Research summary: galaxy haloes

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Galaxies are a linchpin in our understanding of the history of the universe—bridging the physics of star formation on small scales with structure formation on large scales, and encompassing the evolution of matter from early times to the present day. As advancing instrumentation probes galaxies' basic properties (morphologies, star formation rates, etc.) at higher and higher redshifts, it is vital to ascertain the detailed properties of *nearby* galaxies, delving for the fossil imprints of their formational processes.

While several programmes have been studying the dynamics of the central regions of nearby galaxies[1,2,3], an under-explored arena is galaxies' haloes—the transitional regions where dark matter is presumed to dominate, and where the complicating effects of dissipation are minimal. Some of the key halo properties to be established are the distributions of **mass**, of **angular momentum**, and of **stellar orbit structure**, as well as any **substructure** left over from accretion and merging events. Most of these properties are relatively well established for spiral galaxies but quite unknown for early-type galaxies (ellipticals and S0s), which do not have on hand such simple dynamical tracers as spirals' cold gas disks.

There are several main lines of inquiry into the characteristics of early-type haloes: *gravitational lensing*, *X-ray emitting gas*, *globular clusters*, and *planetary nebulae*. Each of these approaches can probe a different set of halo properties, and each carries its own set of systematic uncertainties. With advances underway in the exploitation of all these techniques, we are now on the cusp of major strides forward in our knowledge of early-type haloes—and ultimately, of galaxy formation. Having used all of the above methods to investigate galaxy haloes, I am continuing to take a multi-pronged approach to this subject, as detailed below.

Planetary nebulae (PNe) are potentially the single most useful tracer in early-type haloes, since they are representative of the overall stellar population, and thus can probe *all* of the halo properties mentioned above. The observational appeal of PNe springs from the strength of their emission in the [O III] line at 5007 Å, which when isolated allows them to be observed in galaxies to large distances and at arbitrarily large radii. There are hundreds to thousands of PNe in the brightest decade around an early-type galaxy—suitable numbers for dynamical studies. Unfortunately, PN kinematical observations have proven too problematic with standard instrumentation and techniques. To address this shortfall, our collaboration has designed and commissioned a purpose-built instrument: the *Planetary Nebula Spectrograph* (PN.S)[4], which has proved to be a major advance in this field.

The PN.S employs a variation of slitless spectroscopy termed *counter-dispersed imaging* (CDI). In this technique, an image is taken of a galaxy field through a narrow-band filter with a dispersing element but no slit; the continua of stars in the field show up as long spectral segments (truncated by the filter bandpass), while emission-line objects such as PNe appear as point sources. Rotating the dispersion direction 180° between two exposures allows one to find a PN's line-of-sight velocity by measuring its positional shift; thus, one both *detects* and *finds velocities* for PNe in a single observing run (see Figure 1, left)—a major improvement in terms of efficiency and simplicity over traditional methods.

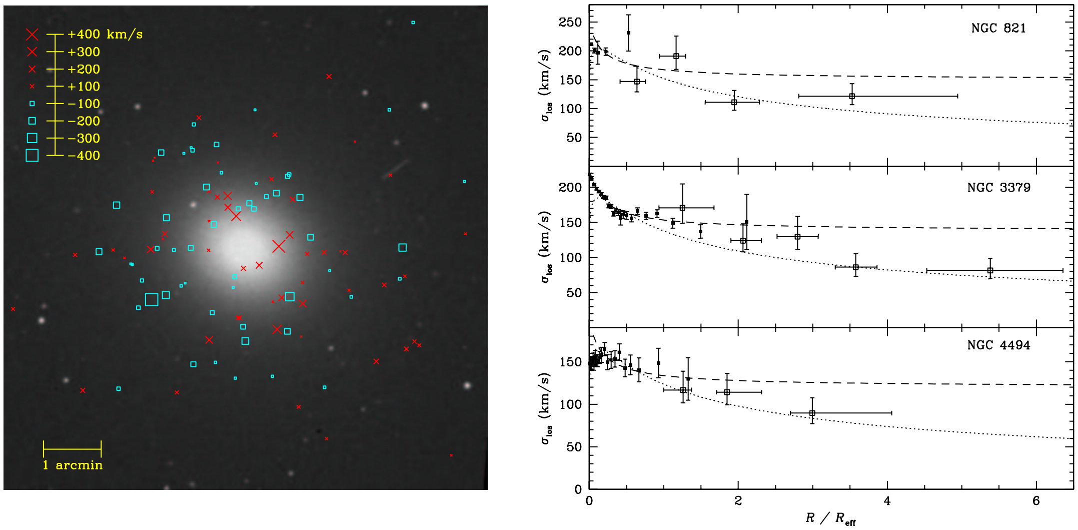

Figure 1. *Left*: Line-of-sight velocities of planetary nebulae (PNe) around NGC 3379, relative to the systemic velocity. Red crosses represent receding velocities, and blue boxes are approaching, where the symbol sizes indicate the velocity magnitudes. *Right*: Line-of-sight velocity dispersion profiles for three elliptical galaxies, as a function of effective radius. Open points show planetary nebula data (from PN.S), solid points show long-slit stellar data[5,6,7]. Predictions of simple isotropic models are shown for comparison: a singular isothermal halo (dashed lines) and a constant mass-to-light ratio galaxy (dotted lines).

The primary programme of the PN.S is to study a representative sample of 12 giant, round ellipticals. We have so far obtained 100–200 PN velocities in each of a few galaxies. The early results are already very intriguing. For the three intermediate-luminosity ellipticals NGC 821, NGC 3379 and NGC 4494, we find a stellar velocity dispersion profile that declines at large radii (Fig. 1, right), in contrast to the constant profiles that one would expect based on our knowledge of spiral galaxies[8] and X-ray-bright ellipticals[9]. Detailed dynamical analysis (see below) of NGC 3379 determines that its total B-band mass-to-light ratio Υ_B inside 5 $R_{\rm eff}$ (effective radii) is 7 ± 1 $\Upsilon_{B,\odot}$, which is consistent with the properties of the stellar population alone. The results for the other two galaxies, as well as another from the literature[10], are similar, thus implying that many ordinary ellipticals contain **little or no dark matter** inside these radii[11]. Possible explanations are that these galaxies have had their haloes inexplicably stripped away, or that the missing dark matter lies at still larger radii—requiring more diffuse haloes than predicted by simulations of galaxy formation[12].

A further result from the PN.S survey and from other PN studies (below) is that the outer parts of ellipticals show weak rotation ($v/\sigma \sim$ 0.1–0.3). But if ellipticals form via the mergers of spiral galaxies as commonly supposed, they should show rapid rotation in their outer parts ($v/\sigma \sim 1$) [13,14]. We will see if this finding, as well as the dark matter results above, may be supported in a broad range of elliptical galaxies upon the completion of the PN.S primary programme—which has been granted long term status from the UK at the 4.2-m William Herschel Telescope (WHT) on La Palma.

Another PN.S project is the in-depth study of the other giant Local Group spiral, M31. We have recently made a high-quality survey of 3 square degrees in this galaxy, obtaining velocities of $\sim$2500 PNe, and an upcoming survey will probe further out into its halo and along its disk major axis. From these data, we are not only reconstructing the dynamical structure of the stellar disk, but also probing the mass distribution in the inner halo, whose total mass has been found surprisingly to be no larger than that of the Milky Way[15]. Further, we are examining the dynamics of the satellite galaxies M32 and M110 and looking for kinematical signatures of any interactions between them, M31, and the faint stellar streamers photometrically discovered in M31's halo[16,17].

CDI methods may also be adapted to improve existing standard spectroscopic methods. One of the obstacles to obtaining PN kinematics with follow-up spectroscopy has been unreliable astrometry in the original survey images, which is unfortunate because of the large quantity of such surveys already in existence. We have developed a new technique, *masked CDI*, whereby a normal multi-slit mask is used to observe a sample of PNe, but the slits are enlarged to a width of $4''$, ensuring that the PN spectra will be acquired. A pair of dispersed images is taken with opposite dispersion directions, and then the PN velocities can be deduced without any need to know the original positions accurately—the astrometric errors cancel out. Using the Mask eXchange Unit of FORS2 at the 8-m Very Large Telescope (VLT), we have obtained many PN velocities around the giant ellipticals M87 and M49 ($\sim$200 and $\sim$100, respectively). We hope to continue using masked CDI to acquire more velocities around these and several other galaxies.

Globular clusters (GCs) are not only useful as abundant kinematical tracers of halo mass, but are interesting in their own right because as some of the oldest known structures in the universe, they are witnesses to most of the long history of galaxy formation. Many galaxies are now known to have *bimodal* globular cluster systems, with the GC subsets broadly characterizable by distinct spatial distributions, kinematics, ages and metallicities[18,19]. Thus, there have been at least two universal modes of GC formation (with a relative importance that varies from galaxy to galaxy)—modes that likely are deeply connected to distinct evolutionary phases in the host galaxies. One of the fundamental ways of discerning these connections is by determining the detailed dynamical structure of the GC subsystems in at least a few archetypal galaxies. With the advent of new powerful multi-object spectrographs on large telescopes, it is now possible to efficiently obtain extensive GC kinematical data in a large sample of galaxies, and so this long latent field is now entering its prime.

M87 is one of the best studied galaxies, boasting $\sim$300 GCs with published line-of-sight velocities[20]. The GC population is distinctly bimodal, with the metal-rich GCs probably on more radial orbits than the metal-poor GCs; in the outer parts, both populations show a large rotation of 200–300 km s^{-1}—thought to be a signature of a dissipationless major merger[21]. Our analysis of the PN velocities (above) indicates that the galaxy's halo stars rotate much more slowly ($\simeq$ 80 km s^{-1}). This is consistent with theories of galaxy spin-up via accretion events, and thus the major merger scenario no longer seems required. Also, the halo stars are on preferentially circular orbits, and so resemble more the *metal-poor* GCs in orbit structure—in contrast to all the currently prevailing theories, in which the stars should be strongly associated with the *metal-rich* GCs[22,23].

Like M87, M49 hosts a population of thousands of GCs, and 263 velocity measurements have been published[24,25]. These indicate GC dynamics markedly different from the case of M87, so further study is warranted. Based upon wide-field multi-color photometry of M49, we have performed a spectroscopic follow-up using the WYFFOS/AF2 multi-fibre spectrograph at the

WHT, yielding spectra for $\sim$70 GCs at very large radii (4–10 $R_{\rm eff}$)[26]; and we have been granted time at the Very Large Telescope with the FLAMES/GIRAFFE multi-fibre spectrograph to further expand this data set by $\sim$200 GCs. Once analysed in combination with the PN data, these will provide excellent constraints on the orbit structure and dark matter distribution in the galaxy's halo.

As large data sets of PN and GC velocities become available, advances in modelling methods are required in order to make constraints on the galaxy properties that are as rigorous and exploitative of the data as possible. In particular, one must allow for the systematic uncertainty in the distribution of orbit types, and make use of the higher-order velocity moment information implicit in the discrete measurements. To this end, we have developed an extension of the now established approach of orbit modelling[27].

We start with an assumed functional form for the galaxy's gravitational potential, and build within it a library of different orbit types, representing stars or GCs; their distribution function is then fully nonparametric. The model is projected onto a number of observables, and fitted to the data (including the discrete velocities) using maximum likelihood techniques (see Fig. 2, left). Different mass normalizations and functional forms for the potential are then tested for the best statistical fit. We have applied our models to M87, fitting 234 GC velocities in combination with a limited amount of integrated-light stellar data. We find a massive dark halo with a radial profile remarkably consistent over the region of overlap with that found using X-ray data[28] (see Fig. 2, right)—attesting to the reliability of both approaches. The SAURON team has developed complementary techniques for their studies of the inner parts of early-type galaxies[2], and I plan to collaborate with them on a combined analysis of our joint data sets with a high degree of generality—probing these galaxies' dynamics from central black hole to outer dark halo.

I have in the past used X-ray emission data to study the shapes of elliptical haloes[29], and plan to continue such work, analysing data from the new telescopes Chandra and XMM-Newton. This is a further powerful avenue for constraining mass distributions (directly) and stellar and GC dynamics (indirectly). We thus have tools in hand—observational and theoretical—to plumb the mysterious depths of galaxy haloes, and so to elucidate many unrevealed aspects of the evolutionary history of the universe.

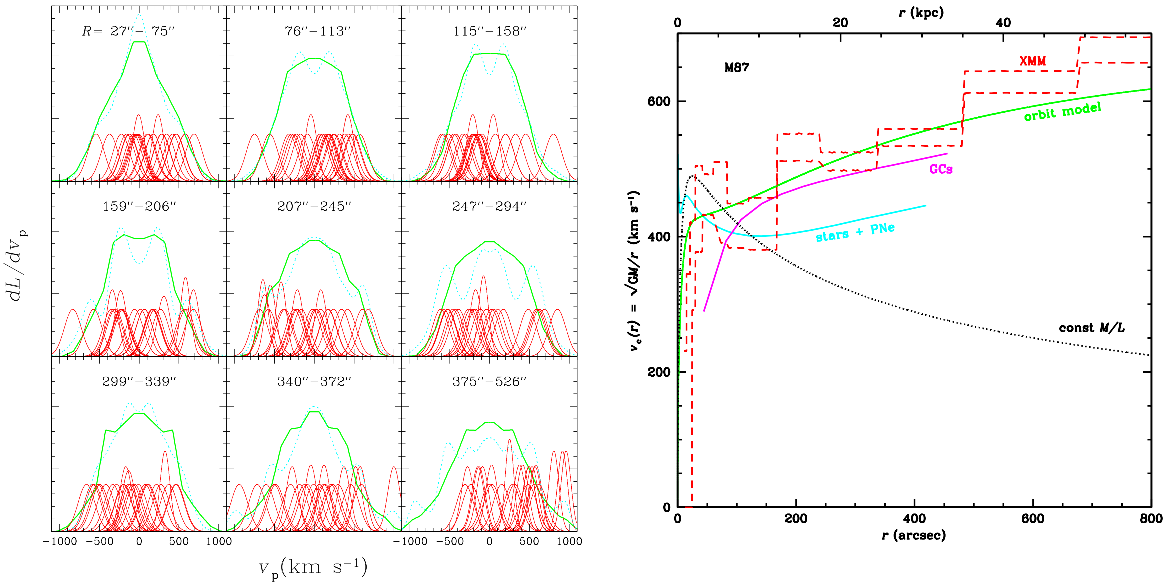

Figure 2. Orbit models of M87. *Left*: Line-of-sight velocity distributions (LOSVDs) for the globular cluster system, in nine radial bins. The light green lines show the best-fit singular isothermal solution, averaged in each bin. The dark red lines show the data (26 points in each bin). The dotted blue lines show simulated LOSVDs derived from the superposition of the data in each bin. *Right*: Circular velocity profile. Lines show the best-fit orbit model, and results from isotropic Jeans modelling using the GC data or the stellar + PN data. The dashed lines show limits from analysis of the X-ray emission[28]. The dotted line shows a constant mass-to-light ratio solution.

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