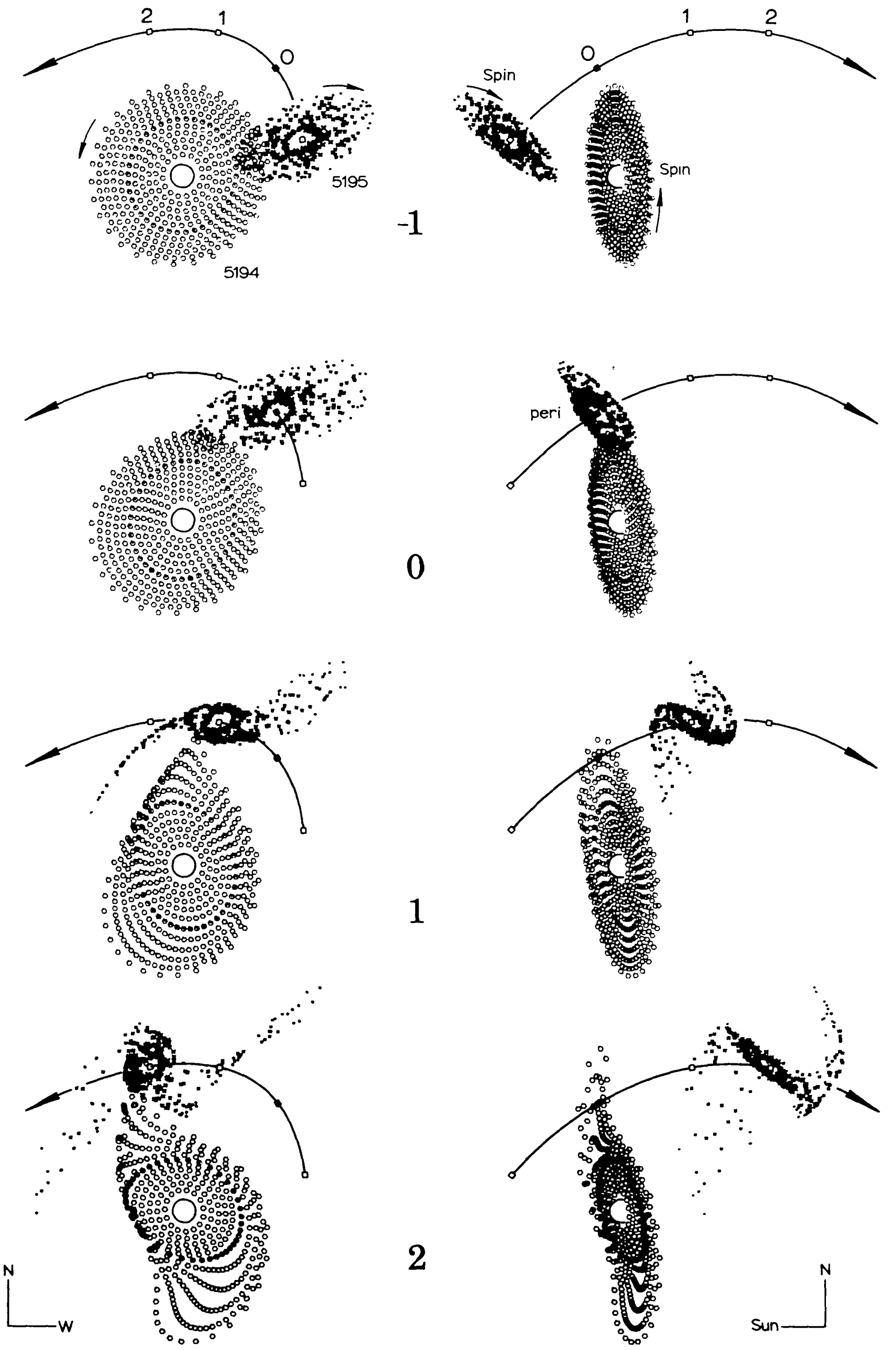

Figure 2. An improved model of the tidal encounter between NGC 5194/5. The left scenes are as if viewed from the Sun, the right set as if from the west. The main revisions from Figure 21 of TT are that the final (= present) time here is only 2.0 instead of 2.4, and that the satellite angles have been changed to $i_5 = -75^\circ$ and $\omega_5 = +10^\circ$ (from -60°, -15°). Less important, the line of intersection of the 5194 spin plane with the "sky" has been turned to a more realistic PA = -10°, and the main orbit angles have become $i_4 = -75^\circ$ and $\omega_4 = -20^\circ$. The tilt $\beta_4 = -22\overset{\circ}{.}5$ now. The gravity was also softened moderately at close range.

and I were frankly "peeking at the answer" as we then sought to *imitate* those striking features published already by van den Bergh.

This is not to imply that I remain very happy with the naive model concocted by TT. In retrospect, we were surely too greedy in presuming that the counterarm of 5194 had already narrowed itself kinematically, by mere lapse of time, into a curving feature more photogenic than the broad southern extension seen in Figure 1 and, incidentally, also in the 21-cm radio data of Shane and Bajaja (1975). And those tidal plumes from our make-believe 5195 were themselves perhaps unduly droopy, since we had not bothered to "optimize" them via adjustments of the angle ω_5. Fortunately, as Figure 2 illustrates using still only the massless particles without any original random motions, it was easy to lessen those flaws considerably via modest changes of parameters.

Enough about the outer shapes. Now what about the velocities? Obviously models such as shown in Figure 2 also imply something about those. For instance, as TT noted already, the purported tidal plumes in Figures 1 and 2 make sense only if it is the "east or southeast side of the main surviving body of NGC 5195 which most nearly approaches us". If that side were to recede, the tidal model would be dead. Schweizer (1977) checked: the east side approaches.

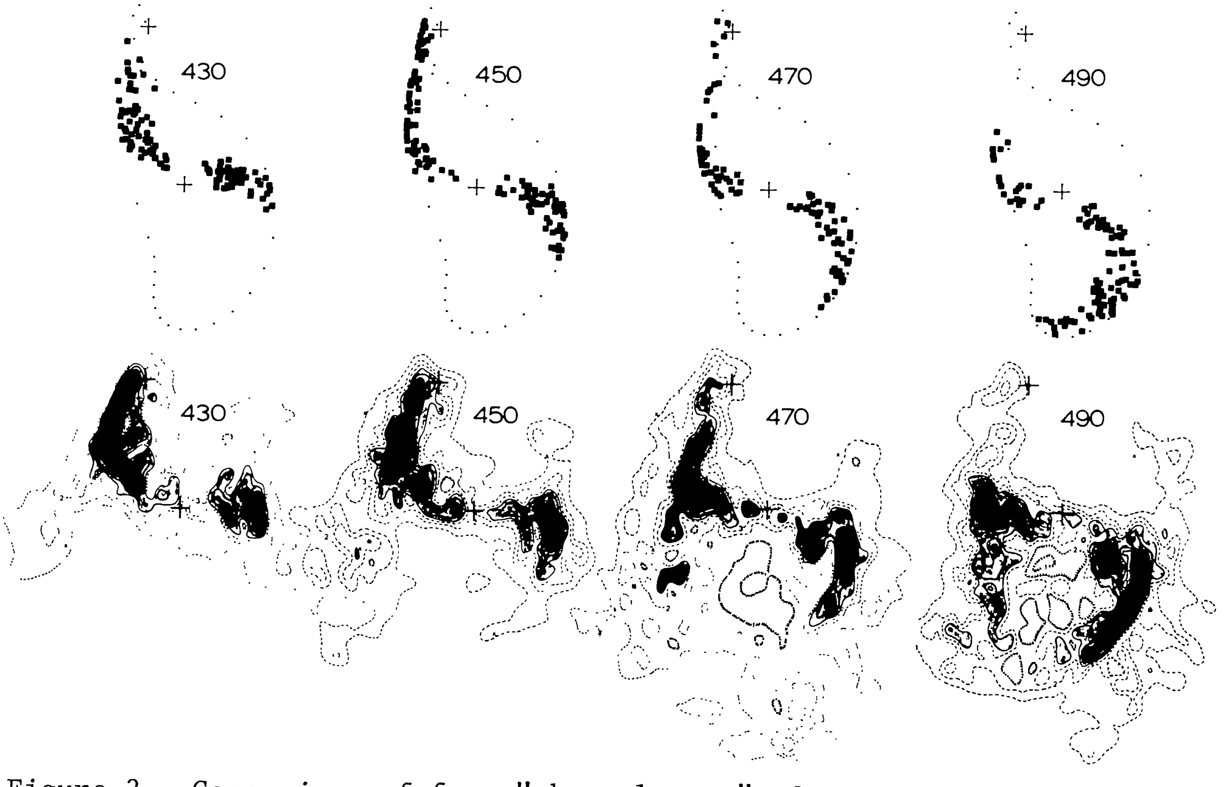

Figure 3. Comparison of four "channel maps" of neutral hydrogen in NGC 5194, obtained by Shane and Bajaja (1975; see also Shane 1975) with the WSRT and filters of ∿27 km/s width centered upon heliocentric speeds of 430, 450 ... km/s, against four similar maps implied by Figure 2 after adopting systemic velocities of 464 and 594 km/s for 5194/5.

Another interesting check is provided by Figure 3. As its lower row indicates, there is something odd about the 21-cm narrow-filter maps of neutral hydrogen produced with the Westerbork radio array and kindly made available by W.W. Shane. Instead of the familiar sectors symmetric about the major axis that one expects for a flat disk in normal rotation, these maps convey more the impression of an S shape, particularly in the two channels closest to the systemic velocity. A natural suspicion, voiced in part already by Weliachew and Gottesman (1973) in discussing their Owens Valley results with 4× coarser angular resolution, is that such abnormalities are further evidence of tidal damage. The four theoretical maps in the top row hardly discourage that notion.

Before leaving the M51 system, however, two ironies or conceivable difficulties also deserve to be aired. One irony of course concerns the spiral structure of 5194, situated mostly in deeper regions that suffered little in this simple tidal picture. As one who has also wondered aloud (TT, p.664) whether even that splendid structure might nevertheless have resulted indirectly from the encounter, I must here repeat sadly that such hopes seem to be fading. A truer story may well be that a fine pre-existing spiral got rather *dented* lately in its exterior.

A second and very different irony is that suddenly even the plumes in Figure 1 seem short in comparison with the 15+ arc min long region to the northwest in which Burkhead (1977) discovered and traced a distinct excess of faint light at about B = 25 or 26 mag/sec^2 level. And to compound that surprise, Giovanelli, Haynes and Burkhead (1977) reported that they in turn had detected, among various 21-cm residue in the surroundings of M51 known in part already to other observers like Shane (1975), also some with speeds as large as 650 to 700 km/s and roughly coincident with Burkhead's optical extension! Whether tidal debris (from yet farther out in 5195?) or something more primordial, here surely is a reminder that even old friends may not be entirely what they appear.

2. THE CARTWHEEL

Figure 4 shows the clearest photograph of the Cartwheel that I have yet seen. As noted already, the explanation of ring galaxies like this one has lately turned out to be astonishingly simple. According to Theys and Spiegel (1977), that accomplishment was almost entirely theirs — though I have recently been told also that Eneev, Kozlov and Sunyaev noticed the basic phenomenon in their own experiments three years ago.

To repeat this explanation, Figure 5 shows the transient outcomes of six different vertical bombardments of a given disk of randomly set test particles by another imagined galaxy which penetrates without any influence except its own inward pull of gravity. I used to think, in all the work leading to the TT paper and even for some time afterwards, that intrusions deeper than the one shown at the top of Figure 5 — and still yielding shapes reminiscent of M51 — would leave the target disk much too splattered. This impression remains valid for orbits rather

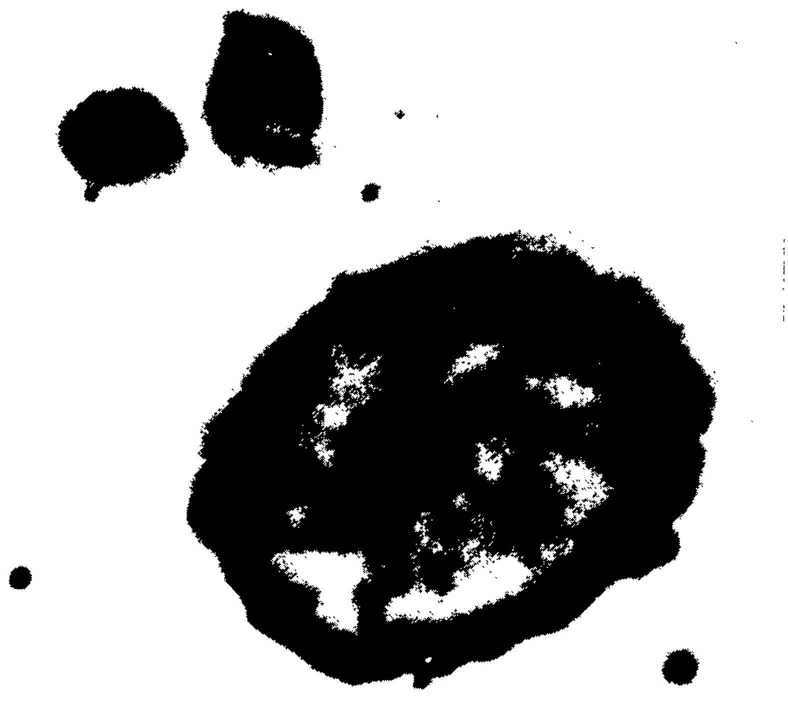

Figure 4. IIIaJ photograph of the Cartwheel, taken by Blanco with the 4-m telescope at Cerro Tololo Inter-American Observatory. North is up, and east is again to the left.

inclined in the *direct* sense relative to spin, but evidently the vertical orbits (with $\omega = 0$) already contradict my old intuition. In fact, although not shown here, I now know conversely that shapes with off-center "nuclei" like those resulting from impacts 2 or 3 in Figure 5 can themselves be improved by the arrival of the intruder in a *retrograde* orbit tilted as much as 45° from the vertical.

The Cartwheel itself appears to have required nothing even as fancy as tilting the orbit. We see that something like the next-to-bottom row in Figure 5 already provides a fair imitation. In reality, as Fosbury and Hawarden (1977) discussed, the blame probably belongs to the more easterly neighbor: unlike the other, its velocity increment is plausibly small, and so is its gas content. On a dark print of Blanco's negative, this galaxy even shows a semblance of a tidal hook. Most important, Fosbury and Hawarden also estimated that the intense HII regions which mark the ring have a net *expansion* (assuming the "spokes" trail) equal to about one-third of their rotational velocity — which indeed jibes with the "expansion that is perhaps smaller by a factor of 2 or 3" conjectured by Lynds and Toomre (1976) in a similar context.

As one final corroboration, notice that the simulations near the bottom of Figure 5 — just like the movie which Bob Reynolds from Ohio State University kindly prepared and lent me for this Symposium — even

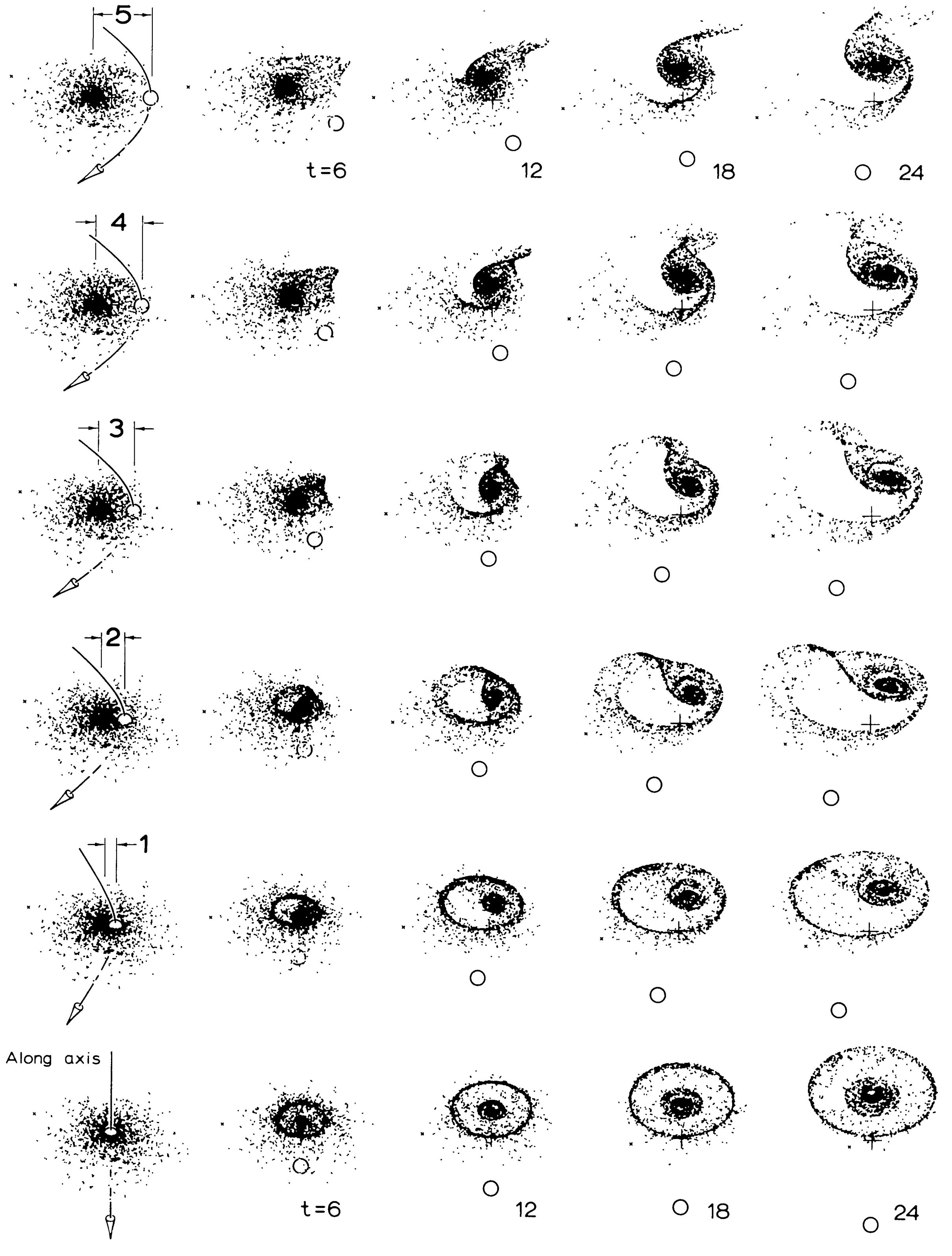

Figure 5. Six vertical penetrations of a disk of 2000 test particles. Long ago, these merely circled an unmarked central body 2× as massive as the parabolic intruder. Viewed from 45° latitude, their rotation appears counterclockwise. Gravity was softened again near both massive bodies.

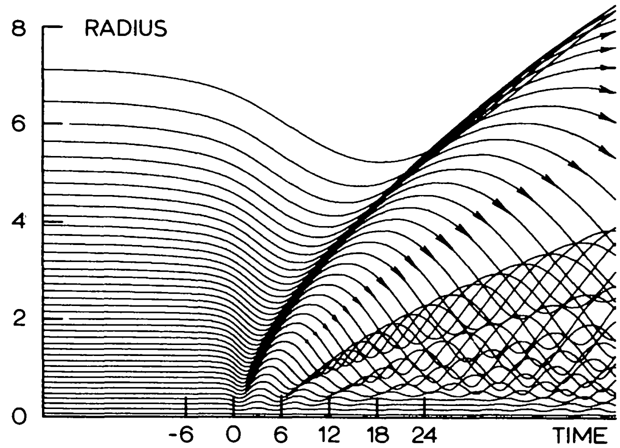

Figure 6. Radial locations of 40 particles from the symmetric encounter shown at the bottom of Figure 5.

manage to imitate the observed *inner* ring. Very reminiscent of later ripples that develop after a pebble has been dropped into water, this new zone of crowding here results (at least in theory) from the falling back and second rebound of the many independent "oscillators" that were yanked inward by the intruder. Figure 6 tells the same in more detail.

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REFERENCES

Burkhead, M.S.: 1977, *Astrophys. J.*, submitted.
Fosbury, R.A.E., and Hawarden, T.G.: 1977, *Monthly Notices Roy. Astron. Soc.* **178**, 473.
Giovanelli, R., Haynes, M.P., and Burkhead, M.S.: 1977, *Proc. IAU Symp.* **77**, in press.
Lynds, R., and Toomre, A.: 1976, *Astrophys. J.* **209**, 382.
Schweizer, F.: 1977, *Astrophys. J.* **211**, 324.
Shane, W.W.: 1975, in *La Dynamique des Galaxies Spirales*, CNRS, Paris (ed. L. Weliachew), p. 217.
Shane, W.W., and Bajaja, E.: 1975, private communication.
Theys, J.C., and Spiegel, E.A.: 1977, *Astrophys. J.* **212**, 616.
Toomre, A.: 1974, *Proc. IAU Symp.* **58**, 347.
Toomre, A., and Toomre, J.: 1972, *Astrophys. J.* **178**, 623.
van den Bergh, S.: 1969, *Astrophys. Letters* **4**, 117.
Vorontsov-Vel'yaminov, B.A.: 1975a, *Pis'ma Astron. Zh.* **1**, 3.
Vorontsov-Vel'yaminov, B.A.: 1975b, *Astron. Zh.* **52**, 491.
Vorontsov-Vel'yaminov, B.A.: 1977, *Astron. Astrophys. Suppl.* **28**, 1.
Weliachew, L., and Gottesman, S.T.: 1973, *Astron. Astrophys.* **24**, 59.
Zwicky, F.: 1941, *Applied Mechanics* (von Kármán volume), p. 137.
Zwicky, F.: 1959, *Handbuch der Physik* **53**, 373.