M87 as a Galaxy

Walter Dehnen

Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, United Kingdom

Abstract. I review recent studies about the gravitational potential and stellar dynamics of M87 in particular, and the dynamics of the stars in the presence of a super-massive central black hole, in general.

At large radii, investigations of both the X-ray emitting gas and the velocity distribution of globular clusters indicate the presence of large amounts of non-luminous matter, possibly belonging to the inner parts of the Virgo cluster.

At small radii, there is no evidence from the stellar kinematics, at most a hint, for the existence of a central point mass, whereas the gas dynamics reveal the presence of a highly concentrated mass in the centre of M87, possibly a super-massive black hole (BH). Given the existence of such a central mass, the stellar kinematics indicate a strong tangential anisotropy of the stellar motion inside a few arcseconds. The implications of this result for the evolution and formation history of M87 and its central BH are discussed. I also discuss in more general terms the structural changes that a highly concentrated central mass can induce in its parent galaxy.

1 Introduction

According to their observable properties, elliptical galaxies can be divided into two classes. This dichotomy is most clearly revealed in the central brightness distribution (cf. Fig. 3 of Gebhardt et al. 1996). Consequently, the two classes are commonly called ‘power-law galaxies’ and ‘core galaxies’ (though – as so often in astronomy – the latter term is highly misleading: these galaxies actually do not have a core of constant density). Core galaxies have shallow central luminosity density profiles with \( j \propto r^{-\gamma} \), \( \gamma \lesssim 1.3 \), ellipticities E0 to E3-4, elliptic to boxy isophotes, and negligible rotation \( v_{\text{rot}} \ll \sigma \). They are on average bright (\( M_V \lesssim -19.5 \)) and often radio-loud and X-ray-active, possess extended stellar envelopes and rich (\( N > \sim 2000 \)), extended globular cluster (GC) systems which are multimodal in their properties. These galaxies are thought to be of round to triaxial shape supported by anisotropy in the stellar motions.

Power-law galaxies, on the other hand, have steep central density cusps with \( \gamma \sim -1.5 \), ellipticities up to E7, elliptic to disky isophotes, and significant rotation velocities \( v_{\text{rot}} \sim \sigma \). They are on average fainter (\( M_V \sim -21.5 \)) and show no radio or X-ray activity; their surface density follows a de Vaucouleurs profile and their GC systems are poor (\( N \lesssim 1500 \)) and with a profile following that of the stellar light. These galaxies are believed to be of near-oblate shape supported by rotational motions.

Clearly, M87 having a shallow density cusp (\( \gamma \approx 1.2 \)), round isophotes, negligible rotation, radio and X-ray activity, an extended stellar envelope, and
a rich and bi-modal globular cluster system is a generic representative of the class of core galaxies. It is generally believed, that the core galaxies are formed by one or more major merger events. In face of this hypothesis, it is important to ask whether M87 is consistent with being a merger remnant.

Fig. 1. Velocity dispersion for M87 as measured for stars (filled circles, van der Marel 1994) and planetary nebulae (open squares, Cohen & Ryzhov 1997). The full line is the rotational velocity measured by the latter authors.

2 The Matter Distribution at Large Radii

The presence of dark matter around spiral galaxies was established by studies of the motions of their gaseous disk, whose emission lines can be traced to large radii. Elliptical galaxies in general have very little cold gas and one has traditionally used stars as dynamical tracer population. However, at large radii the stellar absorption-line spectra are very hard, if not impossible, to observe with useful signal-to-noise ratio. Thus, in order to probe the potential at large radii of elliptical galaxies, one needs different kinematical tracers. Possible candidates are gas rings, planetary nebulae (PN), and globular clusters (GC). Gas rings are rather rare among elliptical galaxies, and in general one is left with PNs or GCs. The problem with using these or stars as tracers is that they do not move on circular orbits like the gas, but form dynamically hot systems, which complicates the interpretation of the measured kinematics.
Fig. 2. Mass enclosed in radius $r$ as derived from studies of stellar kinematics (open circles, Sargent et al. 1978), globular clusters (triangle, Mould et al. 1990, and filled circles, Cohen & Ryzhov 1997), and X-ray gas (thin lines: lower and upper limits, Nulsen & Böhringer 1995, corrected for the difference in the adopted distance to M87). The solid line represents a power-law fit to the filled circles: $M \propto r^{1.7}$.

Recently, Cohen & Ryzhov (1997) have studied the GC system of M87. The derived rotation velocity $v_{\text{rot}}$ and velocity dispersion $\sigma$ are displayed in Fig. 1 together with stellar kinematical data for the central parts. There is a clear change in the kinematic properties at about $100''$ from the centre: in the inner parts $v_{\text{rot}} \approx 0$ and $\sigma$ decreases from $\approx 400\text{km}\text{s}^{-1}$ to $\approx 200\text{km}\text{s}^{-1}$; in the outer parts $\sigma$ increases reaching $\approx 400\text{km}\text{s}^{-1}$ at $400''$ and $v_{\text{rot}}$ becomes significant. This kinematical behaviour is very similar to that observed for NGC 1399 (cD galaxy in the Fornax cluster) by Arnaboldi & Freeman (1996) using PNs as tracers (their Fig. 2). An obvious explanation is that the change in kinematical properties constitutes the transition from the highly concentrated galaxy to the less concentrated and dark-matter-dominated Virgo cluster.

Cohen & Ryzhov have analysed their data in terms of the mass distribution and found that in the range $3\text{kpc} \leq r \leq 30\text{kpc}$ (using a distance to M87 of $15\text{Mpc}$) their data imply a mass density $\rho \propto r^{-1.3}$ and a mass of $\approx 3 \times 10^{12}\text{M}_\odot$ inside $44\text{kpc}$. These findings are in agreement with estimates derived from X-ray observations (Fabricant & Gorenstein 1983, Nulsen & Böhringer 1995), see Fig. 2. It is intriguing that the derived density slope of $\gamma = 1.3$ agrees well with 1.4 recently predicted for the inner parts of dark matter halos by high-resolution
3 Small Radii: Stellar Kinematics and the Black Hole

Because of its stellar kinematics, M87 has for a long time been suspected to harbour at its centre a super-massive black hole\(^1\) (BH), though this conclusion was always controversial (cf. Sargent et al. 1978, Binney & Mamon 1982, Merritt 1987). The best currently available photometry (Lauer et al. 1992) and stellar kinematical data (van der Marel 1994) show a weak density cusp and a slightly centrally peaked velocity dispersion \(\sigma\) (see Fig. 1). As van der Marel’s analysis showed, these data can easily be interpreted by a pure stellar model with constant mass-to-light ratio and anisotropy\(^2\) of \(\beta \approx 0.5\) (van der Marel 1994), i.e. radially anisotropic as expected for a galaxy formed by violent relaxation. Alternatively, one can explain the centrally peaked \(\sigma\) by a central BH of a few billion solar masses. However, such a model does not work with radial anisotropy near the BH, which would give too high a central \(\sigma\), and requires the opposite: isotropy or tangential anisotropy, depending on the mass of the BH.

Bender et al. (1994) found a change in the profile of the stellar absorption lines: the coefficient \(h_4\) of the Gauss-Hermite expansion of the profile changes sign at \(r \approx 3''\), such that \(h_4 < 0\) inside and \(h_4 > 0\) outside. This implies a change in the underlying dynamical properties in the sense that \(\beta_{r<3''} < \beta_{r>3''}\), as predicted by models with central BH (though it would be very hard to quantify this).

Actually, since 1994 we know from HST observations of a central gas-disk that M87 hosts a central BH of \(M_\bullet = (3.2 \pm 0.9) \times 10^9 M_\odot\) (Harm et al. 1994, Ford et al. 1994, Marconi et al. 1997 and this volume). Starting from this fact and assuming spherical symmetry and a constant stellar mass-to-light ratio, Merritt & Oh (1997) solved simultaneously the projection equation for the stellar kinematics and the Jeans equation describing dynamical equilibrium. This gave them a non-parametric estimate for the anisotropy implied by the observed stellar kinematics and the BH. Their results for a BH of 1, 2.4, and 3.8 billion solar masses are displayed in Fig. 3. For a sufficiently massive BH, the central stellar motions are strongly tangentially anisotropic (\(\beta \lesssim -1\)). The more massive the BH, the

\(^1\) Clearly, from stellar dynamical and similar arguments, one cannot infer that the dark object is of the size of its Schwarzschild radius. However, lacking other plausible explanations for the high mass concentrations at the centres of many galaxies, it is generally believed that these are actually black holes, and I adopt this hypothesis throughout this paper.

\(^2\) The anisotropy parameter is defined to be

\[ \beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}, \]

where \(\sigma_t\) and \(\sigma_r\) denote the tangential and radial velocity dispersions. For an isotropic system \(\beta = 0\); for radial anisotropy \(\beta > 0\) reaching \(\beta = 1\) for pure radial orbits; and for tangential anisotropy \(\beta < 0\) with \(\beta = -\infty\) for pure circular orbits.
Fig. 3. Velocity dispersions and anisotropy vs. radius for M87 as inferred by Merritt & Oh (1997) from the stellar kinematics for a BH with assumed mass of (a) 1, (b) 2.4, and (c) 3.8 billion solar masses. Dotted lines give 95% confidence bands.

stronger the inferred anisotropy and the larger is the radius at which $\beta$ changes sign. Outside of this radius, the stellar motions are slightly radially anisotropic in agreement with van der Marel’s (1994) study. For the most recent estimate of $M_\bullet$, the effect is very significant leading to highly tangential anisotropy. In the following section, I discuss possible explanations for this effect.

4 Stellar Dynamics Around a Black Hole

Can we understand the abrupt change in the stellar motions from radial to tangential anisotropy near the BH? Let us consider various possible scenarios for the formation of the BH at the centre of a galaxy.

Adiabatic Growth of the Black Hole

If the BH grows slowly over a long period of time, the actions of the stellar
orbits are conserved. However, the mapping between actions and ordinary phase-space coordinates changes as the potential evolves from harmonic (for an initially isothermal core) to Keplerian. This change results in a stellar density cusp with $\rho \propto r^{-3/2}$ and a mildly tangential anisotropy of at most $\beta = -0.3$ (Young 1980, Goodman & Binney 1984, Quinlan et al. 1995) inside the sphere of influence of the BH, which has radius

$$r_h = \frac{GM_*}{\sigma^2} \left( \simeq 1'' \text{ for } M87 \right).$$

While this radius is of the correct size, the effect is much too weak in order to explain Merritt & Oh’s result of $\beta \lesssim -1$. Furthermore, M87 has a central density slope $\gamma \approx 1.2 < 3/2$.

**Growth by the Capture of Stars**

A BH may grow by tidally disrupting and capturing stars that happen to come too close to it. Such stars will predominantly have low angular momenta, while near-circular orbits are hardly affected. Hence, this process gives rise to $\beta < 0$. However, the distance from the BH that a star must reach before it gets destroyed is of the order of the BH’s Schwarzschild radius, which is smaller than $r_h$ by several orders of magnitude.

**Growth by the Accretion of Black Holes**

If two galaxies, each hosting a massive BH at its centre, merge, the BHs will sink to the centre of the remnant and finally merge as well (Ebisuzaki et al. 1991). Begelman et al. (1980) have outlined the stages of this process:

1. Due to dynamical friction with the background stars, the BHs sink into the centre and form a BH binary.
2. The binary loses energy and angular momentum (it “hardens”) due to three-body interactions with passing stars.
3. When the separation between the BHs has become sufficiently small, gravitational radiation becomes very efficient in hardening the binary until it finally merges to a single BH.

Depending on the time-scale of the whole process, repeated events of this kind are possible\(^3\), in particular for a central-cluster elliptical, such as M87, which over its lifetime has likely cannibalised many minor companions. The least understood mechanism here is (2), which is also the process most relevant to the possible effect on the stellar dynamics. One problem, for instance, is whether or not the eccentricity of the binary BH increases, which in turn is relevant for (3), since for a highly eccentric binary gravitational radiation can take over at higher energies, i.e. earlier, than for a less eccentric binary. Another problem is loss-cone depletion: three-body interactions that harden the binary eject stars out

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\(^3\) One BH-merger has to be finished before a third BH arrives, since more than two BHs cannot co-exist for long in a galaxy’s centre, as all but two of them will quickly be ejected by sling shots.
of the centre, and the number of interaction candidates diminishes. Eventually, this may even halt the hardening before gravitational radiation can take over (the re-fueling of the loss cone due to two-body relaxation is much too slow).

It is clear that process (2) will create tangential anisotropy, since, as for the tidal disruption, low-angular-momentum stars are more likely to interact with the BHs – they are, however, not eaten by the BH but ejected via a sling-shot. Evidently, this process reaches out to the radius $r_h$, where the circular motion around the BH equals the mean stellar velocity dispersion.

![Fig. 4. Response of a Jaffe model to the hardening of a BH binary as computed by Quinlan & Hernquist (1997). The dashed lines show the initial (a) density, (b) velocity dispersion, and (c) anistotropy. The solid lines show these quantities when the binary reaches a certain hardness. The binary’s components have equal mass of 0.04, 0.02, 0.01, 0.005, and 0.0025 (leftmost) in units of the total mass in stars. Reprint from New Astronomy, Vol. 2, Quinlan & Hernquist, “The dynamical evolution of massive black hole binaries - II. Self-consistent N-body integrations”, p. 533-554, 1997 with kind permission of Elsevier Science - NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.](image)

Recently, Quinlan (1996) and Quinlan & Hernquist (1997) have studied processes (1) and (2) by detailed simulations. They developed an $N$-body code in which the BH-BH interaction is computed exactly (Newtonian; relativistic effects are unimportant before stage 3), the BH-star interactions by a softened Keplerian force, and the star-star interactions via an expansion of the stellar potential in basis functions, i.e. essentially collisionless. Their code thus follows the dynamical evolution of the BHs and stars in a self-consistent way. In their simulations, Quinlan & Hernquist started with the stars being in spherical isotropic equilibrium following a Jaffe model (which has $\gamma = 2$) and various choices for
the masses and initial positions of the BHs. Their general conclusions relevant here are as follows. (i) The total mass of the stars ejected from the centre by three-body interactions is about twice the mass of the BH binary. (ii) Wandering of the BH pair significantly increases the loss cone and mitigates the problem of its depletion. (iii) Inside about $r_h$, the density profile has become much shallower, almost flat, the velocity dispersion increases in a Keplerian fashion, and the stellar motions are significantly tangentially anisotropic with $\beta \approx -1$ (see Fig. 4).

Thus, at least qualitatively, this process can explain the presence of a shallow stellar cusp with significant tangential anisotropy around a central black hole. However, there are some points where M87 does not fit smoothly into this picture. For example, the radius inside which the density of M87 becomes shallow ($\approx 10''$) is clearly larger than the radius inside which $\beta < 0$ ($\approx 3''$), while the simulations indicate that these radii should be similar. Also, the central cusp of M87 is not completely dug out as in Quinlan & Hernquist’s simulations. These discrepancies indicate that reality is more complicated, possibly involving several such accretion events with “small” secondary BHs and/or dissipational processes (e.g. star formation) as indicated by the presence of the central gas-disk.

5 Influence of a Central Black Hole on Larger Scales

The processes discussed in the last section influence the structure and dynamics of the stellar system only in the immediate neighbourhood of the BH, i.e. inside $r_h$. A central BH, however, will influence all those stars that ever come near the centre. Many stars in triaxial galaxies are on box orbits, which pass arbitrarily close to the centre after a sufficiently long time. It was argued by Gerhard & Binney (1985) that scattering and re-distribution of box orbits by a central BH would cause at least the inner parts of a triaxial galaxy to become rounder or more axisymmetric. Using a modification of the N-body code employed by Quinlan & Hernquist, Merritt & Quinlan (1998) have recently studied this process numerically. They created a stable triaxial equilibrium model by the simulated collapse of a non-equilibrium configuration, and followed the time-evolution of this model when at its centre a point mass was slowly grown. Fig. 5 shows, for three different BH masses, the time-evolution of the shape of the model. In all simulations, the galaxy model tends to become axiymmetric, even at the half mass radius. For the lightest BH with $M_\bullet/M_g = 0.003$ ($M_g$ denotes the mass of the galaxy), this process is still ongoing at the end of the simulation, whereas for $M_\bullet/M_g = 0.01$ it is nearly finished. The most interesting result, however, is that for $M_\bullet/M_g = 0.03$ the process is almost finished at the time $t_{\text{grow}}$ when the BH has reached its final mass. Further simulation of the authors with varying $t_{\text{grow}}$ confirmed this result: for $M_\bullet/M_g = 0.03$ the shape becomes axiymmetric as soon as possible, i.e. at $t = \max\{t_{\text{grow}}, t_{\text{dyn}}(r)\}$, where $t_{\text{dyn}}(r)$ denotes the dynamical or crossing time at radius $r$. 
Fig. 5. Time-evolution of the axis ratios $b/a$ and $c/a$ (full lines) and the triaxiality index $T = (a^2 - b^2)/(a^2 - c^2)$ (dashed) in the simulations of Merritt & Quinlan (1998). The mass $M_\bullet$ of the BH grown in $t_{\text{grow}} = 15$ is 0.003 (a), 0.01 (b), and 0.03 (c) of the total mass in stars. The numbers in the left corner of each frame are the fraction of particles, ranked by binding energy, that were used in computing the shape parameters.

This behaviour can be explained by the BH inducing chaos in the orbital motions of the triaxial galaxy. For small $M_\bullet$, the orbits become weakly chaotic, i.e. they behave like a box orbit over some time, but after a sufficiently long time they fill their energy surfaces. For ever larger $M_\bullet$, the orbits become ever more strongly chaotic until at some critical $M_\bullet$ the Liapunov time (the time in which two neighbouring trajectories diverge) equals the dynamical time, i.e. the orbits no longer resemble box orbits at all. In the simulations of Merritt & Quinlan this critical $M_\bullet$ is about 2.5% of $M_\odot$. In general, this number should depend on details of the triaxial configuration, but is likely to be of the same order, i.e. $\sim 10^{-2}M_\odot$.

From the existence of this critical $M_\bullet$, Merritt & Quinlan draw a very interesting conclusion. In order for BHs to grow by gas accretion (the standard
model for AGNs), the gas has to reach the BH from large radii, i.e. it has to lose its angular momentum. In axisymmetric galaxies, the conservation of angular momentum along ballistic orbits renders gas-fueling of the centre very difficult. Thus, a BH may cut off its own gas supply by changing the shape of its host galaxy. If this picture actually applies, the BH mass should be no larger than the critical $M_\bullet \sim 10^{-2}M_g$. A correlation in this sense is indeed observed: $M_\bullet$ inferred from the dynamics of several early-type galaxies is always of this order (cf. Kormendy & Richstone 1995). In M87, $M_\bullet/M_g$ is only $\sim 0.5\%$, which might be a consequence of mergers that convert disks into spheroids and hence increasing $M_g$ (Merritt, private communications).

Several BHs, however, are hosted by barred spiral galaxies (e.g. the Galaxy, NGC 1068). Tumbling bars are mainly made of stars on so-called $x_1$ orbits, which avoid the very centre. Hence, the mechanism working on box orbits for triaxial bulges may not (or not as well) work for barred spirals.

6 Summary

The kinematics of M87 are well studied, which make this galaxy a good test case for the theories of galaxy formation. Outside $\sim 100''$, the velocity dispersion profile rises indicating the presence of large amounts of non-luminous matter. The inferred density profile $\rho \propto r^{-1.3}$ is consistent with predictions from CDM cosmogony for the inner parts of dark-matter halos.

The massive black hole (BH), detected in the very centre of M87 by gas motions, together with the observed stellar kinematics implies a significant tangential anisotropy of the stellar motions. Among the formation histories discussed for a BH in a galactic centre, only the model of accretion of other massive BHs, originating from the centres of cannibalized companions, can explain such a strong anisotropy. This scenario also predicts a shallow stellar density cusp as observed for M87. (Quantitatively, there are some discrepancies, which may well be due to over-simplification in the simulations of this process.)

A massive BH at the centre of a triaxial galaxy renders, by the destruction of box orbits, the shape of its host axisymmetric. This mechanism becomes very fast once the BH mass reaches a critical value, which is of the order of 1% of its host’s mass. Since the conservation of angular momentum along ballistic orbits in an axisymmetric galaxy obstructs gas-fueling of the centre, this process may pose an upper limit for the mass a BH can reach by gas-accretion. An upper limit of this order is indeed observed among BH masses inferred from the dynamics of early-type galaxies.

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References

Arnaboldi M., Freeman K., 1996, in Arnaboldi, Da Costa, Saha, eds., The Nature of Elliptical Galaxies A.S.P. Conf.Ser. 116, 54
Begelman, M.C., Blandford, R.D., Rees, M.J., 1980, Nature, 287, 307
Bender, R., Saglia, R.P., Gerhard, O.E., 1994, MNRAS, 269, 785
Binney, J.J., Mamon, G.A., 1982, MNRAS, 200, 361
Cohen, J.G., Ryzhov, A., 1997, ApJ, 486, 230
Ebisuzaki, T., Makino, J., Okumura, S.K., Nature, 354, 212
Fabricant, D., Gorenstein, P., 1983, ApJ, 267, 535
Ford, H.C., et al., 1994, ApJ, 435, L27
Gebhardt, K., et al., 1996, AJ, 112, 105
Gerhard, O.E., Binney, J.J., 1985, MNRAS, 216, 467
Goodman, J., Binney, J.J., 1984, MNRAS, 207, 511
Harm, R.J., et al., 1994, ApJ, 435, L35
Kormendy, J., Richstone, D., 1995, ARA&A, 33, 581
Lauer, T.R. et al., 1992, AJ, 103, 703
Marconi, A., et al., 1997, MNRAS, 289, L21
Merritt, D., 1987, ApJ, 319, 55
Merritt, D., Oh, S-P., 1997, AJ, 113, 1279
Merritt, D., Quinlan, G.D., 1998, ApJ, in press
Moore, B., et al., 1997, submitted to ApJ Letters (astro-ph/9709051)
Mould, J.R. et al., 1990, AJ, 99, 1823
Nulsen, P.E.J., Böhringer, H., 1995, MNRAS, 274, 1093
Quinlan, G.D., 1996, NewA, 1, 35
Quinlan, G.D., et al., 1995, ApJ, 440, 554
Quinlan, G.D., Hernquist L., 1997, NewA, 2, 533
Sargent, W.L.W. et al., 1978, ApJ, 221, 731
van der Marel, R.P., 1994, MNRAS, 270, 271
Young, P., 1980, ApJ, 242, 1232