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Balcells, M

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Marc Balcells
Instituto de Astrofísica de Canarias

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Letter to the Editor

Interpreting asymmetric line profiles in merger remnants

M. Balcells[1,2]

[1] Kapteyn Astronomical Institute, Postbus 800, NL-9700 Groningen, The Netherlands
[2] Observatorio del Roque de los Muchachos, Apartado 321, E-38700 Santa Cruz de La Palma, Islas Canarias, Spain

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Abstract. Absorption line profile asymmetries in ellipticals with peculiar core kinematics, and their role as diagnostics of mergers, are analyzed using self-consistent numerical merger models. The remnants of mergers involving a denser secondary component show asymmetric line-of-sight velocity distributions at their cores. Skewness is negative where the rotation curve is positive and positive where the rotation curve is negative, in close agreement with observations. In the models, the asymmetry is not due to a disk of accreted secondary material; it is intrinsic to the distribution of primary particles, and has been added during the merger. It is argued that the asymmetries are a consequence of the transfer of the orbital energy and angular momentum to the primary particles during the merger; for the mergers studied here, profile asymmetries are a relic of the formation dynamics rather than the signature of superimposed components.

Key words: galaxies: kinematics and dynamics – galaxies: mergers

1. Introduction

Three years after their discovery, kinematically peculiar cores are seen as one of the most important signatures of mergers in ellipticals; central subsystems with kinematics independent from that of the main body of the galaxy strongly suggest the accretion of external matter. However, exactly what types of merger lead to the formation of kinematic peculiarities, and what implications this has on the merger history of ellipticals, is not clear yet. Proposed formation scenarios include the merger/accretion of a gas-rich satellite with dissipation and star formation (sE merger; Illingworth and Franx 1989); the swallowing of a compact ellipsoidal satellite (eE merger; Kormendy 1984); the merger between two equal-mass spirals (Schweizer 1990), and others (for reviews, see Bender 1990a, Balcells 1991). Each of these mechanisms suggests quite a different merger history for elliptical galaxies.

Of the aforementioned scenarios, the dense elliptical merger hypothesis has been studied in detail. Balcells and Quinn (1990a, hereafter BQ90) show, using self-consistent numerical simulations, that the smaller, denser secondary survives the tidal field of the primary, and counterrotating cores with properties similar to observations are formed if the merger is retrograde.

Several authors have proposed that clues on the structure and the formation of peculiar cores can be obtained by analysis of the absorption line broadening functions. Clear instances exist in which the line profiles are asymmetric, including counterrotation prototypes such as IC 1459 (Franx and Illingworth 1988, hereafter FI88) and NGC 5322 (Bender 1990a); the effect is also seen in ellipticals without peculiar rotation curves (Bender 1990b) and could in fact be quite common. Typically, spectral lines to the right and left of the center of the galaxy are mirror–symmetric images of each other, the skewness having the opposite sign to the mean velocity. Line profiles can be modelled with a superposition of two Gaussians, a broad one with low rotational velocity, plus a narrow one, with lower power and high rotation; its position shifts from right to left of the broad Gaussian as one moves from one side of the galaxy center to the other. An example of asymmetric line profile is shown in Fig. 1 (for NGC 5322 at 3.6″from the center, together with a two–Gaussian fit; see details in Bender 1990a).

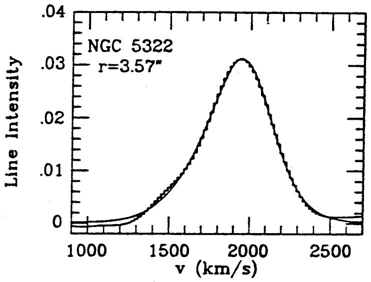

Fig. 1. Line-of-sight velocity distribution of NGC 5322 at 3.57″from the center along the major axis (from Bender 1990a). The data are given as a step function. The solid line is a two–Gaussian fit to the velocity distribution (see text).

A clear interpretation of the two–Gaussian decomposition is that one might be seeing a "bulge" and a small "disk". The disk would most likely have an external origin, especially so when the core counterrotates: after a merger with a gas-rich satellite, a gaseous disk might form near the center by dissipation, and turn into stars (Illingworth and Franx 1989); alternatively, a mostly-stellar satellite which disrupted near the center would create an accreted disk or ring (FI88). Thus the line profile shapes of ellipticals with counterrotating cores quite naturally suggest a "disk" interpretation of counterrotating features. This picture is atractive because it makes use of the paradigm that galaxian systems can be analyzed into independent components of the disk–spheroid types; it also is consistent with the conventional wisdom that gas accreted in a merger dissipates to the center and *feeds the monster* in active galaxies.

In this letter I show that embedded disks are not the only explanation for asymmetric line profiles as these arise also in a merger scenario which does not result in a visible accreted disk, namely the eE merger. Measurements of the line-of- sight velocity distributions in numerical eE merger models show that velocity distributions are asymmetric, just as in observations, but this asymmetry is not due to the added secondary material; the velocity distribution of primary particles is itself asymmetric. I argue that velocity distributions in eE mergers owe their asymmetries to deposition of orbital energy and angular momentum. After line asymmetries have been accounted for, resulting counterrotation velocities can be quite high, comparable to those of IC 1459.

These results imply that asymmetric line profiles do not by themselves indicate that material has been accreted and has settled into a nuclear disk. Nor can they be taken as evidence for dissipation during the merger. While dissipative processes plausibly form a disk and result in asymmetric line profiles, this observational signature results as well from the merger with a denser, mostly stellar companion with dissipationless dynamics. The strong rotation imprinted onto the core exemplifies the importance of the organizing effects that dissipationless mergers can have on the internal dynamics of the remnant (Quinn et al. 1990). Making this point seems necessary, given that it is customary to identify disk signatures at the centers of galaxies with processes involving gas dynamics.

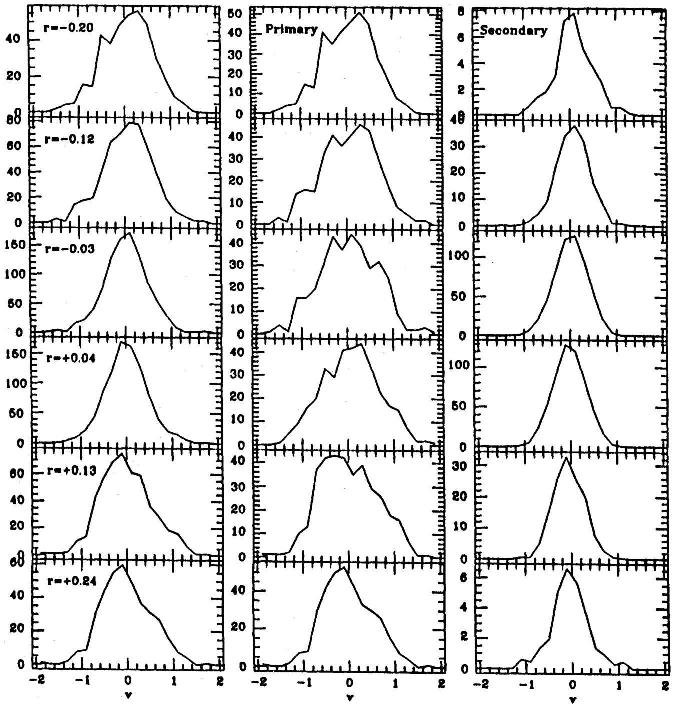

Fig. 2. Line-of-sight velocity distributions for a numerical merger model at the region of the counterrotating core. Left column: Velocity distributions at six positions along the major axis at given distances from the center. Central column: Velocity distributions of primary particles only, at the same positions. Right column: Velocity distributions of secondary particles only, at the same positions. The radius labels give the radius in units of the effective radius of the remnant. Abscissae are in reduced velocity units; one velocity unit corresponds to $463(5\cdot 10^{11} M/M_{\odot})^{1/2}\cdot(r_e/6\mathrm{kpc})^{-1/2}(\mathrm{km\ s}^{-1})$. Ordinates are in particles per bin (50 bins total).

2. Velocity distributions in merger models

Results from numerical simulations show that, after the merger with a compact secondary, a central region of distinct kinematics is created where both primary and secondary particles rotate in the plane of the merger orbit (see BQ90). Analysis of line-of-sight velocity distributions of the BQ90 merger models reveals that, for lines of sight close to the plane of the merger orbit (those that show rotation in the core) the velocity distributions are asymmetric. This occurs irrespective of whether the core counterrotates or not. Here I analyze the shapes of the line-of-sight velocity distributions in a merger model which contains a counterrotating core.

A sequence of line-of-sight velocity distributions is shown in Fig. 2, left column. They can be directly compared to line profiles such as that in Fig. 1, the only difference being the statistical accuracies, as absorption profiles have good signal in the wings whereas the count level in the models drops to zero at the wings. The line-of-sight velocity distributions are asymmetric to the left and to the right of the center. Where the peak velocities are positive the distributions are extended toward negative velocities, while distributions with negative velocity peaks have positive tails. Table 1 gives the mean, median, standard deviation and skewness for each velocity distribution. The median values give better estimates of the line centroids than the means, and are used here to define the rotation curve. The skewness is not a robust measure of asymmetries in the main peak of the distribution and is very sensitive to noise in the wings, which is high in the model distribution functions as the count level drops to zero. Nevertheless, the skewness profile follows the trends seen by visual inspection of the distributions; positive velocities give negative skewness and vice versa, just as in observations. The velocity distributions to the left and to the right of the center are mirror images of each other. Comparison of Cols. 3 and 4 in Table 1 shows that the core is a slow rotator: $V/\sigma \approx 0.1$, thus rotation cannot account for the observed asymmetries (see Bender 1990b).

I carry out another estimate of asymmetry, a two–Gaussian fit to the velocity distributions such as done by Bender (1990a) for NGC 5322 (see Sect. 1). The distributions corresponding to distances to the center $r/r_e = -0.12$ and $r/r_e = +0.13$ were least-squares fitted to the sum of two Gaussians. The results are shown in Fig. 3. Parameters for the fits are given in the caption to that figure. They imply a broad Gaussian at zero velocity, plus a narrow Gaussian with $V/\sigma \sim 1-2$. These parameters are comparable to those for the fit to NGC 5322 shown in Fig. 1 (Bender 1990a). The fits are acceptable given the noise of the data. They are not unique, just as in the fits to

Table 1. Statistical parameters of the velocity distributions. e_{skew} are statistical errors (calculated for an underlying Gaussian distribution)

$M_\odot$	$V_{\rm ave}$	$V_{\rm med}$	σ	*skew*	e_{skew}
-0.20	0.04	0.06	0.53	-0.15	0.08
-0.12	0.05	0.02	0.55	-0.14	0.05
-0.03	0.03	-0.02	0.54	-0.21	0.03
0.04	-0.04	-0.04	0.61	0.13	0.03
0.13	0.01	-0.05	0.54	0.16	0.06
0.24	-0.03	0.00	0.60	0.25	0.08

observed velocity distributions (FI88). In particular, the width of the narrow component is poorly constrained by the data. But the two–Gaussian model is a good representation of the line-of-sight velocity distributions. At the 99.73% confidence level the narrow component with non-zero velocity improves the fit to the velocity distributions. Attempts at single–Gaussian fits give poor results.

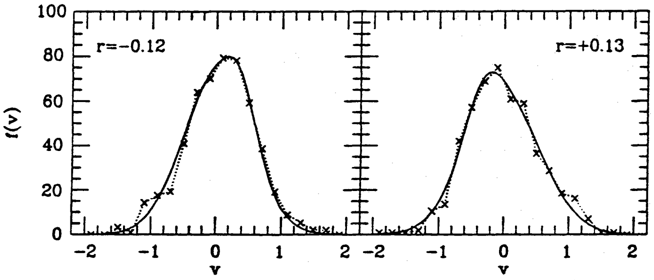

Fig. 3. Two–Gaussian fits to the asymmetric velocity distributions of a numerical merger remnant. The velocity distributions corresponding to distances $r = \pm 0.12$ effective radii are shown together with the fits (smooth curves). Abscissae are in reduced velocity units; one velocity unit corresponds to $463(5 \cdot 10^{11} M/M_\odot)^{1/2} \cdot (r_e/6{\rm kpc})^{-1/2}({\rm km\ s^{-1}})$. Ordinates are in particles per bin (50 bins total). **Fit parameters,** $r = -0.12$**:** *Gaussian 1*, Peak: 71.1; $v_0 = -0.03$; $\sigma = 0.52$; *Gaussian 2*, Peak: 18.4; $v_0 = 0.38$; $\sigma = 0.24$. **Fit parameters,** $r = +0.13$**:** *Gaussian 1*, Peak: 59.9; $v_0 = -0.02$; $\sigma = 0.58$; *Gaussian 2*, Peak: 19.0; $v_0 = -0.35$; $\sigma = 0.28$

The contributions of primary and secondary material to the velocity distributions are shown in the central and right columns of Fig. 2, respectively. Despite the higher noise of the partial distributions, the distributions of primary particles tend to reproduce the asymmetries in the total velocity distributions. The secondary particles form a low-velocity dispersion system near zero velocity. Where the light is secondary-dominated ($|r/r_e| \leq 0.04$; compare vertical scales), the lines are symmetric. It is at $|r/r_e| \geq 0.1$, where the contribution of the secondary becomes less important, that the lines become asymmetric; at these radii the total velocity distributions closely follow the distributions of primary particles.

3. Discussion

These results indicate that the secondary material accreted in the merger is not responsible for the asymmetry in the velocity distributions; the asymmetry comes from the velocity distribution of the primary particles. This asymmetry must be a result of the merger. Before, it did not exist (or it had the opposite sign). The most natural explanation is that the asymmetries arise from the transfer of the orbital angular momentum $J_{\rm orb}$ to the primary particles. At a given point in the galaxy, this absorption overpopulates orbits with a given sign of $J_{\rm orb}$ and depletes orbits with opposite sign. The wings of the velocity distribution are fixed by the virial theorem. The result is a compressed peak at non-zero velocity plus a wing of the opposite sign populated by particles which occupy a permitted but somewhat depleted region of orbit parameter space. By this process the absorption of $J_{\rm orb}$ generates asymmetric velocity distributions.

Bender's observations (Bender 1990a) show that rotation curve anomalies such as counterrotating cores or rapidly rotating cores are due to changing asymmetries, rather than to global displacements, in the line profiles. For eE mergers the numerical models show a similar situation (Fig. 2, left Column). The reasoning in the previous paragraph relating asymmetries to angular momentum transport would imply the following picture for the formation of counterrotating cores in eE mergers: the secondary core deposits orbital angular momentum into the primary core; this introduces asymmetries in the velocity distributions; the asymmetries cause shifts of the cross-correlation peaks which are recorded as reversals in the rotation curve. Counterrotating cores would then be a signature of the dynamical friction which slowed down the satellite and caused it to merge.

It appears that, for eE mergers, the link between counterrotating cores and mergers is more subtle than originally suspected; in a reversal of the rotation curve we may be seeing not the superposition of components with opposite rotation (embedded disks or spheroids) but a fossil signature of the merger dynamics. The merger has an organizing, in addition to a mixing, effect on the dynamics of the final system, which creates a differentiated core with organized rotation.

The dynamics of an eE merger is comparable to a dissipationless clumpy collapse, in which the most bound material before the collapse loses energy and thus transports energy and angular momentum to the core (Quinn, Salmon and Zurek 1986). It is then likely that asymmetric distributions of tangential velocity are general properties of equilibrium systems formed in a clumpy collapse.

BQ90 (see also Balcells and Quinn 1990b) did not measure the shapes of the velocity distribution functions in our merger models, but we found a suggestion that spectral lines in eE merger remnants are not asymmetric in the fact that both primary and secondary material counterrotate at the core. That reasoning, rooted in the expectation that asymmetries are caused by a rapidly rotating system of secondary particles superimposed on a slowly-rotating, high-σ, Gaussian-distributed background of primary particles, no longer applies if the primary velocity distribution becomes asymmetric during the merger. Because of that, the comment of BQ90 on line profiles just says that, after an eE merger, the line-of-sight velocity distributions contain no observable signatures of a disk of secondary material (after planar mergers, without orbit precession, a disk of secondary material appears, with surface brightness several magnitudes fainter than the primary material).

In the view of the asymmetry in the velocity distributions, the predictions of BQ90 for the maximum counterrotation expected from the eE merger models may be reevaluated. Comparing models to observations is not straightforward as each uses different methods to obtain a velocity value out of the velocity distribution. Using a median algorithm, BQ90 report typical counterrotating velocities of $40(M/5 \cdot 10^{11} M_{\odot})^{1/2} \cdot (r_e/6\mathrm{kpc})^{-1/2}$(km s^{-1}). Now, I use two-Gaussian fits in Fig. 3. In this particular case, the peak of the narrow Gaussian components occurs at $v_{\mathrm{narrow}} = 0.364 = 169$km s^{-1} (scaling as above). I scale this value to the high-counterrotation prototype IC 1459 ($\sigma = 308$km s^{-1}, $r_e = 6.24$kpc [Franx, Illingworth and Heckman 1989; $H_0 = 50$km s^{-1}Mpc^{-1}], $M = 9\sigma^2 \cdot r_e/G = 1.24 \cdot 10^{12} M_0$), and obtain $v_{\mathrm{narrow}} = 260$km s^{-1}. This value is close to the $v_{\mathrm{narrow}} = 300$km s^{-1} of IC 1459 (FI88) the fastest counterrotator known. This indicates how effective angular momentum transport is in organizing the motions at the core of the merger remnant, and suggests that this process can generate rotational velocities much higher than we are used to expect in the context of ellipticals.

It can be argued that maybe the primary material causing the line profile asymmetry forms in fact a disk (see discussion after Balcells 1991); we know that the core rotation becomes more organized as a result of the merger. The point is irrelevant in regards to identifying merger-induced accretion (which demands a *secondary* disk), or to finding evidence for dissipative processes, but may be relevant for the interpretation of pointed isophotes at the cores of ellipticals. From the two-Gaussian decompositions (Sect. 2) the material causing the asymmetry has as much as $V/\sigma \approx 1-2$. Such values are sometimes referred to as "disky" in the context of ellipticals; they are also consistent with a rapidly-rotating, flattened spheroid. Calling such a system a disk is largely a matter of personal preference; selecting these particles just on the grounds that they fall beyond the Gaussian velocity distribution is somewhat artificial. But the absorption of orbital angular momentum adds flattening and possibly pointedness to the core isophotes, and in that sense (only), one could say that the merger has formed a "disk". While the evidence from the models is not conclusive, this discussion does suggest that disk signatures seen at the cores of true ellipticals (Nieto et al. 1991) might in some cases be the result of angular momentum transport into the core during merger processes.

Finally, it is interesting that our expectations that line profile shapes would reveal the type of merger which forms kinematically peculiar cores have not been met. In fact, rapid rotation can account for asymmetric line profiles without the need to invoke a merger. In regards to mergers, we now know that eE mergers generate asymmetric velocity distributions; but, in principle, a merger involving gas dissipation and star formation (sE merger) can form a stellar disk at the core, with, presumably, the right surface brightness to create asymmetric line profiles. While theoretical understanding of some processes involved in the latter mechanism is incomplete, observational evidence for the presence of vast amounts of gas at the cores of recent mergers is well established. To complicate matters, real cases may correspond to a combination of both eE and sE processes; many small disk galaxies have bulges of exceedingly high density which will sink following collisionless dynamics, while the gas will dissipate. For now, we are to conclude that eE and sE mergers share similar observational signatures and that, in real cases, distinguishing between the two remains an elusive task.

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