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IFU Observations of the Black Hole in NGC 3377

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Abstract

We constrain the central black hole (BH) mass and the stellar mass-to-light ratio (M/L) of the E5 galaxy NGC 3377, using complementary integral field spectroscopic observations from both SAURON and OASIS. We model this combined set of data with an orbit-based modeling technique à-la-Schwarzschild. From our best-fit model of NGC 3377, we find that this galaxy contains a BH of $5^{+5}_{-2} \times 10^7 \mathrm{M}_\odot$ and its stellar M/L is $2.1^{+0.2}_{-0.1}$ (*I*-band). In addition, we have checked several aspects of the method using simple isotropic models.

1.1 The Schwarzschild Method

In the orbit-superposition method (Schwarzschild 1979) for constructing dynamical models, a large library of orbits is computed in a fixed potential that corresponds to the deprojected stellar density through Poisson's equation. The gravitational contribution of a central BH is easily included in the total potential. During the numerical integration of the equations of motion, the orbital properties are stored on various grids, e.g., projected and intrinsic density and line-of-sight velocity profiles (VPs) of each orbit (see Cretton et al. 1999). The orbits are combined with weights, such as to fit the input model density and a set of kinematic constraints. One strength of this method is that several datasets can be used simultaneously to constrain the models. Galaxies for which general anisotropic models have been constructed are listed in Gebhardt et al. (2000); for recent applications, see Cappellari et al. (2002), Verolme et al. (2002) and Gebhardt et al. (2003).

The major difficulty in trying to constrain any dark mass by modeling kinematic data is that one needs to solve simultaneously for the potential (including dark mass) *and* for the unknown orbital structure, i.e., the amount of anisotropy in the stellar orbits (see e.g., Rix et al. 1997). This long-lasting problem (known as the "mass-anisotropy degeneracy") can be solved using the higher order moments of the observed VPs, or simply the entire VPs (Gerhard et al. 1998).

We have computed libraries of orbits in the combined potential of the luminous stellar body of NGC 3377 and a central point mass representing a BH. A grid of models with different values of the stellar M/L and BH masses has been constructed. Each $[\mathrm{M/L},\mathrm{BH}]$-model is fitted to the data and the goodness of the fit is assessed by its χ^2 value. Contours of equal $\Delta\chi^2 = \chi^2 - \chi^2_{\mathrm{min}}$ are drawn in the $[\mathrm{M/L},\mathrm{BH}]$ plane and can be translated into confidence levels.

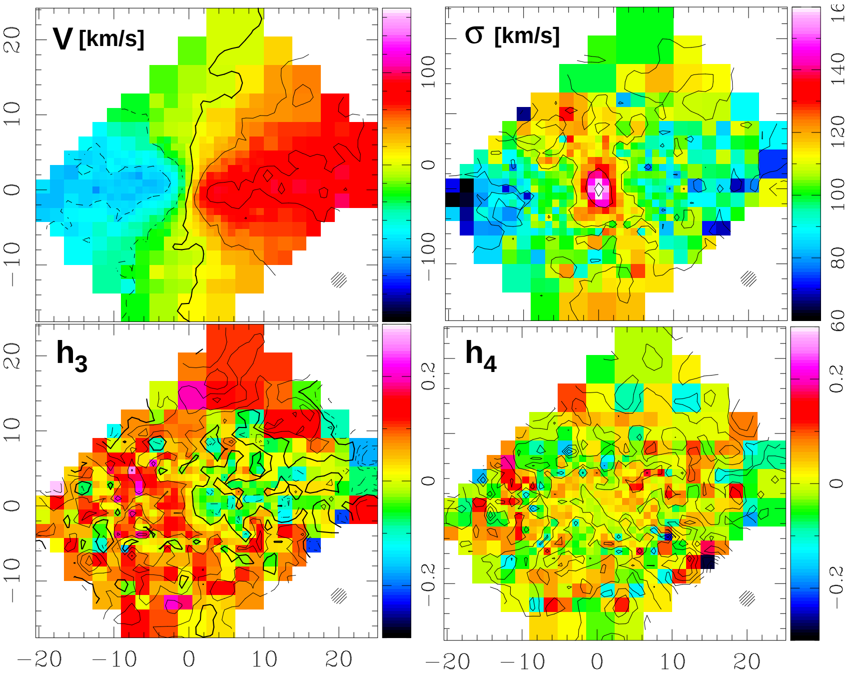

Fig. 1.1. SAURON kinematics of NGC 3377: velocity field (*upper left*), velocity dispersion field (*upper right*), Gauss-Hermite moments h_3 (*lower left*) and h_4 (*lower right*). The Gauss-Hermite high order moments (h_3, h_4, ...) quantify the deviations from a purely gaussian VP (van der Marel & Franx 1993). These maps are based on four 1800 seconds exposures.

1.2 The SAURON Data

The SAURON instrument and some of its observations are described in Bacon et al. (2001) and de Zeeuw et al. (2002). SAURON data for NGC 3377 cover the inner $46'' \times 42''$ at a spatial sampling of 0.″95. The seeing PSF during these observations had a FWHM = 2.″1. To increase the S/N in the outer parts, pixels have been binned following a new Quadtree–based 2D binning scheme (Cappellari & Copin 2003). In Figure 1.1 we show the 2D–binned mean velocity, velocity dispersion, h_3 and h_4 fields. The iso-dispersion contours are boxy in the center, which is a consequence of the strong rotation on the major axis. A small (but non-zero!) velocity can be seen on the photometric minor axis, which reveals some triaxiality in this galaxy. Our axisymmetric models can not take this into account.

1.3 The OASIS Data

OASIS is an integral–field spectrograph dedicated to high spatial resolution observations, which can be used with the adaptive optics system of the CFHT (Emsellem 1999). The inner $6'' \times 3''$ of NGC 3377 were observed with OASIS at a spatial resolution of 0.″25 (Figure 1.2). The mean seeing PSF had a FWHM of 0.″62. No spatial binning is performed here. We only retain the higher quality data of the inner $4'' \times 2''$ as constraints for the dynamical models. Note that the minor axis rotation is also present at this smaller scale. We

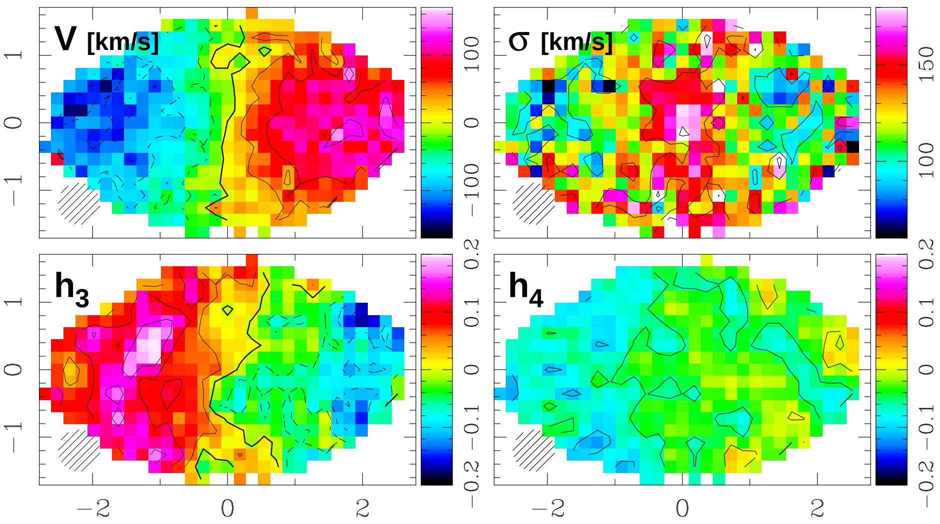

Fig. 1.2. OASIS kinematics of NGC 3377: velocity field (*upper left*), velocity dispersion field (*upper right*), Gauss-Hermite moment h_3 (*lower left*) and h_4 (*lower right*) fields. The OASIS data are based on seven 1800 seconds exposures.

confirmed that the OASIS data are compatible with the SAURON data, given their respective PSFs.

To constrain efficiently the BH mass and the orbital structure of NGC 3377, we use the full VPs derived from this combined data set: large-scale and lower resolution data from SAURON and small-scale but higher resolution observations from OASIS.

1.4 Test on Isotropic Simulated Data

We generate artificial constraints from a $f(E, L_z)$ axisymmetric model built with the Hunter & Qian (1993) method (hereafter HQ). These constraints are computed adopting many characteristics of the real data: pixel size, PSF, data extension and velocity resolution. However, contrary to the real data, these constraints are perfectly symmetric (by construction). We then fit these artificial constraints as if they were real observations. The input model has a BH of $10^8\,M_\odot$ and M/L= 2.4 (indicated by a red circle in Figure 1.3). For this test, we use *orbital components* that depend only on (E, L_z) (Cretton et. al 1999; see also Verolme & de Zeeuw 2002). However, to fit the real data, we use "classical" orbits depending on all three integrals of motion. We find that our best fit model is located very near the input values for M/L and BH mass, therefore giving us confidence that many aspects of the modeling code work well with IFU data. The computations for Figure 1.3 are performed in the OASIS setup, but we reach similar conclusions with SAURON.

1.5 How to Deal with Asymmetries in the Data?

When we constrain the orbit models with the SAURON data only, we get unrealistically tight $\Delta\chi^2$ contours. At 99.73% confidence level, the allowed BH is smaller than

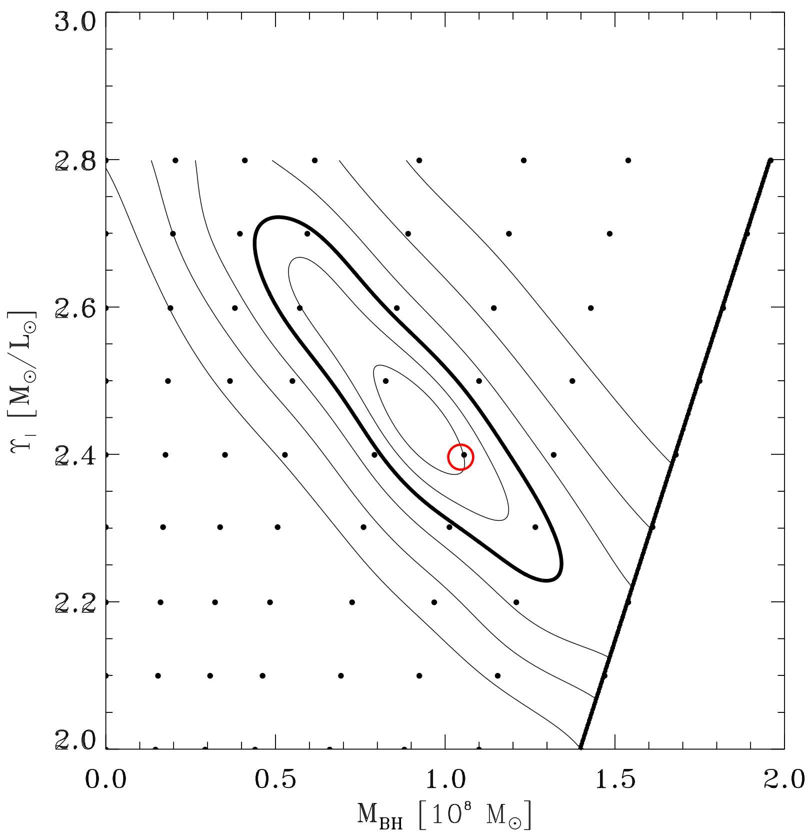

Fig. 1.3. $\Delta\chi^2$ contours measuring the quality of the fit to the isotropic data in the OASIS setup. Model parameters along the abscissa and ordinate are the BH mass and the (*I*-band) M/L respectively. Each dot indicates an orbit model that has been computed and fitted to the constraints. The contours are obtained through spline interpolation. The first three contours define the formal 68.3%, 95.4%, and (thick contour) 99.73% confidence level. Our best fit model is indeed very close to the input parameters of the HQ model (indicated by the red circle).

$\sim 2 \cdot 10^7\,M_\odot$. This appears to be surprisingly small, given the low spatial resolution of the SAURON dataset. If NGC 3377 had a $2 \cdot 10^8\,M_\odot$ BH, its radius of influence would be $\theta \sim 1''$, therefore it seems unrealistic that an upper limit of $2 \cdot 10^7\,M_\odot$ could be placed on the BH mass by the SAURON data. An additional reason for suspecting that the tightness of such contours is not "real" is given by the following test. We use the artificial HQ constraints in the SAURON setup. As before, a BH of $10^8\,M_\odot$ has been included into the HQ model. This artificial dataset looks similar to the SAURON data, but when we fit the orbit models to it, we obtain very different $\Delta\chi^2$–contours that allow BH masses up to $1.5 \cdot 10^8\,M_\odot$ at 99.73 % confidence level !

Departures from axisymmetry such as those present in the SAURON data will increase

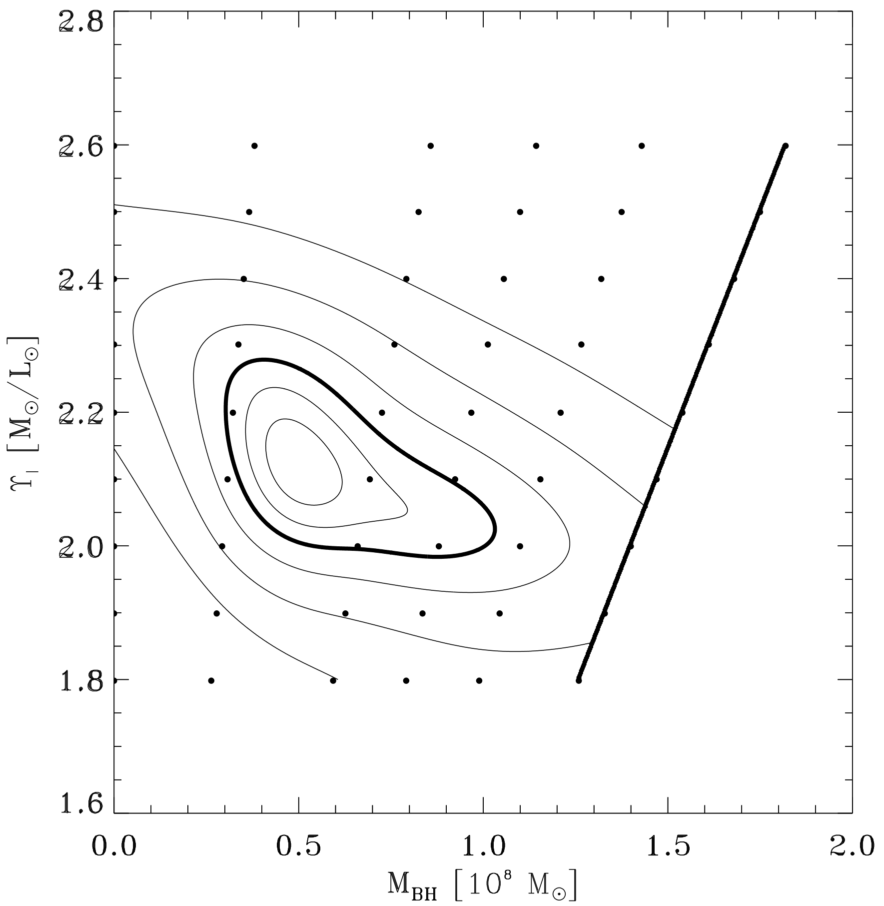

Fig. 1.4. Same as Figure 1.3, but for the combined set of SAURON and OASIS constraints. In addition, we use here the new errorbars defined in Section 1.5.

χ^2 and $\Delta\chi^2$, if one uses an axisymmetric modeling technique like here. We therefore define new errorbars that take these systematic differences into account. Using these new errorbars, we constrain the models with the SAURON and OASIS datasets. The results are shown in Figure 1.4: we find that this galaxy contains a BH of $5^{+5}_{-2} \times 10^7 M_\odot$ and its stellar M/L is $2.1^{+0.2}_{-0.1}$ (*I*-band).

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