Toward a detailed view on the kinematics of intermediate luminosity early-type galaxies no dark matter candidates

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Abstract. In several nearby $L \sim L_\star$ early-type galaxies, recent observations at large radii have shown a indications of a lack of dark matter, substantially at odds with the prediction from the Cold Dark Matter (CDM) hierarchical merger models. Here we discuss a pilot observational project for the study of the internal kinematical and dynamical properties of this remarkable sample of galaxies. Using the VIMOS-IFU in its high spectral resolution mode, it would be possible to investigate the regions up to $\sim 1.2 R_e$, taking advantage of the much larger field of view and telescope diameter. This will allow to disclose the presence of any kinematical substructures which could affect the conclusion on the mass modeling and definitely clarify the inner structure of this particular class of early-type galaxies.

Key words: galaxies: elliptical; galaxies: kinematics and dynamics; instrumentation: spectrographs

1. Introduction

Intermediate luminosity early-type galaxies ($L \sim L_\star$) are interesting laboratories where to test both the galaxy formation theories and the presence of the dark matter. Their structural and kinematical properties make them a different class with respect to the brightest systems. Indeed, from the photometric point of view, bright galaxies have usually boxy isophotes and flat inner cores in the light distribution while fainter galaxies are mostly disky with power-law inner light profiles (Nieto & Bender 1989, Capaccioli et al. 1992, Faber et al. 1998).

These isophote shapes appear to be correlated with a variety of properties of these systems (Kissler-Patig 1997, Pellegrini 1999 and references therein), in particular with the kinematics: bright/boxy systems are slowly rotating in the inner parts, while faint/disky galaxies are rotationally supported at least within $1 R_e$ (the effective radius $R_e$ encloses half of the galaxy projected light), the typical observational limit for kinematical studies by integrated light long-slit spectroscopy (Bertola & Capaccioli 1975, Davies et al. 1983, Scorza & Bender 1995).

Recently, some lines of evidence has been found about the persistence of such a dichotomy also in the dark matter properties of these systems. Capaccioli et al. (2003) and Napolitano et al. (2003) have discussed the correlation between the structural parameters and the radial trend in the mass-to-light ratios (M/L) using archive kinematic data up to $\sim 6 R_e$ for an heterogeneous sample of ellipticals: faint/disky galaxies show small or null M/L radial gradients, i.e., almost constant M/L, while bright/boxy objects have larger gradients in agreement with a substantial amount of dark matter in the outskirts of those systems. In particular the evidence of a dearth of dark matter in the intermediate luminosity galaxies has been confirmed by Romanowsky et al. (2003) using planetary nebulae (PNe) kinematics out to $4 R_e$. Confirmation of these preliminary results by new observations with larger PNe samples or new techniques is very important, since a possibly tight connection between structural properties and density environment (i.e., the dark matter halo) where the galaxies have grown would deeply affect our understanding of galaxy formation and evolution.

The formation and evolution of these intermediate luminosity galaxies with almost null M/L gradients is still not clear. As a class, disky galaxies can be considered close to the bulge dominated S0 galaxies since disky isophotes could reflect the presence of an embedded faint stellar disk (Capaccioli 1987; Bender et al. 1988). Scorza & Bender (1995) have shown that the information on both photometry and line profile of a sample of disky galaxies is compatible with simple disk+bulge models where the two subcomponents have parallel angular momenta. This latter evidence could be an hint of a contemporary evolution for these galaxies rather than a late accretion or merger events.

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However, disky isophotes are also expected in hierarchical merging scenarios in a CDM cosmology (Meza et al. 2003): boxy/disky isophotes are found for inclinations which minimize/maximize $v_{rot}/\sigma$. Furthermore, clues on angular momentum alignment could change when looking at the halo regions of these systems. Preliminary results on PNe radial velocity fields of NGC 3379 and NGC 4494 from the Planetary Nebula Spectrograph, (PN,S, Douglas et al. 2002), have revealed that there is a tilt of the major kinematical axis of the PNe sample with respect to the stellar long-slit data as it is clearly shown in Fig. 1. In the same figure a quite good alignment is found for NGC821 as well as it has been found also in earlier studies (NGC 4697: Mendéz et al. 2001). Incidentally, the latter are viewed quite edge-on, while NGC 3379 and NGC 4494 are possibly nearly face-on. Furthermore, at least for the four systems mentioned above, the rotation velocity curves increase in the inner parts (up to $R_e$) and rapidly drop in the outer parts down to zero at the outermost points. Is this an indication of some secondary evolution processes in some of these galaxies (i.e., tidal interactions or merging), or is this the result of different stellar population inhabiting inner (disk population) and outer (bulge/halo population) regions, which appear to dominate depending on the viewing angle?

The geometry can play a major role even in modeling the mass distribution, in particular for the systems seen almost face–on (Magorrian & Ballantyne 2001). If the presence of a disk is kinematically relevant up to large radii, then we could expect radial orbits to dominate in projection, causing an apparent decreasing velocity dispersion and then a mass underestimate, i.e., we would erroneously conclude that there is a lack of dark matter.

So far traditional long-slit spectroscopy has been employed to address these problems, resulting in one dimensional information mostly performed along the main principal photometrical/kinematical axes of galaxies (Bender, Saglia & Gerhard 1994, Statler & Smecker-Hane 1999).

Nowadays, integral field spectrographs are opening a new era in the understanding of the galaxy structure and evolution. We discuss here an observational project to study a preliminary sample of intermediate luminosity/disky galaxies using the Integral Field Unit (IFU) of VIMOS. The most important wide field integral field spectroscopy instruments used to study nearby elliptical galaxies are published in de Zeeuw et al. (2002).

At the moment a new IFU is available to the astronomical community, with a wider field of view, the VIMOS - IFU. It is one of the three possible operation modes of VIMOS, the new survey-designed instrument mounted on VLT-UT3: wide field imaging, multi-object spectroscopy (up to several hundred slits) and integral field spectroscopy. Detailed information on the instrument, the IFU and its operational modes can be found at the ESO web site; see also Foucaud et al. (2003) for a brief description of the data analysis and D’Odorico et al. (2003) for a review of its performance. Up to now, the VIMOS-IFU has the largest f.o.v. among the instrument devoted to integral field spectroscopy: up to $54^\prime\prime \times 54^\prime\prime$ in the low (spatial and spectral) resolution mode, allowing to obtain up to 6400 spectra. In high spatial resolution mode the f.o.v. is $27^\prime\prime \times 27^\prime\prime$ and fibers of $0.5^\prime\prime$. First results from this SAURON survey of early-type galaxies are published in de Zeeuw et al. (2002).

The HR-Blue grism (420-615 nm) covers the spectral range traditionally used to study kinematics of local galaxies with a spectral resolution, $R \sim 2500$, i.e., $\Delta \lambda = 2.0$ Å at $\lambda = 5000$ Å; indeed it allows to observe the following spectral lines in the local Universe:

- Mg b triplet @5170 Å
- Fe lines @5270, 5335 Å
- [OIII] @4959, 5007 Å
- H$\beta$, @4861 Å

while with the redder grism HR-Red (635-860 nm) it will be possible to cover also the H$\alpha$ emission line. The first two of these lines would allow to probe the stellar kinematics, while [OIII] and H$\beta$ can be used to derive information on the properties of the ionized gas (morphology, kinematics and ionization state). The larger wavelength coverage, compared to the one used from the SAURON team will allow to pursue the same kinematical and dynamical study beyond the local Universe.  

There are some other advantages of VIMOS-IFU with respect to SAURON: in the higher resolution mode the field of view is comparable to the one of SAURON, but with a slightly lower instrumental dispersion ($\sigma_{inst} \approx 80$ km s$^{-1}$ at $R = 0.5R_e$ in a single pointing for nearby luminous galaxies.

The SAURON project is a large and ambitious survey of a representative sample of 72 nearby early-type (E, S0 and Sa) galaxies ($z \leq 0.01$). The f.o.v. is $33^\prime\prime \times 41^\prime\prime$ in the low resolution mode ($\Delta \lambda = 3.6$ Å, i.e., $R \sim 1400$, each fiber covering $0.5^\prime\prime$.94), and $9^\prime\prime \times 11^\prime\prime$ in the high resolution mode ($\Delta \lambda = 2.8$ Å, $R \sim 1800$ at 5000 Å, each fiber covering $0.2^\prime\prime$.28). The 1520 spectra cover the range from 4800 to 5400 Å. The instrumental velocity dispersion $\sigma_{inst}$ is 105 and 90 km s$^{-1}$, in the two modes, allowing to measure the line of sight velocity dispersion of stellar spheroidal components of galaxies that have velocity dispersions larger than about 100 km s$^{-1}$. First results from this SAURON survey of early-type galaxies are published in de Zeeuw et al. (2002).

2. Integral field spectroscopy of nearby galaxies

Since integral field spectrographs are available on 4-meter class telescopes, the study of the kinematics and the internal structure of local early-type galaxies has been one of the most important applications of such instruments. In particular, a long term project has been undertaken by the SAURON team (de Zeeuw et al. 2002), using the integral field instrument SAURON (Bacon et al. 2001) at the WHT (La Palma). SAURON has been the first IFU with a field of view (f.o.v.) larger than $10^\prime\prime$, i.e., wide enough to obtain data up to $0.5R_e$ in a single pointing for nearby luminous galaxies.

http://www.eso.org/instrument/vimos

2 In the near future, it is planned that SAURON will operate also in the range 4500-7000 Å, in order to cover also the H$\alpha$ emission line, but for the same set of $z < 0.01$ galaxies.
obtained with extended PNe kinematics (e.g., Bertin et al. 1994). Since this result clearly does not conform with the CDM evolution scenarios, more detailed studies (using reconstructed continuum image from IFU data) as well as better constraints on the intrinsic inclination (see, e.g., Verolme et al. 2002).

Using such a full 2D kinematical map, we expect to definitely disclose the presence of any substructure that could affect the projected kinematics like faint disks seen at high inclination, by means of the azimuthal modulation of the velocity moments on the sky plane (for instance, a non-cylindrical rotation velocity in proximity of the main kinematical axis).

For the galaxies in Table I, Romanowsky et al. (2003) have applied a full spherical Schwarzshild orbit library method (Romanowsky & Kochanek 2001) for modeling the PNe kinematics with different degree of anisotropy. Such a kind of studies would be greatly advantaged by a full 2D kinematical map of such a galaxies, as it could be obtained by combining the 2D discrete radial velocity field of PNe with the integral field data. In Fig. 1 a smoothed version of the PNe radial velocity fields Romanowsky et al. (2003) is shown: this is the kind of data which we expect to complement with the VIMOS-IFU observations. In particular we expect to obtain:

- a description of the fine structure of the stellar kinematics with a spatial resolution of $0.67^\prime\prime$, mapping the line-of-sight rotation velocity $V$, velocity dispersion $\sigma_v$, and higher Gauss-Hermite coefficients $h_3$, $h_4$. These maps can be quantified via Fourier methods.
- the possibility to reveal the presence of subcomponents along the line-of-sight both from $h_3$ and $h_4$ distribution and possibly using the double-Gaussian fit as performed in Scorza & Bender (1995)$^5$.
- the association between kinematical and photometrical structures (using reconstructed continuum image from IFU data) as well as better constraints on the intrinsic inclination (see, e.g., Verolme et al. 2002). For instance, with 6 VIMOS-IFU pointings it is possible to cover an area of $81'' \times 54''$ around NGC3379 center, corresponding to $1.2R_e \times 0.8R_e$ with an average S/N of 30 in a total of 14 hours integration. In this area a sample of at least 60 PNe is present, which is expected to be sufficient for any check of consistency between kinematical estimates (Napolitano et al. 2001).

Such a kind of studies would be greatly advantaged by a full 2D kinematical map of such a galaxies, as it could be obtained by combining the 2D discrete radial velocity field of

\[ \lambda \simeq 5000 \ \text{Å}, \] allowing to study galaxies with slightly lower velocity dispersion, and the smaller spatial elements dimensions ($0.67^\prime\prime$) is well suited to the excellent average seeing on Paranal. Of course, VIMOS takes advantage of the VLT collecting power: for example, using the HR-Blue grism, combined with the high spatial resolution mode, it will be possible to to cover the region within 1.2 $R_e$ of NGC 3779 with 6 different pointings in 2 nights (see next section). In general, it will be possible to reach the same signal-to-noise ratio as in SAURON observations in about half of the exposure time (since, taking into account background effects, the exposure time scales as the inverse of the diameter).

### 3. Deep IFS of no dark matter candidate

In Table 1 we show the characteristics of a sample of galaxies for which previous observations at large radii have shown the intriguing result of presence of little, if any, dark matter.

These galaxies have the common properties to have disky isophotes ($a_2 > 0$) and a power-law slope of the inner density profile ($\gamma > 0$), while their M/L at 5 effective radii, $\Gamma_{BS}$, obtained with extended PNe kinematics$^3$ are in good agreement with typical stellar mass-to-light ratios. This suggests a small amount of dark matter enveloping the luminous part of these systems. It is interesting to note that the possibility that many ordinary early-type galaxies are deficient in dark matter content was already discussed in previous dynamical studies (e.g., Bertin et al. 1994). Since this result clearly does not conform with the CDM evolution scenarios, more detailed observations are needed to confirm it.$^4$

$^3$ For NGC4697, Napolitano (2001) obtained a constant M/L integrating the Jeans equations up to infinity.

$^4$ In this respect, it is interesting to note that the MOND theory appears to be in agreement with the findings of Romanowsky et al. (Milgrom & Sanders 2003).

Fig. 1. Gaussian smoothed PNe velocity field from PN.S data (R+03), darker to brighter regions are negative to positive radial velocities. Dashed line is the P.A. of the inner stellar major kinematical axis. Misalignment of the PNe axis with respect to the inner stellar kinematics, kinematical substructures and twist of the isovelocity contours are evident. Signatures of such features in the inner stellar population can be investigated by VIMOS-IFU in great detail.

$^5$ Here they investigate the internal structure of disky systems with long-slit spectroscopy and instrumental errors similar to those expected with IFU-VIMOS.
modeling approach could be greatly improved with the 2D information of the stellar kinematics in the inner parts, where higher order velocity moments can help to break the mass-anisotropy degeneracy (Lokas 2002). The results of such a modeling procedure can be compared with the use of 2 (or 3) integral Jeans models for axisymmetric systems (Pignatelli & Galletta 1999, Napolitano et al. 2001).

4. Conclusions

The ubiquity of dark matter in early-type galaxies is a debated topic: already Saglia et al. (1993), using stellar kinematics observations, hinted at the possible existence of two classes of early-type galaxies, according to the velocity dispersion trend at large radii. They studied several early-type galaxies with decreasing velocity dispersion which required no dark matter (see also Capaccioli et al. 2003). However, long-slit spectroscopical stellar kinematics studies are generally confined to the inner luminous regions ($R < R_e$). A remarkable improvement has been possible using PNe as kinematical tracers in the outskirts of early-type galaxies with dedicated instruments like the PN.S: preliminary results have already been published, and a larger sample of early-type galaxies is being observed with the same technique. However, in order to improve our knowledge of the kinematics of the inner luminous regions, deep IFS observations are mandatory, and they are already being performed on large sample of nearby galaxies by the SAURON team.

Here we discussed an observational project to survey the full 2D kinematics of intermediate luminosity/disky galaxies, up to about 1.2 $R_e$, in order to overlap the region where PNe data are available. The preliminary sample includes galaxies which have been modeled with nearly constant mass-to-light ratios up to about 6 $R_e$ using the information from PNe discrete radial velocity fields (Romanowsky et al. 2003). This finding is extremely interesting, as it seems to violate the expectations from CDM hierarchical merger models (e.g., Navarro, Frenk & White 1997), which predict a substantial amount of dark matter in the outskirts of ellipticals.

As discussed above, there are still some indeterminacies due to the intrinsic structure of disky systems (like the presence of faint disks or multicomponent with misaligned kinematics) and geometry (i.e., inclination): the use of the detailed 2D kinematics and high velocity resolution is therefore necessary to clarify any presence of biases in the dynamical modeling due to kinematical substructures.

IFU-VIMOS is a very suitable instrument for such a purpose as it allows to combine an adequate spatial and spectral resolutions with a large survey field and the advantage of an 8m telescope collecting power.

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Table 1. Intermediate luminosity galaxies no dark matter candidates.

| galaxy   | Type   | $V_{sys}$ | $R_e$ | $M_B$ | $a_4$ | $\Gamma_{\sigma}$ | $\Gamma_{\phi}$ | reference  |
|----------|--------|-----------|-------|-------|-------|------------------|-----------------|------------|
| NGC321   | E2     | 1735      | 50$''$| -20.5 | 2.5   | 0.64             | 13-17           | R+03       |
| NGC3779  | E1/S0? | 877       | 35$''$| -20.0 | 0.2   | 0.18             | 5-8             | R+03       |
| NGC4494  | E0     | 1232      | 49$''$| -20.6 | 0.3   | 0.6              | 5-7             | R+03       |
| NGC4697  | E3     | 1310      | 90$''$| -20.5 | 1.4   | 0.74             | 12±1           | Np01       |

References

Bacon, R. et al. 2001, MNRAS, 326, 23
Bender, R., et al. 1988, A&A, 74, 385
Bender, R., Saglia, R.P. & Gerhard, O.E., 1994, MNRAS, 269, 785
Bertin, G. et al. 1994, A&A 292, 381
Bertola, F. & Capaccioli, M., 1975, ApJ, 200, 439
Capaccioli, M., 1987, in IAU Symposium 127, Structure and Dynamics of elliptical galaxies, p. 47, ed. T. de Zeeuw, R. Dorthrect
Capaccioli, M., Caon, N., & D’Onofrio, M. 1992, ESO ESP/EIPC Workshop on Structure of Early-type Galaxies, eds. J. Danziger, W. W. Zeilinger, and K. Kjar, ESOC: Garching, 43
Capaccioli, M., Napolitano, N. R., Arnaboldi, M., 2003, Sakharov Conference of Physics, Moscow, June 2002, in press, [preprint astro-ph/0311332]
Davies, R., et al. 1983, ApJ, 266, 41
de Zeeuw, P.T. et al.: 2002, MNRAS 329, 513
D’Odorico, S. et al. 2003, The Messenger 113, 26
Douglas, N.G., et al. 2002, PASP, 114, 1234
Faber, S.M. et al. 1997, AJ, 114, 1771
Foucaud, S. et al.:2003 this volume
Kissler-Patig, M., 1997, A&A, 319, 83
Lokas, E., 2002, MNRAS, 333, 697
Magerrian & Ballantyne 2001, MNRAS 322, 702
Méndez, R.H. et al. 2001, ApJ, 563, 135
Meza, A., et al., 2003, ApJ, 590, 619
Milgrom, M. & Sanders, R.H. 2003, preprint [astro-ph/0309617]
Napolitano, N.R., Arnaboldi, M., Freeman, K.C. & Capaccioli, M. 2001, A&A, 377, 784
Napolitano et al., 2003, on ASP proceedings of the IAU Symposium 220 "Dark matter in galaxies", eds. S.Ryder et al., in press, [preprint astro-ph/0310798]
Napolitano, N.R. 2001, Extragalactic Planetary Nebulae as tracers of the mass distribution in early-type galaxies and clusters, PhD Thesis, Università “Federico II”, Naples (Italy) (Np01)
Navarro, J.F., Frenk, C.S. & White, S.D.M. 1997, ApJ 490, 493
Nieto, J.L., & Bender, R. 1989, A&A, 215, 266
Pellegrini, S. 1999, A&A, 351, 487
Pignatelli, E. & Galletta, G., 1999, A&A, 349, 369
Romanowsky, A.J. & Kochanek, C.S., 2001, ApJ, 553, 772
Romanowsky, A.J. et al. 2003, Science, 301, 1696 [see also, astro-ph/0308518] (R+03)
Scorza, C. & Bender, R., 1995, ApJ, 293, 20
Statler, T.S. & Smecker-Hane, T.: 1999, AJ 117, 839
Verolme, E.K. et al. 2002, MNRAS 335, 517