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Report on the ESO Workshop

The Galactic Bulge at the Crossroads

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The Galactic bulge is of great interest to researchers working in several different areas and it has seen a surge of interest in recent years; indeed, half of the papers discussed at the meeting were published after 2014. This interest is motivated for several reasons: it is a primary component of the Milky Way, comprising ~ 25% of its stellar mass; and all major stellar populations intersect there, reaching their highest densities, thus making it truly a crossroads. Its formation is intimately related to that of the Milky Way, therefore it offers clues to understanding the structure, formation, and evolution of the Galaxy. A variety of bulge morphologies are seen in the local Universe, so a comparative study of the properties of the Galactic bulge helps with understanding bulge formation in general. Finally, ever more detailed studies of galaxies at high redshift promise to catch Milky Way proxies in their infancy, thus revealing the initial conditions of bulge formation. All of these aspects were reviewed by invited and contributed talks, and in poster sessions.

Motivations

In March 2017, some of the participants at the conference "On the Origin (and Evolution) of Baryonic Galaxy Halos" met over dinner at Puerto Ayora to consider the organisation of a conference in Chile to discuss recent progress on the Galactic bulge. A workshop proposal was then submitted to ESO, which was successful. Following intense preparatory work, coupled with additional fund raising, the meeting started on the afternoon of Sunday 9 December 2018, with a welcome cocktail on the terrace of the Gran Hotel Pucón. The hotel offers stunning views of the Villarrica lake. Later in the week, the weather was mostly cloudy, but interestingly, on Wednesday the sky cleared just in time to let us enjoy the free afternoon — set apart in the programme — and the impressive view of the Villarrica volcano was finally revealed! The day after, the weather was cloudy again, but in the evening the hotel terrace was illuminated by the folklore group *MasDanza*, who provided participants with a fascinating show of Easter Island dances, ahead of dinner at the hotel restaurant. The venue hosted five days of excellent presentations and lively discussions, which started on Monday morning with a welcome address by the deputy mayor of the city of Pucón. The healthy diversity of the participants is also worth stressing, with significant representation from the Chilean astronomical community, demonstrating its impressive growth in the last few years.

This article presents just a short summary of the main results that emerged during the conference, and their possible interpretation. This is followed by a discussion of open questions and the scope for future research.

Authors	Title
Kormendy & Kennicutt (2004)	Secular evolution and the formation of pseudobulges in disc galaxies
Somerville & Davé (2015)	Physical models of galaxy formation in a cosmological framework
Bournaud (2016)	Bulge growth through disc instabilities in high-redshift galaxies
Brooks & Christensen (2016)	Bulge formation via mergers in cosmological simulations
Fisher & Drory (2016)	An observational guide to identifying pseudobulges and classical bulges in disc galaxies
Shen & Li (2016)	Theoretical models of the Galactic bulge
Naab & Ostriker (2017)	Theoretical challenges in galaxy formation
Barbuy, Chiappini & Gerhard (2018)	Chemodynamical history of the Galactic bulge

Table 1. A list of recent reviews related to the formation of galactic bulges[a].

The basic facts

An impressive array of new observations was presented at the conference, so we attempt here to give the current overall picture of the Galactic bulge. This overview is of course biased, both because only a fraction of the literature was presented, and because it is based on our own interpretation of what was discussed. For a more comprehensive view, we refer readers to the Zenodo link to the presentations[1], and to the reviews listed in Table 1.

Like the Milky Way, most spiral galaxies populating the local Universe are barred (~ 60%); and if their mass is similar to that of the Milky Way, they have an 80% chance of having boxy or peanut-shaped bulges with high levels of cylindrical rotation. Velocities in the strongest barred galaxies are like those in the Milky Way. In addition, recent integral-field unit observations of barred discs show kinematics that are consistent with the Galactic bulge. Cosmological simulations are consistent with this picture; their end products are mostly pseudo-bulges formed *in situ*, with a fraction of them containing a classical component.

The emerging picture of the Galactic bulge is that of three components with different metallicities and different cylindrical rotation speeds, which first appear as a bimodal metallicity distribution function (MDF) with a metal-poor tail, and because the relative fraction of metal-rich to metal-poor stars decreases far from the Galactic plane, a vertical metallicity gradient is observed. The two main structures are a spheroidal bar with [Fe/H] ~ −0.5 and alpha-enhanced stars, with relatively slow rotation; and a boxy bar at [Fe/H] ~ +0.3 which can be further split into a slower, more metal-poor component ([Fe/H] ~ –0.24) and a faster, more metal-rich component ([Fe/H] ~ +0.18). The boxy bar hosts stars with solar to below-solar alpha-enhancement abundances. Furthermore, an X-shaped component (a manifestation of a boxy/peanut structure) becomes more and more evident as metallicity increases. B/P components are thought to be the inner 3D parts of a longer, flatter bar such as seen in NGC 4314, which has been detected by Wegg, Gerhard & Portail (2015).

The run of alpha elements vs. iron indicates that stars in the boxy component were formed later, and at a lower rate compared to the spheroidal component. However, while star formation certainly started more than 10 Gyr ago, as signaled by blue horizontal branch stars, the subsequent star formation history is still a matter of debate, with some studies finding an age-metallicity relationship extending to 3 Gyr ago. Indeed, cosmological simulations that can resolve bulges predict complex star formation histories, so reaching a consensus on the age distribution of Millky Way bulge stars will be essential to validate them and the evolutionary timeline pictured below.

The presence of a pressure-supported, classical bulge is still debated, but a non-rotating system of 43 confirmed globular clusters indicates that a relic of such a component should be present, even if significantly less massive than the others described above.

A small population of metal-poor ([Fe/H] < –1) stars not belonging to any of the above components is also detected, which could either be another signature of a minor classical bulge, or the inner extension of the Galactic halo. RR Lyrae stars have metallicities comparable to those of these stars, but it is unclear whether both belong to the same population; they are not rotating and might be a relic of an accreted system.

Finally, there exists a nuclear bulge of $1.4 \times 10^9 M_\odot$, which consists of an r^{-2} nuclear stellar cluster at the centre, a large nuclear stellar disc with radius 230 pc and scale height 45 pc, and the nuclear molecular disc of same size. And of course, at the very centre sits the supermassive black hole, which constitutes about 15% of the bulge mass.

Figure 1. Conference photo.

Open questions

While there appears to be broad consensus on the main characteristics of the Galactic bulge, it appeared at the conference that many fundamental questions still remain to be answered. We try to capture some of the main ones in the following paragraphs.

Age of bulge stars

For several decades the consensus has been that bulge stars are as old as those of Galactic globular clusters. However, some recent studies, (such as those of one of the speakers, Thomas Bensby), have suggested that younger stars could also be present in those regions. Using helium-enhanced isochrones might reduce Thomas's ages somewhat (Nataf & Gould, 2012; Nataf, 2017), but the conundrum is not completely solved. Elena Valenti and Cristina Chiappini suggested that this controversy might be solved by asteroseismology, which could yield ages with 20% uncertainties.

To stress the difficulty of obtaining ages, Elena Valenti pointed out that, even starting from the same set of Hubble Space Telescope (HST) photometric data, Renzini et al. (2018) and Bernard et al. (2018) come to different results. The latter find that most stars were formed earlier than 8 Gyr ago, while the former find that no more than ~ 3% of the metal-rich component can be ~ 5 Gyr old.

More support for old ages came from Francisco Nogueras Lara and his survey called GALACTICNUCLEUS (Nogueras-Lara et al., 2018), which uses the High Acuity Wide field *K*-band Imager (HAWK-I) at the VLT in combination with speckle holography (Schödel et al., 2013). On the other hand Francesca Matteucci predicts a non-negligible fraction of young stars, by modelling magnesium abundances vs. iron from Rojas-Arriagada et al. (2017).

How many MDF peaks?

The metallicity distribution function (MDF) was extensively discussed by Alvio Renzini, Christina Chiappini, Manuela Zoccali, and Thomas Bensby. While all authors agree on a broad metallicity range of –1.5 < [Fe/H] < +0.5, the details of the MDF differ, in particular the number of peaks and their position, with the added complexity that the MDF depends on the projected spatial position. The greatest variety is seen in the more central regions, where either two (GIRAFFE Inner Bulge Survey, GIBS) or three (ARGOS survey) peaks are detected. Away from the centre the Bulge RAdial Velocity Assay (BRAVA) found only one peak corresponding to the metal-rich population, because the metal-poor one is more centrally concentrated. To solve this conundrum, sharing data among different groups was suggested, in order to understand the origin of discrepancies and reach a consensus on the MDF vs. location.

Figure 2. The local organising committee members at the kickoff meeting on 16 October 2017.

No X-shaped component?

The presence of the X-shaped component rests on the assumption that the two clumps seen near the red giant branch in colour-magnitude diagrams represent helium-burning stars at different distances. This assumption was challenged by Martín López-Corredoira and Young-Wook Lee. The latter recalled that most globular clusters host multiple stellar populations, with a fraction of their stars having enhanced helium abundances. Stars with higher helium abundance end up on a brighter red clump compared to those with normal helium abundance; thus if the two red clumps were due to different abundances, and not to different distances, then stars in the two red clumps could have come from disrupted globular clusters, and the 3D structure of the bulge would be a bar embedded in a bulge with a more classical origin that would have formed at high redshift.

Martín López-Corredoira supported the idea of the absence of an X-shape by showing that only old and metal-rich red clump stars have an X-shaped distribution, while other distance indicators do not recover it.

Abundances of bulge vs. thin and thick discs

Bulge formation scenarios could be constrained by checking whether the bulge stars could have come from the thin or the thick disc. One way to do this is by using abundance signatures, which were discussed by several speakers. The consensus was that the three populations do differ in the run of abundances vs. iron, but larger stellar samples would help to settle this topic (see, for example, talks by Bensby, Rojas-Arriagada, Barbuy, Zasowski).

Which bulge structures are defined by RR Lyrae stars?

As noted above, MDFs show a tail of stars that are metal-poor, at [Fe/H] < –1, but their numbers are too small to allow them to be reliably associated with one of the known components. Thus, whether RR Lyrae stars and the metal-poor tail of red clump stars belong to the same population, is still an open question.

Another puzzle is the discrepancy between the results of the VVV and OGLE surveys, as shown by Manuela Zoccali and Igor Soszynski. While the Optical Gravitational Lensing Experiment (OGLE) finds a barred spatial distribution (Pietrukowicz et al., 2015), the VISTA Variables in the Via Lactea survey (VVV) finds a spheroidal one (Dékány et al., 2013; Gran et al., 2015).

Outlook

In the course of their presentations, many speakers listed potential valuable additions that would be necessary to improve on our current knowledge about the bulge. Some of their main ideas are listed here.

Abundances:
- Measure abundances (alpha elements in particular) of RR Lyrae stars, to understand to which population they belong.
- Check the extent of the multiple-populations phenomenon in the bulge, by measuring sodium abundances from high-resolution spectroscopy.
- Confirm the relative fractions of stars in different metallicity intervals by collecting data for stars closer to the Galactic plane, where current surveys have a gap.
- Agree on a common abundance scale, perhaps by giving the same data to different groups and exploring ways to make them converge.
- Measure [Fe/H] of dwarfs (not microlensed ones) with future large-aperture telescopes.
- Follow up Gaia stars with the 4-metre Multi-Object Spectroscopic Telescope (4MOST).
- Measure helium abundances, for example by resuming the R-method, using detached red giant branch eclipsing binary twins, or with Wide Field Infrared Survey Telescope (WFIRST) asteroseismology.

Extinction:
- Get 3D extinction maps, using diffuse interstellar bands (DIBs) and proper motions from WFIRST, the Multi-Adaptive Optics Imaging CamerA for Deep Observations (MICADO), and the Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE); also, higher-resolution maps of the variations of the extinction law across the bulge area.
- As shown by Kathy Vivas and Abhijit Saha, use RR Lyrae stars to obtain a reddening map at ~ 0.30 arcsecond resolution and use it to recover intrinsic colours of all stars in a region of the sky.

High-redshift observations:
- Find the time/redshift when the first bars can be seen.
- As suggested by Natascha Förster-Schreiber, exploit the improved spatial resolution of future instruments to increase the chances of detecting bars (for example, MICADO on ESO's Extremely Large Telescope will allow a 100-pc resolution at $z = 2$).
- Observe globular cluster formation — as suggested by Renzini (2017) — to

have a direct view of the origin of one of the bulge components.

Morphology:
– Prove or reject the existence of the X-shaped component with Gaia trigonometric parallax distances.

Ages:
– Measure ages via asteroseismology, to solve the age discrepancy issue. In addition, it would be interesting to give Thomas Bensby's spectra to other teams and see whether they can reproduce his results.

Complete census of bulge stellar clusters:
– For a census of clusters gravitationally bound to the bulge, we need to get their 6D kinematics and reconstruct their orbits, as noted by Angeles Perez-Villegas.
– Felipe Gran's talk was along the same lines and showed the promise of Gaia proper motions (coupled to the VVV survey) to discover new bulge clusters (he has already found a new one).

A wish list:
– Dante Minniti provided his own list of desirable data additions, which include Gaia Data Release 3, Vera C. Rubin Observatory observations of the Galactic plane and bulge, JWST observations of bulge RR Lyrae stars, the Multi-object Optical and Near-infrared spectrograph (MOONS) instrument for the VLT, and a *K*-band filter for WFIRST. He would also like to determine the specific frequency of globular clusters in the Milky Way and compare it to other galaxies.

Exploit current and future high-resolution and/or panoramic imagers:
– Roger Cohen highlighted the complementary nature of ground and space observations. Ground-based facilities offer higher flexibility, allowing observations in many bandpasses which permit spectral energy distribution (SED) fitting and determination of reddening values, followed by multi-object spectroscopy to characterise large samples of stars. Space observatories offer greater stability in the point-spread-function (PSF) thus allowing precise astrometry. This is the promise of the James Webb Space Telescope (JWST) with the caveat that in the bulge stars will be saturated down to the red clump.
– Sara Saracino showed the potential of the Gemini Multi-Conjugate Adaptive Optics System to obtain high-resolution imaging in the infrared, which can be matched to HST images in the optical.

Current and future surveys

Livia Origlia presented her view of the future of surveys aimed at the bulge stellar populations. These will represent a large jump in the number of stars with measured proper motions (VVV, UKIDSS, JWST, LSST, WFIRST), ages via main sequence turn-off photometry (JWST, LSST, ELT+MCAO imaging), and turn-off spectroscopy (extensive micro-lensing surveys and follow-up high-resolution spectroscopy at 8–10-metre-class telescopes, and then high resolution spectroscopy of main sequence stars with the ELT (for example using HIRES). Abundance and kinematics data will be obtained at low latitudes with multi-object spectroscopy and wide fields: for example, MOONS and later the Maunakea Spectroscopic Explorer (MSE); and integral-field units in dense fields (for example, with MUSE and ERIS on the VLT, and then HARMONI on the ELT). She also noted that multiplexing spectrographs will help with chemical tagging of stars but will not be enough for detailed chemical studies. For these, ELTs will be needed, in order to collect significant samples in a short time, such as with ELT/HIRES, which she described in more detail.

Formation

With the caveat that many aspects of the Galactic bulge are still being investigated, and thus the scenario will likely change in the future, we propose here a possible timeline that could link the findings presented above. This overview is based on talks by Alvio Renzini, Beatriz Barbuy, Manuela Zoccali, Sandro Tacchella, Juntai Shen, Victor Debattista, Natascha Förster-Schreiber, and Ignacio Gargiulo, but any misunderstandings are entirely ours!

While galaxy candidates are detected up to z = 10, there are only enough of them below z = 8 (i.e., ~ 13 Gyr-old candidates) to infer the cosmic star formation rate (SFR), which is about 15 times lower than its peak at $z \sim 2$. At all epochs most star formation happens in galaxies located on a main sequence, where the SFR is proportional to the stellar mass, up to a maximum of $10^{11}\ M_\odot$.

Cosmological simulations show gas flowing to the centre of such a protogalaxy, triggering a starburst. Then, as more gas is accreted in the outskirts, a disc forms. While observations show clumpy protogalaxies, in some simulations those clumps can survive and reach the centre, whilst in others they disperse quickly, so their significance in terms of galaxy evolution is not clear.

At z = 6 we start acquiring data on black hole accretion rates, which afterwards closely follow the trend in the cosmic SFR. At z = 3.5 we have the first measurements of the molecular gas fraction in galaxies, which decreases until today, when 90% of its mass has been converted into stars.

The star formation history of the Milky Way can be reconstructed from z = 3 (11.5 Gyr), at which point its stellar mass was ~ $10^9\ M_\odot$, or 2% of the current value. Then at z = 2.4 (11 Gyr) the first measurements of (negative) radial metallicity gradients are obtained in the discs of (lensed) galaxies.

At z = 2 the mass of the Milky Way would have grown to ~ $6 \times 10^9\ M_\odot$ or 30% of the current bulge mass. Observations of galaxies of that mass show that they are clumpy rotating discs, with no bar detected (clumps are luminous but minor in mass). Also, they have high velocity dispersion and gas density ~ 150 times that of a present galaxy with the same mass. Larger galaxies show central density enhancements (bulges) growing in importance with mass, until $10^{11}\ M_\odot$, when they are about 60% of the total mass. Observations at z = 2 have a 1.5 kpc resolution (for example, with the Wide Field Camera 3 WFC3 on HST), therefore in a galaxy like the Milky Way a central primordial bulge might go undetected. Indeed, the presence of globular clusters confined in the centre of the Galaxy suggests that a classical bulge must have been created in its early stages.

After a few hundred Myr, at $z \sim 1.5$, the Milky Way progenitor would have reached the mass of today's bulge. Because most of its stars are older than 8 Gyr, if the bulge was formed out of that early disc star formation should have stopped soon after $z = 1.1$. Possibly star formation was not reactivated because equatorial accretion streams had too high angular momenta to feed the bulge, which effectively remained "starved"; feedback from active galactic nuclei (AGN) could also have a role. On the other hand, some studies find evidence for the continuation of star formation after that epoch, so this remains an open question.

To account for observed correlations between metallicity and kinematics, stars should form continuously in a kinematically cool gaseous disc and acquire large radial random motions with time. Therefore younger, kinematically cooler, and more metal-rich stars should have coexisted in the $z = 2$ disc with older, radially hotter, and more metal-poor stars. According to models, age differences of 1–2 Gyr are enough to produce large observable differences in the properties of different [Fe/H] populations.

If gas in the bulge region was exhausted quickly as suggested above, then *n*-body models can be used to follow its later evolution. Starting from an exponential stellar disc, these models develop an instability that forms a bar, which then buckles into a boxy-peanut structure. Such simulations can also account for observed vertical metallicity gradients, by assuming that the initial axisymmetric disc had a radial metallicity gradient, or that the disc sees an increase of radial velocity dispersion with time. Thus the older and more metal-poor stars in the disc, which are kinematically hotter at the time of the bar formation, turn into a weaker bar and become a vertically thicker box. Stars born later are more metal-rich and radially cooler and form a strong bar, which is vertically thin and peanut-shaped.

If there were no exchanges between the disc-turned-bulge, and the later disc, then the bulge and disc might have stars with different age and chemical properties. On the other hand, abundances might be similar, if the later disc was formed out of pristine gas and experienced rapid SFR.

According to Debattista et al. (2019), the bar cannot have formed later than $z = 0.33$, so this event must have happened between 10 Gyr and 3.7 Gyr ago. An interesting endeavour would then be to look for the time/redshift when the first bars are seen.

Demographics

Almost one hundred participants attended (see Figure 1), from 19 countries, with Chile representing the largest fraction (34%). The second-largest population came from the USA (11%), followed by Germany, Brazil, Italy, and South Korea. Attendees from other countries represented 26% of the total; 32% of the participants were female, and a healthy 50% were young researchers (graduate students or post-docs).

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The success of the conference was largely due to the efforts of the Local Organising Committee, and in particular María Eugenia Gómez, Paulina Jirón, Cesar Muñoz, Doug Geisler, and Joyce Pullen; most of the Local Organising Committee members are shown at the kickoff meeting in Figure 2. Ivo Saviane would also like to thank all of the speakers who provided their slides.

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Links

[1] Zenodo collection of talks: https://zenodo.org/communities/galacticbulge2018
[2] Conference programme: http://www.eso.org/sci/meetings/2018/gbx2018/program.html

Note

[a] Recommended reading: *Galactic Bulges*, in Astrophysics and Space Science Library, 418, ed. Laurikainen, R., Peletier, R. & Gadotti, D., (Switzerland: Springer).