Southern Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 339, 2019
E. Griffin, ed.

doi:10.1017/S174392131800220X

Understanding the Galaxy

INVITED TALK

L. Eyer

Geneva Observatory, University of Geneva, Switzerland
email: Laurent.Eyer@unige.ch

Abstract. This general overview of our understanding of the Galaxy followed the lines of its main structures (halo, disc, bulge/bar) and emphasized some time-domain astronomy contributions. On the one hand the distance and tangential motions of the stars are essential to that understanding, and are obtained through multi-epoch surveys. On the other hand the chemistry of the stars and their radial velocities are also key elements for mapping the Galactic(sub-)structures, and unravelling their history and evolution. Contemporary surveys are revolutionizing our view of the Milky Way and of galaxies in general. Among those, the Gaia mission excels through its precise astrometry of 1.3 billion stars that populate the Milky Way and beyond, providing the first 3-D view of a major part of the Milky Way.

Keywords. Galaxy: general, Galaxy: structure, Galaxy: stellar content, Galaxy: evolution, stars: general, stars: variables, surveys, astrometry

1. Introduction: Understanding our Galaxy

Even the most simplistic yet satisfactory description of an object as complicated as our Galaxy demands a high-dimensional parameter space covering distributions in 6-D phase space and age, and in the multi-dimensional chemistry of its stars and interstellar medium, as well as the dark matter. These distributions are inherently complex, as there are several components (disc, bulge/bar, halo), and the disc (at least) is persistently forming new stellar generations. Furthermore, the Galaxy is not in equilibrium; it shows transient structures like the transient spiral arms, current accretion events (e.g. the Sagittarius dwarf), or bending waves and a disc warp.

Our ability to gather data – despite the apparently impressive amount of what we have currently – is still limited, and within those limitations there are some selection functions which can induce strong changes depending on the 'age-[Fe/H]-distance' space. The latter strongly affects the balance in samples comparing different populations. Moreover, the statistical properties of some fundamental parameters derived from certain observables are very tricky, one example being the distance. Some dynamical processes also need to be accounted for before we can decipher the Galactic past.

1.1. *The observables*

Knowledge in astronomy is mostly based on three main observational techniques†: astrometry, photometry and spectroscopy. The multi-epoch nature of these observables considerably expands the picture, as shown in Fig. 1. That Figure highlights the central role of time-domain observations in nearly all fields of stellar and Galactic astronomy.

† There are additional techniques such as the detection of particles (e.g. neutrinos), and gravitational waves.

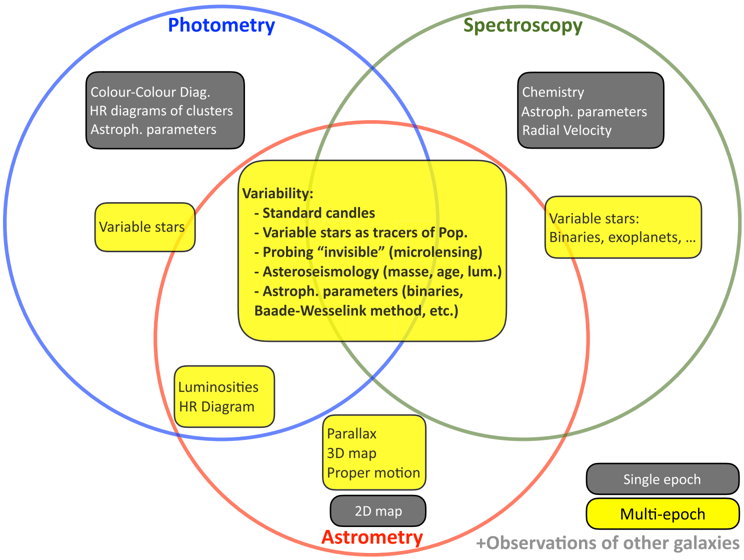

Figure 1. Venn Diagram of the three major observational techniques and the knowledge to which they contribute. The grey boxes with white writing explain what quantities can be derived with single measurements; the boxes with writing in black list what unique additional insight is being provided by multi-epoch observations.

1.2. *Deriving properties of stars from time-domain astronomy*

Stellar parallaxes and proper motions enable one to produce 3-D maps with tangential motions, and to determine absolute stellar magnitudes (though corrections should be applied to allow for interstellar extinction). There are, however, other fundamental contributions from time-domain astronomy. Some variable objects can serve as tracers of specific populations (e.g., RR Lyrae stars for the halo, or Cepheids for young stellar populations), while variable objects can contribute knowledge about their fundamental astrophysical parameters, e.g., the study of pulsating stars (asteroseismology), or the Baade-Wesselink method for binary stars. Variability can also be harnessed to establish the cosmic distance ladder (e.g., eclipsing binaries, Cepheids, RR Lyrae stars, supernovæ).

1.3. *Methods of modelling the Galaxy*

Modelling the Galaxy can be carried out through several broad approaches. (a) Jeans models. This approach determines mass distributions from the observed kinematics by using the Jeans equation. (b) Made-to-measure methods. Here the modelling can be achieved through N-body simulations (which are computationally expensive), or Schwarzchild methods. In both cases, the uniqueness of the model is not assured, i.e. several solutions may fit the data equally well. With the Schwarzschild method, models are very difficult to achieve since the parameter space is very large. That is because many orbits are needed to describe a galaxy, and too few orbits do not guarantee the right coverage of different orbit classes. In addition, the stability of a solution is not assured, and there is also a need to make some assumptions about the distribution of dark matter. (c) Action angle variables (Binney 2012). In this case the system is considered to be in axisymmetric equilibrium. Any non-axisymmetry is treated as a perturbation of the model.

In order to reach a more complete description of our Galaxy, there is the additional need to model its chemical evolution.

https://doi.org/10.1017/S174392131800220X Published online by Cambridge University Press

1.4. *Some examples of simulations*

Some researchers are simulating galaxies in isolation and are following the structure and the chemistry of the galaxies through self-consistent N-body chemo-dynamical modelling; see Revaz *et al.* (2016). Others are simulating the formation of a galaxy in a cosmological context; compare, for example, the Fire-2 (Wetzel *et al.* 2016), EAGLE (Schaye *et al.* 2015) and Illustris (Vogelsberger *et al.* 2014) simulations. These two approaches touch to some extent on the debate of 'nature versus nurture', i.e., how much is due to isolated natural evolution through physical laws, and how much is due to the perturbation of the environment or some initial conditions?

1.5. *The data flood*

In terms of observational facilities, astronomy has reached a very favorable state; technological and computational developments and space missions are benefiting observational astronomy fully. Such developments translate into a vigorous expansion of the three observational techniques described in Fig. 1. This tremendous evolution is not only qualitative but also quantitative: (1) in astrometry, with Gaia; (2) in photometry, with the major surveys like Gaia, LSST, Pan-STARRS, SkyMapper, OGLE, SDSS, Catalina, PTF/ZTF, Superwasp/NGTS, VVV, etc. Photometric projects have also provided, or will provide, dense sampling for asteroseismology through Kepler, CoRoT, TESS and Plato; (3) in spectroscopy, there are also many surveys such as SDSS, SEGUE, Gaia ESO Survey, Gaia (RVS instrument), APOGEE, RAVE, LAMOST, Galah, WEAVE, 4MOST, etc.

2. The Gaia Mission: an Exceptional Time-Domain Survey

Gaia is a space mission of the European Space Agency. It has already started to have an impact on many fields of astronomy. In particular, one of its primary science cases is to study the composition, formation and evolution of the Galaxy (cf. Perryman *et al.* 2001). Gaia fits that goal well, because its instrumentation covers all aspects of Fig. 1. Gaia is at heart a time-domain mission. It is making an impressive improvement in astrometric precision. It is also detecting and measuring tens of millions of variable stars.

2.1. *The Gaia Data Releases*

For the nominal 5-year mission (2014–2019), four data releases (DR) have been planned (DR1 in 2016, DR2 on April 25 2018, DR3 in 2020 and DR4 in 2022–2023)†. The second data release will contain a catalogue of more than 1.3 billion stars with the 5-parameter astrometric solution. The performance is magnitude dependent, and will reach parallax precision of 0.04 milliarcsecs. for sources at $G < 15$, and 0.7 milliarcsecs. at $G = 20$. DR2 will also contain over half a million variable stars.

2.2. *Distances with Gaia*

Deriving distances from astrometric measurements is tricky. It is often better to work in parallax space, where the assumption of symmetric distributions can be often made. That is not the case for distances, as explained by Luri *et al.* (2019).

† The mission can be extended by (at most) 5 years owing to limited fuel reserves. The ESA Science Programme Committee has decided to extend the mission to the end of 2020. Further extensions will be discussed by ESA in the general context of extending all ESA missions.

https://doi.org/10.1017/S174392131800220X Published online by Cambridge University Press

3. The Milky Way Global Structures in 2 Pages

Several reviews about the Milky Way have been published relatively recently, e.g., Bland-Hawthorn & Gerhard (2016), or in the 42^{nd} Saas Fee course book (Clarke, Mathieu & Reid 2015), so only a brief summary is needed here.

3.1. *The Galactic halo*

The stellar halo is the most extended structure of the Milky Way. The density of stars in the halo follows a power law, $\rho = r^{-3}$, with a cusp at small radii and a cutoff at large ones. About 150 Globular Clusters have been discovered in the halo, and a significant part of the halo field stars stems from them (Starkenburg *et al.* 2009).

The RR Lyrae stars prove to be extremely useful tools, both for the description of the halo and Globular clusters. On account of RR Lyrae stars, Catelan (2009) could exclude the possibility that the "Galactic halo may have formed from the accretion of dwarf galaxies resembling present-day Milky Way satellites". Sesar *et al.* (2017) were able to trace the Sagittarius stream in an unprecedented way by using Pan-STARRS data. In fact, many streams and concentrations have been observed, especially with SDSS data (Belokurov *et al.* 2006); some are due to accretion events and are composed of disc stars (Sheffield *et al.* 2018), or may have emerged from vertical waves in the outer disc (Xu *et al.* 2015). The interpretation of the streams is complicated, as the location currently observed deviates from the actual trajectory of the accreted objects (Eyre & Binney 2011). Indeed, it could be difficult to roll back the history of mergers (Jean-Baptiste *et al.* 2017), because the integrals of motions are not precisely conserved owing to further mergers, disc structure or dynamical friction, etc. Stars diffuse through phase space in angular momentum owing to stellar migration, or otherwise through heating, for example by spiral structure (mostly radial) and molecular clouds (mostly vertical). Their chemistry encodes the age and origin of each star and thus helps us reconstruct Galactic history and that diffusion or redistribution.

The duality of the halo has been under debate, both in respect of its composition and of its kinematic behaviour; see Beers *et al.* (2012), Schönrich *et al.* (2011), Schönrich *et al.* (2014). With the second Gaia data release, it is anticipated that the halo kinematics will be clarified. The region has been probed by several multi-epoch surveys in order to detect massive compact halo objects (MACHOs), which were thought to be forming the dark halo. In fact very few candidates were found towards the Magellanic Clouds. However, microlensing events are common in the direction of the bulge: about one variable star in 500 is a microlensing event. These multi-epoch surveys (MACHO, OGLE and EROS) brought to light many other diverse results besides constraining MACHOs; they include exoplanet detections through microlensing or transits, the discovery of many $\times\ 10^5$ variable stars, and new classes of variables. Gaia will determine the distances to the nearest Globular Clusters, and will detect new variable stars such as RR Lyrae or SX Phoenicis stars. Some maintain that the halo is nearly spherical, e.g., Read (2014) and Küpper *et al.* (2015), though there is no consensus. As Read pointed out, 6-D phase-space information from Gaia will be transformative for this topic.

3.2. *The Galactic disc*

The disc is comprised of many components, structures and substructures: field stars, interstellar matter, giant molecular clouds, clusters, spiral arms, and warps or waves. Some structures are being formed, others become transformed or even dissolved. Many processes are at play, yet despite such complexity the density distribution of stars can be described relatively simply by 2 exponential profiles in scale height (300 and 900 pc)

https://doi.org/10.1017/S174392131800220X Published online by Cambridge University Press

and scale length (2600 and 3600 pc); see Jurić *et al.* (2008). The thin disc and its general properties can be explained by the properties of the gaseous disc from which stars emerge, along with some heating mechanisms and angular momentum changes. The thick component represents 30% stellar surface density; it is composed of older stars, and therefore has a lower average metallicity, a higher α-element content and greater random velocities. Its origin has long been debated. Radial migration definitely plays an important role (Sellwood & Binney 2002, Roškar *et al.* 2008, Schönrich & Binney 2009). However, a mechanism is still needed to thicken the inner regions in order for radial migration to transport heat to the outer disc regions and thence form the thick disc (Aumer *et al.* 2017).

Asteroseismology contributes to Galactic studies by determining the ages of red giants. Their positions in an H–R diagram are not very informative because different masses and ages converge there, but direct measurements from stellar oscillations remedy the problem – see Casagrande *et al.* (2016); by combining Kepler data with Strömgren photometry, they found a vertical age gradient of 4 Gyr/kpc. However, there is large dispersion in age at all heights, and there is a flat age–metallicity relation for disc stars. In respect of dark matter, evidence for its presence in the form of a dark disc is weak; see Read (2014) and Schutz *et al.* (2017).

3.3. *The inner regions of the Galaxy*

The central black hole: Over 25 years of astrometric observations of stellar orbits revolving around the black hole at the centre of our Galaxy have enabled us to constrain the mass of that black hole at the 5% level; it is estimated to be $4.28 \times 10^6\ M_\odot$ (Gillessen *et al.* 2017). The black hole is surrounded by a nuclear star cluster (Schödel *et al.* 2009).

The nuclear disc: There was some evidence for a nuclear disc (Catchpole *et al.* 1990; Launhardt *et al.* 2002). More recently a kinematic detection and characterization of it with APOGEE spectra was made by Debattista *et al.* (2015); Schönrich *et al.* (2015) estimated its radius as 150 pc and its rotation velocity as 120 km s^{-1}.

The bulge/bar: The bulge/bar has been deduced from observations of several variable-star types: OSARG (Wray *et al.* 2004), Miras (Catchpole *et al.* 2016) or RR Lyrae stars (Pietrukowicz *et al.* 2015). It can also be traced by red-clump stars (Wegg *et al.* (2015) and Portail *et al.* 2017). The latter produced made-to-measure models based on VVV, UKIDS, 2MASS, OGLE, BRAVA, ARGOS surveys, determined the bar pattern speed, and derived stellar and dark-matter mass distributions. However, the bar's orientation – the angle made to the Sun–Galactic Centre line of sight – differs considerably from one study to another. Although there have been long-standing arguments about the distinct nature of the bulge and the bar and their origin(s), it seems that an *in situ* model of the formation and evolution can explain the present observations (Debattista *et al.* 2017).

4. Conclusion

The time domain is central to our understanding of the Galaxy, but spectroscopy (for deriving stellar chemistry and radial velocities) is also needed to comprehend it fully. New global multi-epoch surveys, in particular Gaia, will raise that understanding significantly.

Acknowledgements

I am indebted to Dr R. Schönrich, and also to Prof. D. Pfenniger and Drs Y. Revaz and P. Eggenberger for helpful discussions and for comments on this text.

https://doi.org/10.1017/S174392131800220X Published online by Cambridge University Press

References

Aumer, M., Binney, J., & Schönrich, R. 2017, *MNRAS*, 470, 3685
Beers, T. C., Carollo, D., Ivezić, Ž., *et al.* 2012, *ApJ*, 746, 34
Belokurov, V., Zucker, D. B., Evans, N. W., *et al.* 2006, *ApJ*, 642, L137
Binney, J. 2012, *MNRAS*, 426, 1324
Bland-Hawthorn, J., & Gerhard, O. 2016, *ARAA*, 54, 529
Casagrande, L., Silva Aguirre, V., Schlesinger, K. J., *et al.* 2016, *MNRAS*, 455, 987
Catchpole, R. M., Whitelock, P. A., & Glass, I. S. 1990, *MNRAS*, 247, 479
Catchpole, R. M., Whitelock, P. A., Feast, M. W., *et al.* 2016, *MNRAS*, 455, 2216
Catelan, M. 2009, *Ap&SS*, 320, 261
Clarke, C., Mathieu, R. D., & Reid, I. N., 2015, in: C. P. M. Bell, L. Eyer, & M. R. Meyer (eds.), *Dynamics of Young Star Clusters and Associations* (Springer), p. 205
Debattista, V. P., Ness, M., Earp, S. W. F., & Cole, D. R. 2015, *ApJ*, 812, L16
Debattista, V. P., Ness, M., Gonzalez, O. A., *et al.* 2017, *MNRAS*, 469, 1587
Eyre, A., & Binney, J. 2011, *MNRAS*, 413, 1852
Gillessen, S., Plewa, P. M., Eisenhauer, F., *et al.* 2017, *ApJ*, 837, 30
Jean-Baptiste, I., Di Matteo, P., Haywood, M., *et al.* 2017, *A&A*, 604, 106
Jurić, M., Ivezić, Ž., Brooks, A., *et al.* 2008, *ApJ*, 673, 864
Küpper, A. H. W., Balbinot, E., Bonaca, A., *et al.* 2015, *ApJ*, 803, 80
Launhardt, R., Zylka, R., & Mezger, P. G. 2002, *A&A*, 384, 112
Luri, X., *et al.* 2019, in: B. Montesinos, et al. (eds.), *Highlights on Spanish Astrophysics X*, p. 16
Perryman, M. A. C., de Boer, K. S., Gilmore, G., *et al.* 2001, *A&A*, 369, 339
Pietrukowicz, P., Kozłowski, S., Skowron, J., *et al.* 2015, *ApJ*, 811, 113
Portail, M., Gerhard, O., Wegg, C., & Ness, M. 2017, *MNRAS*, 465, 1621
Read, J. I. 2014, *J. Physics G: Nuclear Physics*, 41, 063101
Revaz, Y., Arnaudon, A., Nichols, M., Bonvin, V., & Jablonka, P. 2016, *A&A*, 588, A21
Roškar, R., Debattista, V. P., Quinn, T. R., Stinson, G. S., & Wadsley, J. 2008, *ApJ*, 684, L79
Schaye, J., Crain, R. A., Bower, R. G., *et al.* 2015, *MNRAS*, 446, 521
Schödel, R., Merritt, D., & Eckart, A. 2009, *A&A*, 502, 91
Schönrich, R., & Binney, J. 2009, *MNRAS*, 396, 203
Schönrich, R., Asplund, M., & Casagrande, L. 2011, *MNRAS*, 415, 3807
Schönrich, R., Asplund, M., & Casagrande, L. 2014, *ApJ*, 786, 7
Schönrich, R., Aumer, M., & Sale, S. E. 2015, *ApJ*, 812, L21
Schutz, K., Lin, T., Safdi, B. R., & Wu, C.-L. 2017, arXiv:1711.03103
Sellwood, J. A., & Binney, J. J. 2002, *MNRAS*, 336, 785
Sesar, B., Hernitschek, N., Dierickx, M. I. P., Fardal, M. A., & Rix, H-W. 2017, *ApJ*, 844, L4
Sheffield, A. A., Price-Whelan, A. M., Tzanidakis, A., *et al.* 2018, *ApJ*, 854, 47
Starkenburg, E., Helmi, A., Morrison, H. L., *et al.* 2009, *ApJ*, 698, 567
Vogelsberger, M., Genel, S., Springel, V., *et al.* 2014, *MNRAS*, 444, 1518
Wegg, C., Gerhard, O., & Portail, M. 2015, *MNRAS*, 450, 4050
Wetzel, A. R., Hopkins, P. F., Kim, J-h., *et al.* 2016, *ApJ*, 827, L23
Wray, J. J., Eyer, L., & Paczyński, B. 2004, *MNRAS*, 349, 1059
Xu, Y., Newberg, H. J., Carlin, J. L., *et al.* 2015, *ApJ*, 801, 105