MARIANGELA BERNARDI: RESEARCH (April 2019)

Summary:
As an Assistant Professor at Penn, I used primarily the Sloan Digital Sky Survey (SDSS) to quantify various properties of early-type galaxies in the Universe. As an Associate Professor, my expertise has grown to include the photometric analysis of galaxy images (my background as a student and postdoc was with spectroscopic rather than photometric data). In addition, my interests now extend well beyond early-type galaxies, although their formation and evolution is an issue which is still particularly dear to me! As I describe in more detail below, my more recent work has had broader impact:

- My group produced the UPenn SDSS PhotDec Catalog of *all* galaxy types in the SDSS survey. Among other things, this has led to a substantial upward revision of the world's estimate of the mass in stars in the local universe, and so has garnered hundreds of citations.

- My group identified a new mass scale, $2 \times 10^{11} M_{\rm Sun}$, in the galaxy population: we argue that, above this mass, assembly by mergers matters at least as much as in-situ star formation.

- My group were pioneers in the use of Deep Learning techniques to estimate galaxy morphologies directly from the image pixels in galaxy surveys. Such algorithms are necessary to turn the next generation of Big Datasets into Big Discoveries. The longer term goal is to extend DL methods to estimate stellar population properties (age, star formation history, chemical abundance) directly from the spaxels provided by spatially resolved spectroscopic surveys such as MaNGA.

- My group produced two Value Added Catalogs which were included in the official SDSS-IV Data Release 15: the `MaNGA PyMorph DR15 photometric catalogue` and `MaNGA Morphology Deep Learning DR15 catalogue`. We use these to illustrate the power of combining reliable photometry and morphological classifications with spatially resolved spectroscopy. We showed that the stellar populations of slow (SR) and fast (FR) rotator ellipticals are significantly different and that one should not ignore the FR/SR dichotomy when studying galaxy formation and assembly histories.

- My collaborators and I identified what may prove to be an important bias in Jeans-equation estimates of the masses of galaxies. We showed that self-consistently accounting for M_*/L gradients when estimating the stellar (M_*) and dynamical ($M_{\rm dyn}$) mass yields good agreement between the two (gradients reduce $M_{\rm dyn}$ while only slightly increasing the M_*; this contradicts many recent studies which ignore gradients and conclude that agreement can only come by increasing M_* significantly while leaving $M_{\rm dyn}$ unchanged). Thus, even for the most massive galaxies, the concordance value for M_* is close to that associated with a Kroupa (not Salpeter) IMF. These results, in addition to affecting models of how and why star formation shuts off in massive galaxies, also impact the constraints that observed galaxy velocity dispersion profiles place on modified gravity models.

- My collaborators and I identified an important bias in currently available catalogs of super massive black holes. Accounting for this bias resolves a number of puzzles associated with the connection between galaxy formation and black hole growth, the relation between quiescent and active galactic nuclei and their host galaxies, as well as gravity wave non-detections.

Most astronomers agree that a galaxy is a collection of stars embedded in, or surrounded by, a much larger dark matter halo. However, there is no concensus on how galaxies actually formed. Dark matter itself cannot make starlight (hence the name) – for this, one needs 'baryonic' matter. The baryonic matter is expected to have initially been a smoothly distributed gas, mixed in with the non-baryonic dark matter. As gravity rearranged the smooth distribution into a clumpier one, the gas formed stars which were eventually assembled into galaxies. A complete understanding of this process is confounded by the fact that not all galaxies are the same. Galaxies come in a range of masses, luminosities, colors, sizes, morphologies, and so on. Nevertheless, most galaxies are one of two types: spirals, which are flattened and look slightly bluer because they are still forming new stars, and spheroidals, which are rounder and look redder because they stopped forming stars a few billion years ago, so they are loosely referred to as being 'red and dead'. Although both types have approximately spherical dark matter halos, the stars in spiral galaxies are arranged in a flattened disk as they rotate together around a small central bulge. In contrast, the stars in spheroidals are essentially all in a bulge, in which there are no collective ordered motions, and there is no disk. The physical mechanisms which govern galaxy formation are expected to leave signatures in the stellar orbits and hence the light profiles of the galaxies. So, the community and I have invested significant effort in quantifying the photometric and spectroscopic observable properties of galaxies.

`PyMorph` and the UPenn SDSS PhotDec Catalog:
Over the last eight years, my group has spearheaded the development and use of a fast algorithm – `PyMorph` – for quantifying the distribution of starlight in galaxies (Meert et al. 2013, 2015, 2016). `PyMorph` provides a unified framework for fitting a number of different parametric one- and two-component models (de Vaucouleurs, Sérsic, de Vaucouleurs+Exponential, Sérsic+Exponential) to the 2-dimensional images of galaxies. It also makes a much better estimate of the brightness of the night sky – a crucial step in estimating the light from distant galaxies – than was used previously. The *UPenn SDSS PhotDec Catalog* provides on-line access to our `PyMorph` fits to the $\sim 670,000$ galaxies in the SDSS DR7 Main Galaxy Sample. Fits in several visible bands (g, r and i) are provided, as well as additional data collected from other sources (different estimates of stellar masses, morphologies, Yang and MaxBCG group catalogs, UKIDSS, GALEX, and more) to facilitate other synergistic analysis. As such, this catalog represents a significant service to the community.

`PyMorph` and stars in the local Universe:
The simplest constraints on galaxy formation models are obtained just by counting how many low and high mass galaxies there are. Until recently, galaxy formation models which were able to match the observations of distant galaxies tended to over-predict the counts locally. As I describe below, this is largely due to what many believed was the least likely reason: problems with the local counts.

My students and I have used `PyMorph` to show that previous work significantly underestimated the light in the most nearby massive galaxies (Bernardi et al. 2010; Bernardi et al. 2013). The reason is two-fold: First, it is necessary to separate the amount of light in the image into a component which comes from the background sky rather than the galaxy of interest, and previous work overestimated the contribution from the sky, and hence underestimated the contribution from the galaxy (Meert et al. 2015). Second, the simplest (single-component) parametrizations of the light profile which were used a decade ago turn out to not be good enough; two-component fits are much more reliable (Meert et al. 2013; Bernardi et al. 2014). While it is well known that one must get the sky and the parametric model right, the fact that systematic errors associated with previous work on these two effects add, and contribute about equally, is new (Fischer et al. 2017). A number of other groups now agree that `PyMorph` is a significant improvement. As a result, a consensus is now emerging that systematic differences in the photometry of massive galaxies now account for less than 25% uncertainty in the local stellar mass density (Bernardi et al. 2017a). This is 10× better than the state-of-the-art a decade ago: clearly, our investment in this project has paid off.

Furthermore, our improved estimates result in a substantial increase in the world's estimate of the mass in stars in the most massive galaxies in the local universe (Bernardi et al. 2010, 2013, 2016, 2017a,b). Therefore, they alleviate tension between previous measurements which suggested that there was more mass in stars five billion years ago than there is today (clearly problematic!), and also dramatically affect inferred correlations between the stellar mass in a galaxy and the mass of the dark halo which surrounds it (Shankar et al. 2014): extreme feedback processes which shut off star formation are no longer needed. For this, our work has garnered hundreds of citations, and now serves as the low redshift benchmark against which evolution studies of higher redshift galaxies are compared.

A second mass-scale for galaxies: What's so special about 200 billion Suns?
Additional constraints on models come from the fact that different observable properties of galaxies are correlated with one another. E.g., the more massive galaxies tend to be redder, have larger sizes, and so on. Changes in these correlations are taken to indicate a more fundamental change in the population, such as how the stars were formed, why star formation was eventually shut off, or how the stars were assembled.

At low redshift, these correlations, often called scaling-relations, are particularly well-studied for the 'red and dead', 'early-type' galaxies which contain more than half the stellar mass in the local universe. My work provides the local benchmark of these relations (Bernardi et al. 2003b,c; Hyde & Bernardi 2009a,b; Bernardi et al. 2014), a prerequisite to studying evolution. E.g., it is the low redshift anchor in our study of mass assembly and morphological transformations over the last 10 billion years of cosmic evolution (Huertas-Company et al. 2016), and was a crucial step in our work on the size evolution of spheroids (Shankar et al. 2013, a study that has garnered more than a hundred citations).

It has been known for nearly two decades that the mass scale $3 \times 10^{10} M_{\rm Sun}$ is special: below this mass, gas dissipation (mass growth because of in situ star formation) plays a significant role, whereas mergers (mass growth by assembly of smaller pieces, rather than in situ formation) matter more above this scale. Soon after becoming tenured, I showed that galaxy properties appear to change dramatically again, at $\sim 2 \times 10^{11} M_{\rm Sun}$ (Bernardi et al. 2011a,b). Above this mass early-type galaxies are redder, larger and have smaller velocity dispersions and color gradients than expected based on simple extrapolation of the scalings at lower mass. In addition, there are essentially no spiral-like galaxies above this mass (Bernardi et al. 2014). Other groups have since shown that galaxies above this mass scale are slow-rotators and have cored profiles. This is also the mass scale where the specific star formation rate of the galaxy (the ratio of the mass being formed to that already present) is the same as the specific mass accretion rate of the halo which surrounds it. In contrast, there is no feature in most correlations with velocity dispersion (Bernardi et al. 2011b). Why this is so is an open question.

Deep Learning for Galaxy Morphology in the Big Data Era:

Astronomy is entering the Big Data era. The wealth of data which are/will soon be available, from the Dark Energy Survey (DES), EUCLID and the Large Scale Synoptic Telescope (LSST), will be invaluable for our understanding of galaxy evolution. However, extracting and interpreting information from these enormously rich datasets is a challenge with no sufficiently efficient, demonstrated solutions to date. Morphology is a key observable for constraining galaxy formation models, but quantifying morphology is currently a time consuming process that is severely compromised by this big-data transition.

My own group were pioneers in the use of Deep Learning (DL) – a technology implemented in most technology giants for performing complex image recognition tasks – towards fully automatizing the classification of galaxy images. We have produced some of the best photometry and morphological classification of SDSS galaxies, providing the most accurate classification of 600000 galaxies. Our goal was to provide a joint analysis of galaxy structure and morphology from the relatively local SDSS sample out to higher redshifts (DES, Candels). In Dominguez-Sanchez et al. (2018) we present the first DL analysis of galaxy morphology in the SDSS. Dominguez-Sanchez et al. (2019) shows that the DL algorithm used for the SDSS can be transfered to DES images, just like a good grad student who was trained on one dataset can apply what was learned to another one. This results in a significant savings in time and cost. We are currently extending our DL analysis to estimate the morphology of galaxies in DES (Dominguez-Sanchez et al. 2019, in prep). This will result in the largest catalog of galaxy morphologies available today covering the redshift range $0.5 < z < 1$.

In Fischer, Dominguez-Sanchez & Bernardi (2019) we show that the more reliable morphological classifications which our DL returns allow one to construct a cleaner picture of how the angular momentum varies across a population of fixed morphological type; this constrains models of how the population was assembled. In addition, galaxy formation models predict that the morphological mix of galaxies evolves; we are in the process of using our DL morphologies to test these predictions. When combined with the spectrocopic analyses described below, we can address questions like: Is the bulge of a galaxy older than its disk? Does the answer depend on galaxy mass?

The development of Deep Learning algorithms which quantify galaxy morphologies is the first step towards automated classification of other aspects of galaxy structure. My longer term goal is to develop algorithms which transform astronomically Big Data into Big Discovery in astrophysics.

MaNGA – Synergies from a joint analysis of photometry, spectroscopy and morphology:
Improvements in technology over the last decade have ushered in a new era in my field. Until recently, the spectrum of an object was estimated from a single aperture – typically a circle centered on the image, or a long slit aligned with the major or minor axis of the image – at a time. Now, however, it is possible to measure the spectrum from multiple apertures covering different parts of a galaxy simultaneously. This spatially resolved spectroscopy will revolutionize our understanding of galaxy formation. The MaNGA survey is the most ambitious of this new breed of data-set, and I played an important role in ensuring that Penn postdocs and students can participate in this collaboration.

My (all female!) group – postdoc Helena Dominguez-Sanchez and graduate student Johanna-Laina Fischer – have made a number of significant contributions. In recognition of the importance of good photometric and morphological information to complement the spatially resolved spectra, our work was included as two Value Added Catalogs of the SDSS Data Release 15:

– SDSS-IV VAC: MaNGA PyMorph DR15 photometric catalogue

– SDSS-IV VAC: MaNGA Morphology Deep Learning DR15 catalogue

A paper which describes the catalogs and illustrates how combining our Deep Learning morphological classifications with our PyMorph photometry and MaNGA rotation speeds and velocity dispersions has been published (Fischer, Dominguez-Sanchez & Bernardi 2019). This represents the tip of the iceberg of what such data enable.

MaNGA – Stellar population gradients and constraints on galaxy formation:
We are currently using MaNGA to study, not just global properties of objects, but gradients – changes from the center to the outskirts – in the stellar motions and chemical abundances in massive galaxies. By comparing spectroscopic gradients with `PyMorph`'s bulge-disk decompositions of the photometry, our analysis provides sharp constraints on models of galaxy formation and evolution. These gradients allow one to take a galaxy apart – much like peeling layers off an onion – to see directly if it formed from the inside out, or vice versa.

Two papers on spectroscopic gradients are under review: The first presents our estimates of age, metallicity, α-element abundance ratio and stellar initial mass function of elliptical galaxies (Dominguez-Sanchez et al. 2019). We use our estimates of the stellar populations to quantify how stellar mass-to-light ratio gradients vary across the elliptical galaxy population, finding a factor of 2 decrease from the central regions to the scale which encloses half the light. This is large enough to matter for dynamical mass estimates as discussed in Bernardi et al. (2018b). Self-consistently accounting for M_*/L gradients when estimating M_* and $M_{\rm dyn}$ yields good agreement between the two: gradients reduce $M_{\rm dyn}$ by ~ 0.2 dex while only slightly increasing the M_* inferred using a Kroupa IMF. Thus, even for the most massive galaxies, the concordance value for M_* is close to that associated with a Kroupa (not Salpeter) IMF.

A companion paper (Bernardi et al. 2019) expands our analysis showing that, at fixed luminosity and velocity dispersion, fast rotator ellipticals (FRs) are ~ 5 Gyrs younger, more metal rich and less α-enhanced than slow rotators (SRs). (Since these are ellipticals, the fast rotators are *not* disk galaxies!) Their stellar population gradients are also different (all quantities light-weighted from single stellar population synthesis models). At a given L_r and σ_0, FRs tend to be smaller than SRs. This explains why when one combines SRs and

FRs, objects which are small for their L_r and σ_0 tend to be younger. This also strongly suggests that gas dissipation leading to relatively recent star formation matters at least as much as the redshift of assembly in setting the sizes of ellipticals. This paper also presents a new detection of a sample of anomalously old, metal poor and [α/Fe]-enhanced ellipticals (galaxies with $\sigma_0 \sim 230$ km s^{-1} and $M_* \sim 10^{11} M_{\rm Sun}$). These tend to be central objects in halos less massive than about $3 \times 10^{13} M_{\rm Sun}$, but they are not satellites in more massive halos. It is probably no coincidence that this population straddles the same mass scale we mentioned above (from Bernardi et al. 2011a,b), at which early-type galaxy scaling relations change.

Stellar population gradients and constraints on gravity:
Since the structure of a galaxy is determined, at least in part, by the interplay between gravity and the nature of dark matter, our `PyMorph`/MaNGA estimates of the structure of galaxies potentially allows novel tests of both. In Bernardi et al. (2018b) we made the point that a factor of 2 change in the stellar mass-to-light ratio within galaxies, if unaccounted for, leads to biased constraints on the nature of gravity. Accounting for this is one of the reasons why Prof. K.-H. Chae (Sejong University) spent his sabbatical year working with me at Penn. This resulted in three published papers (Chae, Bernardi & Sheth 2018, 2019 and Chae, Bernardi, Sheth & Gong 2019).

Black holes, galaxies and gravity waves:
The most massive galaxies are expected to contain the most massive black holes in the Universe. However, directly measuring black hole masses in all but the nearest galaxies is beyond current capabilities. Therefore, it is common to estimate these masses using another more easily observed proxy; one calibrates the relation between black hole mass and proxy for the few (nearby) galaxies where this can be done, and then assumes that the same correlation applies for the more distant galaxies. This is only reasonable if the galaxies which host black holes are not a special subset of all galaxies.

While I was an Assistant Professor I showed that black hole hosts appeared to be different from most other galaxies (Bernardi et al. 2007). I argued that this is *not* because black hole hosts are intrinsically different, but because it is easier to find black holes in some galaxies than others (similarly to how it is easier to find Jupiter- rather than earth-like planets). However, since the correlation between black hole mass and observable proxy was calibrated on a biased subset, any proxy-based estimate of super-massive black hole masses is biased.

In a series of recent papers, my collaborators and I have been exploring the consequences of this for models which link galaxy evolution with the growth of the central black hole – the epoch when most of the stars in early-type galaxies formed coincides with the time in the Universe's history when quasars powered by accreting black holes were most active – and for searches for the gravitational wave signal associated with the mergers of these black holes. In Shankar et al. (2016, a paper which the Royal Astronomical Society highlighted with a press release in June 2016, and which has been cited nearly a hundred times), we argued that the bias in the calibration samples leads to systematic *over*-estimates of the true black hole mass. Accounting for the bias brings existing models of the galaxy-black hole connection into better agreement with the observations (Barausse et al. 2017); gives better agreement between black hole scaling relations of active and quiescent galaxies (Shankar et al. 2019a); shows consistency with clustering (Shankar et al. 2019b); implies significantly higher radiative efficiencies/black hole spins; and explains why pulsar timing arrays have yet to detect the gravitational wave signal expected from black hole mergers without having to resort to exotic physics (Sesana et al. 2016).

Finally, these studies also show that the mass of a black hole is determined by the velocity dispersion σ, rather than the mass, of its host galaxy (Shankar et al. 2016, 2017). My work on galaxy scaling relations has shown that σ is the controlling parameter for the stellar population of a galaxy (Bernardi et al. 2005), so our finding that σ is also the controlling parameter for the central black hole simplifies and constrains models in which the star formation history of a galaxy and the growth of the central black hole in its center are coupled. In particular, accretion onto the black hole is thought to power jets which can disturb the surrounding gas, perhaps heating it and preventing it from forming new stars. Smaller black holes are less able to shut off star formation, so are consistent with my upwards revision of the stellar mass in the local universe. In this respect, my work on producing more reliable black hole scaling relations, like my work on producing more reliable estimates of a galaxy's stellar mass, connects directly to the broader question of what shuts off star formation in massive galaxies.