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# Kinematic decoupled cores: counter-rotation or just inner warp?

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**Abstract.** We show that the kinematical decoupled cores (KDCs) can be explained by inner warping of the equatorial plane defined by the observed stellar rotation. The rigid-body like rotation in the central region of galaxies, makes the vertical frequency to be closely similar to the circular frequency, what enhances the stability of the disk-like central region and may lead to decouple it from the outer region.
Under the condition of smallest angular momentum difference between the outer stellar subsystem and its KDC, angles not larger than 30 degrees between inner and outer equatorial planes may explain fast and slow rotators of the "Sauron paradigm" in a unified scenario. The trends of geometrical vs. kinematic properties of the radial velocity fields are consistent with the scenario proposed here, which can mimic counter-rotation in one third of the warp cases (also consistent with the observed high fraction of counter-rotating KDCs).

**Key words.** galaxies: kinematics and dynamics – galaxies: structure – galaxies: evolution – galaxies: individual (NGC 7742, NGC 4382, NGC 770) – techniques: radial velocities

## 1. Introduction

A consensus has been established about the existence of decoupled central structures, on scales from tens of parsecs to a kiloparsec, in a variety of galaxies with brightness between $-22 < M_B < -16$ (Efstathiou et al. 1982, Franx et al. 1989, de Zeew et al. 2002, Emsellem et al. 2004). There is no unified scenario for the KDC phenomenon, but a widespread one was proposed by Balcells & Quinn (1990) who conclude that retrograde merging orbits might produce counter-rotating cores. A caveat of these models is that the smaller galaxy has to survive tidal stripping and dynamical friction, before arriving intact at the center of the main elliptical, a phenomenon which is not possible to reproduce by some numerical simulations (e.g. Bak 2000); and is not detected by central brightness distribution studies with HST (e.g. Franx & Illingworth, 1995). The merging scenario is also challenged by the presence of co- or counter-rotating KDCs in a disturbing number of dwarf ellipticals with $M_B > -19$ (de Rijcke et al. 2004; Geha et al. 2005; Emsellen et al. 2004; Thomas et al. 2006), and the striking similarity in the stellar content of the KDCs and the host galaxy (Davies et al 2001; Emsellen et al. 2004). VCC 510 in the Virgo cluster is the smallest dwarf currently known to exhibit a

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counter-rotating core ($M_B \approx -15.7$, Thomas et al. 2006). According to the authors, cases like VCC 510 should not be expected more than once per 400 galaxies in a Hubble time.

We propose in this paper that bending waves that produce disks warps are damped in the central region where the rotation approximate that of a rigid-body making the vertical frequency similar the circular one. In turn, that may lead to the decoupling of inner and outer stellar subsystems. Bending waves can be produced by external forces as well as by triaxiallity, what might explain why isolated galaxies also present KDC. In elliptical galaxies with KDC, the equatorial plane of the central oblated spheroids, might also be affected in the same way. Within this scenario, a simple issue, namely, the relative position of the inner and outer disk with respect to the plane of the sky may explain KDCs.

## 2. The quasi-rigid-body rotation curve and bending waves

The geometry and projected kinematics of a warped disk have been extensively discussed in the literature (e.g. Rogstadt et al. 1976). In the external part of most common rotation curves where $\Omega \propto 1/R$, slow and fast bending waves are produced which lead to warp the disk (Binney & Tremaine 1991). The situation is different for the central part where in general rotating disks present a rigid-body-like rotation curve with $\Omega \approx$ cst up to a turnover radius. For that to happens, the disk center must be dominated by a central spheroid with approximately constant density. In that case the vertical frequency $\nu \approx \Omega$ (Binney & Tremaine 1991), there will be no winding of the bending wave and the center of the disk would remain stable against this type of perturbation. This property allows us to examine the problem in the context of a sharp warping, physically separating the central part from the outer region of the equatorial plane of a rotating ellipsoidal galaxy, which we will simply call the disk.

## 3. Effects of projection on observed kinematics of a central warped rotating system

No distinction has been made in the Sauron paradigm literature, between disk galaxies (as NGC 7742, de Zeeuw et al. 2002) or galaxies with a strong spheroid (as NGC 474, Emsellem et al. 2004), we will in general refer to disk warps or tilts in the stellar rotation equatorial plane. The line joining the two points of contact between the inner and outer disks will be called the *line of warping*, and the angle between the planes of the outer and inner disks the *angle of warping*, $W$. The inclinations of the outer and inner disks with respect to the plane of the sky are called $i_o$ and $i_i$. A close inspection of SAURON 2-D velocity fields (Emsellem et al. 2004) reveals a variety of inclinations of the inner and outer disks intersection with the plane of the sky (line of nodes). From these velocity fields we can measure $i_o$, $i_i$, and the angle between the two lines of nodes $w = PA_o - PA_i$. In so doing, we can determine the angle of warping $W$ as: $\cos W = -\cos i_o \cdot \cos i_i + \sin i_o \cdot \sin i_i \cdot \cos w$, which allows us to recover the spatial location of the disks. The solution is not unique, and we can select the one in which inner and outer disk present the smallest difference in angular momentum, leaving open the possibility of having a real case of a counter-rotating KDC.

As an example, we take the radial velocity field of the circumnuclear ring of gas in NGC 7742, studied by de Zeeuw et al. (2002, their Figure 13). This otherwise normal SA(r)b galaxy (NED) is clearly face-on. The circumnuclear ring is indeed circular in appearance in the HST imagery, and the amplitude of the stellar velocities is modest. Our simple kinematic model, constructed from a typical H$\alpha$ rotation curve for a circumnuclear ring, co-rotating and tilted just 15 degrees with respect to the stellar disk, would explain the apparent counter-rotation. The angular momentum difference would be 3% of that required in the counter-rotation model.

We also developed a simple kinematic model for NGC 4382, which is one of the paradigmatic and extreme objects observed

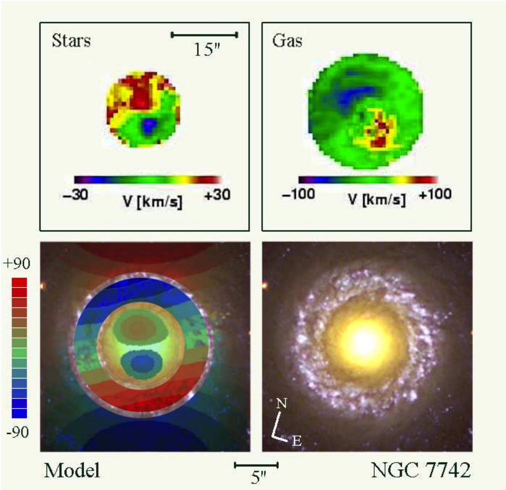


**Fig. 1.** Upper pane: Radial velocity fields of NGC 7742 (de Zeeuw et al. 2002). Bottom, left: model for the gaseous disk, with $i_g = +10^o$, $PA_g = 40^o$, and for the stellar radial velocity field $i_s = -5^o$, $PA_s = 30^o$, assuming a seeing of 1.5″. Bottom, right: Hubble Heritage optical composite image of NGC 7742.

with SAURON (Emsellem et al. 2004). It presents a counter-rotating KDC with a small rotation amplitude (∼ 30 km/s). The *g r i z* image of this SA(s)0 galaxy (see NED) depicts an internal region region with low axial ratio and a remarkable circular outer region. We modeled the radial velocity field with a Plummer spheroidal mass component up to 20″ .The external component has a small inclination ($i_o = +10^o$, $PA_o = 90^o$). For radii smaller than 2″ an abrupt but small change of inclination, and a line of nodes are introduced ($i = -10^o$, $PA_o = 70^o$). In that way we were able to reproduce the observed radial velocity field with an angular momentum difference of 6% of that required in the counter-rotating model (see Figure 2 in Diaz & Dottori 2008).

Another well known case is that of NGC 770, the dwarf elliptical galaxy satellite of NGC 772, observed at the Gemini telescope with GMOS-N (Geha et al. 2005). The cannibalism origin seems statistically implausible for this small galaxy. Geha et al. (2005) surface photometry shows a change in the photometric major axis at the KDC outer radius, but their spectra do not show a change in the chemical properties of the underlying stellar population, within the observational uncertainties. The UV-Far UV image (NED) shows a young stellar disk with axial ratios not smaller than ∼ 0.85, implying a disk inclination not larger than ∼ $30^o$. These facts are more consistent with a strong inner warp in the stellar disk, $W \leq 65^o$ in the example model, which requires an angular momentum difference of 40% of that required in the counter-rotation model.

## 4. Characterizing the warps families

We studied the radial velocity fields of 28 early type disk and spheroidal galaxies, compiled from the works of Emsellem et al. (2004), Mc Dermid et al. (2004), de Zeew et al. (2002), Copin et al. (2004), Wernli et al. (2002). We included those galaxies that exhibit KDCs. The host properties were taken from Tully (1988).

As Fig. 2 shows, the sample clearly separates into two halves at a rotational velocity maxima of ∼ 50 km/s. The fast inner rotation correlates with the outer rotational velocity amplitude and, strikingly, there are no counter-rotations over the 50 km/s limit. This is fully consistent with the fact that a fast rotator projection can be mimetized by a small warp only when the near sides of the inner and outer disks are on the same side of the plane of the sky. The correlation of maximum rotational velocities shown in the lower panel of Figure 4 agrees with the fact that we are looking at the same rotation curve. These observed trends in geometrical vs. kinematical properties support the small warp model ($W \leq 30^o$), which can mimic counter-rotation with any positional angle difference $w$ in one third of the cases, consistent with the observed high fraction of counter-rotating KDCs.

It is worth to note that there is no correlation of these parameters with the host properties such as magnitude, HI content, environment density, galaxy type, or total mass. As mentioned before, some spheroidal galaxies down to $M_B = -16$ show apparent counter-rotation, suggesting that some inner mechanism such as gravitational instabilities, might be acting over the nuclear stellar disks, as

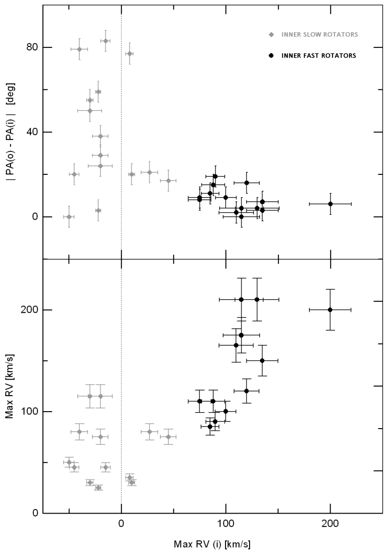


**Fig. 2.** Upper panel: position angle difference $w = PA(o) - PA(i)$ vs. maximum velocity of the KDC. Lower panel: maximum velocity of the outer radial velocity field vs. maximum velocity of the KDC.

quoted by Peletier et al. (2007) in a large fraction of the early type galaxies so far observed with 3D spectroscopy techniques.

## 5. Final Remarks

The stability of galactic disks central region against bending waves for rigid-body like rotation curves, may lead to kinematically decouple the center from the rest of the rotating system, phenomenon that we generically call "inner warp".

The spatial orientations of inner and outer equatorial planes can be retrieved from 3-D spectroscopy and imagery, namely, as used to interprete KDCs as counter-rotation. The distribution of differences in position angles of the inner and outer rotating subsystems tends to agree better with a scenario of warping than with the scenario of mergers. Warping includes a more simplistic explanation of central fast-, slow- and counter-rotating KDCs. The presence of KDCs in galaxies with wide variety of masses is, dynamically speaking, less traumatic in the warp scenario than in the counter-rotation scenario. They also seem to be well-integrated in a scenario in which a large fraction of early type galaxies harbor young stellar circumnuclear disks (Peletier et al. 2007).

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