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MODELS OF THE CARTWHEEL RING GALAXY: SPOKES AND STARBURSTS

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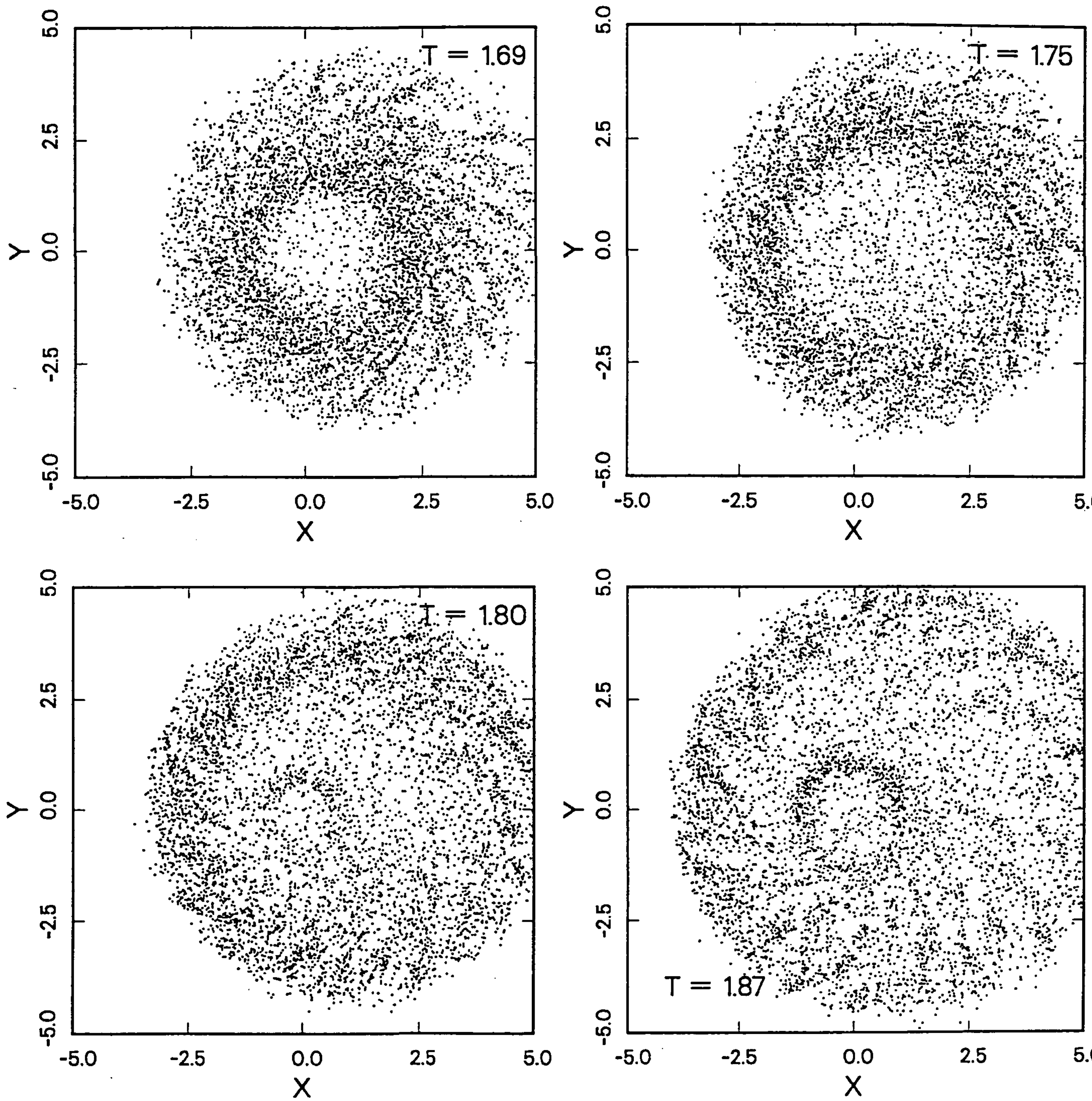
Recent observations of this famous ring galaxy, including optical and near-infrared CCD surface photometry (Higdon 1992a,c, in prep.; Marcum, Appleton and Higdon 1992, ApJ submitted), and VLA radio continuum and 21 cm. line mapping (Higdon 1992b, in prep.), have inspired a renewed modeling effort. Toomre's (1978, in The Large-scale Structure of the Universe, eds. Longair and Einasto) series of restricted three-body simulations demonstrated how the multiple rings could be produced in a nearly head-on galaxy collision. New models with a halo-dominated potential based on the 21 cm. rotation curve are able to reproduce such details as the spacing between rings, ring widths, offset of the nucleus, and several kinematical features, thus providing strong support for the collisional theory. (For details on these and the following results see Struck-Marcell and Higdon 1992, ApJ submitted).

The new observations have shown there are little or no old stars in Cartwheel; it may consist almost entirely of gas and stars produced as a result of compression in the ring wave. To model this process Smooth Particle Hydrodynamics (SPH) simulations of the Cartwheel disk have been performed. Fixed gravitational potentials were used to represent the Cartwheel and a roughly 30% mass collision partner. The interaction dynamics was treated treated as in the usual restricted three-body approximation, and the effects of local self-gravity between disk particles were calculated. We are particularly interested in testing the theory that enhanced star formation in waves is the result of gravitational instability in the compressed region (see e.g. Kennicutt 1989, ApJ 344, 685). The gas surface density in a number of simulations was initialized to a value slightly below the threshold for local gravitational instability throughout most of the disk. The first ring wave produces relatively modest compressions (a factor of order a few), triggering instability in a narrow range of wavelengths. Self-gravity in the disk is calculated over a comparable range of scales. Simulations were run with isothermal, adiabatic, and adiabatic with radiative cooling characterized by a relatively short timescale. The isothermal approximation is good except in the vicinity of the strong second (inner) ring, and several snapshots from one case are shown in the figure below.

Flocculent spiral segments are present before the collision, and these are compressed into dense knots in the ring wave. These knots are likely to be sites of vigorous star formation. In the strong rarefaction behind the outer ring most of the knots are radially stretched and sheared, giving rise to spoke-like features. A few dense knots are evidently very tightly bound, because they retain their coherence and are stretched relatively little through the rarefaction. This is in accord with evidence for continuing star formation in some spokes (Marcum, Appleton and Higdon 1992). The number and spacing of spokes is a direct function of the scale of the gravitational instability in the disk. Thus, the gravitational instability theory, together with the hypothesis that massive stars are only formed in dense knots of gas, can account for most of the distinct morphology of the Cartwheel. Some fine-tuning is required- the instability growth time must be less than the wave passage time. (In the Cartwheel models there are only a few growth times during the compressed phase.) But this helps explain why not all ring galaxies have multiple spokes. The simulations show that neither strong shocks, nor a greatly enhanced cloud collision rate, occur the outer ring, so evidently these processes are not the cause of the strong star formation in this galaxy.



Snapshots of particle positions in a two-dimensional isothermal hydrodynamical simulation with local self-gravity computed over distances of $\Delta r = 0.4\gamma$, where γ is the scale-length of the gravitational potential. X and Y positions are also given in terms of this scale-length, see Struck-Marcell and Higdon (1992, ApJ submitted) for details.